2020 AA 498: Design Build Fly Project

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The goal of the Design Build Fly Conceptual Design Project is to develop an aircraft capable of meeting the requirements of the American Institute of Aeronautics and Astronautics (AIAA) Design Build Fly competition. The mission and design requirements are a representation of a set of customer requirements that would be submitted to an engineering firm as a project. The project will consist of the division of team members into subsystem groups, the completion and analysis of potential options within each group, and the integration of results into an overall design. The result of the work done by the project team is an aircraft that excels at all of the customer required flight missions and meets all design parameters.

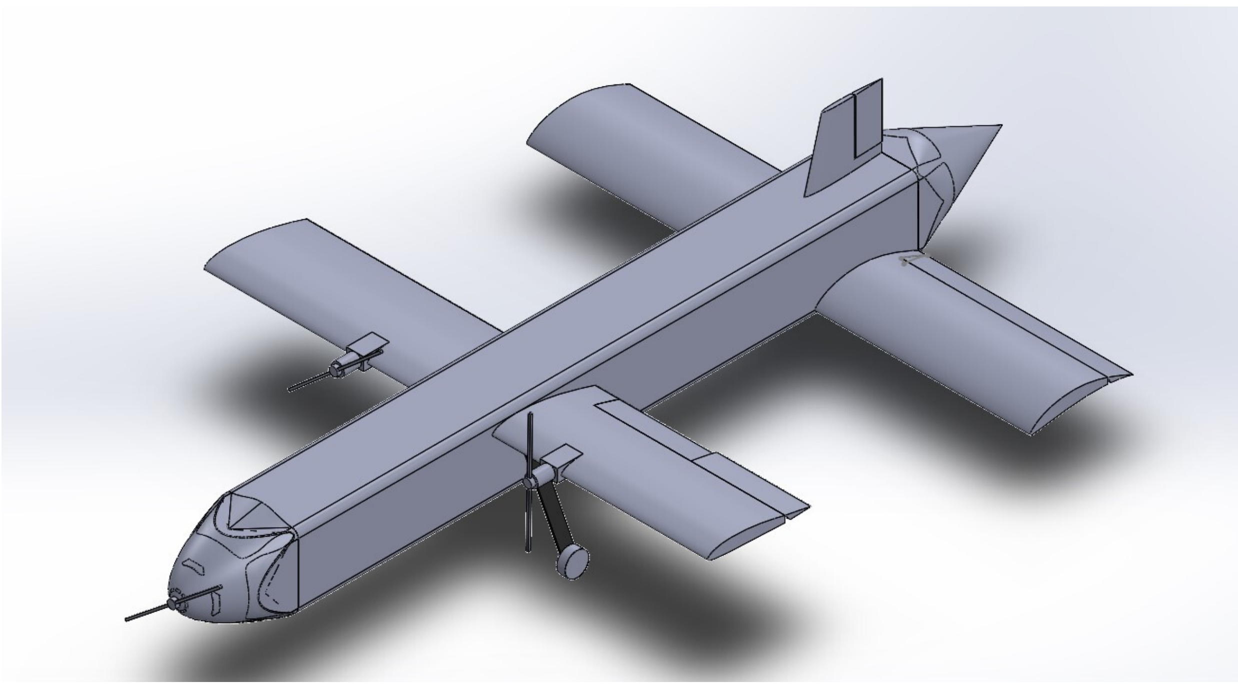

Fig. 1 An Isometric View of the 2021 DBF Plane Design by Kenneth Wiersema, DBF CAD Lead

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Nomenclature

A	=	Amplitude of oscillation
a	=	Cylinder diameter
b_w	=	Wingspan
$B_{storage}$	=	Total battery power stored
C_{D0}	=	Zero lift drag coefficient
C_L	=	Lift coefficient
C_p	=	Pressure coefficient
C_{vt}	=	Vertical stabilizer volume coefficient
Cx	=	Force coefficient in the x direction
Cy	=	Force coefficient in the y direction
c	=	Chord
$\mathrm{d}t$	=	Time step
e	=	Oswald efficiency factor
E_{sb}	=	Specific energy of battery
Fx	=	X Component of the resultant pressure force acting on the vehicle
Fy	=	Y Component of the resultant pressure force acting on the vehicle
g	=	Gravitational acceleration
h	=	Height
i	=	Time index during navigation
j	=	Waypoint index
k	=	Induced drag constant ($\frac{1}{eA\pi}$)
K	=	Trailing-edge (TE) nondimensional angular deflection rate
K_v	=	Stabilizing surface coefficient
$\frac{L}{D}$	=	Lift to drag ratio
n_{max}	=	Maximum g-loading
S_w	=	Wing area
S_{vt}	=	Vertical tail area
$\frac{T}{W}$	=	Thrust to weight ratio
V_{cruise}	=	Nominal cruise velocity
V_{Stall}	=	Nominal stall velocity
$\frac{W}{S}$	=	Wing loading
q	=	Dynamic pressure
α	=	Angle of attack
η	=	Efficiency
η_F	=	Tail efficiency
ρ	=	Air density
ψ	=	Yaw angle

I. Executive Summary

The Design, Build, Fly (DBF) project is a roughly eight-month long design competition sponsored by the American Institute of Aeronautics and Astronautics (AIAA). Over 100 international and domestic universities compete annually to design the best remote controlled (RC) aircraft in the accelerated time-frame of the project. The only overarching requirements annually (save those specified on a year-to-year basis) are that the aircraft adheres to the codes specified in the Federal Aviation Administration (FAA) Part 107 standards, has a propulsion power-plant under 200 Watt-hours (FAA) and is not of vertical-takeoff or lighter-than-air configuration.

The objective for this year is to design, build and test a unmanned aerial vehicle (UAV) with a deployable, towed sensor. Missions will include delivery of the UAV, high-capacity transportation of sensors in shipping containers and surveillance by deploying, operating, and retrieving a towed sensor.

The main challenge with the design this year is to balance the opposing variables of cargo capacity and thrust/drag ratio in order to create an optimized solution. High-capacity cargo planes are the backbone of the modern-day shipping and industry while sensor towing planes allow for the collection of atmospheric and global emission data amongst many other multi-faceted applications. The issue is that the majority of modern-day aircraft specialize in one of these objectives, not both. For example, a high-capacity aircraft calls for the minimization of structural weight in order to maximize internal space and fuel/weight ratios. In contrast, a sensor towing plane needs to include a deployment mechanism and have the power to resist the added drag during deployment. Essentially, adding the towing/deploying ability to a high-capacity plane reduces the amount of storage and range due to the added weight and size of the mechanism. Currently only military reconnaissance aircraft and specially built research aircraft are capable of towing sensors. However, these aircraft are not capable of carrying large internal loads, so the team's aircraft design is able to fulfill a niche currently not filled by an existing aircraft. The team's research into maximizing lift and airspeed with regards to heavy, variable loads also matters, as that is something the industry has been conducting research into for decades.

The design approach for this project mirrors the design process of large industry entities like Boeing and Airbus. Work is divided between several relatively small subsystem teams, each of whom are tasked with optimizing a specific section or system of the aircraft. With regards to DBF, the three main subsystem teams are Aerodynamics, Structures and Avionics/Propulsion. This allows members from each subsystem team to come up with creative solutions without feeling the need to filter their ideas in order to meet the overall design goal. In order to ensure that the competitive ideas can be brought together in a cohesive design, the Chief Engineer leads the integrative design team which contains a small group of seasoned members tasked with meshing the design elements and monitoring the overall configuration. This approach allows the most competitive ideas to lead the design phase and results in a more aggressive and innovative end product.

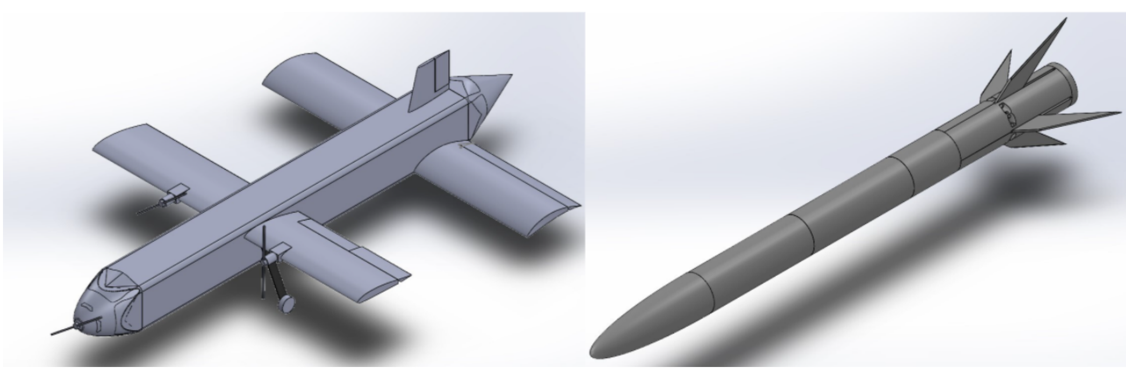


Fig. 2 Conceptual Aircraft and Sensor Design, CAD Models by Kenneth Wiersema - DBF CAD Lead

This year, the Aerodynamics Team determined that the optimal configuration would be a tandem wing. This was chosen to maximize the lift-to-drag ratio of the aircraft while staying within the five-foot wingspan limit of competition. By having two wings, the team was able to roughly double the lift while keeping roughly the same lift to drag ratio. This allowed for the accommodation of a larger, high-capacity fuselage. However, the main challenge with this tandem wing design was the stability margin. Since tandem wings are less common, the stability analysis had to be derived by hand, making it much more complex. The results of the stability analysis led the team to select a different airfoil for the front and rear wings (a Clark Y and CH10 respectively). Furthermore, the Clark Y was inclined upwards by five-degrees with respect to the body of the aircraft to force it to stall at a lower angle of attack than the rear wing. By doing this, when the aircraft starts to stall, the front wing loses lift sooner than the rear wing which drops the nose and allows the pilot to regain control. Furthermore, the downwash created by the front wing results in reduced lift over the rear wing however, since the CH10 has a higher c_l value than the Clark Y, this actually helps both wings produce equivalent lift.

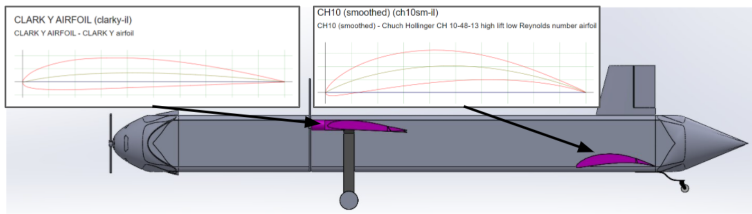


Fig. 3 Side Profile View of the Wing Configuration, CAD Model by Kenneth Wiersema - DBF CAD Lead

The main takeaway from the aerodynamic design is that the tandem configuration maximizes overall lift. This was done to accommodate the eight-foot long, high-capacity fuselage designed by the Structures Team. The expected payload capacity is 15 sensors with a boxed dimension of 2"x2"x19.5" (Width, Height, Length) and total weight of 17 pounds. Furthermore, since the designed structural and propulsion weight of the aircraft is 20 pounds, nearly half the weight of the 37 pound aircraft is for cargo. To put this in perspective, the Lockheed Martin C-5 Galaxy is one of the best high-capacity transport aircraft in industry and its payload to takeoff weight ratio is 0.37. The current 2021 DBF aircraft has a ratio of 0.46, making it pound-for-pound more capacity efficient than the C-5. In order to achieve such a high payload to takeoff weight ratio, the DBF aircraft is designed for a monocoque, sandwich-structure composite fuselage. A carbon-fiber/kevlar, 0/90 degree woven sheet was chosen for the matrix element while a 0.125" thick closed-cell PVC scored foam sheet was chosen for the sandwich core. This monocoque design allows the team to minimize the internal ribbing and support structures while maximizing the cargo capacity. Furthermore, since access points need to be cut into the aircraft for bomb-bay doors (sensor deployment) and top-side loading hatches (payload), the local rigidity of the monocoque fuselage compared to its semi-monocoque variant makes it more structurally efficient. Since overall cost was less restrictive this year (due to increased funding) the monocoque design came out on top as shown in Table 1 below.

Table 1 Detailed breakdown of the monocoque vs semi-monocoque design

	(weight)	monocoque	semi-monocoque, 4-longeron
Structural Weight Efficiency	0.2	10	7
Low Ribbing Complexity	0.1	10	6
Manufacturability	0.3	6	8
Compatibility with Doors	0.1	6	9
Structural Interfacing	0.1	8	9
Volume Capacity	0.2	10	6
Low Cost	0.1	6	9
(normalized score)		8	7.55

Since this is an RC aircraft, the propulsion and avionics systems are largely comprised of off-the-shelf products from reputable manufacturers. The majority of the propulsion design involved motor and battery thrust analysis in order to determine the most efficient thrust to weight ratio configuration for the cost. Additionally, an iFlight flight controller was chosen for its performance and reliability. Notably, the designed max and cruise thrust to max takeoff weight (MTOW) ratio is 0.77 and 0.54 respectively. Since competition rules allow for a 100-foot ground roll on takeoff, a less conservative thrust to weight ratio was chosen this year compared to years past.

Finally, the Lead Payload Engineer worked with all three of the main subsystem teams to design what is essentially a horizontal rocket. This 18-inch long sensor is equipped with three MOSFET controlled LED's and retractable stability fins. It was designed to be robust and compact for its designed length and will serve as the payload for the second flight mission as well as the towed device in the third mission. This sensor is designed to deploy from a bomb-bay door near the center of gravity (CG) of the aircraft with a 15-foot long towline. Multiple designs were flight tested in order to determine the most compact and stable iteration.

II. Project and Team Organization

The AA 498 DBF project consists of 12 seniors in the Department of Aeronautics and Astronautics that were split up and assigned various roles that support the end goal of a conceptually designed aircraft per the AIAA DBF governing rules. For organizational purposes, one Chief Engineer was chosen to facilitate and direct communication between the other 11 members as well as the rest of the DBF club in order to ensure productive, collaborative work. The other 11 members were given a lead role that fell under either Aerodynamics, Structures or Controls with the Lead Payload Engineer interfacing between all three areas. Project roles were designated based on empirical knowledge of the project needs and members were assigned based off of demonstrated interest. The roles for both the AA 498 members and the overall DBF Club are shown below in Fig.4.

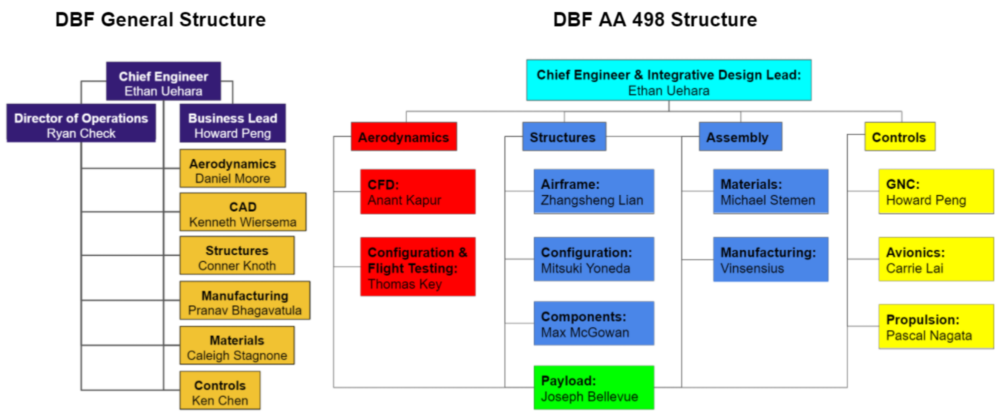


Fig. 4 The Organizational Structure for DBF at UW and the AA 498 portion

Since this AA 498 project runs directly in line with what DBF at the University of Washington Club already does, the Chief Engineer was tasked with integrating efforts between the two groups in order to ensure that everyone worked towards designing one exceptional aircraft rather than two poor ones. Furthermore, the amount of work that is called out in this project vastly exceeds what a team of 12 members can create over the course of 10.5 weeks, thus additional support was needed to ensure that a strong end-product was produced. This means that some of the figures contained in this report will be from members of the DBF team that are not in AA 498. If this is the case, the member responsible for that work will be directly cited in the caption. This also means that since not every aspect of the aircraft was designed by an AA 498 team member, that there may be a few design elements that are not discussed due to the need to present individual work. If that is the case, the contributing design work from another team member will be briefly mentioned and cited in order to provide a holistic view of the aircraft design process.

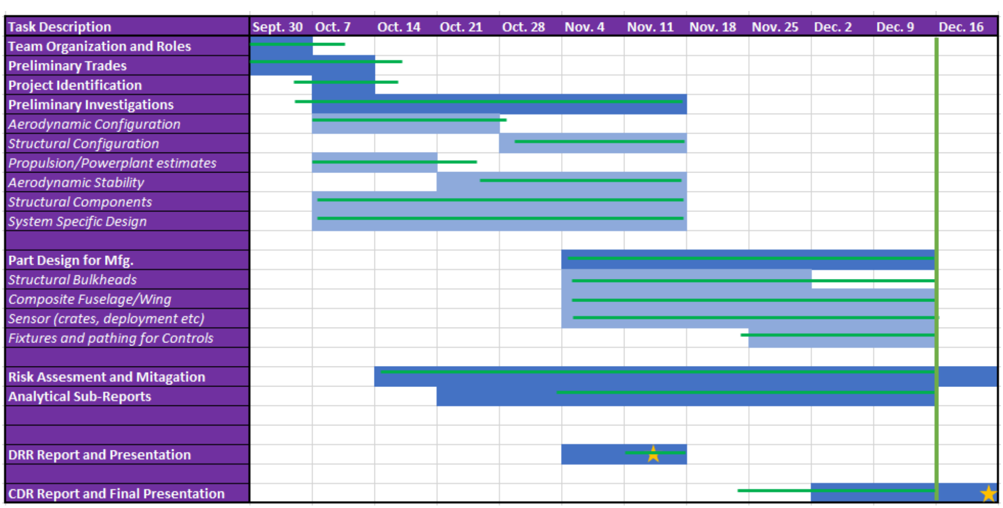


Fig. 5 The Up-To-Date Gantt Chart for the AA 498 DBF project

Fig. 5 shown above, outlines the Autumn Quarter workflow for the AA 498 team. The efforts can be divided into three main sections, Preliminary Trade Design (done in the first two weeks) followed by the Preliminary Investigations (until Mid-November) and finally Part Design (until end of quarter). The two major milestones were the Design Requirements Review (DRR) and the Conceptual Design Review (CDR).

