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 take-off 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 energy 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 take-off, 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 increasing need for efficient and versatile aircraft has driven ongoing innovation in vertical take-off and landing (VTOL) technologies, [1]. While traditional VTOL designs offer clear advantages in operational flexibility, they often face limitations in range, payload capacity, and cruise efficiency. This paper presents a novel approach to address these shortcomings by introducing a convertible tiltrotor aircraft,[2].

The increasing demand for ever-more capable unmanned aerial vehicles (UAVs) has driven significant advancements in vertical take-off 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. [3]

To address these problems, researchers are exploring the exciting potential of convertible UAVs [3], [4], [5], [6], [7]. These innovative aircraft can transform their configuration mid-air, transitioning between vertical take-off/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 tiltrotor 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 the transition, the rotors progressively tilt forward, converting their thrust into forward propulsion for efficient cruise flight. While tiltrotor 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.

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- Increased mechanical complexity: Tiltrotor 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 involve each author using their perspective to develop a rotor-actuator configuration in order to develop a workbench that is capable of making hybrid missions. Some of them are listed below:

- A prevalent configuration within the realm of convertible UAVs involves a quadrotor design equipped with a tilting mechanism, as addressed in [8]. 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 et al., 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 [9].

- The research explores the application of a tail-sitter configuration for convertible UAVs, expanding the diversity of model configurations, as presented by Flores et al.. 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 [10].

- Zhao et al. 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 [11].

- Bronz et al. 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 [4].

- Fayez et al. research builds on this concept by prioritizing long-endurance capabilities. This approach aligns with the need for UAVs capable of undertaking long-range missions. Fayez et al. 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 [12].

1.1 Convention and approach

This proposal builds upon the concept of a convertible aircraft design to explore a variation with unique features for superior performance. The symmetrical dual-tiltrotor configuration is avoided by introducing independent tilting mechanisms for the frontal rotors. This design grants the aircraft increased agility and maneuverability during hovering and low-speed flight, allowing for more precise control during critical phases such as search-and-rescue operations or navigating confined spaces.

Moreover, the design features a full fuselage with an FX-63 airfoil and a 40cm wingspan. This optimized fuselage profile is anticipated to significantly improve airflow, potentially reducing drag during forward flight. The FX-63 airfoil, renowned for its balanced lift and drag characteristics, is specifically selected to enhance overall aerodynamic efficiency, as demonstrated in our velocity distribution over the airfoil, as studied in figure ef CFDdis. The quadrotor 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.

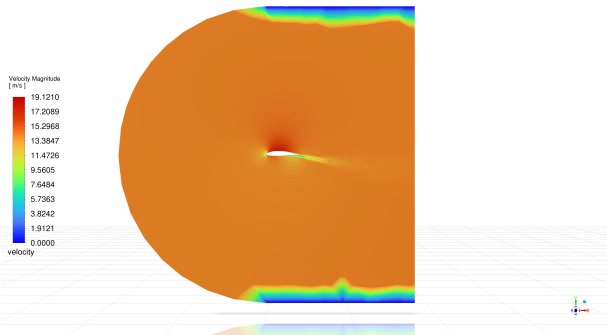

Figure 1: Airflow Distribution.

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

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aircraft design, warranting further investigation through simulations and flight testing.

2 CONCEPTUAL DESIGN AND OPTIMIZATION

Convertible UAVs, offering capabilities on both vertical flight and cruise flight, 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), structural analysis (FEA), and Solid Isotropic Material with Penalization method (SIMP) for optimization, are employed to refine these parameters, ensuring optimal aerodynamic performance and structural integrity.

- Performance analysis and trade-off studies: Conducting detailed performance analyses help 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 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 fundamental considerations, the conceptual design and optimization process aims to develop a convertible UAV that meets the dual requirements of rotary wing 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 CFD helps identify and mitigate 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; the most important one was made for ABS as the main structure and carbon fiber tubes for external beams, as seen at 2, with a maximum of 0.9258mm, considering max force estimate by rotors of 200gr each, and fixed at the center of gravity, condition for hover flight. For a fixed-wing based flight, small

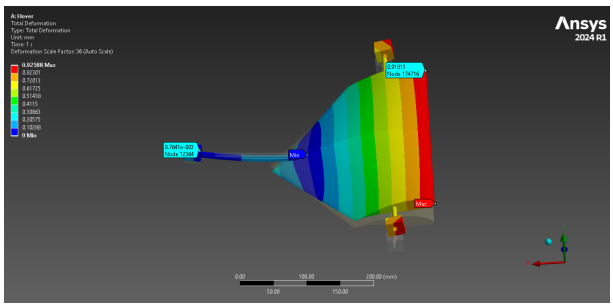

Figure 2: Structure deformation on hover condition.

forces are considered on rotors for propulsion and bottom rotors just to balance, as seen in figure 3. Preliminary results shows that cruise flight is less demanding to the structure, considering a distributed force on the wing of same value of structural mass, for this case 4.41N.

