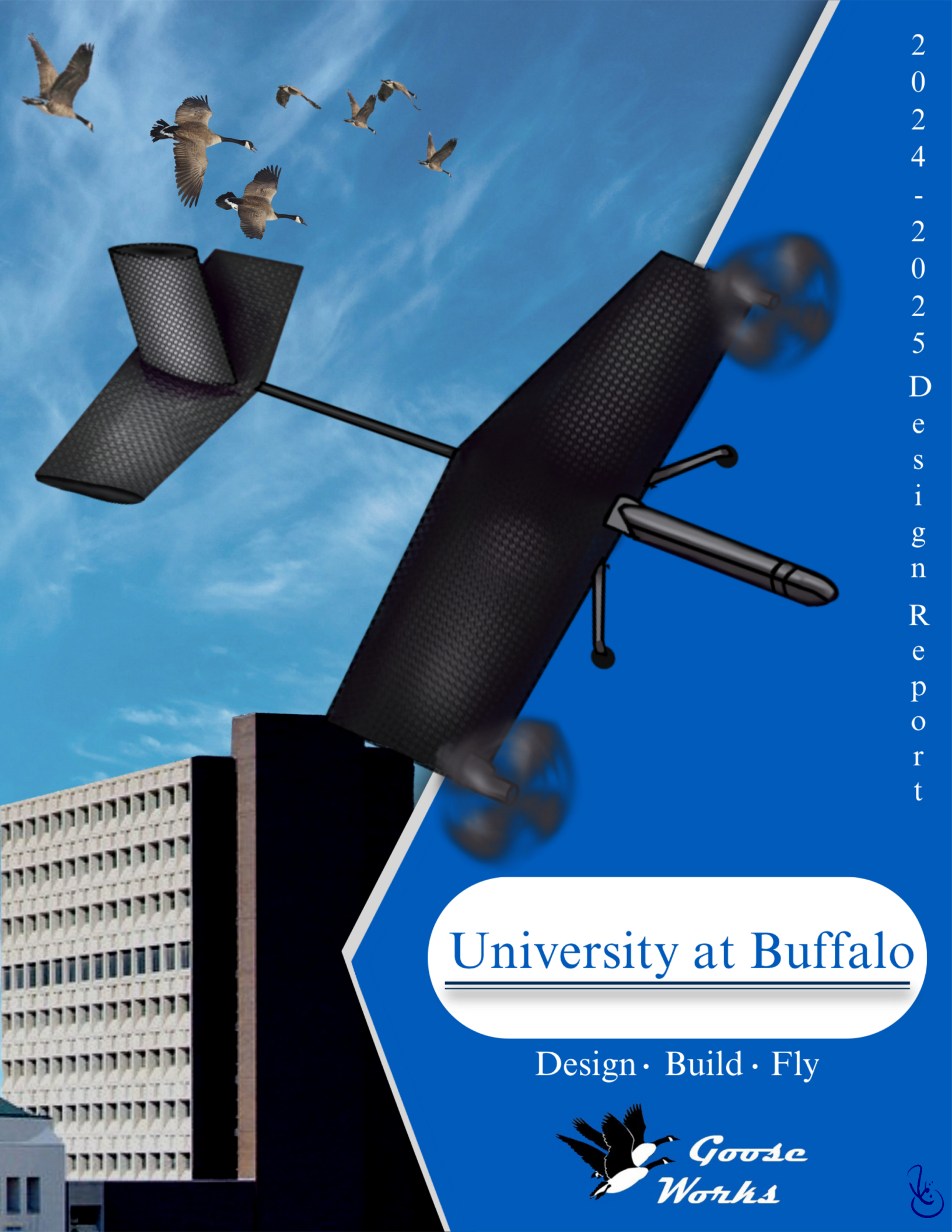


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Abbreviations, Acronyms, and Symbols

AGL	Above Ground Level	GPS	Global Positioning System
AIAA	American Institute of Aeronautics and Astronautics	GSM	Grams Per Square Meter
A	Flight Path Angle	I	Current
AOA	Angle of Attack	IF	Interference Factor
AR	Aspect Ratio	IMU	Inertial Measurement Unit
ASA	Acrylic Styrene Acrylonitrile	k _{CRUD}	CRUD Factor
b	Wing Span	L	Lift
BM	Bending Moment	L/D	Lift-to-Drag Ratio
CAD	Computer-Aided Design	M1	Mission 1
C _D	Drag Coefficient	M2	Mission 2
C _{Dmin}	Minimum Drag Coefficient	M3	Mission 3
CF	Friction Coefficient	MAC	Mean Aerodynamic Chord
CFD	Computational Fluid Dynamics	P	Power
CG	Center of Gravity	PF	Packing Factor
C _{HT}	Horizontal Tail Volume Coefficient	ρ_{binder}	Density of Binder
C _L	Coefficient of Lift	ρ_{mixer}	Density of Mixer
C _i	Section Lift Coefficient	ϕ	Bank Angle
C _M	Pitching Moment Coefficient	Re	Reynolds Number
C _{M0}	Zero-Lift Pitching Moment	RPM	Revolutions Per Minute
C _{mα}	Pitching Moment Slopes	RX	Receiver
CNC	Computerized Numerical Control	S	Planform Area
C _{VT}	Vertical Tail Volume Coefficient	S _{wet}	Wetted Area
DBF	Design/Build/Fly	SD	Selig-Donovan
δ_e	Elevator Deflection	TX	Transmitter
δ_{max}	Maximum Deflection	U	Voltage
EI	Flexural Rigidity	UB	University at Buffalo
EPS	Expanded Polystyrene	V1	Version 1
ESC	Electronic Speed Controller	V2	Version 2
FDM	Fused Deposition Modeling	V3	Version 3
FEA	Finite Element Analysis	V _{bottle}	Bottle Volume
FF	Form Factor	V $_{\infty}$	Freestream Velocity
FOM	Figures of Merit	W	Weight
FOS	Factor of Safety	W _{fuel}	Weight of Fuel Tanks
γ	Angle Between x-axis and Freestream Velocity	XPS	Extruded Polystyrene Insulation
GM	Ground Mission		

1. Executive Summary

This design report documents the design, manufacturing, and testing of Bull Shark, the RC aircraft developed by the University at Buffalo Design, Build, Fly (UB DBF) team for the 2024-25 American Institute of Aeronautics and Astronautics (AIAA) DBF competition. Bull Shark was designed to complete four missions simulating the X-1 Supersonic Flight Test Program. Mission 1 (M1) is a trial flight showcasing the aircraft's flight capabilities. Mission 2 (M2) is a timed captive carry flight of the X-1 test vehicle featuring loaded fuel tanks. Mission 3 (M3) is a transport and launch flight of the X-1 test vehicle, which must autonomously achieve stable flight, perform a 180° turn, and land at a designated location upon release at 200–400 ft above ground level (AGL). Lastly, the Ground Mission (GM) is a timed demonstration of the aircraft's transition to the test program airplane via the installation of fuel tanks and the X-1 test vehicle.

UB DBF applied an iterative design process entailing conceptual, preliminary, and detailed design phases to develop Bull Shark. The conceptual design identified the initial configuration and key design parameters—wing area, load factor, propulsion sizing, X-1 weight, fuel tank weight, and GM time—based on system requirements and sensitivity analysis results. The preliminary design sized the aircraft lifting surfaces, weight, and propulsion system for stability and high scoring through comparative and MATLAB-based optimization studies. The detailed design ironed out the internal structure and payload integration.

Through this process, Bull Shark converged to a 6 ft wingspan, high wing, conventional tail, and taildragger monoplane with a dual wingtip-mounted propulsion system (see Fig. 1). A high wing was selected to reduce GM time by accommodating the X-1 release mechanism internally. The wing was sized to an AR of 4.03 to reduce turning times and landing speeds, thereby optimizing for fuel tank weight and lap count. A conventional tail was favored for its

good stall recovery capability and low weight. The taildragger configuration allowed the aircraft to balance on its gear without the battery during staging and offered lower weight and drag compared to tricycle gear. Wingtip motors were chosen for reduced induced and propwash skin friction drag, thereby increasing endurance. Two 28.75 oz external fuel tanks filled with copper and epoxy are configurable under the wing using a quick snap-rail pylon attachment mechanism; an internal tank was avoided to further shorten GM time despite detriments to roll rates and drag. The X-1 is of conventional configuration for enhanced static



Figure 1. Bull Shark and X-1

Table 1. Estimated Performance of Bull Shark

Parameter	M1	M 2	M3	GM
Fuel Weight [lb.]	/	24.78	/	/
X-1 Weight [lb.]	/	0.157	0.157	0.157
Mission Time [s]	74.09	93.71	296.37	28.94
Number of Laps	3	3	12	/
Cruise Velocity [ft/s]	110.19	131.43	110.17	/
Consumption [Wh]	21.88	70.67	87.52	/

margin, and features a GPS, IMU, Arduino PID controller, and two servos controlling the elevator and ailerons for autonomous flight. Table 1 conveys the capabilities of Bull Shark and provides a mission performance estimate.

2. Management Summary

UB DBF, comprised of 50% seniors and 50% underclassmen, is a student-run team making up the UB AIAA chapter. UB AIAA is funded by the University at Buffalo Student Association (UB SA) and the School of Engineering and Applied Sciences (SEAS). Dr. Aaron Estes is the club's faculty advisor, responsible for assisting student leadership and providing executive guidance.

2.1 Organizational Structure

As indicated by Fig. 2, student leadership is subdivided into administrative and technical roles. The four administrative roles handle fundraising, material procurement, and cultivate a positive and safe club environment while collaborating with UB SA and technical leadership.

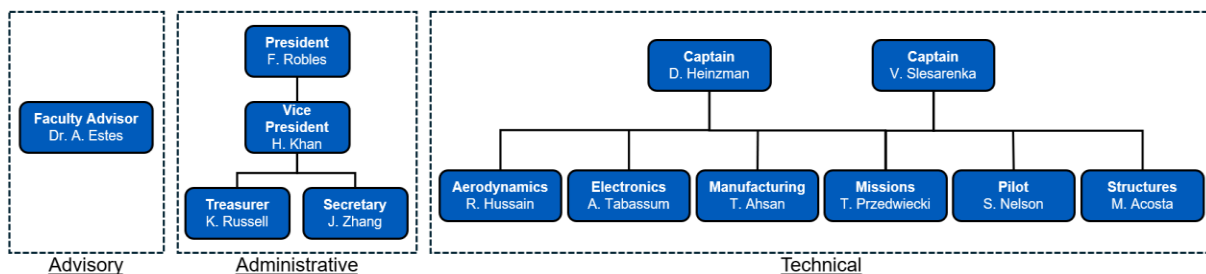


Figure 2. UB DBF Organizational Hierarchy

The technical roles consist of two captains that oversee the five sub-team leads and team pilot, whose individual responsibilities are covered in Table 2. Leveraging their experiences, captains decompose system requirements into tasks for each respective sub-team lead in their field of expertise and assign appropriate deadlines to ensure major milestones are reached in a timely manner. Sub-team leads address their designated tasks by holding meetings, attended by general members and leadership alike, that freely vary between brainstorming, design, analysis, construction, and testing as necessary.

Table 2. UB DBF Roles

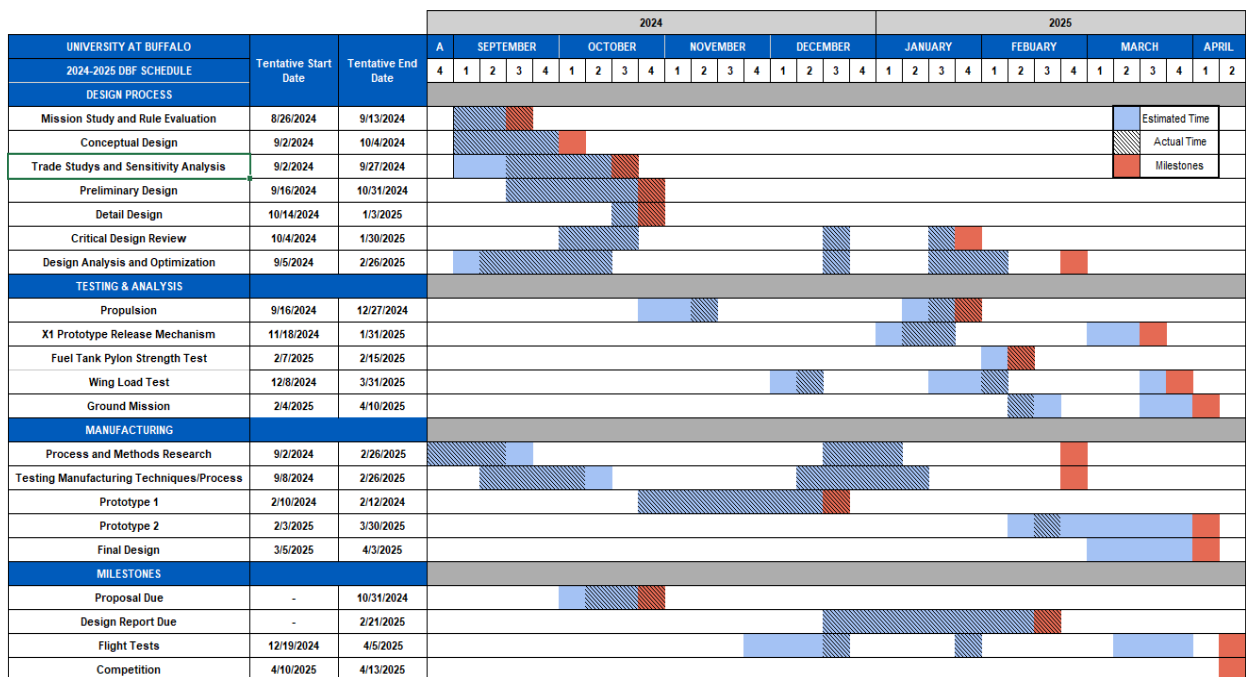
Roles	Responsibilities	Skills
Captain	Manage schedule and sub-teams. Assist leads where necessary. Perform scoring analysis. Lead proposal and design report writing sessions.	Proficiency in MATLAB. Knowledge of optimization. Strong leadership, organization, and aircraft design skills.
Aerodynamics	Select airfoil and geometry of wing and tail. Perform flight stability analysis. Run CFD on components.	XFLR5, OpenVSP, CFD, and CAD. Knowledge of flight dynamics.
Missions	Configure and test X-1 controls and attachment. Devise fuel tank and pylon designs.	CAD, Arduino, and 3D printing.
Structures	Design and analyze aircraft structural components. Configure and model overall aircraft assembly.	Design, CAD, GD&T, and FEA.
Manufacturing	Fabricate aircraft. Work with sub-teams to ensure manufacturability of components.	CAD, 3D printing, composite layups, CNC hot-wire.
Electronics	Size batteries, motors, and propellers to maximize performance. Integrate avionics.	MATLAB, INAV, RC electronics, thrust testing, crimping, soldering.
Pilot	Fly aircraft for test flights and assess performance.	RC piloting experience.

Progress on outstanding tasks is reviewed during weekly design review sessions held primarily by the technical leadership. Should solutions be deemed compliant with competition rules and system requirements, new tasks are assigned to sub-teams. If progress on a critical task stalls, the captains would collaborate with the associated sub-team to expediate the task. In the event of conflicting requirements, independent analyses are performed and dissected during the subsequent design review session to determine the path to optimal scoring: Design decisions of this nature are often made through weighted decision matrices, optimization results, and general discussion. After arriving at a decision, subsystem requirements are updated so that each sub-team can work on their design solution without much concern about seamlessly integrating with other subsystems. Documentation of the design process is conducted by sub-team leads and compiled by captains.

2.2 Project Schedule

A Gantt chart, as depicted in Fig. 3, was created early in the project to manage workload expectations and set key milestone dates. By consistently tracking the Gantt chart and secondary schedules, the team was able to effectively develop an optimally scoring aircraft.

Figure 3. UB DBF Gantt Chart



3. Conceptual Design

The conceptual design phase first began by defining the problem statement and tabulating system and subsystem requirements. Then, after qualitatively defining high scoring requirements using the scoring functions as a guide, a sensitivity analysis was conducted to determine the key design parameters to optimize for. Finally, the optimal aircraft configuration was determined through weighted decision matrices and is summarized in Section 3.5.

3.1 Mission and Score Summary

The 2024-2025 DBF competition [1] is a simulation of the X-1 Supersonic Flight Test Program. The competition will include three flight missions (M1, M2, M3) and one ground mission (GM). Observing Eqs. 1 through 3, the competition score depends on the proposal, design report, mission and participation scores. The participation score ranges from 0 to 3 based on the fly off attendance, tech inspection completion, and attempt of a flight mission. UB DBF's proposal score is already known to be 79.

$$\text{Total Mission Score} = M1 + M2 + M3 + GM \quad (1)$$

$$\text{Total Report Score} = 0.15 \times \text{Proposal Score} + 0.85 \times \text{Design Report Score} \quad (2)$$

$$\text{Competition Score} = \text{Total Report Score} \times \text{Total Mission Score} + \text{Participation Score} \quad (3)$$

3.1.1 Staging

Before each flight mission, the aircraft will be positioned in the staging box with all battery packs, pylons, fuel tanks, and the X-1 flight vehicle removed and hatches closed. The assembly crew member will then have 5 minutes to install all required payloads and battery packs. After the plane is flight-ready and the throttle is advanced for takeoff, the pilot will have 5 minutes to complete the selected mission by following the course layout shown in Fig. 4. As indicated, a single lap consists of two 1000 ft straightaways, two 180° turns, and one 360° turn. For M3, there will also be a bonus score zone consisting of two 275 ft by 200 ft 1-point boxes either side of the 2.5-point 200 ft by 200 ft bonus box centered at the start line. Notably, there is no takeoff distance limit requirement for this year.

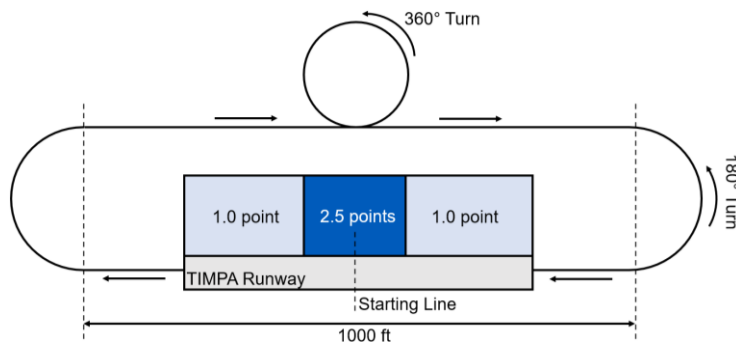


Figure 4. Course Layout

3.1.2 Mission 1

M1 is a delivery flight consisting of three laps. Completing the laps within the time limit and successfully landing warrants a score of 1.

3.1.3 Mission 2

M2 is the captive carry flight. The payloads for this mission are the fuel tanks and the X-1 flight test vehicle, with a minimum of two external fuel tanks carried and an allowance for an additional internal tank. Fuel tanks are commercially available beverage bottles that can be filled with varying quantities of inert materials, such as water and sand. The score is determined by the total fuel tank weight carried and time to fly three laps, normalized by the highest score.

$$M2 = 1 + \frac{\left(\frac{Fuel\ Weight}{Time_{3-Laps}}\right)_{UB}}{\left(\frac{Fuel\ Weight}{Time_{3-Laps}}\right)_{MAX}} \quad (4)$$

3.1.4 Mission 3

M3 features the fuel tanks, which may be empty, and the X-1 test vehicle as payloads, the latter of which must be released at 200 – 400 ft above ground level before completing the final lap and mission. The score depends on the number of laps flown prior to release of the X-1 glider and the bonus box score, which is divided by the X-1 weight. Bonus points are earned by having the X-1 test vehicle achieve stable flight upon release, perform a 180° turn, and land within one of the bonus boxes shown in Fig. 4. The strobe lights installed on the X-1 test vehicle must also remain powered on throughout its sequence. The score is normalized by the maximum at the competition.

$$M3 = 2 + \frac{\left(\# Laps + \frac{Bonus\ Box\ Score}{X-1\ Weight}\right)_{UB}}{\left(\# Laps + \frac{Bonus\ Box\ Score}{X-1\ Weight}\right)_{MAX}} \quad (5)$$

3.1.5 Ground Mission

The GM showcases the timed transition of the aircraft to the test program configuration by a ground crew member and consists of two stages. In the first stage, pylons are installed given the quantity of external fuel tanks declared in Tech Inspection. In the second stage, all declared fuel tanks and the X-1 test vehicle are configured into the aircraft before closing hatches. Finally, flight controls and the X-1 glider release are tested. If successful, the recorded mission time is applied and normalized against the lowest GM time.

$$GM = \frac{(Mission\ Time)_{MIN}}{(Mission\ Time)_{UB}} \quad (6)$$

3.2 System and Subsystem Requirements

The major system and subsystem requirements were identified to develop Table 3. UB DBF revisited Table 3 extensively to ensure all rules and regulations were satisfied (S). If not satisfied (NS), the requirements were marked down as such and investigated further. Table 4 explored key design allowances and Table 5 analyzed the mission rules and regulations to construct high scoring aircraft requirements.

