

A Drone with Insect-Inspired Folding Wings

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Abstract— Flying robots are increasingly adopted in search and rescue missions because of their capability to quickly collect and stream information from remote and dangerous areas. To further enhance their use, we are investigating the development of a new class of drones, foldable sensorized hubs that can quickly take off from rescuers’ hands as soon as they are taken out of a pocket or a backpack. With this aim, this paper presents the development of a foldable wing inspired by insects. The wing can be packaged for transportation or deployed for flight in half a second with a simple action from the user. The wing is manufactured as a thick origami structure with a foldable multi-layer material. The prototype of the foldable wing is experimentally characterized and validated in flight on a mini-drone.

I. INTRODUCTION

The use of small and autonomous airborne vehicles after natural disasters for imaging, mapping and victim localization is rapidly becoming commonplace with well documented cases where drones have been sent into areas too dangerous for rescue workers [1]. While the issues surrounding robustness, perception and control are frequently cited as being key areas for research [2], another important aspect is how to make drones easily transportable and quick to deploy. In search and rescue scenarios, the possibility to quickly gather images to assess damages and plan an intervention is key for success and damage mitigation [1]. To tackle this challenge, we envision a new class of portable drones, which function as flying sensor hubs that are readily available to take off from the users’ hand as soon as they are removed from a pocket or a backpack.

Size reduction and foldability are different solutions to enhance drone portability. Nowadays, the miniaturization of core technologies has fostered the development of “pico drones” that fit the palm of a hand. However, the usability of miniature drones is affected by their reduced endurance and payload [2]. On the other hand, foldable drones can be large enough to carry a useful payload when fully deployed while being transportable when folded and stowed [3].

The majority of foldable drones rely on detachable (e.g. the eBee™ by senseFly) or foldable appendages composed of multiple joints [4][5]. The results are fragile and poorly scalable foldable structures, that often require multiple manipulations to deploy, which is time consuming and can lead to errors. Other drones, equipped with inflatable or continuously deformable wings [6], can autonomously deploy without human intervention. Inflatable wings are composed of a series of longitudinal pressurized tubes approximating the desired wing shape, however the

requirement of a high-pressure distribution system generates additional weight, thus reducing payload and flight autonomy. Continuous deformable elastic wings have better manufacturability and scalability, but folding is constrained by the material’s strain limit. The emerging technique of manufacturing origami structures offers an elegant solution for the development of foldable structures [7]. Complex folding patterns can be engraved in multi-layered materials using two-dimensional laser micromachining, leading to lightweight structures with complex folding behaviors. The viability of origami manufacturing for foldable drones has been demonstrated by the authors in a miniature self-deployable quadcopter equipped with foldable arms [3].

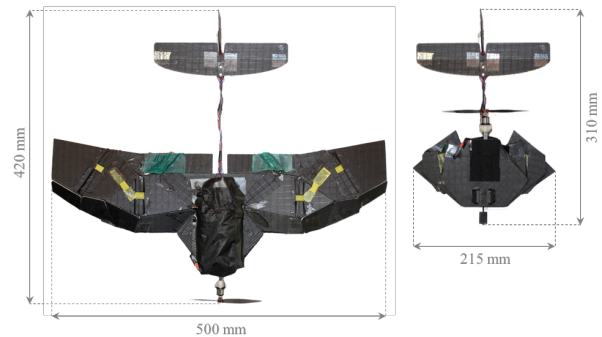


Figure 1. Foldable fixed-wing drone in the deployed and stowed configurations. The drone is remotely controlled during flight and has a take-off weight of 82 grams.

We describe here a novel, foldable, origami wing design inspired by insect wing folding patterns (Fig. 1). The user can fold the wing with a single and intuitive movement in a short amount of time. In the stowed configuration, the wingspan is 43% and the surface is 26% of the respective dimensions in the deployed configuration. This is to authors’ knowledge the first time a fully-functional origami wing has been successfully designed and tested in a flying drone. We tackle the challenges of designing the crease pattern and the selection of materials by looking at insects’ wings, which are small and sturdy when folded, but can be quickly deployed.

