Performance analysis of jump-gliding locomotion for miniature robotics

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Abstract

Recent work suggests that jumping locomotion in combination with a gliding phase can be used as an effective mobility principle in robotics. Compared to pure jumping without a gliding phase, the potential benefits of hybrid jump-gliding locomotion includes the ability to extend the distance travelled and reduce the potentially damaging impact forces upon landing. This publication evaluates the performance of jump-gliding locomotion and provides models for the analysis of the relevant dynamics of flight. It also defines a jump-gliding envelope that encompasses the range that can be achieved with jump-gliding robots and that can be used to evaluate the performance and improvement potential of jump-gliding robots. We present first a planar dynamic model and then a simplified closed form model, which allow for quantification of the distance travelled and the impact energy on landing. In order to validate the prediction of these models, we validate the model with experiments using a novel jump-gliding robot, named the ‘EPFL jump-glider’. It has a mass of 16.5 g and is able to perform jumps from elevated positions, perform steered gliding flight, land safely and traverse on the ground by repetitive jumping. The experiments indicate that the developed jump-gliding model fits very well with the measured flight data using the EPFL jump-glider, confirming the benefits of jump-gliding locomotion to mobile robotics. The jump-glide envelope considerations indicate that the EPFL jump-glider, when traversing from a 2 m height, reaches 74.3% of optimal jump-gliding distance compared to pure jumping without a gliding phase which only reaches 33.4% of the optimal jump-gliding distance. Methods of further improving flight performance based on the models and inspiration from biological systems are presented providing mechanical design pathways to future jump-gliding robot designs.

1. Introduction

Energy efficient locomotion is one of the major challenges in mobile robotics. One promising way of moving through rough terrain at a low energetic cost is to adopt jumping for miniature robots [1–14]. Compared to other locomotion methods, jumping allows small robots to overcome relatively large obstacles compared to their body size and is among the most energy efficient modes of terrestrial locomotion [15, 16].

We define jump-gliding as jumping with a gliding phase. It is a form of efficient locomotion that has been observed in various animals in nature. Different species, with differing evolutionary history, including spiders, locusts, gliding ants, bats, gliding mammals, gliding lizards, flying snakes, gliding geckoes, flying fish, flying squid and many birds utilize jump-gliding as a locomotion strategy. The interested reader may be referred to [17–39] for in depth reviews on the morphology and locomotion capability of these animals.

Recently, it has been suggested [8, 14, 16, 40–42] that jump-gliding could be used to reduce the energetic cost of locomotion using a hybrid mode of jumping and gliding. The combination of ground and aerial locomotion has been shown to be promising, such as in recent related work which combines powered flight using flapping wings [43] or propellers [44] with the
ability to run and crawl on ground, leading to increased locomotion capabilities compared to those using only a single locomotion mode.

Armour et al [8] have been pioneers in this direction and have implemented a relatively heavy 0.7 kg jumping robot of 50 cm size called Glumper that jumps and deploys membranous wings with the intention of increasing jumping distance. However, the final prototype jumps further without wings than with them, and has been shown to perform only a single jump.

Scafogliero et al [6] mention in their future work section eventual extensions of the Grillo robot with wings to increase its jumping distance, but no realization has been presented so far. Previous versions of our Self Deploying Micro-glider [42] include exploratory prototypes of gliding robots, which can deploy themselves into the air by means of a jumping mechanism. As a second design iteration we presented a jump-gliding robot called the EPFL jump-glider [14, 45] which includes a study of different biologically inspired foldable and rigid wing designs that are integrated with the jumping mechanism allowing for successful jump-gliding locomotion. This winged robot has a mass of 16.5 g with on board energy and control and is able to jump from elevated positions and perform steered gliding flight at a gliding angle of 26°. Once on level ground, it can progress with autonomous repetitive jumps.

