Bioinspiration & Biomimetics

PAPER

Development and experiments of a bio-inspired robot with multi-mode in aerial and terrestrial locomotion

Won Dong Shin¹, Jaejun Park¹ and Hae-Won Park²*©

¹ Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, United States of America
² Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea

E-mail: haewonpark@kaist.ac.kr

Keywords: robotics, bioinspired design, multi-modal

Abstract
This paper introduces a new multi-modal robot capable of terrestrial and aerial locomotion, aiming to operate in a wider range of environments. The robot was built to achieve two locomotion modes of walking and gliding while preventing one modality hindering the other. To achieve this goal, we found the solution from Pteromyini, commonly known as the flying squirrel. Pteromyini utilizes its flexible membrane to glide in the air, and it shows agile movements on the ground. We studied Pteromyini to mimic the key features that allow Pteromyini to perform aerial and terrestrial locomotion. We adopted the flexible membrane and gliding strategy of Pteromyini to the robot. Through dynamics analysis and simulations, the overall design was determined. The flexibility of the membrane was also chosen considering the robot’s performance in the air and on the ground. The leg was optimized to perform with regulated motor torques in both walking and gliding. From gliding tests, the robot showed an average gliding ratio of 1.88. Inspired by Pteromyini, controlling the robot’s angle of attack with leg and tail movement was also adopted and tested. Different gait patterns and changing walking directions were tested to demonstrate the robot’s terrestrial performance. The average walking speed was 13.38 cm s⁻¹. The experimental results demonstrated the robot’s functionality in aerial and terrestrial locomotion.

1. Introduction

The ability to perform aerial and terrestrial locomotion is desired for searching robots in unstructured terrains, such as disaster areas and battlefields [1, 2]. Robots having such versatility have been built with inspiration from nature [3–9]. The jumping gliders proposed in [3–5] use stored energy to jump and then glide to reach their destinations. The jumping-gliding strategy is adopted by animals for both energy efficiency and long distance jumping [3–5]. Another platform introduced in [6] first climbs rough surfaced walls using its actuated claws, detaches from the wall, and then glides with its rigid wings. This locomotion strategy is known as the ‘top–down’ approach [10] and is found in many animals. Inspired by Desmodus rotundus [7] uses a propeller and wings for flying and transforms its wings to legs for walking. The wing-assisted robots in [8, 9] utilized their wings to enhance their terrestrial locomotion. Flapping wings to assist ground mobility is also found from birds.

Although these robots well match their expectations, their functionalities in one modality are limited compared to the other. The jumping gliders are unable to operate without certain ceiling heights due to their saltatorial strategy. The wall climbing glider in [6] did not demonstrate ground mobility. The robot inspired by Desmodus rotundus [7] is unable to fly without initial launching, and the robot leg had only one degree-of-freedom (DoF), which might limit the robot’s ground performance through a variety of obstacles. The wing-assisted robots in [8, 9] were not built to have two different modes.

To design a robotic platform that can achieve both versatile terrestrial and aerial locomotion, we have got inspiration from Pteromyini, commonly known as the flying squirrel. While on the ground, Pteromyini shows excellent terrestrial locomotion utilizing its quadru-
ped walking with high DoF legs. While in the air, *Pteromyini* glides by obtaining lift forces from the membrane between its legs. This distinguished multimodality comes from *Pteromyini*'s flexible membrane [11]. Although the membrane connects the fore and hind legs, the flexibility of the membrane allows the unconstrained movement of *Pteromyini*'s legs. Besides providing flexible movements of the legs and lift forces, the flexible membrane enhances *Pteromyini*'s gliding ability.

Several studies have focused on the advantages of flexible membranes found in animals [12, 13]. Song *et al* [12] showed that a flexible membrane has a higher lift coefficient than rigid plates and delays the angle-of-attack (AoA) at which stall occurs. Gordinier and Attar [13] performed a large eddy simulation to analyze the flexible membrane at low Reynolds number using a sixth-order Navier–Stokes solver. Also, flexible membranes have been applied to micro aerial vehicles [14–16] and to a jumping robot with wings [17], and recent research demonstrated the practical use of flexible membranes for a flapping robot [18].

Taking inspiration from *Pteromyini*, the purpose of this research is to design a legged robot (shown in figure 1) for aerial and terrestrial locomotion using a flexible membrane. In order to design such legged robots, the following design considerations are taken into account: (1) the membrane’s shape and area have to be carefully selected so that the membrane can provide desired aerodynamic performances. Because the membrane is attached to legs, the choice of shape and area of the membrane will also affect the design of legs; (2) the membrane must be flexible enough for unconstrained leg movement during gliding and walking. However, a flexible membrane could cause undesired energy loss, caused by fluctuations at the edges of the membrane where particularly strong pressure occur [19]; and (3) the robot’s leg has to be designed to provide sufficient torques for walking as well as gliding. To take into account the aforementioned considerations, we extensively incorporated characteristics of *Pteromyini* in the robot throughout design processes of the robot. The robot’s aerodynamic surfaces are designed by a parametric study of the wing design via dynamic modeling and simulation of the aerodynamics of the robot. The aerodynamic surfaces of the robot are further expanded with an application of extra aerodynamic surfaces, propatagium and uropatagium, of *Pteromyini* (section 3). The second consideration was successfully addressed by mimicking thick muscle bundles on the edges of *Pteromyini* membrane to the robot’s flexible membrane. With the mimicked muscle bundles, the membrane edge on the robot showed significantly reduced fluctuation, thereby decreasing the undesired energy loss. In addition, adding retractable wingtips to the robot reduced drag on the wing for better gliding performance (section 4). Lastly, applying the anatomy of *Pteromyini* to the leg design and minimizing motor torques during gliding and walking with a virtual work analysis (section 5), the leg design which provides sufficient torques for walking and gliding is obtained. With the novel integrated design of the legs and membrane wings, the robot achieved an average gliding ratio (GR) of 1.88 and safely landed with its AoA control. Also, the robot walked in several gait pattern and crawled with its high DoF legs. Through these gliding and walking performances, the robot demonstrated its multimodal functionality utilizing its flexible membrane and high DoF legs, which will be required to clear a variety of obstacles. The walking and gliding performances are recorded and provided in the supplementary material (stacks.iop.org/BB/14/056009/mmedia).

An initial version of this work was presented at 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2018) [20]. This extended article augments the initial version with entirely new experiments and simulations. The new results include proving the effects of thick muscle bundles around the membrane edges, wingtip, and EHA gliding strategy. EHA gliding and wingtip effects were analyzed through simulations. Also, a study on the wing area’s effects on aerial and terrestrial locomotion is included. The effect of thick muscle bundles was demonstrated from wind tunnel tests. In addition, the robot’s ability to change walking direction is performed. These augmented simulation and experiment results significantly contribute to the proof of concept for our bio-inspired design.

