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The EPFL jumpglider: A hybrid jumping and gliding robot with rigid or folding wings

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***Abstract*— Recent work suggests that wings can be used to prolong the jumps of miniature jumping robots. However, no functional miniature jumping robot has been presented so far that can successfully apply this hybrid locomotion principle. In this publication, we present the development and characterization of the 'EPFL jumpglider', a miniature robot that can prolong its jumps using steered hybrid jumping and gliding locomotion over varied terrain. For example, it can safely descend from elevated positions such as stairs and buildings and propagate on ground with small jumps. The publication presents a systematic evaluation of three biologically inspired wing folding mechanisms and a rigid wing design. Based on this evaluation, two wing designs are implemented and compared [1].**

I. INTRODUCTION

Locomotion in rough and varied terrain is one of the grand challenges in miniature mobile robotics. One promising way of moving at a low energetic cost is to adopt jumping locomotion, as used by many small insects such as fleas, locusts, frogs and many others. In robotics, several jumping systems have been presented which use the same bioinspired locomotion principles [1]–[13].

Recently, it has been suggested [5,7,14] that wings could be used to prolong the flight phase of a jumping system. The idea is that the robot would jump with closed wings, open the wings on top of the jumping trajectory and perform a subsequent gliding phase. Due to the lack of an existing term for this hybrid jumping and gliding locomotion, we introduce the term 'jumpgliding' for this concept of winged jumping. Armour et al. [7] have pioneered this field by presenting a 0.7kg jumping robot called 'Glumper' that jumps and deploys membraneous wings with the intention of increasing jumping distance. However, the final prototype has been shown to perform only one single jump without the ability to recharge and jump again. Scafogliero et al. [5] mention in their future work section the potential 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 Microglider' [14] include exploratory prototypes of gliding robots which can deploy themselves into the air by means of a jumping mechanism. Although these preliminary prototypes were promising, no systematic evaluation of different wing folding designs has been presented so far as well as no funtional jumpgliding robot has been developed that can perform repetitive jumpgliding locomotion in varied terrain.

[1]This work has been carried out at EPFL. Video footage of the EPFL jumpglider with rigid wings moving in varied terrain can be found at http://www.youtube.com/watch?v=DxugW3XfWao

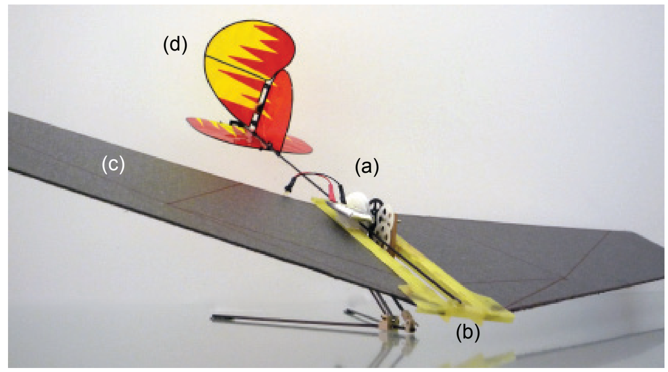

Fig. 1. EPFL jumpglider (version with rigid wings). 16.5g jumpgliding robot that can jump, perform steered gliding flight and move on ground with small jumps. (a) jumping mechanism, (b) CNC cut Polyimide frame, (c) wings, (d) tail with rudder for in-air steering

In the animal kingdom, many animals such as gliding lizard, flying squirrels, gliding frogs, locusts etc. use jumpgliding as their locomotion strategy. Having light weight wings is key to succeed in this kind of locomotion because every additional gram will reduce the jumping height and flight efficiency. In this publication, we consider and evaluate three biologically inspired wing folding designs and one rigid wing design which we prototyped and tested. Based on this evaluations, we chose one wing folding design and the rigid wing design which we integrate with a jumping mechanism to obtain the 'EPFL jumpglider' with foldable and rigid wings (figure 1). Based on this comparison, we evaluate and discuss the advantages and drawbacks of having foldable wings as compared to rigid wings. As well we discuss the advantages of having wings for jumping robots compared to similar jumping robots without wings.