Recently, a similar jumping system weighing 96 g was presented by Woodward et al [46] showing single jumps of an impressive seven times its size. Cutkowsky et al have also developed a 30 g jump-gliding prototype [40, 41], with hinged wings and a dynamic model, demonstrating that a jump-gliding mechanism can travel further using the same energy compared to a similar jumping mechanism. Related work includes the climbing and gliding robot developed by Dickson et al, who have devised a multi-modal design with a glide ratio of nearly 2 and a gliding velocity of 5.3 m s⁻¹ [47].

However, the design criteria under which adding wings to a jumping robot can provide advantages have just started to be explored by the scientific community. The addition of aerodynamic appendages such as wings to a pure jumping robot can have two benefits compared to jumping without wings. First, the wings can create aerodynamic lift to prolong the jump. Second, they can decrease airborne velocity, reducing the potentially hazardous kinetic impact energy that needs to be absorbed by the robot structure on landing. At the same time, one drawback of having wings is an associated increase in mass. This could possibly result in higher impact energy on landing. Thus, the addition of wings to a jumping robot leads to a trade-off, which needs to be carefully estimated.

This publication provides a theoretical basis for understanding the complex dynamics of jump-gliding locomotion which can be used to estimate the quantitative benefit of wings. Previous work by Kovac et al involved developing a simplified Newtonian jump-gliding model [14], which has been further developed by Desbiens et al [40]. In this paper we propose a detailed model which describes the mechanics of passive jump-gliding including non-equilibrium flights. We start by presenting simple methods for understanding the pure jumping and jump-gliding trajectory evolution. We then develop a selection of design parameters and a two dimensional flight model which requires solving a set of coupled differential equations [48]. This model is then used to compare the performance of the ballistic jumper with the jump-glider, demonstrating the two benefits mentioned above, i.e. prolonging the jump and to reducing impact forces on landing. Additionally, we derive a closed form approximation that allows an estimation of the maximal distance that can be reached with a jump-gliding sequence.

We then apply the model to our EPFL jumper v1 and its winged version, the EPFL jump-glider and verify the simplifications and assumption made by the theoretical models using an experimental characterization and analysis of the jump-gliding trajectory. Finally, we present a jump-glide envelope, which is the region in which the glide trajectories of tests taken for a certain gliding robot are encompassed, which allows for performance analysis and better design of miniature jump-gliding robots. The theoretical models also allow the understanding of non-equilibrium flight dynamics in other jump-gliding systems, in nature, such as flying lizards [18, 19] and flying squirrels [49]. This could have further implications in improving pitch control for better glide performance in micro jump-gliders based on applying the models in this paper to the study of these biological jump-gliders and work on inverse dynamics and control curves.

2. Jump-gliding versus jumping: theoretical comparison

In this section we present theoretical models that aim at comparing jump-gliding to pure jumping. We analyse the dynamics of jumping and jump-gliding separately and then compare the trajectory solutions.

2.1 Jumping dynamics

The jumping model relies on a closed form solution to the linear drag model. It has to be qualified that this is applicable primarily to very low Reynolds number flows. However it is chosen because of the insight that can be derived from the simple closed form nature of the solution, and because the total drag to weight ratio is low. This predicts the trajectory evolution of a bluff body [50]. For simplicity, the jumping robot is assumed to be a spherical body of equivalent length scale. The aerodynamic force acting on the body can then be reduced to equation 1, where the coefficient of
dynamic viscosity of air at room temperature is \( \mu \), and \( R \) is the approximate length scale and \( v \) is the velocity of motion [50]
\[
E = 6\pi \mu RV = \kappa V. \tag{1}
\]

The consideration of force equilibrium in both axes allows a D’Alembert formulation of the kinematic equations in differential form, with \( m \) as the mass of the robot and \( \kappa_1 \) and \( \kappa_2 \) as the drag factors in the global \( x \) and \( y \) directions
\[
a_x = \frac{dv_x}{dt} = -\kappa_1 v_x \frac{m_j}{m_j}, \tag{2}
\]
\[
a_y = \frac{dv_y}{dt} = -\kappa_2 v_y - g. \tag{3}
\]

