Design of a Tapered-Wing Tiltrotor UAV for Multi-Mission Applications

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ABSTRACT

This paper outlines the design, development, and flight testing of a novel convertible aircraft with a fixed-wing and dual-tiltrotor configuration. Addressing the limitations of traditional Vertical Take-Off and Landing (VTOL) aircraft, the proposed design combines the efficient cruising of fixed-wing flight with the maneuverability of multirotor systems. Traditional VTOL aircraft face challenges such as limited range and payload capacity due to their dependence on rotorcraft technology, which is not optimized for high-speed travel and results in higher fuel consumption. The new design overcomes these issues by integrating a fixed wing with a dual-tiltrotor system. During takeoff and landing, the tiltrotors provide vertical lift like a helicopter. In forward flight, the tiltrotors rotate to function as propellers, working with the fixed wing to enhance lift efficiency, thus improving cruise range and fuel economy. The design process was supported by Computational Fluid Dynamics (CFD) and structural analysis to ensure optimal aerodynamic performance and structural integrity. A comprehensive flight-testing program validated the feasibility and performance of the design. Multiple tests were conducted covering all critical flight phases, including vertical takeoff, hover, transition to forward flight, sustained cruise, and vertical landing. The collected flight data confirmed the design's improved maneuverability, efficiency, and controllability.

1 INTRODUCTION

The ever-growing demand for efficient and versatile aircraft has spurred continuous innovation in the field of vertical takeoff and landing (VTOL) technologies. While conventional VTOL designs offer undeniable advantages in terms of operational flexibility, they often suffer from limitations in range, payload capacity, and cruise efficiency. This paper presents a novel approach to address these shortcomings by introducing a convertible tilt-rotor aircraft[1].

The burgeoning demand for ever-more capable unmanned aerial vehicles (UAVs) has driven significant advancements in vertical takeoff and landing (VTOL) technologies. While traditional VTOL designs provide undeniable advantages in operational flexibility by enabling take-off and landing from confined spaces, they often face limitations in range, payload capacity, and efficiency during cruise flight. This trade-off between maneuverability and long-range capability restricts their applicability in various scenarios. [2]

To address these shortcomings, researchers are exploring the exciting potential of convertible UAVs [2, 3, 4, 5, 6]. These innovative aircraft can transform their configuration mid-air, transitioning between vertical takeoff/landing like a helicopter and efficient forward flight like a fixed-wing aircraft. This adaptability unlocks a wider range of missions by combining the:

- Vertical agility of multirotor UAVs for hovering, precision maneuvers, and operation in confined areas.
- High-speed, long-range flight capabilities of fixed-wing UAVs for efficient travel and covering larger distances.

A prominent approach within convertible UAVs is the tilt-rotor design. Here, rotors mounted on the fuselage can tilt their orientation. In vertical flight mode, the rotors point upwards, generating thrust for hovering and maneuvering. During transition, the rotors progressively tilt forward, converting their thrust into forward propulsion for efficient cruise flight. While tilt-rotor designs offer a promising solution, there are ongoing research efforts to address challenges associated with:

- Complex control systems: Ensuring smooth and efficient transitions between flight modes requires sophisticated control algorithms to manage rotor tilt, thrust vectoring, and overall vehicle dynamics.
- Increased mechanical complexity: Tilt-rotor mechanisms add weight and complexity to the design compared to simpler multi-rotor or fixed-wing UAVs.
- Aerodynamic efficiency: Optimizing the design for both hovering and forward flight can present trade-offs in terms of aerodynamic efficiency.

Current approaches include different configurations of UAVs, that involves that each author use their perspective to develop a rotor-actuator configuration in order to develop a workbench that is capable of make hybrid missions. Some of them are listed below:

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- A prevalent configuration within the realm of convertible UAVs involves a quad-rotor design equipped with a tilting mechanism, as addressed in [7]. This mechanism grants the ability to dynamically alter the direction of propulsion. Such configurations play a crucial role in investigating the behavior of tilting mechanisms and their significance for the broader field of convertible UAV research.

- A prototype employing vectorized thrust is presented in Oliveira's work, enabling the capability for motion without the need for corresponding body movement. This research holds particular importance in the realm of mechanism and behavior identification due to the methodological approach employed and the successful validation of effectiveness at this particular scale [8].

