

# A Pocket Sized Foldable Quadcopter for Situational Awareness and Reconnaissance

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**Abstract**— Flying robots are rapidly becoming an essential tool in search and rescue missions because they can rapidly gather information from inaccessible or unsafe locations, thus increasing safety and rapidity of interventions. With this aim, we present a pocket sized foldable quadcopter equipped with a camera. The drone is a portable and rugged “flying-eye” that aims to extend or move the field of view of the rescuer for situational awareness and safe reconnaissance. The quadcopter can be packaged for transportation by folding its arms and it self-deploys in a glimpse before usage. Its compliant foldable arms make it rugged, reducing the risk of failure after collisions. The drone is remotely operated and it can stream sound, thermal and visual images in real time to rescuers. The prototype of the foldable quadcopter is experimentally characterized and assessed in preliminary field tests.

## I. INTRODUCTION

Drones are becoming ubiquitous in the daily life and their socio-economic impact is constantly increasing [1]. In the field of search and rescue, we are witnessing the growth of a wide spectrum of applications, such as mapping [2], inspection [3] and multi-modal operations [4], where unmanned aerial vehicles are leveraged to increase safety, productivity and rapidity of intervention, while minimizing operational costs.

While the challenges surrounding perception and control are frequently cited as being key areas for research [1], other important aspects are how to make such robots easily transportable, quick to deploy and robust against collisions. Several applications exist where a resilient, readily available drone would be a game changer. For example, in search and rescue missions where damage relief is subordinate to the rapidity of intervention [5], and where flights in cluttered environments with high probability of collisions are a commonplace [3]. To tackle these challenges, we are envisaging a new class of sturdy and portable drones, which function as a personal “flying eye” that is readily airborne from users’ hand as soon as it is taken out from a pocket or a backpack.

Leveraging the miniaturization of electro-mechanical components, drones that fit the palm of a hand are now commonplace. However, since lift is increasing with the size of the drone, smaller drones have significantly reduced time of flight and payload [1]. This drawback could be addressed by incorporating foldable structures [6] in comparatively larger drone with suitable payload that can be stored and transported in a small volume. Most of the existing foldable drones rely on multi-joint folding mechanisms (e.g. the

eBee™ by senseFly or the Spreading Wings series from DJI), which are bulky, prone to failure in collisions, difficult to scale and require complex and error-prone manual operations from the user to be deployed and stowed. Foldable drones made out of continuous elastic structures are easier to operate, but cannot undergo considerable reduction of size because sharp folds are constrained by the material’s strain limit [7]. Origami based manufacturing partially overcomes the aforementioned limitations, allowing to produce scalable and complex folding patterns in lightweight structures [8][9]. However, conventional origami encompass rigid folds (i.e. made with inextensible materials such as polyamide and nylon), therefore fragile, and prone to tear and failure when overloaded during collisions [8].

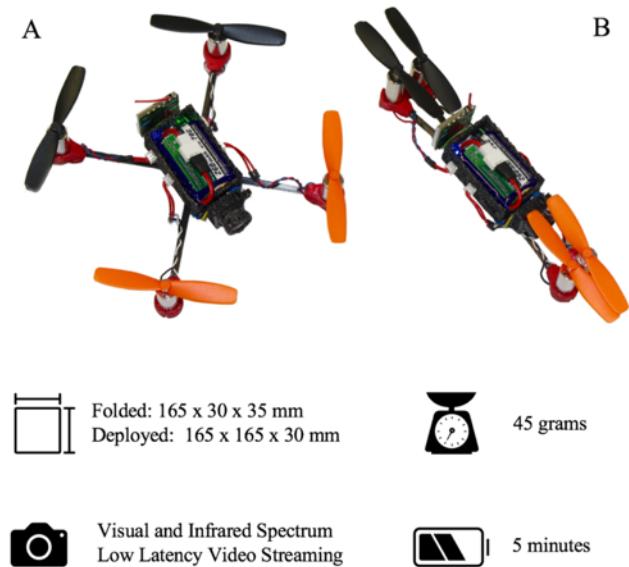


Figure 1. Pocket sized foldable quadcopter in the deployed and stowed configurations. The drone is equipped with a camera and a transmitter for real time video streaming. It is remotely controlled during flight and has a take-off weight of 45 grams.