Table 3. System and Subsystem Requirements

Category	Design Requirements	S/NS
General	Aircraft must be radio-controlled	S
	Aircraft must be capable of performing all missions	S
	Radio must have a programmed fail-safe mode	S
	Wingspan must not exceed 6 ft	S
	Aircraft must be electric powered and propeller driven	S
Propulsion	System must be commercially sourced products	S
	Airplane must use brushed or brushless electric motors	S
	Stored energy must not exceed 100 Watt-hours per battery pack	S
	Current rating of fuse must not exceed 100A	S
	All energy for take-off must come from the on-board propulsion battery pack(s).	S
	Aircraft must enter staging box with propulsion battery packs and payloads removed	S
Structure	Aircraft must be able to carry X-1 test vehicle and fuel tanks	S
	Pylons must be a non-permanent feature of the airplane	S
	All components must be secured properly	S
	No magnet only latches are allowed, all hatches must have a mechanical latch	S
	Aircraft must be able to withstand a wingtip load of 2.5G's during tech inspection	S
	Empty and loaded CG's must be properly marked on the aircraft	S
X-1 Glider	Cannot be radio controlled	S
	Must be carried underneath the airplane fuselage between the left and right external fuel tank	S
	Release mechanism must be radio controlled	S
	Must be launched at an altitude between 200 - 400 ft (AGL) upon command of the pilot's transmitter	S
	Must achieve stable flight autonomously and execute a 180 degree turn	S
	Must have implemented strobe lights which activate upon release of the glider	S
	Strobe lights must remain flashing upon landing	S
	Weight must not exceed 0.55 lbf.	S
	Must be secured to the aircraft during all phases of the flight	S
	Distance of 0.25 inches must be maintained between X-1 wings and any part of the aircraft	S
Fuel Tank	Minimum of two external fuel tanks are required	S
	Fuel tanks must be unmodified commercially available beverage bottles with screw-on caps	S
	All external fuel tanks must be of the same size, shape, and brand	S
	External fuel tanks must have a minimum capacity of 16 fluid ounces	S
	External fuel tanks will be attached to the plane using removable pylons	S
Pylons	External fuel tanks must be completely visible from the front and rear	S
	Must securely attach fuel tanks during all phases of flight	S
	Must be removeable and not a permanent feature	S
	Must attach a single fuel tank per each pylon	S
	Must be able to be installed within timed mission	S

Table 4. Design Allowances

Category	Allowance
Propulsion	Propellers may be changed for each flight attempt
	Batteries may be changed for each flight attempt
	Propellers may be modified
	May use any singular battery chemistry
Payload	An internal fuel tank is optional with no restriction on capacity
	May include an autopilot/flight control with or without GPS on the X-1 test vehicle only
	Multiple X-1 test vehicles may be brought to achieve a desired mission score for any mission attempt.
	If a bomb bay opening is implemented for X-1 attachment, it must be covered with a permanently attached cover
	The fuel tanks may carry varying amounts of inert materials.
	Fuel tanks may a bottle adapter to facilitate a mechanical connection between pylon and bottle
	May attach pylons to 0.25 in. threaded holes or hatched access internal structure

Table 5. High Scoring Design Requirements

Mission	Objective	Sub-system Requirements
M1	• Complete 3 laps within 5 minutes	• Stable flight configuration without payload
M2	• Minimize time to fly 3 laps • Maximize weight carried in the fuel tanks	• High strength attachments for fuel tanks • High cruise velocity in straight and level flight • Rapid acceleration when exiting turns • High lift devices
M3	• Maximize number of laps flown in 5 minutes • Release X-1 during final lap • Autonomously land X-1 in bonus box before completing final lap	• High propulsive efficiency and low drag • Rapid acceleration when exiting turns • Accurate autonomous X-1 navigation system • High luminosity X-1 strobe lights
GM	• Install pylons, empty fuel tanks, and X-1 while being timed • Demonstrate X-1 release mechanism	• Quick attachment mechanisms for X-1, pylons and fuel tanks • Reliable X-1 release mechanism

3.3 Sensitivity Study of Design Parameters

Calculations were performed using a MATLAB script to analyze how various design parameters influenced aircraft performance. The script utilized an iterative approach to model a variety of aircraft configurations. A sensitivity analysis was performed based on the calculations by analyzing how a change in each design parameter influenced total mission score. The analysis concluded that variations in fuel weight, maximum load factor, and X-1 weight correlated to the largest variation of total competition score, as shown in Fig. 5.

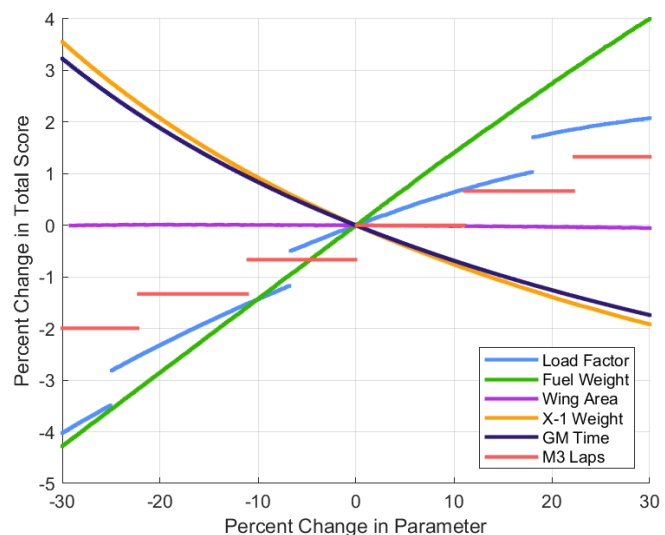


Figure 5. Scoring Sensitivity Analysis

When competing with a constant fuel weight, variation of the wing area proved to have minimal impact on total score, whereas increasing wing area enhanced turning performance due to greater lift generation, while simultaneously diminishing performance in straight flight due to increased drag; this resulted in a small change in lap time which did not influence the total number of laps flown during M3, while marginally influencing M2 score. Consequently, a higher wing area was advantageous, allowing for higher fuel weight during M2, while having a limited consequence on M3 score.

The number of laps flown during M3 was shown to be less sensitive than other parameters analyzed given that it is scored as an integer. Aircraft parameters were varied, resulting in no change in M3 score based on the number of laps remaining constant. This is indicated by the discontinuous nature of load factor on mission score, where the figure shows the sum of both M2 and M3 variations.

3.4 Concept Weighting and Selection Process

Throughout the aircraft configuration down select process, UB DBF employed a series of weighted decision matrices to assess key design considerations from a variety of comprehensive perspectives: Raymer's Aircraft Design [2], past competition experience, sensitivity analysis results, and research studies. The relevant figures of merit (FOM) and the reasoning behind their selection are outlined in Table 6.

Table 6. Reasoning behind FOM

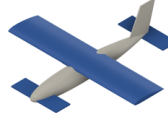
FOM	Reasoning
Stability & Control	Ensuring reliable mission performance is critical to success.
Stall Characteristics	Not recovering from stalls, should they happen, is equivalent to competition failure.
Turning Performance	Significance of turning was a significant outcome of the sensitivity analysis.
Payload Accommodation	Designs must be cohesive with the X-1 glider and fuel tank requirements.
Manufacturability	Conserving testing time and maintaining quality and precision is important, even if not as much as favorable mission performance.
Weight	Should be minimized to increase in-flight performance, fuel weight, and endurance; for the case of the X-1 glider, bonus score.
Drag	Increase endurance, airspeed, and performance.
Durability	Good M2 performance relies on the ability to withstand high landing loads.
Energy Consumption	Should be minimized to increase efficiency and flight time.
Ground Clearance	Prop strikes on landing should be avoided.
Roll Response	Roll rates should be maximized to increasing turning performance and reduce lap times.
Staging Time	Should be minimized to improve GM score, the most sensitive of all missions.

Weights for each FOM ranged from 1 to 5, where 5 means strongly satisfied and 1 means weakly satisfied. Similarly, ranked configurations were graded on a scale of 0 to 5 for how well they satisfied a particular FOM. The resulting quantities were multiplied and summed across all FOM, and the configuration with the highest total was ultimately selected with 1 being the best. Nonetheless, all design considerations were meticulously reviewed to ensure there were no oversights. Specific aircraft sizing was avoided until Section 4, so designs were assessed qualitatively.

3.4.1 Lifting Surface Configuration

Since the layout of the lifting surfaces impacts every other aspect of design, it was evaluated first. Four configurations were evaluated: conventional, canard, biplane, and three-surface. Ultimately, a conventional configuration with a forward main wing and rearward horizontal stabilizer was chosen. The conventional design has the benefit of having the CG range align with the practical longitudinal location for wing-mounted fuel tanks, which allows for minimal CG change across various fuel tank installations. This is reflected by the scores for Payload Accommodation shown in Table 7.

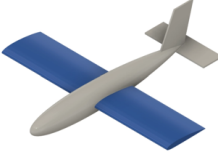
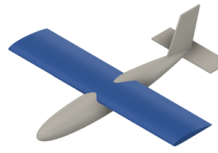
Table 7. Lifting Surface Configuration

					
FOM	Weight	Conventional	Canard	Biplane	Three-Surface
Stability & Control	5	5	3	5	5
Stall Characteristics	2	3	5	3	5
Turning Performance	2	3	5	5	3
Weight	2	3	3	5	3
Drag	2	3	5	1	3
Manufacturability	3	5	4	1	3
Payload Accommodation	5	5	1	3	3
Total		89	68	71	77
Rank		1	3	4	2

3.4.2 Wing Placement

Benefits across the board drove UB DBF to select a high wing (see Table 8). It provides inherently favorable propeller clearance, stability characteristics, and easily integrates with the fuselage with minimum wetted area. Moreover, the greater fuselage volume underneath a high wing allowed for straightforward integration of the X-1 release mechanism.

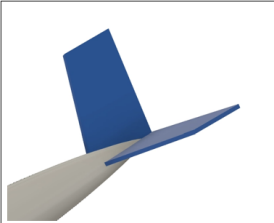
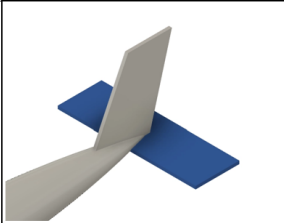
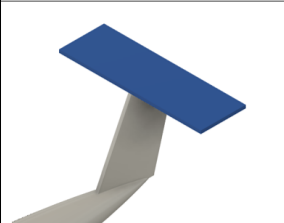
Table 8. Wing Placement

				
FOM	Weight	Low	Middle	High
Stability & Control	4	4	4	5
Manufacturability	2	5	2	5
Ground Clearance	3	3	4	5
Payload Accommodation	5	4	3	5
Total		55	47	70
Rank		2	3	1

3.4.3 Tail Configuration

A conventional tail was chosen because of its acceptable drag, weight, manufacturability, and good stall characteristics (see Table 9). Since the DBF circuit requires tight turns at high angles of attack, the tail must retain good control even if the wing is stalled. This negatively impacts the score of T-tails and to a lesser degree, V-tails. In contrast, a conventional tail provides excellent control in a stall, provided the vertical stabilizer is not blanketed by the wake of the horizontal stabilizer.

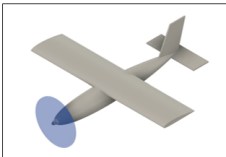
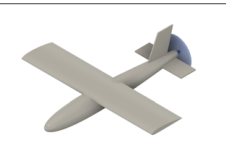
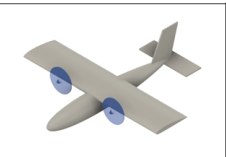
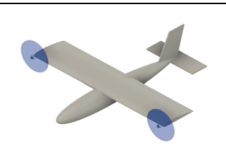
Table 9. Tail Configuration

				
FOM	Weight	V-Tail	Conventional	T-Tail
Drag	3	4	4	5
Manufacturability	3	2	3	3
Stall Characteristics	5	3	5	1
Weight	5	5	3	1
	Total	58	61	34
	Rank	2	1	3

3.4.4 Propulsion Configuration

Propulsion configurations were addressed in Table 10 with a dual wingtip configuration winning out because of its best payload integration, stability, and control characteristics. The single pusher design carried the risk of the X-1 glider colliding with the propeller blade upon release and complications in designing for longitudinal static stability. The twin tractor design has been observed to have slightly worse propulsive efficiency and interferes with the placement of both external fuel tanks and the X-1 glider.

Table 10. Propulsion Configuration

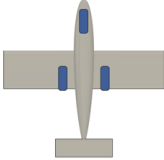
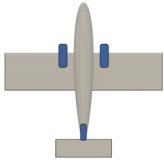
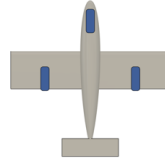
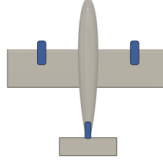
					
FOM	Weight	Single Tractor	Single Pusher	Twin Tractor	Dual Wingtip
Stability & Control	3	3	1	5	5
Energy Consumption	5	4	4	3	4
Manufacturability	2	5	4	4	3
Payload Accommodation	5	4	1	3	5
	Total	59	36	53	66
	Rank	2	4	3	1

Setting aside the detriment of P-factor and unbalanced propeller torque, the single tractor could have followed two distinct design paths: mounting X-1 at the fuselage and idling the motor prior to release or mounting X-1 outboard and the fuel tanks further out. Either case is less than ideal. Wingtip-mounted propulsion avoids any interference with fuel tanks or X-1. Furthermore, the reduction in induced drag from propeller slipstream interactions with the wingtip vortices is hypothesized to balance out the reduced propulsive efficiency of the twin configurations.

3.4.5 Landing Gear Placement

Landing gear configurations were compared for taildragger and tricycle configurations, with both a *wide-stance* gear mounted on the wing and a fuselage mounted *arch* gear. UB DBF selected a fuselage-mounted taildragger configuration, for its excellent durability, weight, and drag (see Table 11). Wide-stance gear would have come with the benefit of less interference drag, but this benefit was outweighed by the increased weight and manufacturing difficulty associated with custom-built gear struts. Fuselage-mounted gear allows for an off-the-shelf *arch* style gear, which is strong, easy to install, and replace. Ease of ground handling was omitted from the FOMs due to the pilot's competence with both taildragger and tricycle gear aircrafts.

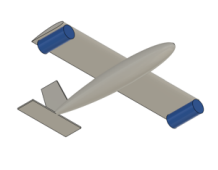
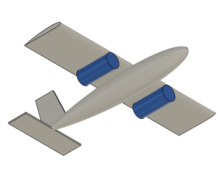
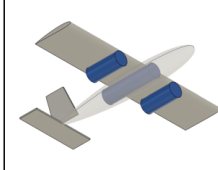
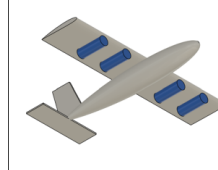
Table 11. Landing Gear Design

					
FOM	Weight	Tricycle	Taildragger	Wide-Stance Tricycle	Wide-Stance Taildragger
Durability	5	3	5	2	2
Weight	2	4	5	3	4
Drag	3	3	4	3	5
Manufacturability	2	5	5	3	3
Payload Accommodation	4	3	4	5	5
Total		54	73	51	59
Rank		2	1	3	2

3.4.6 Fuel Tank Configuration

The fuel tank configuration was selected to be exclusively wing-mounted, consisting of only two fuel tanks (see Table 12). Having fewer fuel tanks minimizes drag due to the surface-area-to-volume relationship when an object is scaled. Fuel tanks in the fuselage were rejected because of the increased number of steps for installation during the GM. Wingtip mounted fuel tanks offered a favorable load distribution, but would greatly decrease the roll rate of the aircraft, which is a key parameter for performing the highly dynamic DBF circuit. Positioning the fuel tanks closer to the wing root reduces the moment of inertia about the roll axis and will thus improve the roll rate.

Table 12. Fuel Tank Design

					
FOM	Weight	Wingtip	Inboard	Fuselage + Inboard	Four on the Wing
Impact on Roll Rate	3	1	4	5	2
Drag	2	4	4	5	4
Structure	2	5	3	2	5
Ease of Installation	5	5	5	1	1
	Total	46	51	34	29
	Rank	2	1	3	4

3.4.7 Full Conceptual Design

Through comparing the options for each aspect of the design, UB DBF selected a conventional, high-wing taildragger with wingtip-mounted motors and two fuel tanks mounted close to the wing root (see Fig. 6).

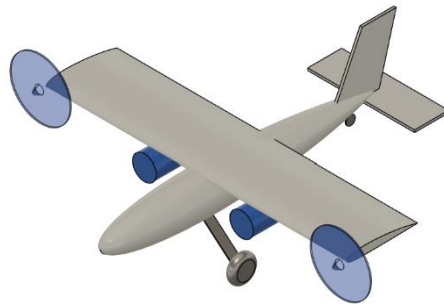


Figure 6. Full Conceptual Design

4. Preliminary Design

The aim of the preliminary design phase was to define and size key aircraft parameters for the configuration conceived during conceptual design. To that end, trade studies and analyses concerning propulsion, weight, and aerodynamics were conducted and the results integrated into a MATLAB-based scoring optimization algorithm. The predicted mission performance and design parameters are summarized in Section 4.6.

4.1 Design and Analysis Methodology

Observing the sensitivity analysis and previous experience, the critical parameters to be optimized were determined to be the wing area, wing aspect ratio, wing loading, fuel tank weight, X-1 weight, and the propulsion configuration. First, trade studies were conducted to size and refine those parameters. Subsequently, aerodynamic and stability models were developed in XFLR5 [3] and OpenVSP [4] and used in conjunction with the MATLAB-based [5] optimization script and SolidWorks [6] to specify the remaining aircraft parameters: weight, wing planform, and tail sizing to strike an optimal balance between M2 and M3.

Afterward, V1 was developed and tested whilst collecting airspeed, power, and inertial measurement data to reconfigure into the optimization and propulsion model. The critical design parameters were then reanalyzed for optimal scoring, and the aircraft was resized for V2 such that only minor design changes would be implemented for V3, the competition plane, whilst ensuring compliance with all system and subsystem requirements and allowances. The aircraft design and analysis methodology are summarized in Fig. 7 below.

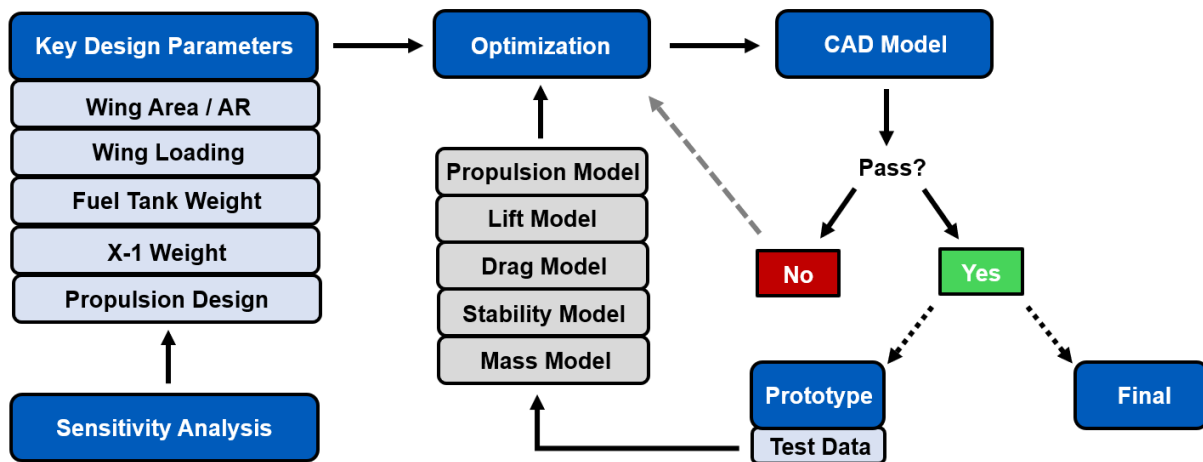


Figure 7. Design and Analysis Methodology

GM and X-1 release operations were feasibly testable, independent of their applications on aircraft prototypes, so they were iterative improved upon by themselves to bring out the best result. On V2 and V3, the most updated designs will be implemented to ensure the highest possible score.

