A Protective Solution for Safe Testing of UAV Control Algorithms Using Fullerene Structures: Methods, Design, and Applications

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Abstract

Unmanned Aerial Vehicles (UAVs) have become increasingly integral to modern life, necessitating the development of new control algorithms to enhance their efficiency. This article presents a protective solution for safely testing these new algorithms. Traditionally, fixed-type test benches or low-altitude free flight modes are employed for testing. However, fixed test benches cannot provide the precise data required for open space flight, and low-altitude free flight testing fails to adequately account for air resistance changes compared to high-altitude flight. To address these limitations, we developed a protective structure specifically for high-altitude flight testing. Given that UAV components are more expensive than the protective structure, implementing such protection is crucial. We constructed a fullerene structure using polylactic acid (PLA+), with joints fabricated via 3D printing. These joints connect Acrylonitrile Butadiene Styrene (ABS) hollow sticks, readily available in local markets in Bangladesh, to each arm of the UAV. This paper provides a comprehensive description of the structure, detailing its benefits such as size adaptability and cost-effectiveness. It also addresses issues like joint damage due to the PLA+ filament's bonding quality and proposes solutions like injection molding and mass production to enhance durability and reduce costs. This protective structure is particularly valuable for supplying emergency food and medicine, especially temperature-sensitive products like blood. In the event of a UAV fault during flight, the protective structure ensures the safety and integrity of critical supplies, preventing damage and ensuring they reach their destination in usable condition.

Keywords: UAV, protective, fullerene, plastic injection molding, UAV testing.

1. Introduction

The integration of advanced materials and novel structural designs in drone technology has become increasingly essential as Unmanned Aerial Vehicles (UAVs) expand their presence across diverse industries, including surveillance, environmental monitoring, and logistics. This study investigates the use of a fullerene-inspired structure, fabricated from Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA), as an external cover for drones. The hypothesis is that this external structure can significantly enhance the strength and durability of the drone, leading to improved performance and resilience under various operational conditions. This approach not only leverages the well-known benefits of ABS and PLA in 3D printing but also introduces a novel application of fullerene structures in drone design, potentially setting a new standard in UAV structural integrity.

The quest for improved structural integrity in UAVs has driven substantial research over the past few decades. Early efforts focused on reducing the weight of drone structures through the use of composite materials. In 2019, Stefan et al. demonstrated the efficacy of carbon fiber composites in achieving significant weight reduction without compromising structural strength. [1] By 2019, Pragati et al. had explored the application of Kevlar-reinforced polymers, highlighting their superior impact resistance. [2]

Again in 2019, Zhang et al. introduced honeycomb structures made from aluminum alloys, which offered excellent strength-to-weight ratios. [3] This work was advanced by Li et al. (2023) who integrated hybrid composites, blending carbon fiber with thermoplastic resins to further enhance UAV durability. [4] The integration of fullerenes and fullerene-like structures in engineering applications emerged as a significant innovation in the mid-2010s. Patel et al. (2021) were among the first to explore fullerene-based nanomaterials in drone components, though their research was limited to internal structures. [5] Later, Kumar et al. (2019) emphasized the potential of 3D-printed PLA structures for UAV applications, focusing on cost-effectiveness and environmental benefits. [6]

Incorporating the findings from the uploaded document, the work of Golubović et al. (2023) provided comprehensive insights into the mechanical properties of ABS and ABS-like polymers across different 3D printing technologies, such as Fused Deposition Modeling (FDM), Stereolithography (SLA), and Digital Light Processing (DLP). Their comparison revealed that FDM consistently produced superior mechanical properties, which is pivotal for our study. [7] Additionally, the research by Nima Zohdi et al. (2024) focused on material anisotropy in ABS parts produced via FDM, underscoring the importance of process parameters in optimizing mechanical performance. [8]

Further studies, such as those by Budrun Neher et al. (2020), examined sawdust-reinforced ABS composites, offering insights into mechanical and physical changes with varying compositions. [9] This research, along with the findings of Trang Khuong et al. (2014) on the tensile and flexural properties of ABS for biomimetic

applications, supports the notion that ABS is a versatile and robust material suitable for complex, high-performance structures like our proposed drone cover. [10] Moreover, the work by Noshin Tasnim Tuli et al. (2024) emphasized the rapid expansion of 3D printing with fiber-reinforced composites, particularly in aerospace and automotive industries, which parallels our approach of using advanced materials in UAV design. [11]

Despite these advancements, no prior research has comprehensively analyzed the use of a fullerene-inspired external structure for drones. This study is the first to conduct a parametric analysis of such a structure using ABS and PLA, thereby addressing a critical gap in the existing literature.