As a final note regarding the structure of the past quarter's efforts, by having the senior AA 498 team work with the largely freshmen and sophomore DBF Club, both parties were able to benefit. The AA 498 members were able to learn part design and workflow skills that are inherent to the structure of the DBF team but not directly taught in the academic setting. For example, many AA 498 were taught CAD, CFD or FEA by DBF members over the course of the project and thus have new skills they can bring to their Winter/Spring Capstone project. On the flip side, many of the DBF members benefited from the advanced technical knowledge that the AA 498 members possessed after going through the majority of the AA curriculum. By learning from the coursework related knowledge of the AA 498 members, the DBF members were able to determine how to translate those concepts over to the practical design setting. Thus, it was a mutually beneficial relationship this past quarter (and one that I (Chief Engineer: Ethan Uehara) encourage to continue in the coming years).

III. Introduction

A. Problem Definition

The objective for this year is to design, build and test a unmanned aerial vehicle (UAV) with a deployable, towed sensor. Missions will include delivery of the UAV, high-capacity transportation of sensors in shipping containers and surveillance by deploying, operating, and retrieving a towed sensor.

The main challenge with the design this year is to balance opposing variables to create an optimized solution in both categories. Essentially, the problem statement is asking for the design of a high-capacity aircraft that is capable of deploying and towing a sensor device. Both of these applications are very important as high-capacity cargo planes are the backbone of the modern-day shipping and industry while sensor towing planes allow for the collection of atmospheric and global emission data (just one of many applications). The issue is that the majority of aircraft will specialize in one of these objectives, not both.

A high-capacity aircraft calls for the minimization of structural weight in order to maximize internal space and fuel/weight ratios. In contrast, a sensor towing plane needs to include a deployment mechanism and have the power to resist the added drag during deployment. Essentially, adding a towing/deploying ability to a high-capacity plane reduces the amount of storage and range due to the added weight and size of the mechanism.

In modern-day industry, most sensor towing planes are a modification of a fighter jet which has no shortage of power to resist the added drag while most transport planes are huge behemoths like the Lockheed C-5 Galaxy or the Airbus A300-600ST Beluga. On both ends, the main limitation is always the endurance/range which stems from the fuel to weight ratio. The current solution that improves the performance of both style of aircraft is to reduce the structural weight (by moving to lighter, more optimized composites) and increase fuel capacity and engine efficiency.

Currently only military reconnaissance aircraft and specially built research aircraft are capable of towing sensors. However, these aircraft are not capable of carrying large storage loads, so the team's aircraft design is able to fulfill a niche currently not filled by an existing aircraft. The team's research into maximizing lift and airspeed with regards to heavy, variable loads also matters, as that is something the industry has been conducting research into for decades.

B. Aerospace Context

The challenges presented in the competition requirements have many parallels in the aerospace industry. For example, one of the main focuses of the design is to maximize its performance as a cargo carrying aircraft. As outlined in the competition rules, the winning plane will not just carry a large amount of sensor containers (weight and volume), it will likely also be able to load and unload the aircraft in a short amount of time. These qualities are clearly important to many commercial aircraft, as the plane that can carry the most and spend less time on the ground will be the most financially viable one. Second, the requirement of a towed sensor creates an unusual challenge for an aircraft, due to needing a detailed deployment and recovery system, and also being able to be controllable while having a potentially heavy object suspended from the airplane. A plane which is able to successfully deploy, tow, and recover a sensor will likely be very stable in normal flight helping it be a safer aircraft. This is of significant interest to the aerospace industry, where multi-role aircraft often have a place within the fleet of both private and public institutions.

C. Functional Requirements/Customer Specifications

The customer specifications originate from the rules document released by the AIAA, as well as official responses to inquiries submitted by competing schools. The main component of these specifications are the completion of the following flight missions, as well as the ground mission.

- Mission 1: Teams must complete 3 laps within the five minute flight window, with no payload.
- Mission 2: Teams must complete 3 laps within the five minute flight window with the payload: a sensor in shipping container, shipping container simulators, and the deployment and recovery mechanism.
- Mission 3: After a successful take-off, the sensor will be deployed by remote command and must be fully deployed prior to the first 360 degree turn. After completion of the final 360 degree turn during flight, the sensor will be recovered by remote command; the sensor must be fully recovered inside the aircraft prior to landing; the recovery does not have to be complete prior to crossing the finish line (the aircraft can continue to fly until full recovery and then complete a successful landing). Three laps must be completed within 10 minutes.

It should be noted that the sensor payload itself is a merely an analogue for a more complex payload. The AIAA has mandated that three LEDs be placed on the sensor in order to verify in-flight stability, but the payload itself has no other internal requirements and is mostly structural in nature. There are also additional design limitations placed on entries. Some important conditions are given below.

- Maximum allowable wingspan is 5 feet.
- The aircraft may be of any configuration except rotary wing or lighter-than-air.
- No structure/components may be dropped from the aircraft during flight.
- No form of externally assisted take-off is allowed. All energy for take-off must come from the on-board propulsion battery pack(s).
- Must be propeller driven and electric powered with an unmodified over-the-counter model electric motor. May use multiple motors and/or propellers. May be direct drive or with gear or belt reduction.
- The aircraft must have an externally accessible switch to turn on the radio control system. It cannot be internal or under a panel or hatch.
- Batteries may not be changed or charged during a flight mission attempt.

A full list of requirements are provided in the appendices.

D. System Design Approach

Since the design phase of this project was limited to a 10-week period, the design approach called for a tandem-workflow method. Thus, the approach taken with the project mirrored the design process of industry entities like Boeing and Airbus. Work was divided between several relatively small subsystem teams, each of which were tasked with optimizing a specific section or system of the aircraft with limited oversight. This allowed members from each subsystem team to come up with creative, unfiltered ideas during the design phase. In addition, the process of developing and analyzing a wide array of trade studies in small groups allowed for more potential solutions to be found and devised. Some alternative design approaches were briefly considered, but as this approach is the standard for industry, it was quickly selected due to its history of success.

The risks and payoffs regarding this project approach were fairly simple. By dividing the work amongst the team members in a subsystem team structure, members that were more experienced with individual aspects of design applied their knowledge in a narrower field. This allowed the team to design better and more competitive subsystem components. However, since subsystem teams started their design independent of each other, integration was more difficult, especially when requirements began to conflict. This ran the risk of delaying the project on several occasions but was mitigated with consistent cross-communication efforts between the subsystem teams and project leadership throughout the analysis phase. In order to ensure that the necessary cross-communication happened between teams, each subsystem team held a weekly design review and the Chief Engineer led a weekly general design review.

Success with this approach is measured by progress reports. Each subsystem team was expected to adhere to a schedule and to complete their trade studies, analysis, and other tasks on time and to the highest standard of work. The majority of the parameters for success were determined during the integration process, when teams came together to finalize a set of subsystem requirements and fit them into the evolving design of the aircraft. This meant that at the end of the quarter, a complete aircraft and payload with all of the finalized subsystems, was produced.

IV. System Design

A. Aerodynamics

The aerodynamic considerations for the project aimed to optimize a variety of options for the body of the aircraft. The given mission requirements went through genetic optimization to determine the most critical performance requirements. The optimization studies from the mission objective provided no bias towards a cargo heavy aircraft or an aircraft optimized for speed and low cargo. This presented a requirement that the plane operates at maximum available lift and minimum drag so that the plane flies sufficiently fast, while carrying the most amount of payload, as there was no trade-off other than maximizing both individually.

To achieve this goal, the aircraft must be shaped appropriately to maintain stable and controlled flight by designing parameters such as the shape of the fuselage, the nose and the tail. More specific requirements and considerations included choosing the airfoil for the (front and rear) wing and the configuration of the wing itself. While the decisions made for aerodynamic performance optimization were critical, the need to remain viable for manufacturing/structural considerations remained heavily at the forefront of the design.

The overall aerodynamic configuration went through a few iterations after the initial mission optimization studies were determined. This led to a few major configuration choices that eventually narrowed down into a tandem wing configuration. The trade studies conducted in advance of the tandem wing design are discussed, as well as any other trade studies performed later on in the design.

1. Subsystem Trade Studies

Trade studies for aerodynamics were wide-ranging and included research on the shape of the entire airplane, fuselage, wing and tail, the configuration and mounting of the wings, the design of the sensors, application of flaps and slats on the wings, implementation of winglets, etc. As a whole, the DBF aerodynamics team researched and presented a variety of topics, some of which were selected to be further worked on in small project groups. The AA 498 team contributed with individual trade studies, which are discussed below.

Slats and Krueger Flaps:

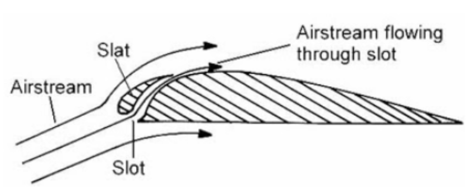


Fig. 6 Slats installed on the front of the wing. They are retractable and allow for air to flow through helping improve coefficient of lift. [1]

Slats are extendable, high lift devices on the leading edge of the wings of some fixed wing aircraft which, when deployed, allow the wing to operate at a higher angle of attack. They are similar to slots but specifically, slats are movable while slots stay fixed in position. A higher coefficient of lift is produced as a result of angle of attack and speed, so by deploying slats, an aircraft can fly at slower speeds, or take off and land in shorter distances. They are usually used while landing or while executing maneuvers which take the aircraft close to the stall point, but are usually retracted in normal flight in order to minimize drag.[1]

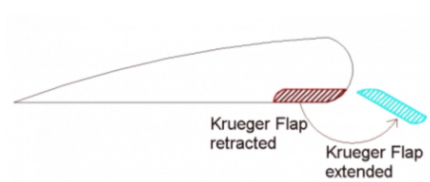


Fig. 7 Krueger flaps installed on the bottom surface at the front of the wing. The mechanics of these flaps is similar to the slats. [2]

Additionally, slats decrease stall speed. For the plane, they could be deployed manually, or be set up in a way that they come out automatically. This may be accomplished by having a spring-loaded slat, that lies flush with the wing leading edge, held in place by the force of the air acting on it. As the aircraft slows down, the aerodynamic force is reduced and the springs extend the slats. This is referred to as a Handley-Page slat.[1]

The aerodynamic effect of a Krueger flap is similar to that of a slat; however, they are deployed differently. Krueger flaps are mounted on the bottom surface of the wing and are hinged at their leading edges. Actuators extend the flap down and forwards from the under surface of the wing thus increasing the wing camber which, in turn, increases lift.[2]

Dual Boom with Dual Vertical Tail:

Due to the cargo considerations - there were two extremes to consider, an aircraft which was either light and fast or one that was slow and heavy. The design later moved to balance between the two after an optimization study, but initially, a trade study was done to determine the benefits of a dual boom aircraft with a small fuselage that aimed to decrease the overall weight while attempting to increase speed. The analysis was performed in VSPaero by Thomas Key in order to get a strong view of the aircraft performance in lieu of significantly more time consuming methods involving more intensive CFD simulation.

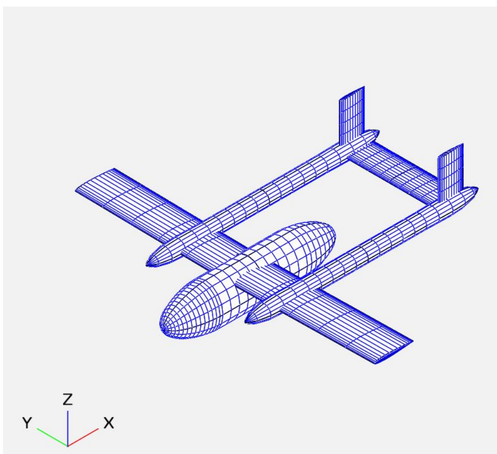


Fig. 8 Dual Boom VSPaero model

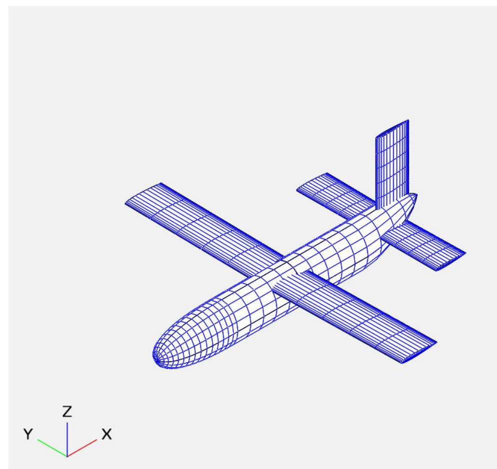


Fig. 9 Single Tail VSPaero model

The main benefits to the dual boom were the structural capabilities - particularly in roll authority - and the weight. The longitudinal stability would be much simpler to calculate and there wouldn't be a fuselage to reduce effectiveness of control surfaces, with the tradeoff of lower cargo capability. The dual boom had also been used in the past as a tow plane for gliders, so it had historical benefit. Two models were generated using VSPaero, a NASA software used for aerodynamic simulation through vortex lattices. Normally the software is used for propulsive analysis but it provided fantastic plots and constants used to compare the two cases.

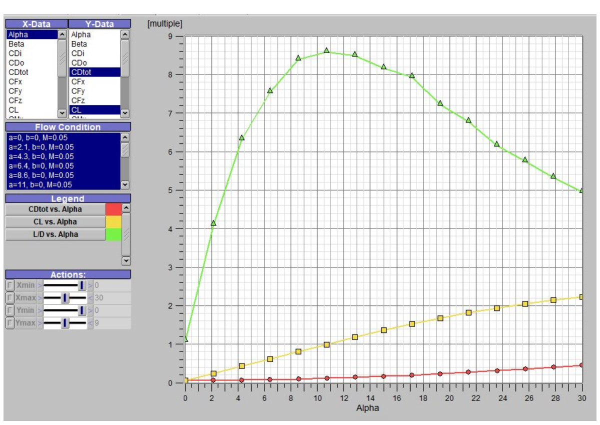


Fig. 10 Dual Boom C_L, C_D, and $\frac{L}{D}$ vs. α

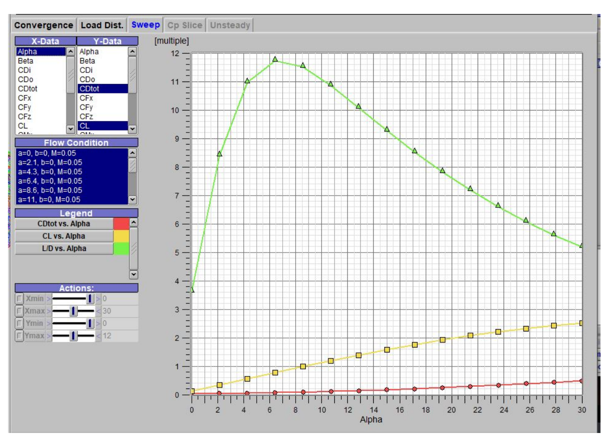


Fig. 11 Single Tail C_L, C_D, and $\frac{L}{D}$ vs. α

The performance of the two cases in Fig. 8 and 9 remained quite similar for an equivalent range of angle of attack. While the dual boom case had a higher drag over that range as shown in Fig. 10, the lift was also slightly higher. However, this didn't provide a sufficient advantage in the $\frac{L}{D}$ when compared to Fig. 11, the single boom case. That aside, the dual boom configuration showed a distinct benefit in the $\alpha_{\frac{L}{D}max}$, which would provide better performance at higher angles of attack. This would allow the dual boom to reach steeper takeoff to get to altitude, decreasing the total run time of the missions - a critical performance metric. However, this data alone was not enough to make a considerable decision for either configuration to be chosen because of the balanced performance between the two. Where one configuration lacked, the other excelled. The volume was the last consideration that allowed these to both be considered in overall aerodynamic configuration, because the dual boom had - for obvious reasons - significantly less volume.

Unfortunately, besides the VSPaero simulations in Fig. 10 and 11 there wasn't a lot of information available on performance for the dual boom configuration, and while the calculations for stability were easier, it would still be difficult to control and the landing gear would be too challenging to manufacture. While VSPaero was still used to determine if the aerodynamic configuration was reasonable, it was determined that a tandem wing had better range and endurance under the specifications received from the propulsion team as shown in the overall aerodynamic configuration section.

Winglets:

On modern airliners, the wing tips are often bent up to form winglets. These devices increase the lift generated at the wingtip (by smoothing the airflow across the upper wing near the tip) and reduce the lift-induced drag caused by wingtip vortices, improving the lift-to-drag ratio. This increases fuel efficiency in powered aircraft and increases cross-country speed in gliders which in both cases increases range. Winglets reduce wingtip vortices, the twin tornadoes formed by the difference between the pressure between the upper and lower surfaces of an aircraft's wing. The wingtip vortex, which rotates around from below the wing, strikes the cambered surface of the winglet, generating a force that angles inward and slightly forward, analogous to a sailboat sailing close hauled. The winglet converts some of the otherwise-wasted energy in the wingtip vortex to an apparent thrust. Though winglets offer these advantages, their implementation on an aircraft depends on the speed of the aircraft and drag contributions relating to the speed. [3]

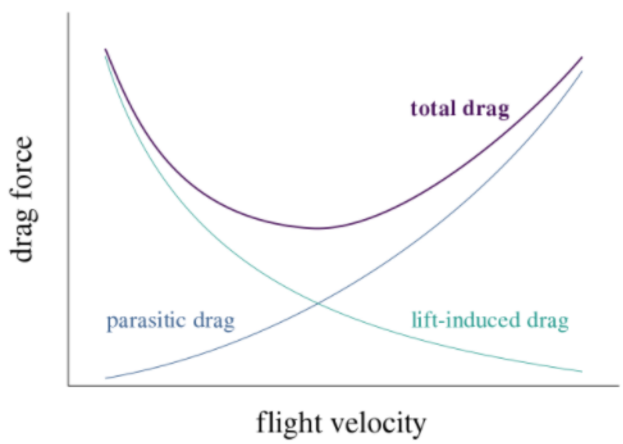


Fig. 12 Drag contribution from lift-induced drag and parasitic drag [4]

Drag has various components that contribute to the overall force exerted on a body. Fig. 12 outlines the relation between the parasitic and lift-induced drag forces acting on the body depending on the speed. If the plane is flying at lower velocities, lift-induced drag is the major component of overall drag. Theoretically, this is where winglets can help reduce the most amount of drag. However, with the implementation of winglets and the increased surface area, parasitic drag is also increasing. The goal is to gain the largest reduction in induced drag for the smallest increase in profile and skin-friction drag.