II. DESIGN

In this section we present the conceptual design of the jumping mechanism which acts as the propulsion device for the jumpglider. Further, we describe three biologically

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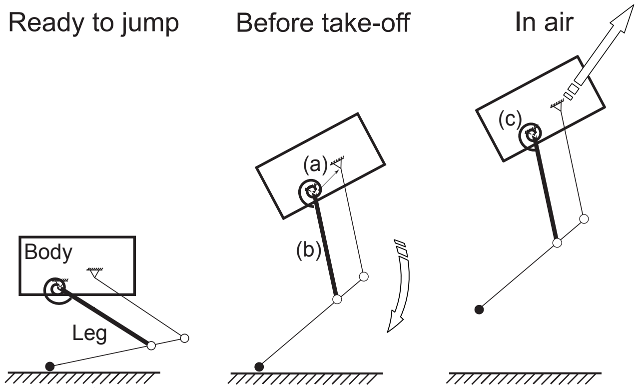

Fig. 2. Working principle for the jumping mechanism. In order to jump, a four bar leg linkage that is attached to the body on the ground link (a) is extended quickly via the input link (b) using a torsion spring (c). Reprinted from [12]

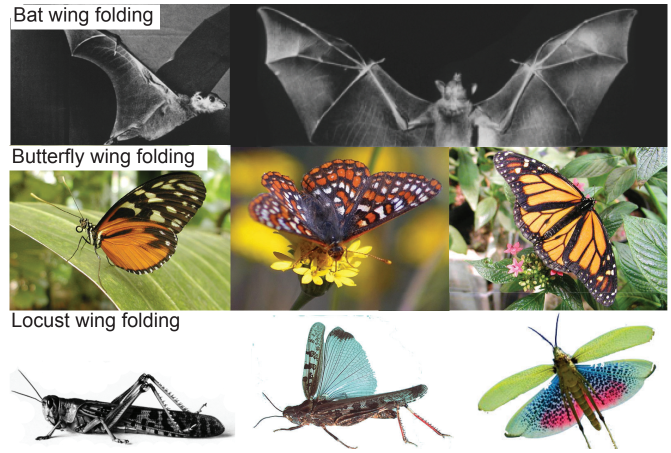

Fig. 3. A selection of folding wing designs in nature

inspired wing folding designs and a rigid wing design, their mechanical integration with the jumping mechanism and we compare them to each other using a comparative evaluation matrix. Based on this evaluation, we integrate the most promising two designs with the jumping mechanism and obtain the EPFL jumpglider with foldable and rigid wings which we then characterize in section III.

A. Jumping mechanism

The main requirement in the development of the jumping mechanism is to build a lightweight propulsion unit for jumping robots, where the jumping height and take-off angle can be adjusted. For small jumping systems it is most beneficial to fist slowly charge an elastic element and then use the legs as catapult to jump [5,10,15]–[17]. This way of jumping is used by small animals such as desert locusts [18], fleas [19] and frogs [15]. The working principle in our design is to first charge a torsion spring and then release its energy to quickly extend a four bar leg linkage to perform the jumping movement, as illustrated in figure 2. This same principle has been implemented for our previously presented minimalist jumping robot [10]. The basic components are the four bar leg mechanism that is connected to the body on the ground link (a) and is actuated via the input link (b) using a torsion spring (c).

B. Wings

In nature, most birds, bats and flying insects are able to fold their wings to protect the often fragile structures when moving on ground and to be able to enter narrow spaces [20]. For the EPFL jumpglider we do not limit the search for inspiration to only flying animals. Nature offers many foldable and deployable structures for different applications. For example, leaves unfold from a very compact package to the complete deployed leaf with very high structural stability [21,22]. Other ways of unfolding can be found in soft animals, such as anemones and various worms [23,24]. Many insects use Origami-like mechanisms to fold their wings, such as the hind wings of *Dermaptera* [20,25]. Most birds and bats fold their wings using an underlying skeleton folding structure, which is covered with skin. Many flies, butterflies and other insects with rigid wings simply fold the wings backwards similar to a japanese foldable fan.