The motivation behind this research arises from the necessity to fill existing gaps in UAV structural design, particularly the underexplored area of external reinforcement. While previous studies have focused on internal components and traditional materials, the benefits of an external fullerene-inspired structure remain largely unexamined. Our research aims to evaluate the mechanical performance and durability of such structures, providing new insights into their potential applications in UAVs.

By conducting a thorough parametric analysis, this study seeks to quantify the impact of using a fullerene-inspired structure on the overall performance of drones. The findings have the potential to influence the design of more resilient UAVs, which are crucial for applications in search and rescue missions, military reconnaissance, and commercial operations. Additionally, the implications of this research extend beyond UAVs, with possible applications in fields where lightweight, durable structures are essential, such as aerospace engineering and automotive industries.

In summary, this study not only addresses a significant research gap but also opens new avenues for the application of advanced materials in UAV design, contributing to the ongoing evolution of drone technology.

2. Materials and Methods

Design of the Fullerene Structures for protection of drone

This paper aimed to evaluate the feasibility of a protective case for testing new UAV control algorithms using a fullerene structure. The design of the fullerene structure as Fig. 1 was created using SOLIDWORKS 2019, a CAD software, which provided a detailed 3D representation of the protective case. This design was intended to safeguard UAV components during high-altitude flight tests, ensuring the safety of the UAV while enabling accurate evaluation of control algorithms in real-life scenarios.

