Tail Sitter VTOL Project Report

Name: Rohan Suresh Mekala
Roll Number: 22B2106

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1 Introduction

A Tail Sitter Vertical Take-Off and Landing (VTOL) aircraft is a hybrid aerial vehicle capable of taking off and landing vertically like a helicopter while transitioning to efficient horizontal flight like a conventional airplane. The unique feature of a Tail Sitter VTOL is that it operates in two distinct flight regimes, utilizing aerodynamic lift during horizontal flight and thrust-based lift during vertical takeoff and landing. This dual capability makes Tail Sitter VTOLs highly versatile and suitable for various applications, such as cargo transport, surveillance, and search-and-rescue operations.

2 Modes of Operation for the Tail Sitter

The tail sitter VTOL aircraft operates in multiple modes to achieve versatile flight capabilities. These modes enable the aircraft to efficiently switch between hovering and forward-flight configurations, providing flexibility for various missions. The key modes of operation are:

1. **Hover Mode:**
   In this mode, the tail sitter behaves like a traditional rotorcraft. The aircraft is oriented vertically, using its rotors to generate lift and maintain stability. This mode is typically used for takeoff, landing, and stationary tasks such as surveillance or inspection.

2. **Forward Flight Mode:**
   Transitioning into forward flight, the tail sitter acts like a fixed-wing aircraft. The rotors provide thrust, while the wings generate lift for efficient cruising. This mode is optimal for covering long distances quickly and conserving energy.

3. **Forward Transition Mode:**
   This mode represents the intermediate phase between hover and forward flight. The aircraft gradually tilts forward, transferring the lift generation from the rotors to the wings. Proper control during this phase ensures a smooth and stable transition.

4. **Backward Transition Mode:**
   The backward transition mode occurs when the aircraft shifts from forward flight to hover. The aircraft tilts upward, redistributing lift from the wings back to the rotors. This mode is critical for preparing the vehicle for a stable hover or vertical landing.

3 Reason for Selecting Configuration

The first VTOL that I designed was a 4+1 configuration. The 4+1 VTOL configuration, designed for simplicity and reliability, combined four vertical lift motors in a quadcopter arrangement with a forward thrust motor for horizontal flight. The design avoided the complexity of tiltrotor mechanisms, reducing maintenance requirements and ensuring mechanical robustness. The airframe featured a NACA 4412 airfoil for the main wing, chosen for its excellent lift-to-drag ratio and aerodynamic efficiency, and carbon fiber for structural components to optimize weight and strength. Stability analysis in XFLR5 confirmed positive longitudinal and lateral stability, with a balanced angle of attack of -0.6° and a neutral point 196 mm from the leading edge.

However, the configuration faced several challenges. Unused quad motors caused significant drag during forward flight, reducing efficiency. The transition between hover and cruise modes required precise synchronization, complicating control systems. Energy consumption during transitions limited endurance, and thermal stress caused PLA motor clamps to fail during tests. Additionally, GPS limitations disrupted positional accuracy in modes like QLOITER. Despite demonstrating stable flight, these issues constrained performance, particularly in endurance and operational versatility. These challenges led to the adoption of the Tail Sitter configuration, which eliminated quad motors, improved aerodynamic efficiency, simplified transitions, and addressed the limitations of the 4+1 design.

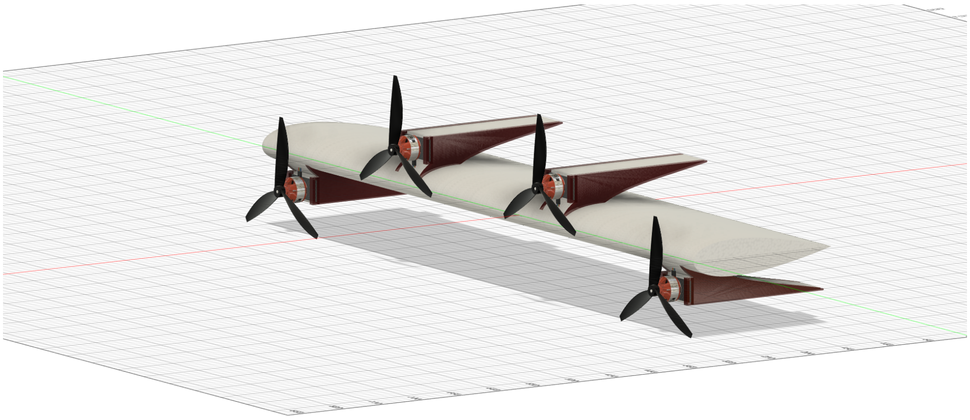
4 Design

The design of my Tail Sitter VTOL prototype was inspired by the Quadshot, a novel VTOL platform. The Quadshot combines the maneuverability of a quadrotor with the range and efficiency of a fixed-wing aircraft in a tail-sitter configuration. Its design allows for seamless vertical take-off and landing (VTOL) while maintaining efficient horizontal flight, facilitated by differential thrust and aerodynamic control surfaces (elevons).

Key features include a modular and extensible design that supports diverse missions by integrating open-source Paparazzi software and custom avionics. The airframe uses a lightweight, durable structure with symmetric airfoils for stable inverted flight and a high lift-to-drag ratio. Control systems enable smooth transitions between hover, forward flight, and aerobatic modes, eliminating the need for complex tilt mechanisms.

Quadshot's innovative use of affordable materials, simplified assembly, and extensible electronics framework inspired my own Tail Sitter VTOL development. Its ability to achieve autonomous transitions and handle various flight conditions demonstrated the potential of the tail-sitter design to overcome the limitations of conventional multirotor or fixed-wing VTOL configurations, such as reduced endurance and complex mechanisms. This paper served as a crucial technical reference for improving my design's aerodynamic efficiency, control algorithms, and modularity.