- The research explores the application of a tail-sitter configuration for convertible UAVs, expanding the diversity of model configurations, as presented by Flores. This configuration is investigated alongside another convertible aircraft design, with the aim of evaluating the potential for different models to enhance efficiency in specific tasks [9].

- Zhao's work delves into the structural domain of deformable quadrotors. This field represents a distinct area of research compared to convertible UAV design, yet it holds significant relevance. This information is of vital importance to encompass the behavior of the aircraft and its effects [10].

- Bronz's contribution to the field of convertible UAVs lies in the exploration of a configuration centered around a fixed wing. This design approach prioritizes simplicity and functionality. The fixed-wing element provides inherent lift capabilities during forward flight, similar to conventional airplanes [3].

- Fayez's research builds on this concept by prioritizing long-endurance capabilities. This focus aligns with the need for UAVs capable of undertaking long-range missions. Fayez's work delves into optimizing these fixed-wing convertible UAVs for extended flight times, potentially unlocking a new generation of convertible UAVs with transformative implications for long-range applications [11].

1.1 Convention and Focus

Building upon the established concept of a convertible aircraft design, this proposal explores a variation that incorporates unique features to potentially achieve superior performance. We deviate from the symmetrical dual-tiltrotor configuration by introducing independent tilting mechanisms for the frontal rotors. This grants the aircraft increased agility and maneuverability during hovering and low-speed flight, allowing for more precise control during critical phases like search-and-rescue operations or navigating confined spaces. Furthermore, the design incorporates a full fuselage crafted with an FX-63 airfoil and a 40cm wingspan. This optimized fuselage profile is expected to contribute to smoother airflow and potentially reduce drag during forward flight. The FX-63 airfoil, known for its balanced lift and drag characteristics, is specifically chosen to improve overall aerodynamic efficiency, as studied at figure 1, which demonstrate our velocity distribution over airfoild mentioned before.. The quad-rotor configuration places two rotors on the wingtips for additional lift and thrust during forward flight. The remaining two rotors are situated on the bottom portion of the fuselage and function differentially, providing precise directional control particularly during low-speed maneuvers and hovering. This configuration aims to achieve a balance between the stability of a conventional quad-copter and the directional controllability offered by a variable-thrust vectoring system.

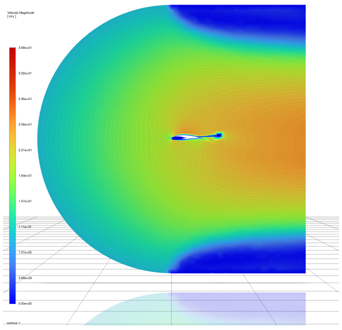

Figure 1: Airflow Distribution

By incorporating these design elements, we intend to explore the potential for enhanced maneuverability, improved aerodynamic efficiency, and overall controllability within the designated flight envelope. The independent tilting frontal rotors, FX-63 airfoil fuselage, and differential thrust bottom rotors collectively represent a unique approach to convertible aircraft design, warranting further investigation through simulations and flight testing.

2 CONCEPTUAL DESIGN AND OPTIMIZATION

Convertible UAVs, offering both vertical take-off and landing (VTOL) and fixed-wing flight capabilities, present unique design challenges. This section delves into the key considerations and optimization strategies for conceptualizing an effective convertible UAV. The selected methodology outlines the subsequent steps to develop the aircraft design:

- **Configuration Selection:** Identifying the most suitable configuration is crucial. This involves evaluating different configurations such as tiltrotors, tail-sitters, and quad-rotor designs with tilting mechanisms. Each configuration has distinct advantages and limitations that must be considered based on the intended mission profile and operational requirements.

- Design Parameters and Optimization: Defining critical design parameters, such as wing span, rotor size, and propulsion system characteristics, is essential. Optimization techniques, including Computational Fluid Dynamics (CFD) and structural analysis, are employed to refine these parameters, ensuring optimal aerodynamic performance and structural integrity.

- Performance Analysis and Trade-off Studies: Conducting detailed performance analyses helps assess various trade-offs, such as balancing VTOL efficiency with fixed-wing cruise performance. Trade-off studies are vital for understanding the implications of design choices on range, payload capacity, fuel efficiency, and overall aircraft performance.

- Mission Profile Integration: Integrating the specific mission profile into the design process ensures that the UAV meets operational requirements. This involves tailoring the design to support various missions, including long-distance cargo delivery, search and rescue operations, and infrastructure inspection.