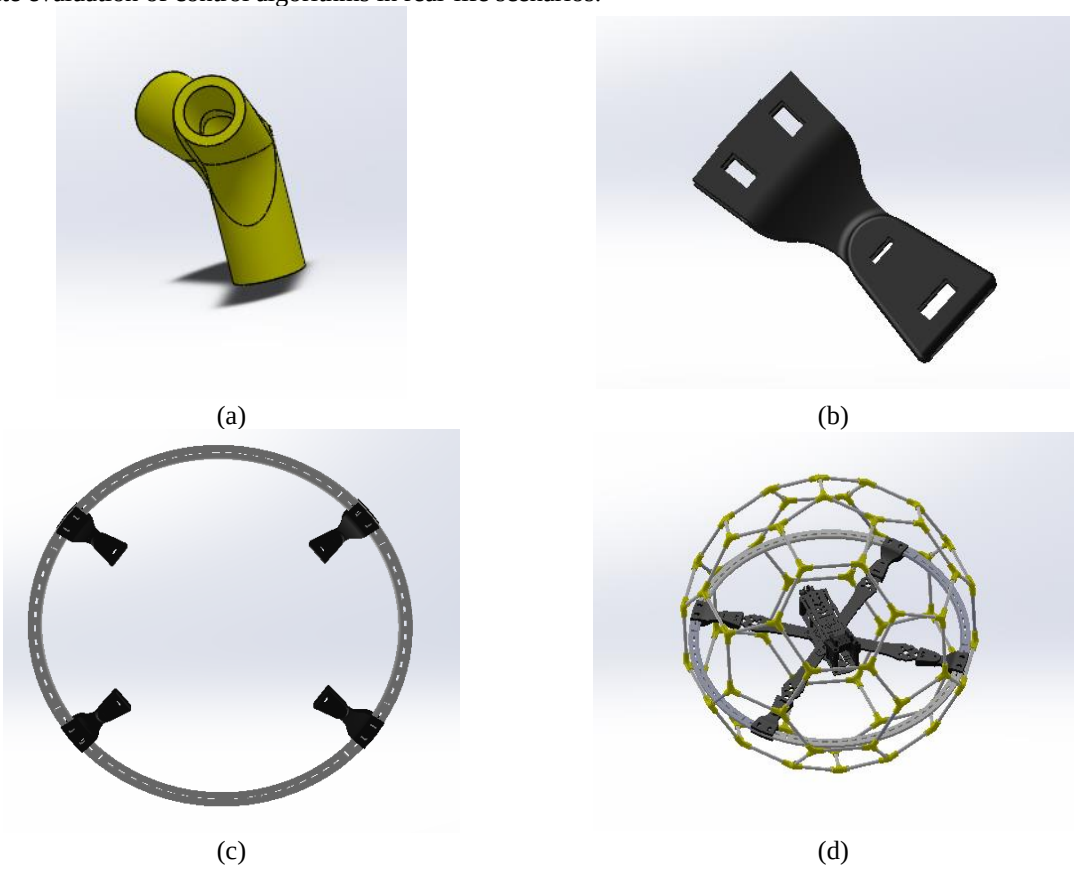


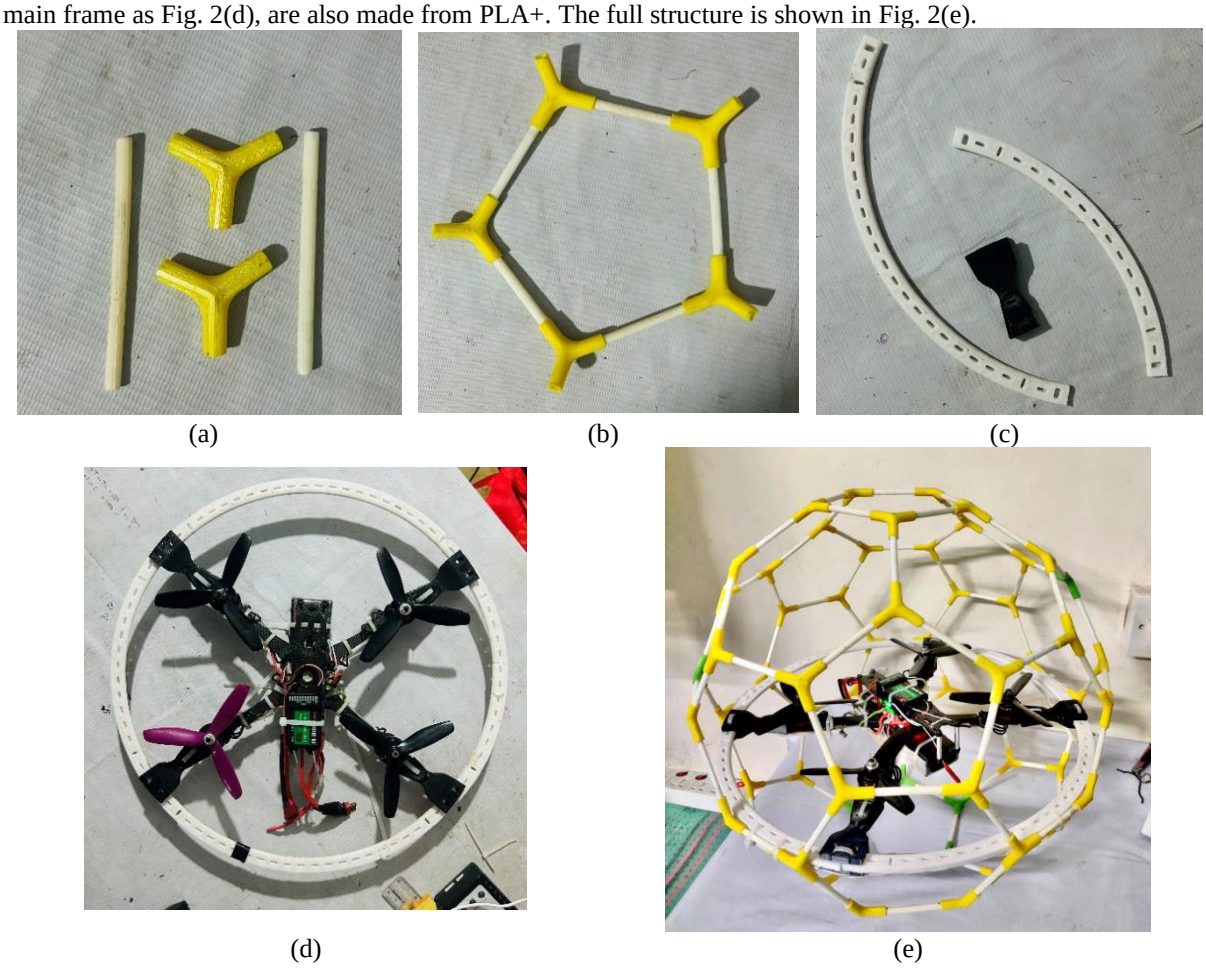
Fig. 1. 3-dimensional CAD model for protective solution. (a) Special Y connector, (b) Connector between UAV and fullerene shell, (c) base for UAV, (d) whole 3D CAD

