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Design of Multi-Rotor Flying Wing Configuration Quadplane Unmanned Aerial Vehicle

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Abstract: Aerial reconnaissance is one of the most prominent applications of UAVs. This research paper elaborates on the complete design lifecycle of a Vertical Take-Off and Landing (VTOL) Unmanned Aerial Vehicle (UAV) with a Flying Wings configuration, specifically aimed at surveying agricultural areas. Innovative methodologies, such as geometric twist and proverse yaw, are employed for sizing and determining the aircraft's parameters. Airfoil selection and the assessment of aerodynamic properties are conducted using XFLR5, with subsequent validation through Computational Fluid Dynamics (CFD) analysis in Ansys Fluent 2022. This research integrates cutting-edge technologies and non-traditional approaches to enhance the precision and efficiency of agricultural surveying, making significant contributions to the field of precision agriculture. An extensive literature review and multiple design iterations were undertaken to create a novel design that resulted in an optimized, innovative, and practical product.

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1. Introduction

India has approximately 154.4 million hectares of arable land, making it the second largest in the world according to the United Nations Food and Agriculture Organization (FAO). The Department of Agriculture and Farmers Welfare, Government of India, reports that India ranks among the top 10 crop exporters globally, with exports exceeding 3 lakh crores in the year 2021-2022. However, India has not fully adapted to the increased application of modern farming techniques. This research introduces an innovative VTOL UAV designed for efficient agricultural surveying. It combines the VTOL capability of drones with the cruising efficiency of aircraft, addressing the runway requirement and power consumption constraints associated with conventional aircraft and drones, respectively. The UAV features a flying wing configuration based on Prandtl's theory and is equipped with an aerodynamically efficient fuselage. This design, due to the absence of an empennage, is modular and lightweight compared to conventional designs. To ensure stability, the concept of geometric twist is incorporated to generate upwash and create a proverse yaw. We discuss the methodology followed in designing the UAV from ideation to the engineering model, highlighting the selection process and rationale behind each decision [1].

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2. Design Methodology

The UAV is a multirotor Quadplane with a flying wings configuration. This design features no empennage, and the fuselage, if present, is seamlessly integrated with the wings as a single unit [2]. The wings are given a geometric twist to address and compensate for the absence of an empennage. When the aircraft rolls along the longitudinal axis, it generates adverse yaw. Conventional aircraft use a rudder to counteract this adverse yaw. In flying wing designs, addressing adverse yaw while managing simultaneous pitching requires a different approach. To achieve this, the drag on the tip region is adjusted to generate thrust using the geometric twist, creating a proverse yawing effect as described by Prandtl's theory. The design of the Quadplane UAV is approached systematically, with detailed explanations provided in the subsequent sections, covering all aspects of the design.

2.1 Airfoil Selection

Airfoils chosen for the wings are in respect to fulfilling the requirement of positive pitching moment at an AOA=0º and maintaining the aerodynamic centre aft of CG for longitudinal stability. The selection procedure is done considering the parameters related to aerodynamic efficiency and flight stability. After considering all the different aspects, the Prandtl-D root airfoil is chosen for the root chord and the whole wing. Fig. 1 and Fig. 2 shows the C_l vs AOA and C_m vs AOA graphs respectively. The Prandtl-D tip is selected for the tip chord. It's C_l vs AOA and C_m vs AOA has been depicted in Fig.3 and Fig.4 The analysis is performed on XFLRv6. The trend of the graphs justifies the selection of the airfoils.

