

Safety Considerations in the Design and Testing of Rotary-Wing UAVs

Agus Budiyo[‡] and Kakuya Iwata[†]

[‡]Indonesia Center for Technology Empowerment (ICTE), Jakarta, Indonesia.

[†]Intelligent System Research Institute, AIST, Japan.

Abstract— Unmanned Aerial Vehicles (UAVs), particularly rotary-wing models, have gained significant traction in a variety of industries, from surveillance and surveying to delivery services and disaster management. As the applications of these systems increase, ensuring their safe operation becomes paramount. This paper presents a comprehensive exploration of the safety considerations necessary in the design and testing phases of rotary-wing UAVs. Our research is divided into two main sections: the design considerations and testing protocols. In the design section, we delve into the necessary safety measures, including propeller safety, rotor balance, control systems, battery safety, and the potential acoustic and vibration impacts. We suggest design solutions aimed at minimizing safety risks associated with each of these factors. The testing protocol section evaluates the importance of rigorous testing under diverse conditions to ensure UAVs respond safely to various operational and emergency scenarios. We focus on propeller performance, engine reliability, control systems' responsiveness, and battery durability, among others. Additionally, we discuss the significance of environmental testing, which analyzes UAV performance under different weather conditions. We provide a holistic view of rotary-wing UAV safety, blending design, and testing considerations into a comprehensive safety protocol. Our research aims to contribute to the growing body of knowledge in UAV safety and inform better design and testing practices for safer UAV operations.

Keywords— Unmanned Aerial Vehicles (UAVs) testing, safety consideration, testing protocol, safety measures.

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I. INTRODUCTION

The proliferation of Unmanned Aerial Vehicles (UAVs), specifically rotary-wing UAVs, in a wide range of sectors has spurred substantial interest in understanding and enhancing their safety. These UAVs are now integral to numerous operations such as agriculture, disaster response, surveillance, and delivery services. Despite the impressive utility and versatility they offer, the increasing prevalence of UAVs

introduces a variety of safety challenges that need to be comprehensively addressed.

Rotary-wing UAVs, encompassing quadcopters and other multi-rotor drones, are particularly complex due to their unique flight dynamics. Their safety considerations are multifaceted, encompassing design features, control systems, operational procedures, and testing protocols. Moreover, the physical danger posed by rotating propellers, potential for system failures, impact of environmental conditions, and concerns surrounding battery management underscore the need for robust safety considerations.

The objective of this research paper is to delve into the key safety considerations in the design and testing of rotary-wing UAVs. In particular, we will explore the essential design features that bolster safety and the testing protocols necessary to ensure these UAVs operate reliably and safely under a wide array of conditions.

In a landscape where UAV usage is predicted to continue its exponential growth, rigorous safety measures are not merely beneficial but essential. By offering a detailed exploration of design and testing considerations, this paper aims to contribute to safer, more reliable, and ultimately, more effective UAV operations.

Through our analysis, we aspire to provide actionable insights for UAV manufacturers, regulators, and operators. In doing so, we hope to foster a culture of safety that accompanies the ongoing innovation in the exciting field of UAV technology.

II. LITERATURE REVIEW

The literature is rich with information about safety considerations in the design and testing of rotary-wing UAVs, encompassing various key domains like sensor applications, material selection, control systems, and operational protocols. Sensor applications, which form a fundamental aspect of UAV safety, have been explored in numerous studies. Balestrieri et al. (2021) provide a comprehensive overview of sensors and measurements related to UAV safety, while a Texas Instruments White Paper by Barrett et al. (2017) explores the

potential of mmWave sensors to enhance drone safety and productivity^[1-2].

