Foldable and Self-Deployable Pocket Sized Quadrotor

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***Abstract*— Aerial robots provide valuable support in several high-risk scenarios thanks to their capability to quickly fly to locations dangerous or even inaccessible to humans. In order to fully benefit from these features, aerial robots should be easy to transport and rapid to deploy. With this aim, this paper focuses on the development of a novel pocket sized quadrotor with foldable arms. The quadrotor can be packaged for transportation by folding its arms around the main frame. Before flight, the quadrotor's arms self-deploy in 0.3 seconds thanks to the torque generated by the propellers. The paper describes the design strategies used for developing lightweight, stiff and self-deployable foldable arms for miniature quadrotors. The arms are manufactured according to an origami technique with a foldable multi-layer material. A prototype of the quadrotor is presented as a proof of concept and performance of the system is assessed.**

I. Introduction

Flying robots are being increasingly adopted in several high-risk scenarios because of their capability to quickly fly to remote, dangerous or even inaccessible areas and provide useful information to users [1]. Their missions range from reconnaissance, inspection of partially collapsed structures, mapping and localization of victims. However, the benefits of aerial vehicles are subordinate to the possibility to easily carry them to the mission area. One solution to solve this transportation issue is to reduce the size of the drones. The shortcoming is a reduction in payload capabilities and in flight time [2]. Therefore, foldable structures, which can be packaged for transportation and quickly deployed for operation, are a promising solution to enable full benefits from the potential of flying platforms. Ideally, the user would simply take the quadrotor out of their pocket and throw it in the air for rapid self-deployment before the start of the mission. The advantages of this approach are even more important if the operator has to carry and simultaneously deploy multiple quadrotors.

The challenge of developing a quadrotor that can rapidly transition from a stowed to a ready to fly configuration is addressed in this paper. A rotor-based platform has been selected for its high maneuverability, its design simplicity and its capability to hover, which enable flight in cluttered environments and accurate inspections.

The design of foldable flying robots requires addressing numerous challenges in order to ensure flight performances comparable to vehicles with a fixed frame. A first challenge is to design a foldable frame that can be stiff when fully deployed in order to preserve maneuverability and at the same time be compliant in order to minimize the efforts required during the folding process. A second challenge is to minimize the impact of the folding mechanisms on the overall weight, robustness and design complexity of the platform. Finally, the aerial robot should be rapidly deployable with minimal effort and manual operation from the user in order to prevent human errors.

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Current foldable aerial platforms adopt either foldable beams or detachable appendages for storage purposes (e.g. DJI Spreading Wings series [3] and SenseFly eBee [4]). Their deployment often requires the operator to manually configure the parts of the system into the deployed state or perform other manual operations. This introduces human user errors and requires time, which increases proportionally with the number of units to deploy, limiting their dispersal. Automatic deployment by self-unfolding structures solves these issues. Deployable structures find applications in multiple fields, ranging from space to architecture [5]. There are two common approaches: on one hand, multi-joint mechanisms ensure design flexibility but the resulting structures are complex and bulky, and therefore difficult to manufacture and to miniaturize, and on the other hand, continuous deformable elastic systems are mechanically simpler but more constrained in their folding capabilities. Therefore, the foldable quad presented in this paper exploits the emerging technique of foldable origami [6]. This technique allows a combination of the benefits from both: structures with complex crease patterns but with a simpler manufacturing process. Self-folding origami structures have been demonstrated as shape shifting and terrestrial robotics platforms [6, 7].