- Design for Manufacturability and Maintainability: Ensuring that the UAV design is manufacturable and maintainable is critical for practical implementation. This includes selecting materials and components that are cost-effective, readily available, and easy to assemble and maintain. Design strategies should prioritize ease of production and long-term reliability.

By addressing these key considerations, the conceptual design and optimization process aims to develop a convertible UAV that meets the dual requirements of VTOL and fixed-wing flight, maximizing operational efficiency and versatility. sectionIterative Design Process and Optimization Techniques

The design and optimization of convertible UAVs involve a highly iterative process where simulations and analyses play a central role. The use of Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) analyses are particularly crucial in creating iterative design improvements.

2.1 CFD and FEM in Iterative Design

- Computational Fluid Dynamics (CFD): CFD simulations are used extensively to analyze the aerodynamic properties of the UAV design. By simulating airflow around the aircraft, CFD helps in identifying and mitigating potential issues such as drag, turbulence, and flow separation. This iterative process involves running multiple simulations, adjusting design parameters, and re-evaluating performance until optimal aerodynamic efficiency is achieved.

- Finite Element Method (FEM): FEM analysis is employed to assess the structural integrity of the UAV. This technique involves creating a detailed model of the aircraft's structure and subjecting it to various stress and load conditions. FEM helps in identifying weak points and areas prone to deformation or failure. Iterative FEM analyses allow for continuous refinement of the structural design, ensuring robustness and durability.

It was carried FEM study to estimate deformation, most important one was made for ABS as main structure and carbon fiber tubes for external beams, as seen at 2, whith maximum of 6.8mm, considering max force estiamte by rotors of 200gr each, and fixed at center of gravity.

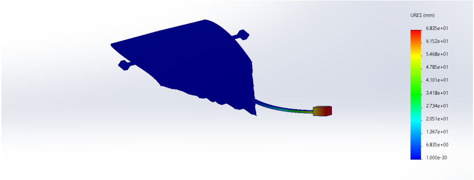

Figure 2: Internal structure deformation

2.2 3D Printing of Internal Wing Structure

Advanced optimization techniques, such as those mentioned above, are also applied in the design and fabrication of the internal structure of the UAV's wing using 3D printing technology. By integrating CFD and FEM analyses, the internal wing structure can be optimized for both aerodynamic performance and structural integrity. This process involves the following steps:

- Design Optimization: Using CFD and FEM analyses, the internal wing structure is designed to achieve an optimal balance between strength and weight. The iterative optimization process ensures that the design can withstand aerodynamic forces while maintaining minimal weight, as shown alt figure 3.

- Material Selection: Selecting appropriate materials for 3D printing is critical. Materials are chosen based on their mechanical properties, such as strength, flexibility, and weight, to ensure they meet the design specifications.

- Additive Manufacturing: The optimized internal structure is fabricated using 3D printing technology. This allows for complex geometries that would be difficult or impossible to achieve with traditional manufacturing methods. Additive manufacturing enables the production of lightweight, strong, and intricate structures tailored to the specific aerodynamic and structural requirements of the UAV.

- Testing and Validation: The 3D printed wing structures are subjected to rigorous testing to validate their performance. This includes static load tests, fatigue tests, and in-flight testing to ensure that the structures meet all safety and performance criteria.

By leveraging these advanced simulation tools, optimization techniques, and 3D printing technologies, the iterative design process of convertible UAVs ensures the development of highly efficient, reliable, and mission-capable aircraft.

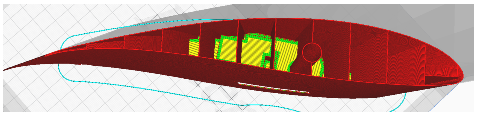

Figure 3: Internal 3D printed Wing structure

In the development of lightweight structures for prototypes, the choice of materials plays a critical role in determining performance, durability, and suitability for specific applications. Experimental testing of materials such as PLA, ABS, PETG, Nylon, and PP provides valuable insights into their deformation characteristics and mechanical properties under load, important data are carried out at table 1.

The deformation and stress data obtained from these tests are essential for evaluating how each material performs when integrated into lightweight structures. For instance, PLA exhibits relatively low deformation and moderate stress resistance, making it suitable for applications where weight reduction is critical but without extreme mechanical demands. On the other hand, Nylon shows higher deformation but offers excellent toughness, making it suitable for applications requiring impact resistance.