5 CAD



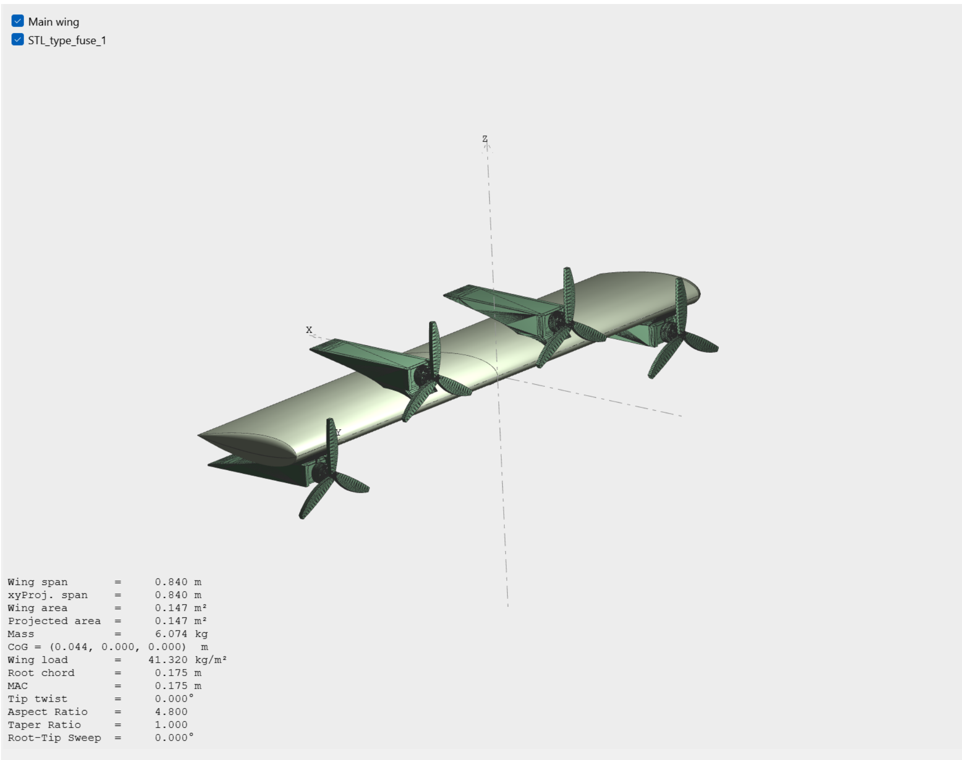
6 Reason for Choosing Flow5

The decision to use Flow5 instead of its predecessor XFLR5 for the aerodynamic analysis and design of the tail sitter is driven by the unique requirements of this project. While XFLR5 is robust and resilient, its limitations make it less suited for complex geometries like those of a tail sitter. These limitations include the inability to handle general 3D surfaces with non-quadrilateral shapes and its uniform panel method, which struggles to model areas with sharp pressure gradients effectively.

In contrast, Flow5 resolves these challenges with its Galerkin-type triangular formulations. The ability to mesh surfaces with triangular panels makes Flow5 ideal for handling the intricate geometry of the tail sitter, particularly at the fuselage-wing intersections, where conventional methods in XFLR5 fall short. Furthermore, Flow5's support for uniform sources and linear doublet distributions enhances its capability to model complex configurations, such as those involving winglets, flap deflections, or sharp transitions in aerodynamic surfaces.

Additionally, Flow5 provides comparable results to XFLR5 for simple configurations while excelling in scenarios with high geometric complexity. For the tail sitter design, which involves transitions between hover and forward flight modes, accurate modeling of these complex aerodynamic interactions is crucial. By using Flow5, the design process benefits from more reliable and precise predictions, enabling better performance optimization and control stability for the tail sitter.

Flow5 provides significant advantages over XFLR5 for fuselage-related aerodynamic analysis, making it ideal for the tail sitter design. Unlike XFLR5, which lacks tools for meshing wing-fuselage connections and cannot account for VLM panel influences on fuselage Dirichlet panels, Flow5 uses OCCT libraries for precise meshing and modeling with source and doublet panels. It supports importing complex fuselage geometries in formats like STEP, IGES, and STL, with STEP ensuring high geometric accuracy. Flow5 also enables the creation of triangular surface meshes for accurate modeling of fuselage-wing intersections, critical for the tail sitter. Additionally, STL models can be scaled, translated, or rotated within Flow5, and preprocessing in CAD software ensures smooth surfaces for reliable analysis. These features make Flow5 superior for handling complex wing-fuselage interactions. In the context of this tail sitter design, I have modeled the pylons, motors and propellers as the fuselage to estimate the drag that they incur upon the VTOL system.



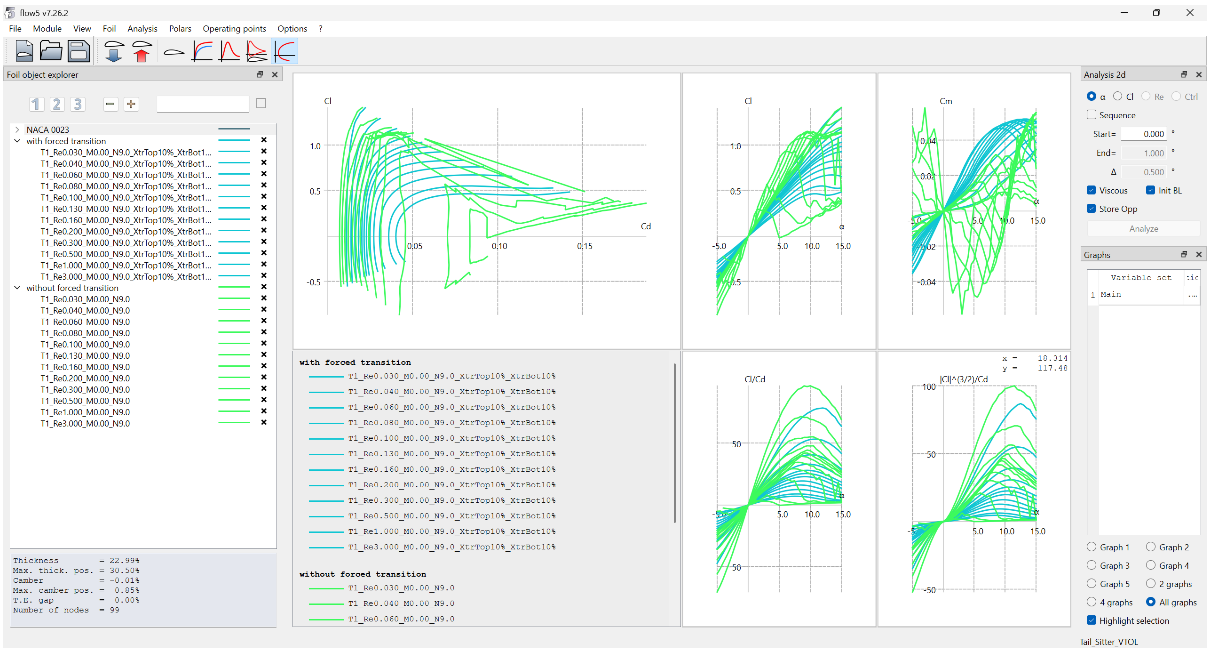
7 Flow5 Analysis

The main wing is a 1m span 0.175m average chord rectangular planform without any taper. The center section, which conforms to the airfoil shape, is meant to house the avionics required by the VTOL. The main wing utilizes a symmetric NACA 0023 airfoil for high maximum lift coefficient and glide ratio. There are mainly two reasons behind choosing a symmetric airfoil:

1. The presence of camber in the airfoil would increase the differential thrust requirement and would unnecessarily complicate basic modes such as hovering.