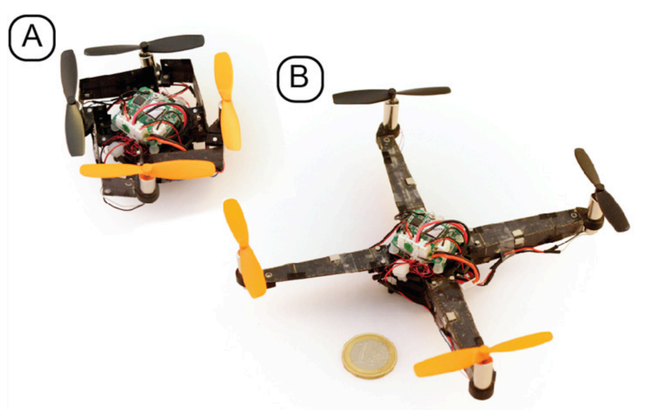

Figure 1. Miniature quadrotor equipped with foldable and self-deployable arms. (A) Stowed configuration with the arms wrapped around a central rigid frame. (B) As soon as the propellers are activated, the arms autonomously deploy and the quadrotor unfolds to a ready to fly configuration. The control board, battery, motors and propellers belong to the commercial quadrotor Walkera QR Ladybird.

This paper aims at describing the design of foldable arms for a pocket sized quadrotor. First, an overview of relevant technologies for the development of foldable structures is presented. Then, the strategies adopted for the design of the origami arms focusing on stiffness, design simplicity, minimal weight and self-deployment are described. A first prototype of a foldable quadrotor (see Figure 1) is built and self-deployment capabilities are tested. A discussion of the results concludes this paper.

II. Related Work

Foldable structures are a type of engineering system that undergo large configuration changes. They preserve the conventional load bearing functionality, but can be folded for easy transportation and deployed before operation [5]. These structures are widely adopted in aerospace applications since antennas, arrays of solar cells and other systems for space vehicles must be packaged in a compact form to fit into the launch vehicle. Foldable structures are also adopted in civil engineering for constructions built for temporary use. The classical design of foldable structures encompasses two main strategies, which are discussed in [5]. The first strategy involves the use of multi-joint structures (i.e. revolute, prismatic or cylindrical joints) that can fold locally [9]. The second approach is a complementary strategy, which involves the development of continuous deformable structures that can be packaged thanks to the intrinsic compliance of their material [10]. An alternative approach involves the use of origami techniques. In this recent field of research [6], foldable structures are manufactured in 2D with embedded crease patterns that allow folding of the structures into complex 3D shapes.

The suitability of the three different solutions can be discussed considering their application in a miniature foldable quad. A multi-joints approach offers wide flexibility of design and freedom in the folding pattern, but this often comes with design and manufacturing complexity and poor scalability (see Figure 2A). Therefore, the use of this approach for foldable quadrotors is limited to large sized platforms with relatively limited number of folding patterns or removable arms (see Figure 2B). Continuous deformable structures are simpler and potentially scalable. However, package compactness and complexity of folding patterns are both limited by the deformation constraints of the material (see Figure 2C). Compared to the previous strategies, origami foldable structures are simpler to manufacture, lightweight, cost effective and allow designing complex 3D foldable structures [7]. Therefore this manufacturing and design technique is a viable solution for a miniature foldable quadrotor.

Multiple types of self-folding origami structures have been developed using smart materials for shape transitioning (see Figure 2D). Although the development of quadrotors with an origami frame is currently under investigation [11] (see Figure 2E), to the best of the authors' knowledge, the quadrotor described in this paper is the first with self-deployable foldable arms.