Design and construction of UAVs also hold significance in ensuring safety. Hirling (2021) discusses operational safety considerations for the type certification of light unmanned aircraft systems, and Cawthorne & Devos (2020) highlight the need to balance capability with safety in UAV design^[7,5]. Uhlig et al. (2006) and Neogi et al. (2007) stress the importance of engineering safety and reliability into UAV systems^[18,13]. Furthermore, Igarashi et al. (2021) present a preliminary experimental report on the effectiveness of protective glasses for small UAV propellers, and Raja et al. (2022) address the investigations of asymmetrical damage aspects in long-range UAVs^[8,16].

Control systems have been a focal point in the literature, with Bucheli et al. (2015) outlining the translation of agent language into code for safety considerations in unmanned aerial vehicles, and Denney & Pai (2016) detailing safety considerations for ground-based detection and avoidance systems for UAVs^[4,6].

Several studies focus on the application and operational aspects of UAVs, especially in challenging environments. Bergevin (1993) discusses the challenges of testing manned and unmanned aerial vehicles with reconnaissance payloads^[3]. Murphy et al. (2008) propose crew roles and operational protocols for UAVs in close urban environments^[11].

The impact and considerations of UAVs at a societal level are also a key part of the discourse. Lee et al. (2022) perform a comparative analysis of safety and privacy regulations for unmanned aerial vehicles^[10]. Peckham & Sinha (2019) consider the future potential of biomedical drones, underlining the need for safety considerations in their design and operation^[14].

Safety risks associated with UAVs in specific industries are highlighted in the works of Namian et al. (2021) and Wang et al. (2016), both of which focus on safety risks of UAVs in the construction industry^[12,19]. Pető (2016) discusses some safety and security issues of UAVs^[15].

Lastly, Schmidt & Pretschner (2022) and Weibel & Hansman (2006), Weibel (2005) discuss the need for and development of testing tools and methods for UAVs^[17,20]. They focus particularly on safety considerations for UAV operations in the national airspace system.

Collectively, the reviewed literature emphasizes the importance and complexity of safety considerations in UAV design and testing, laying the groundwork for continued research in this field.

III. DESIGN CONSIDERATION FOR SAFETY

Safety is an indispensable aspect of UAV design, with multiple facets warranting careful consideration during the design phase. This section delineates several critical design

considerations that have significant implications on the safety of rotary-wing UAVs.

1. **Propeller Safety** : Propeller safety is a paramount concern in the design of rotary-wing UAVs due to the high rotational speeds involved and potential for severe injuries upon contact. Therefore, designs often incorporate safety measures to protect both the UAV and its surroundings from the risks associated with the propellers. A common design solution is the use of propeller guards or shrouds, which serve as physical barriers preventing accidental contact with the propellers. These can be particularly beneficial in densely populated or cluttered environments where the risk of contact is high. However, they also add weight and can affect the UAV's flight dynamics, thus requiring careful design and optimization. In addition to physical guards, some UAV designs use sensor systems to enforce a safety perimeter around the UAV, with the ability to detect nearby objects and either halt the propellers or steer the UAV away to prevent contact. The use of contactless sensors such as LiDAR and ultrasonic sensors is becoming increasingly popular in this context. Recent research in the field of sensor technology has led to advancements in obstacle detection and avoidance capabilities, offering promising avenues for enhancing propeller safety.
2. **Rotor Balance**: Rotor balance is a crucial aspect of the safe operation of rotary-wing UAVs. Any imbalance in the rotor assembly can result in excessive vibrations, which can degrade the UAV's performance, affect its stability, reduce the lifespan of its components, and in severe cases, even lead to system failure.

Design strategies to address rotor imbalance primarily revolve around real-time health monitoring systems. These systems can detect even minor deviations in rotor balance and compensate for it using active control strategies or by prompting the operator to conduct maintenance. The integration of advanced sensors and analytical tools aids in the early detection of imbalances, thereby minimizing potential harm.

Moreover, the concept of dynamic rotor balancing has garnered attention in recent years. It involves the adjustment of the mass distribution of the rotor system while the rotor is rotating, leading to minimal vibrations. Studies have explored the practicality and efficacy of dynamic balancing techniques in UAVs, showing promising results in terms of extending component lifespan and improving flight stability.