4.2 Optimization

An iterative “trial and error” approach was implemented in a MATLAB script to compare multiple aircraft configurations based on wing area, fuel tank weight, and propeller sizing. The script discretized design parameters over ranges of values (judged feasible based on previous competitions), which were then evaluated through a series of constraints such as excessive power draw or stall speed. Configurations that failed to satisfy any constraint were removed from consideration.

The script was structured by utilizing team written functions that modeled stages of flight including takeoff, climb, turning, and straight-line flight. These functions receive inputs describing the aircraft configuration and initial velocity, which then output parameters such as energy consumption, time duration, and final velocity. The functions were used sequentially such that output conditions of one function were used to simulate the input conditions of the following function. For instance, the velocity calculated after takeoff was used as an input to model climb performance.

Second order differential equations that model the aircraft dynamics were derived from the free body diagrams in Fig. 8 below. The optimization functions described below utilize a 4th order accurate Runge-Kutta method to approximate solutions to these differential equations, yielding solutions for time, velocity, and energy for all stages of flight.

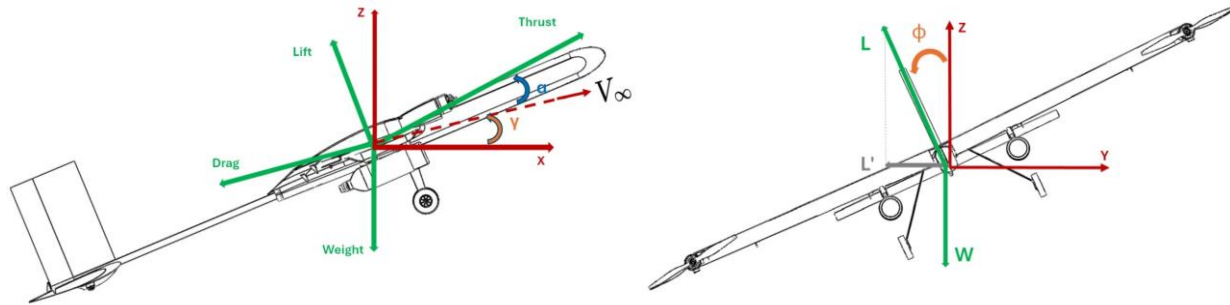


Figure 8. Free Body Diagrams

Takeoff Calculator: Assumes a takeoff speed of 120% of the stall speed to avoid porpoising and 100% throttle.

Climb: Assumes the aircraft will climb at a constant angle from the point of takeoff and the first turn and will reach an elevation of 100 ft. Aircraft that cannot reach this elevation receive a failing score. This constraint was carefully inspected to observe whether configurations failed for reasons other than excessively high wing loading.

Turning: Assumes the aircraft will turn at a calculated load factor. If lift generation is insufficient to do so, then the aircraft will turn at a bank angle which yields a lift coefficient 90% of the assumed maximum. Load factor was later calculated by comparing experimental turning conditions with conditions of each iterated configuration such that load factor was inversely proportional to wing loading.

Straight Flight: Assumes stable and level flight conditions at a constant throttle.

4.2.1 Initial Propulsion Model

The propulsion system performance was initially approximated by curve fitting third order polynomials to APC performance [7] and UIUC [8] propeller test data. The polynomials were found for a variety of different propeller sizes that related thrust and power draw as functions of velocity, where the power was corrected for electrical inefficiencies. The optimization script then iterated between each propeller, while varying desired throttle for M2 and M3, to determine the optimal propeller size and corresponding RPM for both missions. This method was conducted for both single and dual propeller configurations and found minimal variation in performance when comparing the optimal single and dual propeller choices, validating the conceptual design configuration choice.

4.2.2 MATLAB Mass Model

A MATLAB script was written to approximate the empty weight of the aircraft for a variety of wing areas. The script accounted for varying tail dimensions to maintain a constant tail volume with changing wing area. The script assumed horizontal and vertical tail volumes based on previous competitions, which were later re-evaluated to achieve a desired margin of stability. Additionally, fuselage length varied along with tail size such that the motors and batteries could be used to balance the CG of the aircraft about the 25% MAC point when mounted in the nose.

The calculator approximated wing and tail surface weight by using simplified geometries to find volume and surface area of each profile. The volume was then used to calculate the weight of the foam core, while surface area was used to determine the weight of the carbon fiber skin. Servo weight was accounted for in the elevator, rudder, ailerons, and flaps. The tail boom weight was calculated as a function of length by using the linear density of a carbon fiber tube. The fuselage weight was approximated similarly by calculating the linear density of a carbon fiber shell with an assumed cross section. Lastly, the electronics weight was estimated by using typical values from previous competitions.

4.2.3 Design and Analysis Uncertainties

While calculations were performed simulating weather conditions in Tucson, AZ, flight data was gathered in Buffalo, NY, which is a different environment than where the competition is held. This resulted in variations in propulsive and aerodynamic performance considering the 24% difference in air densities at these two locations. Additionally, calculations assumed zero cross winds, while winds at the test site often surpassed 20 mph (29.33 ft/s).

Other notable sources of uncertainty included assumptions made to model aircraft performance during optimization, specifically concerning lift and drag given the lack of high-fidelity CFD simulations or wind tunnel testing. Vortex lattice method solvers such as OpenVSP assumed potential flow and neglected the turbulent boundary layer; as such, empirical methods were applied instead to estimate drag. For initial optimization results, an inflated estimate of 0.032 was assumed for the parasitic drag coefficient to account for interference drag between the landing gear, X-1 glider, and fuel tanks.

After test flights from V1, the recorded data was used to make small adjustments to the optimization code, such that calculations better approximated actual conditions. Such changes included propulsive efficiency and the aforementioned load factor calculation.

4.3 Trade Studies

4.3.1 Wing Area and Wing Aspect Ratio

Fig. 9 indicates how AR and total fuel weight influence total mission score, noting that the full allowable wingspan of 6 ft was used for all configurations analyzed. The highest scoring configuration (25.33 lbf. of payload weight and AR of 3.99) is marked by a yellow star in the figure. Since V1 had an AR of 4.03 and the difference in score between configurations was 0.2%, the same wing area was retained for V2 to simplify analytical comparisons. Fig. 9 shows a mission failure at an AR of 3.53 or lower due to endurance limitations.

To ensure feasible landing conditions, aircraft configurations with stall speeds greater than 50 ft/s were considered as failed configurations. Fig. 9 indicates that lower AR values allowed for greater fuel weight due to increased wing area contributing to lower wing loading. This resulted in an optimal AR for M2 that was well below that of M3, as the fuel weight is a significant scoring parameter for the mission.

The number of laps flown during M3 is influenced by both cruise and turning performance. High ARs yield an aircraft design with optimal cruise performance; conversely, low ARs support aircraft with more optimal turning performance. The optimization found that ARs between 3.99 and 8.65 could fly the greatest number of laps when utilizing the optimal propulsive configuration, as shown in Fig. 10.

Ultimately, tailoring the aircraft towards M3 was more beneficial for overall aircraft performance, since the increased fuel weight required additional fuel tank capacity and increased airframe strength, resulting in greater overall weight and drag. Furthermore, because wingtip vortices increase at AR values lower than 4 due to the relatively short span, Prandtl's lifting line theory [8] becomes less applicable and induced drag and pitching moments rise substantially.

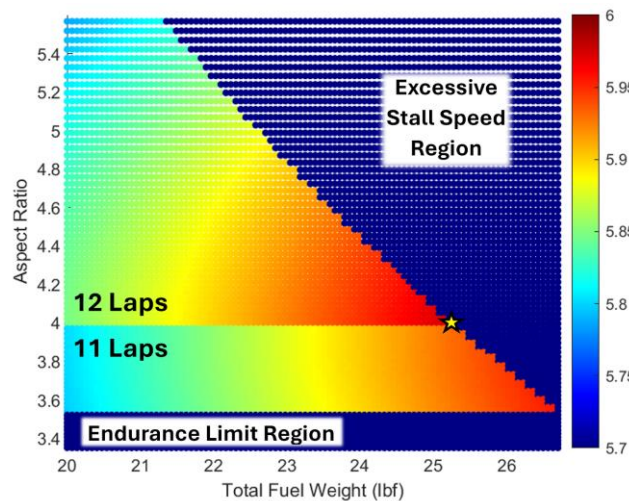


Figure 9. Aspect Ratio vs. Fuel Weight

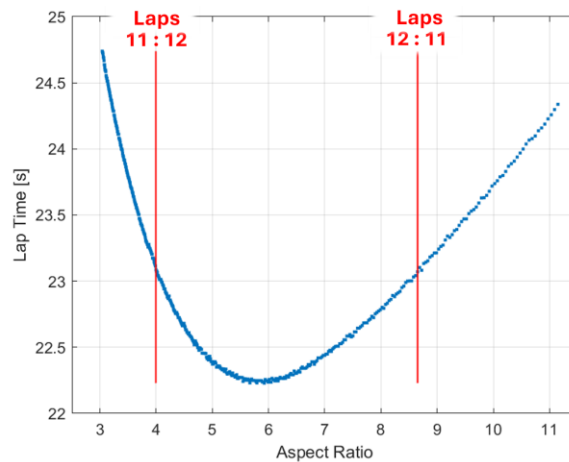


Figure 10. Lap Time vs. Aspect Ratio

4.3.2 Fuel Tank Profile

An analysis was conducted to compare several mixer and binder options that could be used as weight in the fuel tanks. Eq. 7 was used to calculate the expected fuel weight for any given bottle capacity. The packing factor (PF) was determined experimentally by comparing the density of an arbitrary material with the density of that material randomly assorted and granulated. Fig. 11 shows how fuel weight varies with bottle capacity for each material and binder combination considered. Each mixer and binder combination was evaluated at discrete

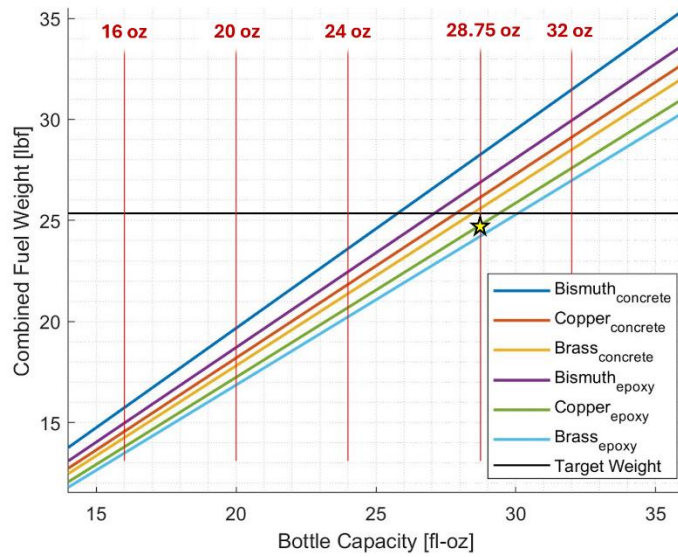


Figure 11. Payload Weight vs Bottle Capacity

bottle capacities found to be commercially available. The two options that most closely resulted in a target weight of 25.25 lbf. were brass mixed with concrete and copper mixed with epoxy; both options required a bottle with a 28.75 fl-oz capacity. Ultimately, copper mixed with epoxy was selected despite being slightly lighter due to the challenges involved with properly mixing with cement to achieve a high packing factor.

$$W_{fuel} = 2V_{bottle} \times [\rho_{mixer}PF + \rho_{binder}(1 - PF)] \quad (7)$$

To get a better understanding of how bottle profile affects drag force, CFD was conducted using ANSYS Fluent [9] to compare bottles of varying diameters given the volume constraint of 28.75 oz enforced for all profiles. The analysis assumed an airspeed of 130 ft/s and bottles were oriented such that the bottle cap faced the trailing edge. As shown in Fig. 12, the results showed that using thinner and longer bottles was the best approach to reduce drag, which led to the selection of the Glaceau Smart Water 850 mL (28.75 oz) bottle for the external tanks.

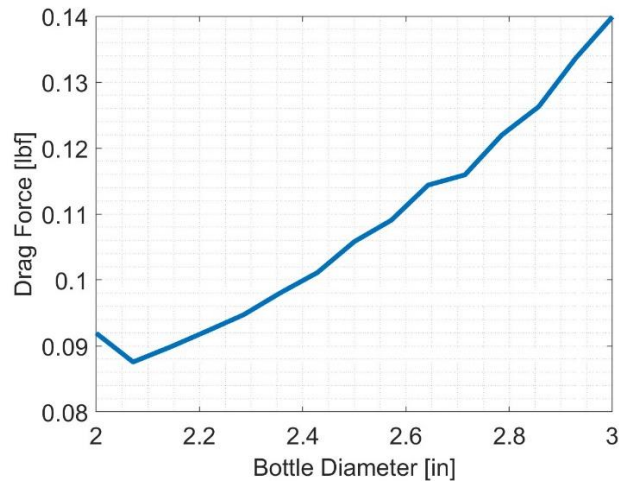


Figure 12: Drag Force vs. Bottle Diameter

4.3.3 X-1 Weight

An analysis was conducted to determine how the X-1 guidance, navigation, and control strategies influenced M3 scores. The methods considered included an empty glider trimmed to fly in a spiral descent, a glider utilizing an Arduino Nano and GPS for navigation, and a glider utilizing ArduPilot's failsafe feature. Fig. 13 shows how bonus box score has a more significant impact on M3 score than X-1 weight. While an empty trimmed glider has the greatest scoring potential, it was deemed impractical when considering the consequences of not receiving the highest bonus box score,

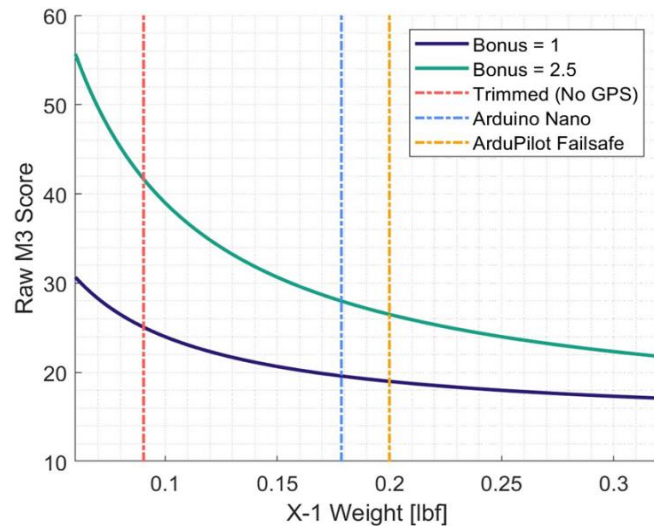


Figure 13. X-1 Weight Scoring Sensitivity

which would be a probable outcome when utilizing this strategy. While using an Arduino Nano and ArduPilot's failsafe feature would yield similar M3 scores, ultimately an Arduino Nano was determined to be the optimal approach due to Ardupilot's limited ability to customize flightpath.

The X-1 weight was estimated for each design strategy by summing an approximated empty weight with the weight of the hardware required for each configuration. The empty weight was estimated by calculating the volume of X-1 when using expected dimensions for wingspan, chord, tail volume, and fuselage profile. This volume was then multiplied by the density of EPP foam, which will be used to make the glider.

4.3.4 Propulsion Design and Sizing

This section details the selection process of the propulsion battery, motors, and propellers to maximize the total mission score.

4.3.4.1 Propulsion Power

Initial optimization results indicated that the total mission score grew without bound as maximum propulsion supply power increased (within practical limits) because M2 proved to not be energy-limited. Higher power draw implies higher thrust and airspeed, therefore M2 could be successfully completed in a shorter time by sizing for higher power.

$$P = U * I \quad (8)$$

Observing Eq. 8, power (P) is the product of voltage (U) and current (I). Noting that the nominal current rating of the arming fuse theoretically constrains the supply current to 100 A, the maximum supply power

can be increased by selecting a higher voltage system. Despite that premise, other considerations warranted a thorough survey into commercially available flight packs spanning a wide range of voltages. The key characteristics of the assessed packs are summarized in Table 13.

The 12S flight pack was neglected because of reliability concerns: high voltage sag under load due to the low amp-hour capacity and the unknown reduction in overall capacity that accompanies it. The 10S flight pack faced the same hurdle; moreover, its capacity of 83.25 Wh was deemed too far below the 100 Wh limit. Stepping the voltage down further, the GAONENG 8S 3300 mAh pack was ultimately selected as it met all the requirements.

Table 13: Flight Pack Selection Characteristics

Flight Pack	Cell Count	Capacity [Wh]	Nominal Power [W]
Tattu R-Line 6S 4500mAh 95C	6	99.90	2220
GAONENG GNB 8S 29.6V 3300mAh 100C	8	97.68	2960
MaxAmps 2250mAh 10S 37 V Pack	10	83.25	3700
MaxAmps 2250mAh 12S 44.4 V Pack	12	99.90	4440

4.3.4.2 Propeller and Motor Sizing

Twenty-three propellers were iterated upon within the first optimization run, where the maximum RPM was constrained by the nominal power limit given in Table 13. Inspecting the results shown in Fig. 14, both M2 and M3 favored higher pitch propellers. These higher-pitch propellers operate optimally between 75 and 140 ft/s, with the 13x10E propeller winning out overall. Conversely, low-pitch propellers that are superior during takeoff and climb scored poorly, agreeing with the intuition that the static thrust required isn't a critical parameter when the takeoff distance is not constrained.

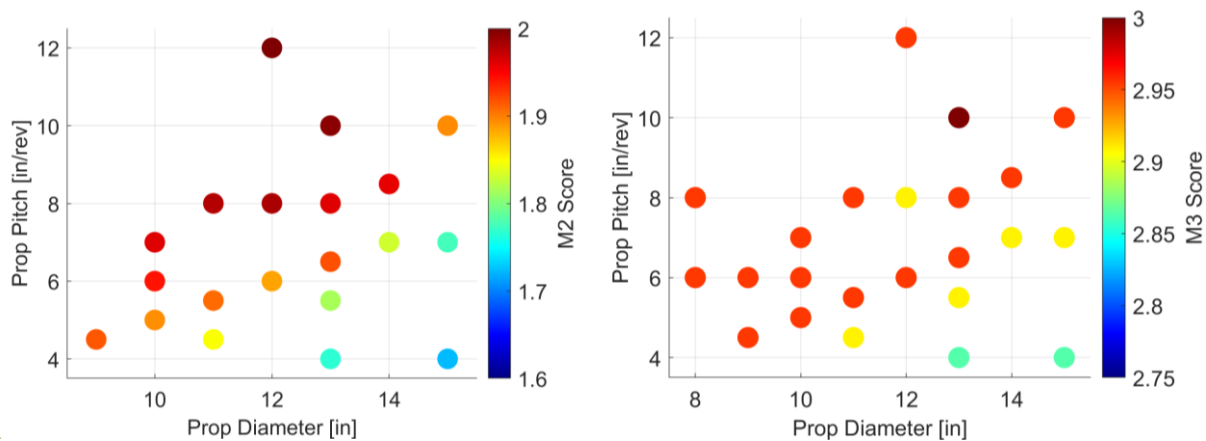


Figure 14: Propeller Sizing Impact on M2 (Left) and M3 (Right)

Initial motor sizing was done for 13x10Es by compiling a list of motors with Kv-ratings ranging from 470 – 520 and matching propeller performance curves with the expected torque and RPM from provided

manufacturer specifications. By drawing inferences from the published test data [10], the Brotherhobby Tornado T7 4215 520 Kv motors were ultimately selected.

Because the best scoring propellers —13x10Es, 12x12Es, and 13x8Es— had similar projected scores and loadings, UB DBF's strategy was to create a refined propulsion model featuring the selected motors by applying power and RPM data collected on V1 and brushless synchronous permanent magnet machine theory [11] to re-run scoring simulations and re-evaluate the optimal propeller configuration for each mission. The results are summarized by the electrical efficiency map shown in Fig. 15, where the fitted static propeller curves and the on-ground (**black**) and in-air load line curves (**black dashed**) intersections constrain the RPM such that the thermally-limited torque (**red dashed**) isn't surpassed. Load line curves reveal the drop off in RPM with load current and are related to the system impedance and stall torque. As propellers unload in-flight, the static propeller curves shift down to enforce a net RPM and efficiency gain.