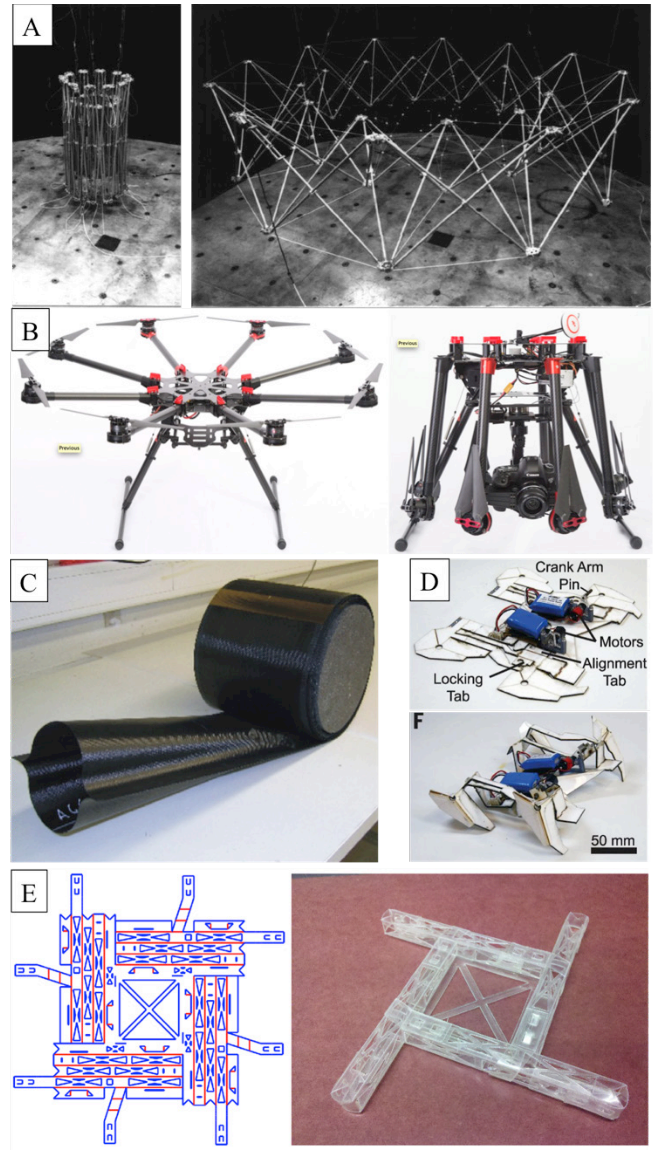

Figure 2. Examples of foldable structures. (A) Circular pantographic deployable structure for space applications [9]. (B) DJI Spreading Wings S1000 quadrotor with foldable arms [3]. (C) Deployable boom [10]. (D) Origami self-folding robot [7]. (E) Origami frame for quadrotors [11].

III. Design Strategies

The design strategies adopted in the development of the foldable quadrotor featuring self-deployment are presented in this section. The description of selection of a manufacturing technique and of a deployment mechanism is followed by the description of selection of a compatible folding pattern.

To this aim, it is important to notice that quadrotors are essentially composed of a central core hosting rigid components (i.e. battery and main control board) and four arms elongating out from this central frame. Therefore, the development of retractable arms is a reasonable choice for a first foldable prototype. Furthermore, as described above, an origami approach is a viable solution for foldable structures with the size and weight constraints of miniature quadrotors.

The mechanism driving the deployment of the arms should be rapid and autonomous in order to maximize dispersal and minimize the risk of human error. A viable solution is to exploit the force or torque generated by the propellers to directly drive the movement. Compared to preloaded elastic elements embedded in the arms, the proposed approach is reversible. Therefore it could offer the possibility to fold back the arms by reversing the rotation of the propellers.

The driving action selected for the deployment affects the folding pattern of the arms. Folds perpendicular to the propellers' axis, or sliding movements parallel to it, are suited to deployments driven by the propellers' thrust. Folds parallel to the propellers' axis are suited to deployments driven by torque. Also the manufacturing process of the arms affects the folding patterns. Adopting an origami approach implies a discarding of sliding movements (i.e. prismatic and cylindrical joints) when deploying the arm, therefore we focused our research on folding patterns based on rotations (i.e. revolute joints).

Based on the aforementioned considerations, the first prototype is designed with arms that can be wrapped around the central frame (see Figure 1 and 3). The folding pattern is compatible with a deployment driven by the torque generated by the propeller and with an origami manufacturing technique. The selected pattern has several advantages. First, it allows the quadrotor to be packaged in a compact configuration for easy transportation. Secondly, the arms are deployed horizontally and therefore the movements are not performed against gravity. Finally, even during deployment, the quadrotor is always contained inside the maximum volume corresponding to the fully deployed configuration.

