Development of a Modular Fixed-Wing Tilt-Rotor UAS for Forest Health Monitoring and Restoration

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Monitoring of forest health conditions as blight and infestations spread across the 33,000 acres of state-owned forests in North Carolina (NC) requires time and resource intensive surveying and treatment. To cover this vast territory, aerial methods are employed, historically involving general aviation aircraft and small teams of forestry personnel. As the resources required to arrange these flights involve high fuel and scheduling costs, blights and infestations are often caught late and require costly treatment. Thus, the NC Forest Service has demonstrated a need for frequently deployable aerial surveying systems and rapid treatment response. This paper details the year-long developmental process of a student-made Unmanned Aerial System (UAS), designed with both the capability for prolonged loitering and low-altitude administration of necessary treatments. The system will be capable of taking off and landing vertically for practical use in a forest environment and for higher accuracy of treatment dispensing and reconnaissance. The UAS implements an imaging system accompanied by GPS to detect and track areas of blight, infestation, or other indications of deteriorating forest health. A prototype UAS is designed that is a fixed-wing tilt-rotor aircraft capable of vertical takeoff and landing. It achieves modularity by employing an extendable wing to tailor aircraft performance based on the mission profile. This remotely controlled aircraft is compact for transportation in a vehicle and is able to be assembled on-scene. A test plan for this prototype is developed and results for some of the tests are discussed.

I. Introduction

This document covers the authors' capstone design process, as a part of team SCHNARBY operating under North Carolina State University's Mechanical and Aerospace Engineering Department in the 2025-2026 academic year. It details the mission overview, design, and testing of a tilt-rotor, vertical-takeoff-and-landing (VTOL) fixed wing prototype. Jessica Allen acted as the Project Manager and Avionics Lead, Noah Fischer acted as the Systems Engineer and Structures Lead, Andrew Dranttel acted as the Communications Liaison and the Flight Stability and Controls Lead, Alex Zeitler acted as the Test/Safety Lead and the CAD/Simulation Lead, Louise Bongala acted as the Financial Lead and Propulsion Lead, and Aaron Lewis acted as the Manufacturing Lead and Aerodynamics Lead. Dr. Felix Ewere, the Aerospace Engineering capstone course instructor, facilitated and supported the team through the design process.

The sponsor for the capstone project was the North Carolina Forest Service. The North Carolina (NC) Forest Service is responsible for the maintenance and protection of the National Forests in NC. This includes protection of forest ecosystems through discovery and prevention of large-scale blights and infestations, with a focus on trees due to their slow re-population [1]. Currently, scouting for regions of unhealthy trees is typically done by forest management experts flying on full-scale aircraft over the canopy, which incurs fuel and logistical costs. Due to such costs, blights and infestations are often caught late and require the NC Forest Service personnel to venture to the affected area and perform large-scale treatments, which wastes time and resources as opposed to if the affliction was caught early [2]. The Forest

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Service recognizes there is a need for a low cost, efficient, and frequently deployable method for surveying large regions of the forest to prevent spread of forest blights and infestations [3]. Aerial scouting of the forest canopy using UAS has been researched and shown effective for identifying a variety of afflictions [2, 4–6].

The goal of this project is to design and manufacture an Unmanned Aerial System (UAS) that is capable of scouting the National Forests for blighted or infested areas and applying a short-term treatment (if applicable) to prevent spread while a Forest Service team is organized for a permanent treatment. For the UAS to be effective, it must be capable of collecting the necessary data on large regions of the forest, as well as accurately dispensing a temporary treatment. The UAS designed by SCHNARBY will utilize a fixed-wing design for high efficiency during cruising flight for maximum endurance. The system will be capable of taking off and landing vertically for practical use in a forest environment and for higher accuracy of treatment dispensing and reconnaissance. The UAS will implement a camera or other imaging sensor accompanied by GPS to detect and track areas of blight or infestation. The UAS will allow the Forest Service to frequently and inexpensively monitor the forest for areas of blight or infestation and apply a rapid treatment, hindering their exponential spread early. Doing so provides a less expensive and more effective forest management system.

