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Design and manufacture of the wing folding mechanism for a Bioinspired Ornithopter*

Lorena Calvente, José Ángel Acosta and Aníbal Ollero

***Abstract*— This paper presents a folding mechanism for ornithopter's wings. The mechanism has been implemented using rods and joints to replicate wing performance of animal flight. In this sense, bio-inspiration has been the baseline of the design but hard requirements as lightweight and integration with the current platform have also been considered. The final specifications of volume ratio folded/unfolded of 1/3 and additional mass < 100 g/wing with respect to the current structure, make this concept quite promising. Moreover, unlike most of the existent creations, it is intended to allow control of the folding while perching. Bench experiments demonstrate its performance and compatibility with the prototype platform.**

***Index Terms*— Bio-inspired, ornithopters, folding wings.**

I. Introduction

Nowadays, bio-inspiration plays an important role in unmanned aerial vehicles, giving rise to robotic birds called ornithopters. Throughout the history of robotics, it has been demonstrated the difficulty of building artificially a system with the behaviour of a bird, specially the wings.

Under the framework of the ERC project GRIFFIN (General compliant aerial Robotic manipulation system Integrating Fixed and Flapping wings to INcrease range and safety) we are exploring the feasibility and reliability of a new type of robots, essentially they are enhanced ornithopters with the ability to perch and perform some tasks. The whole mission is split into: a) take off; b) fly with flapping wings; c) perch in some place and d) perform some kind of task while the system is perched and with the wings folded; all autonomously (see motivational sketch in [1]). This paper focuses on d) stage, and aims to design a wing folding mechanism, whose main functionality is reducing the space occupied by the system, thus allowing a better stabilization while perched. To get more insight of the whole project we refer interested readers to recent related works where we explore: dynamics and control while the robot is perched with its wings folded in [1]; claw based on soft robotics in [2]; nonlinear flight control for perching in [3]; event camera perception as in [4]. We also refer to a recent spotlight article of CORDIS (the European Commission's primary service for EU-funded research results) highlighting the achievements over the past year in [5].

Among all requirements imposed by the GRIFFIN project is the integration with the current prototype. Since the prototype is in constant evolution, the proposed folding mechanism was implemented in an earlier version of the current prototype E-Flap [6], called Max-Power. However, its modular design allowed us an easy adaptation to the updated version, just modifying few pieces. The integration of the folding mechanism proposed in this work is shown in Fig. 1, folded (top) and unfolded (bottom). The materials used for the wings are similar to those in [6] and they consist in a nylon fabric tensed using fiber carbon ribs forming the structure of the wing together with folding necessary pieces.

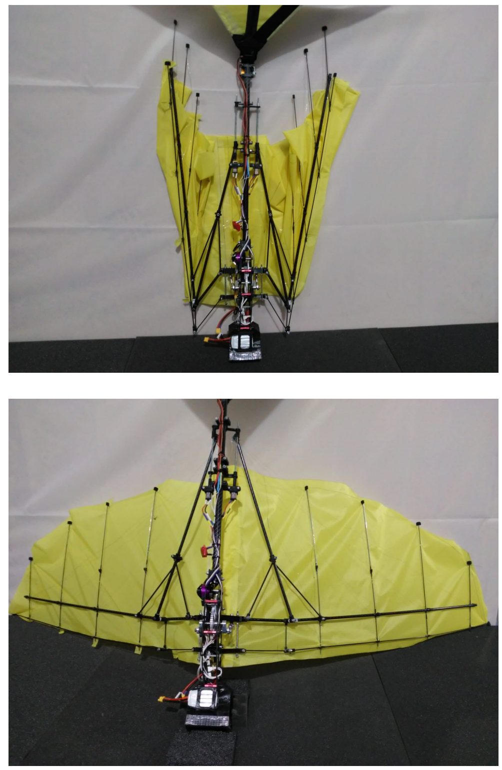

Fig. 1. Folding and unfolding states.

The contribution of this work is a novel folding mechanism for the ornithopter's wings that reduces the volume of the wing to $1/3$. Moreover, when compared with the current wing–without the folding capability–, it adds < 100 g/wing. Experimental bench validation is also provided in a video.

The paper is structured as follows: Section II outlines the state of the art, Section III shows the mechanism topology, the dimensional design methodology for the mechanism is described in Section IV, Section V describes the final prototype including materials, manufacturing, electronics and

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experimental validation. Finally, the paper is wrapped up with a conclusion and future lines are in Section VI.

