NAU Mechanical Engineering Senior Capstone
SAE Aero Micro Design

Final Report

Team 19F11: The Prop Dogs

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DISCLAIMER

EXECUTIVE SUMMARY

The Society of Automotive Engineers (SAE) holds annual global flight competitions which are separated by distinct flight classes including regular, micro, and advanced class. Each flight class must adhere to unique regulations and constraints provided by SAE. The objectives of our Mechanical Engineering capstone project are to design, manufacture, and test a small, fixed-wing aircraft that adheres to the rules and regulations of the SAE Aero Micro Class design competition. Thus, the purpose of this capstone project is to demonstrate the mastery of key engineering fundamentals learned throughout the undergraduate process. This document explains design, manufacture, and testing results for the project.

The goal of the SAE Aero Micro project is to design a propeller-driven, fixed-wing aircraft that carries the highest payload at the lowest empty weight. Noteworthy constraints include a gross weight limit of 10 pounds, disassembled storage contained in a box 12 ⅛" x 3 ⅝" x 13 ⅞", electric-only motor, hand-launch takeoff, and battery storage less than or equal to a 3-cell 2200 mAh capacity. The aircraft must launch, fly straight for 400 ft, turn in 180 degrees, and return to the starting point, where it must successfully land.

The design was executed by decomposing the overall design into five subsystems. The five subsystems are the wing, fuselage, landing gear, propulsion/drive, and in-flight control mechanisms. When generating concept designs, each subsystem allowed for three subsystem concept variants, respectively. The final product of concept generation combined these variants to yield three unique full-design variants. Each design was compared using a pugh chart and decision matrix, where the selection criteria were based on customer and engineering requirements. Furthermore, manufacturability and design constraints were taken into account.

The final design solution featured a single wing, dual ailerons with a rudder and elevator, rear steer, single motor, and tadpole fuselage design with external payload mounting. This design, shown in Figure 1, was superior in meeting requirements and manufacturability constraints. The wing design is a Clark Y airfoil with a 39 inch wingspan and a uniform 6 inch chord length. The drive components include a 8"x4.7" propeller, 800W max brushless electric motor, 45A max electric speed controller, and a 3-cell 1800 mAh LiPo battery. The fuselage internally houses the entire drive system and is 3D printed using ABS. The fuselage connects to a 3/8 " diameter, 12" long carbon fiber rod, which is connected to the T-shaped tail with a vertical stabilizer and rudder. The tail dimensions are a 13 inch span and a 6 inch chord length. The landing gear wheels are 1.5 inches in diameter and supported by aluminum beams.

When manufacturing, the front and tail wing frames were constructed by laser cutting wing ribs from ⅛" thick balsa wood. The wing ribs were joined together using ¼" wooden dowels. Next, the wing frames were covered in Monokote to produce the airfoil shape. The front and rear landing gears were purchased online, and the fuselage and rear connector were 3D printed. The front landing gear, front wing, motor, and carbon fiber rod were all bolted to the fuselage using M3 machine screws. Similarly, the rear end of the CF rod, the rear connector and the tail wing were all bolted using M3 screws. Finally, the control mechanisms including the ailerons, rudder, and elevator were constructed using balsa wood. Servo motors, control horns, and push-pull rods were used to actuate control surfaces.

The final testing procedures included a weight test, assembly test, thrust test, center of gravity test, and flight test. The results are as follows: weight=2.072 lbs, assembly time=2min 36sec, thrust=30 oz at 75% throttle, center of gravity=5.5" behind wing tip, and the flight test yielded a crash upon hand launch. The conclusions gathered from these tests can be found in section 11.

