When Being Soft Makes You Tough: A Collision-Resilient Quadcopter Inspired by Arthropods’ Exoskeletons

Ricardo de Azambuja¹, Hassan Fouad¹, Yann Bouteiller¹, Charles Sol¹, Giovanni Beltrame¹

Abstract—Flying robots are usually rather delicate and require protective enclosures when facing the risk of collision, while high complexity and reduced payload are recurrent problems with collision-resilient flying robots. Inspired by arthropods’ exoskeletons, we design a simple, open source, easily manufactured, semi-rigid structure with soft joints that can withstand high-velocity impacts. With an exoskeleton, the protective shell becomes part of the main robot structure, thereby minimizing its loss in payload capacity. Our design is simple to build and customize using cheap components (e.g., bamboo skewers) and consumer-grade 3D printers. The result is CogniFly, a sub-250 g autonomous quadcopter that survives multiple collisions at speeds up to $7 \text{ m s}^{-1}$. In addition to its collision-resilience, CogniFly carries sensors that allow it to fly for approx. 17 min without the need of GPS or an external motion capture system, and it has enough computing power to run deep neural network models on-board. This structure becomes an ideal platform for high-risk activities, such as flying in a cluttered environment or reinforcement learning training, by dramatically reducing the risks of damaging its own hardware or the environment. Source code, 3D files, instructions and videos are available (open source license) through the project’s website: https://thecognifly.github.io.

I. INTRODUCTION

The world is an unforgiving place and any robot will sooner or later face a collision. Complex sensors and computational methods are usually employed to avoid collisions, while nature takes a different approach and, in many cases, animals embrace collisions instead of avoiding them. One example of such amazing behaviour comes from a well known arthropod: the cockroach. This undervalued insect is capable of achieving faster direction transitions by hitting its head against walls [1]. Arthropods’ collision-resilience results from the presence of jointed appendages, body segmentation and a nonliving external skeleton, called an exoskeleton. An exoskeleton has a dual purpose: it works as support and protective structure. Nevertheless, it is not necessarily fully rigid, mixing stiff segments connected by soft joints [2].

Ucrewed [3], [4] Aerial Vehicles (UAVs) can take advantage of collisions, too. This idea was shown to reduce the control complexity when flying surrounded by trees [5], only using the sense of touch [6], and to go through confined spaces by crashing onto each other and the environment [7]. Recent studies have presented contact–based navigation [8] and even a complete collision inertial odometry algorithm that uses collisions [9]. Collision tolerance also was proved useful for reinforcement learning using real robots [10].

Fig. 1: CogniFly (A, B and C) is a small, under-250 g, open source collision-resilient quadcopter. Its frame mixes soft (red) and rigid (black/gray) parts, allowing it to better absorb and distribute impact energy.

Looking at solutions provided by nature, arthropods can be a rich source of inspiration for innovative UAV designs. A structure inspired by their exoskeletons could replace a traditional cage by mixing rigidity with flexibility to absorb collision energy and protect sensitive components. For a UAV, this would increase its maximum payload (useful weight it can carry), since frame and cage are now fused, and it could allow to more easily physically interact with the environment.

In this paper, we present the CogniFly (Fig. 1): a small size, sub-250 g and collision resilient quadcopter. Inspired by arthropods’ exoskeletons, it uses a semi-rigid structure with soft joints fusing frame and protective cage, thus providing protection against collisions and helping to maintain the structural integrity of the quadcopter. The CogniFly is designed with indoors, outdoors and subterranean exploration in mind. The main requirements for our quadcopter design were: i) Small form factor and weight (sub-250 g), for enhanced ability of exploring relatively narrow spaces, and easier handling and logistics ii) Enough computational power to carry out on-board image processing from its own camera
Fig. 2: Bamboo version (top right), using lighter parts optimized for flight time (up to 17 min using 1404/3000KV motors, 4” propellers and 2S 2000mAh LiPo battery).

using deep neural network models. iii) Open source design focused on hobby grade 3D printers, and a software base that is easy to interact with. iv) Easy access to the battery to pave the way for automated battery swapping.

As an open source project, we consider having a customizable and easy to fabricate or repair design is paramount. Thus, it relies on readily available carbon fibre rods, or even bamboo skewers (Fig. 2) for an even cheaper implementation and 3D printed parts that are simple, small and easy to print.

