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Conceptual Design and Initial Sizing of a Tiltrotor Aircraft: A Comprehensive Analytical Approach

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INTRODUCTION & AIM

The increasing demand for aircraft capable of both vertical takeoff and landing (VTOL) and efficient high-speed cruise has led to the development of tiltrotor configurations, which combine the hover capability of rotorcraft with the aerodynamic efficiency of fixed-wing platforms. These aircraft operate across multiple flight regimes: hover, transition, and forward flight, each governed by different aerodynamic principles. Owing to this hybrid nature, neither conventional fixed-wing nor rotorcraft design methodologies alone are sufficient to accurately represent tiltrotor performance, as fixed-wing approaches emphasize cruise efficiency while rotorcraft methods focus on vertical flight. Treating these regimes independently often leads to inconsistencies, particularly during transition. To overcome this limitation, this study develops and applies a unified preliminary design framework that integrates VTOL performance, transition dynamics, and fixed-wing cruise within a single mission-based sizing methodology. Aircraft sizing is performed using a mission-segment fuel fraction analysis that integrates Breguet range and endurance relations for fixed-wing cruise with a known-time fuel burn equation for VTOL, hover, and transition phases, ensuring consistency across all flight regimes. Using this approach, a conceptual multirole tiltrotor aircraft is designed for utility and search-and-rescue (SAR) operations based on a mission profile that includes vertical takeoff, transition, climb, cruise, loiter, hover, and return phases.

The aim of this work is therefore to establish a coherent and realistic conceptual design methodology for tiltrotor aircraft by combining fixed-wing and rotorcraft principles into a unified framework. This integrated approach ensures consistent performance estimation across all flight regimes and supports early-stage sizing and configuration development for a multirole tiltrotor aircraft, providing a strong foundation for further detailed design and optimization.

METHOD

Concept Selection and Aerodynamic Estimation: Multiple tiltrotor configurations were evaluated through trade studies considering structural complexity, aerodynamic efficiency, and operational feasibility. A twin tiltrotor with tilting rotor modules was selected as the most balanced solution. Key aerodynamic parameters, including wetted area ratio, aspect ratio, and lift-to-drag ratio (L/D = 12.3), were estimated using historical data and comparable aircraft, while airfoil performance was analyzed to finalize the wing and tail sections.

Mission-Based Fuel and Weight Analysis: A detailed mission-segment analysis was conducted to estimate fuel consumption across all flight phases. Appropriate models were applied for different regimes, allowing accurate calculation of segment-wise fuel fractions. This was followed by a refined weight estimation using a segment-by-segment fuel burn approach for different mission scenarios, ensuring realistic prediction of takeoff weight and fuel requirements.