A. Folding Pattern and Stiffness of the Arm

The folding pattern of the arm and its effect on the stiffness are detailed in this section. The design of the arm is illustrated in Figure 3, which also shows how the motor is integrated. The arm has a 2D trapezoidal shape (see Figure 3A) and consists of a layer of 0.3 mm of fiberglass and an underlying layer of Icarex, a lightweight and inextensible fabric. The arm can transition into the wrapped configuration (see Figure 3B) by folding along two vertical mountain folds "a" and "b". Otherwise, the deployed configuration (see Figure 3C) is obtained by folding around the horizontal mountain fold "c". The transition from the wrapped to the deployed configuration always requires passing through the original flat configuration.

Additional housings are cut in the frame to insert small magnets (shown in Figure 3 and detailed in Figure 4) for two purposes: to keep the arms closed in the wrapped configuration and to automatically fold the arm around the horizontal mountain fold "c" during the deployment (see section III-B).

The stiffness of the arms is a critical parameter to ensure the maneuverability of the quadrotor. Indeed, if the arms are too flexible, they could bend and vibrate during flight, causing instability and reducing the quadrotor's reaction time to external commands. On the other hand, the design of the arms should include a "compliant" configuration in order to minimize the folding effort. This design tradeoff is achieved thanks to the aforementioned crease pattern. For example, the Miura-ori origami, which consists of repeatedly folded parallelograms, can change the stiffness of a sheet of paper thanks to its crease pattern [12]. Similarly, in our case, when the arm is in the flat configuration (Figure 3A), it can be easily folded along the horizontal or the vertical folds, therefore facilitating the transition from the wrapped to the deployed configuration and vice versa. However, when the arm is folded around the horizontal fold, it locks in a rigid configuration with respect to the thrust and momentum generated by the propellers during flight. The stiffening behavior of the arm is directly encoded in its folding pattern, therefore the design of the arm is simple and its weight is minimal since additional stiffening/locking mechanisms are not required.

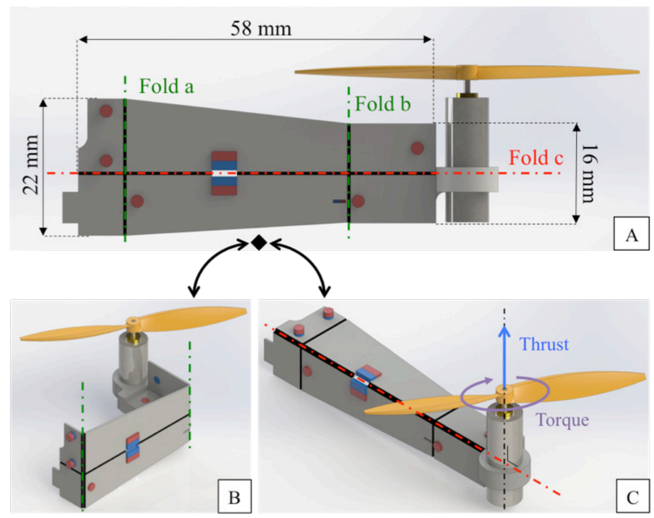

Figure 3. CAD models of a foldable arm with its motor, propeller and magnets. (A) Flat configuration. (B) Wrapped configuration, obtained by folding around folds "a" and "b". (C) Deployed configuration, obtained by folding around fold "c". The axis of rotation of the propeller (vertical dashed line) lays on the plane of the vertical part of the arm. Therefore, the thrust and torque of the propeller generate bending and shear actions on the arm, but not twisting.

When deployed for flight, the arm has an "L" cross-section, different from the circular or square sections traditionally used for the arms of quadrotors with a rigid frame. This choice has been made in order to simplify the folding process by limiting the number of horizontal folds required to deploy the arm (e.g. a square section would have required three horizontal folds). However, an "L" section has a lower torsional stiffness compared to the other sections. This could cause the arms to twist during flight due to the loads generated by the propellers. Therefore, the twisting actions on the arm have been minimized by aligning the axis of rotation of the propeller with the vertical part of the "L" section (see Figure 3C). In this condition, the force and torque produced by the propeller during flight cause only bending and shear actions, which are perfectly suited to an "L" shaped beam. Indeed, the main role of the vertical part of the arm is to withstand the bending and shear stress generated by the thrust of the propeller (primary load), while the horizontal part is mainly added to lock the arm in its deployed status, to prevent instability and to withstand the torque produced by the propeller (secondary load).