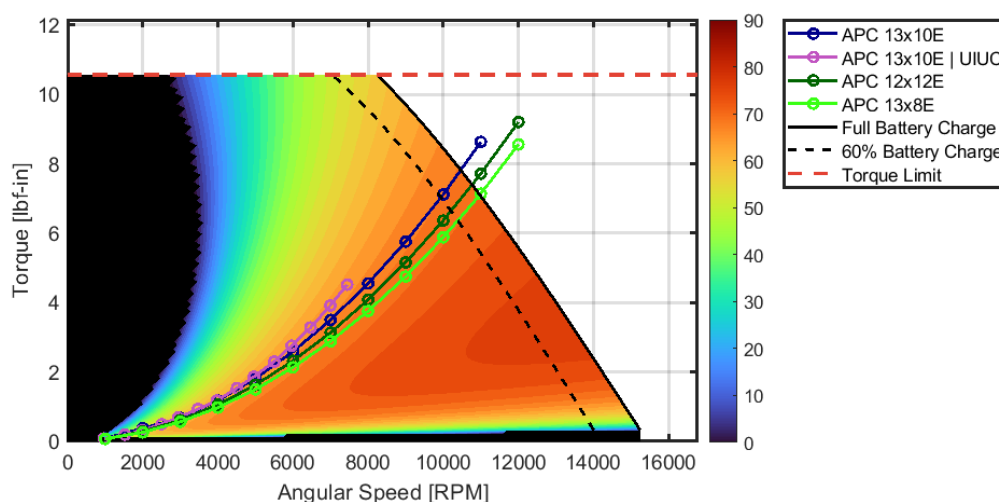


Figure 15: Electrical Efficiency Map

Non-intuitively, APC 13x10Es were again deemed optimal for both M2 and M3 despite being less efficient as they yielded faster lap times by providing better acceleration out of turns than 12x12Es and higher top airspeeds than 13x8Es. By sizing for a lower Kv, the efficiency in M3 would increase but not without the drawback of reduced M2 RPM. Because total score was more sensitive in M2 than M3, UB DBF followed through with the originally chosen motors.

4.4 Aerodynamics and Stability

4.4.1 Wing Airfoil Selection

Wing airfoils dictate the performance capabilities of aircraft and need to be selected with mission requirements in mind. Owing to UB DBF's manufacturing strategy, the minimum airfoil thickness was limited to 10% to prevent foam core from collapsing on the wire channels under vacuum. Given that constraint,

twenty airfoils with diverse characteristics were analyzed at Reynold's numbers ranging from 200,000 to 1,200,000 in the aerodynamic analysis tool XFLR5: Five of the analyzed airfoils with favorable characteristics are shown in Fig. 16.

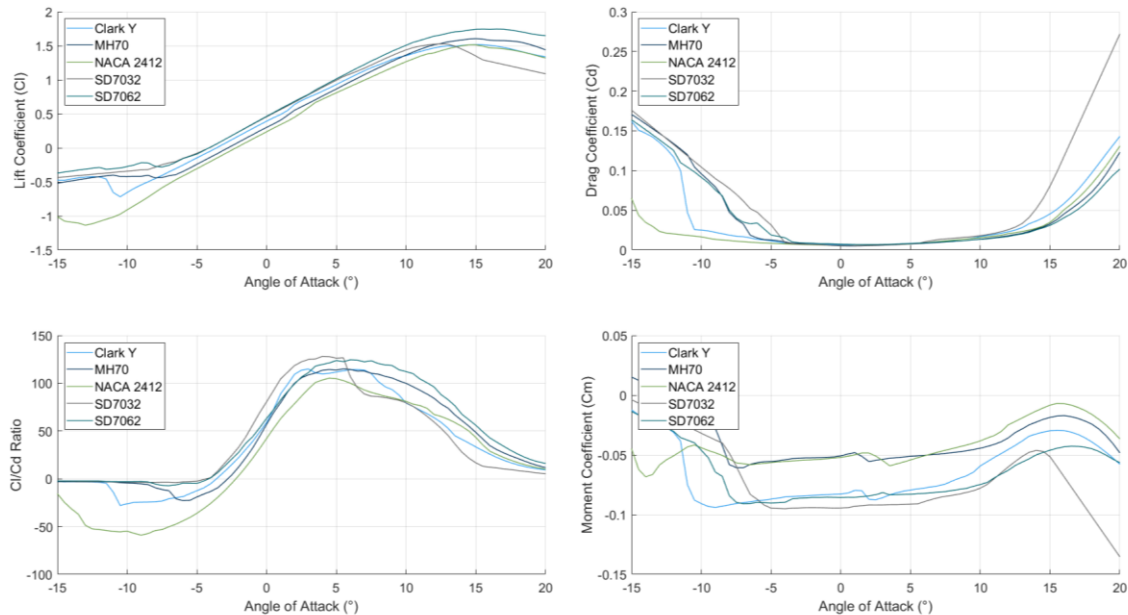


Figure 16. Airfoil Coefficients at $Re = 1,000,000$

Aerodynamic efficiency in the form of high lift-to-drag ratio and low drag was prioritized over a high maximum lift coefficient. Takeoff, climb, landing, and turning are flight regimes that sustain high lift, and scoring analysis results indicated that the latter two were particularly impactful on scoring. Nonetheless, the need for a high maximum lift coefficient was easily bypassed: the low AR design and wingtip-mounted motors [13] reduced the stall tendency in a turn while high lift devices helped minimize landing speeds. The SD7032, which was ultimately chosen, would consume approximately 2.9 Wh less energy in M3 than the MH70 and SD7062, and has a lift-to-drag ratio of 130, greater than the NACA 2412 and Clark Y.

4.4.2 Wing Analysis

Wing washout sacrifices performance for reliability and favorable stall behavior, and based on previous experience, UB DBF decided that the tradeoff was paramount to the success of Bull Shark even with wingtip motors. In a deviation from the prototype, the wing was designed to have 2° of washout instead of 3° because the plane showed little indication of tip stalling during flight testing.

XFLR5 was then used to analyze twisted wings of different planforms with the chosen wing area from Section 4.3.1. Due to the low AR, differences in pitching moment and lift coefficient slope were minimal, as shown in Fig. 17, so UB DBF went with a taper ratio of 0.78 to reuse the same tooling as for V1. Furthermore, 2° of dihedral were added to augment roll stability and make the pilot more assured during M2 in particular.

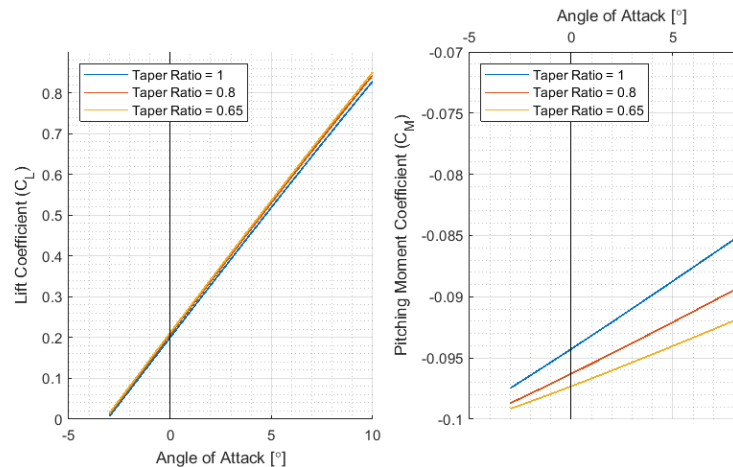


Figure 17. Wing Taper Ratio Analysis

4.4.3 Tail Sizing

The empennage design began by addressing the impact of the tail moment arm length on the empty weight of the aircraft using the MATLAB mass model. The relationship is presented by Fig. 18, where differently sized horizontal stabilizer planforms are expressed in terms of traditional horizontal tail volume coefficients. Previous UB DBF experience with the SD7032 airfoil suggested that a C_{HT} of approximately 0.40 would have been sufficient, but that estimate relied on aircraft with a wing AR greater than 4. At an AR of 4, the stick-fixed neutral point shifts forward because the relatively short span impairs the wing's lift distribution and increases the nose-up tendency of the aircraft [8], so the V1 prototype was sized to a C_{HT} of 0.54 (13% static margin). The V1 prototype was exceptionally stable in pitch, so the tail sizing was retained for V2. Typically, the AR of horizontal stabilizers of subsonic aircraft are designed to be half the AR of the main wing for stall recovery [2]. However, because the horizontal tail was placed below the wing, where aircraft don't observe a pitch-up tendency at stall at subsonic speeds [8], Bull Shark's horizontal stabilizer was safely sized to an AR of 2.86 for minor weight and efficiency benefits. Drawing on inspiration from [2] [8], the vertical stabilizer was sized to a C_{VT} of 0.04 and was positioned such that at most a third of the rudder was blanketed by the wake from the horizontal tail.

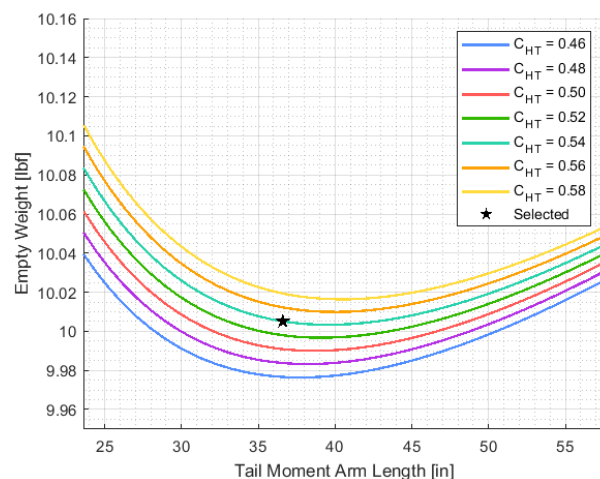


Figure 18. Empty Weight vs. Horizontal Stabilizer Sizing

Observing Fig. 19, the Bull Shark was determined to be longitudinally statically stable irrespective of the solver used [4] [15] because the zero-lift pitching moments (C_{M0}) and pitching moment slopes (C_{ma}) are positive and negative, respectively. Since the fuel tanks and X-1 were designed to be placed at 25% of the mean aerodynamic chord (MAC) for M2 and M3, the pitching moment characteristics would vary slightly between M2 and M3 because of changes to the vertical C.G. location and throttle percentage. Observing Table 14, Bull Shark was furthermore evaluated to be laterally stable for each mission using OpenVSP as the yawing moment coefficient derivative with respect to sideslip ($C_{n\beta}$) and dihedral effect ($C_{l\beta}$) are positive and negative, respectively.

4.4.4 Trim Conditions

Due to the conflicting requirements for cruise airspeeds and gross weights between M2 and M3, it was critical to evaluate the aircraft trim to prevent one or both flight missions from operating sub-optimally. Trim was evaluated in OpenVSP by independently adjusting the wing incidence angle for each mission to adhere to the lift coefficient (C_L) required at cruise and iteratively adjusting the tail incidence and elevator deflection (δ_e) angles until the pitching moment coefficient (C_M) was 0. An inverted NACA2409 was chosen as the tail airfoil over a symmetric airfoil to further reduce drag in cruise.

Table 15. Longitudinal Aircraft Trim Conditions

Mission	Wing Incidence [°]	Tail Incidence [°]	M2 α [°]	M3 α [°]	M2 δ_e [°]	M3 δ_e [°]
M2	1.30	-0.20	0.00	-1.10	0.00	1.50
M3	-0.45	-1.10	1.55	0.00	-2.00	0.00

For selecting the trim conditions, M2 was favored over M3 as it takes the plane longer to accelerate to its cruise velocity in M2 in addition to the fact that the profile drag from the fuel tanks and X-1 glider are considerable enough to merit attention. Given the relative proximities of the mission-optimized wing incidence angles documented in Table 15, favoring M2 trim conditions inadvertently also benefited M3 prior

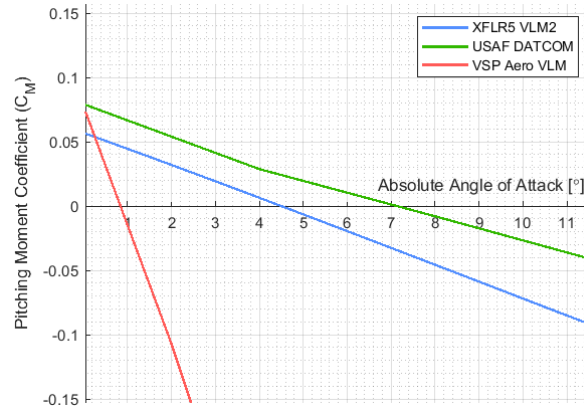


Figure 19. Pitching Moment Coefficient vs. Angle of Attack

Table 14. Lateral Stability Derivatives

Mission	$C_{n\beta}$ [rad ⁻¹]	$C_{l\beta}$ [rad ⁻¹]
M1	0.109	-0.0023
M2	0.109	-0.0075
M3	0.109	-0.0024

to reaching its cruise airspeed. Overall, the selected trim conditions reduced the estimated M2 flight time without impacting the M3 lap count.

4.4.5 Lift Analysis

Using the method outlined in [13], the OpenVSP VLM and disk-actuator models were combined to calculate the aircraft lift with outboard spinning wingtip propellers. The resulting half span wing lift distribution for M1, M2, and M3 at their respective cruise airspeeds of 110 ft/s, 132 ft/s, and 110 ft/s are plotted in Fig. 20.

The maximum lift coefficient and stall angle of attack were then estimated using a USAF DATCOM method [14], which involved using a VLM solver to find the angle of attack at which the section lift coefficient at the wing root was equivalent to the 2D maximum lift coefficient. The corresponding angle of attack was taken as the stall angle of attack, and the resultant lift was defined as the maximum lift coefficient. To complete the lift model depicted in Fig. 21, ANSYS Fluent was used to compute the lift supplemented by flaps at a 45° deflection and landing speed of 56 ft/s. Incidentally, plain flaps were preferred to slotted and fowler flaps because of two reasons: reduced manufacturing complexity and the airflow disturbance caused by the landing gear, fuel tanks, hinges, and X-1 glider wings preceding the control surfaces.

Finally, the lift model was integrated into the optimization process to better simulate the flight missions, where turns were assumed to occur at 88% of the maximum lift coefficient based on the average vertical body force in a turn computed from V1 accelerometer data in Section 8.5.

4.4.6 Drag Analysis

The drag of the Bull Shark was computed using a combination of ANSYS Fluent CFD and the drag component build-up method presented in [14] for parasitic drag and OpenVSP for lift-induced drag.

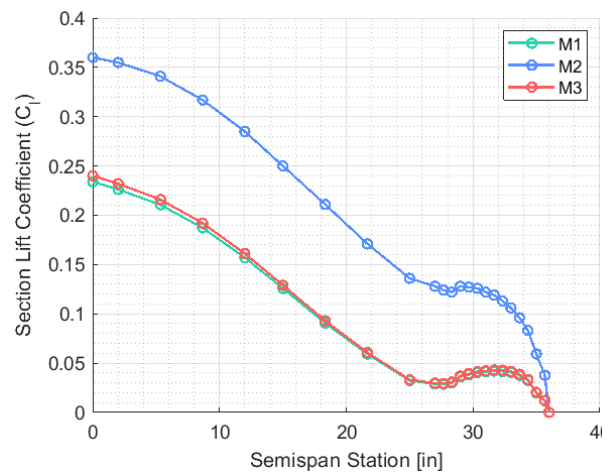


Figure 20. Wing Lift Distribution

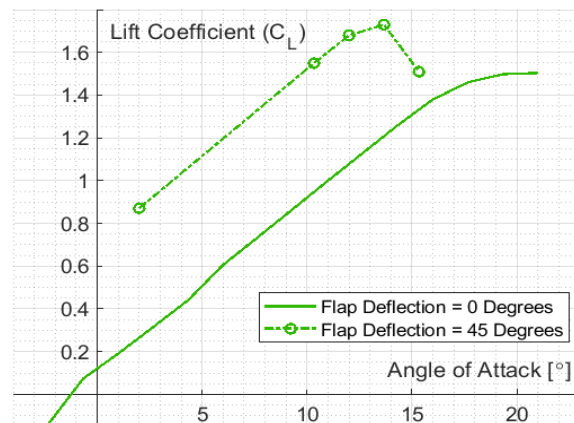


Figure 21. Lift Model

$$C_{D,min} = k_{CRUD} \left(\frac{1}{S} \right) \sum_{i=1}^N C_{Fi} (S_{wet_i}) (FF_i) (IF_i) \quad (9)$$

The wing, fuselage, tail, landing gear, and X-1 glider applied Eq. 9 to get a lower bound for the parasitic drag. These components implemented the turbulent flat plate model to calculate the skin friction drag and were then corrected for form and interference drag by selecting the most appropriate form factor (FF) and interference factor (IF). A CRUD factor (k_{CRUD}) of 1.20 was assumed in this model to account for manufacturing imperfections and uncertainties in the drag component build-up model. That estimate was made relatively low to better agree with V1 results in cruise. To complete the drag model, fuel tank and pylon drag were added in from Section 4.3.2. The drag at the cruise velocities for each mission is thus given by Fig. 22.

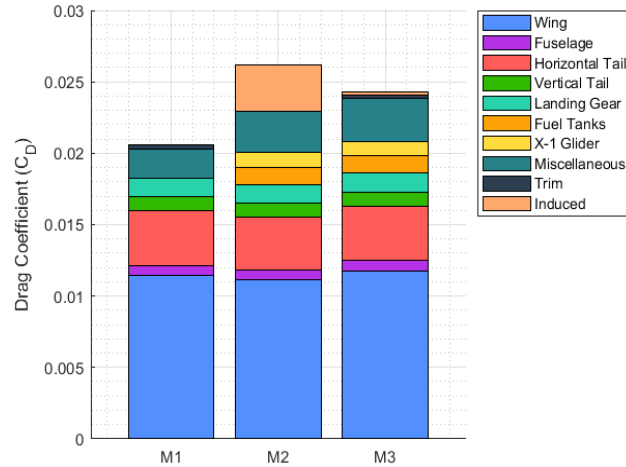


Figure 22. Drag Breakdown

4.4.7 Dynamic Stability

XFLR5 was used to inspect the dynamic stability of Bull Shark for M2 and M3, whereas M1 was omitted because of the likeness between the M1 and M3 configurations. The modal response and root locus plots for all dynamic modes were then generated in MATLAB, as shown in Figs. 23 through 25. The short period, long period (phugoid), Dutch roll, and roll modes were calculated to be stable, as the eigenmodes have negative real values; that is, small perturbations from the equilibrium state in these

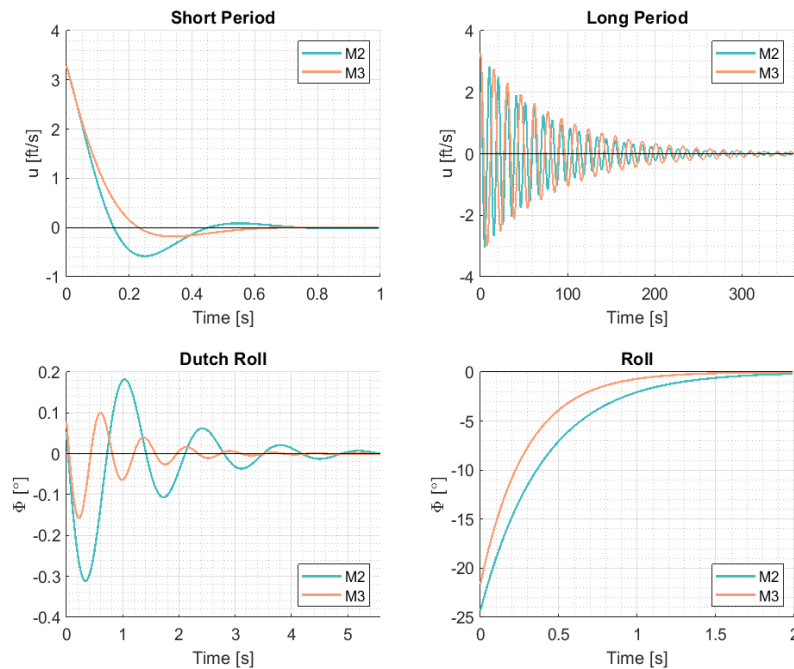


Figure 23. Time Response of Stable Dynamic Modes

modes dissipated over time. By contrast, the spiral mode proved to be unstable as perturbations were

amplified over time. Despite that, the Bull Shark's design was left as is, as the spiral mode is relatively easy for the pilot to control due to its long response time. When flying the V1 prototype, the pilot noted an aileron trim problem which was likely caused by the inherent spiral instability, so the 2° of wing dihedral added to the V2 aircraft was also intended to help alleviate any lateral control challenges.