2. Symmetric airfoils are chosen to maintain stable flight characteristics during inverted operations, minimizing any adverse effects.

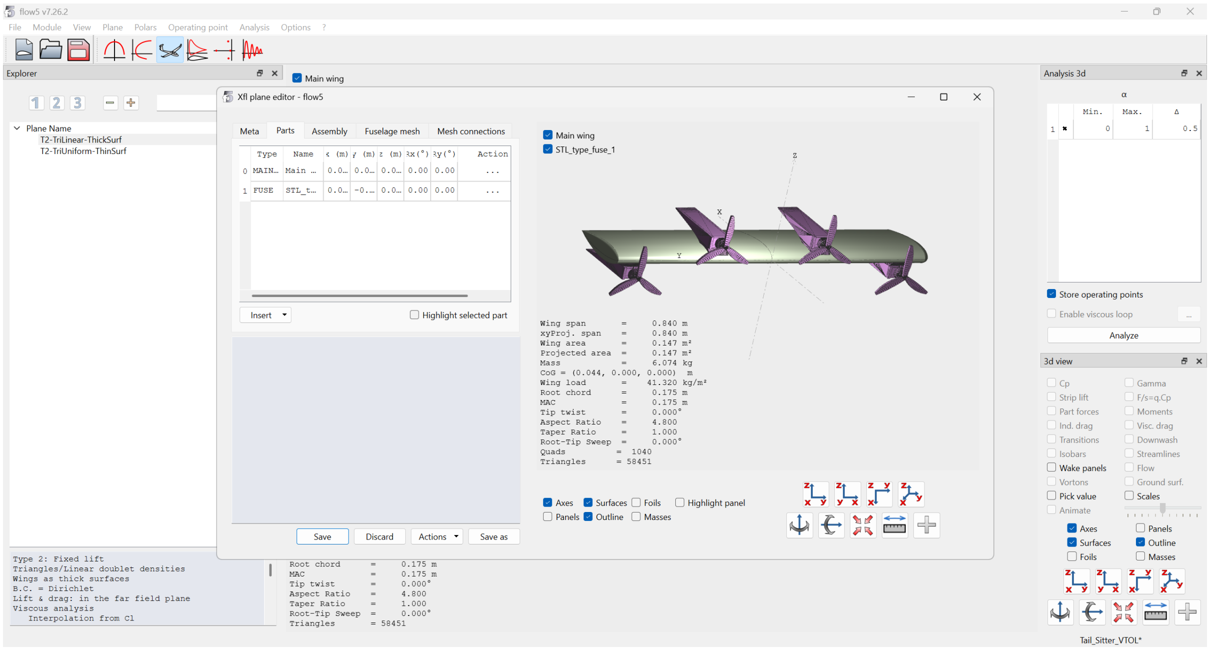
The airfoil analysis was conducted by incorporating forced transition at 10% of the chord to account for manufacturing imperfections due to the use of foam and also to effectively model the turbulent swirl off the propellers. The results obtained indicate an increase in the lift characteristics as well as increased longitudinal stability.



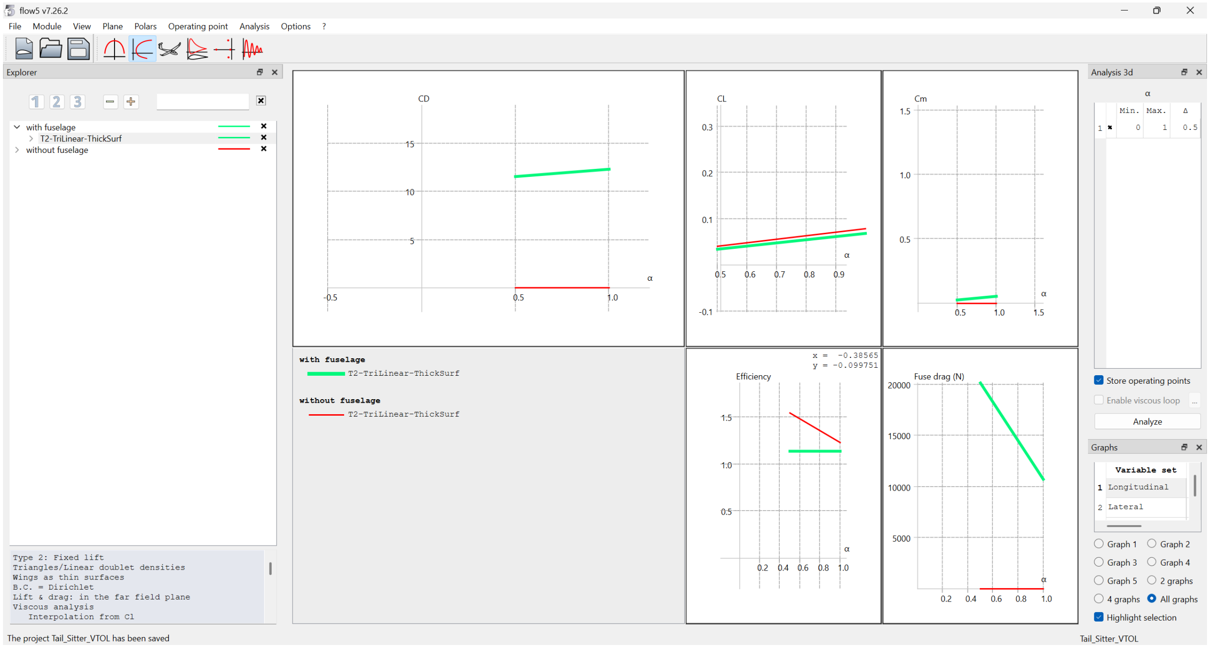
The above figure describes the aerodynamic performance of the entire vehicle. The pitching moment is low throughout the forward flight envelope, reducing trim requirements through differential thrust or surface deflection. Furthermore, the maximum Lift-to-Drag ratio point ($\alpha = 10°$) provides a CL of 0.8, ideally matched to provide adequate lift for the vehicle and a light (150gm) payload.