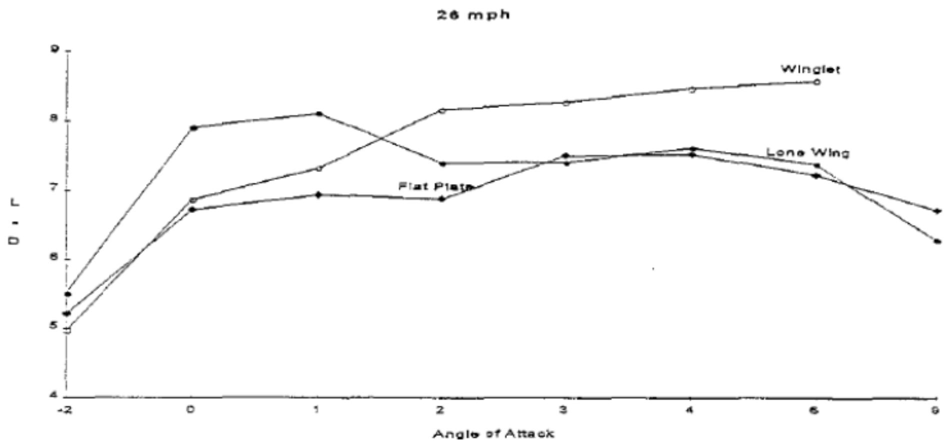


Fig. 13 L/D for naked wing, flat plate wing and winglet in a wind tunnel for various angles of attack at 26 mph [5]

After discussing the purpose and need for winglets, it must also be decided what type of winglet is chosen for the plane: Blended, canted, raked, flat-plate, Hoerner, etc. Since the plane is flying in a low drag regime, reduction of drag forces becomes a secondary factor in selection of winglet while ease of manufacturability becomes the primary factor. Thus, flat-plate winglets that are the easiest to manufacture, were chosen as the wing tip devices to be analysed and selected as winglets.

2. Subsystem Design Analysis

Overall Aerodynamic Configuration:

The overall aerodynamic configuration was the initial step towards the conceptual design of the aircraft. Beginning with a mission optimization performed by members of DBF not involved in 498, the results were used to consider a few important cases. These prioritized a few prominent suggestions from trade studies and other ideas. Due to the mission optimization showing no leaning on speed vs. capacity, the options were all considered to determine which would perform best for the mission. The configuration choices are shown in Fig. 14. There were small modifications to the single tail and dual boom configurations from the original trade study.

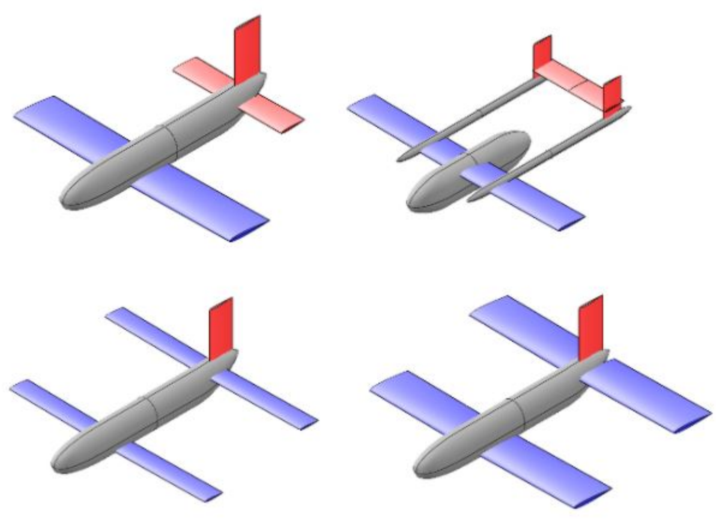


Fig. 14 Significant configurations tested for optimal mission performance

The initial metric to compare the configurations against were both the wing loading ($\frac{W}{S}$) and thrust to weight ratio ($\frac{T}{W}$). The physical descriptions of the aircraft were defined by both VSPaero using the models shown in Fig. 14, as well as equations from Raymer [6]. The oswald efficiency factor being calculated in particular by $e = 1.78(1-0.045A^{0.68})-0.64$ under an unswept wing assumption. The aspect ratio is defined by competition requirements, and the $\frac{L}{D}_{max}$ and C_{D0} values are calculated by VSPaero. The equations for the $C_{L,optimal}$ were calculated by optimal values in propeller range and endurance in Raymer [6].

Table 2 Aerodynamic constants for analysed configurations

Configuration	C_{D0}	AR	e	$C_{L,optimal}(E,R)$	$(\frac{L}{D})_{max}$
Single Boom	0.0256	5	0.901	1.04 , 0.602	11.8
Dual Boom	0.0243	5	0.901	1.02 , 0.586	12.1
Tandem	0.0238	10	0.757	1.30 , 0.752	11
Tandem ($2S_{ref}$)	0.0173	5	0.901	0.857 , 0.495	14.3

From those physical parameters, there were also other design constraints from the genetic optimization, structural requirements, and competition requirements. They are shown below as a set of equations, but they describe the set of constraints that allow for an optimization to occur. The structural requirement was that the aircraft is a given structural expectation with an added factor of safety of 1.5, providing the maximum loading.

The propulsion team also held requirements for energy considerations. Primarily that the battery specific energy remained at the provided value below, with a propeller efficiency and battery efficiency of 0.85. The velocity requirements and the total energy storage are artifacts of the competition design requirements. The battery storage is also limited to two batteries of 100Wh each, to ensure that they can be shipped by plane as the FAA only allows two batteries with a maximum of 100Wh each. The $C_{L,max}$ value is determined by the 100ft takeoff requirement.

All of the physical parameters in Tab. 4 and the equations below are what define the values used to generate the initial $\frac{W}{S}$ and $\frac{T}{W}$. The results of the calculations are calculated by superimposing the criterion in Eq's 1, and finding the minimum wing loading and the maximum thrust to weight criterion without violating any of the provided constraints.

$$\begin{aligned}
n_{max} &= 3 \\
C_{L,max} &= 1.5 \\
V_{Cruise} &= 98\frac{\text{ft}}{\text{s}} \\
V_{Stall} &= 45\frac{\text{ft}}{\text{s}} \\
E_{sb} &= 150\frac{\text{Wh}}{\text{kg}} \\
\eta &= 0.85 \\
B_{Storage} &= 200\text{Wh}
\end{aligned}$$

Stated below are the equations for the thrust to weight and wing loading criterion. Note how some of the equations are effectively 'coupled', where the thrust to weight is dependent on the wing loading. These constraints are interdependent and must all satisfy the defined region. The first equation is to constrain sufficient thrust for takeoff, the second to maintain straight and level flight, the third is the amount of thrust for a given g-loading, the fourth to generate the appropriate lift per wing loading, and the final equation is based off of the drag to lift equation.

$$
\begin{aligned}
\frac{T}{W} &\geq \frac{1.4}{Sg\rho C_{L,max}}\frac{W}{S} \\
\frac{T}{W} &\geq \frac{1}{(\frac{L}{D})_{Cruise}} \\
\frac{T}{W} &\geq 2n\sqrt{C_{D,0}k} \\
\frac{W}{S} &\geq \frac{1}{2}\rho V_{Stall}^2 C_{L,max} \\
\frac{T}{W} &\geq C_{D,0}q(\frac{W}{S})^{-1} + \frac{W}{S}\frac{k}{q}
\end{aligned}
\tag{1}
$$

Setting up these equations, the results show that there isn't a significant difference (to the second decimal place) for either value under consideration of each configuration.

Table 3 Initial comparison metrics for optimal configuration choice

Configuration	$\frac{T}{W}$	$\frac{W}{S}$
Single Boom	0.49	3.36
Dual Boom	0.49	3.36
Tandem	0.49	3.36
Tandem ($2S_{ref}$)	0.49	3.36

Given that these metrics did not favor any particular configuration, the range and endurance were determined to compare the values. These were calculated by equations (20.3) and (20.4) from Raymer[6], for electric propeller aircraft. The results are as such:

Table 4 Final aerodynamic comparison metrics for optimal configuration choice

Configuration	Endurance [min]	Range [km]
Single Boom	30.5	54.6
Dual Boom	31.3	56.1
Tandem	41	66.7
Tandem ($2S_{ref}$)	37.1	66.7

After generating the calculations of the range and endurance, the values for the individual configurations begin to have significant variances. It becomes evident that the most optimal solution is with the tandem wing with twice the initial reference area. The graphs used for the optimization and criterion matching are shown in the appendix.

Winglets: As mentioned earlier, due to manufacturability reasons, only flat-plate winglets were considered to be put on the wings of the plane, So two designs were made: the first design was a modified version of the one used in last year's plane and the second design was a newly made winglet. The winglets were created in Solidworks CAD software.

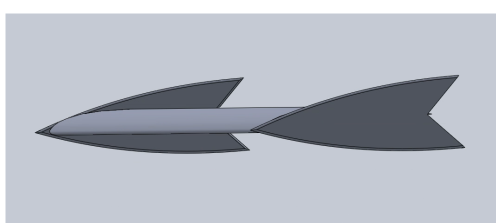


Fig. 15 CAD of the modified version of the old winglet design (based on the 2020 DBF Phoenix 1) modeled by Anant Kapur

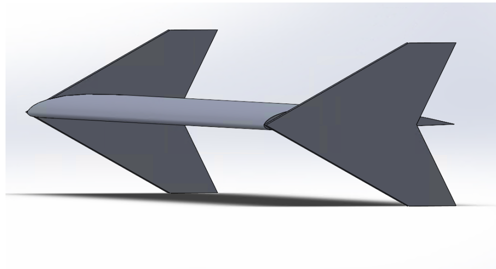


Fig. 16 CAD of the new winglet design for the 2021 DBF Dragonfly modeled by Vinsenius

Analysis was to be carried out in three steps: First the naked wing would be run, followed by the old modified design and the new design. This was to be done for both the Clark Y and CH10 airfoils. Initially, the fluid simulations were to be run on Ansys CFD software but a few issues arose. 3D meshing of the wing in Ansys did not seem to work. It should be noted that the cell size that these wings were to be using for the simulation were in the range of several millions, while the student version of Ansys only allows for a maximum cell size of 512,000. This would mean that the mesh and subsequent analysis carried would not be accurate and hence, Solidworks' built-in add-on of fluid simulation would have to be used.

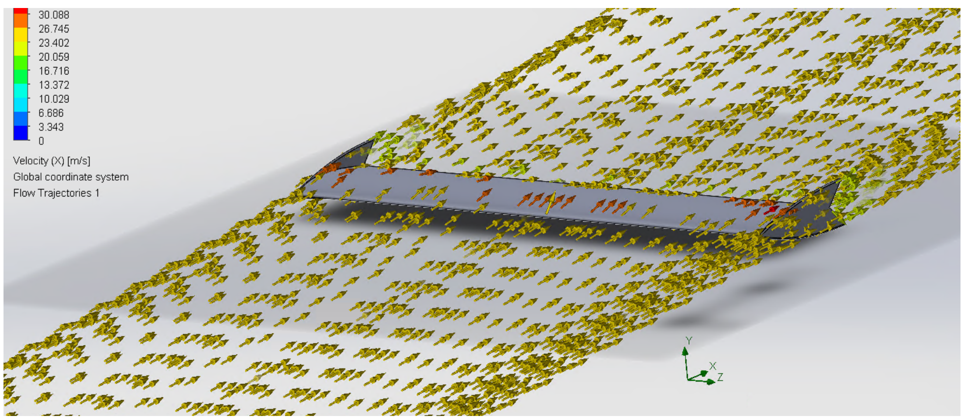


Fig. 17 Visualization of the airflow over Clark Y with winglet design included to determine optimal design. The 3D simulation allows one to observe the vortices being generated at the wing tip.

Table 5 Lift and drag values for naked airfoil and airfoil with winglets for CH10 and Clark Y

Airfoil	Winglet Design	Lift [N]	Drag [N]
CH10	Naked	133.18	18.8646
CH10	Old-modified	126.027	14.6843
CH10	New	145.13	15.1458
Clark-Y	Naked	101.037	0.23128
Clark-Y	Old-modified	125.7	-2.504
Clark-Y	New	95.7511	-0.2478

Solidworks' fluid simulation though convenient, is also far from accurate. Looking at table 5, the drag values for the Clark-Y become negative which is not possible. At least for the CH10 it is evident that the modified version of last year's winglet gives more drag reduction. If more-negative values for drag is considered better, the same design is better for the Clark Y as well. However, that is not how analysis should be carried out and it would be advised that none of these values be used for final decision on winglet design selection. Instead, more research should be done to either make Ansys software work for 3D wings or Solidworks' fluid sim be refined for more consistent and acceptable values.

Vertical Tail Sizing:

The vertical tail sizing was done using a method that was less typical of other sizing design concepts such as the use of the volume coefficient which is defined by the equation below found in [6].

$$C_{vt} = \frac{L_{vt} S_{vt}}{b_w S_w}$$

The volume coefficient method is described in the Raymer text, which doesn't provide much data for calculating for optimal sizing of stabilizing surfaces. Therefore the references of Raymer were chosen to more accurately determine the sizing of the control surfaces.

$$K_v = \frac{S_{vt}}{S_B}(\frac{\rho}{L})(\frac{dC_{LF}}{d\psi})(\eta_F)$$

The equation above was chosen from [7] and describes the stabilizing surface coefficient. This value takes into account the fuselage length, location from the center of gravity, and surface area of the fuselage side to determine the sizing needed to properly stabilize the aircraft in the yaw axis. The method allowed for a much more trustworthy result than the volume coefficient alone.

$$S_{vt} = \frac{K_v S_B L}{\eta_F \rho \frac{dC_{LF}}{d\psi}}$$

Parameters in the above equation were left as variables to ensure that the optimal sizing for the vertical tail could be determined given any (reasonable) chord length or required height. This was done not as a method of convenience for aerodynamic considerations - but to ensure that a solution could be reached for manufacturing and control considerations.

$$\begin{aligned}\frac{dC_{LF}}{d\psi} &\approx 2\pi \\ \eta_F &= 0.90 \\ C_{vt} &= 0.07\end{aligned}$$

The assumptions for the given equations were chosen by the expected yaw angles during flight as well as book values provided for similar aircraft, such as the tail efficiency and the volume coefficient for the vertical tail. Sizing for both the vertical stabilizer and the rudder were both done simultaneously to determine the optimal ratio for the flapped area and the area required for stability along the yaw axis. The aforementioned equations were then simulated to determine the best ratio for the control surface (rudder), and included with the required manufacturing sizing. The reference text expressed that a thickness of 10% or more was unsatisfactory for the control surface, and therefore the thickness of the vertical stabilizer was decided to be 0007 due to ease of manufacturing, thickness that matched the qualification of the reference text, and enough space to hold a servo within it.

3. Subsystem Design Integration

Airfoil Selection: Airfoil selection was carried out by finding airfoils that were appropriate for the wants of the airplane. Lift, drag, subsequently Lift/Drag (L/D), thickness, stall angle and stability were to be analysed for selection. An ideal airfoil would have high lift and low drag for maximum carry capacity and high speed respectively. Thickness affects flow separation and also impacts the structures team with a thicker airfoil being ideal. Stability was analyzed with checking coefficients of moment with a more negative number being less stable. With criteria listed, 9 airfoils were selected to be scored upon and chosen: NACA 2412, 4412,6412, 23012, Clark-Y, CH10, Prandtl D-Root, NASA/Langley LS 417 Mod and a KFM airfoil based on the NACA 0012. The results for the scoring is as follows:

Table 6 Parameters taken for scoring airfoil decision (Re = 500000, $C_{L_{cruise}}$ = 0.7) **[8]**

Airfoil	$C_{L_{max}}$	$C_{D_{cruise}}$	L/D_{cruise}	$C_{M_{cruise}}$	Stall angle	Thickness max
2412	1.407	0.00833	84.034	-0.0546	15.25	12
4412	1.4467	0.01097	63.81	-0.1018	15.25	12
6412	1.5959	0.00902	77.60	-0.1356	13.5	12
CH10	2.0503	0.03834	135	-0.2238	11	12.8
Prandtl-D Root	1.2103	0.00836	83.73	-0.0486	17.75	12
Clark-Y	1.4329	0.00746	93.83	-0.0855	13.5	11.7
23012	1.4299	0.01039	67.37	-0.0203	14.25	12
KFM	1.2363	0.013872	50.46	-0.0546	14.75	12
NASA 417 MOD	1.7717	0.0129	54.26	-0.0864	16.25	17

Table 7 Relative scoring for the airfoils considered for aircraft performance, stall prevention and stability.

Airfoil (Weightage)	$C_{L_{max}}$ (0.25)	L/D_{cruise} (0.4)	Stall angle (0.15)	Thickness (0.1)	Stability (0.1)	Score
2412	3.09	3.11	5	2.82	1.12	3.16
4412	3.18	0.09	5	2.82	0.6	1.92
6412	3.5	1.59	5	2.82	0.45	2.59
CH10	4.5	5	3.61	3.01	0.27	3.99
Prandtl-D Root	2.66	3.07	5	2.82	1.25	3.05
Clark-Y	3.14	3.47	4.43	2.75	0.71	3.19
23012	3.51	2.48	4.67	2.82	3	3.15
KFM	2.7	1.85	4.84	2.82	1.12	2.42
NASA 417 MOD	3.89	2	5	4	0.70	2.99

The top two choices came out to be the Clark Y and CH10 airfoils. The Clark Y is a well-balanced airfoil that has favorable characteristics in all categories. The CH10 has superior lift and L/D values but lacks stability. The decision was made to use the Clark-Y in the front and it would be mounted at an angle of attack of 5-degrees, while the CH10 would be mounted at 0-degrees in the back. The Clark Y incidence is required so the front wing stalls before the rear wing for stall recovery.