First, an overview of insect wings is presented highlighting relevant features that can be transferred into the design of origami wings. Then, the design and manufacturing of the origami wing are discussed. A prototype of a fixed-wing drone equipped with the foldable wing, built and experimentally characterized during this work is presented. A discussion of the results and proposals for future work conclude the paper.

II. FOLDABLE WING IN INSECTS

The wings of insects are considered by biologists and engineers as the ultimate deployable structures. Because of their load-bearing capability at high flapping frequencies,

lightness, compactness when folded, and rapid deployment, insect wings offer a fruitful source of inspiration for the development of foldable drones [8].

Several species of insects evolved foldable wings as an adaptation for multi-modal locomotion. In order to prevent damages or hamper terrestrial locomotion, the fragile but large wings required to sustain the insect's weight during flight are folded at low volume along the abdomen under protective and robust fore-wings, called tegmina or elytra.

Geisler [9] suggested that insect wings, which are composed of stiff cuticle tiles interconnected through flexible joints made of resilin, can be approximated by origami structures. Cuticle is a biological fiber composite material that is arranged as a thin membrane, reinforced by veins that run both from the wing root to the tip, and transversely, and acts as a scaffold. Resilin is an elastomeric protein notably found in specialized regions of the wing of most insects. It is among the most efficient elastic protein known, and is often located along the folds of the wings to provide better compliance and prevent fatigue and tear during folding cycles and collisions. Wing folding behavior is dictated by the distribution of veins and internal joints and can be broadly categorized in three main families [8]: longitudinal folds, fan-like folds and transverse folds. However, these folds are often combined to achieve a greater level of compactness when stowed at the expense of a more complex crease pattern (Fig. 2A). The folding ratio is a measure of folding efficiency, defined as the ratio of the deployed wing surface to the surface of the folded package. For example, the earwig (*Forficula auricularia*) and the rove beetle (*Staphylinidae*) display efficient folding patterns with folding ratios of ten [10] and eight [8], respectively.

Haas derived mathematical models that describe the kinematics of transversally foldable wings [11]. These models build on the combination of flat-foldable “four-creases knots”, which are elementary patterns composed of four tiles joined by a knot [12] (Fig. 2B). Between two tiles, or panels, is what is called a crease, or fold. Flat-foldability, namely the capability to achieve a flat state in the stowed and deployed configuration, requires respect of the following constraints:

- the sum of all angles (α , β , δ , γ) around a knot must be equal to 360° ;
- the sum of the non-adjacent angles (α , γ and β , δ) around a knot must be equal to 180° ;
- there must be three valley folds (for example the one between the green and blue tiles in Fig. 2B) and one mountain fold (like the one between the yellow and red tiles in Fig. 2B), or one valley and three mountain folds intersecting in the knot.

These constraints can be leveraged as the basis for the development of origami wings because they allow the design of theoretical (i.e. infinitely thin), flat foldable structures. The obtained crease pattern can be subsequently modified to take into account the thickness of the material used to manufacture the wing (see section III B).

The crease pattern not only contributes to the compactness of the wing when stowed, but also dictates the way the folding process is accomplished. Insect wings are

passive structures (i.e. they do not embed actuators), therefore the folding process is triggered at the base of the wing, by muscles inside the thorax or by the abdomen motion [9], and propagated to the tip of the wing thanks to specific crease patterns. Therefore, at first approximation, insect wings are single degree of freedom (DOF) mechanisms. By adapting their crease patterns, it could be possible to develop artificial wings with complex folding behaviors that can be intuitively deployed with a single movement by the user.

In addition to crease patterns, insect wings provide useful insights into the use of soft materials in origami structures. It has been shown that the wings of several insect species have flexible joints made of resilin, that have the roles of preventing wing tear [13] and storing elastic energy [14]. The way the wing stores energy (Fig. 2C), confers a bistable behavior that results in fast transitions and rigidity when stowed or deployed. Indeed, insect wings display very fast deployment, ranging between 25–40 ms for Coleopterans [15] to almost 1s for Dermapterans (earwigs) [10] and have sufficient strength and stiffness to withstand 20–1,000 beats per second during flight. Artificial wings can achieve the same behaviors as their natural counterpart by replacing resilin with soft materials (see section III B).