To construct the fullerene structure, 60 specially designed Y connectors and 120 sticks are used to interconnect them, forming the protective shell. This shell is attached to the UAV's main frame using a custom connector linked to a base circle. The fabrication of the structure can be achieved through three methods:

1. Using readily available materials from the local market,
2. Injection molding for plastic parts,
3. 3D printing.

While options 1 and 2 are ideal for making the fullerene structure and connectors, the unavailability of suitable materials and the high cost of injection molding make 3D printing the more feasible solution in this case.

Only ABS sticks are available in the local market for constructing the fullerene structure. For a 225mm UAV frame, each ABS stick is approximately 30 cm in length, and a 7.5 cm section is cut from each stick. The sticks have a diameter of 5mm, so the Y connector holes are designed with a 5.2 mm diameter to allow for easy fitting like Fig. 2(b). The thickness of the Y connectors is 2mm, and they are fabricated using PLA+ due to its availability and cost-effectiveness for 3D printing. Other connectors Fig. 2(c), used to attach the fullerene shell to the UAV's main frame as Fig. 2(d), are also made from PLA+. The full structure is shown in Fig. 2(e).



(a) (b) (c)

(d) (e)

Fig. 2. The whole structure. (a) Special Y connectors and ABS stick, (b) a pentagon made of Y connectors and sticks, (c) connector and base circle to connect UAV and fullerene structure, (d) base of UAV, (e) UAV protected by fullerene structure

Testing Methods and Procedure

The main concerns for UAVs are balance and impact resistance. To ensure proper balance, the UAV must be able to fly in open air without issues, even when the protective shell is attached. Our tests as Fig. 3 confirm that the UAV maintains stable flight while equipped with the protective shell, demonstrating that the added structure does not interfere with its balance or performance. This allows for safe testing and operation, reducing the risk of damage from impacts during flight.



Fig. 3. Free flight of UAV with protective shell.

For impact testing, an MPU 6050 sensor is connected to the ESP32, which is integrated with the AnyFC F7 flight controller, to get acceleration values. Calibration of the MPU 6050 is essential, and it is done by allowing MPU 6050 sometime after powering the system with a 12V DC lithium-ion battery. Once calibrated, the UAV is throttled and controlled via a remote controller to measure three-axis acceleration. The whole data is collected in MATAB R2024b. To simulate an impact, the UAV is deliberately flown into a wall, and the change in velocity is measured using the collected acceleration data. Vibration filtering is applied to ensure the accuracy of the measurements during and after the impact. This testing helps in analyzing how well the protective shell absorbs impact and protects the UAV's components.

3. Data collection and Result

By striking the UAV against the wall and conducting a free fall from a height of 3 meters, the raw acceleration data is got which has noise and vibration showed in Fig. 4. After applying a suitable filtration method, such as a low-pass filter or Kalman filter, the processed data will provide a clearer representation of the true acceleration during these impact events. This filtered data will allow for more accurate analysis of the forces experienced by the UAV during collisions and falls, helping to evaluate the effectiveness of the protective structure in minimizing damage to the UAV.