By investing in rotor balance during the design stage, the safety, longevity, and overall reliability of rotary-wing UAVs can be considerably enhanced. These considerations are integral to the safe and efficient operation of UAVs.

3. **Control Systems** : The control system is the backbone of a UAV's operation, directly influencing its stability, response to disturbances, and safe handling of unexpected scenarios. Ensuring robustness and reliability in the control system is a key safety consideration in the design of rotary-wing UAVs.

The control system should be able to handle various disturbances such as wind gusts or system faults, and maintain stability even under adverse conditions. Advanced control strategies like adaptive control or model predictive control are often employed in UAVs to ensure robust performance. These techniques can adapt to changing conditions and provide optimal control inputs based on the predicted behavior of the UAV.

In addition to robustness, redundancy in control systems is another crucial design aspect. Redundant systems provide a backup in case of component failures, enhancing the UAV's ability to safely handle such situations. Many UAV designs incorporate redundant control actuators or sensors to maintain functionality even in case of a fault.

Research in the domain of fault-tolerant control systems and autonomous decision-making has led to significant advancements in UAV safety. These developments allow UAVs to autonomously identify faults, reconfigure their control systems, and safely continue or terminate their mission, greatly enhancing their safety and reliability.

4. **Battery Safety** : Battery safety is a significant concern in the design of rotary-wing UAVs, given the widespread use of Lithium Polymer (LiPo) batteries. These batteries, while offering high energy density and flexibility in form factor, can pose serious safety risks due to their susceptibility to catching fire if damaged, overcharged, or subjected to extreme temperatures.

A crucial design consideration for battery safety is the physical protection of the battery. Protective casings or compartments are often incorporated to shield the battery from impact damage, reducing the risk of a thermal runaway condition that can lead to a fire. Also, secure mounting systems prevent unwanted movements that could damage the battery during flight.

An equally important factor is the use of smart Battery Management Systems (BMS). A BMS continuously monitors the battery's health, tracking parameters like voltage, current, temperature, and state of charge. It can provide warnings of unsafe conditions, prevent overcharging, and even initiate emergency procedures in critical situations, thus ensuring safe operation.

Recent advancements in BMS technology, along with research into fire-resistant materials and safer battery chemistries, are continually enhancing battery safety. By incorporating these developments into UAV design, it is possible to significantly mitigate the risks associated with battery operation.

5. **Acoustics & Vibrations** : Acoustic noise and vibrations, while sometimes overlooked, can have a profound impact on the safety and performance of UAVs. Excessive vibrations can damage delicate onboard equipment, reduce component lifespan, and cause instability during flight. High acoustic noise levels can also disturb people and wildlife, posing a significant environmental concern.

Design strategies aimed at reducing vibrations and noise primarily involve careful selection and design of the propulsion system. For example, the use of specially designed propellers, improved motor mounts, and vibration-damping materials can substantially reduce the transmission of vibrations to the rest of the UAV. Techniques such as dynamic balancing, which aims to balance the mass distribution of rotating parts, can also help minimize vibrations.

In terms of acoustics, numerous factors contribute to the noise generated by a UAV, including propeller design, motor type, and flight speed. Efforts to reduce acoustic noise have led to the development of quieter propeller designs, quieter motors, and flight strategies that aim to minimize noise.

Research into noise reduction technologies, such as active noise cancellation and sound-absorbing materials, is contributing to the creation of quieter UAVs. By addressing noise and vibration at the design stage, UAVs can become less disruptive, safer, and more environmentally friendly.

By attending to these safety considerations in the design phase, the safety and reliability of rotary-wing UAVs can be significantly improved. Each of these areas continues to evolve as research brings new knowledge and technologies into play,

underlining the dynamic nature of safety considerations in UAV design.