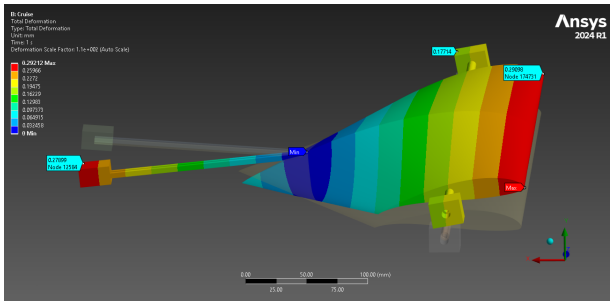

Figure 3: Structure deformation on cruise condition.

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 wing using 3D printing technology. By integrating CFD for forces distribution on flight and FEM analyses for deformations, stress, and strain are carried out, the internal wing structure is 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 in figure 4.
- 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.

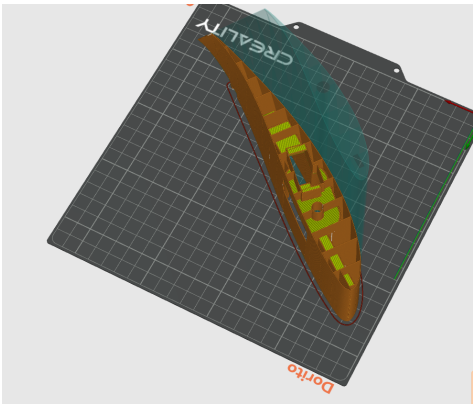

Figure 4: Internal 3D printed Wing structure.

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 in 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 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.

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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

Figure 5: Multiple techniques used for Wing.

2.3 *Prototyping and final design*

The optimization techniques mentioned above were used to develop a series of 26 prototypes in order to test and refine the UAV design. The process is illustrated in Figure 5, which shows multiple iterations and the final wing development. 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 that were 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.

3 FLIGHT CONTROL SYSTEM DESIGN

Convertible UAVs, due to their ability to switch between rotary wing and fixed-wing flights, 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 rotary wing 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 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 flights 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 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 allows us to monitor and design all the interactions with our system and include model-based control schemes, as shown in figure 6. Many communications

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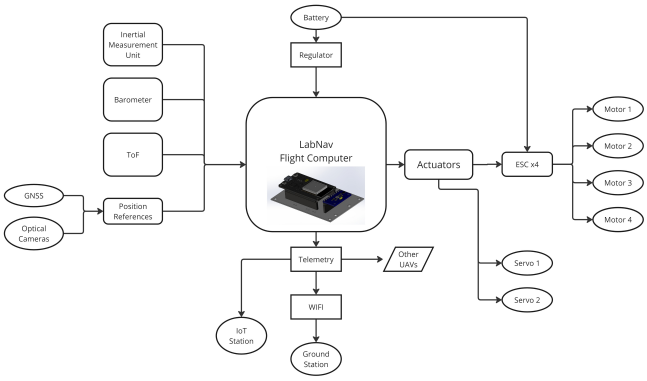

Figure 6: Sensor capabilities Diagram.

and implementations are allowed.

Control scheme for this continuous convertible UAV is devolved at others works, for this case is only presented main scheme on figure 7

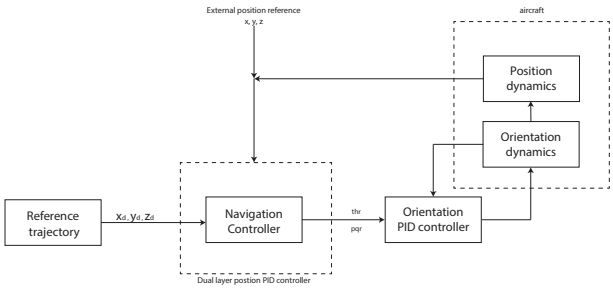

Figure 7: Control Scheme.

4 FLIGHT-TESTING PROGRAM

Convertible UAVs, with their rotary wing 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 comprehensive design of experiments (DoE) approach, enabling thorough 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 performance across various scenarios that may not inherently support convertibility due to constraints related to tracking position. These missions provide valuable insights into the system's adaptability and performance under different operational contexts.

The Navigation Laboratory, at the Aerospace Engineering Research and Innovation Center, Faculty of Mechanical and Electrical Engineering, Autonomous University of Nuevo Leon, features a tracking system based on 16 VICON T-40 cameras, which obtain the information processing at a ground station to estimate general angular and linear position states. Figure 8 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.

Figure 8: VICON Tracking system.

4.1 *Vertical take-off*

Vertical take-off 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 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 influenced by geometrical errors that are inherent to actuator resolution limitations. These limitations are visible in slight deviations observed in online trajectory representations. Despite these challenges, the trajectory closely follows the intended path, maintaining acceptable tracking accuracy with minimal drift.

