OrbiComb: Orbital Honeycomb metamaterial based shell for collision-resilient tactile drones.

by

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Abstract

Current drones face considerable challenges regarding safety and robustness, especially when operating near humans, or flying in cluttered and dangerous environments. Attempts to scale up into multi-agent systems further complicate the successful integration into the real world. Traditional approaches to mitigating these issues often involve developing complex and computationally intensive obstacle avoidance systems or designing strong protective cages. This paper presents an alternative framework for designing an adjustable and reconfigurable metamaterial drone shell capable of absorbing the shock and using tactile feedback for simpler control. The design incorporates a negative stiffness honeycomb structure placed in several orbits to handle different forces. Integrated within each orbit are triboelectric nanogenerator (TENG) sensors that detect collisions based on binary contact signals. Our experiments demonstrate that each orbit's honeycombs achieve different buckling and shock absorption levels, allowing sensing for both the direction and the depth of external force impact. The system enhances drone safety and introduces a novel approach to sensing and control, reducing the need for extra computational power and complex equipment.

Thesis Supervisor: Zhanat Kappassov
Title: Associate Professor

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Chapter 1

Introduction

1.1 Introduction to the subject

With continuous advances in the UAV industry, drones have been finding various applications, including commercial usage in everyday life [9]. Although the opportunities and complexity of such technology grow annually, human safety remains a major concern while interacting with them. To increase the safety in human-drone interaction and efficiency in flight control, different approaches have been branching out, each having their own advantages and disadvantages [10]. Besides that, the drones themselves are prone to breaking or malfunctioning after collisions and thus require protective measurements, usually by including propeller guards or developing complex collision avoidance algorithms.

1.2 Importance of the subject

The topic of making drones both robust and safe for humans is important because overlooking one aspect could lead to inefficient or dangerous consequences. As [1] suggests, in some scenarios, people prefer to interact with drones via touch as it is less mentally demanding than other methods, and they feel safer when quadrotors have propeller guards. Furthermore, with the shortening number of semiconductors in the world, the need to make drones efficient with fewer resources becomes substantial.

Numerous papers have recently been striving to solve relevant issues by changing the paradigm regarding drone architecture and integration.

1.3 Literature review

When it comes to designing and implementing UAVs, there is a general system for dealing with collision avoidance, which consists of two main parts - perception and action [10]. To perceive the world through sensors, UAVs use either active (Sonar, LIDAR, RADAR, etc.) or passive sensors (Camera, IR, etc.). This determines how computationally heavy, power-consuming, accurate, and responsive the system will be, usually leading to trade-offs between parameters. Regarding the action, there are four methods that perform differently with different constraints such as velocity constraint, dynamic obstacles, swarm compatibility, etc. From the paper, we observe that choosing the right design approach is crucial as meeting all requirements with one setup is hard.

Delving deeper into design considerations, there are several works that stand out in one or more dimensions. Work done by [6] presents one of the fastest and most efficient autonomous drones that has an onboard computer to dynamically avoid obstacles at high speeds. However, it doesn't have a prop guard and requires powerful sensing and computational units to process the data. Another work by [13] delivers a design and implementation of relatively small-sized quadcopters forming a swarm capable of traversing through dense forests. Their proposed system, as they state, has high computing capability, extensibility, and optimality while having less size and weight. However, they still don't consider human safety and collaboration when evaluating their setup. Some researchers have used compliant mechanisms and custom sensors to make drones collision-resilient, as in [8]. Their collision sensor consists of a spring-damper system with a hall effect sensor and a propeller guard can absorb the shock by utilizing that system. Another approach concerned making the propellers themselves soft and bendable, as presented in [3]. They show that soft blades can make drones more robust but they remain unguarded, which is still dangerous for humans to touch. Authors of the tensegrity design drone in [12] state that it performs better than traditional propeller-guarded drones in the Monte Carlo study. While it dissipates the applied forces efficiently, the tensegrity beams don't fully cover the drone, which means humans potentially could not collaborate with them comfortably.

1.4 Knowledge gap

So the knowledge gap remains to combine not only efficiency and collision resilience in drones but also human safety for more friendly human-drone interaction. All previously done works mostly focus on hardware challenges but omit human safety as a potential degree of evaluation metric. Moreover, it is hard to integrate heavy processing units and custom collision mechanisms when the payload capacity is a limiting factor. Some papers use honeycomb-inspired metamaterials for shock absorption and tactile sensing with low cost and simple structure [2, 4, 5], which could be used to make a protective drone shell. As a collision sensor, the TENG sensor could be used as a binary state force sensor as shown in [7].

