

Enhancing UAV safety with an innovative anti-collision cage: Design, testing, and future prospects

Hanqin Zhai

Shanghai American School, Shanghai, 201201, China

hanqing2006@student.cup.edu.cn

Abstract. The rapid evolution of Unmanned Aerial Vehicles (UAVs) or Unmanned Aircraft Systems (UAS) has revolutionized aviation across military and civilian domains with their pilotless flight capabilities. Despite their versatility, UAVs pose challenges in in-flight piloting precision, leading to potential mishaps. Addressing these concerns, this research introduces an innovative UAV Anti-Collision Cage designed to enhance drone safety. Constructed from C60-shaped carbon fiber rods and 3D-printed connectors, the cage resembles a football's geometry, offering 360° protection. Experimental validations, including rolling, collision, and flying tests, were conducted to assess the cage's performance. While the cage demonstrated resilience against minor impacts, significant impacts posed challenges. The study concludes with recommendations for future improvements, emphasizing geometric refinements, material choices, enhanced rolling abilities, sensor integration, and payload capacity. This research underscores the importance of safety mechanisms in UAV operations, paving the way for safer and more efficient drone operation in confined and complex environments.

Keywords: Unmanned Aerial Vehicles, Unmanned Aircraft Systems, UAV Safety, Anti-Collision Cage, Safety Mechanisms.

1. Introduction

The domain of aviation is undergoing a remarkable transformation with the proliferation of Unmanned Aerial Vehicles (UAVs), also known as Unmanned Aircraft Systems (UAS). A defining characteristic of these machines is their ability to take flight without a human pilot onboard, a feature that sets them apart from conventional aircraft. Over time, UAVs have diversified their utility across various sectors, bifurcating predominantly into military and civilian domains [1].

Military UAVs, including unmanned combat aircraft, have not only demonstrated performance capabilities akin to traditional attack planes but have also proven to be exceptionally cost-effective. They provide comparable operational outputs while significantly reducing expenses compared to their piloted counterparts [2].

In the recent past, there has been an observable upswing in the global dynamics of the UAV market [3]. UAVs have transcended their origins as hobbyist gadgets to become indispensable tools in numerous industries, government operations, and even individual or consumer utilities. Their versatility has found applications in fields such as construction, where they facilitate surveying tasks that were once challenging for humans to perform. Energy companies, particularly those in the oil and natural gas sectors, employ UAVs to monitor extensive pipelines and critical infrastructure, ensuring timely

maintenance and enhancing safety measures [4]. In agriculture, these aerial machines are instrumental in crop health monitoring and pest control. Moreover, UAVs have proved their mettle in disaster relief efforts, particularly in challenging and disaster-stricken terrains.

UAVs play a pivotal role in specialized tasks, from capturing stunning aerial visuals for photography and filmography to protecting crops in agriculture, exploring uncharted territories for resource assessment, creating intricate maps for engineering projects, and meticulously monitoring geological phenomena like landslides. Their operational deployment guarantees a steady stream of precise data, an element of paramount importance, particularly in scenarios like geological assessments [5].

Despite UAVs' myriad benefits, operating them present unique challenges, particularly in terms of piloting precision. Novice users often struggle with controlling these vehicles, resulting in mishaps like collisions, crashes due to loss of control, or damage to the UAV's blades, which can compromise its aerial capabilities. Even more experienced flyers will have trouble operating UAVs in environments where obstructions cannot be easily avoided. These challenges raise concerns regarding the safety of UAV operations, especially in densely populated or complex environments [6].

In response to these challenges, both the research community and the tech industry have continuously strived to elevate UAV safety standards. Innovations like touch-based human-drone interaction have been explored to foster more intuitive and secure human-drone interfaces. Additionally, concepts like the Ball Drone Project have envisioned UAV designs enclosed within spherical cages, capable of deflecting impacts and ensuring safety during flight.

Industry leaders like Flyability have invested extensively in designing drones tailored for challenging environments, emphasizing "collision resilience." Scientific papers [7,8] have contributed significantly to advancing UAV safety discussions, exploring concepts like "morphing cargo drones" capable of altering their physical structure for safer flight, especially in close proximity to humans. Another notable research area involves the use of UAVs for inspecting underground electricity distribution networks, offering a safer and more efficient alternative to conventional inspection methods [9].