In robotics, wing folding designs have been proposed which allow flying systems to move on ground and through narrow openings such as the hybrid locomotion platform MMALV [26]. Other projects aim at developing morphing wings to steer MAVs in air [27].

For the EPFL jumpglider, we considered three biologically inspired wing folding designs. Their biological counterparts are depicted in figure 3.

As a first design, we considered a bat inspired solution (figure 4.A). It consists of carbon rods (a) and hinges (b) with embedded torsion springs that keep the wings (c) open. When the jumping mechanism charges for the next jump, it rolls a thread (d) and releases it on command using a Shape Memory Alloy (SMA) based click mechanism (e) located under the wings. This design has been used for the previously presented 'Self Deploying Microglider' [14].

The second wing folding design that we considered is inspired from the butterfly (figure 4.B), although butterflies fold the wings upward, where this design folds the wings on the other direction. The working principle is that when the jumpglider jumps, the air friction keeps the wings closed. As soon as it reaches the top of the jumping trajectory and starts to descend, the air enters under the wings and opens them which then allows the jumpglider to glide. Once on ground, it charges for the next jump and closes the wings by means of a thread (a) which is attached to the frame (b) of the jumping mechanism.

The third design is based on the wings being folded backwards, similar to many insects, such as locusts (figure 4.C). A spring provides the force to keep the wings open. When charging for the next jump, two threads (a) which are attached to the wing root and the legs fold the wings by way of two pulleys (b). After take off, the wings start to open allowing the jumpglider to perform gliding flight with open wings once on top of the jumping trajectory.

As the fourth design we consider a version based on the locust inspired wing folding mechanism with the same dimensions but without a folding mechanism. The motivation for this rigid wing design is that the wings could contribute with lift already during the jumping phase and that the mechanism design could be much simpler and robuster than a wing using a folding mechanism. In this design, the wings are integrated on the jumping mechanism using a rigid wing frame and are deployed and rigid during all times.

C. Evaluation of the wing designs

In this section we evaluate the three wing folding designs using a weighted comparative evaluation method [28]. The evaluation criteria are (i) low weight (ii) high compactness when folded (iii) high rigidity when open (iv) high lift to drag ratio during the jumping phase (v) low mechanical complexity, (vi) high robustness to failure on landing. The evaluation matrix is illustrated in table I.

The main advantage of the bat inspired design is its compactness when folded due to its flexible wings and skeletal structure. Its main drawback is a relatively low mechanical rigidity when open and low mechanical robustness on landing compared to the other designs. Its need for six hinges with integrated springs also leads to a large increase in weight.

The main advantages of the butterfly inspired design is its low mechanical complexity and high rigidity when open. Its main drawback is that the wings are closed using aerodynamical friction which inevitably reduces the jumping height significantly.

The locust inspired design offers a rigidity and simplicity similar to the butterfly inspired design, but with lower aerodynamical friction during take-off. Its main drawback compared to the bat inspired design is a lower compactness when folded.

The rigid wing design offers a very high robustness and rigidity when open compared to the previous three wing designs. Because of its absence of a wing folding mechanism it reduces the weight of the robot and reduces the potential bulkiness of the wings which would increase aerodynamical drag. As well do open wings offer the benefit to not only reduce drag during the jumping phase, but also to create lift which potentially increases the jumpgliding distance as compared to a wing folding design which does not create lift during the jumping phase. Its main drawback is that it is less compact on ground which could make it more difficult to move in cluttered terrain.

Based on this evaluation matrix and the experience with these designs and initial experiments, we consider the locust inspired design and the rigid wing design to be the most promising solutions for miniature jumpgliders. Their main advantage compared to the other designs is that it is mechanically robust, simple to implement and light weight.