This is then solved analytically to give the following expressions for horizontal displacement, \( s_x \) and vertical displacement, \( s_y \)
\[
s_x = \frac{m_j}{\kappa_1} v_0 x \left( 1 - e^{-\kappa_1 t} \right), \tag{4}
\]
\[
s_y = -\frac{m_j g}{\kappa_2} + \frac{m_j}{\kappa_2} \left( v_y + \frac{m_j g}{\kappa_2} \right) \left( 1 - e^{-\kappa_2 t} \right). \tag{5}
\]

2.2. Jump-gliding dynamics

For jump-gliding, we decompose the flight trajectory into three phases as illustrated in figure 1. The jump-gliding sequence starts with the ‘ascending phase’ where the jump-glider performs a jump such as in the case without wings. Once on top of the jumping trajectory it enters the ‘transition phase’ where the jump-glider reaches the range of critical angle of attack and it accelerates to a given gliding speed and enters the subsequent ‘gliding phase’. In the following, we describe the detailed modelling and assumptions of these three phases.

Ascending phase

We model the ascending phase as pure jumping with the same model used for a pure jumping robot. The drag coefficient in the height direction is much larger than that in the forward direction due to the presence of wings. In this case we will assume a constant of proportionality \( \beta \) that relates the aerodynamic force experienced by the body to distinguish it from \( \kappa \), the corresponding drag factor for the pure jumping robot. Wings are modelled as flat plates, which have low drag at low angles of attack but large drag when placed perpendicular to the flow direction. In this description, \( \beta_1 \) and \( \beta_2 \) are the horizontal and vertical components of the drag factor. Consequently, in this case, \( \beta_1 \), and \( \kappa_1 \) are similar but \( \beta_2 \) is much larger than \( \kappa_2 \) due to the presence of wings.

The time taken to reach the peak height \( t_h \) is given by, where \( v_{x0} \) and \( v_{y0} \) are the initial \( x \) and \( y \) components of the velocity
\[
t_h = \frac{m_j g}{\beta_2} \ln \left( \frac{\beta_2 v_{y0}}{m_j g} + 1 \right). \tag{6}
\]

The height reached \( h_{jg} \) and distance travelled \( d_{jg} \) are given by
\[
d_{jg} = \frac{m_j g}{\beta_1} v_{x0} \left( 1 - \left( 1 + \beta_2 v_{y0} \frac{m_j g}{\beta_2} \right) \right), \tag{7}
\]
\[
h_{jg} = h_0 - \frac{m_j g}{\beta_2} \ln \left( \frac{\beta_2 v_{y0}}{m_j g} + 1 \right) + \left( \frac{m_j}{\beta_2} \right) v_{x0} + \left( \frac{m_j}{\beta_2} \right) v_{y0} + \left( \frac{m_j g}{\beta_2} \right). \tag{8}
\]

The horizontal velocity on top of the jump, \( v_{xh} \) can be expressed as
\[
v_{xh} = v_{x0} \left( 1 + \frac{\beta_2 v_{y0}}{m_j g} \right). \tag{9}
\]

Transition phase

During the transition phase the jump-glider moves from the jumping (ascending) phase to a descending phase where it accelerates under the action of gravity and against drag into the subsequent gliding phase. In reality, this is a dynamic manoeuvre in which the jump-glider recovers from the top of the jumping trajectory, accelerates to the required gliding velocity in order to then perform a dynamic gliding sequence. The angle of attack of the jump-glider also changes
into the critical range for which wings recover from a jumping phase into a gliding phase whereby flow is attached and lift and drag are produced as would be for a lifting body.