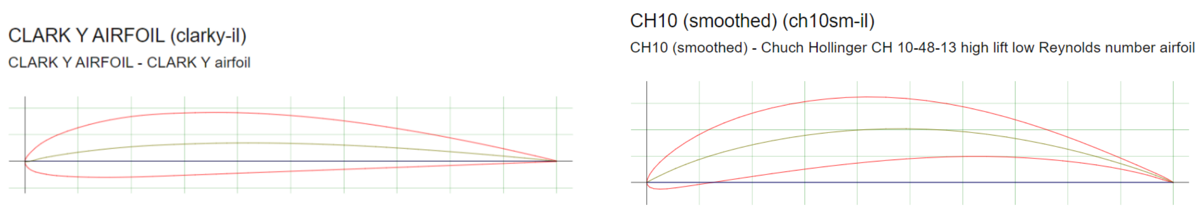


Fig. 18 Cross-sectional views of the Clark Y (left) and CH10 (right) airfoils that are used for the front and rear wings respectively. [8]

Fuselage Shaping and Stability: It should be noted that other members of the DBF aerodynamics team helped and contributed in fuselage shaping and stability conditions. Since this was not worked by the AA498 students, only results of their study will be discussed. With the fuselage, the shape is of importance. The two shapes being considered were rectangular (rounded edges) or cylindrical. The drag for the former (without rounded edges) is twice that of the cylinder but these values are not high since the operating speed is subsonic. From a manufacturing perspective though, rectangular shape fuselage is preferred. So as a compromise, the rectangular shape with rounded edges was considered. As for stability, since the tandem wing configuration was chosen 3 stability conditions were derived:

- $C_{m_0} > 0$ - At zero lift, the aircraft needs to pitch up to provide lift again
- $d(C_m)/d(\alpha) < 0$ -the aircraft shouldn't diverge with a pitch up compounded by an increasing tendency to pitch up
- $h_n > 0$ - the aerodynamic center (point about which $d(C_m)/d(\alpha) = 0$) needs to lie behind the center of gravity.

4. Subsystem Risks

Table 8 Risks Associated with the configuration and design of the aircraft.

Title/Description	Type	Lead	Chance	Conseq.	Prevent by
Tail Performance Proper tail sizing and shaping is necessary to balance out the aerodynamic moments and ensure proper control.	Design	Thomas Key	3	3	Iteratively designing the tail and making adjustments as necessary to ensure stability throughout design development
Stalling of Plane/Airfoil Each airfoil has its unique stalling angle, and with tandem design one of the wings might stall earlier than the other.	Operational	Anant Kapur	3	4	When choosing a pair of airfoils keep in mind which airfoil has what stalling angle and have the one with lower stall angle in the back, preventing excessive spin.
Airfoil Stability Each airfoil has its unique coefficient of moment based on its geometry and we need to balance moments or else the airplane will be hard to control.	Op/Design	Anant Kapur	2	3	When choosing airfoils, the type of airfoil along with its placement on the plane must be done with care. Static and dynamic stability analysis needs to be done.

The overall aerodynamic considerations are understandably widespread for the aircraft, as any component that touches the air will change the flow condition, and the components within will change the weight distribution and subsequently the stability analysis. Three of the most notable risks in the aerodynamic design are listed in Table 8 to express what considerations were held throughout the overall aerodynamic configuration. Two considerations that were held at high standard were the static and dynamic stability of the aircraft and manufacturability. All of the decisions for the tail were made to generate appropriate room for control surfaces by providing the required space to hold actuators, as well as the appropriate amount of area for control surfaces and sizing, and the wing placement and airfoil choice were designated to provide stall prevention and allow a better margin for spin recovery as well as accommodation for fuselage structure and landing gear.

Each airfoil has its own unique stalling angle, and with a tandem wing design one of the wings might stall earlier than the other. Therefore, when choosing a pair of airfoils - the stall angle for each wing must be held such that the lower stall angle remains in the back. This is part of why the Clark Y and CH10 were selected. These airfoils were chosen so that the Clark Y would be installed in the front, and would have a higher stall angle, ensuring that stall would occur on the front wing first to prevent one of the most chaotic forms of failure that the aerodynamics subsystem is responsible for.

Failure of the aircraft is never completely impossible, and for aerodynamics it would likely yield from improper calculation of the aerodynamic coefficients or incorrect stabilizer sizing. If the flow over the aircraft is vastly different than the expected conditions, there may be unexpected effects to the aircraft stability and there may be an increased structural loading on the aircraft - causing a structural failure of the plane. These conditions would constitute failure on the design requirement end of the aircraft. Static stability failure is something that falls directly onto the aerodynamic team, as well as the controls team, but the dynamic stability falls more heavily onto controls. If the control surface sizing and actuators are limited in space/performance due to the outer mold line of the aircraft then the error was generated within the aerodynamics subsystem.

B. Sensor (Payload)

As stated in the AIAA DBF rules package, the sensor must have a minimum diameter of 1 inch and must have a length to diameter ratio of at least 4:1. The sensor must remain aerodynamically stable (no spinning or rotating) during deployment, flight and recovery. The payload will be towed behind the aircraft for Mission 3 of the DBF competition. The payload must have a minimum of three external lights that can be viewed while in flight in the deployed position, and these lights must operate in a predetermined pattern and will be used to verify the stability of the sensor pod during flight. The lights must also be bright enough to be visible during the day time from the ground. The lights must be controlled remotely via the flight controller or a separate payload controller, but the signal to turn on must come from a physical connection to the aircraft via the tow cable. The sensor needs to contain its own power supply. The sensor must be carried internally to the aircraft prior to deployment, and the deployment and recovery mechanism must remain internal to the aircraft for the entirety of the mission. The sensor must also be deployed a minimum distance via a tow cable at least 10-times the length of the sensor.

1. Subsystem Trade Studies

The first problem to address was that of stability. Three designs were initially proposed for consideration of different types of stabilizer fins. The first was an RPG style drag stabilization fin design that would fold out toward the rear of the sensor. The second fin proposal was a retractable or semi retractable fin toward the rear of the sensor body, and the third proposal was a full body length fin that runs the majority of the length of the sensor body. Each of these designs initially seemed to have pros and cons that were investigated more in depth via individual trade studies. Considerations for the trade study were the overall stability of the fin design, the ease of manufacture, ease of retraction with different retraction method designs, and the ability to easily integrate with different deployment techniques. Since the method of deployment was not been finalized at the time these trade studies were performed, flexibility was a critical factor. When these designs were analyzed, many factors were analyzed including stability, drag, and storage footprint, since the dummy sensor boxes must be the same dimensions as the box that the actual sensor fits in. Also, the tradeoff between increased complexity and increased storability for hinged/retractable fins was analyzed. After realizing how long the RPG style fins are and research indicating that they have very poor roll stability, the trade studies were narrowed down to the body length fins, and the retractable fins for further analysis.

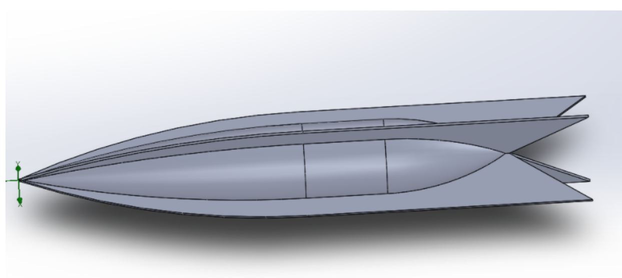


Fig. 19 Body Length Stabilizer Fin (CAD by Kenneth Wiersema)

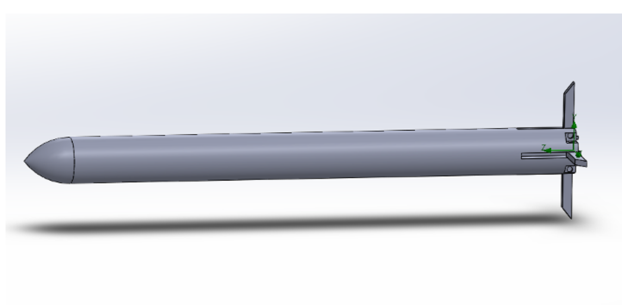


Fig. 20 Drag Style Stabilizer Fin (CAD by Kenneth Wiersema)

For the body length fin design, the main benefit that was analyzed was the large fin area with a relatively small cross sectional footprint. This would aid in stability while still allowing the sensor to be packaged small which is a benefit when it comes to scoring. To quantify these benefits, the relative "footprint" areas created by a body length fin and one created by a fin of equal area that was placed at the rear of the sensor only were compared. First a body length fin was designed with an arbitrary fin area for the sake of comparison. Then a rear fin was designed as a simple isosceles right triangle with equal area to that of the body length fin. Since the effectiveness of the fin is impacted on its distance from the axis of rotation of the sensor, an additional rear only fin was designed with the same moment of area as the body length fin for a more accurate comparison. One aspect of this calculation that was ignored for ease of computation is the fact that the two rear fins have slightly different location of centroid. This was considered not to be impactful given the arbitrary nature of many of the dimensions to begin with. The table below shows the results of this analysis. The results showed a factor of 5.1 increase in the square footprint area for the equal area rear fin, and a increase of a factor of 3.4 for the weighted area rear fin. These results confirm what was suspected that the body length fin could generate a larger fin area for the same effective storage footprint, or conversely a smaller storage footprint for the same effective fin area.

Table 9 Relative Footprint Area Analysis for Body Length Fin vs Rear Only Fin. Shows significant decrease in the footprint area for a given fin area when using full length fin.

Fin Type	**Fin Area** (in^2)	**Max Rad.** (in)	**Weighted Area** (in^3)	**Circ. Footprint** (in^2)	**Sq. Footprint** (in^2)
Full Length Fin	24	2	120	12.6	8
Rear Only	24	4.5	204	63.6	40.5
Rear Weighted	14.12	3.7	120	43	27.2

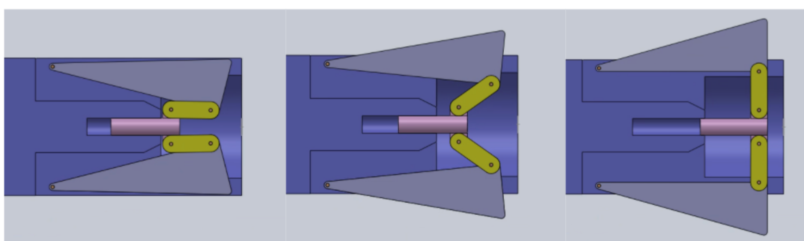
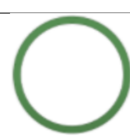
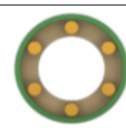


Fig. 21 Retractable Fin Design (CAD by Aaron Greisen)

Trade studies were performed to determine the best structural design for the main sensor body. Factors such as structural strength, weight, manufacturability, and internal space were examined so that the body could be strong and also have good integration qualities with the electronics inside the sensor. Perhaps unexpectedly, the monocoque design was selected primarily due to its internal space and manufacturability properties, even though it had the worst strength rating out of all the designs examined. This occurred because the monocoque design was uncontested in some aspects, mostly due to its simple one part design. This decision allowed the sensor to easily interface with any avionics as well as have fewer resources allocated to its construction during the winter and spring quarters.

Table 10 Optimization table for the Sensor Body Construction. The maximum scores were distributed on a 1 to 3 scale, with 3 being the best possible score

				
Figures of Merit	Score Factor	Monocoque	Semi-Monocoque	Space Frame
Strength	2	1	2	3
Material Usage	3	3	1	2
Manufacturability	8	3	2	1
Internal Space	5	3	2	1
	Total Score	50	33	25

Manufacturing and material options were explored for the main sensor body to address needs of the avionics team in regards to the LED's and other electronics placed inside of the sensor pod. The criteria and weights chosen to evaluate the different options were designed to select a material which can successfully interface with electronics but also remain feasible for the manufacturing division of the DBF club. In general, the materials were divided into two categories; ones which had high strength and rigidity characteristics but were expensive and others which had less strength but also were significantly cheaper. As a rule of thumb, stronger materials such as the carbon composite tube were found to be difficult to work with and construct which hurt their modification and manufacturing scores. Materials such as the XPS foam tube should be noted because they had superior performance in a crash event when compared to the other options. The best selections overall were the 3D printed tube and the plastic pipe, mainly due to their very good manufacturability and internal space while having adequate performance in other areas. The results of this trade study are summarized in Table. 11

Table 11 Optimization for the material used in the Sensor Body. All sub-scores range from 1 to 3, with 3 being the maximum a single material can score, except for one situation where exceptional performance was rewarded with an additional point.

Figures of Merit	Score Factor	Cardboard tube	Carbon Composite tube	3D Printed Tube	Plastic Pipe	XPS Foam Tube	Fiberglass Tube
Price	4	3	1	2	2	3	2
Strength	3	1	3	2	2	1	3
Manufacturability	1	3	1	3	2	1	1
Internal Space	5	3	3	3	2	1	2
Ability to be Modified	4	2	1	3	2	2	1
Protection from Internal Damage	3	1	3	2	2	4	3
	Total Score	44	42	50	44	43	36

2. Subsystem Design Analysis

Several design variations were tested in initial flight testing with the use of a quad rotor drone. The two main items that were being analyzed were the location and size of the stabilizer fins, and the location of the mounting point for the tow cable. These two items were closely linked together because the body length fin has more specific requirements for the location of the tow cable than the rear located retractable fin. This initial flight testing revealed some crucial information with regard to the stability implications of the mounting point location. One piece of information that was discovered is that mounting the tow cable on the nose of the sensor has negative impacts on the roll stability of the sensor. This makes sense since placing the cable at this location causes the axis of rotation of the mounting point to lie along the roll axis. This is undesirable and therefore it was determined that the tow cable had to mounted elsewhere. This was also an indication that the body length fin may not be the best design since it favored the nose mounted tow cable. The next mounting location that was tested was a top mount near the center of gravity. The benefits to the stability of the sensor were seen immediately. This also had the benefit of keeping the sensor oriented closer to horizontal, and therefore reduced the drag generated by the sensor. It quickly became clear that the flexibility of mounting point of the rear retractable fin was a benefit. Based on the results of these flight tests, the rear mounted fin with a top mounted tow cable located at the center of gravity was the best choice.

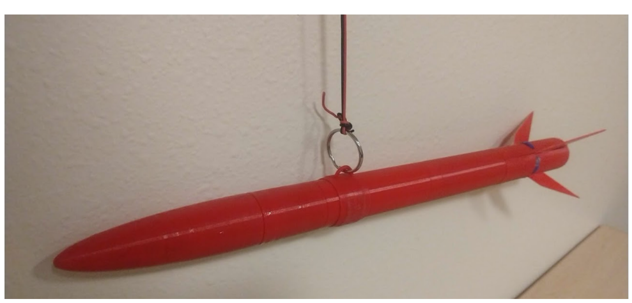


Fig. 22 Prototype Sensor Used in Flight Testing (Photo by Raymond Ingram)

3. Subsystem Design Integration

From the perspective of design integration, this subproject has a lot of integration issues within its scope. One of the most obvious integration considerations is that the size of the sensor directly impacts the size of the storage box, and that will impact the number of storage boxes that can be carried within a given fuselage configuration. Creating a sensor that has some form of retractable fins will aid the design of a smaller storage box, while adding complexity to the manufacture of the sensor itself. Decisions about the style of deployment door cannot be made in a vacuum either. They will have an impact on where tow cable will be attached, which can impact which fin styles are viable. While the drag generated from the sensor will likely not be large enough to have a major impact on the thrust requirements of the aircraft it still has to be accounted for. The type of door opening chosen will also have to be coordinated with the structures and materials teams to make sure that the door can be supported and that the opening will not have an adverse effect on the rigidity of the fuselage, and that the materials chosen can be supported. All of these considerations came into play when deciding on the final design of the sensor. The benefits of the retractable fin from a design integration standpoint played a large role in its selection as the best fin style, since a nose mounted tow cable was not feasible. Since a top mounted tow cable was chosen this meant that a bomb bay style door was the best choice and this was relayed to the deployment mechanism team.

4. Subsystem Risks

Table 12 Risks Associated with the Towed-Sensor. These are operational risks that must be mitigated both with standard operating procedures as well as properly designed safety margins.

Title/Description	Type	Lead	Chance	Conseq.	Prevent by
Tow Line Breakage The tow line could break due to excessive drag, or fatigue due to many test runs. This could damage equipment or harm personnel.	Operational	Joseph Bellevue	1	4	Materials testing, pre-flight inspection of cable integrity, and integrating large safety margins to account for the full range of possible load magnitudes
Sensor Destabilizing Tow Vehicle Towing the sensor in inherently more unstable than flying without towing, and it is possible the sensor causes the airplane to become less stable and more difficult to control	Operational	Joseph Bellevue	3	5	Sufficient testing and design refinement to ensure stability over the entire operational envelope of the aircraft.

Risks that must be accounted for with this subsystem consider how the sensor will behave during flight and its affect on the handling and stability of the plane. In the event of a sensor detachment from the main aircraft, the point of failure and responsibility could be in any of the teams that relate to the sensor. Starting from the airframe team, the aircraft fuselage or a mount could have been under-designed which could cause a failure of the entire sensor system. Next, the sensor deployment and recovery system could itself suffer a breakage in a mechanism and also would cause the loss of a sensor. And finally, the tow cable or the sensor could be overloaded causing the sensor team to be responsible. This risk will be mitigated by utilizing high strength tow cables with a large margin of safety. Care must be taken that the tow cable is strong enough to withstand the drag from the sensor and the dynamic loading that will occur during maneuvers. The tow cable breaking could cause harm to ground personnel or damage to the aircraft or other equipment. Currently under consideration is high strength fishing line with a minimum of 100-lb test, although Kevlar fiber is now being considered as well to avoid possible stretching oscillation issues. This matter will have to be investigated further before a final determination can be made. The stability of the sensor is critical, because if the sensor starts to become unstable or erratic it could negatively impact the ability of the pilot to control the aircraft which would present a danger to personnel and equipment. During initial flight testing there did not seem to be noticeable effects on the stability of the tow vehicle, but this will need to be considered as further design changes are made and more testing is performed. These considerations will have to underpin all decisions as they are being made since safety must always be the number one priority.