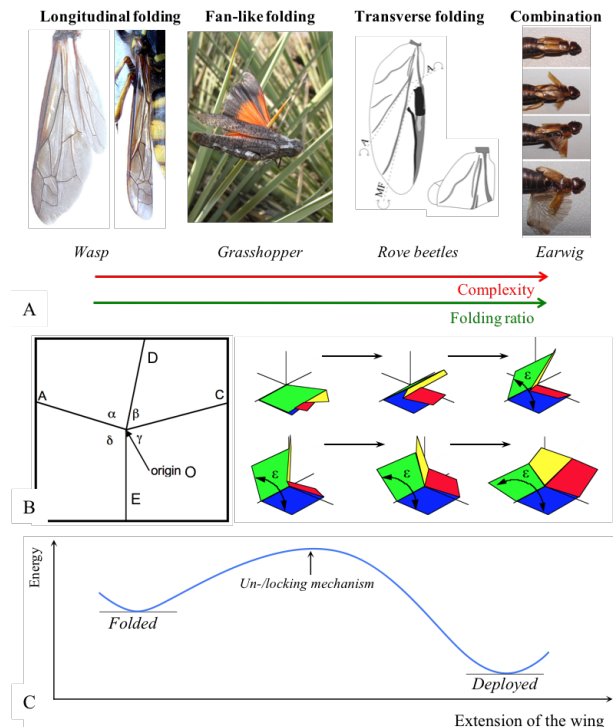


Figure 2. (A) Main categories of crease patterns encountered in the wings of insects. A high value of folding ratio is achieved at the expense of a more complex crease pattern. (B) Folding process of a flat-foldable “four-creases knot” mechanism composed of three valley and one mountain folds. (C) Elastic energy stored in the wing as a function of its extension during folding.

III. WING DESIGN AND IMPLEMENTATION

The foldable wing has been developed in a two step process. At first, a crease pattern is developed for a flat-foldable wing under the theoretical assumption of zero thickness. Then, the design of the wing was modified to account for the actual thickness of the tiles required to withstand aerodynamic forces during flight.

A. Selection of the Crease Pattern

An ideal crease pattern for an artificial foldable wing should generate the highest folding ratio and require a single DOF for easy deployment. In coleopterans, both these features are directly encoded in the crease pattern of the wing. Coleopterans exploit transversal folding patterns (Fig. 2A) that can achieve a folding ratio of approximately four. Furthermore, like in single DOF mechanisms, the folding process is triggered at the base of the wing by specific muscles in the thorax, and passively propagates to the tip of the wing. Therefore, coleopterans provide useful insights for the development of a crease pattern for artificial foldable wings.

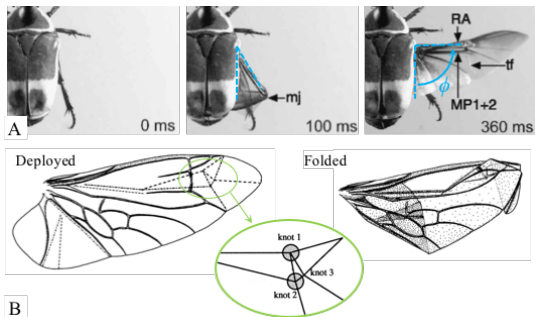


Figure 3. (A) Snapshots of the wing deployment process in *Pachnoda marginata*, adapted from [14]. (B) The crease pattern of the *Zophobas rugipes*, adapted from [12].