This article describes the design and preliminary field tests of a pocket sized foldable quadcopter capable of streaming video to the user (Fig. 1). The quadcopter is equipped with a new magnetic foldable joint that leads to intuitive folding and sturdiness. Indeed, the quadcopter can be packaged for transportation by manually folding its arms, and deploys autonomously just by activating the propellers or by manually shaking the drone with a simple and intuitive gesture. Moreover, the foldable joint behaves as a mechanical fuse. In the event of collision, the joint disengages the arms that fold in order to prevent overloading, therefore limiting the probability of permanent structural damages.

The drone is conceived as a wearable “flying eye”, that rescuers can always carry with them during operations with the main goal to extend or move their field of view. The drone can be equipped with miniaturized cameras operating either in the visible or in the infrared spectrum, and can stream low latency video feedback to the user. This makes the drone suited for situational awareness and reconnaissance from a safe distance. It can be used in different scenarios:

- to peer around corners, over walls, inside windows and other obstacles for damage assessment, hidden danger identification, point of access identification, and life detection;
- to provide a panoramic view of the rescue area from an elevated perspective;

First, an overview of the design of the foldable quadcopter is presented and relevant features and performances are analyzed. Then, results of preliminary field tests are reported to highlight strength and limitations of the current design. A discussion of the results and proposals for future work conclude the paper.

## II. DESIGN AND CHARACTERIZATION

Quadcopters are extremely widespread aerial robots because of their minimalistic mechanical design, intrinsic robustness and hovering mode of flight. Their design encompasses a frame composed of a central core and four arms. The central core hosts the autopilot, battery and payload. The arms connect the propulsion units to the central core. Since the most cumbersome components in quadcopters are the arms, foldable quadcopters commonly implement collapsible arms. As discussed in Mintchev *et al.* [8], the design of foldable frames encompasses three main challenges: the stiffness, an intuitive, potentially autonomous deployment, and the robustness. Stiffness is desirable in the design of foldable drones in order to prevent unwanted oscillations during flight, that could lead to control instabilities or an increase in energy consumption. Intuitive or self-deployment is fundamental to reduce the number of manual operations required by the user to make the platform

airborne. This is crucial when the user is deploying the platform during stressful conditions, like in search and rescue missions, or for swarm operations, when multiple drones are deployed. Finally, robustness is instrumental during flight in highly cluttered or unstructured environments, where collisions are often inevitable [3], or when the drone is controlled by unexperienced users.

### A. Overall Design of the Quadcopter

The quadcopter comprises a central frame that hosts the autopilot (Micro SciSky 32bits) and the battery (nano-tech, single cell, 260 mAh). These components are housed inside a 3D printed rubber box (NinjaFlex, NinjaTek, PA, USA), that protects them during collisions. The drone is lifted by four brushed motors coupled with 55 mm propellers that can generate a maximum thrust of 32 grams each.

TABLE I. MAIN COMPONENTS AND FEATURES OF THE FOLDABLE QUADCOPTER

Size	Folded $\rightarrow$ 165 x 30 x 35 mm Deployed $\rightarrow$ 165 x 165 x 35 mm
Visible spectrum camera	1.3 MP resolution 170° field of view
Infrared spectrum camera	80 x 60 pixels 50° field of view Thermal sensitivity <50 mK
Video streaming	5.8 GHz analog video streaming 25 mW 100 meters range (within line of sight)
Weight	45 g
Autonomy	5 minutes

The video system is composed of a miniature camera and a transmitter. The camera operating in the visible spectrum has a resolution of 1.3 MP, it is equipped with a 170° wide angle lens, and with a microphone. The quadcopter can also be equipped with the miniature thermal camera Lepton®