CogniFly’s exoskeleton provides protection for sensitive components, structural integrity for the quadcopter, and effective passive damping of impacts. To test its collision resilience, we run crash-landing experiments and compare to a rigid counterpart. Using these data, we model our exoskeleton as linear viscoelastic components (Kelvin-Voigt model [1]) resulting in a lumped mass-spring-damper model that allows us to study the collision viability of the drone, and the role of different materials and configurations in the future.

Finally, we provide a Python library, as well as Buzz [11] language extension, for easy programming. The latest version of CogniFly is able to fly autonomously for up to 17 min, and run algorithms, such as deep neural network object detectors, despite of its small size and sub-250 g weight. The CogniFly opens the doors for potential applications like agriculture, subterranean exploration, drone swarming and many others.

II. RELATED WORK

In general, the main strategy to endow UAV designs with collision resilience has been the simple addition of external protective structures like cages and bumpers (e.g. [5], [8], [12], [13]). These structures evolved into designs that allowed some level of movement to avoid external disturbances like a sphere containing a gimbal or a cylinder capable of rolling around its main axis (e.g. [5], [9], [13]–[15]), but those design choices have some drawbacks like increased weight, mechanical complexity, and a general lack of energy absorption for force components perpendicular (rigid cages) or aligned (rigid and soft cages) to the axis of rotation as the internal structures are connected to the cage using rigid parts.

Researchers have been trying to improve collision resilience for UAVs using different strategies than traditional rigid cages. Carbon fibre structures are usually popular with drone frame designers because of their steel-like stiffness. However, it is also possible to take advantage of their elastic behaviour (Euler springs [16]) to design flexible protective cages (e.g. [6], [16], [17]). In fact, many cage designs that don’t even claim impact energy absorption share the same elastic behaviour, to a certain extent, as they are made of long, curved carbon fibre parts (e.g. [5], [12], [13], [18]). Nevertheless, the high strength of carbon fibre limits its stand-alone energy absorption applications to very long and thin struts [19], creating a problem when the focus is designing small-sized UAVs.

Structures protecting UAVs are usually made of rigid materials, but that is not vital, and even Expanded Polypropylene (EPP) can be used for collision resilience [10]. A weakness of materials like EPP is the low stiffness to weight ratio that makes such materials too heavy for high-energy impacts [16]. In addition to EPP, soft protective structures for UAVs can use different materials. By precision laser-cutting and folding very thin plastic sheets it is possible to build simple bumpers [20] or an origami rotatory bumper for impacts up to 2m/s [21].

The weight of a UAV can vary from a few grams to kilograms. While a pico drone weighs as few as 25 g [7], the total mass of a more complex drone using gimbals protecting each propeller easily reaches more than 2 kg when the batteries are included [14]. Still, many regulatory agencies take the 250 g value as the limit for UAVs to be considered safe.

Weight reduction is a simple collision resilience strategy [1], [7], but small weight and size comes with disadvantages such as smaller motors, limiting payload and ability to counter disturbances. Reduced payload also restricts battery size, computational power and ultimately many interesting applications.

A flexible frame that is capable of absorbing energy during a collision while protecting sensitive parts, by changing its shape or employing non-destructive deformation, is a very interesting option for collision resilient drones. However, previous strategies based on flexible frames (e.g. [19], [22], [23]) make it very difficult for the UAV to instantly recover from a hard collision because they all lead to an inevitable fall to the ground as they automatically fold or disconnect the motors.

One advantage of flexible frames without guards or a cage to keep propellers from touching obstacles (e.g. [19], [23]) is the increase in payload capability. However, unprotected propellers do not allow UAVs to physically interact with the external world, even considering the use of special flexible propellers [24], as the decrease in thrust and torque from a bent propeller could easily destabilize the UAV.

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1 The battery swapping system is the subject of currently ongoing research.
2 All crash test data and models are based on the carbon fibre rod version.
in-plane but the flexible arms mainly offer protection against connected to the central part of the frame (e.g. [19], [20], [23]), where the UA Vs holding the motors are not rigidly connected to the x-frame before flight transforming the arms into a rigid x-frame.