2. Background on *Pteromyini*

*Pteromyini* enhances its gliding ability with many beneficial physical characteristics, such as extra membranes, thick muscle bundles around the edges of its membranes, wingtips, and tail [19]. We took design principles from these biological advantages of *Pteromyini* and applied them to the robot to improve its gliding ability. This section introduces the features of *Pteromyini* applied to the robot and how *Pteromyini* utilizes these features when gliding.

Plagiopatagium (shown in figure 2) is the main source of lift [11, 19] and obtains several benefits from its flexible muscle structure. Being composed of thin muscles, plagiopatagium allows the flying squirrel to control tension on the membrane by contracting and expanding [19, 21]. This ability to control tension can reduce fluttering of the membrane, ultimately decreasing energy loss. In addition, while gliding, the compliant membrane forms a curve due to aerodynamic loading. The curve delays the angle at which the stall occurs and increases the lift to drag ratio (L/D) at high AoA and maximum lift C_L and drag C_D coefficients [12, 22]. After landing, *Pteromyini* contracts its membrane to prevent sagging of the membrane while walking [19].

In addition to plagiopatagium, propatagium and uropatagium expand aerodynamic surfaces of *Pteromyini* for more lift. The propatagium is located between the head and forelimbs of *Pteromyini*, and the uropatagium is located at the tail and hind limbs.
These surfaces at the front and back also decrease the aspect ratio (AR), which allows Pteromyini to glide at higher AoA. Higher AoA gliding provides Pteromyini more agility and more drag for landing [19, 23].

Pteromyini also has thick rope-like muscle structures on the extremities of the membranes to rigidly hold the shape of the membranes [19]. These muscle structures, called platysma, tibiocarpalis, and semitendinosus, are located on the propatagium, plagiopatagium, and uropatagium, respectively. During gliding, Pteromyini experiences particularly strong pressures against the edges of the membranes. This strong pressure can cause fluttering, a source of energy loss, on the edges. Pteromyini’s thick muscle structures reduce undesired fluttering and energy loss [19].
The main roles of the wingtips shown in Figure 2, located at the forelimb wrists, are to form an airfoil and to reduce induced drag on the body due to the development of wingtip vortices [11]. As mentioned, a low AR is beneficial in gliding agilely and inducing drag when landing. However, the consequence of a lower AR is the larger area, from the wrists to the ankles, for vortices to induce drag. The wingtip serves to weaken the vortices and prevents the induced drag from affecting the entire wing [11]. Using its thumbs, the flying squirrel unfolds its wingtips during gliding and folds them upon landing to avoid unwanted sagging of the wingtips [11].

The tail plays an important role to improve Pteromyini’s gliding ability. Unlike other vertebrates, the tail of Pteromyini is flattened to obtain more aerodynamic surface during gliding [10, 24]. Pteromyini is also able to control its tail for pitch angle stability during gliding [10].While landing, Pteromyini controls its tail to suddenly increase its pitch angle to induce more drag for deceleration and then gently lands on the ground or trees [19].

With the help of introduced body features, Pteromyini controls its gliding direction using its legs and tail. Because the shape of the membrane is flexible with leg movement, leg adjustments lead to control of (a) chord angle, (b) dihedral angle, between the membrane and the coronal plane of the body, and (c) membrane tension. The angle parameters are illustrated in Figure 3. Utilizing (a) and (b), Pteromyini is able to generate rolling, pitching, and yawing moment, which can be used to control body attitude as well as speed and direction of the gliding [25, 26]. Pteromyini also controls (a)–(c) to land on trees by utilizing EHA gliding [19, 24]. During EHA gliding, Pteromyini reduces its gliding speed by increasing drag with a rapid change in pitch angle, which is accomplished using its membrane and tail control [19, 24]. At the final moment of landing, Pteromyini further increases air resistance by loosening the tension of the membrane between its legs. As a result of decreased tension on the membrane, the membrane is inflated like a parachute [21, 24].

For the robot, we applied the introduced Pteromyini’s physical advantages such as extra membranes, thick muscle bundles, wingtip, and tail. Gliding and EHA motion control methods of Pteromyini were also programmed into the robot. Later sections explain how these characteristics are achieved in the robot.

3. Gliding analysis

This section introduces the design process of the wings for gliding capability. Taking inspiration from Pteromyini, the robot was designed to have propatagium, uropatagium, and tail, providing sufficient aerodynamic surfaces for gliding. The dimensions of the aerodynamic surfaces on the robot were initially modeled on the anatomy of Pteromyini [27, 28]. To verify the robot’s gliding availability, the stability margin has been analyzed via the dynamic modeling of the robot. Stability margin is an indicator representing the relationship between the neutral point (NP) and the center of mass (CoM) for stable flight [29], which determines the basic design parameters such as aerodynamic surfaces’ areas and locations based on expected weight. Stability margin is expressed as

\[ \frac{x_{np} - x_{com}}{c} \]

where \(x_{np}\) and \(x_{com}\) are the positions of NP and CoM from a reference point, respectively, and \(c\) is the average wing chord length. NP is the CoM position at which the system has neutral stability. For static stable gliding, the stability margin must be greater than zero [29]; consequently, the CoM must be located ahead of the NP for stable gliding.

We simulated gliding of the robot, both to verify whether the aerodynamic surfaces on the robot generate sufficient lift forces for gliding and to obtain the location of the CoM and NP for stable gliding. We also simulated EHA gliding by providing sudden changes in chord angles of the wing and tail. These simulations are described in the following sections.

Figure 3. Angle parameter pictorial explanation. The chord line is the line connecting forefoot and hind foot, and AoA is the angle between the chord line and the velocity vector.
3.1. Dynamic modeling

Three assumptions are made to simplify the model used for our robot: (1) We assumed a planar model on the sagittal plane to focus on pitch, which dominantly affects $C_l$ and $C_D$ during the gliding. We also omitted roll and yaw rotations. (2) The membrane and the tail are assumed to be flat and rigid using the quasi-steady flat model. This model is shown to provide a reasonable representation of the aerodynamic characteristics, even for post-stall [30, 31]. (3) The aerodynamic center is assumed to be located at one-fourth of the chord line from the front [32, 33]. Taking account of these assumptions, three reference frames are set: a fixed world frame $O$, a body attached frame $B$, whose origin is at the CoM of the body; an aerodynamic force frame $A$, whose $x$-axis is aligned with the direction of the robot’s velocity, and whose origin is located at the CoM of the body. The frames and parameters used for modeling are depicted in figure 4.

For this section, subscript $w$ and $t$ are used to represent the wing and tail, respectively. Superscripts represent the direction of the parameters are pointing in the negative directions (reused from [20] with permission of IEEE Xplore).