Among the tested materials, ABS stands out due to its equilibrium between deformation, stress resistance, and thermal stability. ABS demonstrates a balance of strength and flexibility, making it well-suited for lightweight structures where structural integrity under varying loads is essential. Moreover, ABS's thermal resistance ensures stability in diverse environmental conditions, crucial for applications exposed to fluctuating temperatures.

Based on these findings, ABS was selected for our prototype's lightweight internal lattice structures. Its combination of mechanical properties and thermal stability aligns with the operational requirements, ensuring reliable performance under real-world conditions. This informed decision underscores the importance of rigorous material testing in optimizing prototype designs for maximum efficiency and durability.

By leveraging material testing data, engineers can make informed decisions to enhance the structural integrity and performance of lightweight prototypes, paving the way for innovative solutions in various industries from aerospace to automotive and beyond.

Table 1: Comparison of Deformation and Stress of Lightweight Structures

Material	**Deformation (%)**	**Stress (MPa)**
PLA	1.50	51.20
ABS	2.20	39.80
PETG	1.80	45.35
Nylon	3.50	33.07
PP	2.80	25.25

2.3 *Prototyping and Final Design*

Using the optimization techniques mentioned above, a series of 26 prototypes were developed to iteratively test and refine the UAV design, as seen at figure 4. Each prototype incorporated feedback from previous iterations, allowing for continuous improvements in performance, efficiency, and structural integrity. The final prototype was manufactured using Acrylonitrile Butadiene Styrene (ABS) material, chosen for its durability and lightweight properties. Additionally, the internal structure of the wing featured lightweight lattice structures, 3D printed to optimize strength while minimizing weight.

- Prototyping Process:The iterative prototyping process involved creating and testing 26 different prototypes. Each iteration was subjected to rigorous CFD and FEM analyses, as well as practical flight tests, to identify and address any design issues.
- Final Prototype Design: The final prototype incorporated lessons learned from all previous iterations. It was constructed using ABS material for the external shell, providing a balance of strength and weight. The internal wing structure utilized advanced 3D printed lattice structures, which were optimized through FEM analysis to ensure maximum structural integrity with minimal material usage.
- Testing and Validation: The final prototype underwent comprehensive testing, including static load tests, dynamic flight tests, and endurance trials. These tests validated the design's performance, confirming that it met all operational requirements and performance benchmarks.

Figure 4: Multiple techniques used for Wing

3 FLIGHT CONTROL SYSTEM DESIGN

Convertible UAVs, due to their ability to switch between VTOL and fixed-wing flight, require a sophisticated flight control system (FCS) to ensure smooth transitions and stable flight across all regimes.

The flight control system (FCS) architecture for a convertible UAV plays a critical role in ensuring seamless transitions and stable flight across VTOL and fixed-wing regimes. This architecture typically comprises a central Flight Controller (FC) unit responsible for real-time data processing, control algorithm execution, and actuator command generation. Various sensors, including an Inertial Measurement Unit (IMU) for orientation and acceleration, a Global Positioning System (GPS) for positioning, an airspeed sensor for wind speed and direction, and motor encoders for precise thrust and tilt angle control (in tilting rotor/duct configurations), provide essential feedback to the FC. Actuators, such as servo motors for control surface movement and Electronic Speed Controllers (ESCs) for electric motor control, translate electrical commands from the FC into physical actions on the UAV.

The software architecture leverages a modular design, separating functionalities like sensor fusion for unified state estimation, flight mode control for managing transitions and activating specific algorithms, stabilization control for real-time adjustments based on sensor data, navigation control for path planning and execution, and health monitoring for system diagnostics. Communication protocols facilitate data exchange and control commands between modules and with the ground control station (GCS). Redundancy in critical components and fail-safe mechanisms enhance system robustness and ensure safe operation in case of potential sensor or actuator malfunctions. This well-defined system architecture empowers the FCS to effectively manage the complexities of convertible UAV flight and maintain optimal performance across diverse flight modes.

In the context of convertible UAVs, where transitions between VTOL and fixed-wing flight modes demand rapid adaptation of control strategies, the ESP32's capabilities are particularly advantageous. Its multicore capabilities and robust sensor fusion processing, implemented through C++ programming, empower UAV systems with enhanced real-time control, agility in flight mode transitions, and reliability in adverse conditions. Future research may explore further optimizations and applications of the ESP32 platform to expand the operational capabilities and resilience of convertible UAVs in diverse environments.