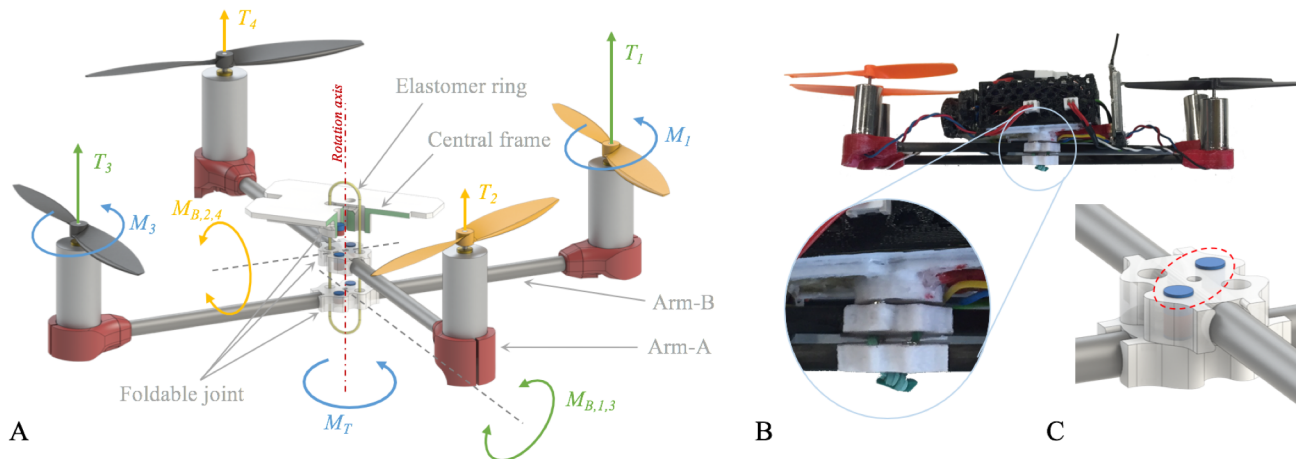


Figure 2. (A) Exploded view of the foldable frame of the quadcopter. It is composed of two arms hosting two propulsion units each, the central frame and the foldable joint. The forces ( $T_n$ ) and torques ( $M_n$ ) generated by the propellers produce a bending ( $M_B$ ) and a torsional torque ( $M_T$ ) that are balanced by the magnets and the elastomer ring in the joint. (B) Detailed view of the magnetic joint in the folded configuration. The magnets are disengaged and the arms and frame are held together by the elastomer ring. (C) Detail view of the magnetic joint with the magnets that come out 0.2 mm from each housing of the magnetic joint and penetrate the one above.

(FLIR® Systems, Inc), with 80x60 pixel and 50° field of view. This camera is useful for life detection, especially when the visibility is reduced due to smoke or low illumination. The video transmitter works at a frequency of 5.8 GHz, has a power of 25 mW, and can stream analog video and audio signals up to 100 meters (within direct line of sight). In this configuration, the quadcopter has a take-off weight of 45 grams and can fly approximately 5 minutes while continuously streaming video. The low weight makes the quadcopter inherently safe for persons or equipment. The main features of the quadcopter are summarized in Table 1.

The user can manually control the quadcopter with a traditional remote controller while visualizing the video streamed on a portable screen.

### B. Design and Characterization of the Folding Mechanism

The design of the foldable frame is illustrated in Fig. 2A. It is composed of three main assemblies, two arms with two motors each (arm A and B), and the central frame. These assemblies are connected together with a foldable joint. The foldable joint is distributed among the three assemblies, each one comprising a housing with magnets that attract each other. Two magnets (neodymium N48, 2x2 mm cylindrical magnets with axial magnetization) are placed inside each 3D printed housing. The joint also comprises a pre-stretched elastomer ring that connects the three housings. The magnets and the elastomer ring lock the frame in the deployed configuration by counteracting the forces and torques that are produced by the propellers during flight. The joint is designed in such a way that the drone can be manually folded by rotating the two arms one against each other around the axis of rotation, represented by the dot dashed line in Fig. 2A. In this configuration, the magnets disengage and lose their attractive force, but the pre-stretched elastomer ring holds together the components of the quadcopter (see close-up picture Fig. 2B).

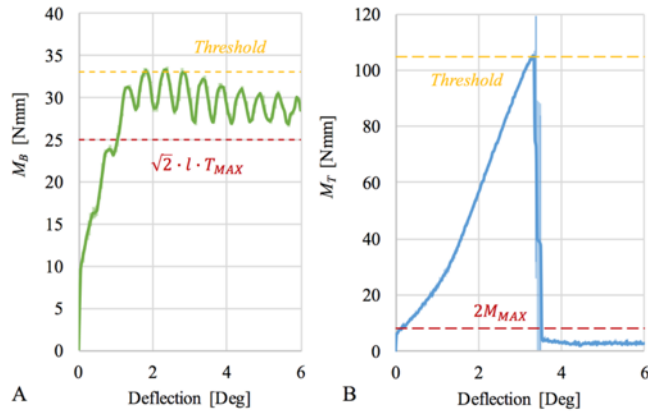


Figure 3. Experimental measurements of the flexural (A) and torsional (B) behavior of the foldable joint. Of note that, in both cases, the joint is rigid within the flight envelope (until the red dashed line), but undergoes large deformation when the loads exceed a threshold (yellow dashed line). This behavior makes the foldable joint a “mechanical fuse” that prevents to overload the arms of the quadcopter during collisions.