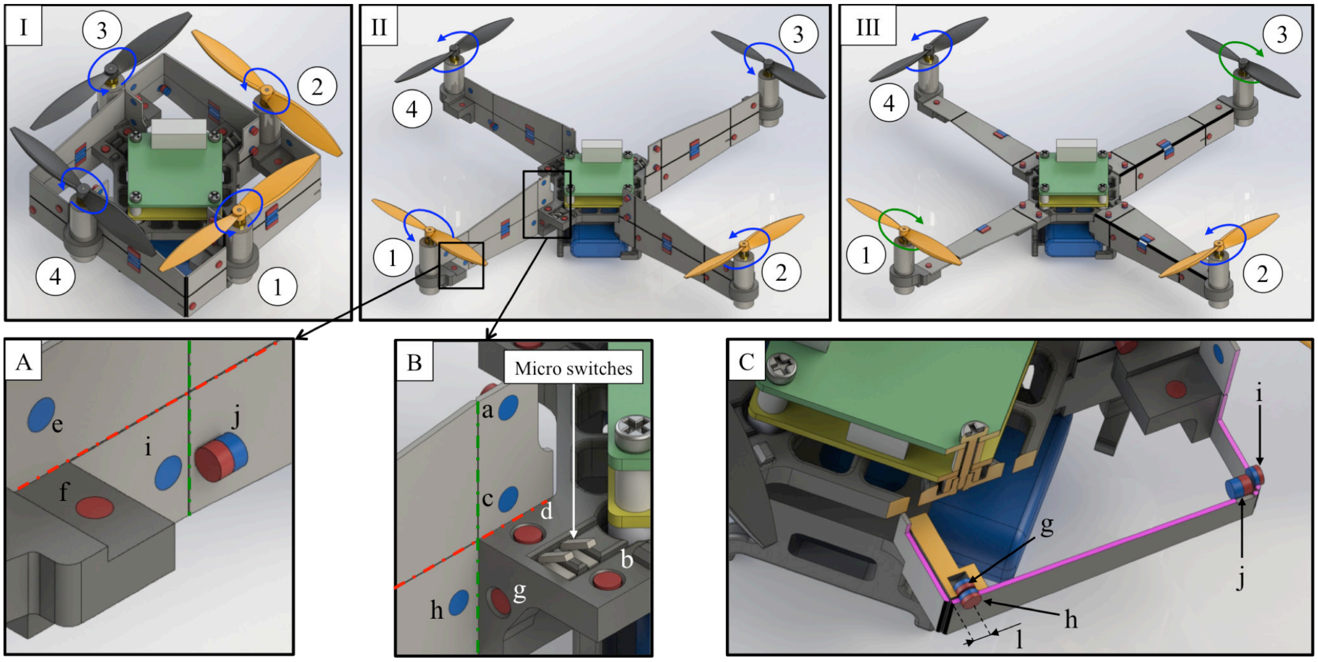

Figure 4. The figure illustrates the three main steps of the deployment process I, II and III. (A and B) Detailed view of the permanent magnets and of the switches embedded in the quadrotor. (C) Partial section to show the magnets used to maintain the arm in the wrapped configuration during transportation. For the sake of clarity one arm has been removed. The pairs of magnets a-b, c-d and e-f are used to lock the arm in the deployed configuration. The pairs of magnets g-h and i-j are used to lock the arm in the wrapped configuration.

B. *Arm Self-Deployment*

One of the main design challenges is to enable a rapid and autonomous deployment of the arms. This is fundamental to reduce the manual operations required by the user and to deploy multiple platforms in a short length of time, thus increasing their dispersal. The deployment exploits the synergy between the folding patterns of the arms and the torque generated by the propellers when they spin, therefore no additional deployment mechanism is required.