For simplicity, we assume that, in order to identify the range of the transition phase, the only component to consider is a ballistic acceleration from the top velocity \( v_h \) to the entry to gliding velocity \( v_g \), which is the velocity of the glider as it starts the gliding phase. We assume that the velocity value is minimal on top of the ascending phase, which is naturally the case when no propulsion is applied to the system during the ascending phase. Based on a simple energy balance we can express the required transition height \( h_t \), for a jump-glider of mass \( m_{jg} \), to reach the gliding velocity as

\[
 h_t = \frac{1}{2} g \left( v_g^2 - v_h^2 \right) = \frac{1}{2} g \left( v_g^2 - v_h^2 \left( \frac{\rho v_h \rho}{m_{jg}g} + 1 \right) \right). \tag{10}
\]

**Gliding phase**

We assume the gliding phase to be dynamic, stable gliding from the height \( h_g = h_{tg} - h_t \). In order to get an accurate model of the glide trajectory, it is important to consider once again the D’Alembert formulation of equilibrium equations for the glider in flight. For the scope of this paper, a simplified planar model describing the longitudinal dynamics of the jump-glider is developed.

In order to study the global trajectory mechanics a model has to be derived [51]. In this respect, figure 2 illustrates the flight parameters that would be used to formulate this model. This requires a description of the state of a body in three dimensional space, which requires nine key descriptors as follows, where \((U,V,W)\) are the linear velocities, \((\theta, \phi, \psi)\) are the angles and \((q,p,r)\) are the angular rates

\[
 x = \begin{bmatrix} U \\ V \\ \theta \\ P \\ \phi \\ \psi \end{bmatrix}, \tag{11}
\]

The starting point for the model, then, would be the full set of coupled state equations for a body in flight, where the dynamic force acting on the body is expressed as the sum of the gravitational, aerodynamic and the nonlinear components of force of the body \[51\]

\[
 F_D = M x = G(x) + F_a(x, \dot{x}) + N(x). \tag{12}
\]

Each of these components are defined as the D’Alembert formulation of the dynamic force \( F_D \), the nonlinear component of the force \( N \), the aerodynamic forces acting on the body \( F_a \) and the gravitational forces acting on the body \( G \)

\[
 M = \begin{bmatrix} m & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & I_{yy} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & m & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & I_{xx} & -I_{xz} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -I_{xz} & I_{zz} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}, \tag{13}
\]

\[
 N = \begin{bmatrix} m(Vr - Wq) \\ m(Uq - Vp) \\ (I_{zz} - I_{xx})pr - I_{xz}p^2 + I_{xx}r^2 \\ q \cos \phi - r \sin \phi \\ m(Wp - Ur) \\ (I_{yy} - I_{xx})qr + I_{xz}pq \\ (I_{xx} - I_{yy})pq - I_{xz}qr \\ p + q \sin \phi \tan \theta + r \cos \phi \tan \theta \\ q \sin \phi \sec \theta + r \cos \phi \sec \theta \end{bmatrix}. \tag{14}
\]
The longitudinal planar mode is extracted as follows

\[
G = \begin{bmatrix}
- \text{mg} \sin \theta & \text{mg} \cos \theta \cos \phi & 0 \\
\text{mg} \cos \theta \cos \phi & \text{mg} \cos \theta \sin \phi & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix},
\]

\[
F_i = \begin{bmatrix}
F_{xa} \\
F_{za} \\
F_{ma} \\
F_{la} \\
F_{na} \\
0
\end{bmatrix},
\]

Starting from this generalized description it is possible to derive simplified mechanics by first decoupling the lateral and longitudinal flight parameters. The key assumptions are that there is no out of plane motion, the jump-glider is approximately bilaterally symmetric about the plane, and the rolling modes are fully decoupled from the pitching modes. In this case \(p, V, r, \phi, \) and \( \omega \) are considered negligible and the longitudinal planar mode is extracted as follows

\[
\dot{x} = \begin{bmatrix}
\dot{U} \\
\dot{W} \\
\dot{\theta} \\
\dot{q}
\end{bmatrix} = \begin{bmatrix}
0 \\
0 \\
\frac{1}{\text{mg}} (F_{xa} + \text{mg} \cos \theta \cos \phi) \\
-\frac{1}{\text{mg}} (F_{za} + \text{mg} \cos \theta \sin \phi)
\end{bmatrix},
\]

\[
F_i = \begin{bmatrix}
F_{xa} \\
F_{za} \\
F_{ma} \\
F_{la} \\
F_{na} \\
0
\end{bmatrix}
\]