An important idea implemented in the Quadshot paper was to add a sufficient gap at the trailing edge (approximately 1.8% of the chord length) to further account for manufacturing defects. However, this has been excluded from my analysis as Flow5 requires that the wing must form a closed solid to cut the fuselage shell for the OpenCascade API that it utilizes to work. Hence, to account for the wing-fuselage interactions and the drag incurred due to the fuselage, we have slightly relaxed the correction analysis of manufacturing defects at the trailing edge.

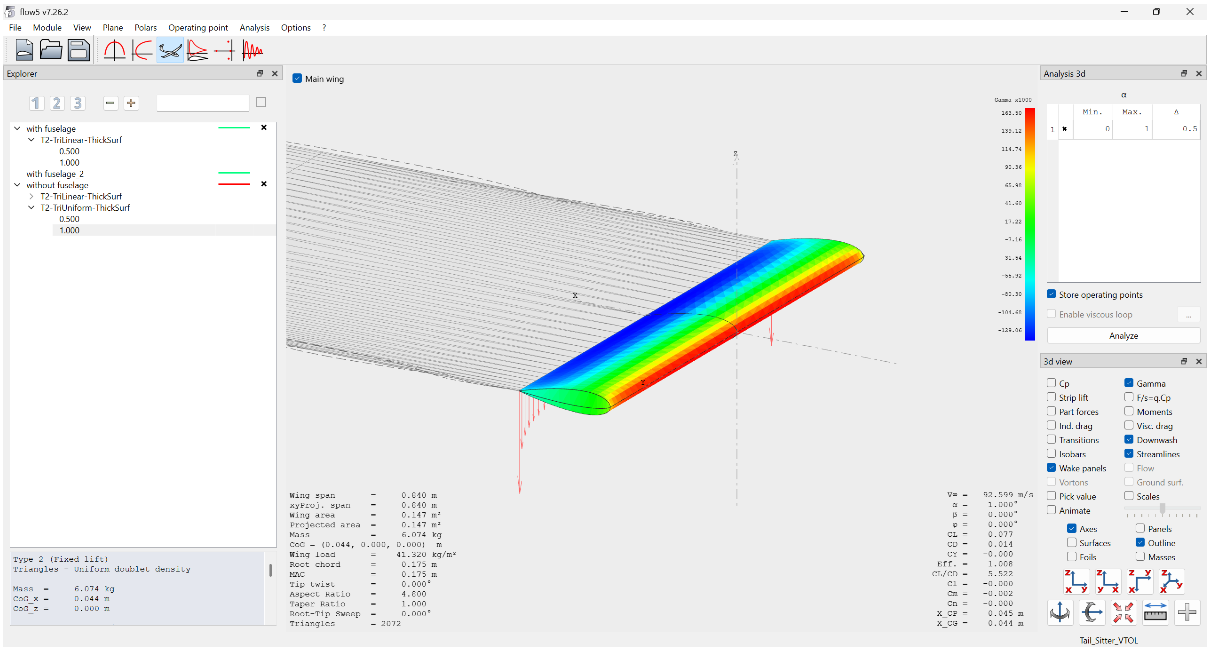
The swept and tapered vertical pylons are developed using the same NACA 0023 airfoil with 0.175 m average chord and a 0.04 m span to ensure an almost continuous and smooth flow profile from the main wing onto the pylons. The sizing is designed to ensure a stable base for landings, sufficient clearance for the propeller blades, and a long enough moment arm to enable rapid pitch maneuvers. Moreover, the vertical pylons contribute lateral forces to counter side-slip during turns and support relaxed spiral stability. The staggered quadrotor configuration enhances pitch inertia and propeller damping, resulting in improved controllability. Additionally, it provides a clear central area beneath the wing, ideal for unobstructed placement of the avionics and other payloads.

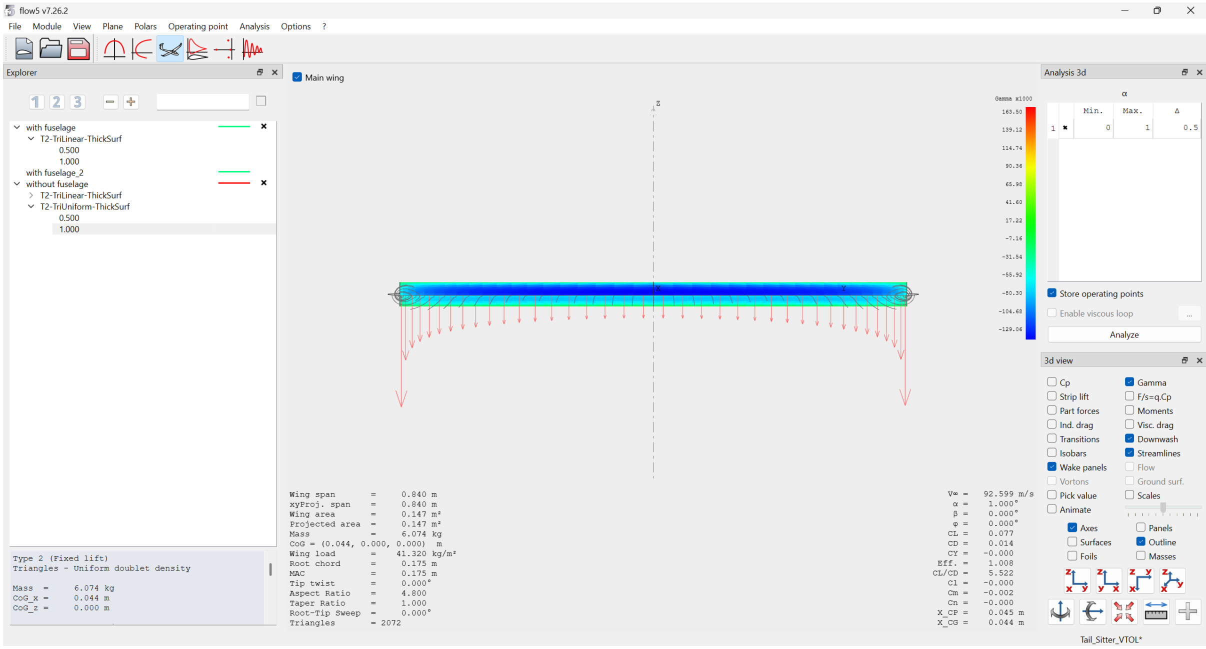


Using the fuselage modeling capabilities of Flow5, I was able to compare the aerodynamic parameters with and without the fuselage. As expected, the presence of the fuselage increases drag, with the drag value for the fuselage alone shown as approximately 20,000 N in the analysis. However, this magnitude is clearly far-fetched for the given configuration and likely stems from a combination of factors, including potential inaccuracies in mesh resolution, improper settings for the viscous loop, or incorrect boundary condition assumptions. These issues often arise in preliminary computational setups, particularly when handling complex geometries.