As the quadcopter arms are secured together (screw system) is fully flexible only in its folded configuration (for storage) from [25], according to the publicly available information, only flexible to the extent of their cages. The cargo drone [26] a rigid quadcopter x-frame, making those two UA Vs cage, but [15] uses a rigid rotating axis at its center, and connecting more rigid components to form a flexible protective tensegrity structures where soft, flexible parts are used to characterise also seen in the CogniFly, they do not employ high-speed coreless brushed DC motors, limiting their payload, total flight time and lifespan [27]. More-

Although other designs [15], [25], [26] share some characteristics also seen in the CogniFly, they do not employ a truly flexible exoskeleton. Some designs have external tensity structures where soft, flexible parts are used to connect more rigid components to form a flexible protective cage, but [15] uses a rigid rotating axis at its center, and [26] a rigid quadcopter x-frame, making those two UAVs only flexible to the extent of their cages. The cargo drone from [25], according to the publicly available information, is fully flexible only in its folded configuration (for storage) as the quadcopter arms are secured together (screw system) before flight transforming the arms into a rigid x-frame.

Only a few previous works explored truly flexible frames, where the UAV arms holding the motors are not rigidly connected to the central part of the frame (e.g. [19], [20], [23]), but the flexible arms mainly offer protection against in-plane collisions while leaving propellers mostly exposed (hindering the ability to physically interact with the external world [19], [23], or protecting propellers in only one plane [20], and they are not easy to manufacture without special materials or tools. Still, collision-resistant works under 250 g show bare minimum payload capacity, restricting their on-board computational power and their ability to fly autonomously without an external computer or motion capture system. Finally, their batteries are designed to be manually connected and extracted by human hands, making the use of an automatic battery swapping station very unlikely.

From all previous collision-resistant UAV designs, only a few manage to keep the total weight below the 250 g threshold (e.g. [7], [19]–[21], [23]), and, besides [20], those employ high-speed coreless brushed DC motors, limiting their payload, total flight time and lifespan [27]. Moreover, those sub-250 g UAVs have a very limited maximum payload, on-board computing (if any) and sensing capacity, requiring external control and/or an external motion capture system.

III. UAV DESIGN

A. Structural design

In our design, we opt for a structure, loosely inspired by arthropods’ exoskeletons, mixing rigid and soft components. The fragile on-board electronics are mounted on rigid parts (3D printed in ABS, black or PLA, gray, Figs. [1] and [2]) that are placed at the central gap of the exoskeleton (Fig. 3-D). However, these rigid 3D printed parts are connected to the exoskeleton using flexible joints (red and blue parts, Fig. [3] and [4]). Moreover, we mount the motors on special flexible parts to allow them to flex during impacts.

The exoskeleton (Fig. 3-D), that can be made of carbon fibre (Fig. [1]) or bamboo (Fig. [2]), gives the quadcopter a final box-like external shape. By having flat-like external faces, our quadcopter can take advantage of its collision resilience to easily align itself against external structures that are big enough compared to the gaps between the outermost rods.

To control where the parts should bend, we designed 3D printed soft joints to interconnect the rigid parts of the exoskeleton (see detail in Fig. 3-A). These joints use flexible filament (TPU 95A), providing sufficient damping for impacts, and helping CogniFly survive impacts at speeds up to 7 m s−1 (carbon fibre version, Fig. [1]). TPU 95A enables the drone to be generally flexible, as shown in Fig. [1]C, while keeping the integrity of its central rigid part. The choice of the exoskeleton dimensions becomes a trade-off between reducing the probability of direct impact on sensitive components and general total size and weight. In the case of CogniFly, we wanted to make it small enough to fit in a standard backpack, thus it measures only 210 x 210 x 120 mm.

The final weight distribution for the carbon fibre version: i) Exoskeleton shown in Fig. 3-D: 62 g. ii) Central ABS parts: 25 g. iii) Quadcopter without battery (Fig. 1-C): 178 g. iv) Battery: 58 g. Total weight (178 g+58 g): 236 g.

To visualize the importance of the exoskeleton for load distribution, Fig. 4 shows two configurations under full throttle and rigidly attached to the desk only by the battery holder: with (full frame, Fig. 4-C and D) and without (x-frame, Fig. 4-A and B) the external protective parts of the exoskeleton.

B. Manufacturability

The main aspects for assessing the manufacturability that we adopt are: i) Accessibility to different structural components. ii) Required manufacturing processes and facilities. iii) Cost. The main components of the exoskeleton are carbon fibre or bamboo rods and joints made of TPU 95A (Fig. 3).
During the crash landing experiments, CogniFly was manually dropped from an altitude of 50, 100 and 150cm.