The folding process and crease pattern of coleopterans’ wings have been extensively studied by Haas [11]. Fig. 3A and B illustrate two representative examples of wing folding process and crease pattern. The deployment process involves a rotation of the wing by roughly 90° (angle ϕ in Fig. 3A). The wings are aligned with the abdomen when stowed, so as to be protected under the *elytra*, and are deployed perpendicular to the body for flight. Furthermore, several species of coleopterans have a crease pattern composed of three “four-creases knots” arranged as a triangle (knot 1, 2 and 3 in Fig. 3B), that contributes to the size reduction of the outermost part of the wing.

These observations inspired the development of the artificial origami wing illustrated in Fig. 4A. The wing has a symmetric wing pattern composed of two main parts: an innermost and outermost respectively pictured in the blue and green frames of Fig 4A. The innermost crease pattern is an

adaptation of the well-known Miura-ori pattern [16], and it is responsible for a 90° rotation of the wing during folding. The outermost crease pattern account for almost 75% of the surface of the wing, it exploits the three “four-creases knots” mechanism found in some species of coleopterans (K_{1-3} in Fig. 4A), with an additional “four-crease knot” (K_4 in Fig. 4B). It mostly contributes to wing size reduction during the folding process.

The proposed crease pattern is not a direct copy of the one evolved by coleopterans. Instead, it has been adapted through a series of iterations alternating computer simulations and cardboard models, while respecting the three constraints reported in section II. First, the surface of the wing was defined as 600 cm^2 , which is enough to sustain 100 grams at the moderate flight speed of 5-10 m/s. Second, the Rigid Origami Simulator [17] was used to quickly visualize the effects of changes in the crease pattern on the folding behavior of the wing. Third, cardboard prototypes were used to validate the results given by the simulation, to test the non-penetration of the tiles and other properties that could not be easily assessed through simulation, such as single DOF actuation, bending stiffness and 3D shape when stowed or deployed.

The cardboard prototypes provided two results. First, 90° angles should be avoided in the crease pattern because they can cause the mechanism to lock during both folding and unfolding. Furthermore, 90° angles cause unacceptable stresses on the creases, which can cause premature wear and ultimately failure of the entire mechanism. A second result concerns the angle ψ in the Miura-ori crease pattern (see Fig. 4A). It was noted that an increase in its value improves the bending stiffness and critical buckling load that the wing can sustain.

Finally, special care was given in placing the first row of folds (red dashed line in Fig. 4A) close and almost parallel to the leading edge of the wing. Indeed, as will be discussed in the next section, the origami wing implemented with tick tiles will not be in a perfectly flat state when unfolded due to the bistable mechanisms that will be added (see section III B) and misalignments caused by the manual assembly of the tiles. Therefore, a camber will appear along the first row of folds, and for an efficient aerodynamic this camber should be close and parallel to the leading edge.

The folding sequence is illustrated in Fig. 4B, where we

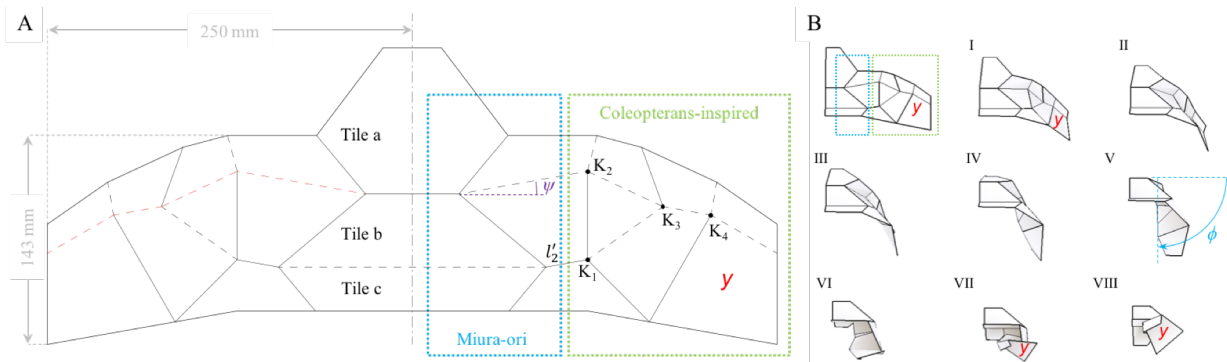


Figure 4. (A) Top view of the crease pattern of the foldable wing. Dashed and full lines respectively represent valley and mountain folds. The crease pattern inspired by coleopterans is highlighted by the green frame and the adaptation of the Miura-ori crease pattern by the blue frame. (B) Main steps of the folding process simulated using the Rigid Origami Simulator software [17], seen from beneath the wing