II. Design Overview

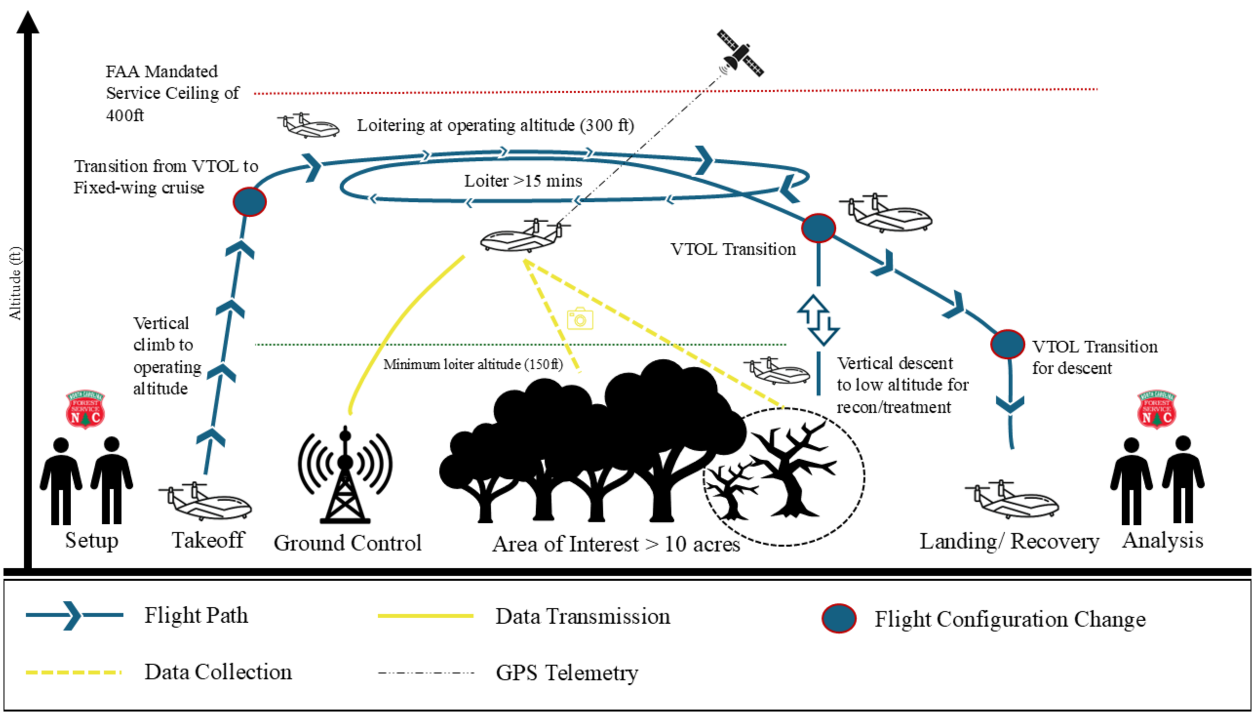


Fig. 1 Concept of operations for the UAS.

Fig. 1 depicts the concept of operations (CONOPs) for the UAS designed by SCHNARBY. The UAS will takeoff vertically under control of one pilot where it will loiter above the tree canopy to identify clusters of trees that appear diseased. During this mission, a high efficiency wing and range extending payload will be used. Once the diseased trees are detected, the UAS may descend to the afflicted areas and capture images. The UAS then returns to the pilot for a vertical landing. The images will be offloaded and analyzed to select a treatment option if necessary. The treatment payload can then be attached with a high speed wing, where the UAS will fly back to the point of interest and descend to deliver the treatment. With live image transmission, a treatment can be deployed in one mission.

The following functional block diagram (Fig. 2) is used to present the connections between the systems, subsystems, and components that allow the UAS to operate. The two primary systems are the ground system and the fixed-wing UAS system. The ground system fundamentally consists of the pilot, transmitter, and receiver, responsible for sending information to and from the UAS. The UAS itself consists of six subsystems which work together for the aircraft to operate: structures, propulsion, control, payload, electrical, and flight data subsystems. More detail on these subsystems is provided later.