IV. SAFETY TESTING PROTOCOLS

As crucial as safety considerations are in the design phase, they also play a pivotal role in the subsequent testing phase. This section elucidates several key safety testing protocols that are routinely used in the evaluation of rotary-wing UAVs.

A. Engine & Propeller Testing

The propulsion system, comprising the engine and propellers, forms the heart of a rotary-wing UAV. Testing these components is crucial to ensure the UAV's safety, performance, and reliability under a variety of operating conditions.

Engine testing involves assessing its power output, fuel efficiency, and durability under diverse operational loads. Safety features such as engine failure detection systems are also scrutinized. Propeller testing encompasses an evaluation of balance, structural integrity, and aerodynamic performance across a wide range of rotational speeds and angles of attack.

One of the challenges in engine and propeller testing is the need to accurately simulate real-world operating conditions in a controlled testing environment. Solutions to this challenge include the use of specialized test stands that can replicate a wide range of operating conditions and loads, as well as sophisticated simulation software that can model various scenarios and predict the engine and propeller behavior.

Another crucial aspect of propeller testing is the inspection for any signs of damage or wear, which could lead to catastrophic failures in flight. The use of advanced inspection techniques, like ultrasonic testing and non-destructive testing, help in early detection of potential issues, thereby ensuring safety and reliability.

The comprehensive testing of UAV propulsion systems, as discussed in the previous paragraphs, serves as the foundation for ensuring the safety and reliability of these aerial vehicles. Propeller testing, in particular, plays a pivotal role in evaluating not only the structural integrity and aerodynamic performance of the propellers but also their potential impact on human safety. This leads us to the focal point of our study, where we delve into the specific challenges and methodologies involved in assessing the harm caused by propeller impacts, such as the 30-inch crash test conducted to replicate real-world scenarios. By bridging the gap between propulsion system testing and the evaluation of harm from propeller impacts, we aim to provide a holistic perspective on UAV safety considerations and contribute to the development of robust testing methods and protective measures.

Figs. 1 to 5 present the test apparatus, a representation of the setup used in our research to evaluate the harm caused by propeller impacts. This apparatus is designed to replicate real-world scenarios where a UAV propeller collides with a human,

such as the head or other body parts. The diagram illustrates the key components involved in the testing process, including the UAV propeller, the human surrogate target, and the controlled testing environment.



Fig 1. Overall Test Apparatus

Figure 2 showcases the bogie and traction device from both the front and side perspectives. This figure provides a visual representation of the mechanical components responsible for guiding and controlling the trajectory of the collision test. These components play a critical role in ensuring the accuracy and reproducibility of the test conditions.

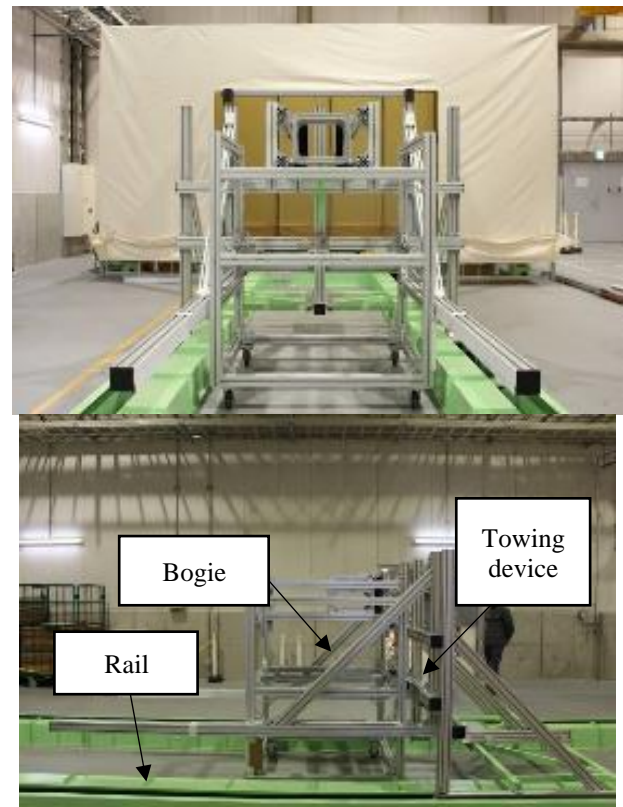


Fig 2. Bogie & Traction Device (Front, Side)