II. State of the Art

The main inspiration of this work came from bat robots, as the Bionic Flying Fox by Festo [7], with rods and pulleys imitating the movement of a bat and [8] where methods to optimize the design and flight of a biologically inspired bat-like robot were presented.

Other interesting ideas came from the evolution of morphing-wing concepts collected in [9], where several main types of morphing are discussed as twist, variable camber, variable sweep, folding wing and span morphing. From there, we could say that the folding wing is a form of morphing wing. Additionally, it has the potential to improve the overall flight performance, by adapting or optimising dynamically the shape to various regimes. In particular, folding wing changes wing area and thus affects various aspects of flight such as climb rate, stall characteristics and lateral stability.

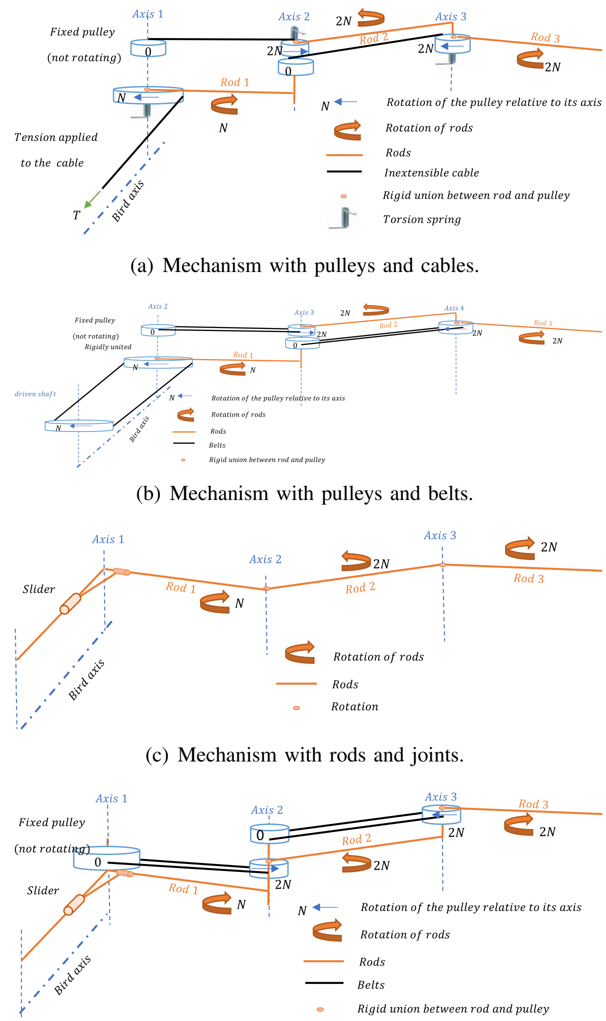
Although in another context, there are other folding research. Other topologies are in [10] that is previous to [7] but with the same mechanics. In [11] and [12] the authors replicates bird feathers in the second half of the wing with the mechanism in the central part, but it is a fixed-wing platform, and [13] follows the same idea. A recent project by Festo [14] is the one closer to nature mimicking the use of feathers of birds in flapping flight but it lacks of folding mechanism.

Other folding concepts to perform the folding found in the literature are summarized next. In [15] where the origami idea has been applied to drones in a fixed-wing platform, but it was discarded due to the extra weight. Variable sweep used in RoboSwift [16]; similar objective can be achieved with the mechanism of Aquatic Micro Air Vehicle (AquaMAV) [17], which focuses on reconfigurable wing to dive into the water from flight. However, none of them are capable of perform flapping, because the wing remains always with the same dihedral angle (fixed-wing). See also [18] where other fixed-wing platforms that allow folding are referenced. A project that employs ribs is [19], allowing flapping as well as folding, however it is based on the performance of a real duck and no experiment of a real flight is presented. All the aforementioned works demonstrate the complexity of the implementation of folding and the novelty of this concept.

III. Mechanism. Topology

An extensive study of the different possible mechanisms was carried out, considering mechanisms with pulleys and cables Fig. 2(a) or pulleys and belts Fig. 2(b)), without pulleys Fig. 2(c) and mixed Fig. 2(d).