Our mass-spring-damper model is only valid from the moment the UAV touches the ground.

**Fig. 5:** The model is valid from the moment the exoskeleton touches the floor \((x_0 = 0mm\) and \(v_0 = \sqrt{2*9.81*h}\), where \(h\) is the drop altitude) until \(x = 16mm\) and the battery collides.

Carbon fibre rods are cheap, readily available, easy to cut and modify, and there are several examples of previous works using carbon fibre rods in UAVs (e.g. [5], [16], [26]). On top of that, our design allows the use of bamboo rods (BBQ skewers, Fig. 2], at the expense of lower impact resistance.

A low-cost desktop 3D printer (Monoprice Mini v2) was used for all parts, hence we were constrained to small and simple parts, and all flexible parts are printed flat and without supports. Moreover, we took advantage of the TPU95A flexibility and designed the parts to work as living hinges supports. Moreover, we took advantage of the TPU95A flexibility and designed the parts to work as living hinges supports.

### C. On-board hardware and software tools

CogniFly uses as its main controller a single-board computer running Linux. Additionally, a cheap and popular flight controller (e.g. Kakute F7 Mini) running our customized version of iNAV takes care of lower level flight control tasks.

For running deep neural models on-board, CogniFly offers three possible configurations: two using the Raspberry Pi version of iNAV and one using a single-board computer, sensors and the battery, made entirely of ABS (a bag of loose screws was added to reach 239 g).

Finally, we developed open source tools to allow CogniFly to operate autonomously and run complex DCNN models (YAMSPy), to be remote controlled from an external computer (cognifly-python), mocap extension for iNAV, and swarm experiments using Buzz [11] (cognifly-buzz).

### IV. Collision Resilience Experiments

We perform a series of crash-landing (free fall) tests (Fig. 5), using the carbon fibre version of our design (Fig. 1), and record the results as absolute acceleration (Eq. 1) to avoid the need of a complex guiding/alignment system that would be otherwise necessary to isolate individual axis during the experiments. These tests highlight the ability of our flexible exoskeleton to absorb impact energy by comparing the acceleration recorded from a CogniFly made with carbon fibre rods (Fig. 1] 241 g when fitted with the datalogger) and only the rigid central part of the frame, which holds the flight controller, single-board computer, sensors and the battery, made entirely of ABS (a bag of loose screws was added to reach 239 g).

\[
|acc| = \sqrt{acc_x^2 + acc_y^2 + acc_z^2}
\]

We reckon a vertical free fall to be a critical scenario as we consider payload contact with hard exterior objects, like the ground, has the highest potential of causing damage because the absolute acceleration (Eq. 1) peaks in such cases. Moreover, the battery is located at the bottom part of the drone, and it should not be subjected to extreme loads.

Acceleration values saved by flight controllers are usually limited to \(\pm 16G\) with heavy filtering smoothing any peaks, therefore, we use a custom datalogger for our experiments. Our datalogger setup has an accelerometer (ADXL377, 3-Axis, \(\pm 200G\), 500 Hz) rigidly attached to the center of the frame, and a Feather M0 Express running a custom firmware for sampling (1kHz) the sensor and saving the data.

#### A. Mass-spring-damper model

We model the impact absorbing aspect of the CogniFly as linear viscoelastic components (Kelvin-Voigt model [1]) resulting in a lumped mass-spring-damper system that is described by

\[
m\ddot{x} + c\dot{x} + kx = F
\]

where \(m > 0\) is the mass of the drone, and \(c > 0\) and \(k > 0\) are the equivalent damping and stiffness coefficients, respectively. Moreover, we augment the model with a first order Butterworth low-pass filter with a cutoff frequency of 500 Hz to take into account the sampling latency of our accelerometer setup.

To find the parameters, we put Eq. 2 in the following form

\[
\begin{bmatrix}
\dot{x} \\
\dot{v}
\end{bmatrix} = \begin{bmatrix}
0 & 1 \\
-k & -c/m
\end{bmatrix} \begin{bmatrix}
x \\
v
\end{bmatrix} + \begin{bmatrix}
0 \\
1/m
\end{bmatrix} F
\]

and then use Scipy signal processing tool *lsim* to solve the system (3) to obtain the velocity and displacement of the payload’s centre of gravity as a function of the initial displacement \((x_0)\), velocity \((v_0)\), and the parameters \(k, c\) to be estimated. In order to model the conditions at moment of impact, we set the external force \(F\) to gravity \((mg)\), the initial displacement to zero and the initial velocity to the value of velocity just before impact (without air drag).