Despite this discrepancy, the analysis still provides a useful starting point for evaluating the relative contributions of the fuselage to overall drag. It highlights the importance of fuselage modeling in determining aerodynamic performance and offers a framework for refining the setup to achieve more realistic results in subsequent iterations.





8 Mass Distribution

For the type-1 fixed speed analysis, modeling the wings as thick surfaces, using the Uniform Density Triangular Panels, and including the skin friction drag due to the fuselage, the various component masses were distributed as follows:

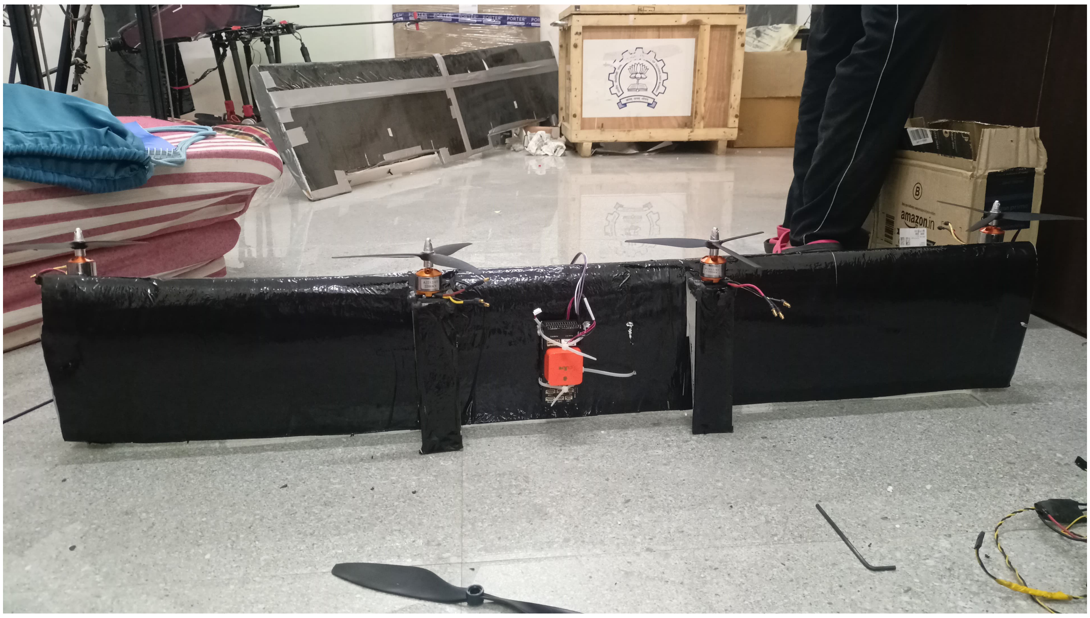
	Mass (kg)	x (m)	y (m)	z (m)	Description
1)	0.15	0.044	0	0	Payload
2)	4.7271	0.044	0	0	Polystyrene
3)	0.6	0.044	0	0	Motors
4)	0.104	0.044	0	0	Propellers
5)	0.343	0.044	0	0	Controller
6)	0.15	0.044	0	0	Avionics

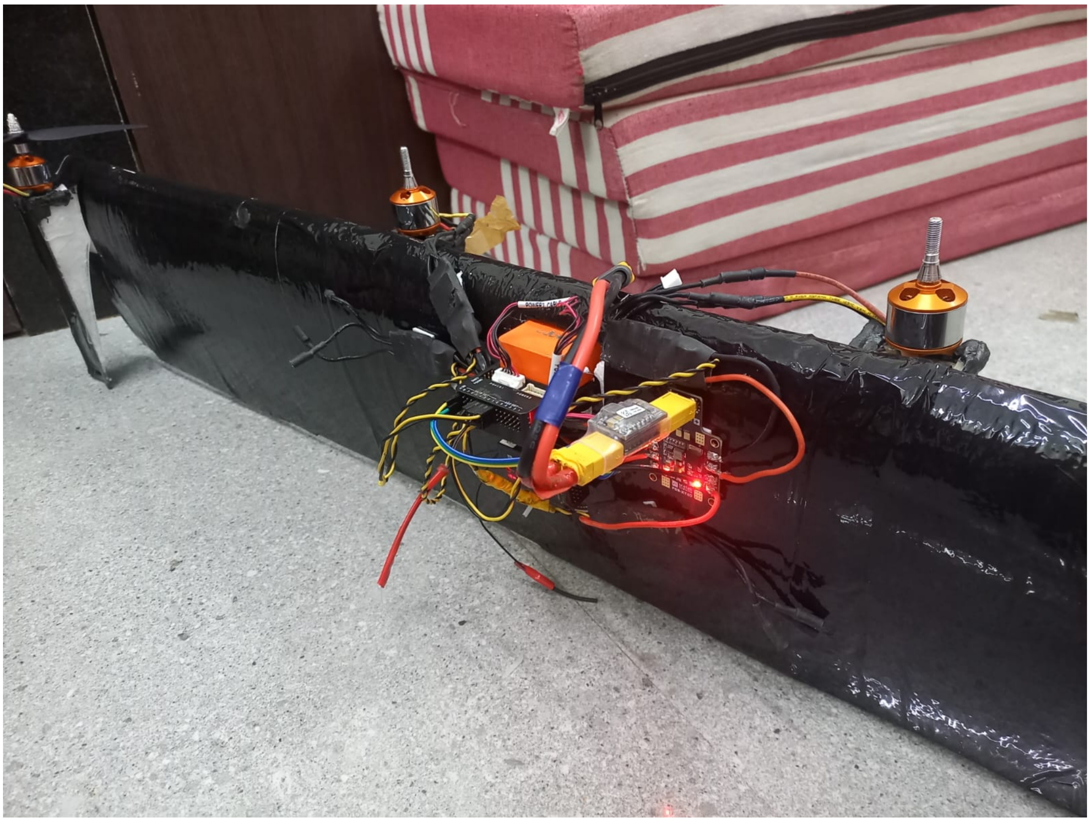
Table 1: Mass distribution of the tail sitter components.

The center of gravity has been placed at the quarter chord point to simplify our analysis.