The scalability of the proposed solution to larger quadcopters is ensured by the fact that the strength of the magnetic interaction is proportional to the mass of the permanent magnets. Therefore, the mass of the required

magnets would increase linearly with the mass of the drone. Interferences between the magnetometer of the autopilot and the magnetic joint can be mitigated with different approaches [10]. In the proposed design, the saturation of the magnetometer is avoided by locating the joint magnets at a distance which exceeds 10 mm. The static nature of the magnetic field allows to compensate for the remaining interference with a calibration of the sensor. For stronger magnets, it is always possible to limit interferences by resorting to magnetic configurations that focus the magnetic field in specific regions [11], or to ferromagnetic elements to confine the field.

The foldable frame guarantees high stiffness within the flight envelope of the quadcopter, while it easily deforms when it experiences high forces, for example during collisions. Stiffness is instrumental for maneuverability and energy efficiency during flight, while deformability allows to achieve resilience during collisions (see Section II.D). Therefore, the foldable joint effectively counterbalances the bending ( $M_B$ ) and the torsional ( $M_T$ ) moment, generated by the propellers, without undergoing significant deflections, or oscillation during flight. The main risk is the failure of the connection between the central frame and the middle joint that would cause a deflection of both arms. The bending stiffness of the frame is maximized by connecting diagonally opposed motors in order to reduce the bending action that must be counterbalanced by the foldable joint during flight ( $M_B$ ). Indeed, the joint is subject to a bending moment which is function of the difference of thrust generated by the propellers:

$$\begin{aligned} M_B &= \sqrt{M_{B,1,3}^2 + M_{B,2,4}^2} = \\ &= \sqrt{(l \cdot (T_1 - T_3))^2 + (l \cdot (T_2 - T_4))^2} \leq \\ &\leq \sqrt{2} l T_{MAX}, \quad (1) \end{aligned}$$

where  $l = 55 \text{ mm}$  is the distance between each motor and the axis of rotation of the arms, and  $T_{MAX} = 0.32 \text{ N}$  is the maximum thrust generated by the propeller. During hovering, each propeller generates the same thrust, therefore the resulting bending moment is zero. While maneuvering, the thrusts are not balanced, but their difference unlikely overcomes 30-50% of the maximum thrust. The magnets selected for the magnetic joints achieve a disengagement threshold of 33 Nmm, which corresponds to a safety factor of 1.3 in the worst scenario (eq. 1). The experimental flexural behavior of the joint is illustrated Fig. 3A, and confirms that the arms undergo minor deformation ( $< 1.5^\circ$ ) during flight. This deformation causes a negligible efficiency loss of 2.6% with respect to rigid, straight arms.

The foldable joint is also subjected to a torsional moment:

$$M_T = M_1 + M_3 \leq 2M_{MAX}, \quad (2)$$

where  $M_{MAX} = 4.1 \text{ Nmm}$  is the maximum torque generated by the propellers. As illustrated in Fig. 2C, the magnets come out 0.2 mm from each housing of the foldable joint, penetrating the one above. This layout mechanically locks the different parts of the foldable joint in order to prevent unwanted rotation of the joint during flight. The experimental



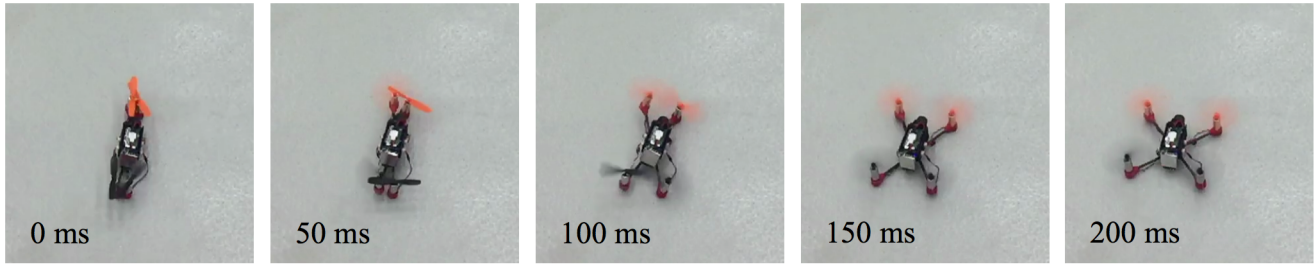


Figure 4. Snapshots of the deployment process, from the activation of the propellers to a fully deployed configuration.

torsional behavior of the joint is illustrated Fig. 3A, and confirms that the arms undergo minor deformations ( $< 0.5^\circ$ ) during flight.