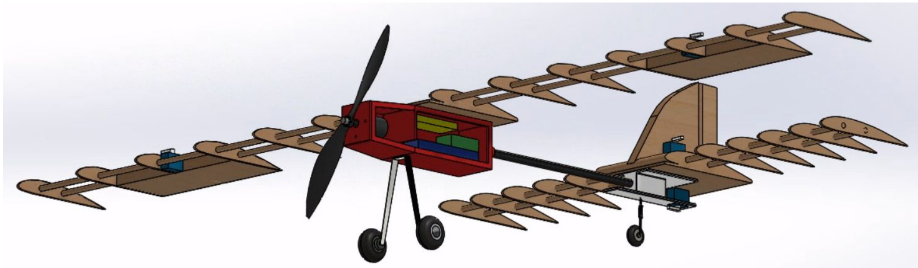

Figure 1: Final Design

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Thank you to W. L. Gore and Associates for providing a generous donation to the NAU Mechanical Engineering Department. Through Gore's generosity, our team was provided a budget that allowed us to purchase, manufacture, and test our entire design. Furthermore, many other engineering capstones were sponsored and therefore fully-funded by Gore.

Thank you to Dr. Tester and Dr. Oman for being our faculty advisors, and thank you to Dr. Oman for assisting in project planning throughout the year. Dr. Oman truly went above and beyond her role as our Capstone instructor and was instrumental in the successes of our project.

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1 BACKGROUND

1.1 Introduction

The SAE Aero Design competition is composed of three classes: regular, advanced, and micro. The SAE Aero Micro Class is a design competition that tasks a team to design, manufacture, and test a small unmanned aerial vehicle (SUAV). The SUAV is a fixed-wing plane that is controlled from the ground by one of the team members via wireless remote controller. The objective of this class is to carry the highest payload with the lowest empty weight. There are various constraints to the design, including a gross weight limit of ten pounds, disassembled storage within a box 12.125 inches X 3.625 inches X 13.875 inches, and a hand-launch takeoff [1]. The competition evaluates teams based on design reports, presentations, and flight performance. The SAE Aero competition is highly renowned and first began in 1986. This year there will be 85 teams competing in Fort Worth Texas from April 3-5 of 2020 for the Western division [1]. Our team, the Prop Dogs, will not be participating in this years' competition. However, the purpose of our Capstone is to design, manufacture, and test an Aero Micro plane that meets all SAE Aero Micro requirements. Our project is sponsored by W.L. Gore and Associates, and the final product will be given to the NAU Mechanical Engineering department to assist future teams in design. Thus, the success of our SUAV is critical to represent our Sponsors and department well.

1.2 Project Description

The following is SAE's original project description:

> "The SAE Aero Design competition is intended to provide undergraduate and graduate engineering students with a real-world design challenge. These rules were developed and designed by industry professionals with the focus on educational value and hands-on experience through exposure to today's technical and technology advancement. These rules were designed to compress a typical aircraft development program into one calendar year, taking participants through the system engineering process of breaking down requirements. It will expose participants to the nuances of conceptual design, manufacturing, system integration/test, and sell-off through demonstration" [1].

2 REQUIREMENTS

Following the original system breakdown for the SAE Aero Micro fixed-wing plane, the next step in the design process is developing design requirements. The purpose of design requirements is to provide necessary data for concept generation and selection. This section presents the customer requirements, engineering requirements, and house of quality developed for the aero micro design.

2.1 Customer Requirements (CRs)

Customer requirements (CRs) are necessary to fully define a complete list of design requirements. CRs are provided by customers/stakeholders to describe what the design needs to accomplish, while also not arriving at a solution for said requirements. These CRs were generated through NAU faculty advisor interviews, the SAE Aero Micro Design competition rulebook, and instructor requirements. First, when interviewing the faculty advisor , Dr. John Tester, the team was provided with the following insight: follow all the rules exactly as stated, or the design will automatically fail. Consequently, the meeting with Dr. Tester yielded no direct CRs, but rather encouraged the team to reference the rulebook. So, in reading the 2019-2020 SAE Aero Design competition rulebook, the team developed the first 15 CRs, shown below in Table 1. Each CR in Table 1 directly corresponds to at least one competition rule. Each CR is weighted based on its importance to success in the competition from 1 to 5. With each CR being a rule directly from the rule book each had a very high weighting. Descriptions of each rule and subsequent CR are provided within Table 1 for reference [1].