D. Mechanical integration

1) Jumping mechanism: The fabricated jumping mechanism is depicted in figure 5. It is based on our previously presented minimalist jumping robot [10]. We use a 4mm DC motor (a) to turn a cam (b) by means of a four stage gear box (c). The motor turns the cam in counterclockwise direction 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 [29]. A jump can be executed every 3s with a power consumption of 350mW. The materials used are aluminum 7075 for the frame and the main leg, carbon prepreg rods for the legs, Polyoxymethylene plastic (POM) for the gears and cam and polyaryletheretherketone (PEEK) for the connection pieces on the legs and the frame. The reader may be referred to [10] for a more detailed explanation and characterization of the jumping principles used. The jumping mechanism is controlled using a 3-channel infrared remote control and powered using a 20mAh LiPo battery.

2) Wings: The implemented version of the locust inspired jumpglider design with foldable wings weights 20.3g, has a wingspan of 49cm and a surface area of 0.039m^2. It starts opening its wings immediately after take-off and reaches completely outspread wings within 160ms (figure 6). It then transitions to a subsequent gliding phase. The EPFL jumpglider with rigid wings has a mass of 16.5g and the same wing dimensions. As wing material we use Durobatics$^{\text{TM}}$, a Polysterene foam which is widely used in the hobbyist community to build lightweight wings for remote controlled airplanes. For steering, we adapted the tail and rudder system from a previously developed microflyer [30]. 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 the video footage of the EPFL jumpglider). The weight budget of the two versions of the EPFL jumpglider is summarized in table II.

III. Performance characterization and discussion

In this section we present the performance characterization of the EPFL jumpglider with foldable and rigid wings and discuss its advantages and drawbacks.

The experimental setup consists of an elevated start position, located 2m above the ground (figure 7). We performed 10 consecutive jumps with the EPFL jumpglider with foldable and rigid wings at a take-off angle of 45°. During those jumps we filmed the flight trajectories from the side at 30 frames per second. Based on these movies we tracked the trajectories using ProAnalyst, a feature tracking software. Based on these movies we measured the horizontal distance traveled from 2m height and the potentially hazardous impact energy which has to be absorbed by the robot structure on landing (figure 8).

It can be seen that the EPFL jumper with rigid wings provides the largest distance traveled for the smallest impact