1.5 Problem statement

From the above information, it follows that the challenge is to make a robust drone shell that covers most of the drone body and can withstand collisions at different speeds and recover from them efficiently using TENG sensors.

1.6 Potential impact

This project could scaled up to both local and global arenas, making the drones more human-friendly and robust at the same time. It also would allow the integration of more design factors with fewer, more sustainable resources.

Chapter 2

Orbital Honeycomb Design

In prior works done by [4] and others, the negative stiffness honeycomb structures have been defined over a straight line, rendering a linear, sinusoidal equation in the form below:

$$x(t) \quad = \quad A/2 * (1 - cos(2 * pi * t/l))$$

where A - amplitude, l - length of the wave. In this work, we propose a new definition of NSHS defined over an arc instead of a straight line. This allows for making more rounded, circular Honeycomb structures and constructing spherical drone shells. The final parametric equations are as follows:

$$(Ri_b + hw_i/2 * (1 - cos(2 * pi * Ri_b * t/s_i))) * cos(t)$$
$$(Ri_b + hw_i/2 * (1 - cos(2 * pi * Ri_b * t/s_i))) * sin(t)$$

The final view of the assembled shell looks like the following:

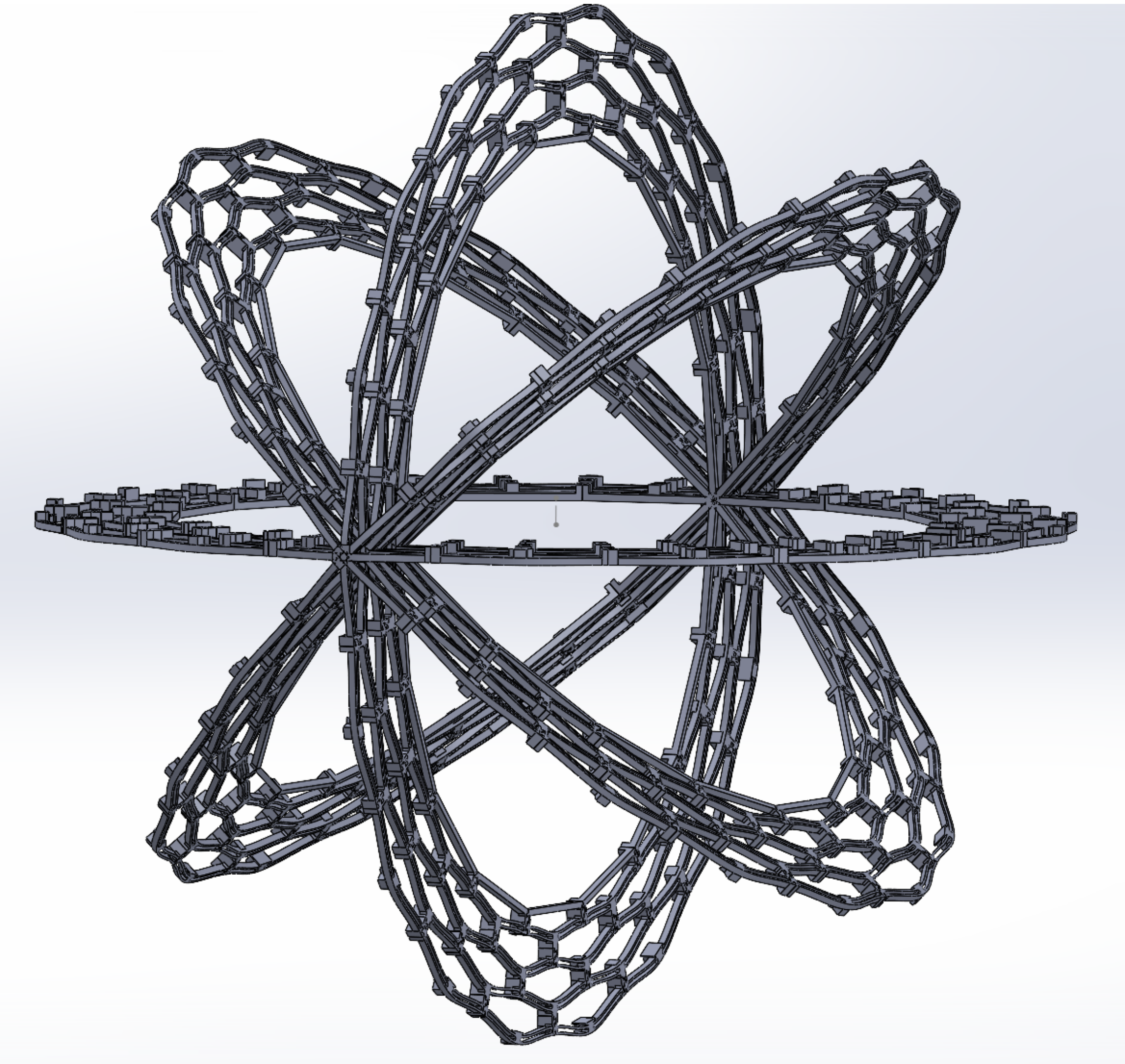

Figure 2-1: Drone shell

Chapter 3

TENG sensor fabrication and Integration

In [11], the authors have presented a sustainable way of fabricating TENG sensors from plastic. In this work, we further modify the sensor by using polymer PET together with PZT5H nanoparticle that have piezoelectric behavior. PET is used instead of PVC in the case of paper and PZT5H instead of ZNO for negative material. We place them on the aluminum and copper tapes that act as electrodes. In the following figure 3-1, the test setup for the TENG sensor on an OrbiComb segment can be seen connected to the Arduino Nano microcontroller. The setup was used to prove the concept of acquiring analog input signals to detect the force impact upon collision with an obstacle.

We acquired the input data from the sensor using both an oscilloscope and the microcontroller. The following figure shows the sensor-generated signal at continuous impacts displayed on an oscilloscope.