The main steps of the deployment process are illustrated in Figure 4. During the first step all the motors are activated and the propellers rotate counterclockwise generating a clockwise torque, which tends to open the arms around the two vertical folds (see Figure 4 I). The arms unfold until they reach their flat configuration, as shown in Figure 4 II. Now the arms can fold along the horizontal fold and lock into the deployed configuration (see Figure 4 III). This movement is driven by the forces generated by a series of magnets, which are embedded in the arms, in the main frame and in the motor bracket. All the magnets generate a torque that tends to close the arm around the horizontal fold “c”. There are two pairs of magnets (see a-b and c-d in Figure 4 B), which attract the foldable arm and keep it connected to the frame. Finally, a pair of magnets is inserted into the arm and in the bracket of the motor (see e-f in Figure 4 A). The deployment process is fully automatic since it starts as soon as the motors are activated and is uniquely driven by the torque generated by the propellers. In the prototype presented in this paper, the folding process for stowing the quadrotor is manual and requires the user to follow the described steps in reverse order. A trained user takes from 5 to 10 seconds to fold the quadrotor in the stowed configuration.

Normal flight condition for a quadrotor requires two diagonally opposed motors to rotate clockwise and the two others counterclockwise, ensuring the balance of the quadrotor around the yaw axis. However, during deployment, all the four motors need to rotate counterclockwise. Therefore, it is necessary to detect when the deployment is completed (step III in Figure 4) in order to invert the rotation direction of the motors. To do so, two opposite arms are equipped with a pair of switches (see Figure 4 B), opened when the arm is wrapped around the frame and closed when the arm folds around the horizontal fold “c” and touches the frame. The switches are connected to a dedicated electronic board designed to revert the rotation direction of the motors depending in the switches' status. Once the arm is fully deployed, the rotation of the corresponding motor (1 and 3 in Figure 4 III) is reversed in less than 50 milliseconds.

The arms are kept in the wrapped configuration by two additional pairs of magnets. The first pair is embedded in the arm and generates a torque, which closes the arm around the fold “b” (see i-j in Figure 4 A and C). The second pair is composed of a magnet embedded in the arm and another one placed in the main frame. These magnets close the arm around the fold “a” (see g-h in Figure 3 A).

IV. PROTOTYPE DESIGN

The first prototype of the self-deployable foldable quadrotor is shown in Figure 1. It is composed of a 3D printed frame hosting the main control board, the board to reverse the rotation of the motors and the battery. The frame also integrates some of the magnets used in the deployment process and the switches used to reverse the rotation of two propellers. Each arm is manufactured according to an origami technique. The arm has a 2D shape and consists of a layer of 0.3 mm of fiberglass glued (Cyanoacrylate) to an underlying layer of Icarex, a lightweight and inextensible fabric. The arm is cut using a CO_2 laser cutter, and the crease pattern is engraved in the fiberglass. Subsequently the arm is manually folded along this pattern. The fiberglass breaks along the folds, but the layer of Icarex keeps the multiple parts of the arms together. This procedure allows manufacturing of unidirectional folds that constrain the rotation of the arms (i.e. each line corresponds to a mountain fold; and therefore can be folded in one direction only).

Table II presents a size comparison between the Ladybird quadrotor and the two configurations of the foldable prototype. In the folded configuration, the proposed quadrotor is 47% shorter and occupies 67% less volume then the Ladybird. Instead, comparing the folded and the deployed configurations, the former is 57% shorter and occupies 82% less volume then the latter. The Ladybird weighs 33 grams, while the developed quadrotor 39 grams. Part of the additional weight is due to the board required to reverse the motors (2.55 grams) and to the main frame, which is 2.1 grams heavier than that of the Ladybird.