### C. Arms Folding and Deployment

The drone can be easily and intuitively folded by pushing the two arms one against each other. This generates a torsional torque that leads to the rotation of the magnetic joint upon exceeding the torsional torque threshold (yellow dashed line in Fig. 3B). While folding, the elastomer ring in the foldable joint is stretched and stores elastic energy. The energy is subsequently released to drive the unfolding process. Once the arms are folded, they are secured in this configuration by means of the magnets of the DC motors, that act as a locking mechanism (e.g. the motors with the orange propeller in Fig. 1B). In the folded configuration, the quadcopter assumes an elongated configuration that facilitates its transportation. Furthermore, the volume when the drone is folded is 18% of the one when the drone is deployed.

The quadcopter can be deployed by unlocking the magnetic sealing in two ways: either manually by shaking the platform around the axis of rotation of the arms, or automatically by activating the propellers. In both cases, when the arms are unlocked, the energy stored in the elastomer ring and the magnetic forces within the joint pull back the arms in the deployed configuration. The automatic deployment process is illustrated in Fig. 4. The quadcopter is on the ground and takes off after the arms self-deploy in 0.2

seconds as soon as the user activates the propellers.

### D. Collision resilience

Drones are often subjected to unwanted collisions while flying in cluttered environments or while controlled by inexperienced users. Also during transportation, especially in a pocket or a backpack, the drone can be overloaded and consequently damaged. Therefore, a major challenge is to design collision-tolerant drones that survive collisions and transportation without major structural failures [3][12]. In a quadcopter, the arms are the most fragile components due to their length that increases their vulnerability to flexural failure. The common practice to prevent damages involves therefore the use of external cages or dedicated structures that protect the sensible arms of the quadcopter [12]. In the foldable quad, we explored a different strategy, that takes inspiration from insects. Mountcastle *et al.* [13] showed that the wings of some species of insects undergo buckling during collisions. Buckling induces large deflections that prevent the wings to irreversibly tear. In the foldable quadcopter, we adopt a similar solution. As illustrated in Fig. 3, the foldable joint behaves as a “mechanical fuse” that endows a dual-stiffness behavior to the arms of the drone: it is rigid within the flight envelope (up to the red dashed line), but disengages and folds when the forces overcome a threshold (yellow dashed line). Therefore, during collisions, when the loads exceed the flexural or torsional thresholds, the arms fold avoiding that the internal stress in the arms reaches the limit of failure. For example, the load that causes the torsional