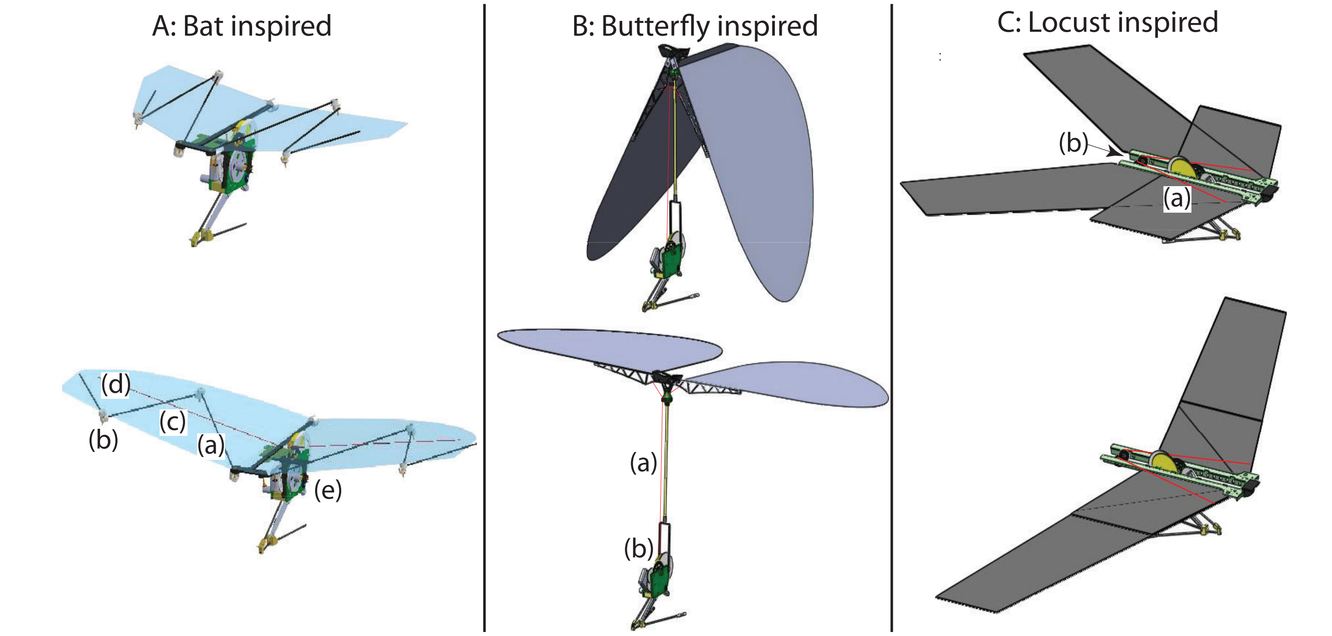

Fig. 4. Biologically inspired wing folding mechanisms which are considered for implementation on the EPFL jumpglider. A: Bat inspired, (a) rod (b) hinges with embedded springs (c) flexible wing material (d) thread (e) SMA based click mechanism B: Butterfly inspired, (a) thread (b) frame of the jumping mechanism C: Locust inspired, (a) threads (b) two pulleys to guide the treads

TABLE I
QUALITATIVE COMPARISON FOR THE THREE DIFFERENT WING FOLDING DESIGNS

Design requirement	Bat inspired design	Butterfly inspired design	Locust inspired design	Rigid wing design
Weight	-	+	++	+++
Compactness when folded	+	- -	-	- - -
Rigidity when open	-	++	++	+++
Lift to drag ratio during the jumping phase	-	- - -	+	+++
Mechanical complexity	- -	+	+	+++
Robustness	- - -	+	+	++

+++ very favorable, ++ favorable, + little favorable, - slightly unfavorable, - - unfavorable, - - - very unfavorable

energy. The added weight and delayed opening of the wing folding mechanism increases the impact energy and makes the transition to the gliding phase more difficult which reduces the traveled distance per jumpglide.

The jumpgliding performance on level terrain has been determined from video footage filming single jumps on ground. The version with foldable wings jumps a distance of 10.1cm and a height of 2.5cm. The EPFL jumper with rigid wings jumps a distance of 30.2cm and a height of 12cm. Both designs can perform such a jump every 3s, which leads to an average forward velocity of 0.03m/s and 0.1m/s respectively.

The second set of experiments aims at illustrating the locomotion capabilities of the EPFL jumpglider when jumping from an elevated starting position and subsequently progressing on ground. This set of experiments is performed using the EPFL jumpglider with rigid wings due to its better flight performance from elevated positions compared to the design with foldable wings. It jumps from a height of 2.53m, glides and lands safely on a table, where it progresses by jumping (figure 9). A closeup view of this hybrid locomotion

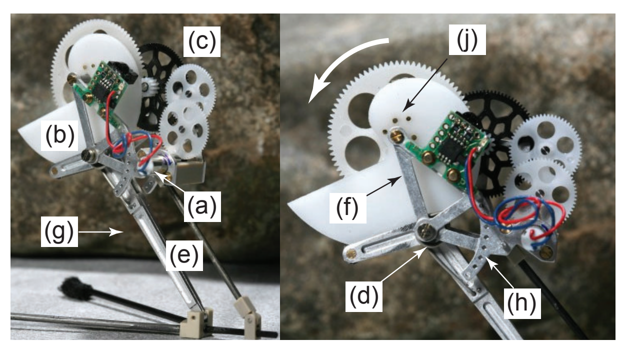

Fig. 5. Jumping mechanism that presents the propulsion unit for the EPFL jumpglider. (a) 4mm DC pager motor, (b) cam, (c) four stage gear box, (d) two steel torsion springs, (e) four bar linkage leg structure, (f) aluminum frame, (g) main leg as input link, (h) spring setting, (j) fixation of the cam to the last gear stage using five bolts. Reprinted from [12]

mode as well as steering during the gliding phase can be seen in the accompanying movie material.