TABLE I. COMPARISON BETWEEN THE LADYBIRD AND THE FOLDABLE QUADROTOR

	Size [mm]	Volume [cm^3]	Weight [g]
Folded configuration	68 x 68 x 35	162	39
Deployed configuration	160 x 160 x 35	896	
Ladybird	128 x 128 x 30	491	33

A. *Assessment of the Arm Stiffness*

In order to assess the design of the arm and the selection of materials, its stiffness has been measured and compared with the Ladybird. The Ladybird is composed of four carbon fiber arms (hollow beams with a square section of 3x3 mm and a 2 mm hole) mounted on a plastic frame. Ladybird's arms are 10 times stiffer than the origami arm (see Figure 5). Although the Ladybird's arms are extremely rigid, its frame is flexible. Therefore, when the arms are assembled on the frame, they undergo a deflection of 0.480 mm when the propeller produces the maximum thrust of 0.17 N, corresponding to a motor voltage of 4V. Instead, the foldable arm connected to a rigid frame has a deflection of 0.110 mm in the same load conditions. This data has been measured using an experiential setup composed of a linear stage (Zaber, T-LSR150B) and a load cell (ATI Industrial Automation, Nano 17 Titanium) to measure the deflection and the load applied to the arms. During manual flight tests, the foldable quadrotor demonstrates similar maneuverability when compared to the Ladybird.

B. *Dimensioning of the Magnets*

As explained at the end of section III-B, the quadrotor is equipped with two pairs of magnets which keep the arms in the wrapped configuration. Their layout has been optimized in order to ensure deployment using the torque generated by the propeller. Both pairs are composed of cylindrical magnets (neodymium N48) with axial magnetization. These magnets have a diameter of 2 mm, one is 2 mm high and the other is 1 mm high. The maximum attraction force between the magnets has been experimentally evaluated at $F_{mag} = 0.62$ N. During deployment, the torque of the propeller drives the rotation of the arm around the vertical folds "a" and "b" overcoming the torque generated by the magnets. The torque generated by the propeller has been experimentally measured when the throttle on the remote is rapidly increased to its maximum value, simulating the command of the user (see Figure 6). The torque has a peak which is variable and then stabilizes at $T_{prop} \approx 1$ Nmm. Therefore, to safely ensure the deployment of the arms, the distance between the magnets and the joints (see "l" in Figure 4C) has been selected according to the following inequality:

$$T_{prop} > l \cdot F_{mag} \rightarrow l > 1.5 \text{ mm} \quad (1)$$

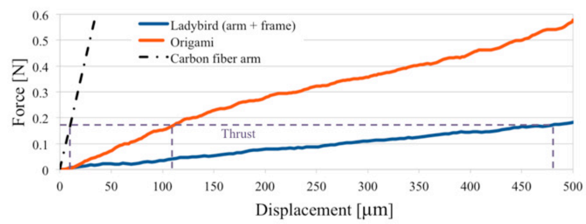

Figure 5. The plot compares the deflection of the arms of the Ladybird and of the foldable quadrotor under a load which simulates the thrust generated by the propeller.

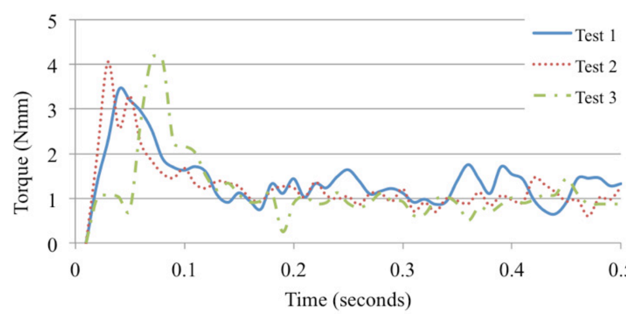

Figure 6. Torque generated by the propeller when the throttle on the remote is rapidly increased to the maximum.

C. *Analysis of the Deployment Process*

The deployment process is shown in Figure 7, which is composed of multiple snapshots from a video captured with a GoPro HERO3 (120 fps). The frame of the quadrotor is retrained and the deployment is triggered when the user rapidly increases the throttle on the remote. The quadrotor accomplish the transition from the folded to the deployed configuration in 0.312 ± 0.015 seconds (measured in 5 trials), time measured from the start of the propellers. From Figure 7, (see circles with solid lines) it is also possible to see that the arms are not synchronized during deployment. The first arm completes the deployment after 192 ms (frame 4), while the last one is ready to fly after 317 ms (frame 9). This lack of synchronization is most probably due to imprecisions during the manual assembly of the quadrotor (e.g. distances between the magnets that keep the arms folded). However, this behavior of the arm does not affect the capability of the quadrotor to take off from the ground after self-deployment (see complementary video). Finally, the circles with dashed lines show when the propellers invert their rotation thanks to