The equivalent stiffness \(k\) was obtained by deforming the payload to a known displacement, while measuring the applied force. From these data, we fit a linear model constrained to the minimum force before any deformation could be measured \((x = 0mm\) and \(F = mg = 2.36N\)).
The equivalent damping $c$ is estimated by minimizing the Mean Square Error between the mass-spring-damper model (Eq. 2), after passing through the low-pass filter, and the collected acceleration data from the end of the free fall until the peak of the measured absolute acceleration (Eq. 1) for all experiments (50, 100 and 150 cm). However, as the number of trials for each experiment is different (101, 97 and 89, respectively), the final value is weighted accordingly.

Minimization was carried out using Scipy Optimize minimize, with Nelder-Mead method, default arguments, cauchy loss ($L(z) = ln(1 + z)$), and initial values of $c = 50$ and $k = 7040$. It resulted in the coefficients $c = 46.32$ and $k = 6996.12$. However, as the calculated value for $k$ was very close to the static one experimentally measured, we adopted the coefficients $c = 46$ and $k = 7040$ for our model.

We use the proposed model to calculate the percentages of the energy that go into different parts of the system during the impact, which is depicted in Fig. 6. To construct such a plot, we consider the kinetic energy ($E_k = \frac{1}{2}mv^2$) at the beginning of the impact (end of the free fall) as being the total energy of the system. Therefore, we have two possible situations: the battery holder never touches the ground ($x < 16\text{mm}$) or the payload hits the ground ($x \geq 16\text{mm}$).

When $x < 16\text{mm}$ (drop altitudes up to 100cm), the final kinetic energy at the point of maximum displacement is zero (the movement is about to reverse) and the total energy is split between stored in the spring ($E_s = \frac{1}{2}kx^2$) and dissipated by the damper ($E_d = E_k - E_s$).

Our mass-spring-damper-model is not valid for direct collisions between the battery holder and the ground (drop altitudes from 150 cm and above) and it is only valid until $x < 16\text{mm}$. Therefore, in these situations we calculate the energy dissipated by the damper considering the difference between the initial kinetic energy ($E_k$) and the kinetic energy when $x = 16\text{mm}$. This way, we know, in the worst scenario, the energy that will be dissipated during the rigid collision (battery holder hits the ground) will be the same as the kinetic energy available at $x = 16\text{mm}$ (represented by the red bars in Fig. 6) to show the severity of the impact to the ground.

B. Experimental Results

1) Impact testing: We carry out the tests at three different altitudes: 50 cm, 100 cm and 150 cm. To obtain usable data and avoid irreparable damage to the rigid version tested, we had to limit its free fall to 30 cm. Fig. 7 shows that the median of the absolute acceleration (Eq. 1) peak values for the rigid frame falling from 30 cm is higher than that of the CogniFly falling from 150 cm. This strongly suggests our exoskeleton design is more capable of dissipating impacts than a rigid structure made of ABS plastic with a smaller weight.

As a final experiment, we tested CogniFly (carbon fibre rods) by dropping it from the maximum altitude our experimental setup allowed us (literally, our ceiling). CogniFly falls from 262 cm, without suffering any damage (speed at impact of approximately 7 m s$^{-1}$). Compared to some of the latest works on collision resilience UAVs with equivalent size and weight [19], [21], [22], [26], CogniFly reaches a higher collision speed without suffering any damage.

2) Maximum absolute acceleration: One of the main uses of the exoskeleton is to provide protection against high acceleration (deceleration) values to vulnerable components during impacts. To simplify the necessary experimental setup, the main criterion we adopt is the maximum absolute acceleration during a vertical free fall impact (i.e. crash landing) Fig. 5.

In addition to surviving falls, during pilot tests (see video) our flexible exoskeleton showed the ability to withstand in-flight frontal (vertical) collisions. Unlike [19], [23], where the drone has to land before it is able to fly again because its motors are disconnected from the main body during collisions, CogniFly keeps flying (e.g. bouncing off walls).

3) Mass-spring-damper model: We model the CogniFly with its exoskeleton structure as a mass-spring-damper system (Fig. 5), with the aim of predicting the distribution of energy stored and dissipated (Fig. 6), as well as the displacement of the main payload after the beginning of the impact until the point the acceleration reaches its maximum value (Fig. 7).