![Figure 4. Definitions of parameters used for dynamic modeling of the robot and the three frames. Frame $O$ is the fixed world frame. The $z$-axis is chosen to point in the same direction as the gravitational acceleration. Frame $A$ is a body attached frame located at the CoM. The $x$-axis of Frame $A$ is pointing in the opposite direction of the air flow. Frame $B$ is located at the CoM of the robot. Its $x$-axis is fixed along the robot’s body and points the front of the robot. The minus signs in front of the parameters indicate that current directions of the parameters are pointing in the negative directions (reused from [20] with permission of IEEE Xplore).](image)

where $\alpha$ is the AoA. Using these coefficients, the aerodynamic forces generated at the wing and the tail can be derived. Since the drag forces are aligned with the $x$-axis of the $A$ frame, the aerodynamic forces expressed in the $A$ frame are

$$
F_w^A = \begin{bmatrix} -D_w^0 & 0 \\ -L_w^0 & 0 \end{bmatrix} = \begin{bmatrix} -\frac{1}{2} \rho \| V_w^0 \|^2 S_w C_{D_w}^0 \\ 0 \end{bmatrix} \tag{4}
$$

$$
F_t^A = \begin{bmatrix} -D_t^0 & 0 \\ -L_t^0 & 0 \end{bmatrix} = \begin{bmatrix} -\frac{1}{2} \rho \| V_t^0 \|^2 S_t C_{D_t} \\ 0 \end{bmatrix} \tag{5}
$$

where $\rho$ is the density of the air, $S$ is surface area, and $V$ is the velocity of the aerodynamic center. The only unknowns in equations (4) and (5) are $V_w^0$ and $V_t^0$. These two vectors can be determined by solving the kinematics of the model. The position of each aerodynamic center (abbreviated to $acw$ and $act$ for wing and tail, respectively) expressed in the $O$ frame are:

$$
X_w^O = P_w^O + R_w^O P_{acw}^B, \quad P_{acw}^B = \begin{bmatrix} x_w + l_{acw} \cos(\phi_w) \\ z_w - l_{acw} \sin(\phi_w) \end{bmatrix} \tag{6}
$$

$$
X_t^O = P_t^O + R_t^O P_{act}^B, \quad P_{act}^B = \begin{bmatrix} x_t - l_{act} \cos(\phi_t) \\ z_t - l_{act} \sin(\phi_t) \end{bmatrix} \tag{7}
$$
where $\mathbf{P}_C^O$ is the position of the CoM and $\phi$ is the chord angle. Differentiating the position vectors results in $V_{Ow}^c$ and $V_{Ot}^c$.

$$V_{Ow}^c = \dot{X}_{Ow}^c$$

$$V_{Ot}^c = \dot{X}_{Ot}^c.$$  

Finally, the dynamic equations of the model are shown in equations (10) and (11) where $\mathbf{G}^O := [0, 0, g]^T$ and $g$ is the gravitational acceleration. These two equations represent the rotational motion of pitch and planar translational motion.

$$I\ddot{\theta} = \{\mathbf{P}_{acw}^b \times \mathbf{R}_{ac}^b \mathbf{F}_{ac}^A + \mathbf{P}_{act}^b \times \mathbf{R}_{ac}^b \mathbf{F}_{act}^A\}_{Y}$$

$$m\ddot{\mathbf{X}}^O = m\mathbf{G}^O + \mathbf{R}_{ac}^b \{\mathbf{F}_{ac}^A + \mathbf{F}_{act}^A\}, \quad \mathbf{X}^O = [x, y, z]^T$$

where $\{a\}_y$ selects $y$-direction component of arbitrary $3 \times 1$ vector $a$, and $x, y, z$ and $z$ are the position of CoM in $O$ frame. $\mathbf{IB}$ in equation (10) is along the $y$-axis.

### 3.2. Simulation

Based on equations (10) and (11), gliding performance of the robot was simulated using MATLAB. The wing and tail chord angles were fixed to $-5^\circ$ and $-18^\circ$, respectively. These values were obtained from gliding experiments with a primitive prototype, which was built to get intuitive ideas about our robot including initial setup for the wing and tail chord angles and gliding velocities. The gliding velocities of the primitive prototype were measured using Vicon motion capture system and used for initial velocities of our model in the simulations. $x_w, x_t$ (shown in figure 4), and $S_t$ were set as the variables because these parameters are easily adjustable when designing the robot and directly related to the location of the CoM and NP. The parameters were iteratively hand-tuned based on the knowledge of the stability margin and physical configuration of the actual robot. We aimed to reduce huge or rapid changes in the gliding velocities, angle of attack and body pitch during the transient responses while keeping the stability margin positive. The simulation results for the trajectory, velocity, AoA and body pitch of the robot are shown in figure 5. As the results demonstrated, the robot glided stably with a GR of 2.14. The CoM and NP locations were 0.5 cm and 1.21 cm from the middle of the fore and hind shoulders, respectively.

With the same parameters, EHA gliding was simulated as shown in figure 6, and the simulation results verified the possibility of inducing EHA gliding with the wing and tail control. The control inputs, changing wing and tail chord angles, were given when the robot reached steady-state. The same $C_s$ and $C_D$ in equations (2) and (3) are used for high AoA gliding in the simulation, as [30] proved the validity of the flat plate theory in high AoA gliding. Without any changes of $\phi_w$
and $\phi_t$, the velocities and AoA were stabilized. When gradual positive changes in $\phi_w$ or $\phi_t$ were applied, the velocities in the $x$ and $z$-direction were reduced, and the AoA and body pitch increased. Gradual negative changes in $\phi_w$ or $\phi_t$ induced the opposite results. The final conditions of the wing and tail chord angles were chosen as $\pm 20^\circ$ and $\pm 30^\circ$ considering the physical limitation of the robot and notable changes in the results.

Since the simulation results demonstrated stable gliding and EHA gliding, the robot was designed with the design parameters and the locations of CoM and NP used in the simulation. The final design parameters are tabulated in table 1. The legs and electrical components were placed so as to achieve the desired CoM location. The desired NP was achieved with a location adjustment of the wings and tail. The membrane location was adjusted by moving the entire membrane with appropriate selections of fore and hind feet locations during gliding mode. We present the gliding experiments in section 8.1.

The dynamic model and simulation proposed in this section will be further used in section 6 to analyze the choice of wing area $S_w$ which is closely related with overall sizing of the robot.

### 4. Membrane design

The second consideration was to ensure that the membrane does not impede leg movement during walking and to reduce energy loss from membrane fluctuations on the edges. The walking performance is ensured by selecting a silicone with an appropriate Young’s modulus considering the Weber number and pretension. Fluctuations on the membrane edges are eliminated by applying the thick muscle bundles on the edges of *Pteromyini* to the robot. As a result, a novel silicone wing design with muscle bundles was developed as shown in figure 7. This section provides the procedure for selecting silicone and the verifying reduced fluctuations of the membrane edges.