Figure 3 offers a detailed view of the stoppers and the dummy doll head, which serve as the target for the propeller collision tests. These stoppers are strategically positioned to restrict the motion of the surrogate target, mimicking real-world scenarios and facilitating controlled impact tests. The dummy doll head represents the point of impact, allowing for the assessment of potential harm caused by propeller collisions.

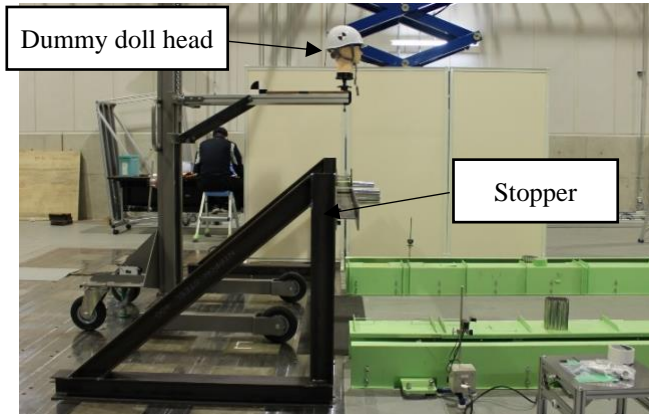


Fig 3. Stoppers & Dummy Doll Head to be Collided With

Figure 4 illustrates a single propeller collision test in action, providing a dynamic view of the experimental setup. This figure captures the moment of impact between the UAV propeller and the surrogate target, allowing for a visual understanding of the test's execution and the data collection process.

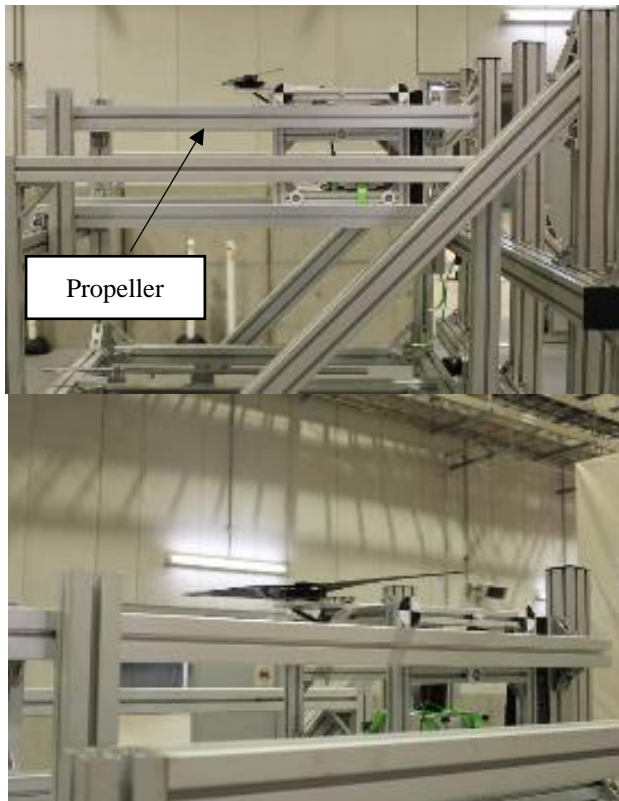


Fig 4. Single Propeller Collision Test

B. Control System Testing

The control system of a UAV is its nerve center, responsible for maintaining stability, responding to disturbances, and executing flight commands accurately. Rigorous testing of the control system is paramount to ensure the UAV's safe operation under a wide array of conditions.