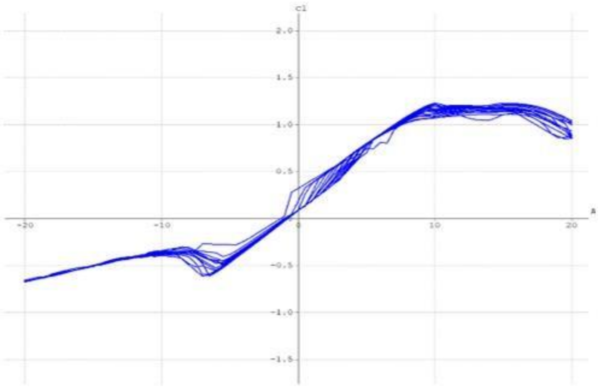


Figure-1. Cl vs AOA graph for airfoil Prandtl-D root

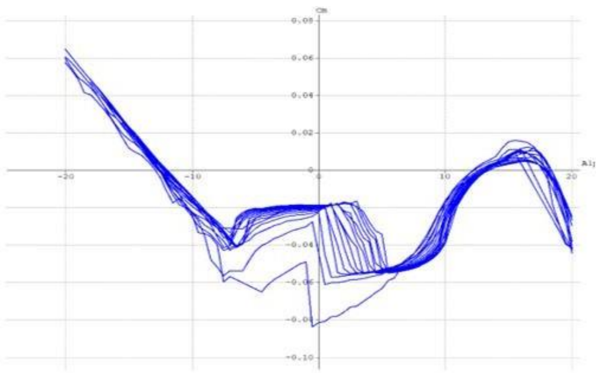


Figure-2. Cl vs AOA graph for airfoil Prandtl-D root

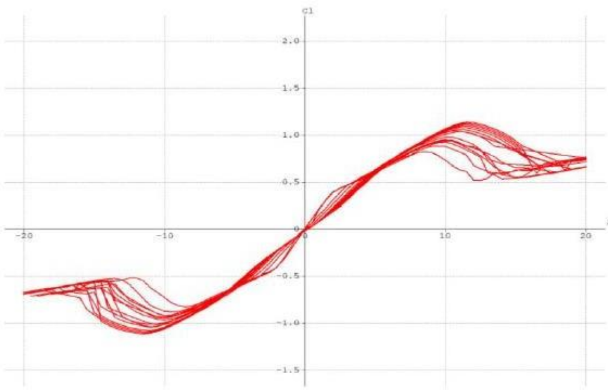


Figure-3. C_l vs AOA graph for airfoil Prandtl-D tip

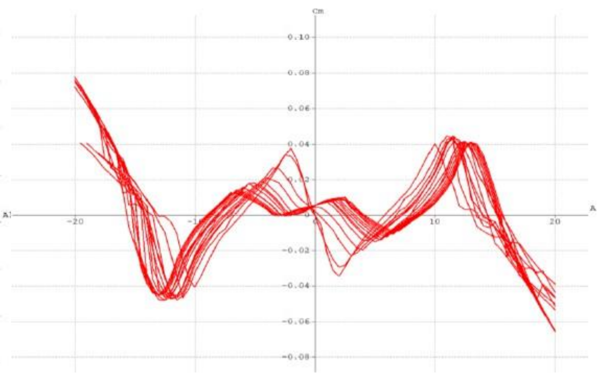


Figure-4. C_m vs AOA graph for airfoil Prandtl-D tip

For the fuselage section, the requirement is of an airfoil with sufficient thickness to accommodate the payload bay and all the avionics. Considering this, the symmetrical airfoil NACA M3 is chosen. It has a maximum thickness of 11.9% at a 30% chord. It provides stability, and also generates enough lift to assist the wings, which can be inferred from Fig.5 and Fig.6.

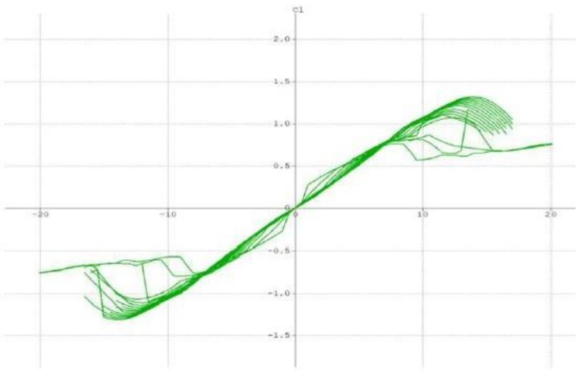


Figure-5. Cl vs AOA graph for airfoil NACA M3

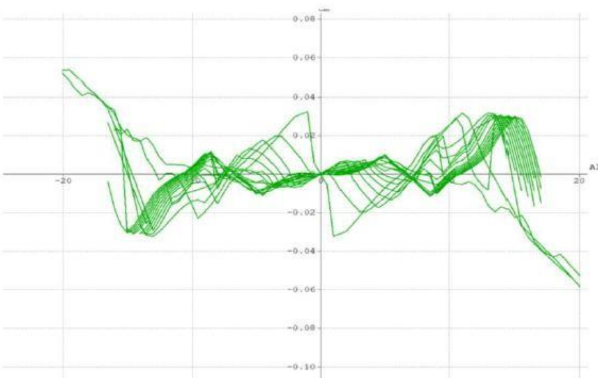


Figure-6 Cm vs AOA for airfoil NACA M3

2.2 Aircraft Sizing

In order to design the aircraft certain assumptions are made which are as follows:

- The total estimated mass of the aircraft is assumed to be 5 kg.
- The approximate value of Cl = 0.3 at AOA = 2.5º is considered for the wings.
- Taper Ratio = 0.25 and root chord = 0.5 m.