C. Sensor Deployment (Payload)

In Mission 3 of the competition revolves around deploying the towed sensor during flight, and later retrieving it back into the aircraft. In order to make this mission a success, a deployment mechanism must be designed to gently release the sensor to a distance 15-ft away from the aircraft, and later tow it back in. Through meetings and logistical discussions, the deployment mechanism was determined to consist of two main bodies, the mechanically operated door/hatch, and the winch to lower and retrieve the sensor. The details around these systems will be analyzed and discussed through the following trade studies.

1. Subsystem Trade Studies

When analyzing the type of door to use, two main styles were proposed. The first being a rear ramp style deployment, such as a C-130 style ramp. This door is located at the aft end of the aircraft and also serves as a fold down ramp to allow for easy deployment of the sensor. The other method suggested is that of a bomb bay style deployment, where a door would be made in the bottom of the aircraft where the sensor would be lowered out. One of the main determining factors in each style was the feasibility of retrieval without snagging. To determine this, aerodynamic studies on the sensor were conducted. From these studies it was determined that the sensor weight force was significantly greater than the air drag force, meaning the sensor would fly almost vertically underneath the aircraft. This information alone was enough to prioritize the bomb bay door selection, because a rear ramp would almost guarantee snagging of the sensor.

In addition to the sensor forces and snagging factors, a bomb bay door allows the sensors point of force to act closer to the center of gravity of the aircraft. This is a big deal because the sensor would be apply a large moment force on the aircraft if too far from the center of gravity. Another issue that comes along with door placement is the structure of the aircraft. A rear ramp is difficult to pull off because it usually interferes with the empennage's structure. Because of the reasons discussed, it was decided upon to design a single bomb bay door.

The other discussions around the winch design were slightly simpler than that of the doors. It focused primarily around how many tow cables we needed, what wire to use, and how to spool the wire back in and out. The first factor was between one or two tow cables. The main argument was the stability of the sensor, but through sensor flight testing it was found that one cable was plenty stable and could reduce the risk of entanglement. Therefore it was decided upon to use one tow cable. For the second discussion on wire, the weight of the sensor was determined, coming in around 1.5 pounds. With this information it was decided upon to use 100-lb fishing line. It has been brought up that nylon stretches, and the oscillations could prove fatal, but with that large of a strength endurance, there will be essentially no elastic stretching under the sensor's forces and fishing line generates very little drag. The final discussion about the spool lifted quite a bit of discussion. Because there needs to be a signal wire along with the fishing line, spooling it up could take up a lot of area. This meant we might want a guided spooling system to prevent tangling, but that would add a lot of complexity. So after some math and designing, the decided route was a V-shaped spool to give extra area to spool, while guiding the wire into the central area, and keeping it simple so no extra space is taken from a guiding system.

2. Subsystem Design Analysis

When considering the design of the bomb bay door, the main considerations were simple functionality, and the least hindrance to the structure of the aircraft. Because the door must take up a portion of the fuselage, it is essential that its effects to the structures stability is monitored. The other considerations that had to be made were to the door specifications. Will a two door or single door system work better on this aircraft was the question being asked. With two doors, you increase complexity and potentially need two servos which will increase weight. With one door, only one servo is needed, but will undergo more loading. It also could create a slight imbalance to the plane. Considering all these factors, it was decided that the simple single bomb bay door would be best, saving us weight and complexity.

For the considerations of the winch design, it was essential that it completed its task without any mishaps. To do this the servo needs to be strong enough to reel in the sensor undergoing weight and drag forces. Almost all servos could accomplish this so that was solved. The biggest potential risk was the entanglement of the wires. To mitigate the potential of this, a wire guiding system was proposed. There was the example of a fishing reel which uses a mechanical system to evenly spool up the wire, but this would take up a lot of space and complexity. The next idea was a lot simpler, creating a slant to the wire's spool so that it's reeling could be controlled to a central location. Testing will need to be done to determine the functioning benefits, but as of now the slanted spool is the top choice.

Table 13 Optimization table for door design.

Type	manufacturing	weight	complexity	Total score
Cargo Bay	2	3	3	8
Single Bomb bay	4	5	4	13
Double Bomb bay	3	3	3	9
Sliding Bomb bay	3	5	1	9

Table 14 Optimization table for spool design.

Type	manufacturing	control	complexity	Total score
Flat Spool	5	1	5	11
Slanted Spool	4	3	5	12
Fishing Pole Guided Spool	2	5	1	8

3. Subsystem Design Integration

The bomb bay door is a large part of the airplane's structure. It will take up a portion of the fuselage and introduce a challenge with airflow changes around the plane when open. This means it has to be integrated in such a way that it doesn't hinder the integrity of the plane. This means that it can't be under the wings where the main structural beams reside on the plane. However, we want it as close to the center of gravity as possible, so just behind the front wings is the best location.

The only considerations for the winch were the location, and whether it could be detachable or not. Being detachable benefits the team on the second mission because it frees up storage space for cargo. The location matters because the sensor will be providing a moment on the plane. To manipulate the force location on our plane to our benefit, it was decided that a pulley could be placed above the bomb bay door which would run the wire across to the spool.

4. Subsystem Risks

Table 15 Primary Risk

Title/Description	Type	Lead	Chance	Conseq.	Prevent by
Sensor Deployment and Retrieval The towed sensor must leave the aircraft a distance ten times the sensor length, then get towed back in without snagging or snapping the line.	Design	Michael Stemen	3	5	Analyzing weight and drag of sensor during flight with the torque of winch servo and tow-line strength. Place winch strategically for least chance of snagging and test vigorously.
Coiling/Tangling of Sensor Wire The wire connecting the towed sensor to the winch is composed of a signal line and a tether line. It must not tangle or else the sensor will not be retrievable.	Design	Michael Stemen	1	5	Testing various options of wire and coil sizes. If the coil holder is wide enough, the line should never unspool.

The sensor deployment subsystem has very high risk repercussion. In the event that things go wrong in mission three, it means the sensor is most likely being lost and a large part of the potential points in the mission are forfeited. The most awakening part of this subsystem is that even the smallest error can ruin the entire system. The wire can tangle and snag, leaving the mechanism inoperable. The servo could blow out, or the pulley could jam. There are a variety of things that can happen which would mean the failure of the mechanism, the entire sensor, and the mission.

D. Airframe (Structure)

The airframe of the airplane must be compatible with the aerodynamic requirements, and maintain integrity under different operational loading conditions. The airframe must provide enough space to house the avionics and the payload. The deign of the airframe must take account of manufacturability, especially during the coronavirus pandemic where manpower and access to workspace is limited. The airframe should be optimized to save weight.

The fuselage follows a monocoque design where the skin has a sandwich structure to be able to bear tension, compression, and shear. An alternative semi-monocoque design serves as a backup plan in case manufacture of sandwich-structured skin failed. The wing follows a typical two-spar design, with a layer of composite skin. The empennage is designed as thin 3D printed plastic shell. The landing gears are off-the-shelf products.

1. Subsystem Trade Studies

The most predominate design choice on fuselage is the overall shape of the fuselage. Typical airliners have round fuselage shape to minimize drag. However, many small airplanes favors rounded square shape due to several conveniences in terms of volume and structure. A trade study is performed, as recorded in Table 16. The main advantage of rounded square fuselage is easy interfacing with other components. On the other hand, it compromises drag. The result demonstrated that a rounded square fuselage is preferred.

Table 16 Trade Study for Fuselage Shape

	(weightage)	circular	rounded square
Low Drag	0.2	10	7
Interfacing	0.2	4	9
Internal Structure Manufacturability	0.2	8	8
Internal Structure Strength	0.1	9	8
Volume Capacity	0.2	7	8
(normalized score)		7.4	8

Typical airplanes have semi-monocoque fuselage structure. The ability to manufacture sandwich structure skin makes it possible for the team to consider monocoque fuselage structure. A trade study is performed to evaluate advantages/disadvantages of two design options, which is tabulated in Table 17. The main advantage of monocoque structure is better structural weight efficiency and larger volume capacity. On the other hand, it compromises manufacturability and cost. As a result of trade study, monocoque structure is preferred.

Table 17 Trade Study for Fuselage Internal Structure

	(weightage)	monocoque	semi-monocoque, 4-longeron
Structural Weight Efficiency	0.2	10	7
Low Ribbing Complexity	0.1	10	6
manufacturability	0.3	6	8
Compatibility with Doors	0.1	6	9
Structural Interfacing	0.1	8	9
Volume Capacity	0.2	10	6
Low Cost	0.1	6	9
(normalized score)		8	7.55

It was identified in FEA simulations that small shear deformation of frame rings and skin may induce a large deflection of the overall fuselage. It is hypothesized that some shear deformation can effectively decouple the upper and lower part of the fuselage: leaving two parts to bear bending moment individually rather than collectively. A trade study is performed on potential materials for the frame ring aiming at finding the appropriate material for rigidity against shear, as shown in Table 18. It is decided to use birch plywood for the frame ring.

Table 18 Material Property and Trade Study for Material Selection of the Frame Ring

	(weightage)	Al-6061 [9]	3D printed PLA [10]	CFRP [11]	Balsa [12][13]	Birch, yellow [12][14]
G in desired direction [GPa]	N/A	24	0.6	5	0.184	1.0286
Density [g/cm^3]	N/A	2.7	1.25	1.6	0.16	0.55
G/ρ [GPa/(g/cm^3)]	N/A	8.89	0.48	3.12	0.4	1.87
Rigidity Score	0.3	10	2	8	2	6
manufacturability	0.5	4	10	2	8	8
Low Cost	0.2	10	8	2	8	8
(normalized score)		7	7.2	3.8	6.2	7.4

In order to load and unload sensor packages, there needs to be access points on fuselage. The possible options were having doors on top, bottom, side, front, or back of the fuselage. Since there is a motor and cables in the nose, it is difficult to remove the nose as an access point. Hence, the front access became out of options. Similarly, there is a bombay door on bottom of the fuselage, so bottom access was also difficult. To get side doors, it becomes harder to open two holes on the sandwich structure composites than one hole for top door. At last, a top door and empennage door became the final decision for the fuselage access point due to the manufacturability. There needs to be two access points because of the long fuselage. Two-thirds of the sensor packages will be loaded from top front door, and the leftover will be loaded from the empennage door. In order to reduce the complexity and loading time, both doors will be locked by magnets.

The wing structure follows the typical design: predominately structured by two spars. No stringer is used in the wing due to limited space for small airplane. No rib is used due to difficulty to apply properly shaped skin on ribs. Instead, foam fills most the space in the wing to ensure the basic shape. A composite skin is applied to provide extra strength and smooth surface.

The empennage of the airplane bears very little load. The main focus of its structure is to reduce weight. There are two options being considered: foam or 3D printed plastic. 3D printed plastic to preferred due to its low weight and possibility to form complex shape to reduce drag.

Landing gear needs to withstand various landing conditions of a 37-lb plane. It is also desirable to have minimum drag and weight and make it possible to do hard landing without major destruction to the fuselage. And in terms of the factor of safety, the landing gear needs to support a 1.5-G load upon initial touch down. The primary configurations are tail dragger and quad design, and presumably, the weight of UW DBF 2020-2021 aircraft is equivalent to an 80cc class gasoline RC plane. Thus the team will purchase a carbon fiber landing gear set and integrate it into DBF's aircraft. The assumptions are that the each wheel can withstand a maximum of 37-lb load and the system can nominally sustain 37-lb load on 2 wheels (tail dragger) or 4 wheels (quad). For these conditions, there were three options: tail dragger landing gear mounted at the bottom of the fuselage, tail dragger landing gear mounted under the wing, and quad mounted at the bottom of the fuselage. After the trade study done by the group, a wing mounted tail dragger is the best choice.

Table 19 Trade study for Landing gear, contribution from Jake Li

Config	Weight	Pitch angle	Strength	Simplicity	Drag	Cost	Sum
Weight	15%	15%	25%	20%	15%	10%	100%
Bottom mounted Tail-Dragger	15	0	25	15	15	9	79
Bottom mounted quad	9	15	25	10	7	5	71
Wing mounted Tail-Dragger	14	13	20	15	15	10	87

2. Subsystem Design Analysis

For axial stress in the fuselage structure, assuming that the fuselage is a simply supported beam with 37-pounds of load evenly distributed on it in a conservative estimation, the maximum bending moment in the fuselage under 3G loading would not exceed 1000 lb-in. Using the smallest cross-section area of the fuselage, the maximum axial stress is smaller than 10^3 psi, which is much smaller than the failure strength of composite fabric used on the sandwich structure. Is is impossible to further reduce the amount of material used for the fuselage skin, because the skin requires at least one lamina of composite on both inner side and outer side. Under beam assumption, deflection of the fuselage is negligible. The use of beam assumption for deflection is questionable, as suggested by some FEA simulations: small shear deformation may induce a large deflection and invalidity of the beam assumption in analysis of deflection. It is very hard if not impossible to perform deflection analysis manually outside the beam assumption, because shear strain and deflection is coupled in a complicated way. FEA is being used to further estimate the deflection induced by shear deformation. An easy fix plan to reduce deflection is to add more frame rings to improve shear rigidity.

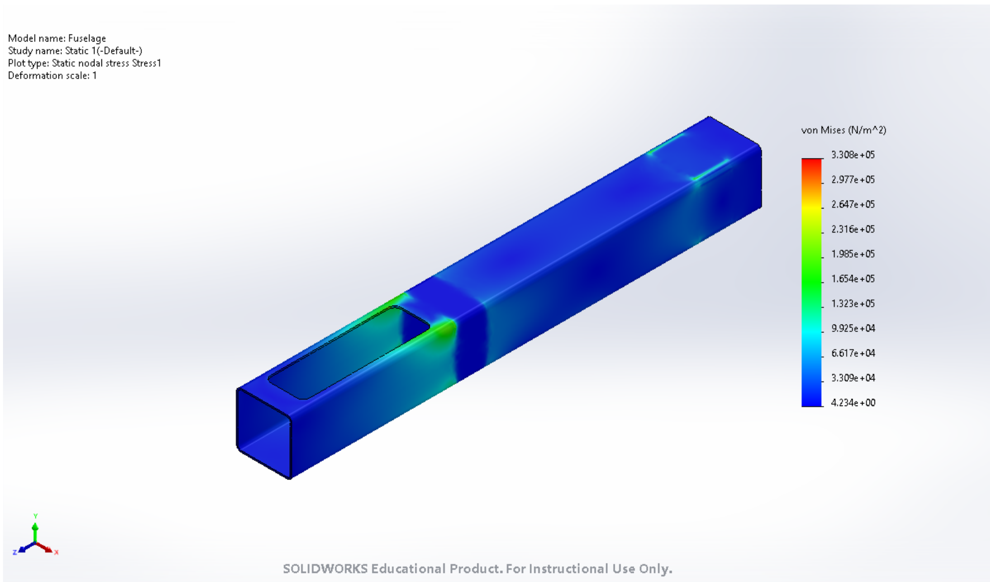


Fig. 23 Stress distribution from rough FEA on Fuselage. Maximum stress is well within material strength. Deflection seems sufficiently small.

There are two major holes on the fuselage, which can induce large stress concentration on the fuselage. Both doors are being modelled as elliptical holes on an infinite sheet of material. This model is plausible even through the fuselage is not large compare to the size of the hole, because axial load on transverse edge of the model sheet is zero. In a conservative estimate, the maximum stress concentration factor would not exceed 20, resulting a maximum axial stress smaller than $20 * 10^3$ psi, which is again smaller than failure strength of composite fabric.

Part of the fuselage skin is under compression load. Algorithms are being applied to quantitatively estimate buckling limit on the skin. Buckling limit depends on the length of unsupported material. An easy fix plan to avoid buckling is to add more frame rings to shorten unsupported length.

For axial stress on the wing structure, assuming that the wing is a simply supported beam where spars are the only load carrying structure, when 14 lb of load is applied on half of the wing, the maximum bending moment on the wing would not exceed 185.5 lb-in. Using two circular carbon fiber tube spars of 10-mm outer diameter and 8-mm inner diameter[15], the maximum axial stress is smaller than 26233 psi, which is smaller than failure strength with a good factor of safety. The spars follow the beam theory pretty much, maximum deflection at wingtip is 1.9 inches.

3. Subsystem Design Integration

Subsystem interfacing the airframe includes aerodynamics, avionics, payload, and sensor deployment. The airframe itself must joint fuselage, wing, landing gears, and empennage together. The airframe also must take account of manufacturability.

The airframe is designed within the geometry provided by the aerodynamic team. The structural deflection of the airframe is analyzed, and the airframe is designed to ensure that the deflection does not deteriorate the aerodynamic performance. The airframe is designed to offer enough space to house both avionics and payload. Space allocation is performed as a joint effort across teams. Space designation for battery, Arduino, motor, and wiring. is determined. Doors are properly sized to allow loading/unloading of payloads, access to avionics for maintenance, and sensor deployment/recovery.

Center wingbox is being designed on joint fuselage, wing, and landing gears together. The rule of thumb for center wing box design is to avoid stress concentration. The center wing box is made of 3D printed plastic, where the team has a large degree of freedom on its shape. Wing spars and landing gears are mounted to the center wingbox without making direct contact with the fuselage skin. The center wingbox has enough surface area to be glued on the fuselage to distribute load.

Throughout the design phase, the team considers about how the airframe would be manufactured. This means answering questions like how the material would be processed, how parts can be assembled in a way that is accessible by hands, and how labor-intense a certain process is.

4. Subsystem Risks

Risks for this subsystem are structural failure, inappropriate spacing, and manufacturability. The airframe must be able to hold the forces, stresses, and moments during flights. If the main structure of the airplane fails such as wings, the fuselage, and the empennage, the airplane would be out of control and crash. If the landing gear fails, it would make landing difficult and may cause crashing. Failure of door lock mechanism and connection between the fuselage and empennage might cause aerodynamic drag and in worst case scenario, the airplane would crash of sensor packages would be released from the fuselage. In order to assure the capability, detailed stress analysis must be done by FEA. Having the large amount of factor of safety also helps the system to reduce the risk of the structural failure. Inappropriate spacing of the fuselage and door size are critical risks, but accurate calculation and having extra margin reduce the risk. In order to decrease the risk of problems in manufacturing, detailed and simplified CAD models are needed. To think about manufacturing process while creating CAD significantly decreases the probability of manufacturing troubles.