Control system testing encompasses a thorough evaluation of the system's stability, responsiveness, and fault-tolerance capabilities. Stability testing assesses how the control system responds to various flight conditions and disturbances. Responsiveness testing evaluates the control system's ability to execute flight commands accurately and promptly. Fault-tolerance testing examines the system's capacity to handle component failures without compromising flight safety.

A primary challenge in control system testing is the unpredictable nature of real-world flight conditions. Replicating these conditions in a controlled test environment can be complex. Advanced simulation tools have proven effective in modeling a multitude of flight scenarios, providing a practical solution to this challenge.

Flight testing, however, remains an indispensable part of control system testing. It allows the UAV to be evaluated in real-world conditions, capturing the inherent unpredictability of such environments. These tests are conducted under carefully planned and controlled conditions to ensure safety. Regular analysis and fine-tuning based on flight test data ensure a reliable and robust control system.

C. Battery Testing

Batteries are a vital component of UAVs, supplying the energy necessary for their operation. Therefore, their performance, reliability, and safety are of paramount importance. Battery testing protocols have been developed to evaluate these characteristics under a range of conditions.

Battery testing typically involves assessments of capacity, discharge rates, and temperature tolerance. Capacity tests check whether the battery can provide the claimed amount of energy, while discharge tests evaluate how quickly that energy can be supplied. Temperature tolerance tests determine the battery's performance under a range of temperatures, which is crucial given that battery performance can significantly degrade in extreme temperatures.

The Battery Management System (BMS) is another critical component that is rigorously tested. The BMS monitors and manages the battery's health and performance. It needs to accurately track parameters like voltage, current, temperature, and state of charge, and act appropriately to prevent overcharging and overheating.

Battery testing can be fraught with hazards due to the volatile nature of commonly used LiPo batteries. Ensuring safety during testing often involves careful planning, using protective equipment, and following stringent safety procedures. Also,

using specialized test equipment designed to safely stress the batteries under controlled conditions can help mitigate these risks. Through comprehensive battery testing, potential issues can be detected and rectified, ensuring the safe operation of the UAV.

D. Environmental Testing

The ability of a UAV to perform safely and effectively under various environmental conditions is a key factor in its overall reliability. Environmental testing is designed to evaluate this ability, exposing the UAV to a wide range of conditions it may encounter during its operation.

Environmental tests can include exposure to temperature extremes, high winds, rain, snow, and even sand or dust. High and low temperature tests are performed to evaluate how the UAV and its components perform under temperature extremes. Wind tunnel tests assess the UAV's stability and control in high winds, while rain and snow tests check for weather sealing and any potential impact on the UAV's performance. Sand and dust tests evaluate how well the UAV can withstand such conditions without the ingress of potentially harmful particles.

Replicating real-world environmental conditions in a controlled test environment can be challenging. Environmental test chambers, which can simulate a wide range of conditions, offer a solution to this challenge. For some tests, carefully selecting test locations and times can also create the desired conditions.

Through extensive environmental testing, designers can identify and address potential vulnerabilities in the UAV's design, resulting in a more resilient and reliable system capable of operating safely in a variety of conditions.

V. DISCUSSION

Our research endeavors in the domain of rotary-wing UAV design and testing have unveiled a wealth of knowledge that bears significant implications for the safety and reliability of these aerial vehicles. The focal point of our investigation lies in the realm of propeller safety, a critical facet of UAV operations, where the need for stringent design standards and meticulous testing protocols is paramount.

Our findings resonate with the fundamental understanding that the safety of UAVs hinges on the integrity and performance of their propellers. In this context, our research has unveiled the crucial role of dynamic balancing techniques in propeller design and maintenance. These techniques are instrumental in ensuring that UAV propellers operate with optimal precision, minimizing vibrations and the potential for structural imbalances that could compromise safety. By incorporating dynamic balancing into propeller design and maintenance routines, UAV operators can significantly enhance the overall safety and reliability of their aircraft.