Figure 9 compares the actual XYZ and ideal trajectories. A primary objective of this design is to minimize the pitch angle, mainly to avoid interference with wing-generated forces.

Figure 10 compares real versus ideal pitch angles, emphasizing minimal deviation (pitch-less) to maintain optimal flight characteristics. The system demonstrates excellent per-

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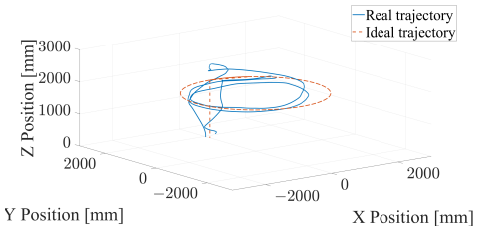

Figure 9: XYZ trajectory tracking, real vs ideal.

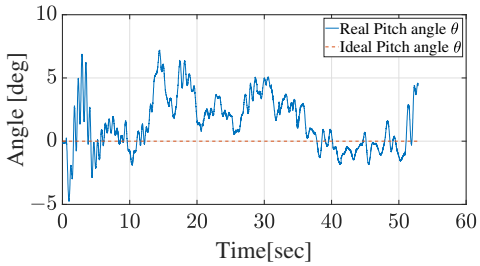

Figure 10: Pitch angle real vs ideal (pitch-less).

formance, maintaining a average error of 126.0183 mm and angular errors within ±3 degrees, as observed at table 4.1.

Axis	Average	Root Mean Squared	Mean Absolute	Maximum Absolute
X	80.0504	585.5509	489.9378	1.5494e+03
Y	126.0183	644.7709	465.6277	1.4141e+03

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

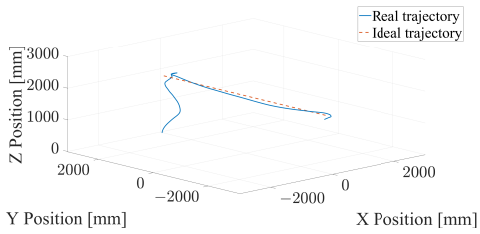

Figure 11: XYZ trajectory tracking, real vs ideal.

Figure 12 displays velocity development 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 is 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.

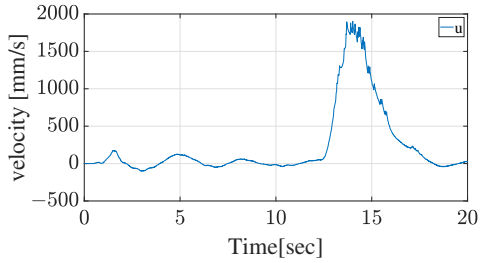

Figure 12: U velocity develop at Ramp

Figure 13 demonstrates the behavior of lift generated by the overall rotor forces, particularly notable between 8 to 13 seconds, where an increase in lift corresponds directly to a reduction in the required signal to maintain altitude.

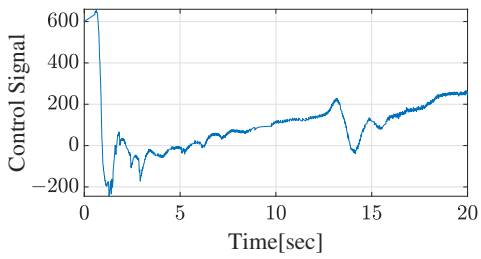

Figure 13: Lift behavior on global rotor forces.

As exemplified here, the transition phase of convertible UAVs underscores the system capability to swiftly and effectively switch between different flight modes, demonstrating crucial dynamics and control responses during such maneuvers.

Axis	Average	Root Mean Squared	Mean Absolute	Maximum Absolute
X	85.1773	232.5250	192.9673	536.5002
Y	407.0696	1.1919e+03	520.0588	4.9525e+03

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

5 CONCLUSION

The presented work explores the innovative realm of convertible UAVs, specifically focusing on a novel tiltrotor 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 take-off and landing and efficient forward flight. The paper emphasizes key challenges such as complex control systems, increased

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mechanical complexity, and aerodynamic efficiency, which are critical considerations in designing and optimizing 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. Integrating 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 take-off, transitions between flight modes, and trajectory tracking. The experiments confirmed the aircraft's operational capabilities, stability, and safety, reinforcing the feasibility of the tiltrotor concept for diverse missions.

In conclusion, this work contributes significantly to convertible UAVs by proposing an innovative tiltrotor 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 civilian and military applications. The flight-testing program conducted rigorous experiments to validate the trajectory path following the capabilities of the convertible UAV, focusing on both vertical take-off scenarios and transitions between flight modes. For the vertical take-off 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 ability to ascend and descend vertically while maintaining stability and accuracy in trajectory tracking. Using its tilting rotor mechanism, the transition experiment evaluated the UAV's capability to switch between hover and cruise flight modes. A linear trajectory was chosen to facilitate smooth transitions and assess dynamic responses during acceleration.

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