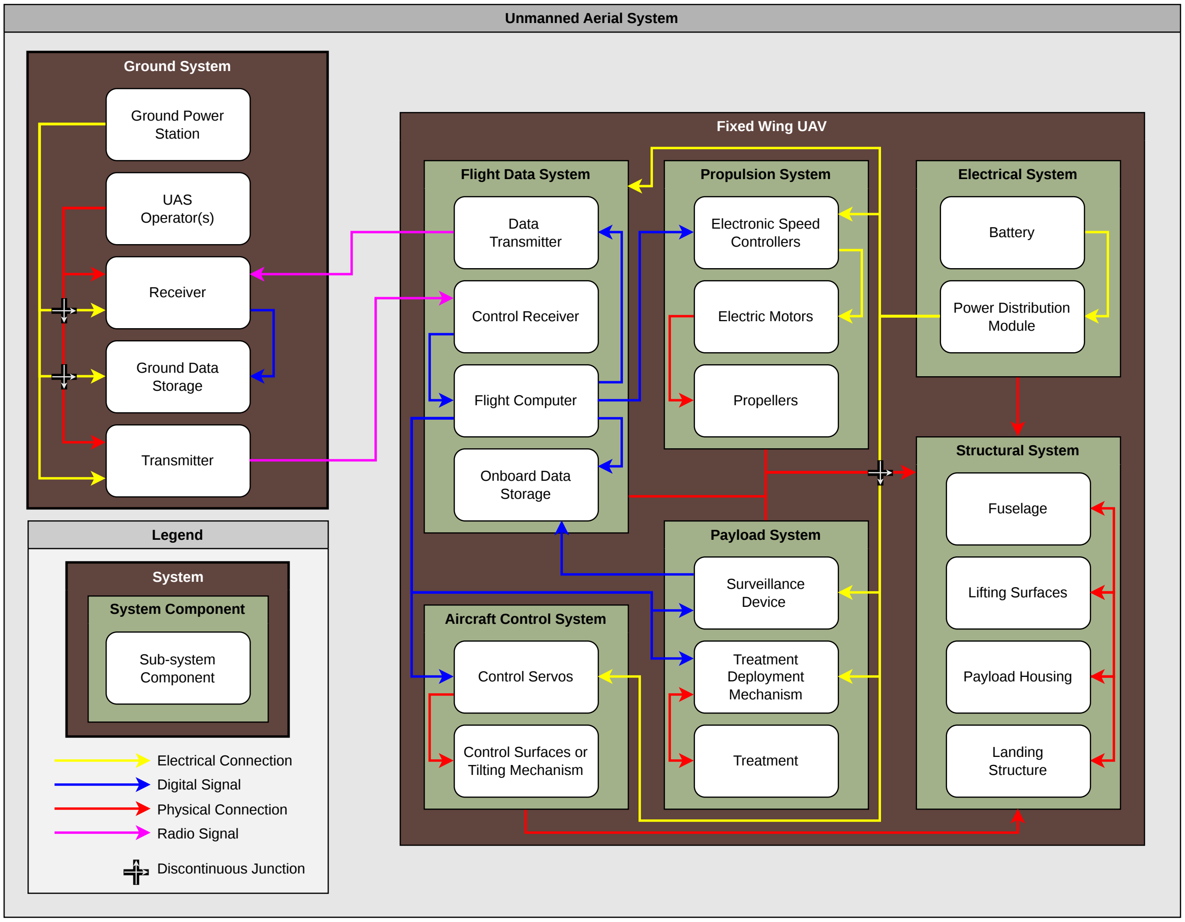
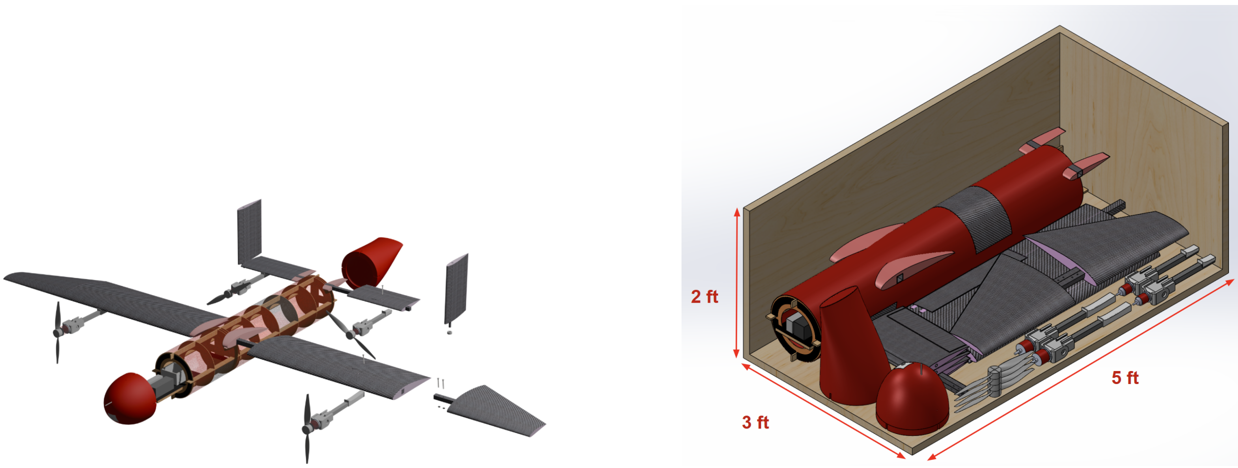


Fig. 2 UAS functional block diagram.