Thus, pulleys transmit motion between different structural elements of the wing, using belts or tense cables/chords. Their main advantage is the easy modification of the turning speed by changing the radius; while their fundamental drawbacks are the need for a structure to accommodate the pulleys (additional weight), and the deterioration of the belts/cables. In fact, belts are a better solution than cables, because even though these are lighter it is difficult to change the direction



(a) Mechanism with pulleys and cables.

(b) Mechanism with pulleys and belts.

(c) Mechanism with rods and joints.

(d) Mixed mechanism.

Fig. 2. Different type of mechanisms.

of the turn to unfold the wings, and so an external system is needed adding extra weight. Besides, belts are more resistant.

On the other hand, the mechanism with rods and joints. Inspired by the folding of a bird's wing, the system should have three principal points of rotation representing shoulder, elbow and wrist. However, this would increase the complexity and add masses far from the longitudinal axis, increasing the inertia. This also applies for the pulleys.

Finally, the last option explored is a mixed mechanism, that combines the advantages and disadvantages of the previous ones.

To select between them, three global options were considered analyzing the pros and cons. For that, properties were enumerated and weighted accordingly depending on their influence as positive and negative factors for advantages and disadvantages, respectively, as shown in Table I. The values were set in the range of 1 to 3, from less to more in agreement with the property. The resulting scores are shown in Table II.

The analysis shows that the 'best' choice in this framework is the one that consists on rods, mainly due to the importance of the effect of flapping in the wing avoiding the dismantle

TABLE I

PROPERTIES AND WEIGHTING FOR MECHANISM TYPES

Factor	Description
-0.1	A1: Need for extra elements to fold
0.1	B1: Absence of elements affected by flapping
0.2	C1: Rotating sections at the desired speed
-0.1	D1: Kinematics conditioned by geometry
-0.1	E1: Need for rotating elements inside wing
0.1	F1: Absence of elements that can decay
-0.1	G1: Possibility of disarming during flapping
0.15	H1: Flapping resistance

TABLE II

MECHANISM TYPES COMPARISON

Prop.	Rods	Pulleys	Mixed
A1	1	3	2
B1	3	1	2
C1	1	3	2
D1	1	3	2
E1	1	2	2
F1	3	1	2
G1	1	3	2
H1	3	1	2
Score	0.85	-0.15	0.3

(falling apart) of the mechanism and the limitations in weight in the system: 100 extra grams per half-wing.

Once the type was selected, several options of this type were also analysed, as shown in Fig. 3. As above, a rank was established after weighting several characteristics shown in Table III. The resulting scores are in Table IV, and the 'best' mechanism is the one in Fig. 3(b). The analysis reveals that, even though it is less bio-inspired, to reduce the complexity and masses (points of rotation) far from the longitudinal axis, this one with two points of rotations is the simplest to implement and perform experiments.

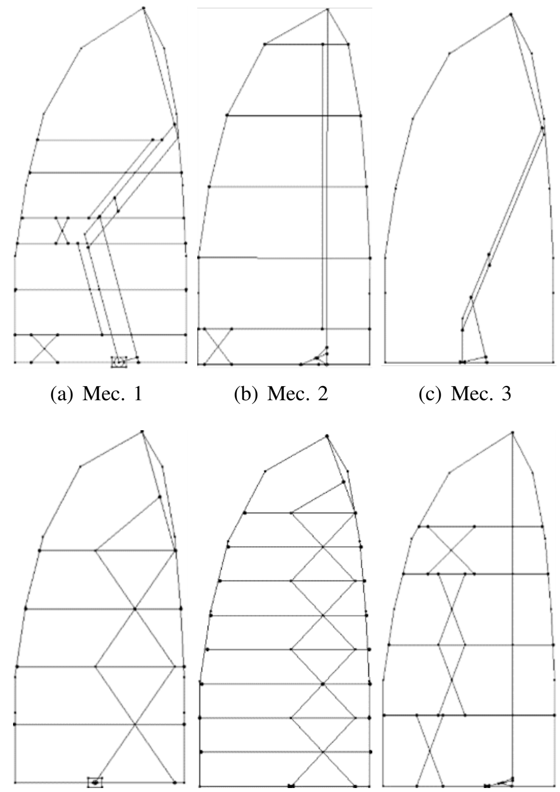
IV. MECHANISM. DIMENSIONAL DESIGN

This section is devoted to describe the methodology used to provide the dimensions of the first prototype, which has been manufactured and built as proof of concept. Thus, the efforts required by the mechanism are analysed from the point of view of power transmission associated with the geometric relationships of the rods. A similar approach has already been applied in [3]–with a good outcome–, by considering the tail of the ornithopter as a simplified