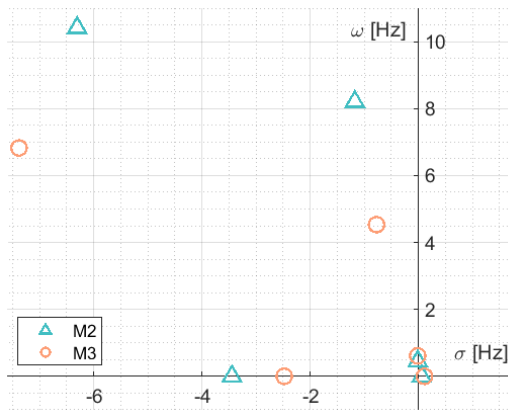


Figure 24. Root Locus of Eigenmodes

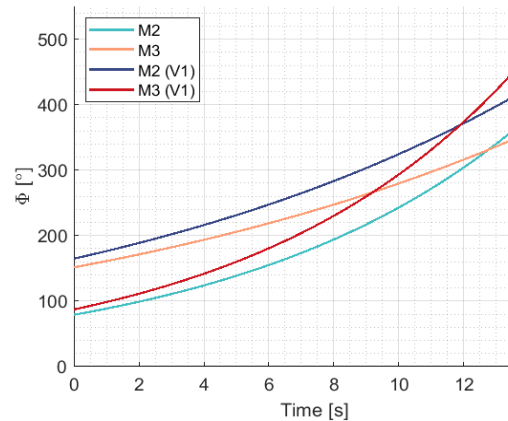


Figure 25. Spiral Instability

4.5

Predicted Mission Performance

The flight mission performance was calculated using the optimization algorithm detailed in Section 4.2 following the updated implementations of the propulsion and aerodynamic analyses conducted in Sections 4.3.4 and 4.4, respectively. The GM performance was estimated from Section 8.3, where the average staging times of the pylon-to-wing, pylon-to-tank, and X-1 glider integration processes were summed and multiplied by a factor of 1.2 to account for the movement of the assembly crew member around the plane when performing the mission.

Table 16. Preliminary Performance Predictions

Parameter	M1	M2	M3
Fuel Tank Weight [lbf.]	/	24.78	/
X-1 Weight [lbf.]	/	0.157	0.157
Energy Consumption [Wh]	22.31	66.78	89.25
Take-off Weight [lbf.]	8.82	33.79	9.01
Empty Weight [lbf.]	8.82	8.82	8.82
Takeoff Distance [ft]	6.33	81.77	6.75
Stall Speed [ft/s]	24.63	46.24	24.98
Cruise Velocity [ft/s]	110.15	132.2	110.13
L/D	3.91	8.27	2.34
Rate of Climb [ft/min]	981.96	1016.94	977.2
Turning Radius [ft]	37.89	140.19	37.87
Mission Duration [s]	73.38	89.94	293.53
Number of Laps	3	3	12
Mission Score	1	1.94	2.96
Ground Mission			
Mission Time [s]	28.94		
Mission Score	/		

The velocity envelopes for M2 and M3 derived from the optimization calculator are shown in Fig. 26, where the values for the takeoff and climb are demonstrated by the first several seconds and any loss of airspeed

after that corresponds to a turning maneuver. The first laps for M2 and M3 were distinct and took longer because of takeoff, and the subsequent laps were all modeled to be continuous.

5. Detailed Design

5.1 Aircraft Specifications

The aircraft specifications along with propulsion and avionics subsystem elements are given in Table 17.

5.2 Structural Characteristics and Capabilities

Bull Shark was designed to handle a variety of aerodynamic, inertial, propulsive, and ground loads to complete all three flight missions successfully. When examining the V-n diagrams in Fig. 27 for the designs of both M2 and M3, the difference between their

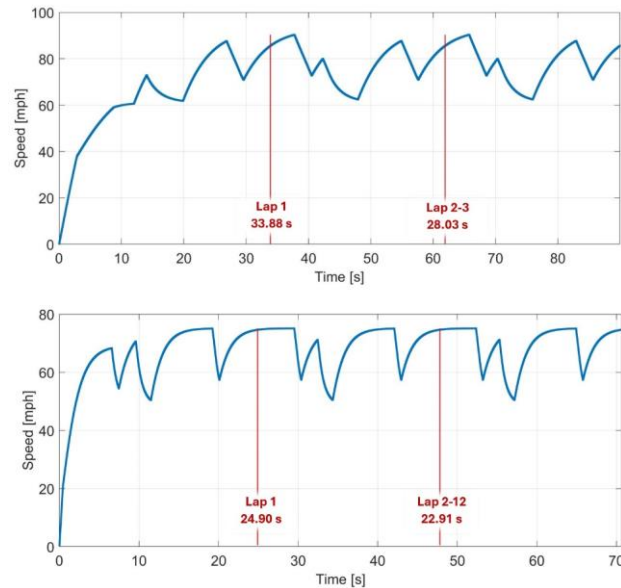


Figure 26. Velocity Profiles for M2 (Upper) and M3 (Lower)

Table 17. Aircraft Design Specifications

Aircraft Specification				Component Specification	
Wing		V. Stabilizer		Avionics	
Airfoil	SD7032	Height	12.50 in	Transmitter	Radiomaster Boxer
Span	6.00 ft	MAC	8.75 in	Receivers	FrSky Archer Plus SR12+ / R-XSR
MAC	17.87 in	V. Area	0.76 ft ²	Battery	URGENEX 7.4V 2S 30C 450mAh LiPo
AR	4.03	Max Deflection	30°		
Wing Area	10.76 ft ²	Taper Ratio	1.00	Servos	KST X10 V2 Wing / KST A15 1810 HV
Root Chord	20 in	Airfoil	NACA0009		
Tip Chord	15.75 in	H. Stabilizer		Propulsion	
Angle of Twist	-2.00°	Span	31.50 in	Motors	Brotherhobby Tornado T7 4215 520 KV
Dihedral Angle	2.00°	MAC	11 in		
Mount Angle	1.00°	H. Area	2.41 ft ²	Propellers	APC 13x10E
Fuselage		Max Deflection	30°	Propulsion	GAONENG GNB 8S 29.6V
Total Length	75.50 in	Airfoil	NACA2409	Battery	3300mAh 100C
Max Width	2.19 in	Landing Gear		ESCs	Skystars Jupiter SL80A 2-8S BL Heli 32
Max Height	3.31 in	Height	7.68 in		
Nose Length	5.72 in	Base Width	16.14 in	Arming Fuse	MAXI 100A

structural demands becomes clear. The M2 configuration features a high wing loading, causing a high stall speed and relatively low design load factor of 4g; Conversely, the M3 configuration needed to sustain load factors as high as 10g when in a turn. As such, the operational limits were in the “caution” regime just past

the M3 dive speed. To account for that, UB DBF designed the wing to take on pylon and landing gear load paths in addition to the bending loads from lift in a turn. To maximize structural efficiency, the wing will be manufactured as a single 6-foot-long part with pultruded carbon fiber strips in the top and bottom surfaces that resist bending. Through FEA stress analysis simulations and V1 flight testing, the solution proved fruitful, and the relatively heavier commercial composite tube spar solution was avoided. With the wing carrying most of the major loads, the fuselage can be extremely streamlined and lightweight. Only the tail boom and the cantilever interface at the fuselage wing junction took bending loads resulting from the inertial and tail control forces, further reducing the fuselage strength required.

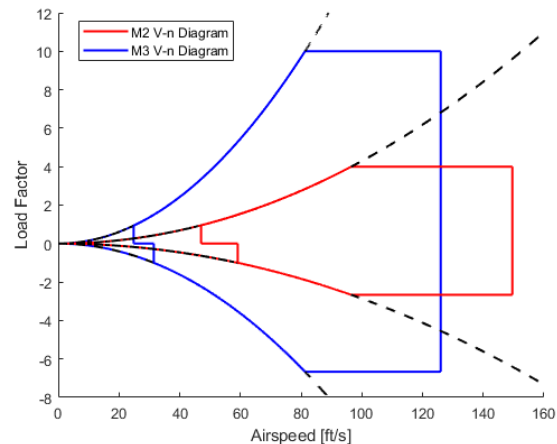


Fig. 27 V-n Diagrams

5.2.1 Wing Finite Element Analysis

ANSYS Structural was used to evaluate deformation of the wing under high loading conditions experienced during flight. Local pressure coefficients were estimated using XFLR5 and were used to approximate the pressure distribution along surface of the wing by splicing the surface into span-wise and chord-wise

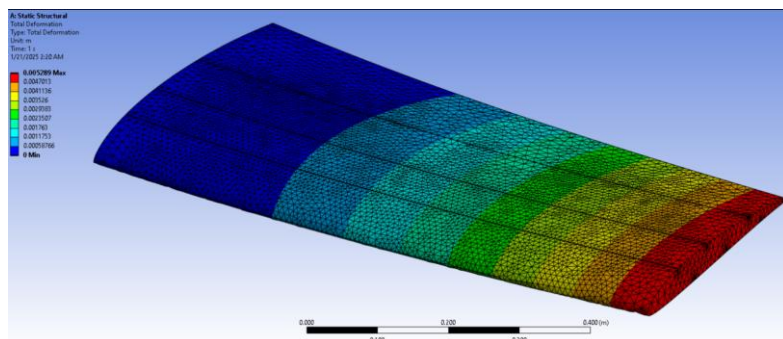


Figure 28. Wing Deflection

segments. The model simulated flight conditions at an angle of attack of 16 degrees, which correlated to a lift coefficient of approximately 1.43. The model was solved utilizing symmetric conditions to reduce computation, and a fixed support boundary condition was applied to the root section to constrain degrees of freedom.

The predicted stress was 221 ksi, which is well below the ultimate strength of carbon fiber, 450 ksi. This gives a factor of safety of 2.03. The deflection at the tip was predicted to be 0.2", which is deemed acceptable for preventing divergent aeroelastic effects.

5.2.2 Landing Gear Finite Element Analysis

Due to high payload weights and fast landing speeds during M2, stress analysis was done to evaluate how the landing gear would respond to a high loading condition. An inertial load of 186 pounds was applied to the axle holes while a fixed support was applied to the upper surface in contact with the wing to simulate a 5.5g landing impact. The greatest stress concentration is shown to occur near the base of the landing gear as indicated in Fig. 29. An ultimate tensile stress of 450 ksi was assumed, which gave a FOS of 3.72.

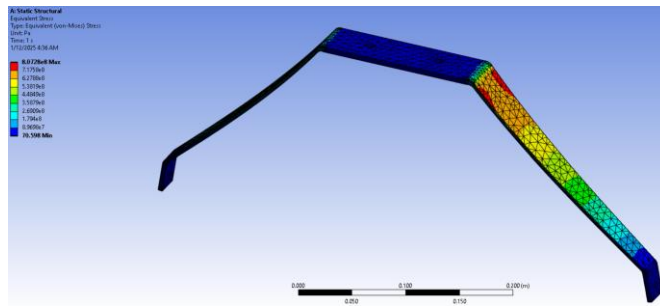


Figure 29. Stress on Landing Gear

5.3 System and Subsystem Design/Integration/Architecture

5.3.1 Fuselage

The fuselage houses the battery, tail servos, and radio receiver inside a molded carbon composite structure. An access hatch was installed on the nose for ease of assembly and wiring. The wing and tail boom are fastened to 3D printed internal components adhered to the inner surface of the molded composite form. To facilitate the attachment of the X-1 drop mechanism, bomb bay doors were incorporated into the underside of the fuselage.

The fuselage was designed to detach from the wing and tail boom such that the aircraft could be shipped to Tuson more easily. Appendages were attached to each component such that the subcomponents could easily be assembled or disassembled. Appendages that attach to the fuselage, wing, and tail boom are colored green, blue, and red, respectively, as shown in Fig. 30.



Figure 30. Appendages

5.3.2 Empennage

The tail surfaces interface with a square tail boom to form a conventional configuration. To reduce weight in the tail, elevator and rudder servos were moved to the fuselage and long control rods were implemented that

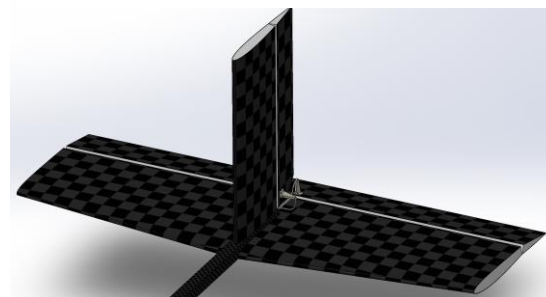


Figure 31. Empennage

pass through the tail boom to the control surfaces. The horizontal stabilizer is tapered to provide a larger thickness at the root, facilitating a stronger connection with the tail boom

5.3.3 Landing Gear

The main gear is a carbon composite arch with 3-inch foam wheels. The main gear is attached to integrated plywood hard points on the lower surface of the wing. The rear wheel is mounted in a carbon-skinned fairing glued to either side of the tail boom with plastic bonder and clamped by the horizontal stabilizer.

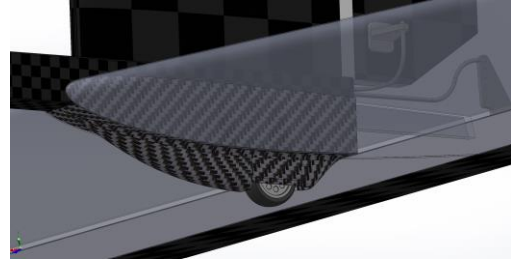


Figure 32. Tail Wheel and Mount

5.3.4 Nacelles

The nacelles are molded from carbon fiber and are designed to fit directly over the wingtip of the tapered and twisted SD 7032 airfoil. They are mounted using screws that thread into plywood hardpoints mounted in the wing. Two balsa disks are sandwiched between the layers of carbon fiber on the front edge to allow for a more rigid bolt connection with the motor.

5.3.5 Fuel Tanks and Pylons

5.3.5.1 Bottle Profile and Contents

A bottle capacity of 28.75 oz is used for each external fuel tank, having an approximate length and diameter of 11" and 2.8" respectively. The fuel tanks are filled with a mixture of granulated copper and epoxy to utilize full bottle capacity while simultaneously adhering to the binder requirement; this mixing method yields a combined fuel weight of 24.78 lbf. To provide a high strength attachment point, an adaptor was implemented made of bent steel brackets along with a Kevlar clamp to secure the brackets to the bottle.

5.3.5.2 Attachment Mechanism

The fuel tank pylons are composed of a set of T-bolts and rail sections screwed through a 0.75-inch-wide 3D printed ASA structure that is 5.75 inches in length and extends 2 inches beneath the wing. The pylon structure has a replaceable compliant mechanism on the tank-facing attachment point along with a set of in-line rail sections. The T-bolts, located on the wing-facing side, slide into two in-line rails integrated into the

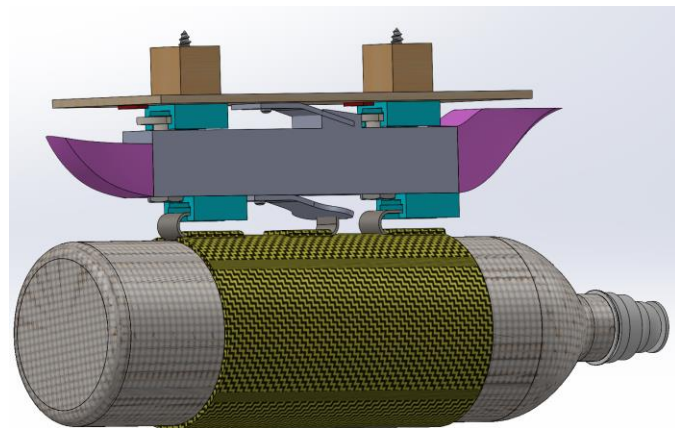


Figure 33. Fuel Tank and Pylon Attachment

lower surface of the wing. During this sliding motion, a wing-side compliant mechanism deflects over a raised section on the pylon and then locks it in place, fixing the translation along the rail. Similarly, on the fuel tank side, the compliant mechanism and in-line rails interface two U-shaped brackets incorporated to create the bottle adapter (under 0.5 inches high and wide and 5 inches apart) in a similar manner. At each end of the main pylon structure is a foam aerodynamic fairing to reduce drag. A push-rod hole was included to release the compliant mechanism from the wing-side attachment point.

5.3.5.3 Adapter Strength

Analysis was conducted regarding the strength of the U-shaped brackets and their attachments to the bottle. In an FEA study, a load was applied to the attachment to simulate conditions equivalent to turning at a load factor of 5.5. A maximum stress of 30.87 ksi was calculated as shown in Fig. 34, which correlates to a factor of safety of 1.49. Additionally, hand calculations were made to ensure the Kevlar clamps could support the forces applied to the brackets; this was done by assuming the perimeter of each bracket supported the load evenly. A value of 8.52 / in was determined, which is well below the peel strength of Kevlar [16].

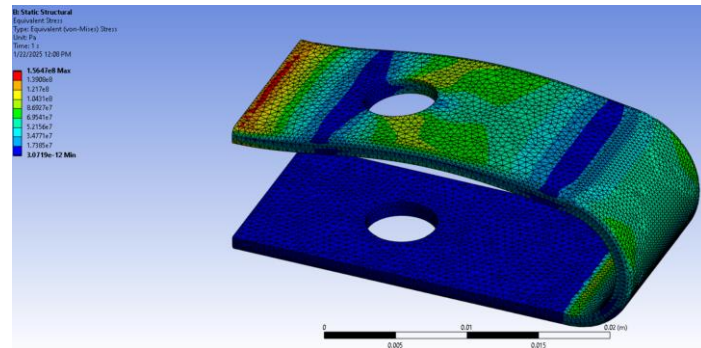


Figure 34. FEA study on U-Bracket

5.3.6 X-1

5.3.6.1 Flight Control System

The flight controller for the X-1 glider utilizes an Arduino-based program, two servos, and a sensor suite consisting of an IMU, GPS, and barometer. The microcontroller chosen for this application is an Arduino Nano 33 BLE Sense Rev2. The board houses an integrated accelerometer, gyroscope, magnetometer, and barometer which are implemented for control. An external Beitian BE-122 GPS module provides location data. Control commands are handled by a pair of 2g servos which actuate the ailerons and elevator. Power for the system is supplied by a 3-cell lithium-polymer battery and a 3.3-volt buck converter.

Table 18. X-1 Glider Hardware

Hardware Component	Mass (grams)
Arduino Nano 33 BLE sense	5
Beitian BE-122 GPS Module	3
2G Servo x2	4
Strobe	3
3.3-volt buck converter	1
3S Li-po Battery	8
Battery holder	3
Wired connections (approx.)	4
Total	31

The control system software employs an extended Kalman filter for sensor fusion, allowing for fused output of altitude, attitude, and position. The fused output of the sensor suite is incorporated into feedback for PID control of servo positions as well as the determination of the aircraft heading and altitude.

Immediately preceding a flight mission, the control system is initiated on the ground where a calibration function executes, the GPS module gets a satellite fix, and the system enters a stand-by phase. The release mechanism triggers the end of the stand-by phase through a pull-out pin while also switching the strobe lights on. Upon release, the flight controller performs a separation maneuver, followed by the turn-to-target area, and descent phases of flight.

5.3.6.2 X-1 Release System

X-1 is released when a servo inside Bull Shark pulls a pin which passes through 3D printed structural parts in both the X-1 and Bull Shark, breaking the mechanical connection between X-1 and Bull Shark. The X-mount is fixed to the X-1 glider and extends into the internally mounted pylon. This mounting mechanism is concealed by a bomb-bay door when the X-1 is not installed. The X-1 mount, and pylon are both slanted on the back surface to take advantage of drag in pulling the glider away from the fuselage. Additionally, X-1 is mounted at a slightly negative angle of attack such that the negative lift force facilitates a quick release.

5.3.7 Wing

The wing utilizes an EPS foam core skinned with spread-tow carbon fiber, with pultruded carbon stringers for increased bending strength. The plywood pylon attachment points are recessed into the wing such that a hatch can cover the area during M1. The pylon attachment point involves a plywood sheet that distributes the load to the surrounding foam and carbon skin as shown in Fig. 35. Wood blocks were added over the rails where the T-bolts interface so screws could be used with sufficient thread grip to support the loads applied to the rails.