Furthermore, our research has underscored the importance of regular inspections to detect wear and damage in UAV propellers. These inspections serve as a proactive safeguard against potential catastrophic failures during flight. By implementing a systematic approach to propeller inspection, UAV operators can identify and address issues in a timely manner, thus mitigating risks and ensuring the continued safe operation of their aircraft.

In terms of control systems, the necessity of creating robust, fault-tolerant systems is clear. Simulation-based testing played a vital role in evaluating and fine-tuning control systems under various simulated conditions. However, the unpredictability of real-world conditions reiterates the importance of extensive flight testing.

Battery safety emerged as a significant concern due to the potential hazards associated with LiPo batteries. Our experiments affirmed the efficacy of protective measures like secure mounting and protective casings. The crucial role of smart Battery Management Systems was further underscored in mitigating risks.

Acoustic noise and vibrations presented another challenge, both in terms of UAV performance and environmental impact. The use of specialized propellers, motor mounts, and vibration-damping materials were proven effective in reducing these issues.

Environmental testing revealed the need for UAV designs to be robust across a wide range of conditions, emphasizing the importance of comprehensive environmental tests.

The successful design and testing of safe, reliable rotary-wing UAVs demand meticulous attention to a host of interrelated factors. Our research provides valuable insights and contributes to the ongoing discourse on UAV safety, thereby supporting the development of safer and more reliable UAVs. Further studies are recommended to delve deeper into these considerations and keep pace with the fast-evolving landscape of UAV technology.

VI. CHALLENGES & FUTURE DIRECTION

While our research has illuminated many crucial aspects of safety considerations in rotary-wing UAV design and testing, it also highlighted several challenges and areas for future exploration.

One of the significant challenges in UAV design is the balancing act between safety, performance, and cost. Making a UAV safer often requires additional components or more expensive materials, which can increase the weight and cost of the UAV. Future research should focus on finding cost-effective and lightweight safety solutions that do not compromise performance.

As UAVs become more complex and capable, new safety concerns are likely to emerge. For instance, autonomous UAVs will rely heavily on AI and machine learning, introducing new challenges related to software safety and reliability. Investigating these areas will be crucial as we continue to push the boundaries of what UAVs can do.

There are also several promising areas for future research. For instance, active noise cancellation technologies could significantly reduce the noise impact of UAVs. Similarly, the development of more advanced, lightweight materials could lead to safer and more robust UAV structures.

Another important direction for future research is the development of standardized safety testing protocols for UAVs. Such standards would help ensure consistency and rigor in UAV safety testing, leading to more reliable and safer UAVs overall.

In conclusion, while we have made significant strides in understanding and improving the safety of rotary-wing UAVs, there remain many challenges and opportunities for further research. It is our hope that this study will inspire continued efforts towards making UAVs as safe and reliable as possible.

VII. CONCLUSION

The pursuit of safety in the design and testing of rotary-wing UAVs is a complex, multifaceted endeavor. Through this research, we have explored a multitude of factors, from propeller safety to battery management, control systems, acoustics, and the essential considerations in safety testing protocols. Each of these elements presents its own unique challenges and solutions, yet they are all interconnected in the quest for overall UAV safety. Our study has demonstrated that a combination of careful design, thorough testing, and meticulous data analysis can significantly enhance the safety and reliability of UAVs. We also identified promising areas for future research and potential solutions to overcome existing challenges. Despite the advances made, UAV safety remains an evolving field. As UAV technology continues to develop at a rapid pace, so too must our understanding and management of the safety issues associated with these increasingly complex systems. We are optimistic that the insights gleaned from this research will contribute to ongoing advancements in UAV safety and propel us towards a future where UAVs can reliably serve a myriad of beneficial purposes with minimal risk.

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