The results indicate that the EPFL jumper with rigid wings outperforms the EPFL jumper with foldable wings in jump-

TABLE II

WEIGHT BUDGET OF THE EPFLJUMPGLIDER WITH FOLDABLE AND RIGID WINGS

Part	EPFL jumpglider (foldable wings)	EPFL jumpglider (rigid wings)
Jumping [g] mechanism	6.03	6.03
20mAh battery [g]	0.94	0.94
Remote control [g] receiver	0.81	0.81
Wings [g]	8.2	4.5
Polyimide frame [g]	2.69	2.59
Tail [g]	1.63	1.63
Total mass [g]	**20.3**	**16.5**
Wing loading [kg/m^2]	0.52	0.42

ing distance as well as impact energy that has to be absorbed by the robot structure on landing. One of the main reasons for this is that the foldable wing design has an increased weight due to the wing folding mechanism and additional parts needed for it. A further reason is that the design with rigid wings provides lift already during the jumping phase right after take-off which increases the total distance traveled compared to the foldable design which opens the wings at the top of the jumping trajectory. However, the amount of lift created with rigid wings depends on the angle of attack and the dynamics of the robot during the jumping phase. Future work could address an optimization of the wings and center of gravity position using a wind tunnel in order to operate at an angle of attack as close as possible to the maximal lift to drag ratio and maximize the horizontal distance travelled. For situations where small size and agility on ground is of very high importance, foldable wings may be an interesting option such as demonstrated in the scenario for a robot using wing folding to enter a half open door [31].

Although it has been suggested that jumping robots can benefit from having wings, no theoretical considerations for this claim has been presented so far. In order to evaluate under which conditions wings provide jumping robots with added benefits, we developed a closed form mathematical model on the design parameters of the wings and the jumping mechanism in [32]. We conclude that for locomotion on level terrain and the jumping performance of the robots presented to date, jumping without wings leads to larger distance covered per jump. For example, the 16.3g EPFL jumper v3 [10] jumps a distance of 46cm and a height of 62cm which is much higher than the EPFL jumper with rigid wings and similar weight. Both robots use the same jumping mechanism and are protected on landing and steerable. However, having wings is beneficial when jumping from elevated position because they can increase the jumping distance due to the gliding phase and can decrease the impact energy which has to be absorbed by the robot structure on landing.

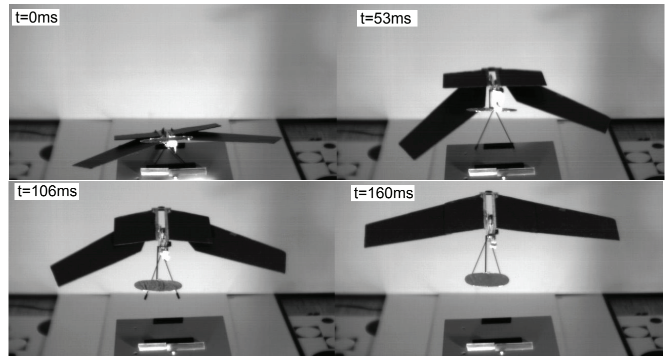

Fig. 6. Unfolding sequence of the locust inspired wing folding implementation. After take-off, it takes 160ms to completely unfold the wings