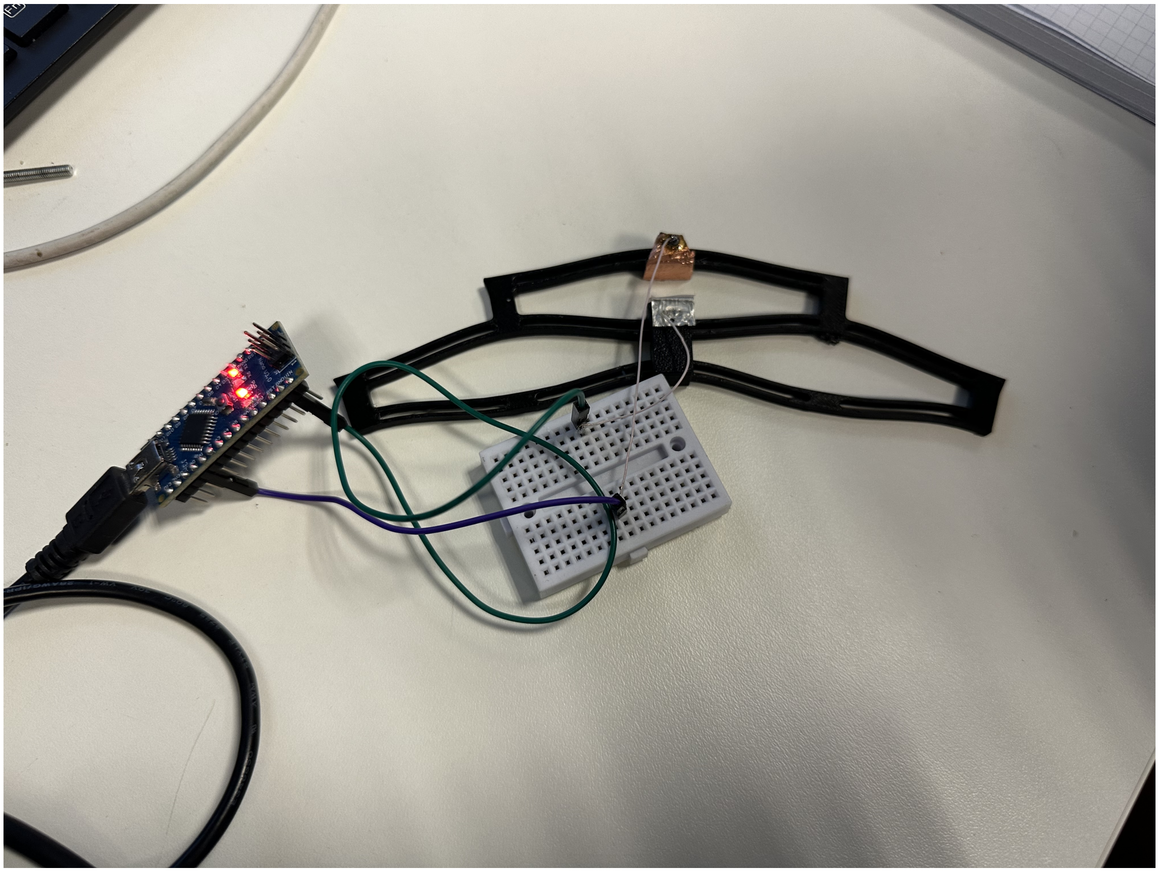

Figure 3-1: TENG sensor placement on an OrbiComb segment for testing.

Figure 3-2: Generated signal values on TENG sensor during continuous impacts.

Chapter 4

Experimental Evaluation

We tested the negative stiffness honeycomb parts on a test stand using a UR-5 manipulator to move the honeycomb and a Wittenstein force sensor to acquire the exerted force data. The force response graph for one orbit is presented in Figure 4-1. One can clearly observe that the structure achieves buckling at during 10s and 16s time interval, displaying negative stiffness behavior.