The three governing equations are then extracted and presented as follows, with mass \(m_j\) and \((L_{\text{tot}}, D_{\text{tot}})\) as the total lift and drag, which include the wing contributions \((L_w, D_w)\), and tail contributions \((L_t, D_t)\)

\[
m_j \frac{dU}{dt} = -\text{mg} \cos (\theta) - \frac{1}{2} \rho \text{SC}_L \text{U}^2,
\]

\[
m_j \frac{dV}{dt} = -\text{mg} \sin (\theta) - \frac{1}{2} \rho \text{SC}_D \text{U}^2,
\]

\[
I_{\gamma \dot{\gamma}} = \frac{1}{\gamma} \text{d} \alpha \text{d} \alpha = I_L + I_m L_m,
\]

\[
\gamma = \frac{1}{m_D} \frac{\rho S}{m_j}.
\]

The lift and drag characteristics of the jump-glider can be described by the following equations, which assume a small angle of attack and flat plate in free stream

\[
L = C_L \frac{1}{2} \rho v^2 S,
\]

\[
C_L = 2 \pi a,
\]

\[
D = C_D \frac{1}{2} \rho v^2 S,
\]

\[
C_D = C_{D0} + \frac{C_s^2}{\pi eAR}.
\]

Empirical results for the lift coefficient and drag coefficient at this aspect ratio and relevant Reynold’s numbers are available from literature [52–54]. For the EPFL jump-glider, the lift and drag coefficients used are 0.694 and 0.275 respectively, corresponding to a lift to drag ratio of 2.52.

As the jump-glider is not powered and there is no pitch control, we assume that the angle of attack, \( \alpha \) only varies throughout the flight profile passively. In reality, the angle of attack \( \alpha \) is invoked in the solution of the differential equations and will cause a short period pitching instability; however, this is highly damped. Whereupon the angle of attack goes out of range, the glider will stall. In this case the angle of attack converges because of the restoring \( \frac{d \alpha}{dt} \), which is derived from the moment equilibrium equation. This is required in the design of viable jump-giders. Expressing these in differential form gives the following set of coupled differential equations. For ease of expression, \( \gamma \) is used to represent the various parameters of the robot

\[
\gamma = \frac{1}{m_D} \frac{\rho S}{m_j},
\]
These differential equations are solved using a fourth order Runge–Kutta time-marching scheme in Matlab to give a model of the trajectory evolution.

However, an approximate simple closed form solution to the longitudinal dynamics problem can also be obtained. These equations are linearized about the equilibrium point in the \( \theta - v \) space, which corresponds to aerodynamic equilibrium glide. This gives the following set of linearized equations, which give a simple eigenvalue problem; this approach provides an approximation of state evolution

\[
\begin{bmatrix}
\gamma C_L v - \frac{g \cos \theta}{v} \\
- g \sin \theta - \gamma C_D v^2 \\
v \cos \theta \\
v \sin \theta
\end{bmatrix}
= \begin{bmatrix}
\theta' \\
v' \\
x' \\
y'
\end{bmatrix}. \tag{31}
\]

As will be shown in the results section, the full nonlinear numerical solution solved using MATLAB fits the experimental results very well. However, the linearized approach has merits in terms of future work on control of the oscillatory flight dynamics. The linearized equations can be used to derive a control law for pitch and velocity. This can then be implemented using wing actuation for the angle or periodic acceleration for velocity to improve the glide performance.