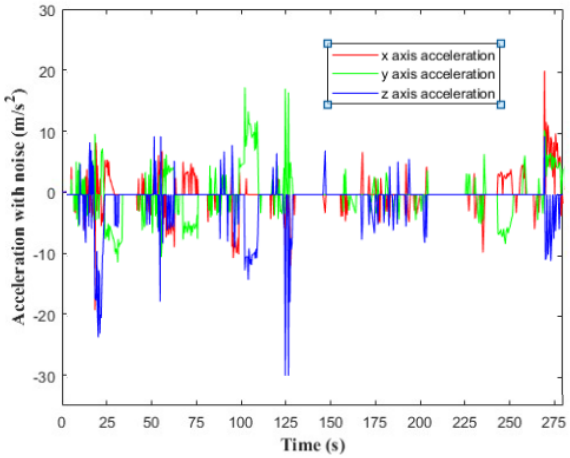


Fig. 4. Raw Acceleration Data of 3 axis with noise and vibration

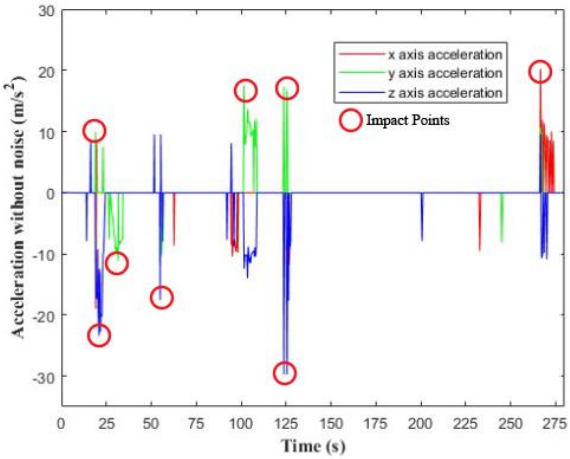


Fig. 5. Acceleration Data of 3 axis after using filter

Considering impact points are marked in Fig. 5 and data required for impact force are here colleced from the MATLAB R2024b using Fig. 5 and Table 1 is made.

Table 1: Collection of data for dynamic impact testing

No. of Impacts	Time (s)	Time Duration $dt\ (s)$	Acceleration in x axis $a_x\ (ms^{-2})$	Acceleration in y axis $a_y\ (ms^{-2})$	Acceleration in z axis $a_z\ (ms^{-2})$
1	18.733	0.334	−18.94	9.958	−17.02
2	20.5547	0.494	0	−2.2463	−23.3577
3	31.4074	0.265	0	−11.1091	0
4	55.1041	0.261	5.441	−10.74	−17.5127
5	102.494	0.435	0	17.5964	−12.4101
6	125	0.404	−18.9403	17.3833	−29.6794
7	269.88	0.462	20.2991	10.5533	9.56

velocity difference is calculated using equation (1), impact is calculated using equation (2) and equation (3) is calculated and listed on Table 2 where the mass of the UAV with protective shell, $m = 0.990\ kg$.

$$\Delta v = a \cdot dt \tag{1}$$

$$F \cdot dt = m\Delta v \tag{2}$$

$$F_{total} \cdot dt = \sqrt{(F_x\ dt)^2 + \left(F_y\ dt\right)^2 + (F_z\ dt)^2} \tag{3}$$

Where a is acceleration in single axis, dt is time duration during impact, v is change in velocity in same direction, $F \cdot dt$ is the impact on same direction.

Table 2: Result values of Impact Testing

No. of Impacts	Velocity change in x axis $\Delta v_x\ (ms^{-1})$	Velocity change in y axis $\Delta v_y\ (ms^{-1})$	Velocity change in z axis $\Delta v_z\ (ms^{-1})$	Impact on x axis $F_x\ dt(Ns)$	Impact on x axis $F_x\ dt(Ns)$	Impact on x axis $F_x\ dt(Ns)$	Total Impact $F_{total}dt(N$
1	−6.326	3.326	−5.68468	−6.263	3.293	−5.628	9.041
2	0	−1.109	−11.59	0	−1.0986	−11.423	11.476
3	0	−2.944	0	0	−2.914	0	2.914
4	1.42	−2.803	−4.571	1.406	−2.775	−4.525	5.491
5	0	7.654	−5.398	0	7.578	−5.344	9.273
6	−7.652	7.023	−11.990	−7.575	6.953	−11.871	15.705
7	9.378	4.876	4.417	9.284	4.827	4.373	11.341

Based on the impact values from Table 2, the protective shell is capable of withstanding forces of up to $16\ Ns$ without sustaining damage. This level of protection is crucial, as it prevents damage to critical UAV components such as the propellers, motors, flight controller, and other sensitive parts. Without this protective structure, a UAV subjected to such impacts could suffer significant damage, leading to costly repairs or replacements. The protective shell, therefore, not only shields the UAV but also ensures the longevity and reliability of its components during high-impact scenarios.