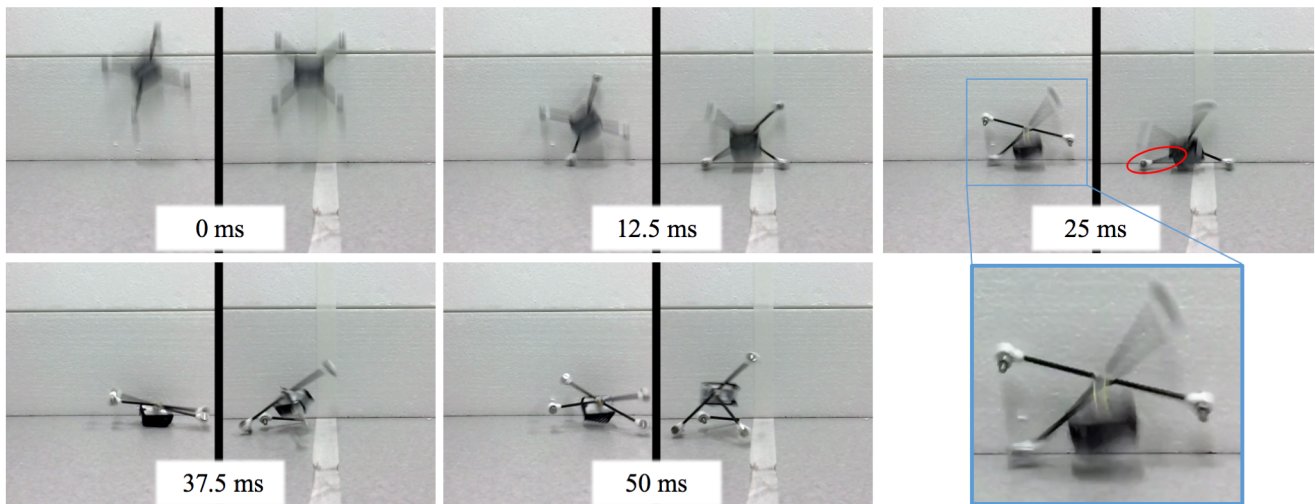


Figure 5. Snapshots of a collision tests of mockups with foldable and rigid frame, respectively left and right frames. Both mockups free fall from 2 meters high and collide frontally against the floor. While the mockup with foldable frame survives the collision undergoing considerable deformations (see close-up image), one arm of the rigid mockup fails (see red circle).

folding of the frame induces 22 MPa of stress in the arm, which is much lower than the tensile strength ( $2992 \pm 700$  MPa [12]) of the carbon fiber used for the arms.

Comparative drop tests have been performed on mockups with foldable and rigid arms in order to assess the viability of folding as mean of protection. Both mockups are comparable to the foldable drone for weight and mass distribution. Fig. 5 illustrates an example of a frontal collision of the two mockups that are dropped on the floor from 2 meters high. In the foldable quadcopter, the arms fold during collisions, avoiding structural failures due to overload. On the other hand, while the quadrotor with the rigid frame collides, one arm fails due to overload. Although an in-depth characterization and comparison with state-of-the-art protection mechanisms are required, this preliminary investigation provides a promising glimpse of the use of foldable frame as a mean to withstand collisions.

### III. FIELD TESTS

The foldable quadcopter has been tested in collaboration with the Swiss Agency for Development and Cooperation (SDC) in one of their rescue training facilities (Pl. d'exercices Epeisses, Chemin de Couchefatte 45, 1237 Avully, Switzerland). The goal of the test was to demonstrate the current capabilities of the robot and gather a critical feedback from the experts in order to better focus the future developments of the drone.

The compact size of the frame and its video streaming capability make the foldable quadcopter a "wearable flying eye" that can be recruited by rescuers for safe reconnaissance and situational awareness. Ideally, the rescuer can carry the drone with him, and deploy it to assess the damages of a building, for a sneak peek inside a window without entering a potentially unsafe structure, or to retrieve a panoramic view of the area in order to quickly assess if there are obstacles on his way. Once the information has been gathered, the quadcopter can be easily folded and stowed in a pocket or a backpack.

Fig. 6A shows a panoramic view of the training facility and the two scenarios where the drone has been tested in order to highlight its potential use: (i) high altitude flight in order to retrieve a panoramic view of the area, and (ii) flight in close proximity to a partially collapsed building to gather close-up images.

In the scenario (i), the drone is manually flown beyond line of sight using the video streaming displayed on an external screen as visual feedback. Upon reaching an altitude of 20-30 meters, the quadcopter is flown in circle to retrieve a panoramic overview of the training field for situational awareness. A screen-shot of the video stream by the quadcopter is given in Fig. 6B.

In the scenario (ii), the drone is deployed in proximity to a building and flown by the operator within the line of sight. The goal is to inspect the upper floors of the building, that are above the field of view of the rescuers on the ground. Rescuers can retrieve precious information concerning the status of the building in order to assess damages, available point of access, and the presence of possible victims, without

entering the potentially dangerous building. Fig. 6C shows a screen-shot of the video collected by the drone.

Overall, the drone is stable and maneuverable while airborne, making it easy to fly in sparse environments as well as in close proximity to buildings. The reader is encouraged to refer to the video attached to this paper for an overview of the different scenarios. The video has been directly recorded on the screen handled by the rescue, showing therefore what the rescuer actually sees.

The drone can be also equipped with a miniature thermal camera which extends its use in environments with low visibility due to smoke or reduced luminosity. Fig. 6D and E compares visual and thermal images captured in a low luminosity (50 lx) environment. While with the visual spectrum camera the human silhouette is hard to spot, it is clearly visible in the thermal image despite the lower resolution of the thermal camera. This highlights the benefit of incorporating a thermal camera in the foldable drone.