Table 20 Primary Risk for Airframe

Title/Description	Type	Lead	Chance	Conseq.	Prevent by
Structural Failure The airframe might fail under load.	Design and Operational	All members	1	4	Design all parts with proper FOS to prevent parts from reaching critical stresses due to poor mfg. tolerance.
Insufficient fuselage space There may not be enough space in the fuselage to fit avionics and payload.	Design	Max Mcgowan	1	4	Carefully allocate space in the fuselage for structure interfacing, avionic equipment, and payloads before the fuselage design freezes.
Lack of the door area It might be very hard or impossible to load and unload the containers.	Design	Mitsuki Yoneda	1	3	Design the doors with extra margin of area for easiness of loading and unloading.
Failure of door lock mechanism If the lock system of the door does not have enough strength, the door might open while flying.	Operational	Mitsuki Yoneda	3	4	Carefully calculate the required strength of the lock mechanism and do some testing.

E. Materials and Manufacturing

Materials and manufacturing has several key aspects of the parameters to cover. For ground mission, a container, with the sensor inside, will be dropped from a height of 10 inches above the ground. The sensor inside must sustain no damage from this, so the container needs to be made with a combination of materials like foam and wood that can protect the sensor. Materials such as foam will be useful for absorbing the shock from the impact, while materials like wood will protect the container itself from minor scratches and incidental damage.

The focus of manufacturing team is also to ensure that any parts designed by other subsystem is able to be done within the time constraint given the capabilities of the team to build the parts. Therefore, manufacturing plans have been drafted up for most of the subsystems. Manufacturability of components was a large aspect of design and was heavily discussed in other sections, but there were also some specific trade studies and analysis conducted specifically in regards to this topic.

To ensure that any designed parts is manufacturable, the manufacturing subsystem research materials, manufacturing process and equipment to be used during the build phase. Other things to consider during the trade studies are the time constraint, number of available people to do the actual build and the budget limit.

The primary requirements of this subsystem are that the materials must be strong enough to withstand the forces on the aircraft and that the materials are light enough to reduce the plane weight. Additionally, manufacturing must accommodate the other teams designs (some materials may be shape limited and won't fit all designs). Finally, the manufacturing methods chosen must be cost-efficient and be easy to manufacture in a limited time frame.

1. Subsystem Trade Studies

Trade studies for the materials and manufacturing subsystems primarily dealt with the sensor box, as the structures subsystem team took ownership of the fuselage. One trade study that was conducted was the comparison between a circular sensor container and a square sensor container. Both have their potential benefits and costs, so the better option for the team's design needed to be identified. The table below shows the comparison between the circular cross section and square cross section:

Table 21 Optimization table for cross section design.

Cross section	manufacturing	space allocation	weight	material cost	Total score
Weight Factor	0.5	0.3	0.1	0.1	1
Circle	4	2.5	2	3	3.25
Square	1	2	2.5	2	1.55

Each considered parameter was graded with a score from 1 to 5, with a score of 1 representing excellence in that parameter. Based on the weighing as detailed in the table, the square shape was chosen as cross section for the container, mainly due to the ease of manufacturing.

Table 22 Optimization table for door mechanism design.

Types	Manufacturing	Structural Integrity (drop test)	Total Score
Weight Factor	0.6	0.4	1
Simple friction	1	4	2.6
Complex friction	2	4	3.2
Screw Lid	5	1	3.4
Notch	4	3	3.5

Using the same scale as the previous trade study, the design of the loading door mechanism was also decided. The mechanism of simple friction to hold the door in place was chosen based on the weights. However, to mitigate the potential risk of the door opening during flight maneuvers, under-sizing the slot the door needed to fit in was considered, in order to better hold that door in place.

The materials for the container consist of two categories, the interior materials and the exterior materials. The interior material will be in contact with the sensor and aim to reduce the shock from the drop test to the sensor, such as XPS or EPS or polyurethane foam. The exterior will be made from a more rigid material and provide the shape for the container.

Polyurethane was chosen as the material for the interior. In general, the polyurethane has good surface texture, so the missile can slide in and out of the sensor container smoothly. The main concern of the polyurethane is that it must withstand the impact force when sensor storage is departed from the plane. The IFD (indentation for deflection), a measure of the firmness of a material, was a method the team used to evaluate this. The smaller the IFD, the softer the material is. For the team's design, an IFD range between 30 and 35 will be ideal. It has medium softness but can still withstand the device without deforming too much. The other reason for choosing the medium firmness is because of the design constraint on the cross section, which means there would be a limit of the foam's thickness that can be used for the container[16].

XPS and EPS were evaluated but not considered because XPS and EPS are closed-celled foams while polyurethane is open-celled. With a closed cell foams like XPS or EPS, the fins from the sensor can puncture the foam since it is prone to a point force. In comparison, an open-celled foam like polyurethane will absorb the point load and be compressed. In addition, closed-cell foams generally are denser than open cell foams due to the material structure of the foam[17].

In conclusion, a mid-ranged IFD value and low density will be ideal properties on the design of the interior of the sensor storage.

Table 23 Optimization table for interior selection.

Materials/criteria	Closed-cell foam (XPS)	Opened cell foam (Polyurethane)	Wood (Birch)	3D printed material (PLA)
Absorption ability(0.4)	5	2	4	4
Manufacturability(0.4)	3	2	3	4
Cost(0.2)	3	2	2	4
Total (1)	3.8	2.4	3.2	4

For exterior material, there are three candidates: Birch wood, Balsa wood, and ABS. Plywood was previously considered, but even though the strength of the plywood is much greater than the birch due to the unique grain structure, the density is significantly greater than balsa wood. The decision was also made to not use ABS because of the cost and time needed to make the exterior part of the container. The below table evaluates the potential choices of woods.

Table 24 Optimization table for wood selection.

Wood Types/Material properties	Balsa	Yellow Birch wood	Source
Yield strength (compressive)	12.7 MPa	19 MPa	Matweb with keyword: PB Standard Balsa Wood
Density	0.155 g/cc	0.550 g/cc	Matweb with keyword: American Yellow Birch Wood

With respect to manufacturing, both have more or less the same difficulty. Considering the strength than the wood needs to resist the drop and we are working with thin material due to the constraint, birch wood will be a better choice even though it is heavier than balsa.

Another trade studying was the overall weighting of materials for more general manufacturing. The Fig. 25 shows how each materials are weighed.

Table 25 Material trade studies [18].

Material comparison					
	Factor	Metals	Foam core	Composites	Covering film
Cost	3	3	5	2	5
Manufacturing speed	2	2	4	2	3
Strength	4	5	1	5	1
Weight	4	1	4	3	4
Difficulty of fabrication	2	3	4	2	3
Total:		43	51	44	47

The overall potential manufacturing methods were also evaluated. Fig. 25 shows how each method of fabrication are weigh.

Table 26 Manufacturing trade studies [18].

Manufacturing technique comparison					
	Factor	Hot-wire cutting	3D-Printing	Laser cutting	Milling
Cost	3	5	4	5	2
Manufacturing speed	2	3	2	5	2
Difficulty of fabrication	2	4	4	5	1
Total		**29**	**24**	**35**	**12**

2. Subsystem Design Analysis

Fig. 24 and 25 are the initial design that the group came up with for the sensor container based on the trade studies. From the side view , the door mechanism is using small rods attach to the door and slide into the hole made in the foam om the front view.

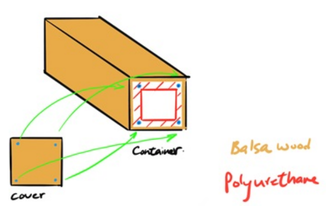


Fig. 24 Front View of the initial container design (Drawn by Jack Tse)

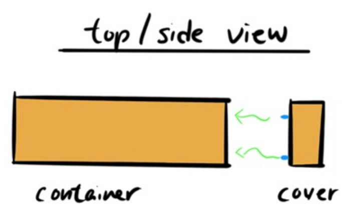


Fig. 25 Side View of the initial container design (Drawn by Jack Tse)

The strengths and weakness of this design was considered as per the following table.

Table 27 Strength and the weakness of the initial container design.

Strength	Weakness
• The door will stick even when it is dropped from the other side.	• Drilling the slot will be difficult in the foam since we are dealing with soft foam. • Difficult for container to fully stabilize the cover while falling without letting the cover fall out of space • Structural integrity might be compromised due to the hole making.

Based on the initial design, the door mechanism needs to be changed due to the complexity in manufacturing and structural issue. The next and finalized design is:

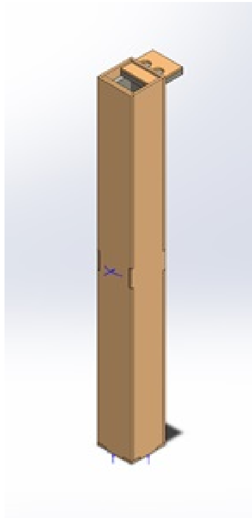


Fig. 26 Isometric View

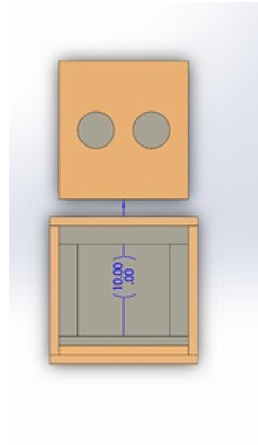


Fig. 27 Top View of the final container design (Credit to Mitsuki Shinomura for making the CAD of sensor container)

Fig. 26 and 27 show two views of the final container design. The door mechanism will consist of a slot mechanism with door made of wood and foam as shock absorber for sensor. However, the problem of door slipping out during drop test still persists. If during drop test simulation, the door do slip out, tape will be used to add thickness and friction.

The container will be 2 in by 2 in by 19.5 in. Considering the sensor has size of 1.25 in of diameter, the thickness of polyurethane foam will be 0.25 in and the thickness of birch wood would be 0.125 in. For the length of the container, considering that the door is mounted on the top and requires structural rigidity because of the stress concentration around the hole, the length will be made longer around the hole to ensure that the door stays in place.

The manufacturing methods of some of airplane components have also been determined.For the wing, a rectangular XPS-foam will be cut to the specified length and width based on airfoils, Clark Y and CH10. A laser cut stencil of each airfoil will be pasted by hot glue gun on both sides of the foam. The foam is then shaped based on the airfoils using hot wired cutter. The foam is then sanded, while the control surfaces, and the placement for motor mount are cut from appropriate sections. The control surfaces will then be attached back with woven aramid fiber and epoxy resin to create seamless, flexible hinge for creating laminar flow. The wing sections are then assembled with one carbon fiber I-beam and one carbon fiber tube spar that span through out the length to increase stiffness and reduce deflections. A layer of balsa wood are applied on top wing using spray adhesive and then sanded smooth.

The manufacturing methods of some of airplane components have also been determined. The fuselage will be composed of a skin, wing-landing gear mount the and laser cut wooden frame to maintain the shape. The skin will be made using sandwich composites with foam core and about three layers carbon-kevlar fabric on either side of foam. Then, epoxy resin will be applied to the carbon-kevlar-foam composites and will be cured by using vacuum bag for 12-16 hours. After curing, the skin will be sanded to give smooth surface. The wing-landing gear mount will be 3D printed and it is where the interface to wings and landing gear.

The nose mount and the skin will be 3D printed. It will house the batteries and motor for the plane. The skin is also functioned as cowling and to direct the heat from the motor to surroundings. The sensor body and fins will be 3D printed in sections for ease of storage and maintenance. The body sections will be filled with electronics, such a servo for fin mechanism, 3 LEDs, and motherboards, and a steel rod. Meanwhile, the container will be made based on birch wood and polyurethane foam. The wood will be laser cut to shape and the foam will be cut by knife and be pasted to wood by spray adhesive(3M-77). The foam-wood part will be then assembled to make the sensor container.

The bomb bay door will be made using the carbon-kevlar skin from the cut opening. It will need to be modified to mount onto the servo and hinge to open and close based on signal input. As for the winch, the attached spool will be 3D printed and connected to the servo through a mount and screws. To hold the servo in place on the fuselage, a mountable carriage will be glued or screwed onto the fuselage which the servo can slide into.

3. Subsystem Design Integration

Integration with the fuselage group involved storage and maximizing the amount of containers in the fuselage. The weight of containers and sensors will be limited by how much payload that the plane can carry based on aerodynamics. Integration was also conducted with the sensor group in regards to the fitting of the sensor into the containers.

Manufacturing plans as shown above were written up in conjunction with the corresponding subsystem groups. Also as stated above, manufacturability was one of the primary design parameters that was enforced throughout the design phase. The manufacturing team will need to come up with a feasible plan to make all the parts and to make sure that all the designs are doable. This to make sure that there is enough time to test and to make sure that the parts integrate together and have enough time to change design if needed to.

4. Subsystem Risks

There are several risks in making the container. Firstly, whether the container can support the weight of sensor. Besides that, whether the container can protect the sensor during the drop test. The verification and validation will be determined by the real drop test based on the mission requirement.

In regards to the risks involved with manufacturing, it comes down primarily to ensuring that things are manufactured as per manufacturing plans. If the plans are erroneous or are not followed, design specifics may not be met, which could result in the inability of the team to fully assemble the plane. Therefore, it is especially important that proper communication between those doing the manufacturing and the designers exists, as miscommunication or lack of communications between those parties can lead to the improper steps being taken when making components. To best mitigate this issue, it is imperative that manufacturing engineers immediately contact the appropriate design team if there are any questions or concerns with regards to the manufacturing procedure.

Table 28 Risk and mitigation table for sensor container, material and manufacturing subsystems

Type/Description	Type	Lead	Chance	Conseq.	Prevented by
Container Failure If not designed properly, the container will transfer the shock from the drop impact to the sensor, damaging it.	Operational	Vinsensius	2	4	Cross communication with the sensor design team and do analysis for the container before finalizing design.
Container and sensor integration If the sensor does not fit within the container structure, the container will transfer the drop impact to the sensor instead of absorbing it. This is very detrimental to the external components of sensor such as LED and fins.	Design	Vinsensius	2	4	Cross communication with the sensor design and avionics teams to figure out if any indentation needs to be made on the interior part of the container.
Improper manufacturing leads to weak structure Manufacturing flaws such as delamination of piles may occur, which results in low structure strength compared to design.	Mfg.	Vinsensius	3	4	Double check before and after any mfg. procedure to make sure that there is no flaw.
University Shop Access This is needed for the mfg. of composite molds but access may be restricted due to covid and administrative regulations.	Mfg.	Ethan Uehara	5	5	Work in advance to identify potential work-arounds with the department and potential outside suppliers.
Material Acquisition Composite materials are difficult to get access to.	Mfg.	Ethan Uehara	2	4	Have a backup structural design that can be done without composite materials.
Material exceeding tolerance load	Mfg.	Vinsensius	2	4	The risk is mitigated by doing analysis and making prototype to run tests.
Time constraints in material manufacturing Limited time to manufacture the plane for flight testing and to get data.	Mfg.	Vinsensius	5	5	The risk is mitigated by making thorough manufacturing plan and clear work division among members to ensure the fabrication goes smoothly.
Fatigue and wear of material As time goes by, the material is subjected to static loading especially where there are connecting parts. With connecting part, there will be stress concentration build up and can wear the materials. During flight testing, repeated take off and landing will induce fatigue on all the materials. This can reduce the materials' lifetime.	Mfg.	Vinsensius	3	5	It can be prevented by checking material before manufacturing to ensure no defect and making sure not to damage the material during fabrication. After manufacturing, do quality control to ensure the material is still in good condition. The parts should be checked again before and after assembly. Before the flight test, do full check on the different parts on the plane especially interfaced parts.

F. Avionics, Propulsion, and Guidance, Navigation, and Controls

Avionics is a category of electronic systems and equipment, including communications, navigation, the display and management of the systems. The focus of sensor circuitry was the LED, signal input, and battery selection. For the aircraft and deployment circuitry, wiring and integration of all circuitry should be located. As for the avionics sensor suite, controls suite and flight codes should be set up properly.

Propulsion is a category of the controls systems and equipment with the focus being motor selection. For the aircraft to be deployed, the placement and integration of the motor should be located as well as set up properly for flight. in order to sustain 15 minutes of flight on a battery no bigger than 200W*h as well as supporting a 37-pound plane at an airspeed no less than 20 m/s while keeping the system as lightweight and reliable as possible to ensure ease of manufacturing and maintenance.

The focus of the Guidance, Navigation, & Controls section was the develop the controls system that would be needed to operate not only the aircraft, but the internal and mission specific mechanisms. It includes the flight controllers, transmitters, and receivers that will detect and translate pilot commands into aircraft maneuvers. In the conceptual design phase, equipment should be finalized and the overall layout of the physical equipment should be considered. It is important that this subsystem is properly integrated into the aircraft via proper consultation with the other subsystem teams as well.

Currently, the control system of the aircraft and the associated sensor pod is still being fine-tuned. The team has a good idea of what the system will look like and has some test code written up, however, a lot of the specifics can only be worked out once we are able to test the flight controllers and other equipment.

1. Subsystem Trade Studies

Several trade studies were conducted regarding the options for controls equipment, as well as some research into potential code. The primary trade study that was conducted was the determination of the necessary equipment to complete the flight missions. The goal of this trade study would be to not only determine the controls equipment that would be needed for the aircraft, but also to allocate space for this equipment within the aircraft.

It was found that most of the equipment necessary for aircraft controls was fairly light, even when combined with the avionics and propulsion equipment. The only thing that was of a substantial weight was the batteries. Therefore, it was determined that the batteries would be fitted in the front-most section of the aircraft, the nosecone, in order to best mitigate the moment from the weight in the plane's rear section from the mission specific mechanisms and sensor payload. An approximation of the distribution is given in Fig. 28.

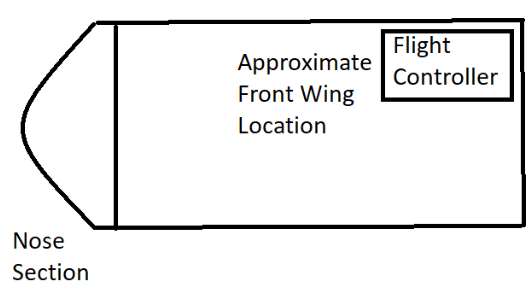


Fig. 28 Approximate location of the flight controller

Due to the increasing aerodynamic loads on the propeller at increasing speeds, as well as decreasing efficiency due to heat, electric motors have the most balanced output in the range of 30% to 60% throttle. Therefore, it was determined that it would be in the interest of efficiency to have many motors spinning at 30% throttle than having a few motors spinning at 60% throttle due to the dramatic increase in efficiency. However, this would lead to slow spinning motors and insufficient propeller speed to keep the aircraft flying faster than stall speed. To counter this, propellers with steeper pitch are required, which in turn decreases low-speed thrust and efficiency. In the end, the power limits of our aircraft yielded a requirement of approximately 4600g of static thrust for prop speeds around 21m/s.