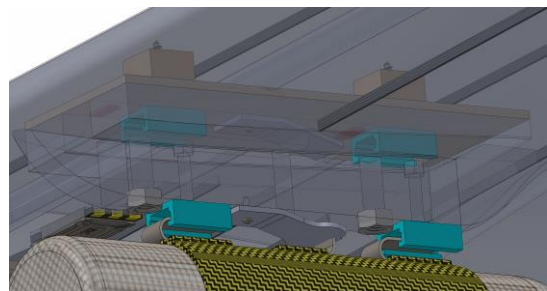


Figure 35. Pylon Hardpoint

5.3.8 Staging Blocks

To increase accessibility of pylon attachment points, staging blocks are used to increase the space between the wing and ground. The blocks are made from wood and include a channel that fixes the wheels in place. The other design allowance besides

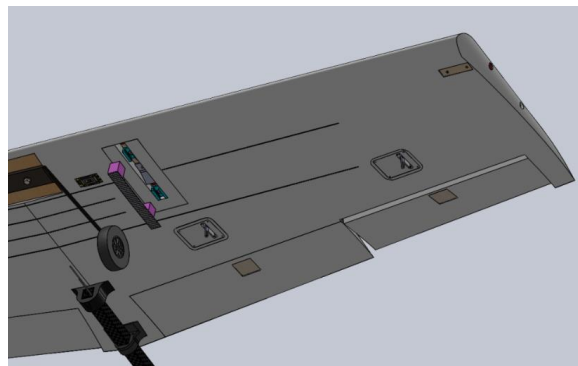


Figure 36. Wing Underside

blocks were pads, though they weren't included as the X-1 test vehicle is durable enough to land from that short height and sustain no damages.

5.3.9 Propulsion and Avionics

The detailed design phase defined the integration of the propulsion system electronics outlined in the preliminary design phase, which remained unchanged. The fuse is situated behind the propeller plane for safety reasons; the ESCs sit in pockets in the underside of the wing and are exposed to the airflow for cooling purposes. To mitigate the risk of in-flight signal loss due to carbon fiber radio interference, the FrSky Archer Plus SR12+ and R-XSR receivers were chosen for their strong anti-interference properties and redundancy features. The KST X10 V2 servos were used for all control surfaces other than the elevator as they met the torque requirement. The electronics layout is shown with Fig. 37.

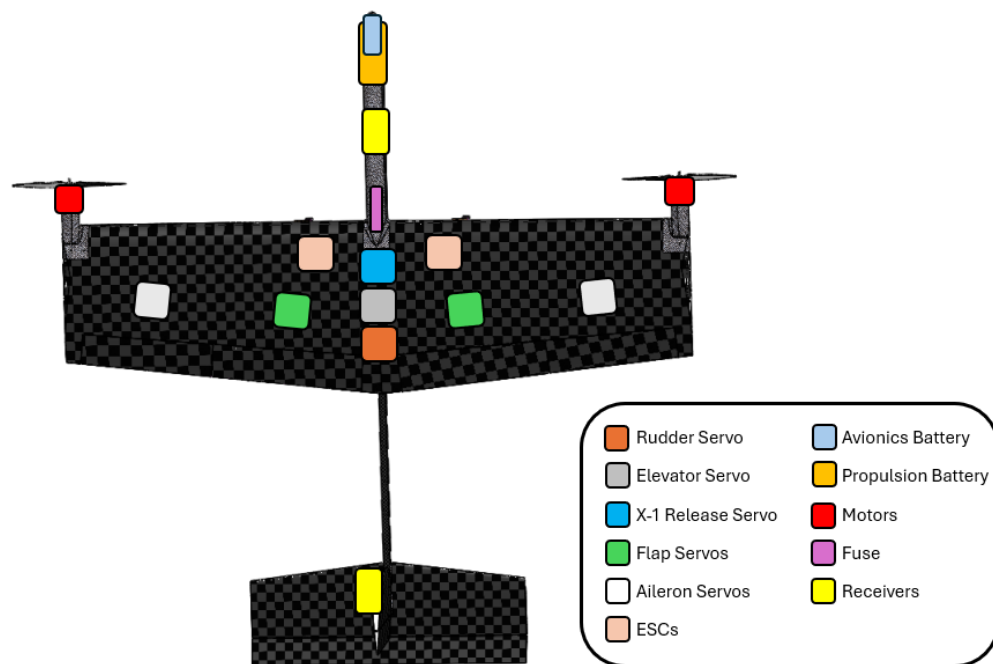


Figure 37: Electronics Layout

5.4 Weight and Balance

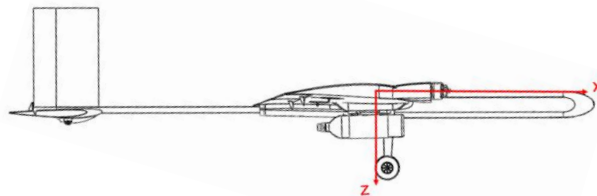


Table 19. Weight and Balance

Overall CG				
Component	Weight (lb.)	CGx (in.)	CGy (in.)	CGz (in.)
BullShark Aircraft (Empty)	8.63	0	0	0
Component	Weight (lb.)	CGx (in.)	CGy (in.)	CGz (in.)
Flap Servo (x2)	0.13	-5.55	5.13	25.07
Aileron Servo (x2)	0.13	-7.09	2.61	9.45
Rudder Servo	0.06	-5.96	0.83	0.18
Elevator Servo	0.09	-7.98	0.65	0.06
Main Landing Gear	0.44	2.13	-1.01	4.58
Tail Landing Gear	0.01	-38.76	-5.54	0.08
Fuselage (Empty)	0.33	8.2	14.79	-2.37
Wing/Wing Structure	0.48	-4.68	2.54	-0.12
Horizontal Stabilizer	0.13	10.29	-4.85	0.95
Motor (x2)	0.57	7.23	1.11	-35.46
Vertical Stabilizer	0.04	-40.36	2.34	0.21
Receiver	0.32	21.08	4.07	-0.67
Avionics Battery	0.05	21.28	4.06	-0.69
Propulsion Battery	1.12	23.16	5.44	-0.86
Mission 2				
X-1 Vehicle	0.16	0	-0.5	0.01
Fuel Tank & Pylons	23.93	0	0.51	0.09
Mission 3				
X-1 Vehicle	0.16	0	-0.5	0.01
Fuel Tank & Pylons	0.48	0	0.51	-0.05

5.5 Flight and Mission Performance

Following the completion of the detailed design phase, the predicted mission performance was again updated using the optimization from section 4.2. The only difference was that the weight of the empty configuration was refined to a better estimate of 8.63 lbf.

5.6 Drawing Package

The configuration, structural arrangement, payload accommodation, and systems overview drawings are shown in the subsequent pages.

Table 20. Predicted Mission Performance

Parameter	M1	M2	M3
Fuel Tank Weight [lb.]	/	24.78	/
X-1 Weight [lb.]	/	0.157	0.157
Energy Consumption [Wh]	21.88	70.67	87.52
Take-off Weight [lb.]	8.36	33.3	8.52
Empty Weight [lb.]	8.36	8.36	8.36
Takeoff Distance [ft]	5.76	95.02	5.88
Stall Speed [ft/s]	22.99	47.94	24.35
Cruise Velocity [ft/s]	110.19	131.43	110.17
L/D	3.73	8.41	3.16
Rate of Climb [ft/min]	993.38	1015.23	869.57
Turning Radius [ft]	37.91	138.56	37.9
Mission Duration [s]	74.09	93.71	296.37
Number of Laps	3	3	12
Mission Score	1	2.95	2.96
Ground Mission			
Mission Time [s]	28.94		
Mission Score	/		

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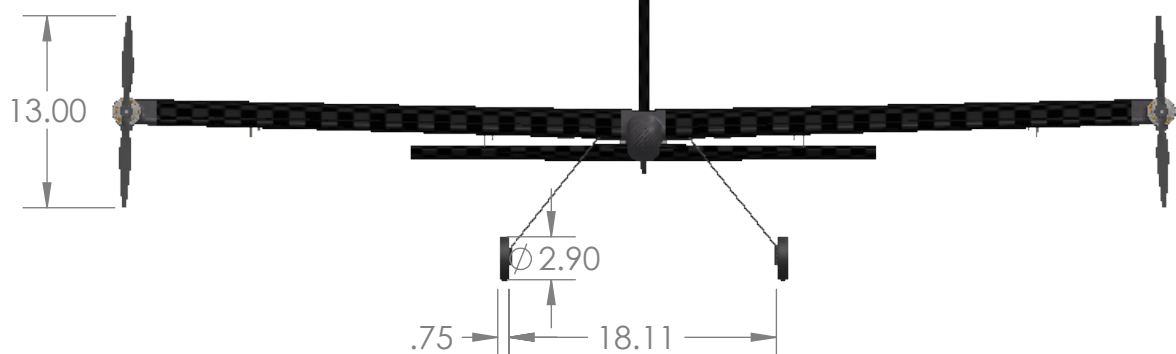
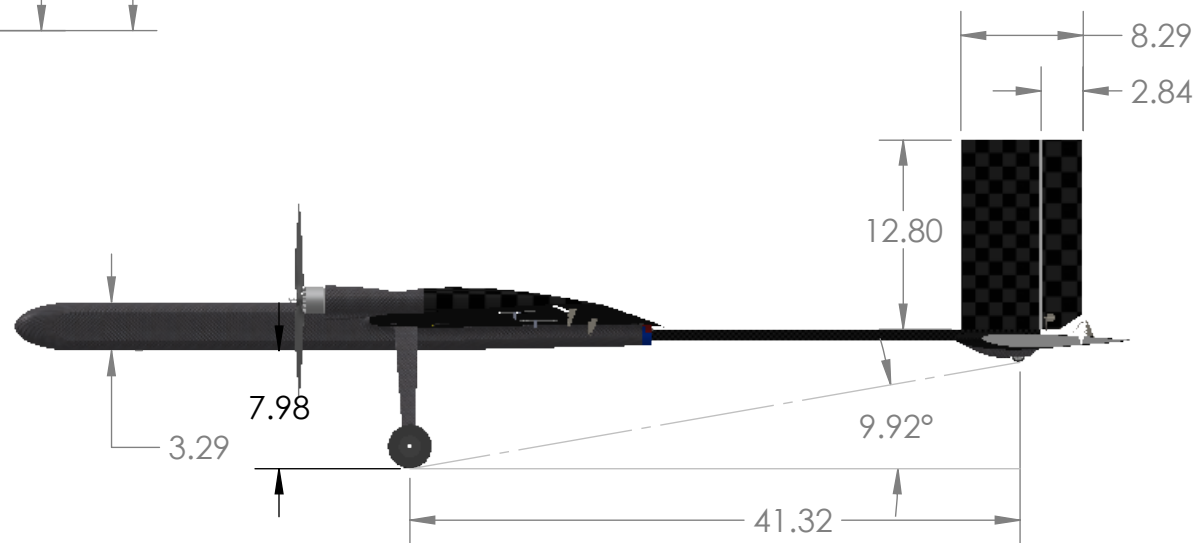
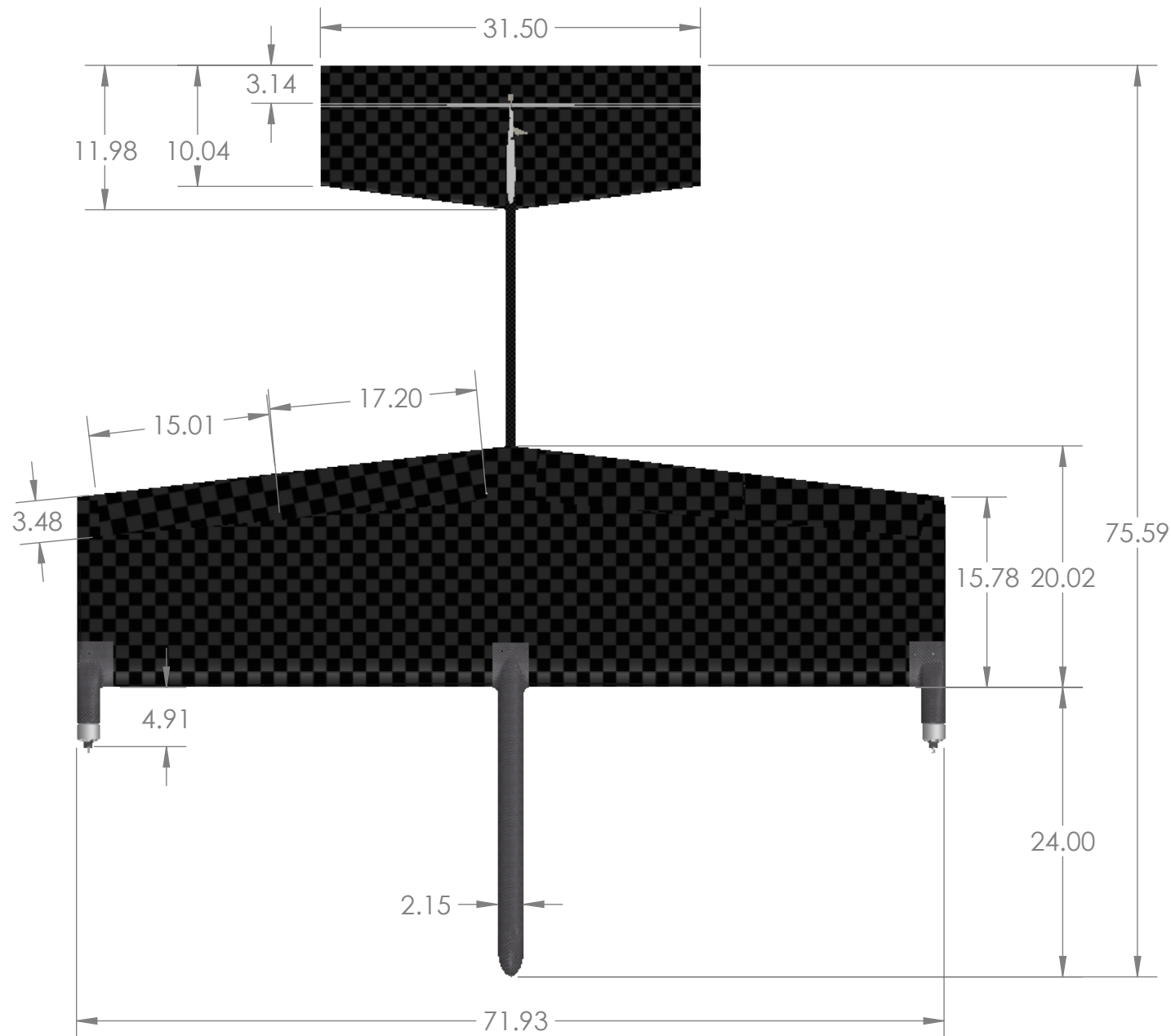
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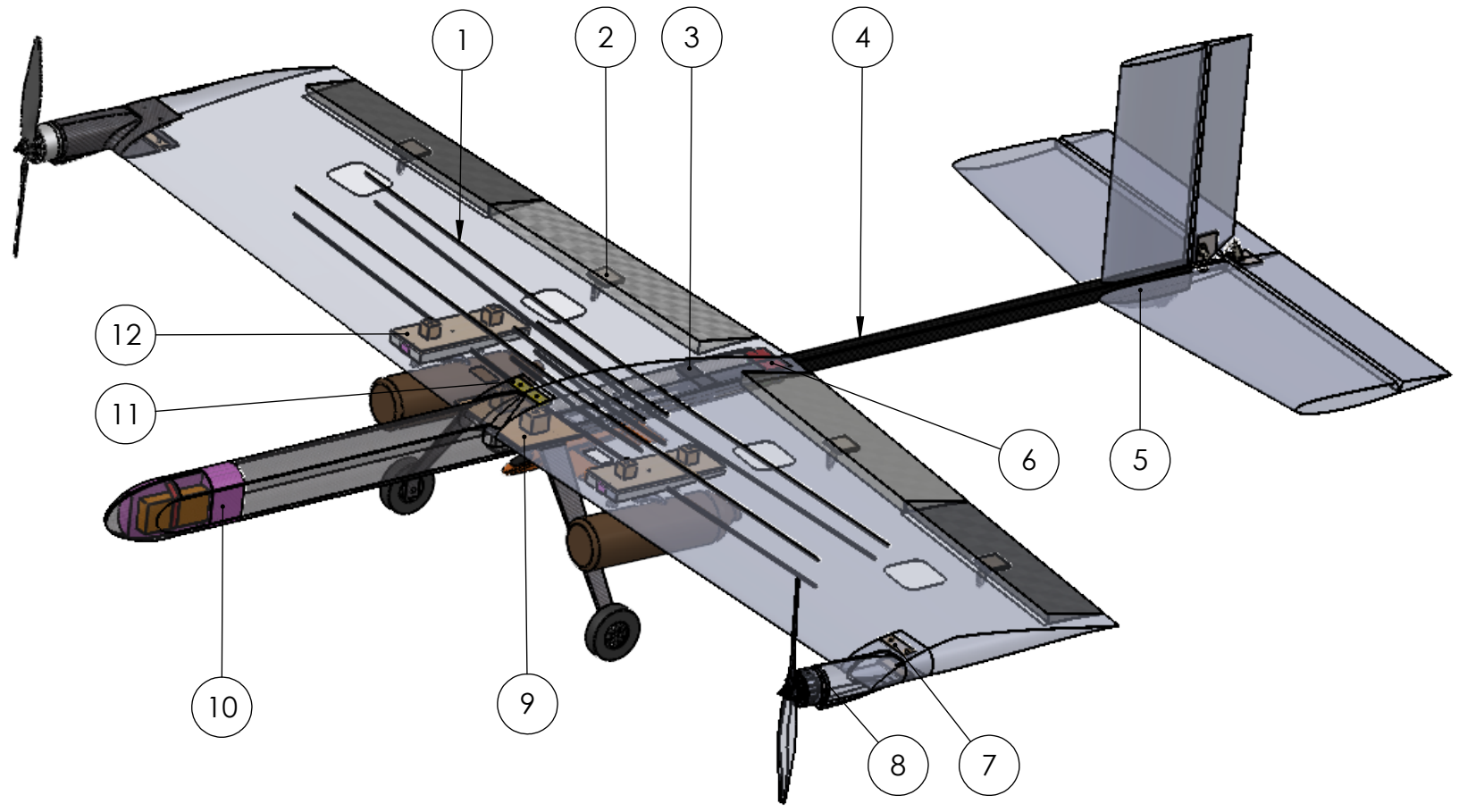
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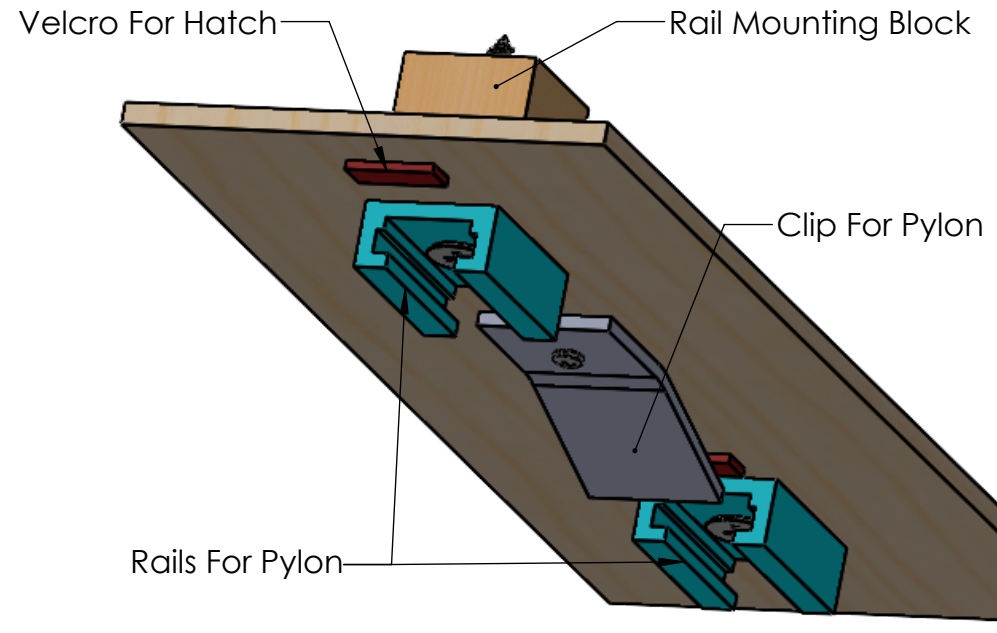
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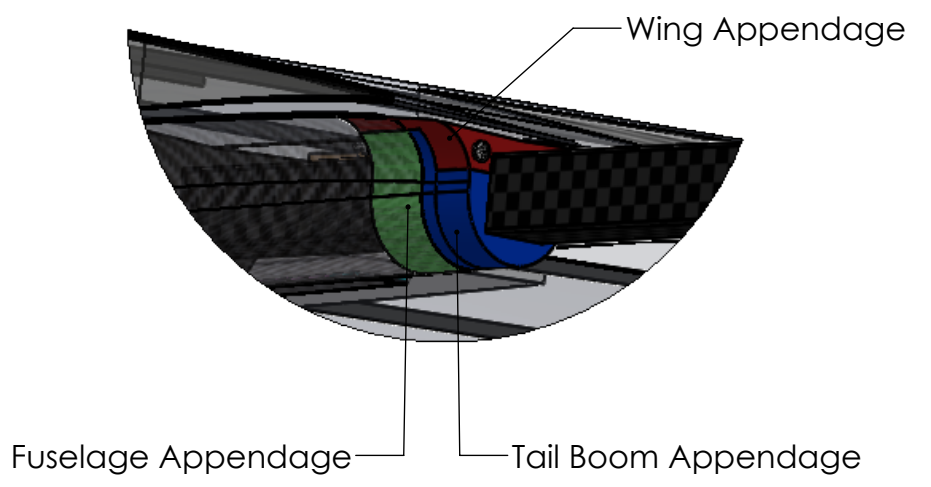