Wings

The velocity of 22 m/s is obtained from the mission plan and the avionics components, the mission profile is in alignment with the avionics, and a rough area is calculated with the estimated values from the following equation of lift.

$$L = 0.5*\rho*A*Cl*v^2 \qquad (1)$$

From the equation, a rough area of 0.6 m^2 is obtained. Using taper ratio and root chord length, a 1.6 m span (without fuselage) is first obtained [5].

Fuselage

The fuselage dimensions are estimated considering the placement of avionics and payload bay and the lift generation. The fuselage is airfoil shaped with a chord length of 0.6 m and span of 0.35 m. Post numerous analyses on XFLR5 and adding geometric twist in the wings, some alterations have been made in sizing, and the final sizing is as mentioned in Table 1.

Table-1 Aircraft Sizing

Parameters	Value
Total Area	0.453 m^2
Wing Sizing	
Wingspan	1.2 m
Root chord	0.514 m
Tip chord	0.128 m
Fuselage Sizing	
Chord length	0.514 m
Breath	0.35 m

Geometric Twist

Providing Geometric twists is a smart approach for designing an efficient wing. In this, a gradual change is made in the angle of incidence spanwise from the root towards the tip of the wing. A negative angle of incidence at the tip will provide a forward thrust at the wingtip and thus will reduce turbulence there. As per Prandtl theory, bell-shaped lift distribution showed a smooth gradual lift distribution **[4]**. A comparison of it with elliptical lift distribution has been shown in Fig. 7. Significant upwash is observed in bell-shaped distribution. This upwash provides a forward thrust around the tip region of the wing. Thus, to bring stability to aircraft, a geometric twist of -4º at the tip and 2º at root has been given, thus producing more lift at the root. This would prevent tip stalling and hence has provided sufficient stability and control to aircraft, thereby compensating for the empennage.

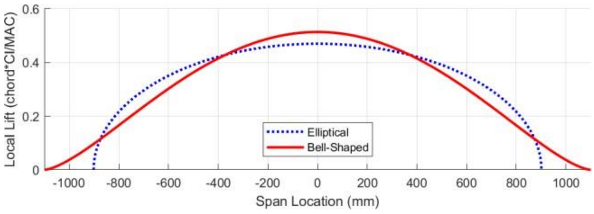


Figure-7 Comparative Lift Distribution [4]

Aileron Dimensioning

For a tapered wing, the aileron dimensions are as mentioned **[3]** (Fig. 8)

- Length of aileron= 0.25 B/2 = 0.15 m
- Breath of aileron = 0.25 C_X

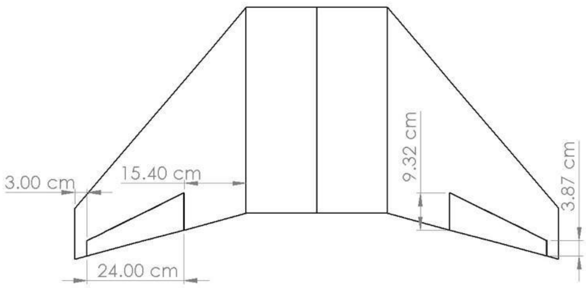


Figure-8 Aileron Dimensions

Parameters	Value
Span	1.2 m
Chord length (fuselage)	0.514 m
Breath (fuselage)	0.35 m
Root Chord	0.514 m
Tip Chord	0.128 m
Taper Ratio	0.25
Area	0.453 m^2
Aspect Ratio	3.17
Wing loading	4.58 kg/m^2
Tilt Angle	4º
Twist (Root chord-both wing and fuselage)	2º
Twist (Tip chord)	-4º
Root-Tip Sweep	34º
AOA (AOA)	2.5º
Cm (at AOA)	-0.252
Cl (at AOA)	0.443
Total mass	4.8 kg