The prototype developed by SCHNARBY, DRAGONFLY, prioritizes efficiency by using a quad-tilt-rotor configuration capable of transitioning between VTOL into steady cruise. All four rotors will tilt on carbon fiber spars attached to the wings and horizontal tail to maximize efficiency during flight. DRAGONFLY boasts multiple forms of modularity with varying payloads within a standard size of 1U that allow for case by case treatment deployment, and modular wing extensions to increase the aspect ratio for longer endurance flight during reconnaissance. Modular components make DRAGONFLY a multi-operational UAS that will be able to identify and treat a variety of insect infestations. DRAGONFLY can be easily deconstructed for ease of transportation between sites of interest and requires minimal time to reconstruct. The use of carbon fiber, XPS Foam, plywood, balsa wood, and PLA create a durable, lightweight, and inexpensive prototype. Fig. 3a shows an exploded version of the final CAD render of the DRAGONFLY design. To demonstrate the portable capability of DRAGONFLY, the disassembled components are shown fitting into a box with dimensions typical of a sedan trunk in Fig. 3b. A dimensioned orthogonal drawing of the prototype is shown in Fig. 4. Lastly, the current manufacturing progress of DRAGONFLY is shown in Fig 5.



(a) **DRAGONFLY semi-exploded design render.** (b) **DRAGONFLY disassembled.**

Fig. 3 Dragonfly design models.

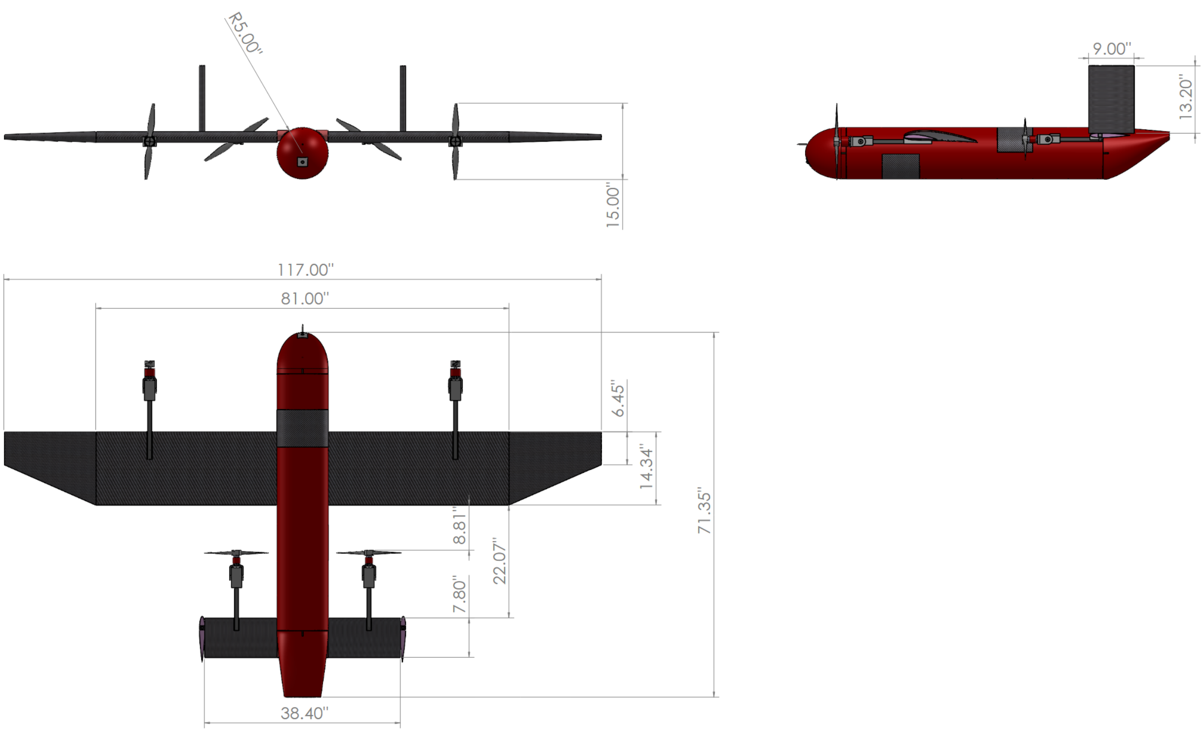


Fig. 4 DRAGONFLY orthographic drawing.