There are two benefits to jump-gliding over a jumping robot. First is the distance travelled by a jump-glider. For a stable jump-glider, as observed from the nature of the governing equations, there will be decaying oscillations that eventually converge to aerodynamic equilibrium glide. As such, the range can be increased compared to the jumping model.

The second potential benefit that we investigate is under which circumstances does jump-gliding lead to less impact energy on landing. The impact energy corresponds to the kinetic energy on impact which is defined as

\[
E_{\text{impact}} = \frac{1}{2} m v_{\text{impact}}^2 \tag{33}
\]

with \( m \) being the robot mass and \( v_{\text{impact}} \) the velocity on impact. For both pure jumping and jump-gliding, the impact velocity corresponds to the obtained solution. We aim at determining from what starting height is the impact energy on landing lower for the jump-glider compared to the ballistic jumper. This condition can be expressed as

\[
E_{\text{impactj}} > E_{\text{impactjg}} \tag{34}
\]

\[
\frac{1}{2} m_j v_j^2 > \frac{1}{2} m_{jg} v_{jg}^2 \tag{35}
\]

with \( E_{\text{impactj}} \) as the impact energy of the ballistic jumper and \( E_{\text{impactjg}} \) as the impact energy of the jump-glider.

3. The EPFL jump-glider design and characterization

In order to practically explore the benefits and limitations of jump-gliding from elevated positions in miniature robotics compared to jumping without gliding, and to validate the model with a case study, we developed the ‘EPFL jump-glider’ (figure 3). To our knowledge it is the first jump-glider design with on board energy and steering ability. It has a wingspan of 50 cm and a maximal chord length of 10 cm and mass of 16.5 g. As the jumping mechanism for this jump-glider, we use a further development of the EPFL jumper v1 [11].

3.1. Mechanical integration of the jumping mechanism

The jumping mechanism is depicted in figure 4. A 4 mm dc motor (a) is used to turn an eccentric cam (b). The motor turns the cam in counter-clockwise...
direction, by way of a four stage gear box (c), in order to charge two torsion springs (d). These two springs are located around the axis of the leg (e) and are fixed to the frame (f) and the main leg (g). Once the most distal point of the cam is reached, the energy that is stored in the springs actuates the main leg which is the input link for the four bar leg mechanism. The jumping height, take-off angle and ground force profile can be adjusted by changing the spring setting (h) and the geometry of the legs [42]. A jump can be executed every 3s with a power consumption of 350 mW. The reader may be referred to [14] for a more detailed explanation and characterization of the jumping principles used.

The difference of the jumping mechanism presented here compared to the system presented in [11] is that it is more resilient to mechanical damage. This is because the frame is fabricated of aluminum instead of Cibatool which leads to improved stability and a better guidance for the axes of the gears. In order to increase robustness of the connection between the cam and the last gear stage we use now five bolts (j) instead of only two that were very close to the axis of the cam. Summarizing, the jumping mechanism has the same weight but is much more robust than the system presented in [11].

The materials used are aluminum 7075 for the frame and the main leg, carbon prepreg rods for the legs, Polyoxymethylene plastic for the gears and cam and polyaryletheretherketone for the connection pieces on the legs and the frame.

3.2. Mechanical integration of wings

The EPFL jump-glider uses this jumping mechanism as propulsion unit and a CNC cut Polyimide frame to hold the wings. The wings have a surface area of 0.039 m² and a wing loading of 4.15N m⁻². As wing material we use Durobatics™, a Polysterene foam which is widely used in the hobbyist community to build lightweight wings for remote controlled airplanes. Jumps are initiated and controlled by means of a 3-channel infrared remote control and powered using a 20 mAh LiPo battery located on top of the wing. For steering, we adapted the tail and rudder system from a previously developed microflyer [55]. Due to the wings, the robot keeps an upright position after landing for the next take-off. This enables the robot to perform repetitive jumps without needing a cage or an uprighting mechanism (see accompanying movie material in the supplementary data). The weight budget is summarized in table 1.