#### 4.1. Material selection

Weber number and pretension are crucial parameters used to define the properties and performance of the flexible membrane [12, 35, 36]. The Weber number is defined as

$$ W_e = \frac{U^2}{\sigma} $$

where $U$ is the velocity, $\sigma$ is the surface tension, and $L$ is the characteristic length. Pretension is defined as

$$ T = \frac{F}{L} $$

where $F$ is the force and $L$ is the length. Table 1. Design parameters (reused from [20] with permission of IEEE Xplore).

| Parameter | Value |
|-----------|-------|
| $x_w$     | -0.027 m |
| $x_t$     | -0.34 m  |
| $z_w$     | -0.041 m  |
| $z_t$     | -0.021 m  |
| $L_{sww}$ | 0.045 m  |
| $L_{st}$  | 0.121 m  |
| $S_w$     | 0.1522 m$^2$ |
| $S_t$     | 0.0271 m$^2$ |
| $m$       | 0.42 kg |
| $I$       | $5.789 \times 10^{-3}$ kg$\cdot$m$^2$ |

*Figure 6.* The changes in (a): $x$ velocity, (b): $z$ velocity, (c): AoA, and (d): body pitch. When the chord angles of the wing ($\phi_w$) and tail ($\phi_t$) were increased, the robot showed EHA gliding and showed the opposite when $\phi_w$ and $\phi_t$ were decreased.
We = \frac{\rho v^2 c}{\sigma} \tag{12}

where \( \rho \) is the density of the fluid, \( v \) is the free stream velocity, \( c \) is the chord length, and \( \sigma \) is the surface tension, which is defined as \( \sigma = E t \), where \( E \) is Young’s modulus of the membrane and \( t \) is the membrane thickness. Arbos-Torrent [22] distinguished between a rigid composite plate and a compliant membrane using their Weber numbers. A higher Weber number correlates with more flexibility of the material. The Weber number for a compliant membrane was roughly \( 10^{-5} \) with a Reynold number of \( 9 \times 10^4 \), 200 \( \mu \)m of thickness and a constant chord length in [22]. Under the same conditions, a Weber number for the rigid composite plate was roughly \( 10^{-10} \). Taking account of these results, we selected Dragon Skin 10 (100% \( E = 0.1152 \) MPa) from Smooth-On, Inc. Dragon Skin 10 has the \( E \)-value resulting in a Weber number of roughly \( 10^{-5} \) with a constant chord-based Reynolds number of \( 9 \times 10^4 \). Considering both better flexibility and elongation break, the membrane was...
manufactured with a thickness of 110–150 µm. An empirically determined pretension was given to the membrane when the membrane was attached to the robot. Therefore, the membrane was stretched without exerting excessive tension on the legs during both gliding and walking.

4.2. Fluctuation reduction
Taking inspiration from Pteromyini, platysma, tibiocarpalis, and semitendinosus were mimicked using elastic cords and embedded at the edges of the membranes. The cords were embedded to passively reduce membrane edge fluttering and maintain the shape of the membranes. In addition, elastic cords stretch according to stride length to avoid hindering the robot’s walking motion. To verify the functionality of the embedded strings on the membrane edges, we observed fluctuations of the membrane edges in a wind tunnel. An experiment was conducted on a membrane with an embedded elastic string; for comparison, the other experiment was conducted on a membrane without an embedded elastic string. To accentuate differences, the flow rate of the wind tunnel was set to 10 m s⁻¹, which is faster than the average gliding speed of the robot. In general, faster wind speed results in more fluctuations [37]. Through analysis of the videos captured by a high-speed camera, the frequency and amplitude of fluctuations were measured. As shown in figure 8(a), the membrane with an embedded elastic string showed an edge fluctuation of 2 mm in amplitude approximately. However, the membrane without an embedded elastic string fluctuated at 34 Hz with 10.6 mm of amplitude, as shown in figure 8(b). These results proved the effective functionality of the embedded string in gliding conditions.

5. Leg design for gliding and walking
This section mainly discusses the design of the legs which will provide appropriate and sufficient torques for walking and gliding. This design was done by studying the relationship between leg design parameters and motor torques and designing an optimal leg that retains motor torques in an acceptable range during operation. We also designed a passive wingtip structure to reduce drag induced from vortices. The following subsections provide detailed explanations of: (1) the torque analysis on the leg design and (2) the passive wingtip structure.

5.1. Torque analysis
The first step of the leg design process was to choose the basic leg structure. A five-bar linkage parallel mechanism [38] was selected as the basic leg structure (shown in figure 9) to locate motors proximal to the body. Such motor placement results in reduced motor torques by decreasing leg inertia. In addition to the five-bar linkage parallel mechanism, a shoulder motor was added for easy control of the dihedral angle during gliding. To finalize the design, the parameters such as \( L_1 = L_5, L_3, \) and \( \theta_1 \) in figure 9 need to be determined. \( L_1 \) and \( L_5 - L_3 \), corresponding to the robot’s length of upper and lower limbs, respectively, were determined based on the affine functions relating weight and limb lengths of Pteromyini from [27]. The length of \( L_2 \), a link directly connected to the hip motor, was set to the maximum length for which \( L_2 \) did not touch the membrane when the hip motor rotated. Considering compactness, \( L_4 \) was minimized to place knee and hip motors as close as possible. Therefore, \( L_3, L_4, \) and \( \theta_1 \) were left undetermined.

To find a set of these undetermined parameters that retain the motor torques during operation within the motor’s torque capacity, we set our objective to minimize the maximum torque during gliding and walking. To observe a more general trend, the three parameters are converted to \( x = [L_3 + L_4, L_3/L_4, \theta_1] \), and lower bounds and upper bounds are set to \( x_l = [0.15, 2, \pi/2] \), \( x_u = [0.2, 4, \pi] \), respectively, considering compactness and the total length of the links. The objective function

\[
g(x) = w_1 f_1(x) + w_2 f_2(x)
\]  

(13)
was evaluated via parameter sweep where \( f_1 \) and \( f_2 \) are the maximum torque values during walking and gliding, respectively, and \( w_1 \) and \( w_2 \) are weights given according to the importance of \( f_1 \) and \( f_2 \).