Figure 4-2 shows the implemented version of the OrbiComb with one ring around the Coex Clover 4.2 drone. Along with that, the pendulum-like structure with the wall in front of the drone is used to measure the linear acceleration from the drone's IMU sensor and derive subsequent impact forces.

Figures 4-3 and 4-4 show the collision response graphs for a drone subjected at 40 40-degree angle and released to hit the wall.

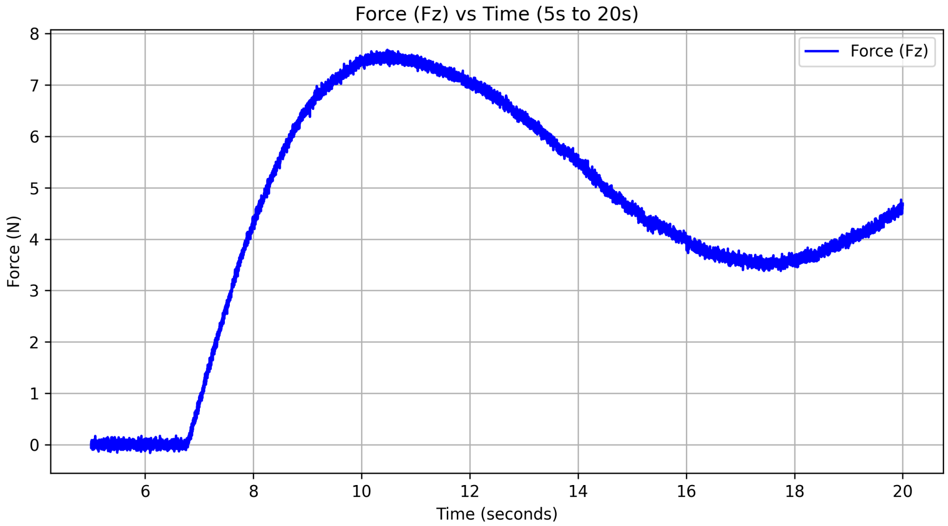

Figure 4-1: Force response for NSHS structures observed after new design

Figure 4-2: Pendulum test setup and an implemented OrbiComb structure around the Coex Clover 4.2 drone.