assume the wing is seen from beneath, and the “tile a” is folding on the “tile b”. The crease pattern has a single DOF, therefore the wing can be completely folded with a single movement, a 180° rotation of “tile-a” with respect to “tile-b”. Starting from a flat configuration, the wing first rotates downwards and to the rear as a result of the Miura-ori crease pattern (steps I-V). Once the wing is almost aligned with the direction of flight, the $K_{1,3}$ triangle makes it collapse backward (steps V-VII). Finally, as the tile y rotates around the knot K_4 , it folds on top of everything else, thus ending the folding process (steps VII-VIII). The unfolding process is the exact reverse of the folding. The reader is encouraged to refer to the videos attached to this paper for a better understanding of the folding and unfolding sequences.

B. Implementation of the Wing as Thick Origami

Most origami theories, including that by Hass concerning folding wings, neglect the thickness of the material. Thin sheet materials often lack rigidity, and thus cannot be used because windy conditions can generate high aerodynamic loads on the wing. Any material with sufficient rigidity to support the kind of stress expected during flight has a non-negligible thickness. Therefore, the capability of developing origami structures with thick tiles is mandatory to enabling the scaling up the design of insect wings to drones. The development of thick origami wings requires three design adaptations.

First, the wing was modified to account for the tile thickness with a method suggested by Chen *et al.* [18], which consists of offsetting the fold lines to allow the model to be flat foldable even with thicker panels. For example, the “four-creases knot” (introduced in Fig. 2B) has been adapted by using standoffs to offset the fold line between the blue and the green panel allowing the whole model to be perfectly flat in both folded and unfolded positions (Fig. 5A). In the wing, not all fold lines of the pattern need to be offset, studying the folding kinematic as well as the relative position of each tile in the folded state helps determine where to offset the fold lines. Standoffs were placed along several of the fold lines on the wing according to two main considerations. First, the folding sequence, which is the order in which the tiles close when actuated, is influenced by the placement of the standoffs on the folds. Their locations have been selected to replicate the ideal deployment process illustrated in Fig. 4B. Secondly, since standoffs can negatively affect wing aerodynamics, special care was taken to minimize their height and to place them as much as possible parallel to the flight direction. Folds that are offset by standoffs are highlighted on the right side of the wing by a dark blue lines in Fig. 5B. The standoffs confer a three-dimensional shape to the deployed wing (Fig. 5C) with surfaces with different heights protruding from the reference plane containing the three central tiles (tiles a, b and c). The level of each surface is described by the color-coded map shown in Fig. 5B.

Introducing thickness in origami by offsetting the fold lines change their folding and unfolding behavior by introducing parasitic movements. This is visible in Fig. 5A, where a circle highlights the gap that appears between two tiles during deployment. This phenomenon is usually referred to as internal DOF [19], and needs to be relieved through some sort of compliance to avoid internal stress that could

cause the mechanism to fail. To relieve the stress, some of the hinges were replaced by pre-stretched latex glued on the surface of the wing to make the mechanism compliant. So, one compliant hinge per knot has been added to keep the wing as a single DOF mechanism (see red circles Fig. 5B), while allowing internal stresses to be relieved during folding.