Table 1: Customer Requirements

	Customer Requirements	Customer Weights
1	Gross Weight Limit (10 lbs)	5
2	In-flight radio control (2.4 GHz) w/ fail safe	5
3	wheeled landing gear steering mechanism	4
4	Payload cannot aid frame integrlty	3
5	Payload attached w/ metal hardware	3
6	Electric motor/Servo	4
7	Red arming plug	5
8	3 cell 2200mAh lithium polymer battery	5
9	gyroscopic assist allowed	2
10	2" dia schedule 40 ASTM D1785 PVC Payload	4
11	Hand launch	4
12	12.125 in X 3.625 in X 13.875 in container	5
13	3 min assembly	4
14	1 min to energize, check, and launch	4
15	fly for 400-foot leg of a flight circuit	3
16	cost within budget	3
17	durable and robust design	4
18	reliable design	5
19	safe to operate	5

The final method of gathering CRs was through implementing mandatory instructor requirements. These requirements (CR's 16-19) are seen above in Table 2. The design must be manufactured within budget to ensure no monetary loss, while subsequently using project funds to develop a durable and robust design which are both weighted at 4 and 5. Finally, the design must operate reliably by functioning predictably and not dangering people upon malfunction.

2.2 Engineering Requirements (ERs)

Given the CRs generated above, the next step in the design process was to translate CRs into engineering requirements (ERs). While customer requirements define what the plane must do, the purpose of ERs are to define how the plane will fulfill those requirements. So, each ER was generated by relating a measurement characteristic to at least one of the CRs. In general, the title of each ER describes which component of design or CR is being measured. The complete list of ERs is shown below in Table 2.

Table 2: Engineering Requirements

Engineering Requirements	Target	Tolerance (+-)	Target and Tolerance Rationale
Control Frequency (GHz)	2.4	0.1	Exact competition requirement
Motor Power (Watts)	350	50	Power limited by 2200 mAh battery
Total Weight (lbs)	5	1.5	Benchmarked weights approx. 4-5 pounds [2,3]
Assembly Time (min)	2	0.5	Competition requires assembly under 3 minutes
Battery Capacity (mAh)	1000	250	Optimize weight, max battery capacity 2200 mAh
Storage Volume (in^3)	72.3	20	Calculated for 2-lb payload given PVC density
Storage Length (inch)	16.3	5	Calculated for 2-lb payload given PVC volume
Current (Amperes)	15	5	Benchmarked value for aero micro planes [2,3]
Launch Angle (deg)	5	1.5	Benchmarked value [2,3]
Launch Acceleration (ft/s^2)	1.3	0.3	Benchmarked average overhand acceleration [2,3]
Propeller Velocity (m/sec)	variable	variable	Variable motor rpm
Motor Speed (rpm)	variable	variable	Variable motor rpm
Lift (lb)	2	0.5	Benchmarked value [2,3]
Thrust (lb)	3	0.5	Benchmarked value [2,3]
Cost ($)	550	100	Calculated given budget and prototype materials
Frame Yield Strength (psi)	145	15	Known yield strength of balsa wood

It is important to note the target and tolerance rationale provided in Table 2. The rationale describes how each value was determined. Prior to conducting testing on components such as propellers and airfoils, many of the target and tolerance values originate from benchmarked values. Other target values are derived by calculations, known values, and competition requirements.

2.3 Functional Decomposition

The Functional Decomposition for the SAE Aero Micro is quite simple. The overall function of our design must fly under certain criteria. There are other guidelines in the SAE Aero Micro rules, but in order to receive any half-way decent result, the aircraft must fly. Some of the important components of the design are the fuselage/payload design, wing design, and propulsion mechanics. In order to carry the desired payload, the design of the fuselage and payload mechanism must be placed in such a way that is aerodynamic and able to be thrown by a human hand. The wing design is strictly based on the airfoil decided, which determines the amount of lift and drag on the aircraft. Finally, the propulsion is based upon the motor and propeller efficiency, which in turn creates thrust. Thrust determines how much weight the aircraft can carry because it is dependent on velocity of the aircraft.