Our custom flight computer allow us to monitor and design all the interactions with our system, but also to include model bases control schemes, as shown at figure 5 many comunications and implementatiosn are allow.

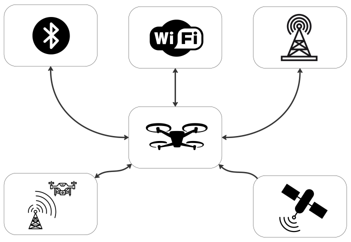

Figure 5: Sensor capabilities Diagram

4 FLIGHT-TESTING PROGRAM

Convertible UAVs, with their VTOL and fixed-wing flight capabilities, necessitate a rigorous flight-testing program to validate performance, stability, and safety across diverse flight regimes. This program typically follows distinct phases. Pre-flight testing commences with ground testing, meticulously examining the entire system (propulsion, flight control system (FCS), communication) through static motor tests, control surface deflection checks, and simulated flight scenarios. The validation of the system employs a design of experiments (DoE) approach, enabling comprehensive testing of the system's capabilities. The chosen experiments focus on tracking missions, facilitating the assessment of the system's performance under consistent patterns and diverse movement combinations. It is crucial to note that each mission is tailored to evaluate the system's performance across various scenarios that may not inherently support convertibility due to constraints related to tracking position. Valuable insights into the system's adaptability and performance under different operational contexts are provided by these missions.

The Vicon platform in the Navigation Laboratory at the Aerospace Engineering Research and Innovation Center, Faculty of Mechanical and Electrical Engineering, Autonomous University of Nuevo Leon, serves as the tracking system. This laboratory features 16 VICON T-40 cameras that utilize optical markers attached to each object for motion capture. The captured information is processed at a ground station to estimate general angular and linear position states. Figure 6 depicts our platform, where the system is distributed across a tracking station that transmits data to the network and communicates with the UAV via a secondary network of individual computers.

4.1 *Vertical takeoff*

Vertical takeoff capabilities of convertible UAVs involve crucial experiments to ensure optimal performance. Comprehensive testing verifies the efficiency and stability of vertical ascent and descent, including:

- Power and Thrust Testing: Evaluating propulsion systems under varying load conditions to validate thrust capabilities.
- Stability Assessments: Testing control algorithms and

Figure 6: VICON Tracking system

flight dynamics to ensure steady vertical flight.

The circular trajectory chosen measures 1750 mm in radius, with a height of 1800 mm and a velocity of 0.03 rev/s. This trajectory assessment emphasizes the tilting mechanism essential for achieving such motion without directly manipulating the rotors; instead, they are controlled solely by the mixer for stabilization.

The trajectory is affected by geometrical errors inherent to actuator resolution limitations, visible in slight deviations observed in online trajectory representations. Despite these challenges, the trajectory adheres closely to the intended path, maintaining acceptable tracking accuracy with minimal drift.

Figure 7 illustrates the comparison between the actual XYZ trajectory and the ideal trajectory. A primary objective of this design is to minimize the pitch angle, particularly to avoid interference with wing-generated forces.

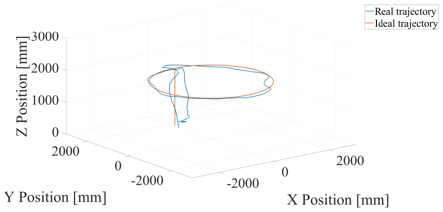

Figure 7: XYZ trajectory tracking, real vs ideal.

Figure 8 depicts the comparison of real versus ideal pitch angles, emphasizing minimal deviation (pitch-less) to maintain optimal flight characteristics. The system demonstrates excellent performance, maintaining a maximum error of 100 mm and angular errors within ±3 degrees.

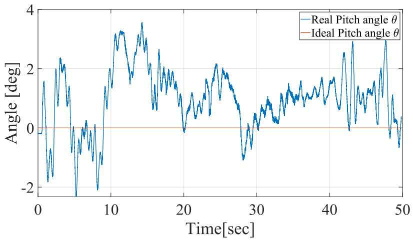

Figure 8: Pitch angle real vs ideal (pitch-less)

4.2 Transition

This experiment highlights the rapid transition capability of the system using tilting rotors, where the input involves swift changes in tilting angles.

Figure 9 illustrates the XYZ trajectory tracking, comparing real-time performance with the ideal trajectory. In this scenario, a linear trajectory is implemented to facilitate the transition between hover and cruise flight modes.