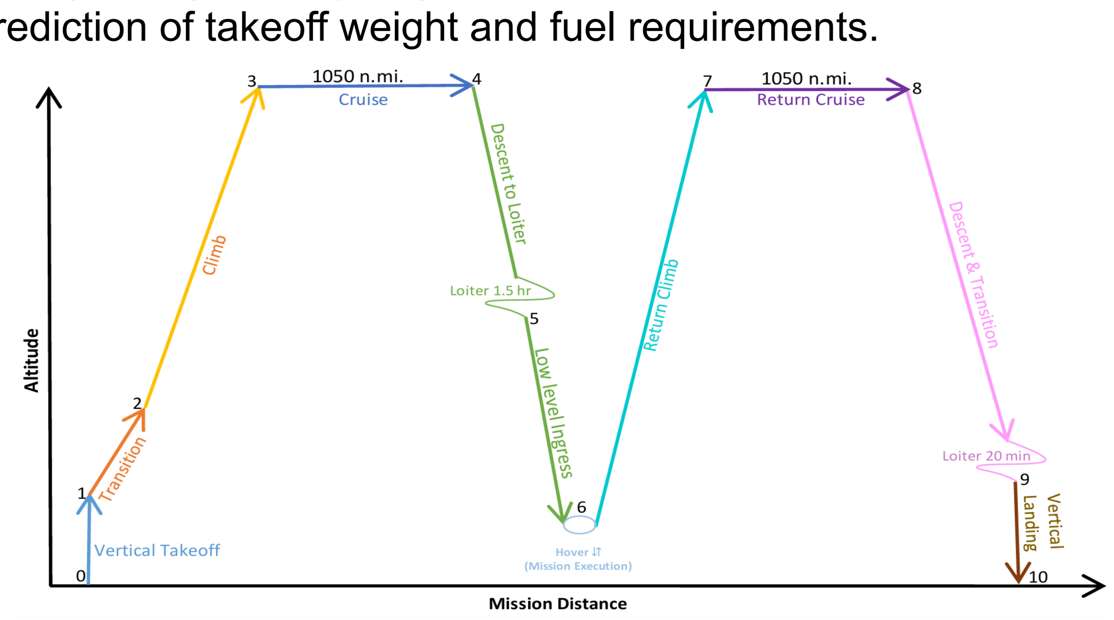

Figure 1. Mission Profile

Performance Sizing and Constraint Analysis: Key performance parameters such as power-to-weight ratio and wing loading were determined by evaluating multiple constraints including cruise, climb, loiter, and ceiling conditions. The final design values were selected to satisfy all operational requirements without oversizing, ensuring a balanced trade-off between performance, efficiency, and structural feasibility.

Geometry, Stability, and System Design: The aircraft geometry, including wing, fuselage, and tail dimensions, was determined using empirical relations and standard design practices such as tail volume coefficients. Control surfaces were sized to ensure adequate stability and controllability, while landing gear configuration and structural considerations were defined based on load distribution and operational requirements. Fuel system sizing was also performed to ensure sufficient storage volume with practical allowances.

Iterative Design and Validation: The overall design process followed an iterative approach, where aerodynamic, performance, and weight parameters were continuously refined using computational tools such as CAD modeling and aerodynamic analysis software. This ensured consistency across all design aspects and improved the feasibility of the final conceptual configuration.