TABLE III

PROPERTIES AND WEIGHTING FOR ROD MECHANISMS

Factors	Description
-0.1	A2: Mechanism rods quantity
0.1	B2: Elbow and wrist
0.1	C2: Shoulder, elbow and wrist
0.2	D2: Simple (joints)
0.2	E2: Joints near wing root
0.1	F2: Easy insertion of rods along the chord
0.1	G2: Number of possible ribs to add >3
-0.1	H2: High number of joints required
0.1	I2: Linear mechanism to introduce motion
-0.1	J2: Large travel of the actuator
-0.1	K2: Intersection with bird's tail when folded



(a) Mec. 1 (b) Mec. 2 (c) Mec. 3

(d) Mec. 4 (e) Mec. 5 (f) Mec. 6

Fig. 3. Rod mechanisms.

TABLE IV

COMPARATIVE AMONG ROD MECHANISMS.

Prop.	Mec 1	Mec 2	Mec 3	Mec 4	Mec 5	Mec 6
A2	3	4	3	2	5	6
B2	1	1	1	1	0	0
C2	1	0	1	0	0	0
D2	3	2	3	6	5	1
E2	3	7	5	1	2	6
F2	1	3	1	4	4	2
G2	2	3	2	4	4	3
H2	3	5	3	2	4	6
I2	2	2	2	1	1	2
J2	2	1	3	5	3	1
K2	0	1	0	0	0	0
Score	1.1	1.6	1.4	1.5	1.1	0.8
Slider	5.3cm	1cm	5.6cm	12.3cm	5.6cm	1cm

mechanism of four rods, with two angles: one acting as an input and the other as an output. Thus, in the folding, we have considered angles φ_3 and φ_6 (see Fig. 4), mostly because they have a higher range. Fig. 4 also includes the remaining angles and lengths that represent the mechanism. In particular, from the point of view of the relative motions between bars, there are two types of joints: pure rotation (A, D and E) and sliders with rotation (B and C). The stress distribution causes compression in rods 2, 5 and 6; flexion and compression in rod 4 and bending and pulling in rod 3. Notice that, it is important that rod 5 is as perpendicular as possible to rod 6, in order to maximize the force $F_{E_{6_n}}$ that somehow controls the folding. This also benefits if the folded φ_4 is the smallest possible and φ_2 is biggest.

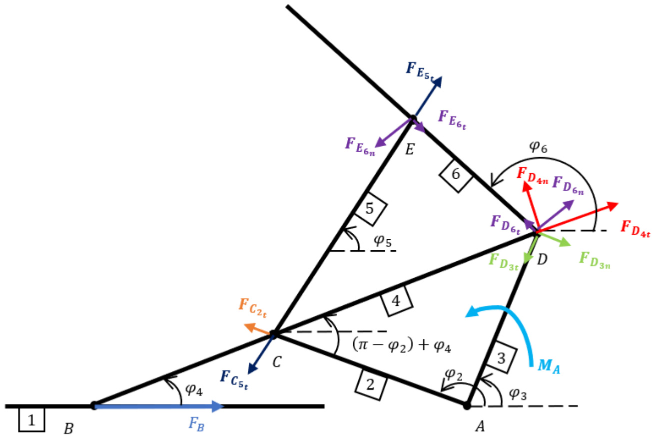


Fig. 4. Mechanism forces.