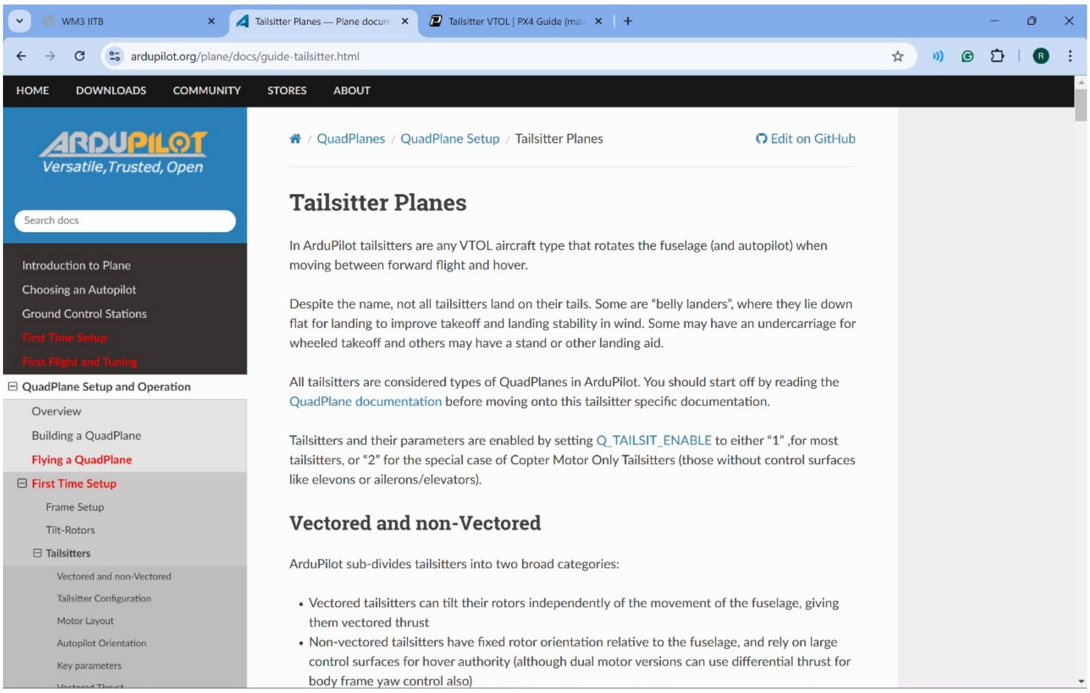
9 Mechanical Design of Prototype

The main wings and pylons have been manufactured using thermocol for the first iteration of the prototype. NACA 0023 airfoil shapes have been laser cut on acrylic and those have been used as guide curves to craft these wings and pylons from thermocol blocks using a custom-developed hot wire cutter. The thermocol pylons will be supported on either side with acrylic for further support during landing. The acrylic supports will have in-built slots to support carbon fiber plates upon which the motor mount will be attached using appropriate bolts. For smooth transitions, we will require a suitable motor propeller combination that can provide high RPM at low torque so that we can have sufficient forward velocity to overcome stall during transition. For this purpose, the tri-blade propellers have been chosen.



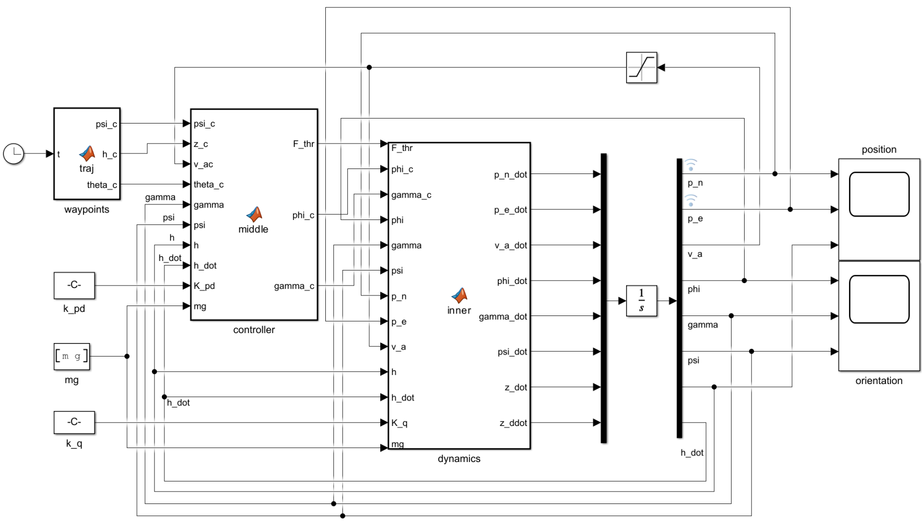


All the motors and ESCs have been calibrated and have been found to be completely operational and flight-ready. I have used an orange cube plus flight controller accompanied by a Power Distribution Board to differentially distribute power to the ESCs. I am currently investigating the inbuilt tail sitter configuration under the QuadPlane documentation in both ArduPilot and PX4 firmware to verify their compatibility with my prototype.



The onboard flight computer will be crucial in controlling the tail sitter, especially during the transition. The PID controller of ArduPilot/PX4 should be adequate to perform smooth transitions. The flight dynamics and control strategy, especially during the transition, have been modeled and simulated in MATLAB to confirm this.

10 MATLAB Modeling and Simulation



The complete Simulink model, as shown in the above image, integrates various subsystems crucial for simulating the tail sitter's dynamics and control. The model includes a waypoint block that defines the desired trajectory, a PD controller block for maintaining stability and control, and a dynamics block to simulate the physical behavior of the tail sitter. This setup allows for a detailed simulation of the tail sitter's performance across various flight modes, from hovering to forward flight, with an emphasis on waypoint tracking and stability.

waypoints

```
function [psi_c, h_c, theta_c] = traj(t)
    psi_c   = 0.0;
    h_c     = 5.0;
    theta_c = pi/2;
```

The waypoint block, depicted in the above image, is responsible for defining the desired trajectory of the tail sitter. It outputs parameters such as the target heading angle (ψ_c), target altitude (h_c), and pitch angle (θ_c) based on the predefined trajectory function. These parameters act as inputs to the controller, guiding the tail sitter toward the desired waypoints and ensuring smooth transitions between flight modes.