Building upon these foundational developments, the groundbreaking UAV Anti-Collision Cage emerges as the logical next step. This innovative structure envelops the UAV, providing comprehensive 360° protection. Its primary purpose is to safeguard the UAV from unexpected collisions during flight, ensuring stable positioning and minimizing the risk of erratic movements that could lead to accidents. The cage's rolling mechanism further enhances safety, enabling the UAV to navigate through obstacles by rolling off them rather than experiencing direct collisions, thereby ensuring the safety of both the UAV and any objects it encounters [10].

2. Mechanical design

The mechanical design of the anti-collision cage for Unmanned Aerial Vehicles (UAVs) is a pivotal component in enhancing their safety and stability during operation. This innovative cage is constructed from C60-shaped carbon fiber rods and 3D-printed three-way connectors, resulting in a spherical structure that resembles a football, as shown in Figure 1. Comprising 12 pentagons and 20 hexagons, the cage incorporates a central horizontal bar connected to a rolling bearing, enabling the UAV's forward and backward rolling motion. Once assembled, the cage equips the UAV to excel in navigating through tight spaces on land or in the air, enabling it to be deployed in various scenarios such as pipeline maintenance in factories, large ships, and other infrastructures. This usage minimizes manual labor and reduces human exposure in hazardous environments where collisions are a significant concern.

The choice of the C60-based geometry for the cage is rooted in its mechanical integrity, renowned for its strength and symmetry. The primary framework relies on 2mm carbon fiber rods, selected for their exceptional strength-to-weight ratio. This lightweight attribute is crucial to ensure that the UAV's flight dynamics are minimally affected by the added weight of the cage. The rods are cut into 10cm segments and securely fastened to the connectors using superglue, ensuring robust structural integrity. The resulting structure takes the form of a truncated icosahedron cage, consisting of 12 pentagons and 20 hexagons.

Central to the cage's design is a 4mm horizontal carbon fiber bar running from end to end through a connector piece atop the drone body. This central bar serves not only as a structural stabilizer but also as a dynamic connector to the rolling bearing. This unique feature allows the drone to execute forward and backward rolling actions, akin to the operation of a gyroscope, ensuring that the drone maintains its orientation and does not flip upside down under challenging conditions.

In the process of selecting the geometric shape for the cage, two contenders emerged as potentially optimal: the icosahedron and the C60 structure. The icosahedron, with its 20 triangular faces, has a rich history in structural applications due to the inherent stability of triangles. However, the challenge of accommodating the central axle within its design presented potential complications.

On the other hand, the C60 structure, composed of 12 pentagons and 20 hexagons, offers both aesthetic appeal and a functional advantage in terms of central axle integration. This feature streamlines the design and assembly process, enhancing mechanical coherence. While the icosahedron promises effective impact resistance, the C60's ease of central axle integration and structural coherence tipped the decision in its favor.

In summary, the selection of the C60 structure for the UAV anti-collision cage represents a harmonious balance between form and function. This design choice prioritizes structural integrity, ease of assembly, and efficient performance of the rolling mechanism, making it the most suitable solution to ensure the UAV's protection and dynamic maneuverability during its operations.

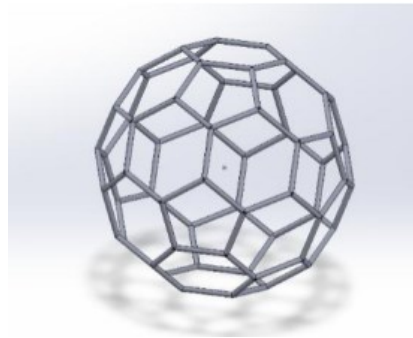


Figure 1. C60 structure cage design.

3. Electronic design

In the context of the four-axis UAV utilizing the FPV250 rack developed with INAV software, the core of its self-stabilizing capability lies in the PID (Proportional, Integral, and Differential) control algorithm. This well-established control algorithm, originating from the 1930s and 1940s, remains a cornerstone in continuous systems control due to its effectiveness even in scenarios where a profound understanding of the controlled model is limited. The PID control algorithm combines proportional, integral, and differential components into a unified strategy, primarily aimed at correcting errors or deviations from a predefined set point. Practical applications and theoretical assessments across various industrial domains have consistently validated its efficiency.