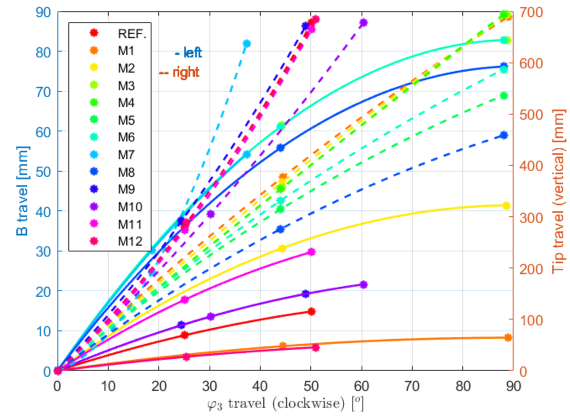


Fig. 5. B and tip travel for φ_3 travel

The mechanism kinematics is described by the following system of equations

$$L_4 = L_{41} + L_{42} \tag{1}$$
$$x_{AB} = -L_2 \cos\varphi_2 + L_{41} \cos\varphi_4 \tag{2}$$
$$0 = -L_2 \sin\varphi_2 + L_{41} \sin\varphi_4 \tag{3}$$
$$L_3 \cos\varphi_3 = L_{42} \cos\varphi_4 + L_2 \cos\varphi_2 \tag{4}$$
$$L_3 \sin\varphi_3 = L_{42} \sin\varphi_4 + L_2 \sin\varphi_2 \tag{5}$$
$$L_{61} \cos\varphi_6 = L_5 \cos\varphi_5 - L_{42} \cos\varphi_4 \tag{6}$$
$$L_{61} \sin\varphi_6 = L_5 \sin\varphi_5 - L_{42} \sin\varphi_4 \tag{7}$$

where rods are denoted as L_i, with $i = 1, ..., 6$. During folding phase, the joint C slides reducing the distance $\overline{BC}$, denoted as L_{41}; and increasing distance $\overline{CD}$, denoted as L_{42}. From here, we solve an optimisation-like problem in such a way to minimise the area and maximise the distance travelled. Roughly speaking, we want to minimise the volume in the folded state, and maximise the area covered in the unfolded state. This can be stated as an optimisation problem as follows. Let u define the input vector data composed by the rod lengths and the angle φ_3 as $u := \{L_2, L_3, L_4, L_5, L_{61}, \varphi_3\}$, with $u \in \mathcal{M}$ for some discrete set of values $\mathcal{M}$, and the output vector (outcomes) defined as $y := \{\varphi_2, \varphi_4, \varphi_5, \varphi_6, x_{AB}, L_{41}, L_{42}\}$. The simplified optimisation problem can be stated as

$$\mathcal{P}(u, y) := \max_{u \in \mathcal{M}} \Big\{ \text{B-travel distance} \bigcap \text{Tip-travel distance} \Big\}, \quad \text{subject to (1)–(7),}$$

where $\mathcal{M} = \bigcup_j M_j$, $j = 1, ..., 12$, with M_j cases defined as modifications from the reference $REF.$. The results are shown in Fig. 5 with M_4 the 'optimum' set of all those considered in $\mathcal{M}$. Fig. 5 shows all evolutions of the search and, hence, M_4 is the furthest from the origin or the top right corner.

V. Prototype and Experimental Validation

The final prototype needs a redesign with the baseline obtained with the optimisation.

Design. First notice that we need a 3D version to be able to implement it. A mechanical option is that the rods are placed at different height, namely levels, Thus, we propose the levels for the mechanism shown in Fig. 6.

Another simplification made for the optimisation was that A and B were considered in the same horizontal axis. However, the integration requirement imposes–among others–that they are not in same horizontal axis. This leads to substitute 0 by the vertical projection of the $\overline{AB}$ distance in (3).

Besides, the stiffness of the fabric in tension does not allow folding unless the leading edge is straight.

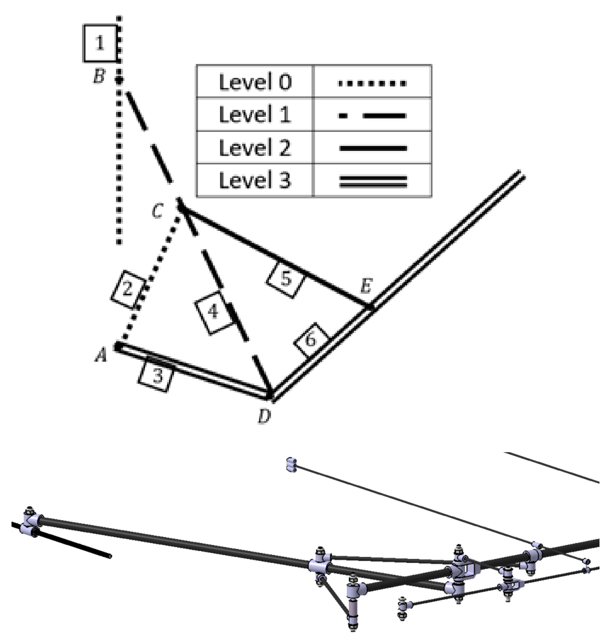


Fig. 6. Levels of mechanism.