Fig. 5 DRAGONFLY preliminary assembly.

III. Prototype Subsystem Design

The mission of the SCHNARBY UAS is broken down into subsystems (see Fig. 2) which collectively perform the necessary tasks highlighted in our mission of detecting and treating forest blights. Design of these subsystems were spearheaded by the respective leads utilizing literature reviews and trade studies. As a team, further trade studies were conducted and debated to determine the final design. The final design solutions are applicable to both the prototype and full scale implementation.

The structural system of DRAGONFLY consists of a semi-monocoque fuselage design comprised of balsa wood and lightweight plywood. The skin of the fuselage will use a lightweight plastic shrink wrap film common in remote controlled aircraft. The wing structure for all lifting surfaces features a hollow carbon fiber monospar with an XPS foam core. The lifting surfaces are wrapped in a hand-laid carbon fiber layup consisting of a 0°/90° twill weave. The structural design of the aircraft keeps the prototype lightweight and inexpensive.

The DRAGONFLY electrical system will be facilitated by a CubeOrange flight controller to which all avionics will be connected. The flight controller is used to switch the UAS between VTOL and conventional flight using tilt rotor servos and ArduPilot. The flight controller will also be connected to the servos responsible for the movement of control surfaces and the electronic speed controllers (ESC) with integrated battery eliminator circuits (BEC). This will allow for the pilot transmitter to maintain full control of the aircraft during conventional flight. Additionally, flight data will be stored using the flight controller onto a microSD card.

The propulsion system of DRAGONFLY comprises four electric motors arranged as two front and two rear units. The front motor pair is equipped with 15x10 thin electric propellers, while the rear pair uses 15x8 propellers. Each motor pair is integrated with a compatible battery and ESC, completing the propulsion assembly.

The stability of the DRAGONFLY is primarily inherent to it's aerodynamic profile as a result of it's physical features. Once the configuration of the aircraft was determined from our trade studies, much of the aircraft's initial design and sizing was based on empirical figures from *Raymer's Aircraft Design: A Conceptual Approach* [7]. Guidelines for sizing were created based on the required lift generation for a 20lb aircraft, providing us with a main wing span and chord that served as the basis of the empirical relations used for the remainder of the sizing. Importantly, the longitudinal thrust line of the motors in the Z-axis are aligned with the CG, preventing adverse thrust-pitch couplings. Once the geometry was determined, the aircraft was analyzed in both AVL and Flow5, for static and dynamic analyses respectively.

A summary of the calculated design specifications of DRAGONFLY can be found in Table 1.

Table 1 Baseline Design Specifications

Subsystem	Element	Specifications
Aerodynamics	General	Max L/D: 9
		Wing Loading (Extensions): 1.87 lb/ft
		Wing Loading (No Extensions): 2.47 lb/ft
	Base Wing	Airfoil: NACA 4412
		Span: 6.75 ft
		Chord: 1.2 ft
		Aspect Ratio: 5.62
		Incidence: 4˚
	Extended Wing	Total Span: 9.75 ft, 1.5 ft extensions/side
		Extension Root Chord: 1.2 ft
		Extension Tip Chord: 0.54 ft
		Aspect Ratio: 8.88
	Horizontal Tail	Airfoil: NACA 0012
		Span: 3.2 ft
		Chord: 0.65 ft
		Aspect Ratio: 5.0
	Vertical Tail (H-Tail, 2x)	Airfoil: NACA 0012
		Span: 1.1 ft
		Chord: 0.75 ft
		Aspect Ratio: 1.5
Propulsion	General	T/W Ratio: 1.5:1
		Total Endurance: 15 minutes
		Propulsion Weight: 5.92 lb
		Avionics Weight: 2.19 lb
	Motors	Front: *Leopard 5055-10T 390kv Brushless* (2x) Rear: *Leopard 3536-14T 560kv Brushless* (2x)
	Propellers	Front: 15x10E (2x)
		Rear: 15x8E (2x)
	Battery	Front: *Turnigy 6s 8000mAh 15C LiPo*
		Rear: *HRB 4s 3300mAh 60C LiPo*
	ESCs	Front: *ZTW Beatles SBEC G2 Series 80A 2-6s LiPo*
		Rear: *ZTW Beatles SBEC G2 Series 40A 2-4s LiPo*
Structures	General	Structure Weight: 8.49 lb
	Fuselage	Construction: Semi-monocoque
		Material: Balsa and plywood
		Skin: Ultracote Film
	Lifting Surfaces	Construction: Monospar
		Spar Type: Carbon Fiber Spar
		Core: Solid Foam Core
		Skin: Carbon Fiber Skin
Totals	Weight	Allowable GTOW: 20 lb
		Projected GTOW: 18.6 lb
		Max Payload: 2 lb
	Stability	CG Location: 5.6in behind leading edge (LE)
		Neutral Point (No Extensions): 9.68in behind LE
		Neutral Point (Extensions): 6.18in behind LE