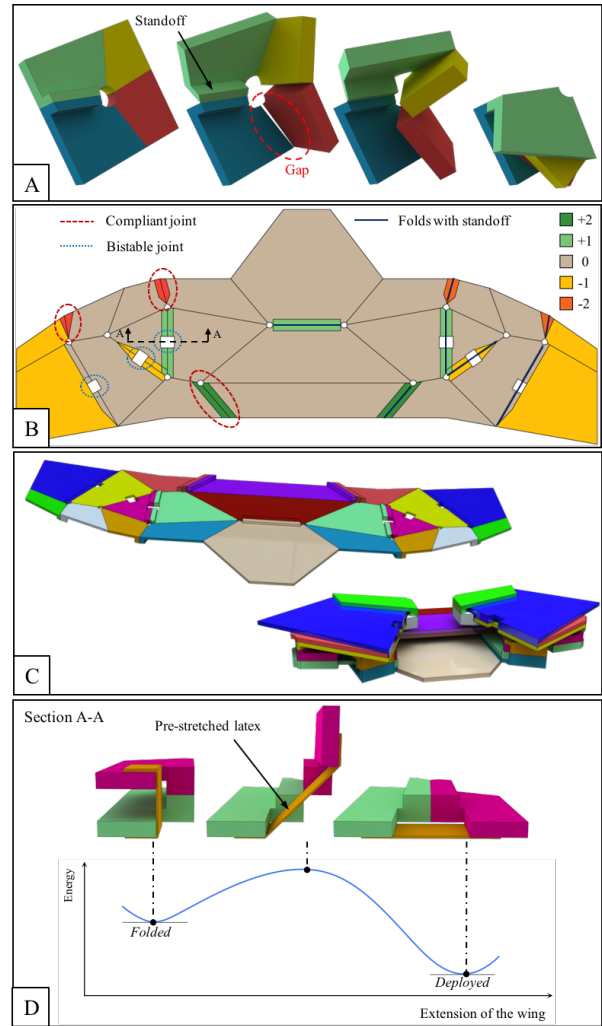


Figure 5. (A) Folding process of a simple flat-foldable “four-creases knot” adapted to thick origami. (B) Placement on the wing of standoffs, compliant joints and bistable joints. Height levels indicate the relative location of each surface with respect to the reference plane (level 0) containing the three central tiles (tile a, b and c). For sake of clarity, standoffs are highlighted on the right side only while compliant and bistable joints on the left side only. (C) Rendering of the wing in the stowed and deployed configurations. (D) Section view (indicated by A-A on Fig. 5B) illustrating the implementation of bistable joints on the wing

The third adaptation consists of modifying the structure to ensure the bistable behavior observed in insect wings for rapid deployment (Fig. 2C). This was achieved by making some bistable joints in the wing (blue circle in Fig. 5B), using the mechanism illustrated in Fig. 5D. These bistable joints are located in the middle of the wing to help the folding process to rapidly propagate from the central tiles (tiles a, b and c in Fig. 3A) to the outermost parts of the wing. The bistable joints are composed of pre-stretched elastic membranes glued on top of the wing and their working principle is illustrated in Fig. 5D. The distance between the attachment points of the pre-stretched membrane is the

shortest one when the system is either stowed or deployed. This results in the hinge snapping shut or open when it passes the 90° opening mark. This increases the force needed to actuate the wing but helps the transmission of the strength from one panel to the other, keeps the wing compact when folded, and increases folding rapidity.

The wing consists of a composite made of 3 mm Depron foam and a polyester (Icarex©) membrane bonded with vacuum cured epoxy. The membrane inextensibility confers the high rigidity in a lightweight package ($\sim 290 \text{ g/m}^2$). The panels and standoffs used for offsetting the fold lines were laser cut (CO_2 laser system Trotec Speedy 300) and manually assembled with cyanoacrylate glue (Loctite 401). Icarex© was used to make the inextensible hinges because of its high durability and thinness. The compliant hinges were made with a pre-stretched latex membrane (TheraBand™ green), which allows the tiles to freely move during actuation while keeping them together in both deployed and stowed configurations. The bistable hinges are made of pre-stretched latex membrane (TheraBand™ yellow). There are three compliant hinges and three bistable hinges per side, their placement is illustrated in Fig. 5B.

To secure the wing in the open position, tiles a and b (see Fig 4A) were equipped with a magnetic latch that engages when the wing is deployed. The latch secures the tiles in the deployed configuration preventing unwanted folding during flight.