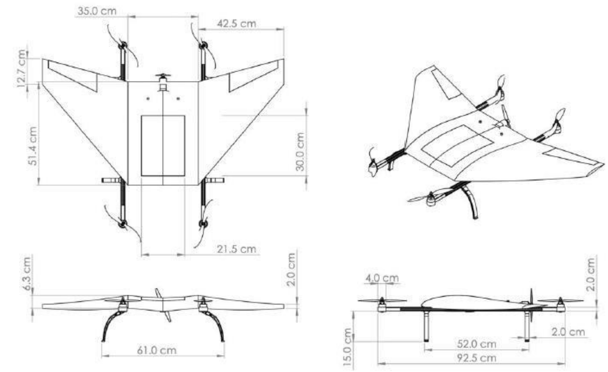


Figure-9 Aircraft Dimension

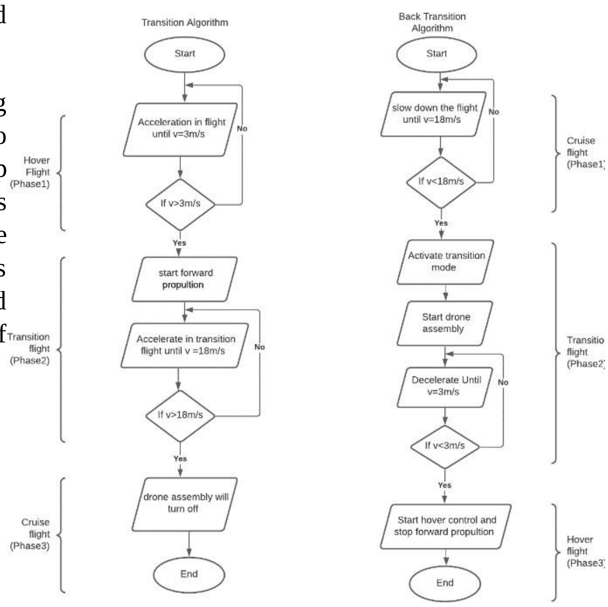
Figure-10 3D CAD Model of Quadplane

3. Rotor Configuration

This UAV is a fixed-wing and fixed-rotor VTOL aircraft. The chosen VTOL configuration has four rotors for the vertical take-off and landing phase. A fifth rotor is installed at the trailing part, which takes control of the cruise condition. Detailed drawing depicting the dimension and complete CAD model is shown in Fig. 9 and Fig. 10 respectively. To achieve cruise flight conditions, the fifth rotor which is a horizontal propeller powered by a pusher motor starts propelling and simultaneously the four rotors slowly turns-off. This transition between VTOL and cruise is smooth enough to stabilize the proposed configuration **[7]**.

The transition mechanism does not contain any moving parts. It is entirely controlled by switching between two sub- assemblies provided in the aircraft. A step-by-step transition flowchart is explained in Fig. 11. This flowchart shows the working algorithm behind the drone assembly and the plane/flight assembly transition. This depicts how the four rotors used for VTOL would transmit the power to the flight propeller and turn itself off and vice-versa. The transition velocity is 18 m/s.

Figure-11 Flight Transition Chart [Towards Right]



4. Results and Discussion

Computational Fluid Dynamics Analysis

CFD analysis of the UAV design has been done to check for the results. The velocity of 22m/s was considered at AOA=2.5º. The velocity contours obtained in Fig.12 depicted the upwash at the tip converges into proverse yaw due to the geometric twist provided. UAV generates a lift of 55.5 N for the given conditions.

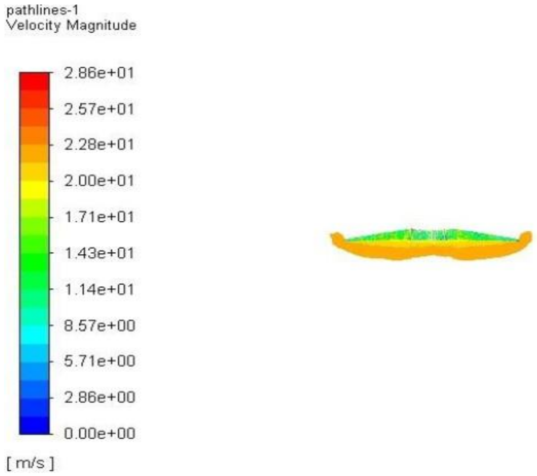


Figure-12. Upwash Formation at tips

Structural Analysis

The UAV model underwent finite element analysis using ANSYS simulation to anticipate potential failure modes and structural vulnerabilities. The resulting Von Mises stress distribution provided a detailed understanding of stress distribution throughout the structure.