### Table 1. Weight budget of the EPFL jump-glider.

| Part                      | Mass [g] |
|---------------------------|----------|
| EPFL jumper v1            | 6.03     |
| 20mAh battery             | 0.94     |
| Remote control receiver   | 0.81     |
| Wings                     | 4.5      |
| Polyimide frame           | 2.59     |
| Tail                      | 1.63     |
| Total                     | 16.5     |

### Table 2. Comparison of measured horizontal distances travelled (ten trials each) with the prediction from the model

|                      | Ballistic jumper | Jump-glider     |
|----------------------|------------------|-----------------|
|                      | experiments | model          | experiments | model          |
| $h_s = 2 \text{ m}$ | 2.03 m (SD=0.03) | 2.10 m (+3.45%) | 4.52 m (SD=0.17) | 4.69 m (+3.76%) |

3.3. Jump-gliding performance

This subsection provides an experimental comparison of jump-gliding and jumping from elevated positions. The experimental setup consists of an elevated start position, located 2 m above the ground. We performed ten consecutive jumps with the jump-glider and the ballistic jumper, which is the same robot but without wings, both at a take-off angle of 45°, and filmed the flight trajectories from the side at 30 frames per second. Based on these movies we tracked the
trajectories figure 5(A) using ProAnalyst, a feature tracking software and calculate the flight velocity figure 5(B). The results show that the flight velocity of jump-gliding increases during the transition phase when descending from the top of its trajectory and converges towards its steady state gliding velocity. On the contrary, the flight velocity of pure jumping increases monotonically until impact. Figure 6 shows the measured average impact velocity $v_{\text{impact}}$, average horizontal distance travelled $d$ and calculated average impact energy $E_{\text{impact}}$ for both, the jump-glider and the ballistic jumper. It can be seen that the velocity on impact is reduced by 53% when jump-gliding, resulting in a reduced impact energy of 54%. Furthermore, as can be seen in table 2, we measured that the horizontal distance travelled by jump-gliding is increased by 123% compared to pure jumping. These results clearly show that jump-gliding from an elevated starting position offers an increased jumping distance and reduced impact energy when compared to pure jumping.

The second set of experiments aims at illustrating the locomotion capabilities of the EPFL jump-glider when jumping from an elevated starting position and subsequently progressing on ground. The EPFL jump-glider jumps from a height of 2.53 m, glides and lands safely on a table, where it progresses by jumping (figure 7). With every jump it progresses an average measured distance of 30.2 cm with a jumping height of 12 cm. It can perform such a jump every 3s, which leads to an average forward velocity of 0.1 m s$^{-1}$. A close-up view of this hybrid locomotion mode as well as steering during the gliding phase can be seen in the accompanying movie material.

### 4. Discussion

The experimental results, as illustrated in figure 6 provide a basis for comparison between pure jumping and jump-gliding locomotion. It is to be noted that only viable stable trajectories are considered and the emphasis is on the spectrum of benefit of wings. However, two factors have to be taken into account. The jump-glider has a mass of 16.5 g, which is 8.72 g more than the jumper. Additionally, the drag factor for the jump-glider at take-off is far greater than that of the jumper because of the presence of wings. These can possibly be alleviated by using lighter, tailored materials for wings and initially folded wings in future versions of the jump-glider.

In order to compare the theoretical model with the experiment, we plot the trajectories for pure jumping and jump-gliding in figures 8 and 9. It can be seen that overall, the model fits the measured values for the jumping phase well. For the jump-gliding, the model is able to capture the damped oscillatory behaviour of the trajectory. The mathematical model predicts that the oscillations will eventually converge into a linear glide, for which the equilibrium lift and drag coefficients can be used to derive the slope of equilibrium gliding.