During subsystem design, SCHNARBY discussed potential risks and risk management. Table 2 is an overview of all perceived risks with our UAS design. Included is a mitigation plan for each issue as well as the associated severity and probability of each risk before and after risk management. Shown in Table 3 is the risk matrix of all risks listed in Table 2 after the risk mitigation plan has been put in effect. Failures of biggest concern include structural failure and loss of control in transition.

Table 2 Risk mitigation plan

Risk	Mitigation Plan	Probability	Severity
R.1 - Hard Landing	- Hard mounted avionics and payload - Test structural systems ability to withstand drops	4→4	3→2
R.2 - Overheating	- Test electronics before flight - Use power limiters if necessary - Use of ventilation holes in the nose	3→1	3→2
R.3 - Tilt Mechanism Failure	- Tilt mechanisms will be tested before flight	3→1	4→4
R.4 - Motor Failure	- Multiple motor tests will be run before flight - The capability of the UAS in unpowered flight will be analyzed	3→2	4→3
R.5 - Battery Failure	- Multiple battery tests will be run before flight - The capability of the UAS in unpowered flight will be analyzed	3→2	4→3
R.6 - Loss of Communication	- Install redundant/secondary receiver	2→1	4→4
R.7 - Loss of Control in Transition	- Will use ArduPilot to assist in transition - Transition will be tested before flight	3→2	5→5
R.8 - Structural Failure	- Elements of structural system will be tested before flight	3→1	5→5

Table 3 Risk matrix after risk management

	Negligible	Minimal	Moderate	Critical	Catastrophic
Highly Improbable		R.2	R.3	R.6	R.8
Improbable			R.4, R.5		R.7
Plausible					
Probable		R.1			
Expected					

IV. Testing

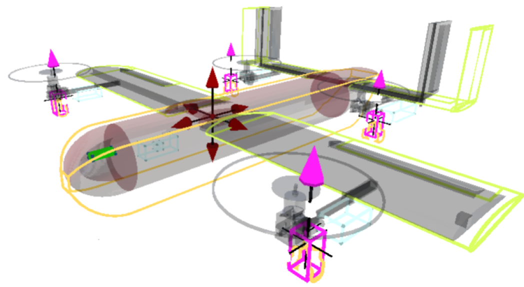
Testing of DRAGONFLY consists of twelve validation and verification tests. Table 4 shows an outline of our verification and validation test plan. At the time of writing, not all tests have been completed. Key tests that have been completed are discussed more in their respective sections below.

Table 4 Verification test plan

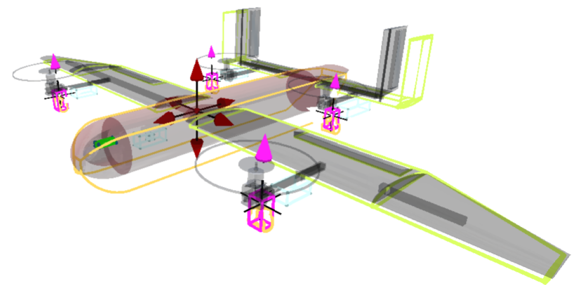
Test	Purpose	Software or Method Used
Flight Simulation Test	To verify DRAGONFLY's flight performance in both vertical and traditional modes.	Create a physics model in RealFlight to test DRAGONFLY's performance in various settings.
Wing Loading	To verify DRAGONFLY's ability to withstand the forces applied on the wings during flight.	Place sandbags on the underside of the wings to simulate loading.
Aerodynamics Sim	To verify the aerodynamic feasibility of DRAGONFLY in multiple flight conditions.	Calculate lift and drag coefficients in ANSYS Fluent at varying angles of attack.
Dynamic Stability Sim	To evaluate the dynamic stability characteristics of the airframe and control system architecture by quantifying the dynamic response to disturbances during flight.	To evaluate the dynamic stability of DRAGONFLY, OpenVSP and Flow5 is used, in addition to physical or CAD measurements of the aircraft.
CG Test	To determine the center of gravity of the aircraft in all payload and modular wing configurations.	Balance point method to find the CG position within the main wing chord.
Hover Test	To demonstrate safe vertical takeoff, hover stability, and basic controllability of the integrated vehicle.	Hover assembled aircraft in an open field while secured to a ground weight via a cord attached to a fuselage frame.
Static Thrust Test	To measure motor-propeller thrust on thrust stand and confirm a T/W ratio greater than 1.	Mount the motor assembly on the thrust stand and determine propeller thrust using moment balance equation.
Tilt Mechanism Test	To evaluate the tilt mechanism effectiveness, power consumption, and structural stability during simulated flight conditions.	Mount the tilt mechanism with the motor, propeller and servo installed and ensure effectiveness through full range of motion and thrust.
Ironbird Test	To evaluate and ensure the performance and functionality of all avionic components onboard DRAGONFLY during simulated flight.	Connect all avionics and motors to the flight controller and ensure servo movement, transition, and motors are functional.
Power Consumption/ Endurance Test	To characterize power draw in hover and cruise and verify the propulsion system can provide an endurance of 15 minutes with margin.	Use a wattmeter to measure each pair of front and rear motors' voltage, current, and power while logging the data every minute for at least 15 minutes.
Material Test	To validate the structural analysis done in the design phase by finding failure stress and Young's Modulus of hand-laid carbon fiber.	Use a tension load frame and material test specimens to determine these properties utilizing standard procedure.
Drop Test	To validate that the final aircraft is capable of surviving harsh vertical landings that may occur.	The aircraft will be equipped with an accelerometer and dropped from a height of 2 feet.