Item	Description	Qty.
1	Carbon Fiber Stringer	16
2	Control Horn Hardpoints	6
3	Tail Boom Mount	1
4	Tail Boom	1
5	Tail Mount	1
6	Mate Between Wing, Fuselage, And Tail Boom	1
7	Nacelle Mount Hardpoint	4
8	Motor Mount Hardpoint	2
9	Main Landing Gear Mount	1
10	Main Battery Mount	1
11	Fuselage to Wing Mount	1
12	Pylon Mount	2

Pylon Mount



Mate Between Wing, Fuselage, And Tail Boom



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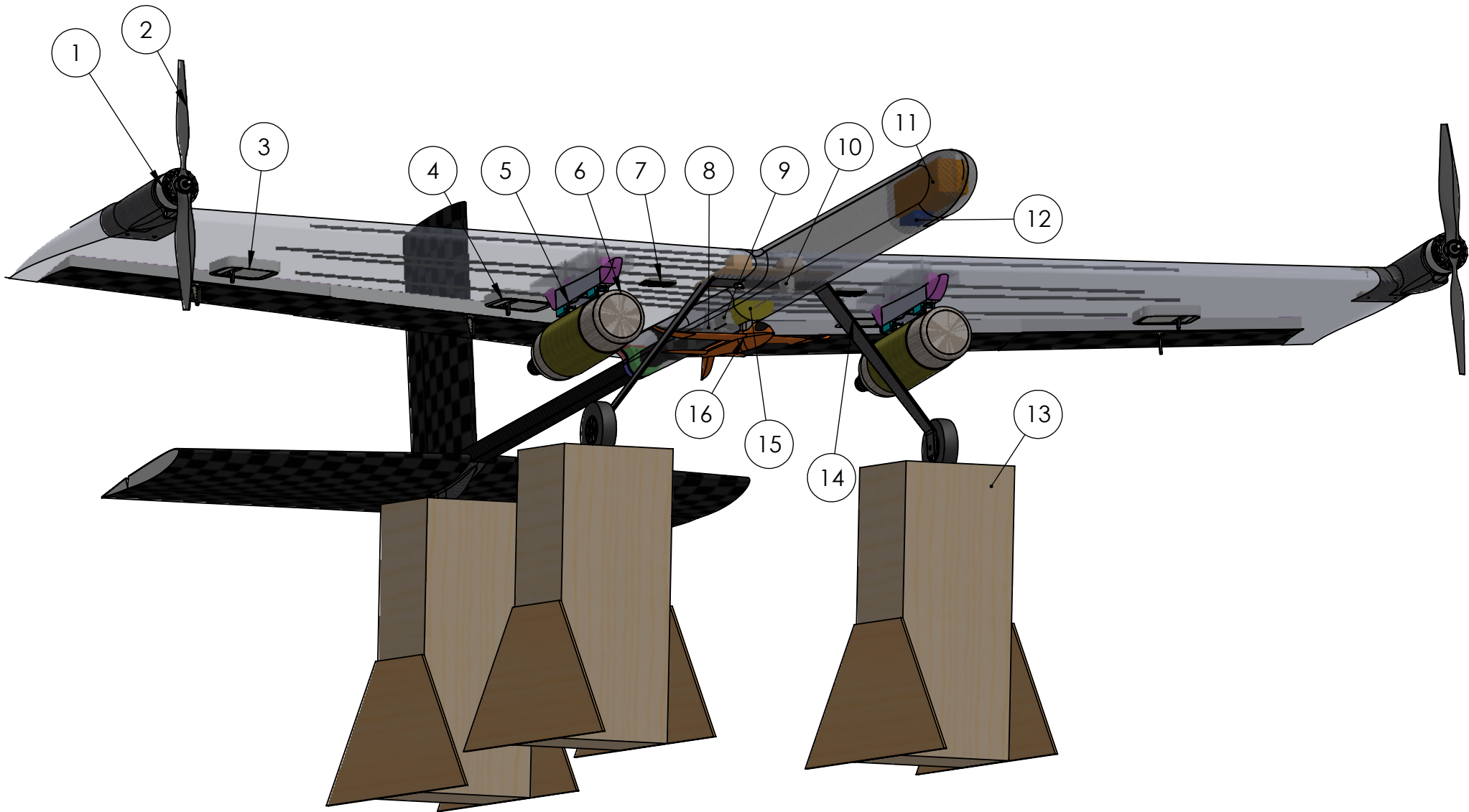
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Item	Description	Qty.
1	Motor	2
2	Propeller	2
3	Aileron Servo	2
4	Flap Servo	2
5	Pylon	2
6	Fuel Tank	2
7	ESC	2
8	Rudder Servo	1
9	Elevator Servo	1
10	X1 Release Servo	1
11	Propulsion Battery	1
12	Servo Battery	1
13	Staging Block	1
14	Main Landing Gear	1
15	X1Pylon	1
16	X1	1



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TITLE:

Systems Overview

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Mission 2&3 Configuration

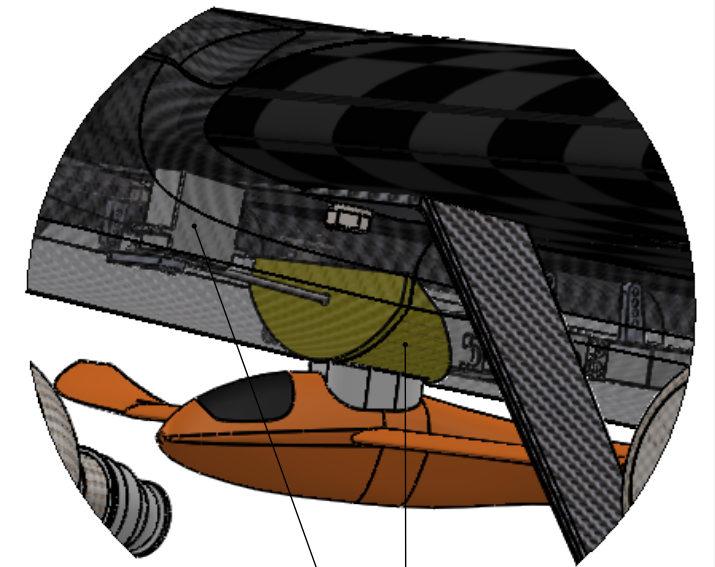
Front View



Side View



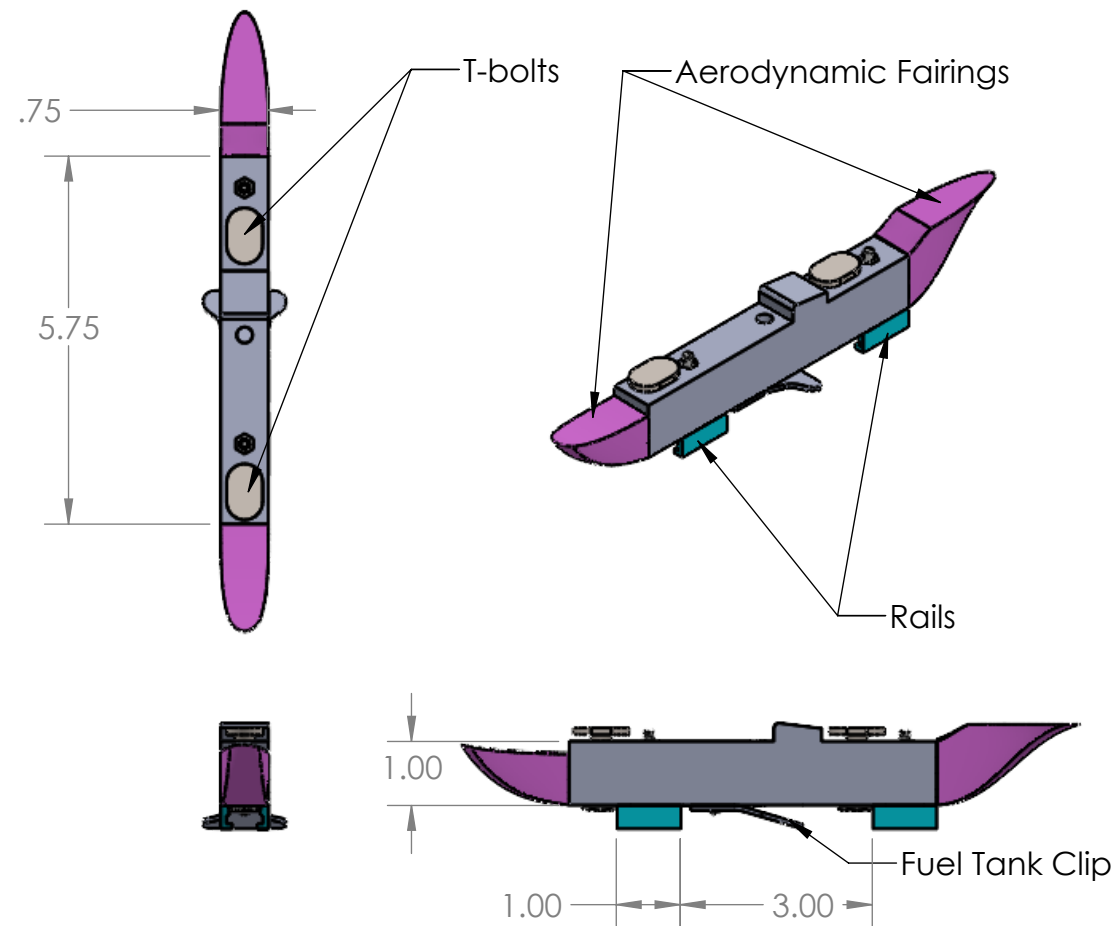
X1 Mount & Release Mechanism



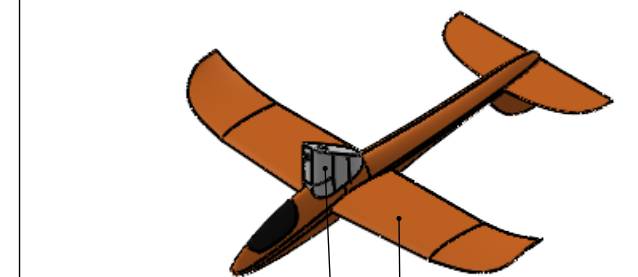
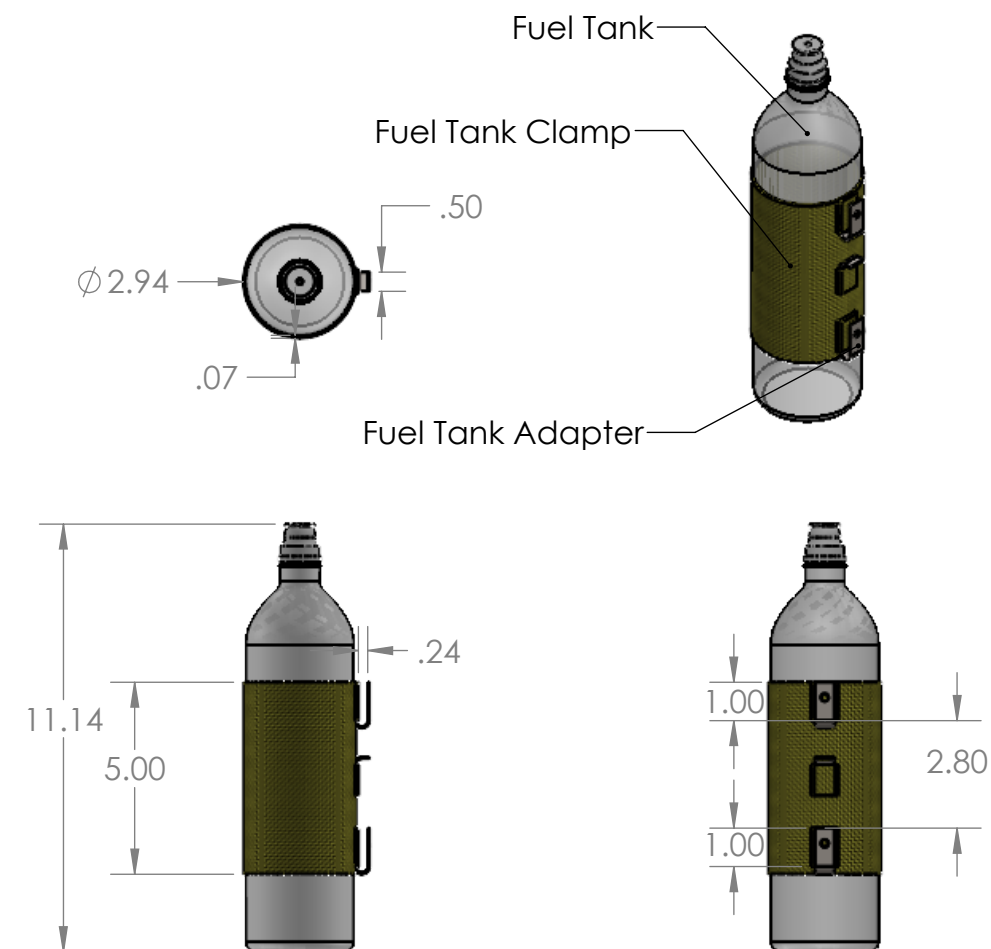
X1 Release Servo

X1 Pylon

Pylon



Fuel Tank & Mount



X1 Glider Mount

X1 Glider

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TITLE:

Payload
Accommodation

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SCALE: /

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SHEET 4 OF 4

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6. Manufacturing Plan

Manufacturing processes have been selected based on evaluations of fabrication time, production feasibility, and component quality. The selected techniques were implemented to produce the major aircraft parts such as fuselage, wings, tails, and nacelles, as well as mission-specific parts such as the fuel tanks, pylons, release mechanisms, and hatches. Fig. 21 outlines the planned and actual manufacturing timeline of prototype 1, prototype 2, and the final model.

Table 21: Manufacturing Milestones

		October				November				December				February				March				April	
		Week No.																					
Prototype 1	Fuselage Mold & Layup																						
	Wing & Control Surfaces																						
	Wing & Tail Composite Layup																						
	3D-Printed Jigs & Servo Mounts																						
	Internal Wiring																						
	Pylon Integration																						
	Landing Gear Mount																						
	Full Assembly																						
Prototype 2 and Final Model	Fuel Tank Locking Mechanism																						
	X-1 Release Mechanism																						
	Fuel Tank Preparation with Weights																						
	Tail Wheel Mount																						
	Landing Gear Reinforcement																						
	Final Wing & Tail CNC Fabrication																						
	Upgraded Fuselage Mold & Layup																						
	X-1 Integration																						
	3D-Printed Final Jigs & Servo Mounts																						
	Wiring & Assembly																						
	Minor Adjustments & Finalization																						

6.1 Manufacturing Processes Investigated

6.1.1 3D Printing

The team leveraged the rapid production capabilities of fused deposition modeling (FDM) technology. This manufacturing process allowed for the production of geometrically complex components with a level of dimensional accuracy not afforded by other fabrication methods. In addition to producing servo mounts and pylon components, additive manufacturing is utilized to create molds for the composite parts such as the fuselage and nacelles.

6.1.2 Molded Composites

Negative molds made utilizing 3D printing technology are used to fabricate parts with complex grooves that would be difficult to produce otherwise. The process allows for reproducibility, enabling rapid prototyping, replacement part production, and manufacturing cost reduction. Additionally, the process generated desirable surface finishes after post-processing sanding.

6.1.3 Hot Wire Cutting

A homemade 4-axis CNC hot-wire foam cutter is used to cut airfoil profiles out of XPS and EPS foam. The machine uses open-source programs Wing Wire and Grbl to generate cut paths and g-code respectively. Hot-wire cut foam parts are used as wing core material, which are then laminated with a composite layup. This method is dimensionally accurate, easy to repeat, and very reliable. Similar results may be achieved with a hand-held hot-wire bow, which is used to cut out small parts of the wings with laser-cut stencils that provide a path for the wire to follow.

6.1.4 Foam Core Composites

Foam core models allow fabricating parts that are lightweight and capable of bearing high loads suitable for mission purposes. The quick production time also makes it a viable option for production wings and tails. A hot-wire Computer Numerical Controlled (CNC) cutter has been used to produce precise and complex wing shapes from airfoils. Carbon fiber layups with the aid of vacuum bagging technology allow the foam core wings to have rigidity and increase loading capabilities while keeping a reasonable strength-to-weight ratio.



Figure 38. Fuselage Layup using 3D Printed Negative Molds

6.2 Manufacturing Processes Selected

6.2.1 Fuselage

The fuselage is a carbon fiber body shell manufactured using 3D-printed negative molds. Two separate molds were made for the left and right sides, such that the fuselage could be glued together from two halves. Due to 3D print sizing limitations, the molds were made in several pieces and were glued together with cyanoacrylate. The seams where each piece came together were filled with Bondo and sanded to maintain a quality surface finish. Two layers of 5.9 oz/yd carbon were wetted out with Aeropoxy to generate a general fuselage profile, while additional layers were added to areas of high stress and complex geometry. After the layup, a vacuum bag was utilized to remove excess epoxy.



Figure 39. Fuselage in Vacuum Bag After Layup

6.2.2 Wing

Four foam sections were initially cut using hot wire CNC for the wings. These sections were glued at the interfaces using Gorilla Glue. 3D printed guides on the root interface allowed easy rod insertion to create accurate wire channels within the wing. Foam filler was used to cover any dents on the foam core providing a good surface finish. Hand routing was used to cut slots for nacelle hardpoints and servo housings, which were then set into place using Gorilla Glue. Ailerons and flaps were cut and hinged using peel ply. Once the foam core was ready and any glue used was cured, it was wrapped in a single layer of spread tow carbon fiber laid up with Aeropoxy. The epoxy composite was then allowed to cure under vacuum until the desired fiber-resin ratio was achieved. For post-processing, any extra carbon fabric was trimmed off and the wing surface was carefully sanded to remove any roughness/ unevenness. Afterward, servos, servo horns, and push rods were installed into the ailerons, flaps, and servo slots. The servo housings were 3D printed using ASA. Finally, the nacelles were installed on the tips, secured using M screws into the hard points.

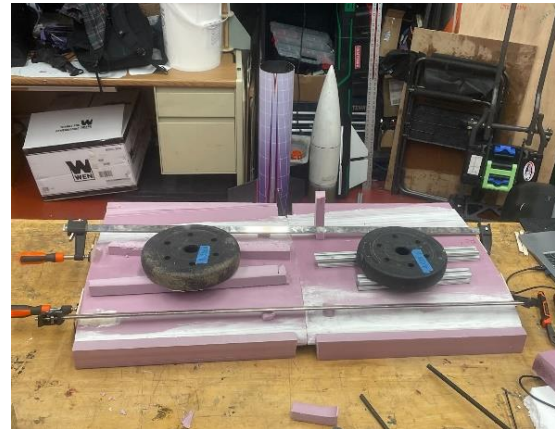


Figure 40. Wing Foam Sections

6.2.3 Nacelles

Negative molds for the nacelles are first designed in CAD before they are produced using FDM printers. The molding surface is prepared by sanding for a smoother finish and coating with Frekote (mold release) to allow ease of part detachment from the mold after the vacuum process. 5 layers of 200GSM carbon fiber cloth rotated at 45° biases were laid up using Aeropoxy. Balsa plates were added to the motor mounting surface to add extra strength and rigidity for mounting screws. The layup was kept in a vacuum bag for 24 hours to allow curing. The final part was detached from the mold, the edges were trimmed, and the surface was sanded to improve aerodynamics/quality.



Figure 41. Nacelle After Finishing

6.2.4 Fuel Tanks

Fuel tanks were made using disposable 28.75 oz water bottles. The bottles were filled with a mixture of granulated copper and epoxy to achieve the desired weight. 2 rails were made using steel angle brackets to serve as an adapter. The rails were epoxied to the bottle and secured with strips of Kevlar laid up using epoxy. The same was done with the interface of the compliant mechanism that prevents the translation of the bottle along the rails.