# of Motors	Motor Choice	Prop	Total Static Thrust at ~35A	Prop Speed at RPM	System Mass	Complexity	System Cost
1	AT4130 450KV	17x10	4039 g	24.26m/s	492g	1	$170
2	AT3530 580KV	14x7	4617 g	19.81m/s	676g	3	$300
3	AT3520 550KV	14x7	5067 g	17.14m/s	788g	7	$390
4	XING 4214 400KV	14x6	5712 g	14.94m/s	1004g	13	$480
6	XING 2814 880KV	9x5x3	4866 g	12.12m/s	890g	21	$502

Fig. 29 Varying Motor Specifications

# of Motors	Thrust Score /20	Speed Score /30	System Mass /30	Reliability /30	System Cost /50	Sum
1	12	30	30	30	50	152
2	14	24	24	27	28	117
3	16	21	21	23	22	103
4	20	18	16	17	18	89
6	15	14	18	9	17	73

Fig. 30 Number of Motors Comparison

A secondary trade study was to determine whether an Arduino-based system or an iNav-based system should be used for the aircraft. While this trade study falls under the GN&C category, it was primarily conducted by members outside of the AA 498 course - however, their work is relevant to the subsystem. After some considerations, it was determined that the preferred system would utilize iNav as a firmware.

The same trade study found that using a micro Arduino board would be the optimal method of controlling the sensor. Active control of the sensor's flight surfaces was ruled out due to complexity and the lack of need, so the only control-related project regarding the sensor was the manipulation of the LED lights. This is an extremely simple task, and can be easily handled by an Arduino.

2. Subsystem Design Analysis

Analysis conducted for this subsystem mostly involved the research and testing of commercially available equipment and the reporting of their results. Due to the scale, nature, and primary purpose of this project, the control system would primarily be off-the-shelf products, especially due to the limited manufacturing capabilities as a result of COVID-19. Testing on controls equipment is currently pending a list of purchases that will be submitted on the week of the 7th, so unfortunately analysis could only be done using information available from online resources.

T-motors, specifically the AT3530 580KV, were selected due to their ability to support both front side mounting and backside mounting with their built-in adapter for the opposite side of the motor. While this is additional weight it proved to be minimal and their seamless integration with the iFlight system was another consideration.

The system will utilize a F765-WING Flight Controller from MATEKSYS, which is specifically designed to run iNav with fixed-wing aircraft, although it can also be used with Ardupilot and other software packages. It boasts all the inputs we need, including camera inputs and airspeed sensor inputs, and can switch between outputs of 5 volts, 9 volts, and even 12 volts. This controller is shown below.

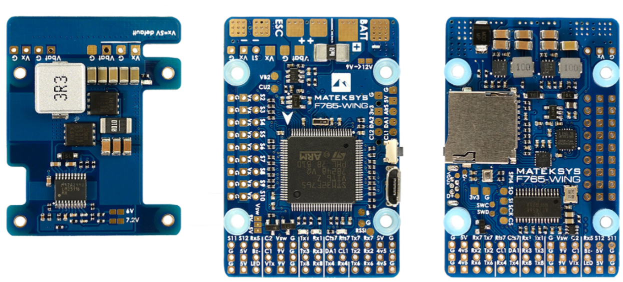


Fig. 31 Physical flight controller [19]

As mentioned beforehand, both iNav and Arduino systems were analyzed to determine the best option for the aircraft. After weighing both options, iNav was the choice for control of the aircraft. While Ardupilot in particular has traditionally been reliable, iNav has some more advanced navigation capabilities and a wider array of supported flight controller. In addition, iNav also was found to overall have more options and less restrictions, which the team's primary coding specialist preferred. Therefore, while the controller would have worked with both iNav and Ardupilot, iNav was chosen as the implemented system.

For the same reasons, an Arduino-based system was more ideal for control of the payload. The loosened restrictions and wider support from iNav is simply not necessary for the task, and the reliability of Arduino outweights is much more important in this case than potential customization. Since the only task required by the AIAA is control of how the LEDs light up, there is no need to customize the firmware to the degree that iNav allows. The Arduino will use a series of electrical switches to drive power to each LED light in a pre-programmed sequence.

Item	Mass per Item (g)	Total Mass (g)	Dimension (mm)	Note
Motor Type 1	270	810	See Link	https://shop.iflight-rc.com/index.php?route=product/product&path=20_26_150&product_id=802
Motor Type 2	304	912	See Link	https://store-en.tmotor.com/goods.php?id=826
ESC	8	24	40x17x14	Thicker due to added capacitors
Propeller Type 1	36	108	N/A	13x10 Bi-Blade
Propeller Type 2	54.8	164.4	N/A	11x10x3 Tri-Blade
6S Battery	588	1176	47x46x140	Incoming Battery Sizes Are Unknown
8S Battery	678	1356	58x45x140	Estimated by Stacking 2 of 4S Batteries
iNav FC	30	30	54x36x13	Will Be Taller When Servos Are Plugged In
Airspeed Sensor (Mass includes Pitot Tube)	8	8	20x20x14	Board Size*
Servos	12	108	23x11.5x24	Remember to Leave Room for Little Side Arms
360 Deg Servo for Spool	40	40	50.4x37.2x20	
RX	20	20	51x34x15	Will Be Longer When Servos Are Plugged In
Total		4756.4		

Fig. 32 Weight Distribution Analysis. Special thanks to Ken Chen.

Again, the code written up has yet to be tested, so that will be ironed out in the future after the project once the purchased equipment arrives. A preliminary look at the code can be found in the GitHub repository given in the appendices of this report. Credits for the current code should be given to Alexander Knowlton and Noah Wagners.

For LED selection, flashing at a rapid rate before switching lights would increase visibility. To increase brightness, heat of the light may be an issue. After discussing with structure team, since the ideas of sensors construction were basically 1 in carbon-fiber rod, 3D printing, and laying up card board tubes, carbon fiber rods would not distort from heat. Also, if the aircraft flies fast enough, it would get enough cooling.

3. Subsystem Design Integration

Integration was conducted via collaboration with the structures, payload, and aerodynamics subsystem teams. The focus of integration was the allocation of space for controls equipment, notably the control wires, power supply, controller, and receiver. Based on the center of gravity analysis conducted by the structures team and fuselage shape determined by the aerodynamics team, the front upper section of the aircraft was allocated for the controls equipment. The flight controller was placed behind the front wing, and wires would be run from the controller to the power supply and other avionics equipment.

For the mass and dimensions of the propulsion system, the total items were the T-motors and considering the space that would be taken up by the sensor payload during the storage system, the avionics system would also be placed between the controller and the propulsion batteries in the nose, in the upper section of the front half of the aircraft. The secondary batteries, used to power the control system, would also be located here. Integration with the payload team for the placement of the sensor batteries was also conducted, and space was allocated for both the battery and the board that would control the LEDs.

For the mass and dimensions of avionics, the total items are motor type 1 and 2, ESC, propeller Type 1 and 2, 6S and 8S batteries, iNav FC, airspeed sensor, servos, servo for spool, RX and the estimate gross weight is 4756.4g. A thicker ESC was chosen for its ability to handle a higher capacity, also, the additional height for the iNav Flight Controller when servos are plugged in was considered. For the servos and for spools, some rooms would be left for little side arms and RX would be longer when servos are plugged in.

4. Subsystem Risks

The primary risk regarding these subsystems can be summarized by the necessity to have everything fit on the aircraft while still being operational. This is primarily an integration risk, since the subsystem team needs to work with other subsystems, primarily to structures team, in order to accommodate all of the necessary equipment. Mitigation of this risk is easy to accomplish with consistent cross-communication between all involved teams.

Both the chance and consequences for this risk were also evaluated. The chance of this risk was rated very low, at 1, because the necessary controls equipment for the aircraft are quite small and easy to fit. However, the consequences for such a failure are quite significant, as the ability to control the aircraft is absolutely essential not only for the mission, but to meet the codes and regulations pertaining to UAV systems.

As for the Propulsion system configuration, if the setup is not done properly or inappropriate motors are selected, it will affect the aerodynamic load on the fuselage with insufficient propeller speed making in increasingly more difficult to keep aircraft flying faster than stall speed. As for the risk of the Avionics circuit wiring, if the work is not done properly, it will affect the aerodynamics load on fuselage or maybe induce extra drag.

Controls also must ensure that control of the aircraft's surfaces are reasonable and effective. Previous years have shown that both inadequate and excessive control surfaces can result in the aircraft spiralling out of control. Mitigation of this risk primarily comes from testing of the code and flight controller before the plane gets in the air, to ensure that angles of actuation are as expected. The pilot will also test control of the aircraft in the flight simulator based on the sizing of the control surfaces and the expected actuation.

An associated risk for controls in particular is the inability to control the sensor pod, especially as the code for the sensor is different from that of the flight controller. However, both the chance and consequences of this risk are very low, as the sensor pod control only affects the performance of the aircraft for the final flight mission, and the control system can easily be tested in the workshop or even on the ground prior to a flight. Mitigation of this risk is easily completed with component testing prior to actual flight missions.

G. Flight Testing

Flight testing is the be all, end all with regards to verification and validation that the designed system meets all requirements. As referred to above, the primary requirements are airworthiness, sub-component functionality and overall performance. All three of these factors are final evaluated in the flight testing phase. Due to the nature of the design phase, since most of the testing and test planning happens after the prototype aircraft is manufactured, the team does not have data to represent. Instead, a breakdown of the test planning and structure will be discussed below.

1. Subsystem Trade Studies

Table 29 Preliminary Trade Study Classifications for System and Component Testing. As a note, this table follows a similar process as Dave Chappelle's where I, A, D, T refer to Inspection, Analysis, Demonstration and Testing respectively. As a final note, components are level 3, sub-systems are level 2, systems are level 1[20].

Component/System	Component Level	Design Verification	Mfg. Verification	System Verification
Aircraft, Aerodynamic Prototype	1	A	D	T
Aircraft: M1 configuration	1	A	D	T
Wing - Component level	2	D	D	D
Motors	3	I	I	T
Electronics	3	I	D	D
Actuators	3	I	D	D
Fuselage - Component Level	2	A	D	D
Landing gear	3	I	D	D
Vertical Stabilizer	3	A	I	D
Aircraft: M2 configuration	1	A	D	T
Payload Box	3	A	D	D
Aircraft: M3 configuration	1	A	D	T
Sensor Configuration	2	A	I	D
Sensor Deployment	3	A	D	D

Preliminary trade studies with regards to flight testing explored the most optimal approaches for the testing of different components in the aircraft. Some of those case specific details are included in the system evaluations detailed in the above sections. Most notably, the in-class lecture on the four types of verification and validation was used as a framework not only to structure the testing but also to minimize the amount of risk in the execution. This was done by attempting to reduce the amount of full system testing needed by performing analysis on what components could be evaluated using Inspection, Analysis and Demonstration methods. A trade study table detailing the team's preliminary breakdown of components by type of testing is shown above in Fig. 29.

As shown above, there are only five planned "tests", the rest of the verification process is done by less rigorous means. Of the five tests, four of them are full system flight tests, one for the aerodynamic proof prototype and three for the full competition ready prototype. Since four of the five planned tests are done on the system level, the other verification methods on the sub levels are designed to mitigate risk. This will be discussed in more detail in section four.

2. Subsystem Design Analysis

Again, since the majority of the team's work on flight testing referred to the planning and organization of how the team would approach flight testing, not a lot of test analysis was done. During the 10-week time-frame of the project, only two flight tests were performed and those were proof of concept demonstrations for the sensor pod by non AA 498 members. Thus the results and analysis will not be discussed in this report for ethical reasons.

In terms of what data is expected from the flight testing, those are two-fold. Visual observation coupled with data analysis from the avionics equipment post-flight will be used to analyze component and system performance. That data will eventually be translated into a detailed expected vs actual performance analysis that will serve to validate the design expectations.

3. Subsystem Design Integration

The requirements of flight testing are embedded into the design setup and choices throughout all of the subsystem teams. Most notably, the team is trying to reduce the risk of a flight test as much as possible by performing detailed analysis and testing the systems and components via the conducted traded study in Fig. 29 shown above.

4. Subsystem Risks

The risks of a flight test are very straightforward and devastating if they do occur. The primary risks that the team identified are shown in the risk register below.

Table 30 Primary Flight Test Risks

Title/Description	Type	Lead	Chance	Conseq.	Prevented by
Safety Hazards Crashes, LiPo fires, equipment malfunctions.	Flight Testing	Thomas Key	1	5	This is mitigated with safety procedures and oversight.
Major Plane Malfunction The plane could crash due to stability error, pilot error, component failure, etc.	Flight Testing	Thomas Key	3	5	This is mitigated by performing subsystem tests in order to verify that components and parts function as they should.

Of the two risks shown above, the Safety Hazards is much easier to mitigate through proper SOP's and documentation. By controlling and creating a regimented procedure and safety plan for use during the test, the team is able to protect its members and the surrounding environment. While this seems like a straightforward answer, there is no limit to the amount of precaution taken while setting up a flight test. LiPo fires and crashes have the possibility to kill or seriously injure team members and civilians if they happen in an uncontrolled manner. Even with the due diligence and preparation for the 2020 flight test, the team nearly ruptured a set of LiPo batteries in the nose of the aircraft upon a crash. Since the aircraft crashed in a field 200 yards away from the team's fire extinguisher, had a fire started, it would have taken members well over a minute to get there and put the fire out. The damage to the batteries is shown below in Fig. 33 below.

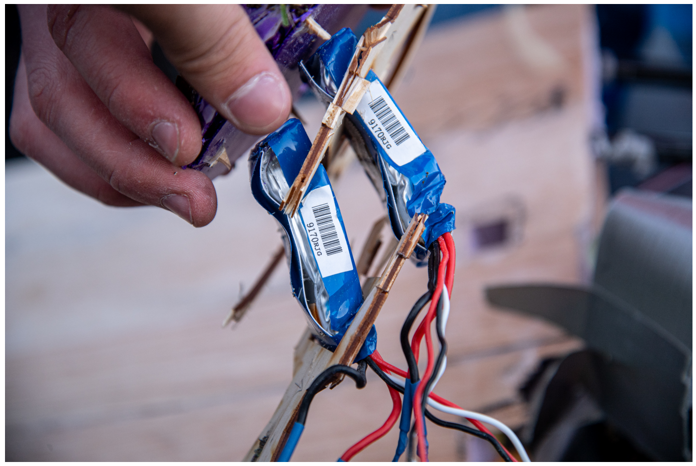


Fig. 33 LiPo battery damage post 2020 Flight test crash of the DBF "Phoenix 1", Photo by Ethan Uehara

With regards to the second major risk of a major plane malfunction (or catastrophic crash), the only real way to mitigate it is to have a high degree of confidence in design. There is a reason flight tests are so largely celebrated when they are conducted successfully. Even large industry entities like Boeing or Lockheed cross their fingers before tests because there is always uncertainty as to whether the system will work as designed. The goal of the engineering team is to prepare in the best manner possible for success while staying attentive and ready to analyze a potential failure. Fig. 34 below details the result of a major plane malfunction that occurred during the 2020 testing of the Phoenix 1.

Fig. 34 After 90 seconds of stable flight, due to a loss of orientation, the DBF Phoenix went into a tip stall and crashed into the ground resulting in a total structural failure. Only the motors, propulsion batteries and avionics system survived the crash. Roughly $1,250 of material costs were noted as a result of the crash. Photo by Ethan Uehara.

At the end of the day, if the aircraft crashes, the engineering team is at fault. On the scale of a design competition like DBF - as long as no one is injured as a result - the crash can be taken as a learning opportunity and analyzed. However, as in industry, crashes like the one shown above result in egregious fiscal and time-based cost and tend to set back a program. Since the time-frame for DBF is already so short, the team cannot afford to have this happen. Unlike the $1,250 cost of the 2020 crash, due to the advanced materials of the 2021 plane design, a major plane malfunction could set the team back by as much as $4,500 which is nearly a third of the overall budget.

As a final note, if anyone is injured as a result of a flight test, the entire DBF program could be shut down. Thus, the primary goal of the flight testing team is and always will be to ensure civilian and team member safety at all times.

V. Ethical Issues

The primary ethical concerns for the team relate to maintaining a safe working environment, especially during manufacturing. In particular, manufacturing will include the use of potentially dangerous tools, such as the laser cutter, hot wire cutter, drill presses, and other machines. Mitigation of these risks will be completed by ensuring that all members working on manufacturing understand the proper safety procedures and protocols for using those machines. In addition, manufacturing will only be completed under the supervision of the manufacturing lead, who has the expertise to ensure that all safety measures are being properly undertaken.

Another safety concern applies to the testing and operation of the aircraft. As the aircraft can reach high speeds and a fairly high altitude, If failure occurs during flight, the plane could crash and potentially injure people and/or cause property damage. To mitigate this issue, the aircraft will not be flown until the proper ground tests have been completed, including testing of the failure mechanism. The failure mechanism will ensure that if the aircraft loses power or its connection to the pilot, the control surfaces will actuate in order to induce a slow, spiraling descent to the ground at low speeds, which will minimize any potential damage and allow the team to evacuate the immediate area, if necessary.

VI. Impact on Society

The immediate impact of this specific project on society or the environment will be fairly minimal. While new designs and small scale manufacturing methods will be tested throughout the project, the scale of the project is too small to make a meaningful impact on society through this quarter.

However, society does have a vested interest in aircraft designs similar to the one proposed and developed by the team. Towable sensors in particular are of interest due to the variety of payloads that could be equipped and operated by the aircraft using a similar system. An atmospheric sensor could collect data on air quality and pressure, or observe the ground to collect research data. This would be incredibly useful for a lot of research, especially if the configuration can be adapted for a VTOL or rotorcraft system, although the DBF rules currently forbid those configurations.