The first function
\[
f_1 = \| [u_{hw}, u_{kw}]^T \|_\infty
\]

is the maximum torque during a complete period of walking where \( h \) and \( k \) stand for hip and knee, respectively, and \( w \) stands for walking. \( u_{hw} \) and \( u_{kw} \) are defined as
\[
u_{hw} = [u_{hw,1}, u_{hw,2}, \ldots, u_{hw,n}]^T
\]
\[
u_{kw} = [u_{kw,1}, u_{kw,2}, \ldots, u_{kw,n}]^T
\]
where the non-bold \( u \) with subscripts is a motor torque at an instance during the cycle, \( n \) is the number of discrete positions consisting the complete period of walking, and \( s \) represents the completion percentage of a cycle. \( J \) is the forward kinematics Jacobian, and \( F \) is the ground contact force, which is set to a quarter of the mass of the robot times the gravitational acceleration in the positive \( z \)-direction. It was assumed that the foot follows an ellipse trajectory and \( F \) is exerted on the foot throughout a complete walking cycle.

where non-bold \( u \) with subscripts is a motor torque at an instance during the cycle, \( n \) is the number of discrete positions consisting the complete period of walking, and \( s \) represents the completion percentage of a cycle. \( J \) is the forward kinematics Jacobian, and \( F \) is the ground contact force, which is set to a quarter of the mass of the robot times the gravitational acceleration in the positive \( z \)-direction. It was assumed that the foot follows an ellipse trajectory and \( F \) is exerted on the foot throughout a complete walking cycle.

The joint and foot trajectories and corresponding motor torques are shown in Figure 10.

The second function
\[
f_2 = \max(u_{hg}, u_{kg})
\]
is the maximum torque during gliding where \( u_{hg} \) and \( u_{kg} \) are torques on the hip and knee during gliding. \( u_{hg} \) and \( u_{kg} \) are scalar quantities since the legs are fixed when gliding. Figure 9 shows the model and parameters used to calculate \( u_{hg} \) and \( u_{kg} \). It is assumed that the tension is only applied in the \( x \)-direction and tension is evenly distributed on the leg. Furthermore, the distributed loading condition is converted to a point loading condition acting in the middle of the links. \( u_{hg} \) and \( u_{kg} \) are obtained by
\[
[ u_{hg} \ u_{kg} ]^T = J_{glide}^T F_{glide}
\]

where \( J_{glide}^T \) is a linear operator, which maps the force vector \( F_{glide} \) to the torque vector \( u_{glide} \).

Since the leg forms a closed loop with a loop-closure constraint at Joint 1 as shown in figure 9, obtaining \( J \) in equation (16) and \( J_{glide}^T \) in equation (18) is not trivial. The following procedure explains how \( J_{glide}^T \) is obtained using the same strategy proposed in [39].

The generalized coordinates of the model are defined as \( q = [q_1, q_2, q_3, q_4]^T \), where \( q_3 \) and \( q_4 \) depend on \( q_1 \) and \( q_2 \) due to the physical configuration of the leg. Having \( P_1 \in \mathbb{R}^{2 \times 1} \) as the Joint 1 position constraint vector, the constraint can be written as,
\[
\partial P_1 / \partial q = 0.
\]

The system loses some DoF because the constraint has rank \( \partial P_1 / \partial q = 2 \). Consequently, the total DoF becomes 2, and the system can be described using only minimal coordinates \( q_{\text{consist}} \in \mathbb{R}^{2 \times 1} \) [40]. The virtual displacements of generalized coordinates, \( \delta q \), and minimal coordinates, \( \delta q_{\text{consist}} \), are related as follows,
\[
\delta q = Q \delta q_{\text{consist}}
\]

where \( Q \in \mathbb{R}^{4 \times 2} \) is the linear operator, satisfying
\[
\partial P_1 / \partial q = Q.
\]

The principle of virtual work is then applied
\[
F_{glide}^T \delta q = (Bu_{glide})^T \delta q
\]

Figure 10. Motor angle trajectories during walking motion and corresponding foot trajectory and motor torques. (a) Shows trajectories of the motor attached joints and (b) represents foot and motor torque trajectories. \( q_1 \) and \( q_2 \) are shown in Figure 9. Ellipse was chosen as the foot trajectory. The torque values are obtained with the finally chosen leg parameters.

\[
\begin{align*}
\text{Figure 10. Motor angle trajectories during walking motion and corresponding foot trajectory and motor torques. (a) Shows trajectories of the motor attached joints and (b) represents foot and motor torque trajectories. } q_1 \text{ and } q_2 \text{ are shown in Figure 9. Ellipse was chosen as the foot trajectory. The torque values are obtained with the finally chosen leg parameters.}
\end{align*}
\]
\( (\delta q_{\text{consist}})^T Q^T (\frac{\partial P}{\partial q})^T F_{\text{glide}} = (\delta q_{\text{consist}})^T Q^T B u_{\text{glide}} \) \tag{23}

is derived. Reordering equation (23), \( J_{\text{glide}}^T \) is obtained from

\[ u_{\text{glide}} = (Q^T B)^+ (Q^T \frac{\partial P}{\partial q})^T F_{\text{glide}} = J_{\text{glide}}^T F_{\text{glide}} \] \tag{24}

where the superscript + represents the pseudo-inverse of the matrix. \( J_{\text{glide}}^T \) in equation (16) is derived in a similar manner.

Regarding \( f_1 \) as important as \( f_2 \), \( w_1 \) and \( w_2 \) in equation (13) are set to 1. Equation (13) was evaluated via parameter sweep, and the result is shown in figure 11, where the color represents \( g(x) \). The regions colored with the darkest blue have the lowest \( g(x) \) values. The final choice is marked with a red dot in figure 11. Except for torque values, we had to consider the compact design and wider workspace. For a compact design, our choice of \( q_f \) value was narrowed down to 90° and 120°. Also considering the wider workspace of the leg, the final values were chosen inside the darkest blue regions with the \( q_f \) value of 90° and 120°. The final values of \( L_3, L_4, \) and \( \theta_f \) were chosen to be 9.5 cm, 2 cm, and \( 2\pi/3 \) rad, respectively. The final values for all leg parameters are tabulated in table 2. This design was successfully implemented in the robot for walking and gliding. The experimental results of gliding and walking are reported in sections 8.1 and 8.2.