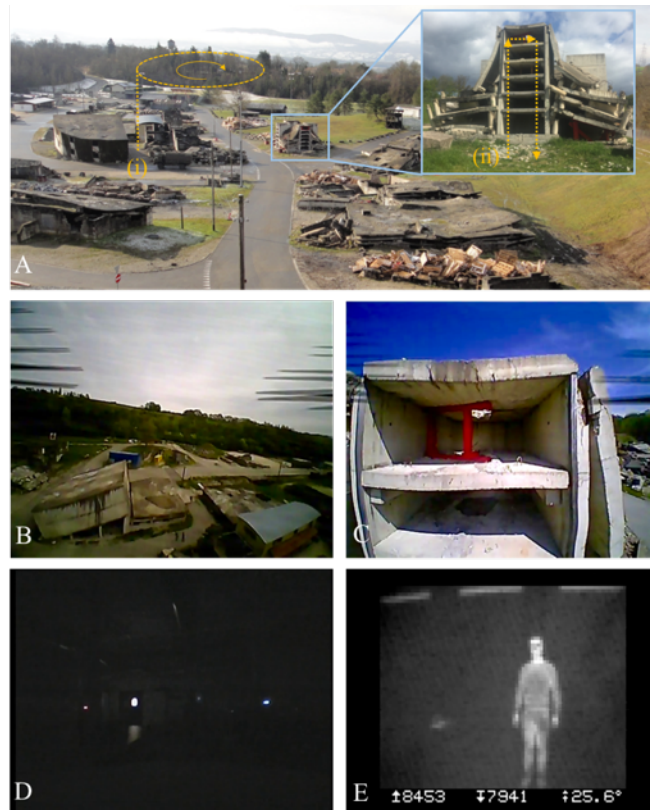


Figure 6. (A) Overview of the rescue training facility. The different test scenarios: (i) panoramic view and (ii) damage assessment. (B) and (C) are still images from the video feedback from the drone during the scenario (i) and (ii) respectively. (D) and (E) are an example of visual and thermal images captured in a low luminosity environment (50 lx).

### IV. CONCLUSION

The article presents the development of a first prototype of foldable "flying eye" conceived for search and rescue missions. It is a highly portable, collision tolerant drone for situational awareness and safe reconnaissance. The foldable quadcopter leverages the recent technological miniaturization to achieve a pocket sized format, that is made even more portable through folding. Folding is exploited not only to enhance transportability, but also to improve resilience

against collisions. Cameras in the visible and thermal spectrum provide low latency visual feedback to the user.

The field tests have highlighted the potential of the foldable quadcopter as well as the needs for improvements. Its pocket size, achieved by folding, is instrumental for ease transportation and deployment. Video streaming extends the field of view of the user, that can peer inside damaged buildings or collect a panoramic view of the area. Overall, these features can greatly improve safety, efficiency and rapidity of interventions. Future work is needed for addressing the main shortcomings that emerged during the field tests. Although the quadcopter is stable during flight, it requires an experienced user, especially to fly in close proximity to buildings, or at long distances where it becomes difficult to spot it due to its small size. More automated flight capabilities, coupled with specific localization and distance sensors (e.g. GPS, sonar, optic flow), would decrease the workload on the operator and make the flight accessible also to inexperienced user. In addition, the control relies on a conventional remote control coupled with a screen to visualize the video feedback. Such devices are cumbersome and much larger than the quadcopter itself, compromising the benefit offered by a foldable frame. A more compact and intuitive user interface should be adopted. A possibility would be to leverage the IMU units of smartphones to intuitively control the drone and use its screen to visualize the video streaming and additional information, like the GPS position and the remaining time of flight. The authors also aim to further investigate the collision resilience strategy inspired by insects' wings. Preliminary results are promising, but a rigorous characterization is required to evaluate the energy absorption capabilities and peak deceleration during collisions with foldable frames. A comparison with rigid frames and other collision resilience strategies for drones [12] is required as well. Although the drone did not suffer from damages of the propellers due to collisions during the development and testing, specific methods for the protection of the propellers will be investigated as well.

In addition of being a promising tool for extending the field of view of rescuers, the foldable quadcopter can also work in synergy with terrestrial robots. The drone could be stowed inside a terrestrial robot and become an "eye in the sky" when released in order to gather images from an aerial perspective. For instance, while moving in unstructured and unknown environments, the elevated viewpoint of the drone could be instrumental for the detection of obstacles making simpler and safer the path planning of a ground robot.

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