Internal Structure

With the MOC of balsa for ribs and Al6061 T6 for rods, the internal framework was subjected to a cantilever test to assess its mechanical performance. A load of 27N was applied at the tip chord, while fixed support was provided at the root chord to simulate extreme conditions. Analysis of the Von Mises stress distribution, depicted in Fig. 13, revealed a peak stress of 88.06 MPa localized on the aluminum rods. The material's tensile yield strength is 276 MPa, so the achieved FOS is approximately 3.13. This indicates a safe structural design, ensuring operational stresses remain within acceptable limits.

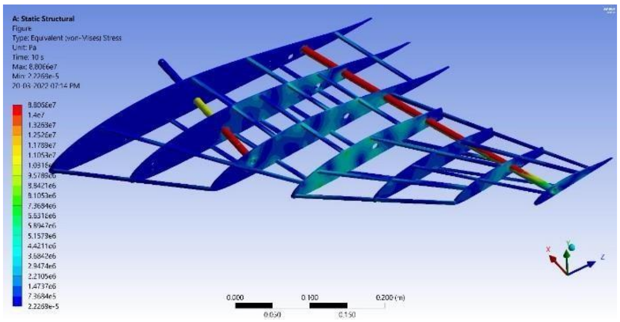


Figure-13. Von-Mises's stress distribution-Half section of UAV

Motor Mount Rods

The motor mounting rods, with the MOC Al6061 T6, were analyzed with a point load of 13.5N evenly at both ends of the rods, with the center point serving as a fixed support. In the equivalent Von Mises stress plot (Fig. 14), it was observed that the maximum stress value registered approximately 11 MPa, giving a higher FOS.

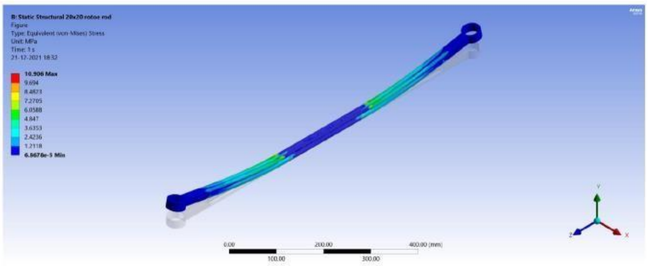


Figure-14 Von-Mises's stress distribution-Support Rod

Landing Stand

The landing stand made of ABS (Acrylonitrile Butadiene Styrene) plastic, exhibits a yield strength ranging between 37-48 MPa. A remote load of 13.5N was applied at the upper surface to examine its structural performance, while the lower end was kept fixed support. Upon analysis, the resultant Von Mises equivalent stress reached a maximum value of 7.1 MPa giving minimum FOS of 5 as shown in Fig.15. This result suggests that the landing stand remains well within its structural resilience threshold under operational loads.

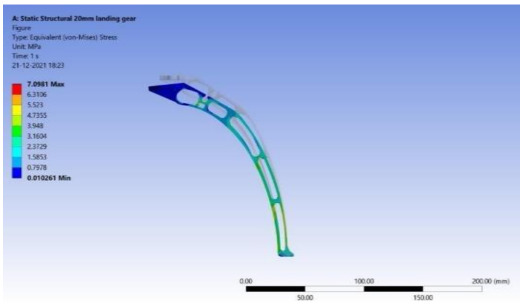


Figure-15. Von-Mises's stress distribution-Landing Stand

Stability Analysis

The value of CG obtained from SolidWorks is x= 22.6 cm from the leading edge of the fuselage, and the value of NP from XFLR is x= 24.68 cm from the leading edge of the fuselage. This means CG is ahead of NP, which is a criterion for achieving stable flight. This condition creates a pitch- down moment required to achieve level flight. The negative slope graph obtained for Cm vs. AOA for the entire UAV confirms the stability of the aircraft (Fig. 16).