2.3.1 Black Box Model

Figure 2 is the Block Box Model that simplifies the Functional Decomposition. The 'material inputs' are components of the actual design: motor, battery, wing, radio controller, and propeller. The airflow is a material component because it is something that is tangible. These 'material inputs' are the 'material outputs' because they do not change. The 'energy inputs' are electrical energy and kinetic energy. The aircraft is wired and is controlled by an RC device, so electrical energy will be the 'energy output' as well. On the other hand the kinetic energy from throwing the aircraft initially is converted into mechanical energy. The 'input signals' are wind direction, radio frequency, aim, and on/off. All of the previous signals will become 'output signals' besides wind direction because while the device is in the air it will be adjusted to the airflow, so it becomes flight direction.

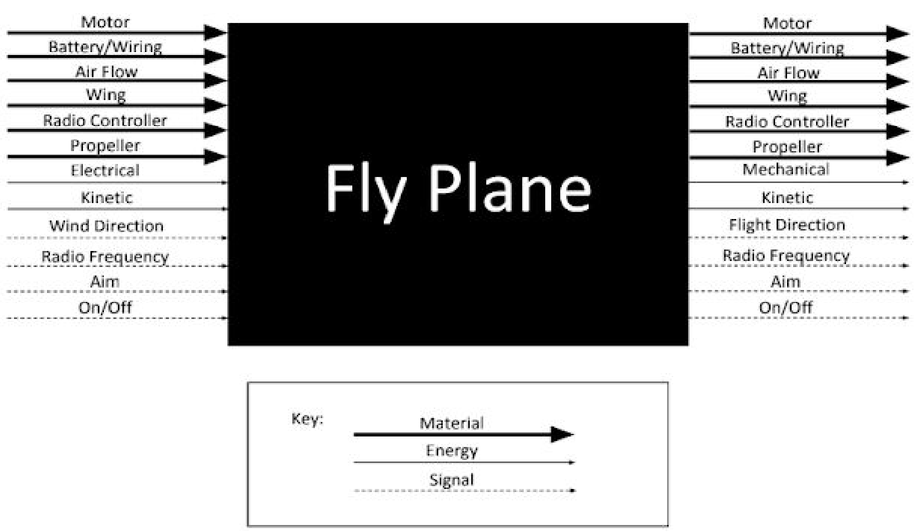

Figure 2: Black Box Model

2.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

The Functional Model is shown below (Figure 3). The flow chart directs all the inputs of the Black Box Model (Figure 3) and describes what they do physically. All the 'material inputs' when they are imported they will then direct the airflow; this will create flight (signal) and lift, thrust, and drag (material). All the remaining inputs are then needed to drive the electricity component of the aircraft. The RC Controller provides an input and integrated with electricity and controller frequency actuates the motor, which converts electrical energy to rotational energy. This then determines the thrust and flight path. All of the following inputs are needed to create a successful flight.