### Table 2. Leg parameters for the robot in figure 9 (reused from [20] with permission of IEEE Xplore).

| Parameter | Value |
|-----------|-------|
| \( L_1 \) | 0.09 m |
| \( L_2 \) | 0.02 m |
| \( L_3 \) | 0.095 m |
| \( L_4 \) | 0.02 m |
| \( L_f \) | 0.11 m |
| \( \theta_f \) | 2\pi/3 rad |

5.2. Passive wingtip structure

Having completed the design of the legs, the next step was to refine the wingtip design. The wingtips reduce induced drag as explained in section 2 [11] and are folded and unfolded by controlling flying squirrel’s thumbs [11]. They unfold the wingtips during gliding for better performance and fold the wingtips in during walking to eliminate interference with the ground [11]. To achieve these actuations without adding extra actuators, the passive wingtip in figure 12 was designed and added to the wrist of the robot. A non-stretchable...
wire and a stretchable wire are connected between the wingtip and the leg. When the robot stretches its legs outward in the gliding formation, a non-stretchable wire unfolds the wingtip by pulling the end of the wingtip toward the body. A stretchable wire is connected right above the wrist and exerts tension continuously. Therefore, when the non-stretchable wire is loose, the stretchable wire folds the wingtip in by pulling it toward the leg. To test the wingtip’s effectiveness at reducing a vortex and cutting down the induced drag on the wing, the airflow around the wingtip was simulated via computational fluid dynamics (CFD) analysis using SOLIDWORKS Flow Simulation. In figure 13, the right picture presents the vorticity result with the wingtip attached. It is shown that the vortex generated at the wing end is reduced when the wingtip structure is added. The maximum vorticity was around 400 s$^{-1}$ without the wingtip, but, with the wingtip, the maximum vorticity was around 330 s$^{-1}$. Also, as the dotted circle area indicates, the result with wingtip shows that the generated vortex on the top of the wing is kept under 40 s$^{-1}$. On the other hand, the vorticity on the top of the wing without wingtip was around 140 s$^{-1}$. These results indicate

---

**Figure 12.** Passive wingtip structure design. Depending on the foot position, the passive wingtip mechanism automatically folds and unfolds the wingtip. The dotted line represents the non-stretchable wire hidden behind the leg. With the passive wingtip design, an extra DoF is added without significant weight gain. The illustration of the front view shows the unfolded mode of the wingtip (redrawn from [20] with permission of IEEE Xplore).

**Figure 13.** CFD simulation results on the wingtip vortex using SOLIDWORKS Flow Simulation. The left-hand side shows CFD simulation vorticity result without wingtip, and the right-hand side shows the vorticity result with the wingtip attached. As the inside of dotted circles indicates, the vortex is weakened when a wingtip is attached.
that less drag will appear to the wing with a wingtip in the consequence of reduced vortex [11]. From this simulation result, it was verified that the wingtip attached to the robot performs the same functionality as the wingtip of Pteromyini.

6. Effects of wing area on aerial and terrestrial performance

In this section, we study the choice of the wing area $S_w$, which is an important design parameter that guides the overall design process of the wing. We varied the wing area and explored its effect on GR, steady-state velocity, mass property, and required torque for walking. We ran simulations with the aerodynamic center of the wing at the same location and with different wing area values, ranging from 50% to 150% where 100% is the setup used for the other simulations in section 3.2. We could calculate the wing mass values corresponding to different wing area values with the wing material’s density. The mass difference due to wing area difference was ranging from 70.83% to 129.17% where 100% is the setup used for the other simulations. Figure 14 shows the simulation results of steady-state $x$ and $z$ velocities and GR. The GR was increased as the wing area decreased and vice versa. This result was due to the significant increase in $x$-velocity and relatively consistent $z$-velocity with respect to the change of the wing area as shown in figure 14. 50% wing area increased $x$ velocity by 52.05%, decreased $z$ velocity by 2.34%, and increased GR by 40.36%. 150% wing area decreased $x$ velocity by 46.87%, increased $z$ velocity by 23.61%, and decreased GR by 56.97%. To increase

![Figure 14](image1.png)

**Figure 14.** $x$ velocity, $z$ velocity and GR corresponding to different wing area values. Blue lines indicate velocity values corresponding to the left $y$-axis, and the red line is the GR graph corresponding to the right $y$-axis. 100% wing area is the value used for the other simulations, and the green vertical dashed line indicates the results of our current model. It is assumed that positive $z$ velocity is along with the gravitational acceleration. Increased wing area slowed down $x$ velocity, slightly increased $z$ velocity, and decreased GR.

![Figure 15](image2.png)

**Figure 15.** Maximum hip and knee motor torque values with different leg lengths according to the changed wing area. When the wing area was 50% of current design, the motor torque values of hip and knee motors were reduced by 45.15% and 46.24%, 150% of current wing area increased the hip and knee motor torques by 58.03% and 60.26%, respectively. The green vertical dashed line indicates the results of our current model.
GR, the wing area can be decreased but it will result in higher steady-state velocities. Increased wing area will provide lower steady-state velocities, but the leg length should be increased accordingly, thereby changing torque requirement for walking. To observe the wing area’s effect on the torque due to changes in leg link lengths, we also calculated maximum torque values for walking with adjusted link lengths according to the different wing area. As figure 15 shows, larger wing areas increased the maximum motor torque values of both hip and knee motors during walking. 50% wing area decreased the hip and knee motor torque values by 45.15% and 46.24%, respectively. 150% wing area increased the hip and knee motor torques by 58.03% and 60.26%, respectively. Although greater GR and lower motor torque values are desired for efficient gliding and walking, when the wing area decreases, higher x-velocities may damage the robot when landing on the ground. Having a larger wing area had an advantage on safer landing due to decreased x and z velocities but showed significantly reduced GR and increased motor torque values. Wing area may be adjusted to obtain higher GR and lower power consumption on the ground or safer landing based on the purpose of the robot. The selected wing area in this study provides a GR similar to that of *Pteromyini*.

7. Fabrication

This section introduces the fabrication processes of the robot parts. Dragon Skin 10 from Smooth-On, Inc. was used to fabricate the membrane. The Dragon Skin 10 mixture is poured over a flat plate where 150 µm thick tape strips are placed on two parallel edges. Then, a flat bar is used to evenly spread the silicone on the plate. After curing is complete, the thin silicone layer is covered with fine powder to prevent stickiness. Table 3. Electrical and physical specifications for the robot (reused from [20] with permission of IEEE Xplore).

| Specifications                           | Value                     |
|-----------------------------------------|---------------------------|
| Body size                               | 72 × 53 × 15 cm (Gliding mode) |
| Body mass                               | 420 g                     |
| Aspect ratio                            | 1.8                       |
| Micro-controller                        | Raspberry Pi zero         |
| Battery                                 | Li-Po 7.4V (430 mAh)      |
| Servo motors                            | MKS DS-6100 × 13          |
| OS                                      | Linux/ROS                 |
| IMU                                     | Xsens MTi 10 series       |
| Servo driver                            | Adafruit-PCA9685          |

8. Experimental results

8.1. Gliding test

In this section, we validated our design of the flying squirrel robot through a series of experiments. We
Figure 17. Gliding trajectory data recorded using Vicon motion capture system. Five trials and their mean data are represented on the graph. The shaded region represents the standard deviation of the five trials. The best GR of the robot was 2.21, and the average was 1.88 (reused from [20] with permission of IEEE Xplore).