6.2.5 Pylons

The main structures of the pylons were 3D printed using ASA filament. The printed parts were sliced in an orientation such that layer lines were deposited along the load path. The lock-in-compliant mechanism was printed with a flat geometry and then bent to the desired shape using a heat gun. All hardware was installed including T-bolts, rails, and lock-in compliant mechanism with the addition of adhesive where needed. Streamlined fairings carved from EPS foam were glued to each end of the structure.

7. Testing Plan

7.1 Testing Schedule

Testing was conducted to verify aerodynamic, propulsive, structural, and mission performance estimations and to improve model fidelity for future iterations. The detailed testing schedule is outlined by Fig. 42.

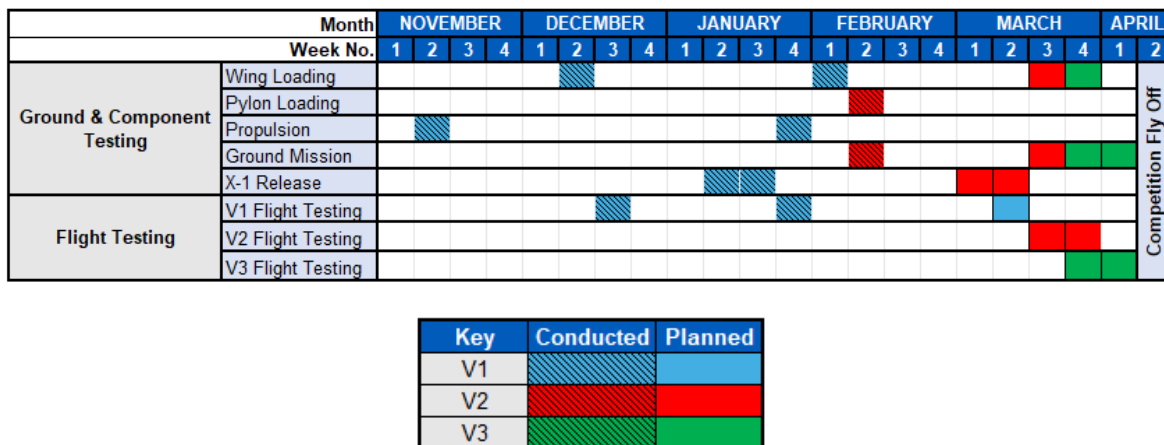


Figure 42. Testing Schedule

7.2 Ground and Component Tests

7.2.1 Wing Strength Test

Because of the significance of turning radius on total score, Bull Shark needs to withstand 4g and 10g loads for M2 and M3 respectively. Because the loaded fuel tanks reduce the bending moment across the span in M2, M3 is the critical loading case. As such, each prototype wing is strength-



Figure 43. Wing Strength Testing

tested for M3 prior to flying to validate FEA simulations and avoid potential structural failures in-flight. Fig. 43 shows an example test rig, where the wing was simply supported and weight was incrementally added at its center until the equivalent design load was attained. For V1, additional strength-testing was performed on the wing to observe its limits to better design V2: Maximum deflections (δ_{max}) were recorded for each increase in weight (F) to solve for the wing's flexural rigidity (EI) and bending moment (BM) using equations 9 and 10 below. This allowed for a quantitative assessment of the wing's elasticity.

$$\delta_{max} = \frac{Fb^3}{48EI} \quad (9)$$

$$BM = \frac{Fb}{4} \quad (10)$$

7.2.2 Pylon Assembly Strength Test

The pylon-to-wing, pylon-to-adapter, and adapter-clamp-fuel tank load paths must handle 6g, or 72.9 lbf equivalent, loads at a minimum when factoring in the FOS of 1.5 for M2. For this test, the pylon-to-wing assembly was installed in a test wing section and loaded until failure by fastening weights to it. The objective was to verify the structural integrity of the design and make corrections if necessary.

7.2.3 Propulsion Battery Endurance

Reliable propulsion battery performance is critical to both M2 because of the high current loads sustained and M3 because of the 89.25 Wh energy demand. To verify the battery's integrity, its testing underwent two stages. In the first stage, a fully charged propulsion pack was discharged at a rate of 1C using a battery charger and the cell voltages and discharged capacity were recorded at discrete intervals. For the second stage, full throttle V1 flight-testing was conducted with the data acquisition system detailed in section 7.3 and the recorded currents and voltages were recorded to extrapolate the discharge profile. The results were used to better model mission performance and validate the flight pack selection for V2.

7.2.4 Static Propulsion

Power and thrust data were recorded for a single motor and propeller in partial loading condition at discrete throttle percentages and full battery charge to test the fuse and motor operational limits. The motor was fastened to a thrust test stand with a calibrated load cell connected to a 24-bit precision ADC (HX711) and Arduino Uno. The voltage, current, power, RPM and thrust readings were logged on a flight controller using the telemetry feature of the Skystars Jupiter SL80A ESCs and Arduino serial plotter. Furthermore, key motor performance variables were collected to create the propulsion model in section 4.3.4.



Figure 44. Pylon Proof of Concept

7.2.5 Mock Ground Mission

GM time was the parameter with the largest impact on total score, so GM testing was necessary to find ways to improve the design and produce reliable estimates of performance. Because the preexisting V1 payload integration mechanisms were rendered illegal by Q&A clarifications, UB DBF tested designs for the pylons, fuel tanks, and X-1 release mechanism independently to better construct V2. For V2 and V3, UB DBF plans to practice the entire GM and follow the checklist in Table 22 below to ensure no steps are missed.

Table 22. Ground Mission Checklist

Pre-GM			GM		
Item	Check	X	Item	Check	X
External Pylons	Not Installed		"GO"	Timer Started	
Fuel Tanks	Not Installed & Empty		External Pylons	Installed	
			"STOP"	Timer Stopped	
X-1 Glider	Not Installed		"GO"	Timer Started	
Hatches	Closed		External Fuel Tanks	Installed	
Bull Shark	Upright		X-1 Glider	Installed	
Blocks	Mounted		Hatches	Closed	
Avionics	Working		"STOP"	Timer Stopped	
Staging Area	Cleared		Control Surfaces	Working	
Assembly Crew	Ready		X-1 Glider	Releases & Turns On	
Pilot	Ready		Mission Time	Recorded	

7.2.6 X-1 Release



Figure 45. First X-1 Release Test

detailed analytical studies. Thus, using other aircraft allowed for more testing opportunities early on.

7.3 Flight Tests

Flight tests assessed aircraft and mission performance, where the initial tests were meant for the pilot to evaluate stability characteristics before proceeding to attempting flight missions. Table 23 delineates the objectives of every flight test.

On V1, an on-board data logging system was implemented: it consisted of a MATEK H-743 Wing V3 flight controller along with sensors to collect video, accelerometer, angular rate, airspeed, power, RPM, RC channel inputs and barometric altitude data. Data was applied to iterate for V2 as detailed in Section 4.



Figure 46. Bull Shark V1

V2 flight testing will be conducted to making fine adjustments in the final stages of manufacturing V3, which will be tested the weekend prior to fly off for final practice.

Table 23. Flight Testing Dates and Objectives

Prototype	Test Date	Objective
V1	12/19/2025	Assess handling qualities
	1/26/2025	Fly M3 and test battery endurance
	1/31/2025	Fly M2 with 5.55 lbf and 18.78 lbf payloads
	3/15/2025	Fly all missions consecutively for practice
V2	3/22/2025	Assess handling qualities
	3/29/2025	Fly all missions consecutively to identify improvements
V3	3/29/2025	Assess handling qualities
	4/4/2025	Fly all missions consecutively for practice
	4/5/2025	Fly all missions consecutively for practice

7.3.1 Flight Test Checklist

Table 24 is the pre-flight checklist, which was employed on flight test days to ensure none of the critical data gathering operations or safety and security was compromised.

Table 24. Pre-Flight Checklist

Pre-Flight Inspection			Pre-Flight Controls		
Item	Check	X	Item	Check	X
Wing	Secured		RX switch	Powered on	
Tail boom	Secured		RX/TX	Range check confirmed	
Landing gear	Secured and undamaged		Failsafe	Correct	
Nacelles	Mounted and secured		Control surfaces	Correct deflections and trim	
Servos and linkages	Secured and connected		Control inputs	Correct	
Propulsion battery	Plugged in and fully charged		Data acquisition	Logging (if implemented)	
Avionics battery	Plugged in and fully charged		Takeoff area	Clear	
Motors	Rotating outboard		Fuse	Armed	
Propellers	Nut tightened, damage free		Propulsion run-up	Completed	
Hatches	Latched and locked		Post-Flight Inspection		
Pylons and fuel tanks	Mounted and secured		Item	Check	X
X-1 test vehicle	Mounted & secured		Fuse	Disarmed	
Wing tip load test	Passed		Batteries	Unplugged	
Wind direction	Verified		Visual Inspection	No or minimal damage	
C.G.	Balances at C.G. mark		Score	Recorded	

8. Performance Results

8.1 Structural

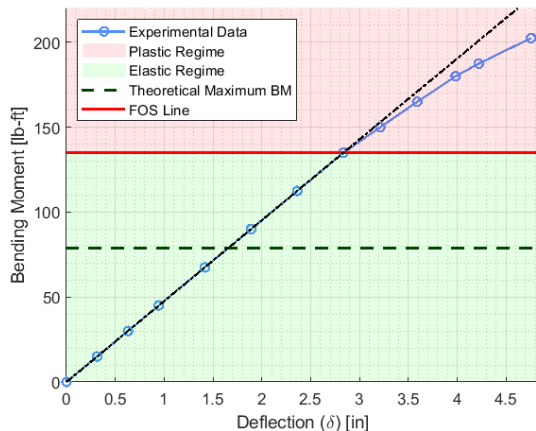


Figure 47. Wing Strength Test Results

Fig. 47 on the left reveals the results of strength-testing V1's wing. The linear-elastic regime, shaded green, coincides with a flexural rigidity value of 246,888 psi-in⁴ and ends when the BM at the root is 135 lb-ft. Past 135 lb-ft, the curve becomes non-linear and at some point, passes the yield point, since the wing plastically deformed by the end of the test. It wasn't directly possible to extrapolate the yield point, so 135 lb-ft was taken as the limit instead. The theoretical maximum bending moment derived from the OpenVSP wing lift distribution at stall was

78.70 lb-ft, so the resultant FOS was 1.71. During flight testing, V1's wing showed no indication of visibly deflecting in a turn because the load was distributed as opposed to concentrated; Given that premise, it was decided that an 8g point load would be sufficient when testing V2 and V3 to not input an excessive FOS (more than 1.5) into the system. To save 0.55 lbf on the V2 wing, the XPS foam core and 2.36 oz/yd² carbon skin on V1 were substituted for EPS foam and 1.89 oz/yd² skin. There was no drawback, because the stringers are what primarily withstand the bending stresses, and the grade of EPS foam considered was rigid enough to prevent buckling.



Figure 48. Pylon Strength Test

Initially, the plan behind pylon testing was to load the assembly until failure. However, as can be seen by Fig. 48, the test wing section buckled at 90 lbf. prior to any of the internal pylon support structure tearing out of the wing because it lacked stringers. From a strength perspective, there weren't any design modifications to be made as the FOS of 1.5 was surpassed.

8.2 Propulsion

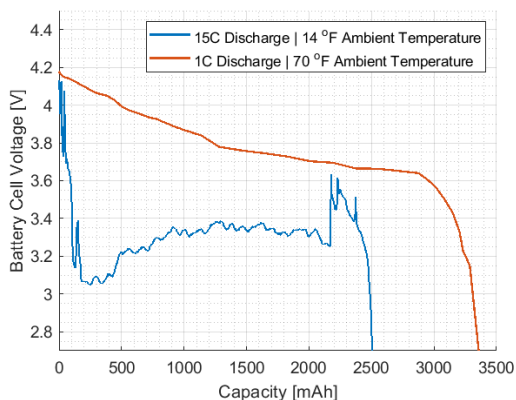


Figure 49. Battery State of Charge

of 3.4 V was assumed by referencing the region in the plot where the flight pack had warmed itself and improved its output.

Fig. 49 indicates that there was a disparity between the nominal capacity rating of 3300 mAh and in-flight energy expenditure in freezing conditions. However, given that the starting cell voltage of the flight test was 4.12 V, the true capacity was closer to 2850 mAh. The remaining 450 mAh difference likely resulted from the high stress on the battery and ambient temperature [17]; Given that M3 will be flown at 80% throttle in a hotter climate, UB DBF judged that the concerning results merited no further attention. For M2 RPM estimations, a cell voltage

Table 25. Static Propulsion Test Results

Propellers	Static Thrust [lbf]	Voltage [V]	Current [A]	Power [W]	RPM	Efficiency
APC 13x10Es	25.30	26.01	88.71	2307.3	9400	0.696
APC 13x8Es	25.14	25.74	78.12	2010.8	9810	0.733
APC 12x12Es	22.06	26.32	88.15	2320.1	9468	0.693
Motor Characteristics						
Inductance [mH]	18.5	Internal Resistance [mΩ]		48.56	KV	508

The static propulsion test, first and foremost, proved that the electronics were functional and allowed UB DBF to progress to flight testing. Secondary considerations were extra data, summarized in Table 25, to apply into the propulsion model: Namely, the motor characteristics and RPM to derive the load line slope.

8.3 Staging

Table 26 reveals the results of the time trials for the major components of GM. Excluding the closing of hatches and assembly crew member movement about Bull Shark, the average GM time resulted to 22.26 s. Through testing, a few parameters, such as the clip thickness of 2.5 mm for ideal stiffness, were

Table 26. Staging Time Trials

Time [s]	Component Installation		
	Pylon	Fuel Tank	X-1 Release
Trial 1	4.50	4.67	6.65
Trial 2	2.67	5.24	5.40
Trial 3	4.00	4.03	4.50
Average	3.72	4.65	5.52

finalized. The only noteworthy modification was the addition of the through hole in the pylon to detach it from the wing-side clip without relying on a separate access hatch, though that doesn't impact staging time. The sole problems were caused by poor manufacturing tolerances, which will be refined via further testing.

8.4 X-1 Release

There wasn't a successful X-1 release test thus far, though several insights were gained from the failings. Initially, X-1 failed to release successfully because it jammed up in the release mechanism: this led to the design of the obtuse angle in the entryway. The other challenge was that X-1 would hit the aircraft on the way out: the chosen solution was to mount X-1 at a negative angle of attack and pitch the main aircraft up prior to release to kill some momentum. On Bull Shark, X-1's wing bent because of the supreme airspeeds and turning loads sustained: this forced the implementation of a pultruded carbon strip wing spar.

8.5 Flight

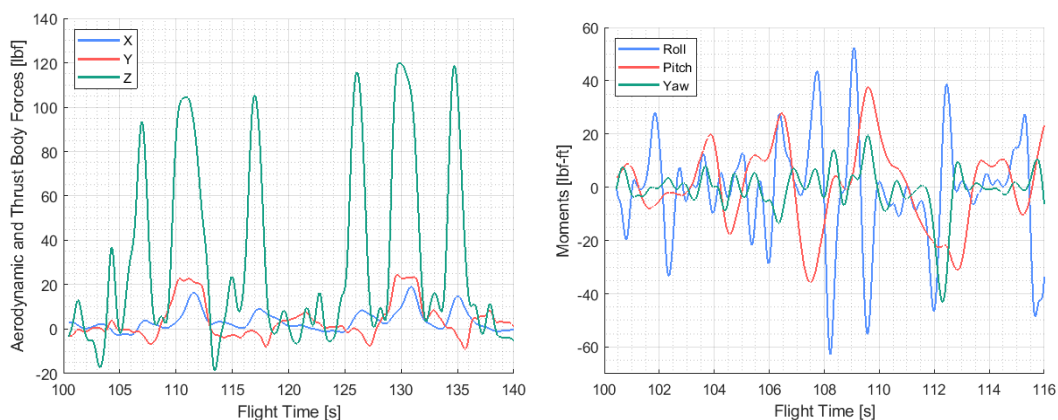


Figure 50. V1 In-Flight Forces and Moments for M3

Fig. 50 is a snapshot of the aerodynamic and structural envelope of Bull Shark within M3 constructed using traditional flight dynamics equations [18], with weight components isolated from the forces in the left plot. As expected, turning loads were the only body force of any substantial magnitude with average and peak values of 118 lbf and 149 lbf. V1 had an M3 weight of 13.30 lbf, so the peak g-load experienced was 11.2g; Considering that the M3 test was mistakenly performed at the wrong throttle and that V2 is expected to be 48% lighter, the modeled average g-force became 8.7 for M3. Similar techniques yielded an average turning load factor of 3.4 for M2.

The highest tested gross weight for M2 was 31.1 lbf with two 17 oz bottles filled with lead shot, an outlawed material. Despite its invalidity, the test had many significant outcomes. V1's pylons vibrated at a high frequency and moderate amplitudes because of imperfect rail tolerances, though that proved inconsequential to the plane's flight handling qualities and payload security. Nonetheless, the issue was corrected for the subsequent prototypes by using tight walls at the wing-side structure and finer tolerances with the bottle adapter design to avoid structural failures caused by rattling at competition.

When landing M2, V1 had an appreciable sink rate. Since the landing gear sustained no damage, the mount design was adapted into future prototypes. Nevertheless, actions had to be taken to improve landing assuredness: the selected solution was to reduce the stall speed by increasing the flap span and deflection. V1 was designed with flaperons for greater roll authority, but the flight test indicated fully deflected blown ailerons allowed for roll rates of 120 deg/s even with the loaded fuel tanks installed. Because flaperons limit the downward deflection of flaps, removing the feature entirely and increasing the flap span from 45% to 55% was prudent. Considering that there was already sufficient elevator authority to handle the increased nose-down pitching moment, the alteration was simple and pursued on V2.

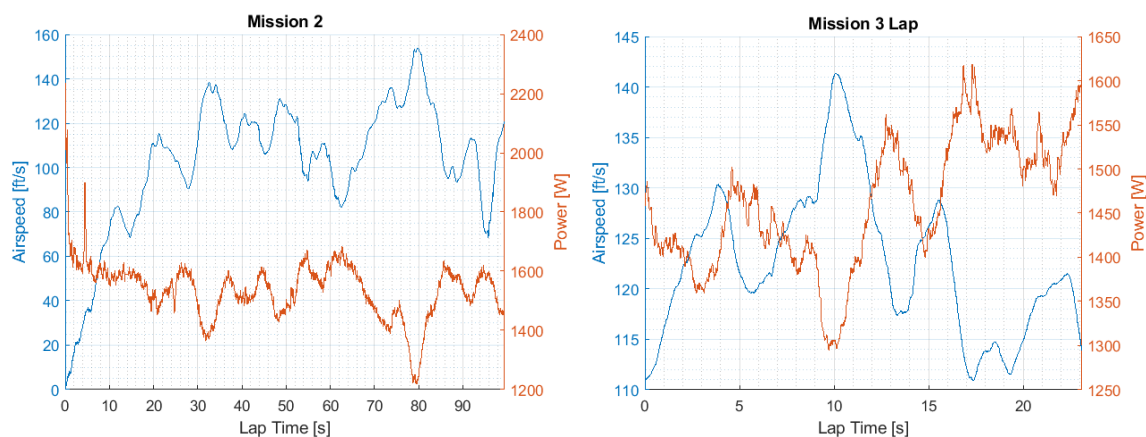


Figure 51. M2 (Left) and M3 Lap (Right) Airspeed and Power Draw

Fig 51. shows the airspeed and power draw for the full M2 and an arbitrary M3 lap. The loading and unloading of the propellers in flight is particularly clear in the M3 plot. Putting aside that M3 was conducted at full throttle, the loss of airspeed in a turn was more appreciable than would be expected because drag increases non-linearly with angle of attack and sideslip. The optimization preliminarily predicted a 23 second

M3 lap time for V2, but it will likely deviate from that estimate given the infidelity of the drag model. However, since the power consumption at the design airspeed for M3 was marginally better than expected, 11 laps would be feasible by utilizing more throttle. For M2, V1 continuously attained higher airspeeds than predicted by APC performance data with less power at the flown RPM, so it can be anticipated that M2 time will be less than estimated. During the flight test, the pilot didn't attempt excessively sharp turns, so the M2 mission time is as high as 98.96 seconds.

To conclude this report, the best mission scores from flying Bull Shark V1 are showcased within Table 27.

Table 27. Flight Mission Performance

Mission	Fuel Tank Weight [lbf]	X-1 Weight [lbf]	Bonus Score	Mission Time [s]	Lap Count	Energy Consumption [Wh]
M2	18.78	/	/	98.96	3	57.30
M3	/	0.20	0	196.40	7 (8)	74.87

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