It is then possible to obtain the theoretical optimal jump-glide trajectory for a particular design of robot by extrapolating the equilibrium glide from the end of the ascending phase. For a passive glide of a stable jump-gliding robot this represents the maximum possible reach within a glide. The minimum glide trajectory is taken as when the jump-gliding robot has fully stalled and is following a purely jumping trajectory. The area between these two provides the 'jump-glide envelope' for jump-
gliding robots, which can be taken as the region in which the jump-gliding robot is expected to perform. This provides a basis for improving the design of the passive jump-glider, by attempting to reach equilibrium glide in the minimum possible time. The oscillations could be decreased by methods such as improving the pitch stability of the glider. This could be done by for example increasing the sweep angle of the wings or by adding a longer tail [56]. The method of pivoting wings and locking pitch in certain angles has been shown as a promising way for jump-gliding [40], albeit at the cost of added mass, system complexity and size compared to passive jump-gliders. Other bio-inspired designs might include flexible wings and actively controlled angle of attack such as in Draco flying lizards [18]. However, it is important to note that the jump-glide envelope does not cover actively controlled or

Figure 6. Measured parameters based on the tracked trajectories with the jump-glider and the pure jumper, when jumping from an elevated starting position of two meters height (10 consecutive trials each). (A) Mean distance traveled $d$ for pure jumping and jump-gliding, (B) mean impact velocity, (C) mean impact energy. The bars indicate the standard errors for the 10 trials.

Figure 7. Illustration of the locomotion capabilities of the EPFL jump-glider. It jumps from an elevated position of 2.53 m height, lands safely on a table and performs three sequential jumps to progress on level terrain. Finally, it jumps off the table to glide down to the floor.
powered jump-gliders and the utility of ground-effect. One possible way to actively minimize the oscillations could be wing actuation to dynamically control the angle of attack to achieve optimal lift. Another possibility is to maintain non-equilibrium glides to achieve a higher maximum velocity and utilize ground effect to achieve prolonged glides, such as performed by jump-gliding animals [18, 49, 57, 58].

5. Conclusion

We conclude that the model and experiments are in good agreement with each other when comparing the jumping and jump-gliding trajectory and distance travelled. It captures the complex oscillatory jump-glide behaviour produced in the experiments and it can be used to evaluate the performance of the jump-gliding robot. As a validation of the model, we presented the EPFL jump-glider, a novel jumping and gliding robot. Compared to pure jumping, the EPFL jump-glider reaches 123% further when jumping from a height of 2 m and reduces the impact forces by 53.9%. Based on the definition of a jump-gliding envelope it can be seen that there is still potential for improvement of the EPFL jump-glider performance. The maximal distance travelled by jump-gliding from a height of 2 m would be 6.08 m, indicating that the EPFL jump-glider reaches 74.3% of its locomotion potential by using a gliding phase in addition to its jumping ability. Future work can include characterising 3D jump-gliding mechanics including the lateral degrees of freedom, developing approximate closed form solutions which can be solved analytically for the dynamic jump-gliding trajectory and the integration of active wing morphing mechanisms that could further improve the jump-gliding performance for a particular robot design. Additionally different situations such as jumping from level ground and from a certain height can be compared to ascertain the effectiveness of wings with respect to take-off height. Similarly, a study could be undertaken to understand the effect of initial conditions such as take off angle and initial velocity on the the range of the MAV. Other work could include a systematic fabrication and experimentation with different jump-glider designs in order to reach optimal jump-gliding. Applying the models developed in this paper to studying successful biological jump-gliders, in particular Draco lizards and flying squirrels, could be insightful in understanding how pitch control and active wing camber

![Figure 8. Comparison of the measured horizontal distance travelled to the calculated distances based on our theoretical model for jumping.](image1)

![Figure 9. Comparison of the measured horizontal distance travelled to the calculated distances based on our theoretical model for jump-gliding.](image2)
can be used to improve the performance of jump-gliding micro aerial vehicles [18, 19, 49].

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