There is also the possibility of alternate payloads being used with the system. Notably, the high lift and high drag profiles of the aircraft make it unsuitable for traditional military aircraft, but the aircraft design and easily be adapted for military use as a bomber due to its large storage capacity and payload deployment mechanism, As for civilian use, the tandem wing configuration results in a more stable flight with higher lift characteristics, and the aircraft could also easily be redesigned for cargo or passenger use.

VII. Impact on the Environment

As for environmental impacts, that should be very small so long as the proper procedures for disposing of waste is followed. There will be no hazardous materials or chemicals used for the project, with the exception of the Lithium-Polymer batteries, which will pose no risk if the proper precautions are taken. In particular, the issue of carbon fiber dust poses a concern, as the particles can spread easily and cause damage. This can be mitigated by working with carbon fiber only within the proper environment, with equipment such as a downdraft table to minimize impact.

Diverging a bit from the scale of the design, a full scale aircraft following the team's design would notably have large drag coefficients, especially in regards to induced drag. The design components for this with three motors to provide propulsion, but a full-scale aircraft would utilize turbojets or turbofan engines. As aircraft are fairly significant sources of pollution, this needs to be taken into account, although the means to do so are currently beyond the scope of this project.

VIII. Codes and Standards

Legislation regarding the operation of UAV systems is enforced by the Federal Aviation Administration (FAA). The below regulations will apply to our aircraft and affect our operations [21].

- Daylight operation, 14 C.F.R. § 107.29: This specifies that the aircraft can only be operated during "civil twilight".
- Visual line of sight aircraft operation, 14 C.F.R. § 107.31: The pilot must always have visual confirmation of the location of the aircraft.
- Visual observer, 14 C.F.R. § 107.33: Visual observers must maintain communication with the pilot in command.
- Operation over human beings, 14 C.F.R. § 107.39: The pilot may not operate the aircraft over human beings not associated with flight. operations.

- Operating limitations for small unmanned aircraft, 14 C.F.R. § 107.51: Aircraft must abide by certain operation limits, including a max speed of 100 mph and no more than 400 feet above the highest structure in the vicinity.

In addition, some COVID restrictions are in effect this year, as per the orders announced by the governor and put into place by the university. These include the prohibition of most public indoor gatherings, a 14 day quarantine period after travel, and other social distancing measures that will affect manufacturing of the aircraft.

IX. Cost Analysis

Unlike the majority of modern-day engineering firms and companies, DBF does not have to pay salary, wages or other benefits to members which means that all of the expected cost comes from material needs. However, the overall project budget is extremely restrictive. Typically the club receives $2,000-$3,000 from the AA Department, $3,000-$4,000 from a crowd sourced fundraiser. Furthermore this year, $4,000 came in from ElectroImpact, $1,500 from Boeing and $3,000 carryover due to 2020 covid cancelling competition and expected travel costs. Club leadership pitches in about $500 in various areas. This gives an operating budget of $15,000.

Current estimates for the manufacturing cost have been roughly calculated. The estimated cost for manufacturing the initial prototype and a foam mock-up for flight testing is around $\$5,000$, with avionics and propulsion devices and equipment for COVID-compliant manufacturing during autumn quarter taking up the bulk of the costs. The initial purchasing order is given in the appendices. It should also be noted that $\$1,000$ had previously been spent this quarter for necessary manufacturing and testing equipment.

There is also another estimated $\$1,000$ to $\$2,000$ that will be required for materials to fine-tune the aircraft during and after testing. The specifics of this purchase are still being negotiated.

X. Conclusion

The results of the conceptual design are quite promising. According the excellent work carried out by the subsystem teams, the final aircraft will be able to excel at all of the required flight missions, and has met all of the design requirements set by both the AIAA and the team. Component testing of the sensor payload also proved the capabilities of the payload to meet the given requirements. Considering all of these factors, the project was overall quite the success.

The final configuration of the aircraft is that of a tandem wing, with a high-wing configuration towards the nose and a low-wing configuration towards the tail. The aircraft itself will be six feet in length and have a five foot wingspan for both the forwards and rear wings, and will be made from a combination of foam, wood, and composite materials, A box-shaped fuselage will hold all of the internal components of the aircraft in place, including the storage payload required for the competition's second flight mission. Batteries will be mounted in the nose section of the aircraft, and wires will be run lengthwise in the aircraft to power all of the servos and other electronic devices necessary for operation of the plane. The payload, a sensor pod attached to the aircraft by a wire, has been designed such that it will retain stability in the air and can be deployed easily from the set of bay doors in the aircraft.

The next steps for this project will be to continue the manufacturing process, and start developing the actual aircraft components that will go into the aircraft headed towards competition. Due to the ongoing Covid pandemic, certain safety measures must be taken during the manufacturing and testing phases, but as the conceptual design is completed, the project is on schedule for the rest of the year.

Appendix

A. Drawings/Figures

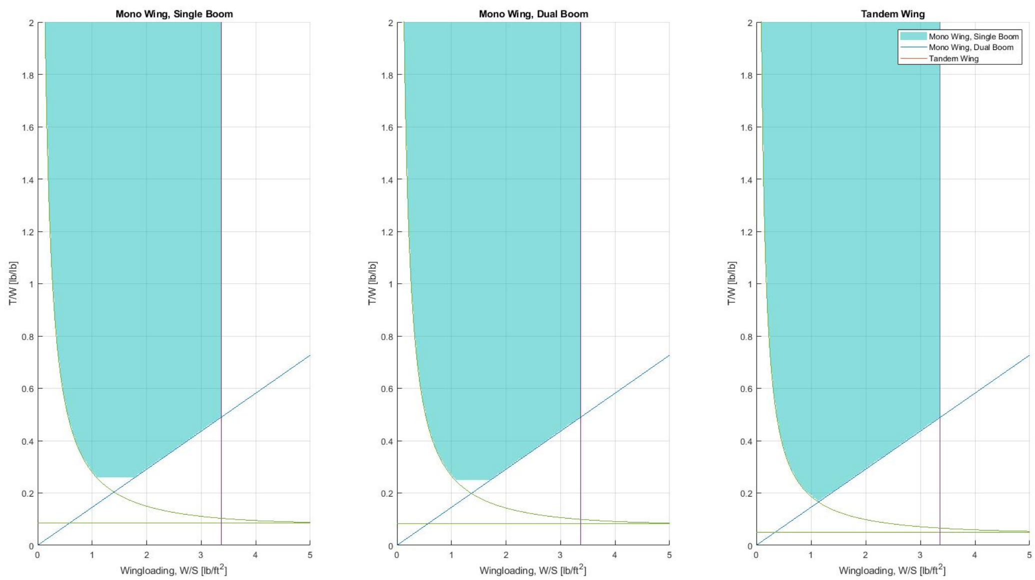


Fig. 35 Final Aerodynamic Comparison Metrics - Generated by Daniel Moore

B. GitHub Repository

https://github.com/Codax2000/dbf-avionics-2020-2021

C. Initial DBF Proposed Budget

Categories	Cost
Equipment	$2,000
Travel	$4,000
Aerodynamics	$1,000
Avionics/Propulsion	$2,000
Structures	$1,500
Materials	$2,000
Manufacturing	$2,500
TOTAL	$15,000

Fig. 36 Proposed Budgeting

D. Initial DBF Large Purchase Sheet

Item	Product Name in full	URL (a clickable link)	Qty (ea/pkg/ft)	Notes or comments about order	Cost per unit	Shipping	Tax	Total	Ordered	Received
1	3M reusable respira	https://www.amazon.com/3M-Comfort-Facepiece-I	8		$ 20.18	$ -	$ 16.14	$ 177.58		
2	3M particle filter, 20	https://www.amazon.com/dp/B00JE6V22O/	6		$ 17.50	$ -	$ 10.50	$ 115.50		
3	Eye goggles	https://www.amazon.com/AmazonBasics-Anti-Fog-	1	One 6-count order	$ 53.00	$ -	$ 5.30	$ 58.30		
4	Vinyl gloves	https://www.amazon.com/Examination-100-Count-	2	2 boxes of 100 each. 1 b	$ 18.00	$ -	$ 3.60	$ 39.60		
5	Swan 70% Isopropyl	https://www.amazon.com/Swan-Isopropyl-Alcohol-	1		$ 39.74	$ -	$ 3.97	$ 43.71		
6	Paint brushes	https://www.amazon.com/Pro-Grade-Professional-I	2		$ 6.39	$ -	$ 1.28	$ 14.06		
7	Quickset Epoxy	https://www.amazon.com/Loctite-Epoxy-0-85-Fluid	4		$ 16.99	$ -	$ 6.80	$ 74.76		
8	1/32" balsa wood	https://www.amazon.com/Midwest-Products-Co-Ba	4		$ 46.79	$ -	$ 18.72	$ 205.88		
9	Hot Glue	https://www.amazon.com/Full-Size-Multi-Temp-All	1		$ 20.50	$ -	$ 2.05	$ 22.55		
10	Spray Adhesive 3M-	https://www.amazon.com/3M-Multipurpose-Perma	3		$ 8.39	$ -	$ 2.52	$ 27.69		
11	Soldering Iron	https://www.amazon.com/Hakko-FX888D-23BY-Dig	1		$ 104.95	$ -	$ 10.50	$ 115.45		
12	Soldering Helping Ha	https://www.amazon.com/KOTTO-Soldering-Works	1		$ 16.99	$ -	$ 1.70	$ 18.69		
13	Solder Fume Extract	https://www.amazon.com/Absorber-Remover-Extra	1		$ 34.99	$ -	$ 3.50	$ 38.49		
14	Soldering Mat	https://www.amazon.com/Anti-Static-Insulation-So	1		$ 18.99	$ -	$ 1.90	$ 20.89		
15	Heat Gun	https://www.amazon.com/SEEKONE-Dual-Tempera	1		$ 25.99	$ -	$ 2.60	$ 28.59		
16	X-Acto Knife Set	https://www.amazon.com/Precision-Professional-B	1		$ 18.00	$ -	$ 1.80	$ 19.80		
17	Copper Foil Tape (2"	https://www.amazon.com/Conductive-Temperature	1		$ 16.98	$ -	$ 1.70	$ 18.68		
18	Micro Arduino Boar	https://www.amazon.com/Seeeduino-Smallest-Mic	2		$ 21.99	$ -	$ 4.40	$ 48.38		
19	XT30 Connectors	https://www.amazon.com/Banana-Connector-Uper	1		$ 10.99	$ -	$ 1.10	$ 12.09		
20	6 AWG Silicone Wire	https://www.amazon.com/WINDYNATION-Welding	1		$ 18.76	$ -	$ 1.88	$ 20.64		
21	14 AWG Silicone Wi	https://www.amazon.com/BNTECHGO-Silicone-Flex	1		$ 15.48	$ -	$ 1.55	$ 17.03		
22	20 AWG Silicone Wi	https://www.amazon.com/Bryne-Flexible-Silicone-T	1		$ 14.98	$ -	$ 1.50	$ 16.48		
23	10 AWG Silicone Wi	https://www.amazon.com/BNTECHGO-Silicone-Flex	1		$ 15.48	$ -	$ 1.55	$ 17.03		
24	32GB SD Card-2 pack	https://www.amazon.com/Micro-Center-Class-Mem	1		$ 8.79	$ -	$ 0.88	$ 9.67		
25	Crimp Pin Connector	https://www.amazon.com/gp/product/B0146DJR9C	3		$ 6.98	$ -	$ 2.09	$ 23.03		
26	Pin Connector Housi	https://www.amazon.com/gp/product/B06XBZQDW	1		$ 9.50	$ -	$ 0.95	$ 10.45		
27	Apex RC Products 2	https://www.amazon.com/Apex-RC-Products-Pack-	1		$ 12.99	$ -	$ 1.30	$ 14.29		
28	Crimp Tool	https://www.amazon.com/Knoweasy-Crimping-0-1	1		$ 15.99	$ -	$ 1.60	$ 17.59		
29	American Terminal T	https://www.amazon.com/American-Terminal-TAN	3		$ 7.99	$ -	$ 2.40	$ 26.37		
30	Dual Fuse Holder Rin	https://www.amazon.com/Dual-Holder-Terminal-St	2		$ 9.99	$ -	$ 2.00	$ 21.98		
31	1.5g Micro Linear Se	https://www.amazon.com/Wishiot-Linear-Digital-Li	1		$ 31.00	$ -	$ 3.10	$ 34.10		
32	Kester Solder 60/40	https://www.amazon.com/KESTER-SOLDER-32117-3	1		$ 26.02	$ -	$ 2.60	$ 28.62		
33	Polyurethane foam	https://www.grainger.com/product/GRAINGER-APP	1	Refer to below notes (1)	$ 5.72	$ -	$ 0.57	$ 6.29		
34	Vacuum Pump	https://www.grainger.com/product/DAYTON-Refrig	1	Refer to below notes (1)	$ 594.00	$ -	$ 59.40	$ 653.40		
35	MOSFET	https://vetco.net/products/power-mosfet-n-channe	5	Refer to below notes (2)	$ 1.74	$ -	$ 0.87	$ 9.57		
36	10W LED	https://vetco.net/products/10-watt-red-led	6	Refer to below notes (2)	$ 8.95	$ -	$ 5.37	$ 59.07		
37	10 Ohm, 10W Resist	https://vetco.net/products/10-ohm-10-watt-resisto	3	Refer to below notes (2)	$ 1.05	$ -	$ 0.32	$ 3.47		
38	Dremel Tool Kit	https://www.homedepot.com/p/Dremel-3000-Serie	1	Refer to below notes (3)	69.99	$ -	$ 7.00	$ 76.99		
39	Calipers	https://www.homedepot.com/p/Husky-6-in-3-Mod	1	Refer to below notes (3)	29.97	$ -	$ 3.00	$ 32.97		
40	36 in. Aluminum Str	https://www.homedepot.com/p/Empire-36-in-Alum	1	Refer to below notes (3)	5.97	$ -	$ 0.60	$ 6.57		
41	3/4"x4ftx8ft Particle	https://www.homedepot.com/p/3-4-in-x-4-ft-x-8-ft	4	Refer to below notes (3)	20.98	$ -	$ 8.39	$ 92.31		
42	XPS Foam (2")	https://www.homedepot.com/p/Owens-Corning-FO	3	Refer to below notes (3)	$ 29.87	$ -	$ 8.96	$ 98.57		
43	XPS Foam (1")	https://www.homedepot.com/p/Owens-Corning-FO	1	Refer to below notes (3)	$ 19.55	$ -	$ 1.96	$ 21.51		
44	0.5"x48" Steel Rod	https://www.homedepot.com/p/Everbilt-1-2-in-x-48-in-Plain-Steel-Round-Rod-801617/204273963	2	Refer to below notes (3)	10.98	$ -	$ 2.20	$ 24.16		
45	Washers with appro	https://www.homedepot.com/p/Everbilt-8-mm-Sta	2	Refer to below notes (3)	$ 0.75	$ -	$ 0.15	$ 1.65		
46	150 grit sandpaper	https://www.homedepot.com/p/3M-Pro-Grade-Pre	1	Refer to below notes (3)	$ 4.97	$ -	$ 0.50	$ 5.47		
47	320 grit sandpaper	https://www.homedepot.com/p/3M-Pro-Grade-Pre	1	Refer to below notes (3)	$ 12.57	$ -	$ 1.26	$ 13.83		
48	400 grit sand paper	https://www.homedepot.com/p/3M-Pro-Grade-Pre	1	Refer to below notes (3)	$ 4.97	$ -	$ 0.50	$ 5.47		
49	Tyvex suits	https://www.homedepot.com/p/Cordova-Defender	6	Refer to below notes (3)	$ 4.57	$ -	$ 2.74	$ 30.16		
50	2Oz INSTA-Cure Gap	https://www.hobbytown.com/bob-smith-industries	2	Refer to below notes (4)	$ 9.99	$ -	$ 2.00	$ 21.98		
51	INSTA-Cure Accelara	https://www.hobbytown.com/bob-smith-industries	1	Refer to below notes (4)	$ 5.99	$ -	$ 0.60	$ 6.59		
52	Polycarbonate (Urba	https://shop.prusa3d.com/en/prusament/1255-pru	1		$ 49.99	$ -	$ 5.00	$ 54.99		
53	PVA	https://shop.prusa3d.com/en/special/169-primasel	1		$ 49.17	$ 14.00	$ 4.92	$ 68.09		
54	Fixed Carbon Fiber L	https://hobbyking.com/en_us/fixed-carbon-fiber-la	2		36.19	$ -	$ 7.24	$ 79.62		
55	Scale Jet/Warbird Al	https://hobbyking.com/en_us/scale-jet-warbird-allo	2		$ 36.41	$ -	$ 7.28	$ 80.10		
56	5mm Steel Axles w/	https://hobbyking.com/en_us/steel-wheel-axle-4mm	2		$ 8.87	$ 23.12	$ 1.77	$ 42.63		
57	BenchCraft 190mm	https://www.motionrc.com/products/benchcraft-19	2		29.09	$ 5.00	$ 5.82	$ 69.00		
58	Multipurpose 6061 A	https://www.mcmaster.com/6546K46-6546K466/	5		$ 7.40	$ -	$ 3.70	$ 40.70		
59	Carbon fiber I-beam	https://dragonplate.com/1-Carbon-Fiber-I-Beam-x-4	3	Requires signature durin	189.99	$ 53.00	$ 57.00	$ 679.97		
60	Sensor Battery	https://www.racedayquads.com/collections/3s-batt	2		9.24	$ 12.29	$ 1.85	$ 32.62		
61	360 Degree Servo	https://www.adafruit.com/product/3614?gclid=Cjw	2		$ 27.99	$ 10.00	$ 5.60	$ 71.58		
62	(Flight Controller) F	http://www.mateksys.com/?portfolio=f765-wing	2	Refer to below notes	$ 47.00			$ 94.00		
63	ASPD-4525 (Digital A	http://www.mateksys.com/?portfolio=aspd-4525	2	Refer to below notes	$ 28.00	$ 20.00		$ 76.00		
64					$ -	$ -	$ -	$ -		
65					$ -	$ -	$ -	$ -		
66					$ -	$ -	$ -	$ -		
67					$ -	$ -	$ -	$ -		
68					$ -	$ -	$ -	$ -		
69					$ -	$ -	$ -	$ -		
70					$ -	$ -	$ -	$ -		

Fig. 37 Initial Purchasing Order

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