The now thick origami wing is capable to withstand aerodynamic loads while still being flat foldable in both deployed and stowed states, as shown in Fig. 5C, where it is visible that each tile adds a layer in the folded configuration. Dimensions of the wing are given in Table 1.

Table 1. Wing dimension comparison between folded and unfolded configurations measured on real wing prototype.

	Size [mm]	Surface [cm ²]	Volume [cm ³]	Weight [g]
Folded config.	115 x 215 x 40	160	989	26
Deployed config.	200 x 500 x 16	620	1600	

IV. EXPERIMENTAL CHARACTERIZATION

The stiffness and aerodynamic performances of the foldable origami wing have been measured and compared with a rigid, non foldable, flat wing made of the same material and with the same shape and thickness, but without standoffs.

The aerodynamic load experienced during flight bends the wing, increasing the dihedral angle. Therefore, the wing strength was measured by pulling it upward from its horizontal position and recording the applied force (Fig. 6). It should be noted that during flight the wing is subject to a distributed load; therefore, this test overestimates the real deflection, but still gives an informative comparison of the flexibility of the origami wing compared to the rigid one. The higher flexibility of the origami wing generates a dihedral angle that is beneficial to roll stabilization during flight and increases the resilience of the wing against collision.

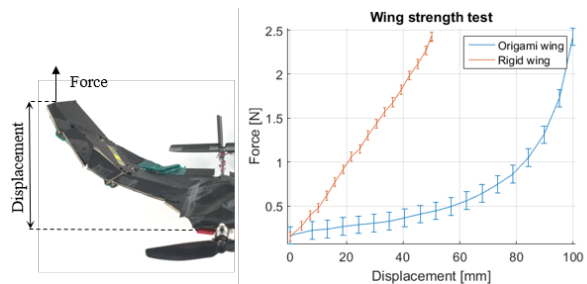


Figure 6. Left: Picture of the wing bent under heavy load. Right: comparison of origami and rigid wing flexibility under different load conditions.

Despite the higher flexibility of the origami wing compared to its rigid counterpart, they have shown very similar performances when placed in a wind tunnel (Fig. 7). When fully deployed, the origami wing presents a cambered profile due to the pre-stretched latex used to build the compliant hinges mentioned earlier (without pre-stretched latex the wing would be flat when unfolded). The two compliant hinges on the leading edge of the wing (Fig. 5B) produce a camber of approximately 15° that confers a better lift coefficient to the foldable wing compared to the rigid one (C_L in Fig. 7). On the other hand, the rigid wing has a lower drag coefficient (C_D in Fig. 7) because it has no standoffs or holes that create small turbulences and vortices. As a result, the rigid wing displays only slightly better performance (C_L/C_D in Fig. 7) without the added benefit of foldability.

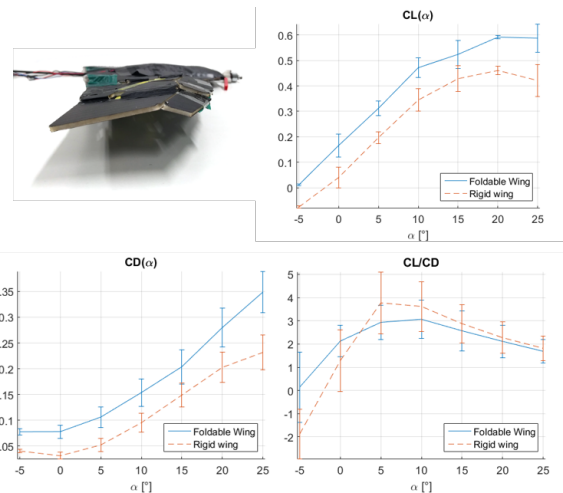


Figure 7. Picture of the wing camber observed from the tip of the wing. Plots of aerodynamic coefficients (lift coefficient C_L , drag coefficient C_D and efficiency factor C_L/C_D) as function of the angle of incidence (α) for a Reynolds number of 44,300 obtained in wind tunnel tests.