4. Conclusion

A study was conducted to evaluate a protective solution for testing UAV control systems using an existing control algorithm (PID). The primary objective was to develop a suitable protective structure for the UAV, inspired by the fullerene (C_{60}) structure, to measure the impact resistance of the shell structure which is the effectively shields valuable UAV components and attached payloads. However, the protective structure adds weight and raises the center of gravity slightly. Despite this, the added protection has minimal impact on overall UAV performance. This system is ideal for transporting sensitive supplies such as blood or food during emergencies. Additionally, this type of drone can be a good example of prototype for soccer drone competition. To improve impact resistance and reduce the total mass of the UAV, future designs may employ injection molding, which enhances bonding between fibers. Future research will focus on identifying the best material for the protective shell.

5. Reference

[1] S. Czypionka and F. Kienhofer, "Weight reduction of a carbon fibre composite wheel," *Science and Engineering of Composite Materials,* vol. 26(1), pp. 338-346, 2019.

[2] P. Priyanka, A. Dixit and H. S. Mali, "High strength Kevlar fiber reinforced advanced textile composites," *Iranian Polymer Journa,* vol. 28(7), 2019.

[3] Y. Zhang, L. Yan, W. Zhang, P. Su, B. Han and S. Guo, "Metallic tube-reinforced aluminum honeycombs: Compressive and bending performances," *Composites Part B: Engineering,* vol. 171, pp. 192-203, 2019.

[4] S. Li, P. Cheng, S. Ahzi, Y. Peng, K. Wang and J. Codrreia, "Advances in hybrid fibers reinforced polymer-based composites prepared by FDM: A review on mechanical properties and prospects," *Composites Communications,* vol. 40, 2023.

[5] P. A. Kumar, V. V. Namboodiri, G. Joshi and K. P. Mehta, "Fabrication and applications of fullerene-based metal nanocomposites: A review," *Journal of Materials Research,* vol. 36, pp. 114-128, 2021.

[6] S. K. Parupelli and S. S. Desai, "A Comprehensive Review of Additive Manufacturing (3D Printing): Processes, Applications and Future Potential," *American Journal of Applied Sciences,* vol. 16(8), pp. 244-272, 2019.

[7] Z. Golubovic, I. Danilov, B. Bojović and L. Petrov, "A Comprehensive Mechanical Examination of ABS and ABS-like Polymers Additively Manufactured by Material Extrusion and Vat Photopolymerization Processes," *polymers,* vol. 15(21), 2023.

[8] N. Zohdi, P. Nguyen and R. (. Yang, "Evaluation on Material Anisotropy of Acrylonitrile Butadiene Styrene Printed via Fused Deposition Modelling," *Applied Sciences,* vol. 14(5), 2024.

[9] B. Neher, N. T. Nova, R. Hossain and M. A. Gafur, "Fabrication and Characterization on Physico-Mechanical and Structural Properties of Sawdust Reinforced Acrylonitrile Butadiene Styrene (ABS) Composites," *Materials Sciences and Applications,* vol. 11(09), pp. 644-658, 2020.

[10] T. Khuong, G. Zhao and M. Farid, "Tensile Strength and Flexural Strength Testing of Acrylonitrile Butadiene Styrene (ABS) Materials for Biomimetic Robotic Applications," *Journal of Biomimetics Biomaterials and Biomedical Engineering,* vol. 20, pp. 11-21, 2014.

[11] N. T. Tuli, S. Khatun and A. B. Rashid, "Unlocking the future of precision manufacturing: A comprehensive exploration of 3D printing with fiber-reinforced composites in aerospace, automotive, medical, and consumer industries," *Heliyon,* vol. 10, no. 5, 2024.