dynamics

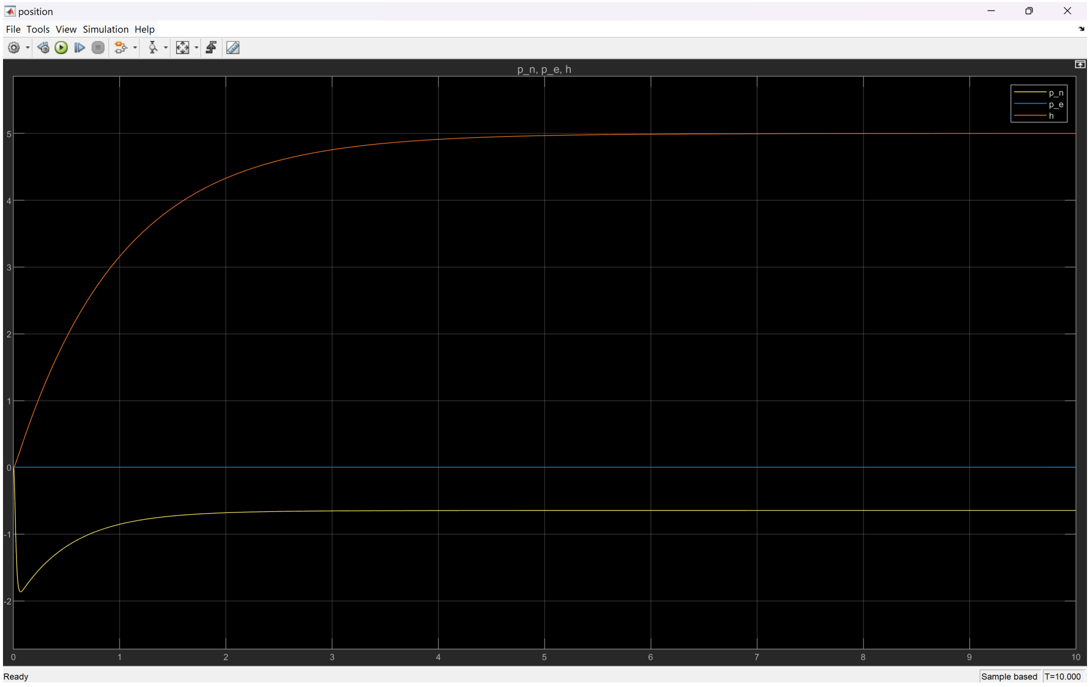
```
function [p_n_dot, p_e_dot, v_a_dot, phi_dot, gamma_dot, psi_dot, z_dot, z_ddot] = inner(F_thr, phi_c, gamma_c, phi, gamma, psi, p_n, p_e, v_a, h, h_dot, K_q, mg)
    k_psi   = K_q(1);
    k_theta = K_q(2);
    k_phi   = K_q(3);

    m = mg(1);
    g = mg(2);

    p_n_dot   = v_a * cos(psi) * cos(gamma) * k_psi;
    p_e_dot   = v_a * sin(psi) * cos(gamma) * k_psi;
    v_a_dot   = F_thr/m - g*sin(gamma);
    phi_dot   = k_phi   * (phi_c - phi);
    gamma_dot = k_theta * (gamma_c - gamma);
    psi_dot   = g * tan(phi)/v_a;
    z_dot     = h_dot;
    z_ddot    = sin(gamma) * (F_thr/m - g);
```

The tail sitter dynamics block, shown in the above image, models the physical behavior of the vehicle. It calculates state variables such as position, velocity, and orientation by solving the equations of motion. The block incorporates key aerodynamic and gravitational forces, as well as control inputs like thrust and attitude commands, to provide a realistic simulation of the tail sitter's behavior under different conditions.

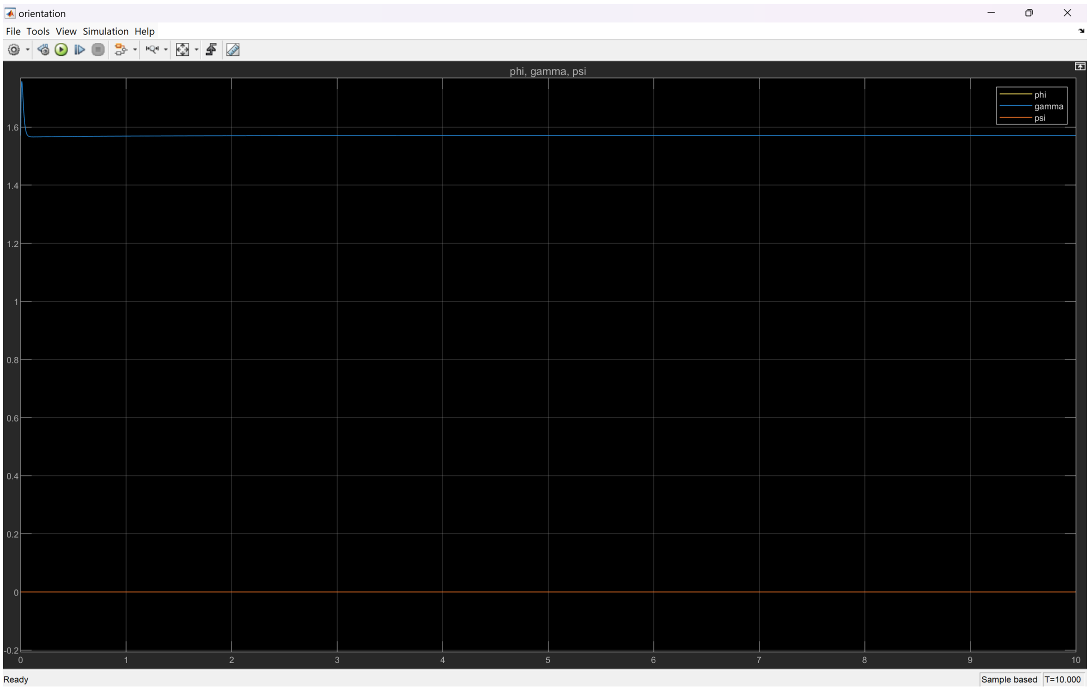
controller

```
function [F_thr, phi_c, gamma_c] = middle(psi_c, z_c, v_ac, theta_c, gamma, psi, h, h_dot, K_pd, mg)
    k_p_psi   = K_pd(1);
    k_p_theta = K_pd(2);
    k_d_theta = K_pd(3);
    k_p_z     = K_pd(4);
    k_d_z     = K_pd(5);

    m = mg(1);
    g = mg(2);

    phi_c   = k_p_psi * (psi_c - psi);
    gamma_c = theta_c + k_p_theta*(z_c-h) + k_d_theta*(0-h_dot);
    F_thr   = v_ac*(1-sin(gamma)) + g*sin(gamma)*(1 + k_p_z*(z_c - h) + k_d_z*(0 - h_dot));
```

The PD controller block, highlighted in the above image, implements proportional-derivative control to regulate the tail sitter's attitude and trajectory. It generates the required control inputs, such as thrust force and commanded angles, based on the error between the desired and actual states. The controller ensures precise tracking of waypoints and stability during dynamic transitions, making it a critical component of the simulation model.