A. Flight Simulation Test

A flight simulation test was conducted in RealFlight for both configurations of DRAGONFLY to allow for testing of dynamic handling in both flight regimes as well as during transition. The simulated aircraft also allowed for the pilot to become familiar with the flight characteristics of DRAGONFLY. The physics models are shown in Fig. 6a and Fig. 6b. DRAGONFLY was recreated in RealFlight with a physics model being built on top of a visual render that was constructed in Blender.



(a) Normal wing configuration

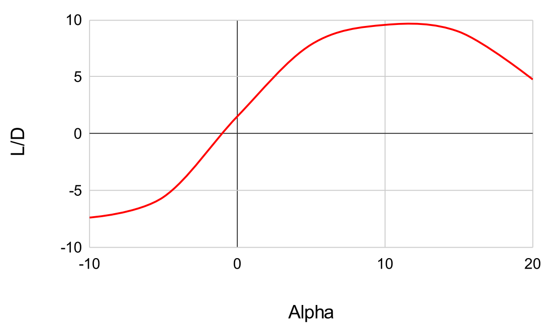


(b) Extended wing configuration

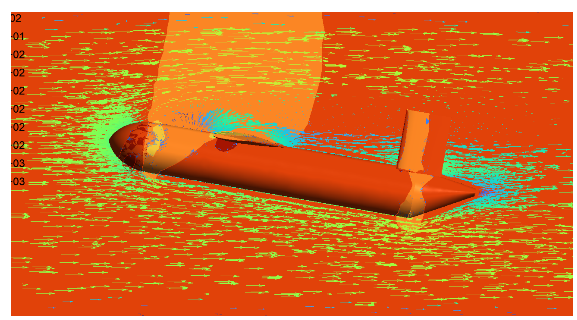
Fig. 6 RealFlight physics models.

B. Aerodynamics Simulation

An aerodynamics simulation test was conducted in ANSYS Fluent to calculate the lift and drag coefficients of DRAGONFLY at varying angles of attack in order to verify the aerodynamic feasibility of the UAS in multiple flight conditions. The calculated lift to drag ratios are shown in Fig. 7a below. Fig. 7b shows a visualization of the flow through the simulation domain at an angle of attack of 10 degrees.



(a) Lift over Drag vs angle of attack



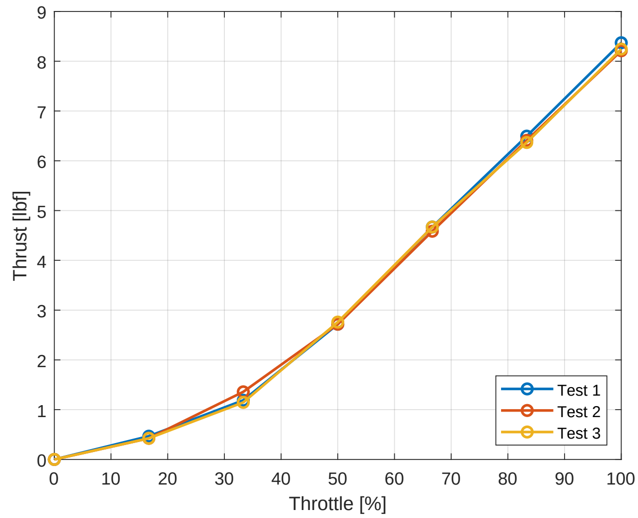
(b) Flow visualization: 10° angle of attack

Fig. 7 Aerodynamic simulation results.