Moreover, the strictest integration requirement for aerial vehicles is the weight. This has also been considered by reducing the thickness of pieces and rods to not introduce unnecessary mass, but keeping in mind its robustness. The final mechanism is shown in Fig. 7 and its integration with the platform in Fig. 8.

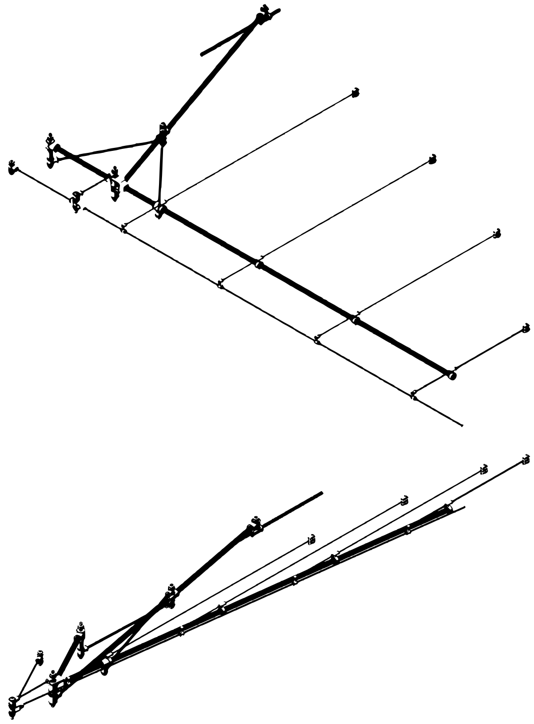


Fig. 7. Extended and folded states.

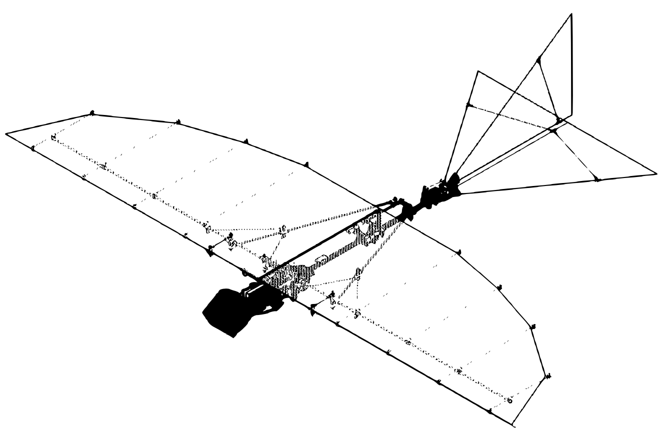


Fig. 8. Integration of the mechanism.

Materials. While the rods are of fiber carbon, the majority of pieces are 3D printed of PLA or TPU 95 whenever flexibility is needed, as in the joint of ribs to the mechanism rods. The pieces subject to higher stress are made of aluminium and manufactured by CATEC, as e.g. the vertex D in rod 6.

Electronics. The actuators to move the folding mechanism are basic POLOLU motors which are actuated through a carrier that integrates the electronics of E-flap [6]. Additionally, to change the direction of the movement, between both states, a H-bridge has also been implemented.

Experiments. The extended and folded states are shown in Fig. 1. In addition, the accompanying multimedia extension of this paper includes a video summarising all the design procedure. Furthermore, the experimental validation includes flapping, folding and unfolding the mechanism.

The final specifications of the prototype are:

Volume. The final number of pieces needed to fold the wing is 233. However, it is important to highlight that, despite that number the final mechanism passes from $0.68m^2$ and $0.034m^3$ in the unfolded state, to $0.24m^2$ and $0.012m^3$ in the folded one. That means a reduction of almost $2/3$, i.e. the folded wing version is $1/3$ the unfolded one.

Weight. The total mass is 731.2 g and its estimate in CATIA 730.8 g. The difference is due to the threads that tighten the fabric and other inaccuracies. The mass of the mechanism is 305 g, which means that the added mass with respect to the current E-FLAP wing is 174 g, less than 100 g in each wing.

VI. Conclusions and Future Work

A folding mechanism for the wings is designed and integrated in a platform of the GRIFFIN project. The design methodology resulted in a prototype with the functionality required. This has been experimentally validated. Currently, work is underway of experimental in-flight validation.

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