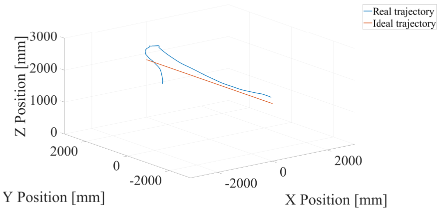

Figure 9: XYZ trajectory tracking, real vs ideal.

Figure 10 displays the development of velocity along the linear trajectory. During this brief experiment, the control scheme effectively compensates for altitude loss while accelerating the aircraft to a maximum speed of 2 m/s. It's observed that the system remains in hover mode during this acceleration, with the rotors not fully transitioning. Nonetheless, this short-duration experiment provides insights into expected dynamic behavior.

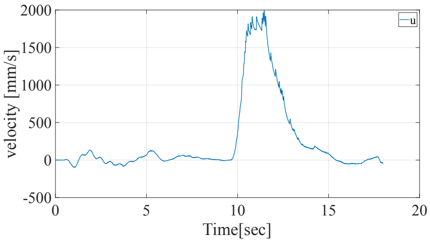

Figure 10: U velocity develop at Ramp

Figure 11 demonstrates the behavior of lift generated by the overall rotor forces, particularly notable between 10 to 12 seconds, where an increase in lift corresponds directly to a reduction in the required signal to maintain altitude. The transition phase of convertible UAVs, as exemplified here, underscores the system's capability to swiftly and effectively switch between different flight modes, demonstrating crucial dynamics and control responses during such maneuvers.

Each of these phases contributes to validating the convertible UAV's overall performance and safety across diverse flight regimes, ensuring that experimental results meet acceptable standards for operational deployment.

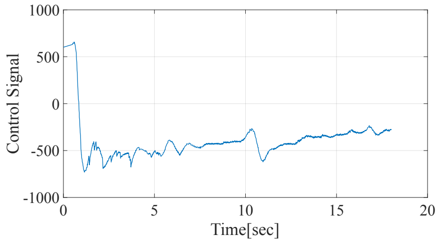

Figure 11: Lift behavior on global rotor forces

5 CONCLUSION

The presented work explores the innovative realm of convertible UAVs, specifically focusing on a novel tilt-rotor design aimed at combining the agility of multirotor UAVs with the efficiency of fixed-wing aircraft. This approach addresses the inherent trade-offs in traditional VTOL designs by enabling seamless transitions between vertical takeoff and landing and efficient forward flight. The paper emphasizes key challenges such as complex control systems, increased mechanical complexity, and aerodynamic efficiency, which are critical considerations in the design and optimization of such aircraft.

Through an iterative design process involving advanced simulation techniques like Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) analysis, the authors developed and refined a prototype convertible UAV. This process included optimizing the aircraft's aerodynamic performance, structural integrity, and overall efficiency. The integration of 3D printing for internal wing structures and rigorous material testing underscored a commitment to lightweight, yet durable, design solutions.

The flight control system (FCS) design was another pivotal aspect, ensuring smooth transitions and stable flight across VTOL and fixed-wing modes. Leveraging sophisticated sensor fusion, modular software architecture, and robust actuators, the FCS demonstrated capabilities crucial for managing the complexities of convertible UAV flight.

A comprehensive flight-testing program validated the system's performance under various conditions, including vertical takeoff, transitions between flight modes, and trajectory tracking. The experiments confirmed the aircraft's operational capabilities, stability, and safety, reinforcing the feasibility of the tilt-rotor concept for diverse missions.

In conclusion, this work contributes significantly to the field of convertible UAVs by proposing an innovative tilt-rotor design, supported by rigorous design methodologies, advanced simulation tools, and comprehensive testing protocols. The findings pave the way for further advancements in hybrid UAV technologies, promising enhanced operational flexibility and mission capabilities in both civilian and military applications. The flight-testing program conducted rigorous experiments to validate the trajectory path following capabilities of the convertible UAV, focusing on both vertical takeoff scenarios and transitions between flight modes. For the vertical takeoff phase, the UAV executed a circular trajectory with a radius of 1750 mm and a height of 1800 mm. The objective was to assess the aircraft's ability to ascend and descend vertically while maintaining stability and accuracy in trajectory tracking. The transition experiment evaluated the UAV's capability to switch between hover and cruise flight modes using its tilting rotor mechanism. A linear trajectory was chosen to facilitate smooth transitions and assess dynamic responses during acceleration.

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