The above plot shows the position response (p_n, p_e, and h) of the tail sitter during the simulation. Here, h (altitude) gradually converges to the target value of 5 units as defined in the waypoint block. This indicates that the PD controller effectively regulates the vertical motion, ensuring smooth altitude tracking with minimal overshoot. The p_n (north position) and p_e (east position) remain close to zero, confirming that the vehicle maintains stability in the horizontal plane, as expected for a hover-like condition.



The above plot illustrates the orientation response (ϕ, γ, and ψ), corresponding to roll, pitch, and yaw angles, respectively. The pitch angle (γ) stabilizes around the target value of $\pi/2$ radians (90°), as set in the waypoint block, demonstrating the controller's ability to maintain the desired orientation. The roll (ϕ) and yaw (ψ) remain near zero, indicating no significant unwanted rotation about these axes. This confirms that the control algorithm effectively stabilizes the vehicle's attitude during the simulated flight condition.

11 Future Work

Expanded Polystyrene

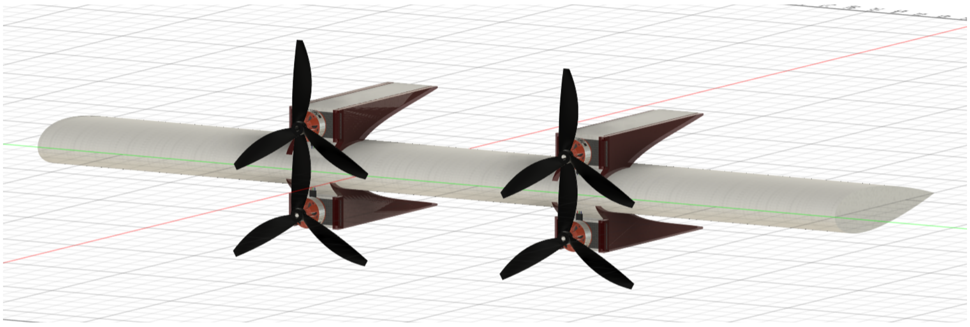
I plan on making the next iteration of the prototype using Expanded Polystyrene (EPS) instead of thermocol due to its superior strength, durability, and smoother surface finish, which enhance the structural and aerodynamic performance of the design. EPS provides better resistance to mechanical stresses, moisture, and environmental degradation, ensuring consistent performance during testing. Its lightweight yet rigid nature, coupled with ease of shaping and compatibility with reinforcements, makes it an ideal choice for improving the prototype's reliability, aerodynamics, and robustness in both hover and forward-flight modes. Its superior shaping qualities will enable us to conform it better to the required airfoil profile allowing our aerodynamic analysis to be better reflected during the flight testing.

Control Surfaces

The use of control surfaces, elevons, will be a critical addition to the design. These can be utilized for pitch and roll control as elevons, but they can also be deflected downward (or upward, if used as spoilers) to function as flaps. When deployed as flaps, they generate additional lift from the wing, enabling the aircraft to carry heavier payloads. The four rotors, on their own, are sufficient for performing roll, pitch, and yaw. However, the use of elevons will greatly increase the coupled moment coefficients due to the propeller downwash, making the tail sitter more maneuverable and reducing the power load on the motors, thereby increasing the endurance.

Tandem Configuration

For the next iteration of the tail sitter prototype, a tandem configuration is being considered. While the staggered arrangement has been effective in increasing pitch inertia and propeller damping, the tandem configuration offers distinct advantages. By positioning all motor-propeller pylons equidistant from the center of the main wing and introducing partial overlap between the opposite propellers, the tandem layout can accelerate airflow in the overlapping region. This accelerated flow may enhance overall lift generation and reduce flow separation near critical areas of the wing. Additionally, the symmetry of the tandem configuration could lead to more balanced aerodynamic forces, improving control precision and reducing vibrational loads. These benefits make the tandem setup a promising enhancement for optimizing the aerodynamic performance and stability of the tail sitter design.



Winglets

For future iterations, incorporating winglets into the tail sitter design can enhance aerodynamic efficiency and control. Winglets reduce tip vortices, lowering induced drag and improving endurance. They also provide increased vertical surface area, enhancing lateral stability and reducing sideslip during turns, which improves maneuverability in critical flight modes like knife-edge flight. Additionally, winglets mitigate unsteady vortex shedding during hover descents with negative airspeed, improving controllability. These benefits make winglets a valuable addition for optimizing the tail sitter's performance and stability.

Custom Transition Strategies

For future work, custom transition strategies are essential to improve the efficiency, stability, and overall performance of the tail sitter during transitions between hover and cruise modes. Research has shown that traditional linear transition methods often lead to unnecessary altitude gains or energy inefficiencies during the transition phase. Optimized transition strategies, such as those using trajectory optimization and non-linear programming, minimize these issues by carefully controlling pitch angles, throttle inputs, and aerodynamic forces. Furthermore, incorporating advanced control algorithms, like resolved tilt-twist angle feedback or hybrid multirotor-fixed-wing controllers, enhances robustness against disturbances and ensures smoother transitions. Implementing these custom strategies in the next iteration will reduce energy consumption, minimize altitude deviations, and improve transition stability, making the tail sitter more versatile and efficient in real-world applications.

Flight Test

I plan on conducting a comprehensive flight test of the current tail sitter prototype to successfully demonstrate all flight modes, with a particular focus on achieving smooth transitions between hover and forward flight. During these tests, flight data will be logged through the ground control station to verify the results of aerodynamic simulations and the dynamics and control algorithms modeled in MATLAB. This data will enable a detailed analysis of deviations between experimental results and computer simulations, providing valuable insights into areas requiring improvement. These findings will guide the implementation of the proposed design and algorithm changes, such as the use of custom transition strategies, tandem configuration, winglets, and elevons, ensuring the next prototype achieves greater stability, efficiency, and performance.

12 References

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3. Transition Optimization for a VTOL Tail-Sitter UAV

4. Design and implementation of a quadrotor tail-sitter VTOL UAV

5. A hovering control strategy for a tail-sitter VTOL UAV that increases stability against large disturbances