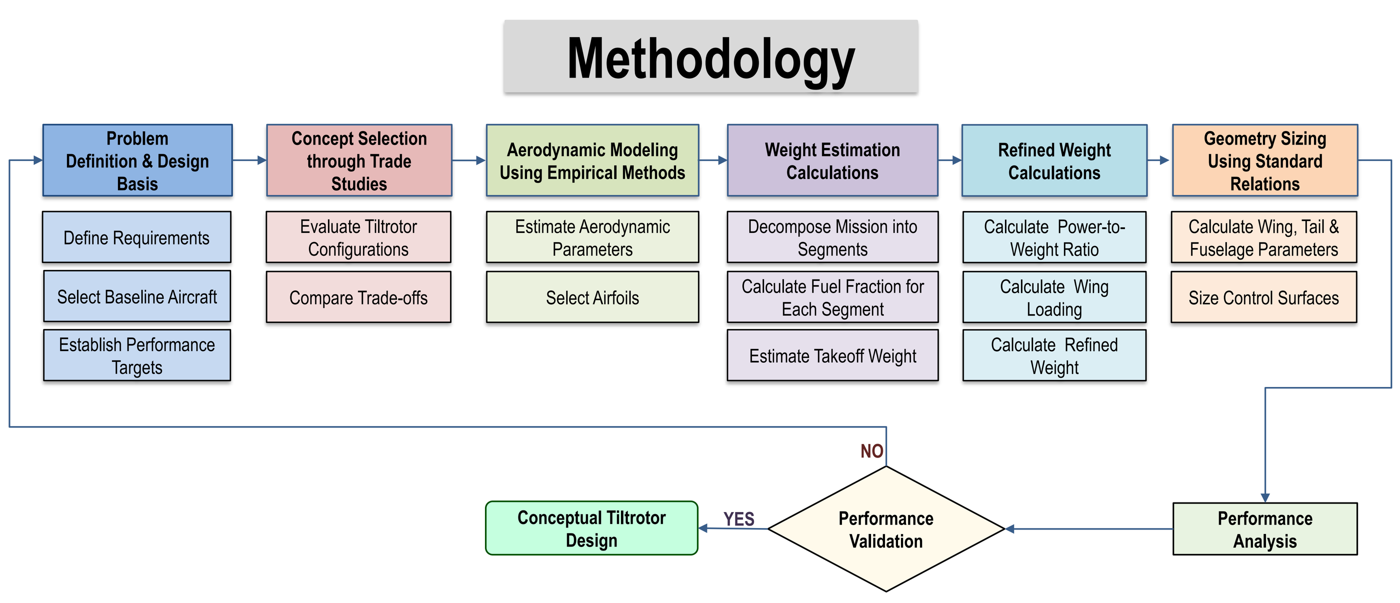

Figure 2. Methodology Flowchart

RESULTS & DISCUSSION

The conceptual design resulted in a feasible multirole tiltrotor aircraft configuration that satisfies the defined mission requirements by balancing aerodynamic performance, weight estimation, and system design. The final geometry, including fuselage, wing, and tail parameters, establishes a structurally practical and aerodynamically efficient layout suitable for both VTOL and forward flight. Performance parameters such as cruise capability, range, power requirement, and wing loading demonstrate that the aircraft can effectively achieve mission objectives while maintaining operational efficiency. Airfoil analysis supports the selection of appropriate wing and tail sections, ensuring favorable lift, drag, and stability characteristics across different flight regimes.

Overall, the results validate the effectiveness of the unified design approach, providing a consistent and realistic conceptual tiltrotor configuration that can serve as a strong foundation for further detailed design and optimization. The performance results summarize key parameters such as speed, range, power requirements, and loading, demonstrating the aircraft's capability to meet the defined mission objectives.

Parameter	Value
Maximum Takeoff Weight (MTOW)	59,724 lb
Engine Power Requirement	6,987 hp
Power-to-Weight Ratio (P/W)	0.23 hp/lb
Wing Loading (W/S)	79.5 lb/ft²
Maximum Lift-to-Drag Ratio (L/D)	12.3
Maximum Cruise Speed	280 knots
Maximum Cruise Altitude	24,000 ft
Mission Range	2100 nmi
Loiter Endurance	1.5 hours (+ additional 30 min reserve loiter)
Payload Capacity	14 personnel + 4 crew
Stall Speed	163.5 ft/s

Table 1. Performance Parameters

Fuselage Parameters		
Parameter	Value	
Fuselage Diameter	7 ft	
Fuselage Length	56.20 ft	
Wing Parameters		
Parameter	Value	
Wing Area (S)	751.23 ft²	
Aspect Ratio (A)	6.38	
Wing Span (b)	69.23 ft	
Chord(C)	10.85 ft	
Mean Aerodynamic Chord (c)	10.85 ft	
Tail Parameters		
Parameter	Horizontal Tail	Vertical Tail
Aspect Ratio (A)	4	1.7
Taper Ratio (λ)	0.33	0.31
Sweep Angle (Λ)	25°	25°
Area (S) [ft^2]	261	145.17
Mean Aerodynamic Chord ($\bar{c}$)	8.756	10.08
Span (b) [ft]	32.31	15.7
Root Chord [ft]	12.14	14.1
Tip Chord [ft]	4	4.376

Table 2. Sizing Parameters

From the XFLR5 analysis, NACA 23015 was selected for the wing due to its superior aerodynamic performance compared to NACA 23018. It provides a higher lift coefficient with a better lift-to-drag ratio in the operating range. The airfoil also exhibits smoother, more predictable stall characteristics. Additionally, it maintains lower drag at moderate angles of attack, improving overall efficiency. For the tail, NACA 0012 was chosen over NACA 0010 based on its balanced aerodynamic behavior. It offers slightly higher lift with minimal drag penalty across the working range. The moment coefficient variation remains stable, ensuring a reliable control response. Its thicker profile also provides better structural strength and easier integration of control mechanisms.