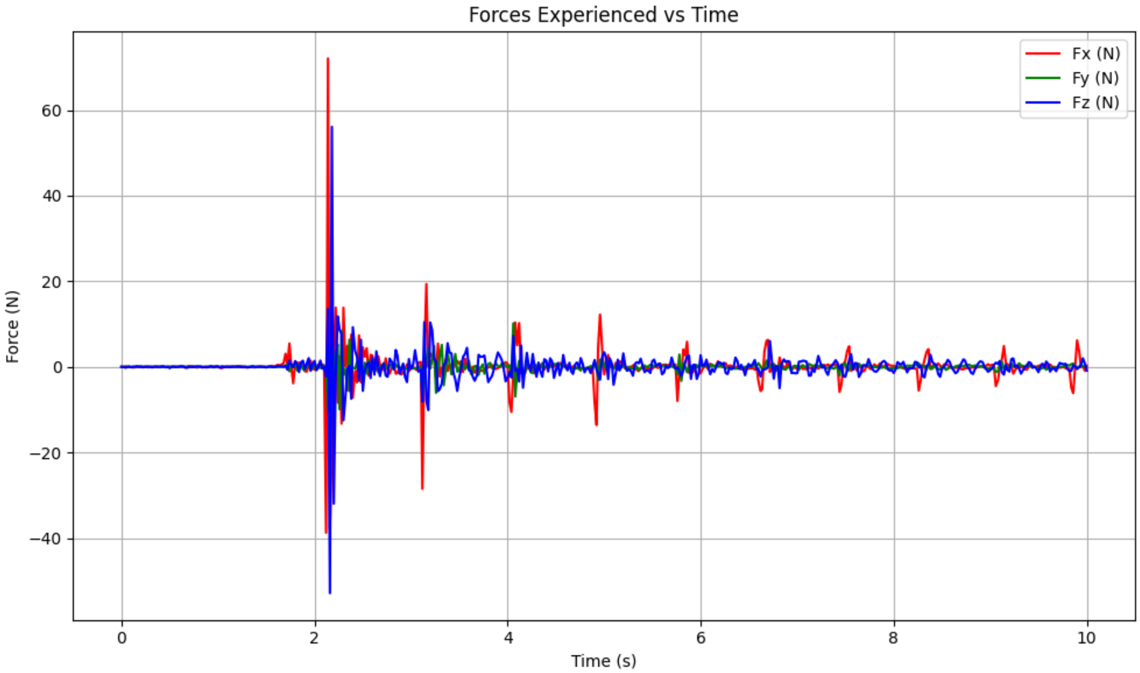

Figure 4-3: Force response for a drone collision with OrbiComb protective ring.

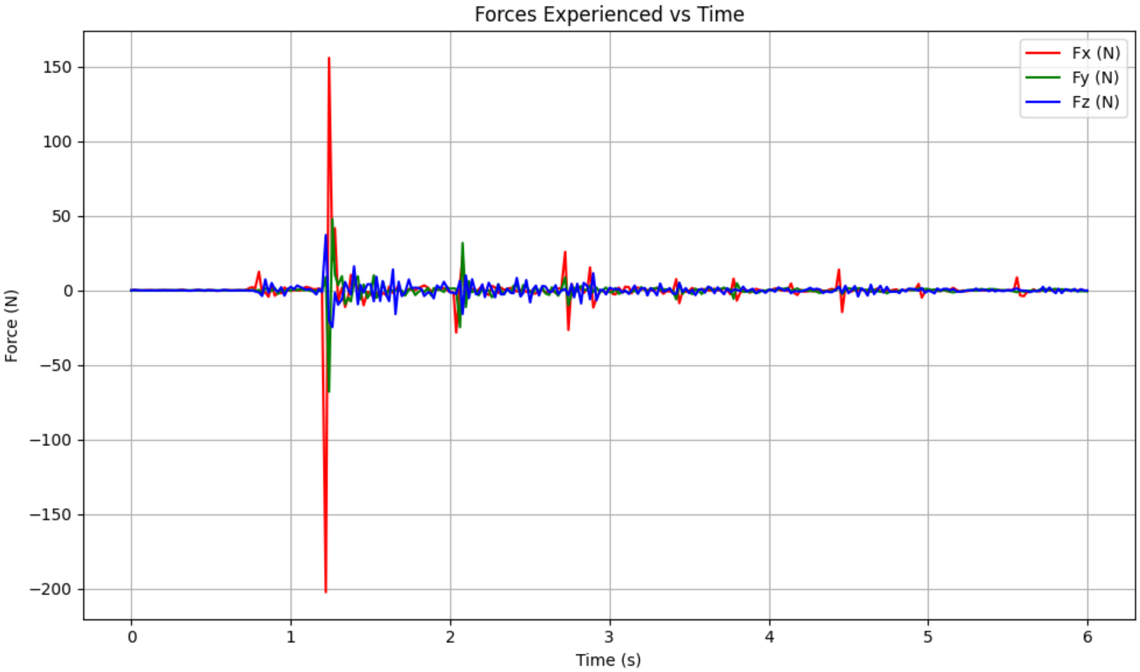

Figure 4-4: Force response for a drone collision with standard Coex Clover protective cage.