Figure 18. EHA gliding test data recorded using Vicon motion capture system. The dotted lines indicate the trajectories after control input is given to move the legs and the tail of the robot. After the control input was given, the AoA increased, and the velocities decreased for a safer landing (reused from [20] with permission of IEEE Xplore).
proceeded GR tests and EHA gliding tests in a facility having a Vicon motion caption system using the robot with specifications in table 3. The Vicon system was capable of measuring roll, pitch, and yaw angles and the cartesian position of the robot. Because of the installation heights of Vicon cameras, the Vicon system could not record motions above 3 m from the ground. For GR tests, an experimenter launched the robot from roughly 2.7 m above the ground at an average initial velocity of 3.17 m s\(^{-1}\) in the x-direction and −0.055 m s\(^{-1}\) in the z-direction. The highest GR of the robot was 2.21, and the average was 1.88, as shown in figure 17. These values were in the GR range of most of Pteromyini, i.e. between 1–3 [41].

EHA gliding tests proved the robot’s ability to control its pitch angle via its legs and tail movements. When the robot was close to landing on the ground, the legs and the tail were controlled by an experimenter’s manual command to increase the pitch angle of the robot. The angles of fore and hind legs and the tail were linearly changed in 0.4 s with user input. The wing angle was changed from −20\(^\circ\) to 80\(^\circ\), and the tail angle was changed from 0\(^\circ\) to 40\(^\circ\). It is known that flying squirrels change their wing and tail angle to

Figure 19. Time sequential trajectory of EHA gliding. EHA gliding was successfully induced with leg and tail control as the red lines on the robot’s body indicates. The two graphs under the picture show commanded angle trajectories of \(\phi_t\) and \(\phi_w\), which are defined in figure 4 (redrawn from [20] with permission of IEEE Xplore).

Figure 20. Gait pattern diagrams of walking trot and crawling. L and R stand for left and right, and F and H represent fore and hind, respectively. (a) Shows the walking trot phase, and (b) shows the crawling phase. For the crawling phase it is assumed that legs on the left are the supporting legs, and legs on the right side are pushing the body forward. Stance phase is when the foot make a contact with the ground, and swing phase is when the foot does not make a contact with the ground.
113 ± 2.8° and 81 ± 8.1° [42], but, due to the physical limitation of the robot, we could not try these angles to the robot. The experimental results are shown in figures 18 and 19. The AoA reached 64.03° on average after the robot controlled its legs and tail to induce EHA gliding. *Glaucomys volans*, commonly known as the southern flying squirrel, has AoA range from 35.4° to 53.5° [25]. Due to induced drag from EHA,
the horizontal velocity was reduced from 6.25 m s\(^{-1}\) to 4.49 m s\(^{-1}\), a 28.1\% reduction, and the vertical velocity was slowed from \(-3.24\) m s\(^{-1}\) to \(-2.41\) m s\(^{-1}\), a 25.7\% magnitude reduction within 0.3 s, showing horizontal and vertical acceleration of \(-5.87\) m s\(^{-2}\) and \(2.77\) m s\(^{-2}\), respectively. After safely landing on the ground by utilizing EHA, the robot could successfully shift to walking mode. The success ratio of shifting from gliding to walking was 83.3\% (5 out of 6). The failure was due to excessive rolling, which caused the robot to land with its legs, and the joints to be damaged.

### 8.2. Walking test

Walking tests were conducted to verify the robot’s ability to walk with different gait patterns and to change the walking direction. Walking trot and crawling (shown in figure 20) were tested because they are commonly found in animals and they tested the robot’s versatility in different heights. Figure 21 shows the velocity data recorded using the Vicon system. The average walking trot and crawling speeds were 13.38 cm s\(^{-1}\) and 12.95 cm s\(^{-1}\), respectively. The average and maximum heights of the CoM of the robot during walking trot were 11.05 cm and 13.82 cm, respectively, while the average and maximum heights of the CoM during crawling were 4.07 cm and 6.07 cm, respectively. The robot demonstrated a transition from a gait pattern to another pattern to pass a low ceiling obstacle, as shown in figure 22.

As the second part of the walking test, the robot’s steering ability was tested via three tasks: walking straight, turning left, and turning right. The robot walked utilizing a walking trot for all three tasks. As shown in figure 23, the robot controlled its walking direction and cleared the three tasks with its 3 DoF legs. The actuated joint angle trajectories for walking straight, turning left, turning right for three complete cycles are provided in figure 24. The crawling straight actuated joint angle trajectory is also added to figure 24 for comparison.

### 9. Conclusion

Taking inspiration from *Pteromyini*, the multi-modal gliding-walking robot was successfully designed and operated with dynamic modeling, a careful material selection, motor torque analysis and addition of beneficial physical characteristics of *Pteromyini*. Through dynamic modeling and the addition of extra aerodynamic surfaces, the robot achieved balanced CoM and NP locations for static stable gliding. A careful selection of silicone allowed walking without significant hindrance from the membrane, and embedded strings on the membrane edges efficiently reduced fluctuations on the edges during gliding. A leg design that reduces maximum motor torques was found via parameter sweep, and a passive wingtip was added to the leg for better gliding performance.

From experiments, stable gliding and walking are shown via the Vicon motion capture system. Also, the robot successfully showed EHA gliding with membrane and tail control, safely landed on the ground, and walked. In addition, the effects of thick muscle bundles on the edges of the membrane and wingtip are verified via experiments and CFD analysis.

For future research directions, the mass of the robot could be reduced by customizing parts such as motors and by changing silicone to lighter material. Reading roll, pitch, and yaw from an IMU sensor, the robot will be able to control its roll, pitch, and yaw with its membrane in real-time and then land at the desired position. Utilizing high DoF of the robot’s legs, the robot will be able to pass more complicated obstacles such as a bumpy and uneven terrain. In addition, adding claws on its feet will allow the robot to land and climb on trees.
Acknowledgment

This work is supported by Defense Advanced Research Projects Agency: Robotics Fast Track (DARPA RFT). The authors would like to thank Hae-Woo Chung and Qinru Li for assisting experimental setup and testing and coding with enthusiasm. The authors also appreciate Intelligent Robotics Laboratory (IRL) for Vicon motion capture system and Renewable Energy & Turbulent Environment Group at the University of Illinois at Urbana-Champaign for providing the wind tunnel. The authors have confirmed that any identifiable participants in this study have given their consent for publication.