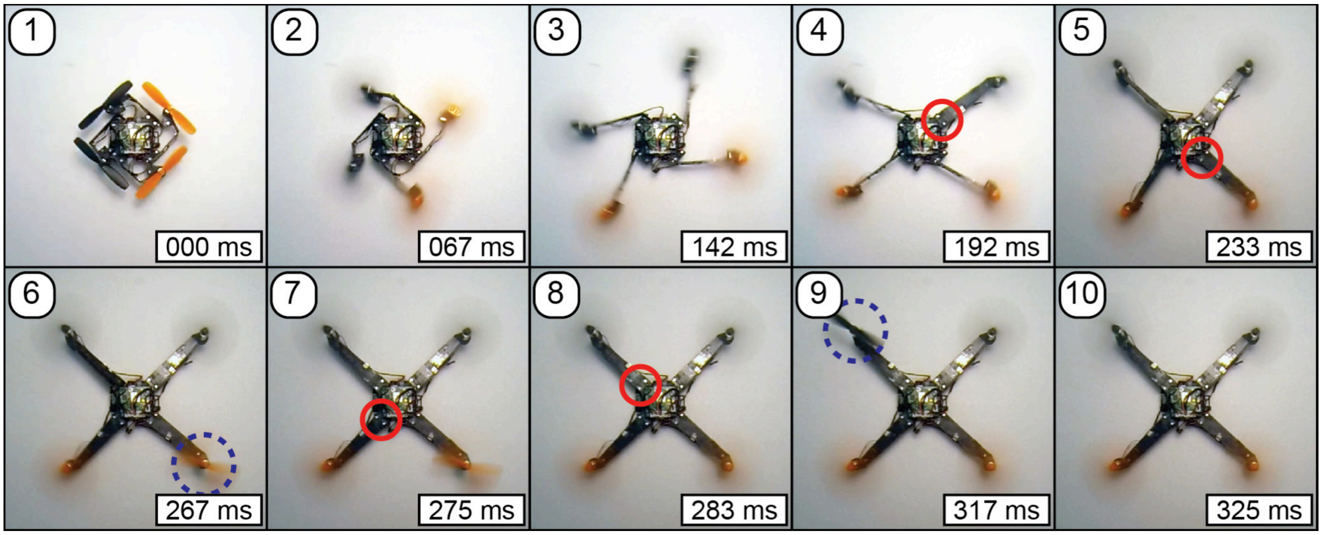

Figure 7. Snapshots of the deployment process, from the activation of the propeller to a fully deployed configuration. The main frame of the quadrotor is retrained.

the triggering of the switches (frames 6 and 9). The deployment success rate has been tested individually on four different arms (autonomous deployment followed by manual folding). The arms were connected to a fixed frame. The measured success rate is 100%. However, the arms are not resilient to collisions, which cause complete failures in the deployment process due to ruptures of the folds or peeling of the Icarex from the fiberglass layer.

V. Conclusions

We developed a pocket sized foldable quadrotor that can self-deploy before usage and be manually packaged for ease transportation. The quadrotor is equipped with foldable arms that can be warped around its central frame. The stowed configuration occupies 82% less volume and is 57% shorter then the deployed configuration. The deployment process is autonomous in order to minimize the risk of human errors and is very fast (0.3 seconds) in order to increase dispersal in case of multiple launches of drones. The arms deploy driven by the torque generated by the propellers, with no additional mechanisms. The arms are manufactured with an origami technique and their crease patters is tailored to ensure stiffness when the arms are fully deployed, ensuring maneuverability comparable to commercial platforms with similar weights.

Future work will focus on further optimization of the design: reduction of the overall weight and improvements of arm's resilience against collisions. Customized electronics will address the stability of the quadrotor in case of self-deployment in the air after launching by the user.

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