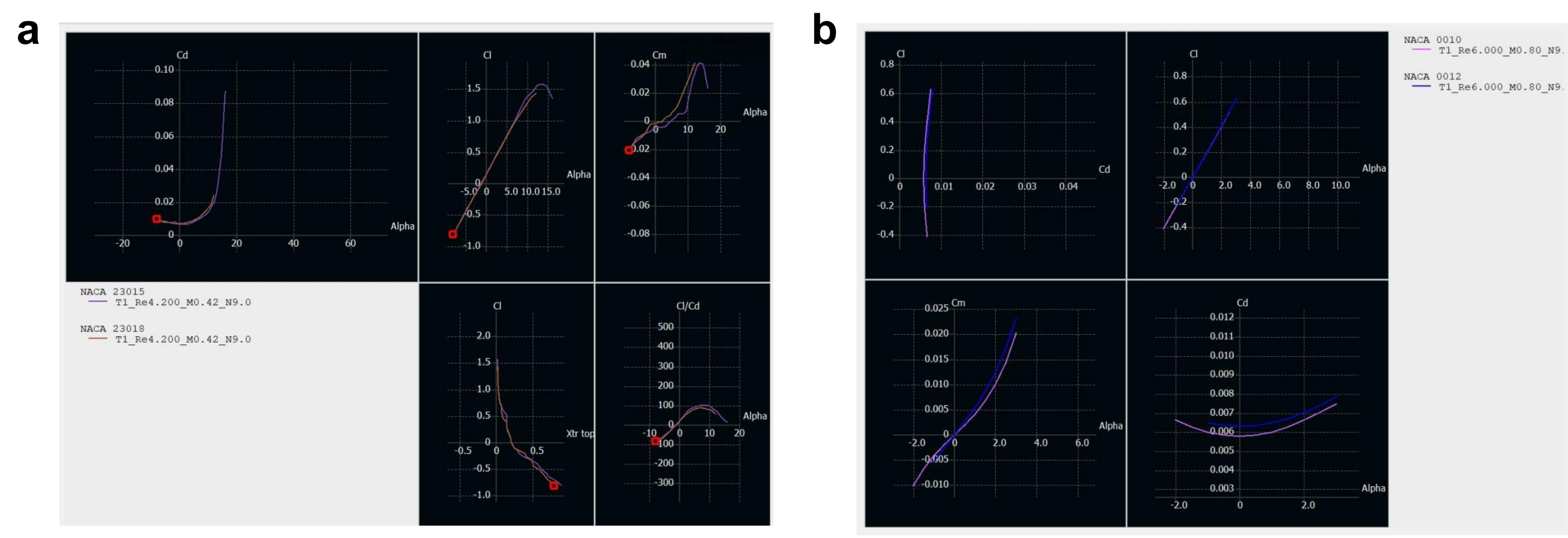

Figure 3. (a) Wing Airfoil Analysis; (b) Tail Airfoil Analysis

The CAD model is developed based on the calculated geometric, aerodynamic, and performance parameters obtained from the conceptual design process, ensuring consistency with all sizing and configuration decisions. It translates the analytical results into a detailed 3D representation of the aircraft, reflecting the integrated design of the fuselage, wing, tail, and overall system layout.