In order to assess the flight performance, the wing was tested in a drone with frontal propeller and a tail comprising of a rudder and an elevator (Fig. 1). Thanks to the dihedral angle formed by the wing, no aileron for roll stability was needed. An RF receptor was added to pilot the drone remotely. Flight tests (see attached video) showed that the wing was capable of withstanding aerodynamic loads and of offering stable flight conditions. The drone was able to perform loops without buckling or folding and also to fly at low speed ($\sim 5 \text{ m/s}$).

The manual deployment process is illustrated in Fig. 8A, which is composed of multiple snapshots from a video

captured at 240 fps (see attached video). The user holds the plane by the tail and unfolds the wing by simply separating the propeller from the tail until the magnetic latch locks. By reversing the same operation, the wing can be stowed. The folding procedure takes half a second to accomplish and requires less than 1 N applied to the tail to actuate. Fig. 8B shows how compliant joints are stretched during the deployment process, allowing the two sides of the hinge to separate, releasing stresses in the overall mechanism, therefore preventing its failure. The contribution of the bistable joints to the optimal folding of the wing is illustrated in Fig. 8C, showing the wing in the stowed configuration. The left side of the wing is equipped with bistable joints and can achieve a compact folded state. Oppositely, the right side of the wing is not equipped with bistable joints (the pre-stretched latex membrane is removed), therefore it is not completely folded.

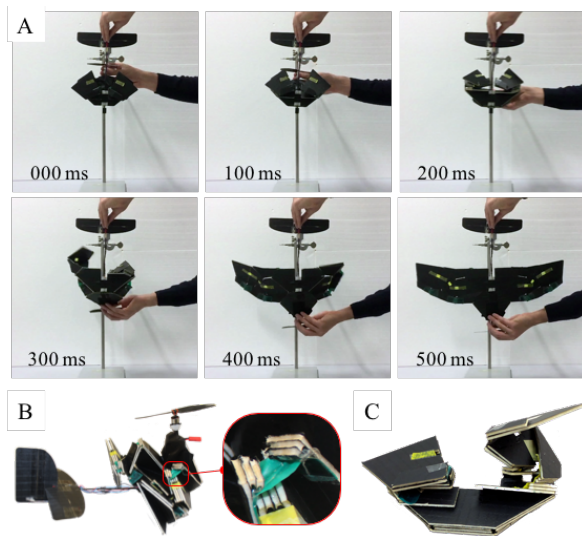


Figure 8. (A) Snapshots of the manual folding process, from the stowed to the deployed configuration. (B) The compliant joint on the leading edge stretches and the fold separate during the folding process (tiles a and b are perpendicular). (C) Effect of bistable joint on the compactness of the stowed configuration. Left side is with bistable joints and right side is without (the yellow latex membrane is removed).

V. CONCLUSION

This study demonstrates the feasibility of implementing a fully operational origami wing on a small scale drone. The capability of developing origami mechanisms with thick tiles is the enabling factor for scalability, as demonstrated by the implementation of a half meter long wing leveraging the design of two orders of magnitude smaller insect wings. Compared to other origami manufacturing techniques [7], the proposed thick origami still relies on manual assembly, a time consuming and error prone process. Despite this fact, the manufacturing scalability, the possibility of encoding the desired folding behavior by tailoring the crease pattern and the integration of soft materials go beyond applications in foldable drones only, paving new prospective for foldable structures at large, for robotic, aerospace and civil applications.

Future work will address the identification of a rigorous methodology for designing the crease pattern to simplify the development of wings with different shape and size. The

study of the mutual influences of crease pattern and joint stiffness on the flexibility of the wing is expected to improve its aeroelastic performances. Finally, a more automated manufacturing process, and the implementation of autonomous folding with an integrated actuator will relief operators from any manual operations, from manufacturing to field work.

ACKNOWLEDGMENT

This work was supported by the Swiss National Science Foundation through the National Centre of Competence in Research Robotics (NCCR Robotics).

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