To ensure optimal drone flight performance, careful configuration of each PID variable is crucial. The electronics system driving this UAV comprises an Omnibus F4 V3S plus flight controller and a HAKRC 45A 2-6S BLHeli_S 4-in-1 ESC, both integrated into the Lannrc stack to control motor speed and direction. This control module is complemented by a radio module, and the propulsion comes from the T-Motor Velox V2 V2207 Motor 2550KV.

For precise fixed-point control, the UAV relies on an optical flow sensor that also incorporates laser ranging capabilities, offering measurements within the range of 8-200cm. This dual-module setup allows the drone to detect horizontal movements and accurately assess its altitude, enabling stable fixed-point flight. Depending on requirements, the module type can be adapted, often favoring a serial port communication module.

In terms of image transmission, the UAV utilizes the existing DJI motion camera, renowned for its anti-shake feature, ensuring the capture of steady and clear videos during flight operations. Additionally, as a backup for map transmission, the ESP32-CAM module is employed. Built upon the ESP32-S2 chip architecture, this compact module is equipped with an OV2640 camera, GPIO peripherals, and a microSD card slot, facilitating real-time image sharing on various platforms, including PCs and mobile devices.

4. Experimental validation

4.1. Rolling test

The maximum rolling speed on flat ground along the central axis of rotation for the drone safety cage was measured through five trials:

Trial 1: 15.552 km/h

Trial 2: 15.342 km/h

Trial 3: 16.753 km/h

Trial 4: 15.817 km/h

Trial 5: 14.985 km/h

These trials indicate that the drone's rolling speed with the safety cage is notably slower than its speed without the cage. This reduction in speed is primarily attributed to the considerable weight of the safety cage, which adds extra mass to the drone, making it heavier and less agile. Additionally, the cage's presence results in increased air drag, further impeding the drone's speed.

Furthermore, the distinctive alternating pentagon and hexagon geometry of the truncated icosahedron shape of the cage contributes to the challenge of rolling along a single straight line. This geometric complexity necessitates constant adjustments by the operator to ensure that the drone maintains its intended flight path while rolling.

Overall, the drone's maximum rolling speed is affected by the added weight and air resistance of the safety cage, as well as the geometric characteristics of the cage's design. These factors collectively result in a reduced rolling speed compared to the drone's performance without the cage.

4.2. Collision test

The collision test was conducted at various drop heights to evaluate the structural integrity of the safety cage. At a 1m drop height, the structure remained intact without any breakage. When dropped from 1.5m, while there was still no observable external structural damage, minor 1-2mm cracks emerged in the connector pieces at 8 joints. At the 2m drop height, although the overall structure of the safety cage remained relatively undamaged, five carbon fiber rod segments broke off entirely, with their connector pieces splitting. Additionally, 3-4mm fractures were evident at 8 joints near the initial impact area. The 2.5m drop resulted in significant damage, with some carbon fiber rod segments breaking, while larger segments remained attached to connector pieces. Finally, at a 3m drop height, the central axel fractured near the connector piece, and substantial damage occurred, with nearly one-third of connector pieces fracturing entirely, causing many rods to detach. It is worth noting that the evaluation relied on visual inspection, lacking a quantitative testing method for assessing structural integrity, suggesting room for improvement in future projects.

4.3. Flying Test

The time required to reach a hover at a height of 3 meters was measured in five trials. Trial 1 took 5.93 seconds, trial 2 took 7.08 seconds, trial 3 took 6.57 seconds, trial 4 took 7.34 seconds, and trial 5 took 5.40 seconds. The maximum load capacity during these trials was approximately 150 grams. These measurements provide insights into the drone's performance and its ability to achieve stable hovering at a specific altitude, indicating variations in responsiveness across multiple trials.