ORCID IDs

Hae-Won Park 🌐 https://orcid.org/0000-0001-6130-6589

References

[1] Tadokoro S 2009 Rescue Robotics: DDT Project on Robots and Systems for Urban Search and Rescue (Berlin: Springer)

[2] Bihel M, Caccia M and Lapierre L 2007 Path-following algorithms and experiments for an autonomous surface vehicle IFAC Proc. Volumes 7 81–6

[3] Desbiens A L, Pope M T, Christensen D L, Hawkes E W and Cutkosky M R 2014 Design principles for efficient, repeated jumpgliding. Bioinspir. Biomim. 9 025009

[4] Woodward M A and Sitti M 2014 MultiMo-bat: a biologically inspired integrated jumping–gliding robot Int. J. Robot. Res. 33 1351–29

[5] Vidyasagar A, Zufferey J-C, Floreano D and Kovačević D 2014 Performance analysis of jump-gliding locomotion for miniature robotics Bioinspir. Biomim. 10 025006

[6] Dickson J D and Clark J E 2013 Design of a multimodal climbing and gliding robotic platform IEEE/ASME Trans. Mechatron. 18 694–505

[7] Ludovic Daler, Stefano Mintschev, Cesare Stefanini and Dario Floreano 2015 A bioinspired multi-modal flying and walking robot Bioinspir. Biomim. 10 016005

[8] Peterson K and Fearing R S 2011 Experimental dynamics of wing-assisted running for a bipedal ornithopter Int. Conf. on Intelligent Robots and Systems (IEEE) pp 8080–6

[9] Peterson K, Birkmeyer P, Pudley R and Fearing R S 2011 A wing-assisted running robot and implications for avian flight evolution Bioinspir. Biomim. 6 046008

[10] Norberg U M, Winkler D W and Hall C 1985 Evolution of vertebrate flight: an aerodynamic model for the transition from gliding to active flight Am. Nat. 126 303–27

[11] Thorington RW, Darrow K and Anderson CG 1998 Wingtip anatomy and aerodynamics in flying squirrels J. Mammal. 79 245–50

[12] Song A, Tian X, Israeli E, Galvao R, Bishop K, Swartz S and Breuer K 2008 Aeromechanics of membrane wings with implications for animal flight AIAA J. 46 2096–106

[13] Gordnier R E and Attar P J 2009 Implicit LES simulations of a low Reynolds number flexible membrane wing Airfoil 47th AIAA Aerospace Science Meeting p 579

[14] Albertani R, Stanford B K, Hubner J P and Ijifu P G 2005 Characterization of flexible wing MAV’s aerelastic and propulsion effects on flying qualities AIAA Atmospheric Flight Mechanics Conf. and Exhibit p 6324

[15] Hu H, Kumar A, Abate G and Albertani R 2009 An experimental study of flexible membrane wings in flapping flight AIAA Aerospace Science Meeting p 579

[16] Wu P, Ijifu P and Stanford B 2010 Flapping wing structural deformation and thrust correlation study with flexible membrane wings AIAA J. 48 2111–22

[17] Li F, Liu W, Fu X, Bonsignori G, Scarfoglieri U, Stefanini C and Dario P 2012 Jumping like an insect: design and dynamic optimization of a jumping mini robot based on bio-mimetic inspiration Mechatronics 22 167–76

[18] Ramezani A, Chung S-J and Hutchinson S 2017 A biomimetic robotic platform to study flight specializations of bats Sci. Robot. 2 eaal2505

[19] Johnson-Murray J L 1977 Mythology of the gliding membranes of some petauristine rodents (genera: Glaucomys, Pteronomys, Petronomys, and Petaurista) J. Mammal. 58 574–84

[20] Shin W D, Park J and Park H W 2018 Bio-inspired design of a gliding–walking multi-modal robot Int. Conf. on Intelligent Robots and Systems (IEEE) pp 8158–64

[21] Jackson S M 2000 Glide angle in the genus Petaurus and a review of gliding in mammals Mammal Rev. 30 9–30

[22] Arbos-Torrent S 2013 Aeromechanical performance of compliant aerofoils PhD Dissertation Imperial College

[23] Torres G E and Mueller T J 2004 Low aspect ratio aerodynamics at low Reynolds numbers AIAA J. 42 865–73

[24] Paikins K E, Bowyer A, Megill W M and Scheibe S J 2007 Take-off and landing forces and the evolution of controlled gliding in northern flying squirrels Glaucomys sabrinus J. Exp. Biol. 210 1413–23

[25] Bishop K L 2006 The relationship between 3D kinematics and gliding performance in the southern flying squirrel, Glaucomys volans J. Exp. Biol. 209 689–701

[26] Bishop K L 2007 Aerodynamic force generation, performance and control of body orientation during gliding in sugar gliders (Petaurus breviceps) J. Exp. Biol. 210 359–606

[27] Thornton R W and Henny L R 1981 Body proportions and gliding adaptations of flying squirrels (Petaurista inaequinae) J. Mammal. 62 101–14

[28] Hayssen V 2008 Patterns of body and tail length and body mass in Sciuridae J. Mammal. 89 852–73

[29] Etkin B 1982 Dynamics of Flight: Stability and Control (New York: Wiley)

[30] Corry R and Tedrake R 2008 Experiments in fixed-wing UAV perching AIAA Guidance, Navigation and Control Conf. and Exhibit p 7256

[31] Moore J and Tedrake R 2012 Control synthesis and verification for a perching UAV using LQR-trees Proc. of the IEEE Conf. on Decision and Control pp 5707–14

[32] Von Mises R 1959 Theory of Flight (Dover Books on Aeronautical Engineering Series) (New York: Dover)

[33] Thomas A L R and Taylor G K 2001 Animal flight dynamics I. Stability in gliding flight J. Theor. Biol. 212 399–424

[34] Tangler J and David Kocurek J 2005 Wind turbine post-stall airfoil performance characteristics guidelines for blade-element momentum methods 43rd AIAA Aerospace Sciences Meeting and Exhibit p 591

[35] Rojratsirikul P, Wang Z and Gursul I 2010 Effect of pre-strain and excess length on unsteady fluid-structure interactions of membrane airfoils J. Fluids Struct. 26 359–76

[36] Abudaram Y J A, Ijifu P G A, Hubner J P and Ukeley L A 2014 Controlling pretension of silicone membranes on micro air vehicle wings J. Strain Anal. Eng. Des. 49 161–70

[37] Galvao R, Israeli E, Song A, Tian X, Bishop K, Swartz S and Breuer K 2006 The aerodynamics of compliant membrane wings modeled on mammalian flight mechanics 36th AIAA Fluid Dynamics Conf. and Exhibit p 2666

[38] Asada H and Youcef-Toumi K 1984 Analysis and design of a direct–drive arm with a five-bar-link parallel drive mechanism J. Dyn. Syst. Meas. Control 106 225–33

[39] Park H W, Park S and Kim S 2015 Variable-speed quadruped robot running of MIT Cheetah 2 Proc. of the 47th AIAA Aerospace Sciences Meeting and Exhibit p 29

[40] Essner R L Jr 2003 Locomotion, morphology, and habitat use in arboreal squirrels (Rodentia: Sciuridae) PhD Thesis Ohio University