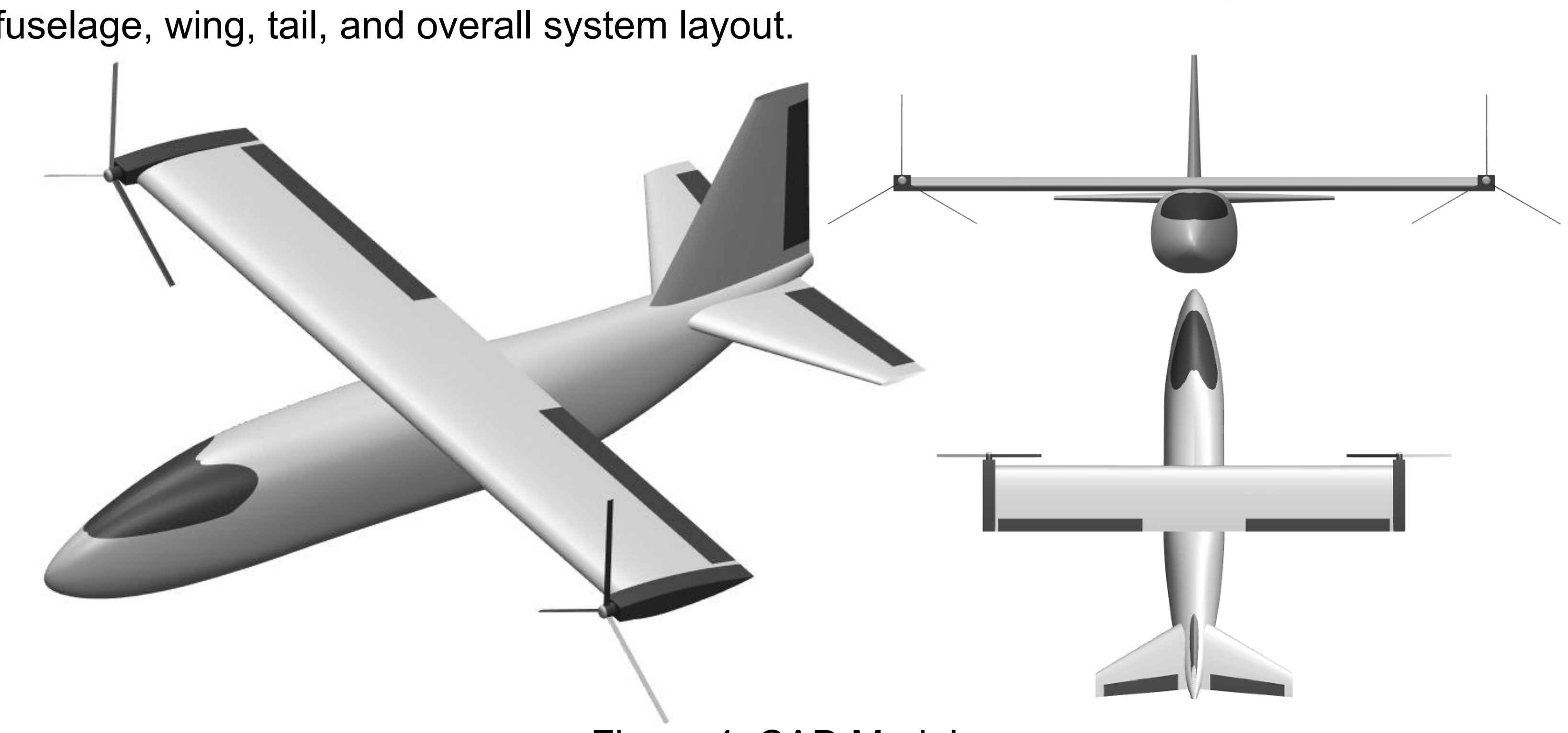

Figure 4. CAD Model

CONCLUSIONS

This study demonstrates the effectiveness of a unified conceptual design approach for tiltrotor aircraft, where VTOL and fixed-wing performance are integrated within a single framework. The resulting design achieves a balanced configuration with a maximum takeoff weight of approximately 59,700 lb, a power requirement of about 7000 hp, and a wing loading of 79.5 lb/ft², enabling efficient operation at 280 knots over a range of 2100 nmi.

The selected aerodynamic configuration, including an estimated L/D of 12.3, supports efficient cruise while maintaining acceptable performance in low-speed flight regimes. The geometry and system-level design ensure compatibility with multirole operations such as troop transport and SAR missions.

The use of mission-segment-based analysis improves the accuracy of fuel and weight estimation across different flight conditions. The overall design demonstrates a practical balance between performance, efficiency, and feasibility.

This work establishes a strong basis for further detailed design, aerodynamic optimization, and experimental validation.

FUTURE WORK/ REFERENCES/ACKNOWLEDGMENT

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