Chapter 5

Conclusion

To conclude, we successfully present a new architecture for drone shells based on a Negative Stiffness Honeycomb Structure placed in several orbits that can absorb the external shock. We demonstrated that by fabricating and integrating TENG sensors we can allow the drone to sense collisions without relying on computationally and physically heavy equipment. Additionally, the experiments showed that the new shell/ring design allows to absorb twice the amount of shock, keeping internal components safe.

Bibliography

[1] Parastoo Abtahi, David Y. Zhao, Jane L. E., and James A. Landay. Drone near me: Exploring touch-based human-drone interaction. 1(3):1–8.

[2] Fahim Faisal Arnob, Md Sayed Anwar, Md Shariful Islam, Md Arifuzzaman, and Md Abdullah Al Bari. Negative stiffness honeycomb structure as automobile leaf spring: A numerical investigation. 11(4):389–400.

[3] Son Tien Bui, Quan Khanh Luu, Dinh Quang Nguyen, Nhat Dinh Minh Le, Giuseppe Loianno, and Van Anh Ho. *Tombo* propeller: Bioinspired deformable structure toward collision-accommodated control for drones. 39(1):521–538.

[4] Rustam Chibar, Valeriya Kostyukova, Soibkhon Khajikhanov, Daryn Kenzhebek, Altay Zhakatayev, Bakhtiyar Orazbayev, and Zhanat Kappassov. Honeycomb-inspired metamaterial for tactile sensors with variable stiffness. pages 1–1.

[5] Dixon M Correa, Timothy Klatt, Sergio Cortes, Michael Haberman, Desiderio Kovar, and Carolyn Seepersad. Negative stiffness honeycombs for recoverable shock isolation. 21(2):193–200.

[6] Philipp Foehn, Elia Kaufmann, Angel Romero, Robert Penicka, Sihao Sun, Leonard Bauersfeld, Thomas Laengle, Giovanni Cioffi, Yunlong Song, Antonio Loquercio, and Davide Scaramuzza. Agilicious: Open-source and open-hardware agile quadrotor for vision-based flight. 7(67):eabl6259.

[7] Gulnur Kalimuldina, Roman Kruchinin, and Yerzhan Nurmakanov. A flexible and wearable textile electrode-based single electrode triboelectric nanogenerator. MA2021-02(31):1911–1911.

[8] Zhichao Liu and Konstantinos Karydis. Toward impact-resilient quadrotor design, collision characterization and recovery control to sustain flight after collisions. In *2021 IEEE International Conference on Robotics and Automation (ICRA)*, pages 183–189. IEEE.

[9] Dante Tezza and Marvin Andujar. The state-of-the-art of human–drone interaction: A survey. 7:167438–167454.

[10] Jawad N. Yasin, Sherif A. S. Mohamed, Mohammad-Hashem Haghbayan, Jukka Heikkonen, Hannu Tenhunen, and Juha Plosila. Unmanned aerial vehicles (UAVs): Collision avoidance systems and approaches. 8:105139–105155.

[11] Shabnam Yavari, Merey Sembay, Yersaiyn Bushanov, Zhumabay Bakenov, Mehdi Shafiee, and Gulnur Kalimuldina. Recycling polyvinyl chloride (pvc) pipe wastes into pvc/zno nanofiber-based triboelectric nanogenerators. *ENERGY & ENVIRONMENTAL MATERIALS*, n/a(n/a):e12884.

[12] Jiaming Zha, Xiangyu Wu, Ryan Dimick, and Mark W. Mueller. Design and control of a collision-resilient aerial vehicle with an icosahedron tensegrity structure. 29(5):3449–3460.

[13] Xin Zhou, Xiangyong Wen, Zhepei Wang, Yuman Gao, Haojia Li, Qianhao Wang, Tiankai Yang, Haojian Lu, Yanjun Cao, Chao Xu, and Fei Gao. Swarm of micro flying robots in the wild. 7(66):eabm5954.