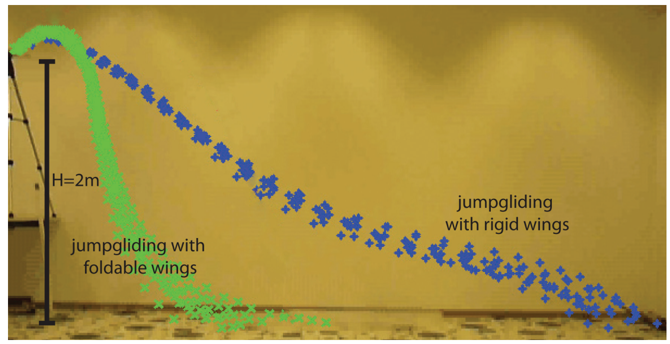

Fig. 7. Flight trajectories, 10 trials for jumpgliding with rigid wings and jumpgliding with foldable wings

IV. CONCLUSION

We conclude that hybrid jumping and gliding locomotion is a possible and an interesting option for miniature robotics. We demonstrated the development and characterization of two versions of a jumpgliding robot, called the EPFL jumpglider. We designed and evaluated three different biologically inspired wing folding designs as well as a rigid wing design and implemented two of them on a miniature jumping mechanism. The results from jumpgliding experiments suggest that jumpgliding with rigid wings is the preferable option compared to jumpgliding using a wing folding mechanism. It increases the jumpgliding distance and reduces the impact energy that has to be absorbed by the robot structure on landing. However, when jumping on level terrain, jumping without wings such as done by the EPFL jumper v1 or the EPFL jumper v3 does offer increased jumping distance and jumping height for a given robot dimension and weight. Future work could include the integration of other tail designs such as the 0.2g SMA actuated tail presented in [33] or a gecko inspired stabilization tail similar to the mechanism in geckos [34].

V. ACKNOWLEDGEMENT

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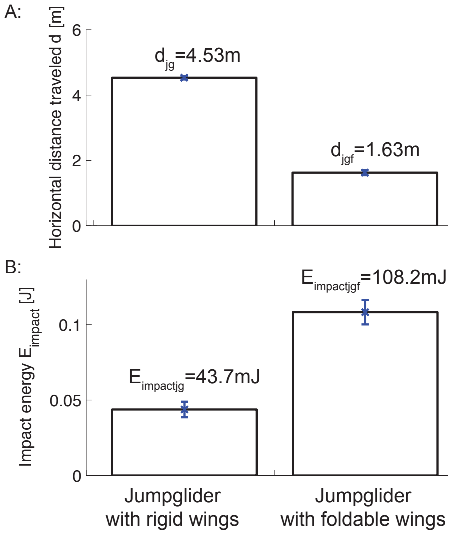

Fig. 8. Measured parameters from the experiments as shown in figure 7. A: Distance traveled d from 2m height for ballistic jumping, jumpgliding with rigid wings and jumpgliding with foldable wings and B: Impact energy. The bars indicate the standard error for the 10 runs

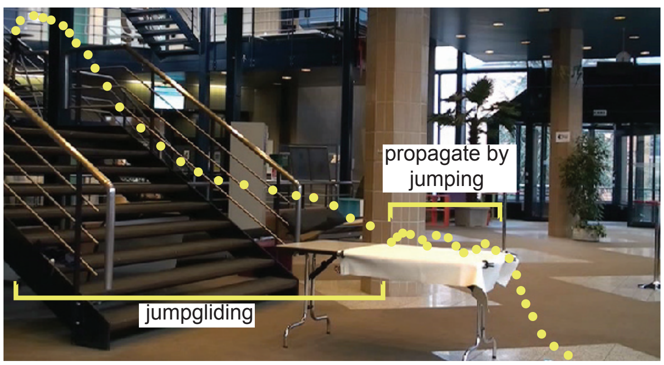

Fig. 9. Illustration of the locomotion capabilities of the EPFL jumpglider. It jumps from an elevated position of 2.53m height from the ground, lands safely on a table and performs three sequential jumps to progress on level terrain. Finally, it jump off the table to glide down to the floor

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