5. Evaluation and discussion

5.1. Discussion surrounding experimental results

5.1.1. Rolling Test

The rolling speed test on flat ground revealed an average speed of approximately 15.689 km/h. The results from the five trials showed that while the cage allows for adequate rolling, it does affect the drone's rolling speed, making it considerably slower than when the drone is without the cage. Notably, the cage's weight and the air drag it introduces play a part in this. Moreover, the structure, based on a truncated icosahedron, poses a challenge in maintaining a straight rolling line, necessitating frequent adjustments by the pilot. This has implications on its utility in environments where rapid responses are crucial.

5.1.2. Collision Test

The drop tests from various heights were particularly telling. At lower drops of 1m and 1.5m, the cage showed remarkable resilience. It was only from a height of 2m that significant damage began manifesting, with visible cracks and broken rods. The level of damage increased substantially with the 2.5m and 3m drop tests. These observations suggest that while the cage offers protection for minor collisions, it may not entirely shield the drone from substantial impacts.

5.1.3. Flying Test

Hovering time tests revealed that the cage does impact the time it takes for the drone to reach a hover at 3 meters. With the times varying from 5.40s to 7.34s, it indicates an inconsistent performance possibly due to the weight and structural design of the cage. Additionally, with a maximum load of only about 150g, it raises questions about the cage's applicability in more demanding applications where carrying additional payloads might be required.

5.2. Future Improvement

The drone safety cage, in its present iteration, has demonstrated valuable utility in protecting drones during their operational phases, particularly in circumstances that might expose them to potential damages. However, to further enhance its efficacy and adaptability, several pivotal areas require more in-depth investigation and subsequent refinement.

Geometric Refinements: Presently, the cage design employs the C60, which has its merits but is not without its limitations as described above. An alternative geometric configuration worth considering is the icosahedron. With 20 equilateral triangle faces, the icosahedron boasts inherent structural strength with the triangular structures, a feature that could be harnessed to offer improved protection to the drone housed within. Such a configuration, drawing upon the exceptional structural integrity of the icosahedron, could potentially distribute external forces more evenly, thereby heightening the cage's impact-resistant capabilities. Nonetheless, this proposed shift in geometry is not without its challenges. One significant hurdle would be reengineering the central axis mechanism. The spatial characteristics of the icosahedron – specifically, its lack of a singular and consistent central axis – would necessitate a reimagining of how the drone anchors itself within the cage.

Material Choices: Drop tests have consistently highlighted a significant vulnerability in the current design – the connector pieces. While carbon fiber offers a blend of lightness and strength, the connectors' tendency to crack under impact stresses the need for alternative materials. Materials that can not only withstand force but also adeptly dissipate kinetic energy upon impact could be the key. This shift would ensure that the energy from collisions is effectively spread out, reducing localized stress points and potentially preventing breakage.

Enhanced Rolling Abilities: The dynamism of drone operation often demands versatile maneuverability. Incorporating two-axis rolling into the cage's design could be transformative. Such an enhancement, which can be implemented with an icosahedron cage geometry, would not only afford the

drone a broader range of movement but also ensure that it can navigate more challenging terrains and environments with ease, making operations smoother and easier for the user.

Sensor Integration: The current cage design seems to impede optical flow sensor readings, with the cage's rods causing obstructions. The cage's design should not compromise the drone's ability to gather accurate data from its environment, so future designs need to ensure sensors have an unobstructed view or implement other computational method to guarantee sensor functionality.

Payload Capacity: For the cage to be more practical in a broader range of applications, the ability to handle larger payloads without significant performance drops is essential. This involves not just strengthening the cage but also ensuring its design does not hinder the drone's balance and maneuverability, even with added weight.

6. Conclusion

The UAV Anti-Collision Cage represents a significant step towards improving the safety and stability of UAVs during flight, particularly in challenging environments. While experimental tests demonstrated its effectiveness in certain aspects, such as collision resilience for minor impacts, the study also highlighted areas for improvement. Future iterations may focus on geometric refinements, alternative materials for enhanced durability, two-axis rolling capabilities, improved sensor integration, and increased payload capacity to broaden the cage's applicability. These advancements will play a pivotal role in ensuring safer and more versatile UAV operations across a wide range of applications, from infrastructure maintenance to disaster relief and beyond. The ongoing development of such safety-enhancing technologies aligns with the ever-expanding role of UAVs in various industries, further cementing their position as invaluable tools in aviation.

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