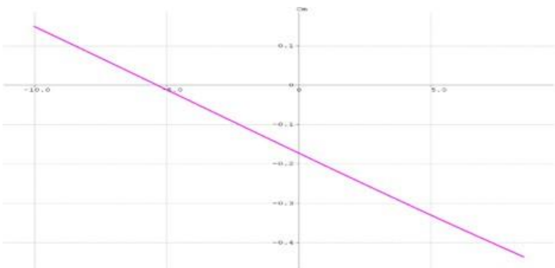


Figure-16 Cm vs AOA for entire UAV

Lift Distribution

The UAV follows the flying wing configuration but with an innovation in it. The incorporation of airfoil-shaped fuselage creates a deviation from ideal Prandtl bell shaped distribution curve, however the span ranging in the wing region follows the trend (Fig. 17).

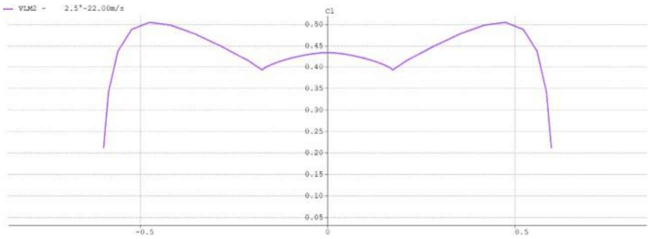


Figure-17 Lift Distribution along the span

5. Scope and Application

This design features a multi-rotor flying wing configuration Quadplane UAV specifically constructed for agricultural surveying. The objective of this design initiative was to develop a flexible and efficient UAV capable of performing the following agricultural surveying functions:

- Crop monitoring and health assessment
- Mapping of soil moisture and temperature
- Crop yield prediction and analysis
- Precision farming and variable rate application
- Agricultural land mapping and surveying

The UAV is intended for use in various agricultural settings, including but not limited to:

- Large-scale farming operations
- Precision agriculture
- Organic farming
- Animal monitoring
- Environmental monitoring

The UAV's design and capabilities make it an ideal solution for agricultural surveying, offering benefits such as high-resolution aerial sensors and imaging, improved productivity, reduced labor costs, enhanced crop management and decision-making, and increased agricultural productivity while minimizing waste **[6]**.

6. Limitations and Future Work

Although this study successfully designed and tested a multi-rotor flying wing configuration Quadplane UAV for agricultural surveying, several limitations and opportunities for future research have been identified.

6.1. Limitations:

1. **Performance Assessment:** The performance evaluation in this study was primarily theoretical, relying on simulations. Future research should focus on empirical validation through wind tunnel tests and flight tests.
2. **Material Selection:** The optimization of the UAV's weight and structural integrity was based on theoretical material properties. Actual material selection and testing are needed to confirm the durability and practicality of the design.

3. **Sensor Integration:** This research mainly focused on the UAV platform design and did not address the integration and calibration of sensors specific to agricultural surveying. Future studies should explore effective sensor configurations and integration techniques.
4. **Autopilot System:** The autopilot system was not fully developed or integrated within the design framework. Future efforts should prioritize developing a reliable autopilot system to achieve stable and efficient flight operations.

6.2. Future Work

1. **Wind Tunnel and Flight Testing:** Conduct wind tunnel tests and flight testing to validate the aerodynamic efficiency and stability of the UAV design.
2. **Integration and Calibration of Sensors:** Investigate and integrate sensors envisioned for agricultural surveying, such as multispectral or hyperspectral cameras, and calibrate these devices for accurate data acquisition.
3. **Development of Autopilot System:** Design and integrate a fully functional autopilot system to ensure stable and efficient flight, including obstacle avoidance and autonomous navigation capabilities.
4. **Materials and Manufacturing Optimization:** Research advanced materials and manufacturing processes, such as 3D printing, to further reduce weight and enhance structural rigidity.

Further research should be conducted in these areas to advance and improve the multi-rotor flying wing configuration Quadplane UAV for effective and efficient agricultural surveying applications.

7. Conclusion

This work successfully designed a multi-rotor flying wing configuration Quadplane UAV specifically for agricultural surveying. The design underwent rigorous numerical assessments to evaluate its structural strength, aerodynamic performance, and stability. The results of these evaluations confirmed the design's viability: structural load analysis demonstrated the UAV's durability under various flying conditions, while CFD simulations validated its aerodynamic efficiency in generating lift and thrust. Additionally, theoretical confirmation using Prandtl's theory further reinforced the aerodynamic soundness of the design. The multi-rotor flying wing configuration Quadplane UAV offers substantial advantages for agricultural surveying, with the potential to revolutionize the field by delivering accurate, high-resolution data for crop monitoring, soil analysis, and yield prediction.

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9. Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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