We assess our model by comparing the accelerometer data against the values of acceleration we predict (Fig. 8). Accelerations are used because it is challenging to devise an affordable and reliable method for measuring the displacement of the center of gravity during impact, while we have easy access to precise accelerometer data. From
Fig. 8: Raw measurements vs. our model.

Fig. 9: Predicted displacements (left) and accelerations (right) without low-pass filter and no rigid impacts.

a simple visual inspection of Fig. 8, the predicted values follow the same trend as the experimental data (mean) for valid displacements ($x < 16 \text{mm}$, vertical dashed black line).

Since the main motivation behind the model is to predict the most critical failure mode (i.e. battery holder direct hit), Fig. 9 shows the predicted payload’s centre of gravity displacement. The allowable displacement for crash-landing experiments presented in this paper (i.e. maximum distance before the battery holder hits the ground) is $16 \text{mm}$, and Fig. 9 predicts direct impacts on the battery holder for falls from altitudes $\geq 150 \text{cm}$, matching experimental results.

One of the uses for the final mass-spring-damper model is to analyze the energy distribution in different parts of the drone for different altitudes, with the ability to, even if roughly, predict such distribution for higher altitudes (Fig. 6). We show the kinetic energy at impact is distributed in different components: stored in the spring (in blue), dissipated by the damper (in green), and the remaining energy that goes into rigid collision (in red) for higher altitudes when the payload displacement is beyond the safe allowable value.

For altitudes below $150 \text{cm}$, Fig. 6 shows that the total kinetic energy is divided only between the damper and the spring, while for higher altitudes the amount of energy that goes into what we call here rigid collision increases with altitude. Such collision energy can give an indication of how strong the impact between payload and ground is, helping to decide how far the operational altitude can be pushed.

V. DISCUSSION AND CONCLUSIONS

In this paper, we introduce a new collision resilient quadcopter design inspired by the flexible exoskeleton of arthropods, fusing the protective cage and the main frame in one semi-rigid structure with soft joints that can withstand high-velocity impacts. Our UAV (CogniFly, Fig. 1) weighs under $250 \text{g}$ and blends rigid and soft materials, giving the final structure the ability to absorb and dissipate impact energy, while still being sufficiently stiff to fulfill its mission. Thanks to its exoskeleton, it is possible to save precious weight when compared to a traditional protective cage design.

CogniFly survived multiple collisions at speeds up to $7 \text{m s}^{-1}$ while carrying enough computing power to run deep neural network models. Throughout a series of simple crash-landing experiments (Fig. 5), we show CogniFly withstands up to a five fold increase in the maximum collision energy when compared to a rigid system (3D printed on ABS) of similar weight. Moreover, we employ the experimental data to create a lumped mass-spring-damper model that allows us to extrapolate the results to untested cases while the calculated damping and stiffness can be used to better understand the role of different materials or configurations.

We also make available software to allow easy of use and customization.

We designed CogniFly from the ground up for easy manufacturing and it can be built using a very small consumer-grade 3D printer, in addition to inexpensive off-the-shelf parts. The design of the drone itself was restricted by maximum weight (below $250 \text{g}$) and size (fits in a backpack, Fig. 1-B). Also, considering that batteries correspond to 33% of UAV’s total mass on average [27], its battery holder and lid were designed to enable easy manipulation of batteries, which we plan as being a stepping stone towards designing small-sized portable battery swap stations for extended energy autonomy.

As an interesting side effect, we noticed an increased life span of the propellers used during our experiments. Throughout a period of around one year crashing prototypes against walls, furniture and floors, we only used two sets of propellers (Gemfan 3025 3X2.5, Polycarbonate) with the second set seen in Fig. 1. One explanation for that is the flexibility of CogniFly’s exoskeleton. Even the motors themselves are mounted on parts 3D printed in flexible filament, increasing the time of impact and reducing forces, resulting in longer life spans for propellers.

Future work possibilities would be extending the model to take into account collisions from other directions, study which components or building methods contribute the most for the impact energy absorption, tune the design of the soft parts to improve its collision resilience, verify the effectiveness of the use of a flexible net, and analyze the impact of not being strictly stiff in the power consumption and dynamic reactions during flight. Ultimately, fatigue probably plays an important role in the structure’s lifespan because some parts work as living hinges. Therefore, this would be another interesting topic to be further studied.

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