C. Static Thrust Test

A static thrust test was conducted to measure the force produced by DRAGONFLY's front and rear motor-propeller assemblies. Each motor is mounted to the thrust stand (see Fig. 8a) with its specific propeller, ESC, wattmeter, and battery, then ran through a throttle sweep from idle to full power. The voltage, current, power, and thrust from the scale are recorded. Testing the front and rear propulsion units separately provides the data needed to verify the total available thrust and compare it to the desired thrust-to-weight ratio. After calculating the moment balance equation from the thrust stand, we were able to determine the actual thrust generated by the propeller. Three test runs were conducted for each motor and the results are analyzed through MATLAB. The results for the front motor are shown in Fig. 8b.

(a) Front motor and propeller mounted on thrust stand



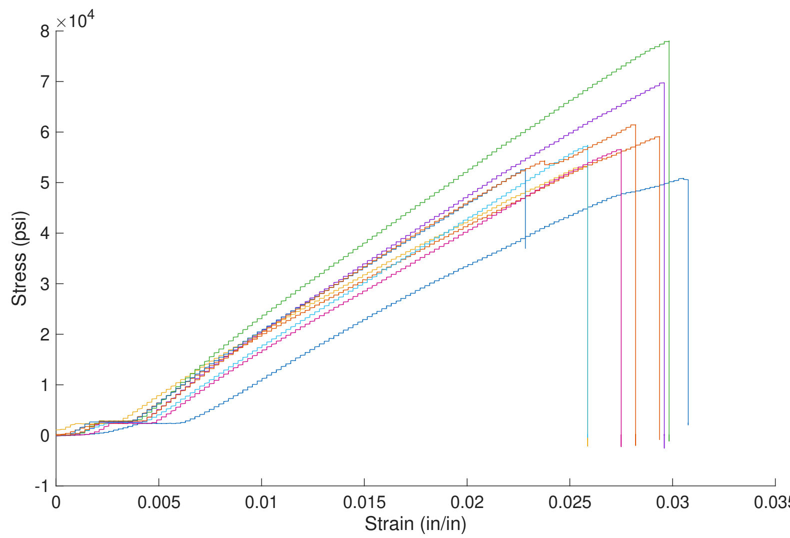
(b) Thrust vs. throttle of a single front motor

Fig. 8 Front motor static thrust testing and results.

D. Material Test

Hand-laid carbon fiber is a commonly used material in the structure of the DRAGONFLY. While analysis was performed to verify the structures ability to withstand the applied flight loads, the assumed properties of the carbon fiber material were that of commercially produced carbon fiber. Thus, to verify the performance of the hand-laid carbon fiber material, a tension test program is developed to find the Young's Modulus and failure stress of the hand-laid carbon fiber material. Material specimens are fabricated from a sheet of the material according to ASTM D638-22 [8] and tested in tension until failure. The stress in the test section is found using the cross-sectional area of each specimen and the strain in the test section is approximated using the change in length between the clamps. The experimental setup is shown in Fig. 9a and the stress-strain curves of all specimens are shown in Fig. 9b. The updated analysis of the wing structure with the new properties was still considered within a safe margin.

(a) Test specimen in load frame



(b) Stress vs. strain of all specimens

Fig. 9 Material test setup and results

V. Conclusion

Under the aerospace engineering capstone project at North Carolina State University, SCHNARBY has proposed and designed a UAS that is capable of assisting the North Carolina Forest Service in monitoring and treating forest blights and infestations efficiently. VTOL, video reconnaissance, multiple treatment payloads, wing modularity, and advanced avionics set the UAS apart as an innovative solution to insect infestation and disease in North Carolina forests.

SCHNARBY has also developed a prototype, DRAGONFLY, that meets the goals of the UAS. DRAGONFLY is a tilt-rotor VTOL aircraft that is designed to maximize flight efficiency during reconnaissance while still being capable of a rapid treatment deployment mission. It utilizes modularity, both in wing planform and payload, to allow for application in a variety of Forest Service missions in an optimal manner. A test plan is developed for DRAGONFLY to ensure its performance in meeting the goals of its mission.

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