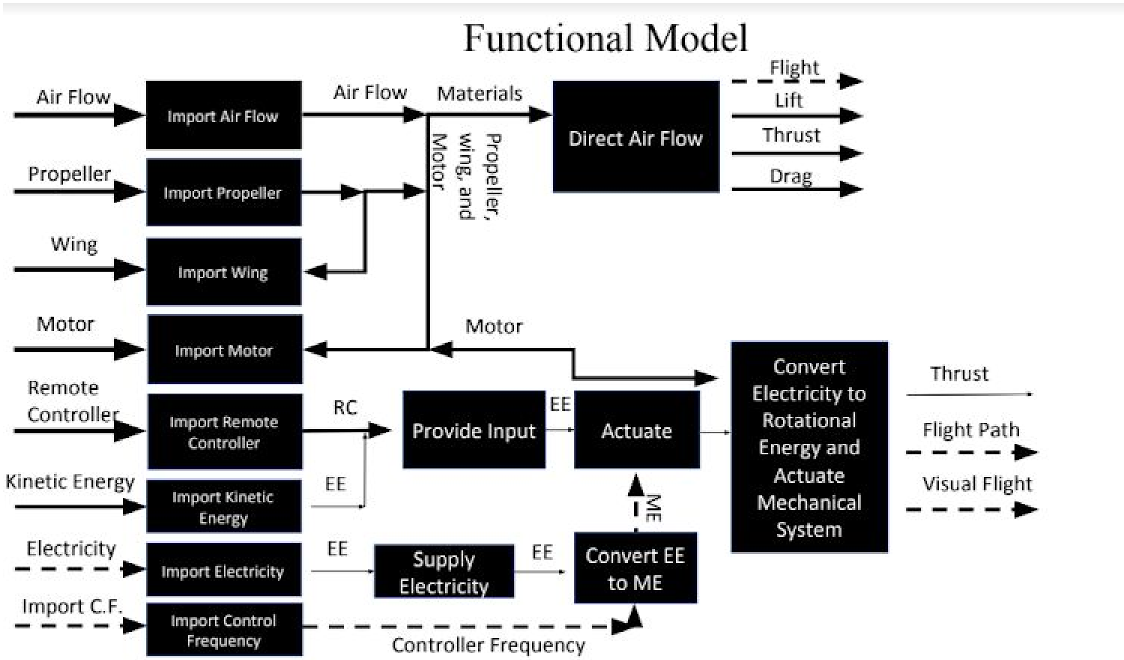

Figure 3: Functional Model

2.4 House of Quality (HoQ)

After defining both the CRs and ERs for the project, the next step was to compare CRs and ERs to each other using a quality function deployment (QFD) system. The purpose of the QFD was to determine the relative importance of each ER and compare how each ER affects other ERs. The relative importance of each ER was determined by how well the ERs satisfied each CR. In this system, CRs are given a customer weight (1-5), and each ER is scored (1,3, or 9) on the relationship with all CRs. Then, the sum of the scoring for each ER is added and compared to yield to relative technical importance. Next, ERs are compared to ERs to determine the design relationships when changing variables. The results for the relative technical importance of ERs and relationships between ERs are shown in the QFD in Appendix Table A1.

Upon completing the QFD, the ranked importance of each ER and the relationships between ERs were defined. As shown in Appendix Table A.1, the top 5 most important ERs were weight, power, thrust, payload storage length, and lift, respectively. The reason the top 5 ERs scored so high is they are crucial measurements to determine flight characteristics. Nearly the entire success of flight is dependent upon the weight, power, thrust, storage length, and lift of the aircraft. Understanding the importance of these engineering requirements provided the team with the necessary knowledge to research and generate concept designs that fulfill such requirements. Furthermore, the QFD shows that weight, power, thrust, and lift are all interconnected. So, if the team considered a smaller motor or battery to conserve weight, this will drastically affect the thrust and lift characteristics of the plane. Realizing this, future iterative designs must account for interrelated variables such as weight, power, thrust, and lift. Testing procedures will be taken to ensure each of the ERs will be satisfied. These testing procedures are fully explained in section 3.

2.5 Standards, Codes, and Regulations

For this project there are some codes and standards that are necessary to be practiced to ensure safety. The first code listed below in Table 3 is provided by the Academy of Model Aeronautics (AMA). The code is titled Devices Academy of Model Aeronautics National Model Aircraft Safety Code and lays out basic safety regulations including; not flying in a careless or reckless manner, flying over unprotected people, vehicles, and occupied structures, etc. The second code on Table 3 provided by the Society of automotive engineers (SAE) is the 2020 SAE Aero design rules. This rule book is the backbone of our design and by following all of the rules which are our customer requirements the team will be successful when it comes to the time of competition. The last code on the list comes from the International Electrotechnical Commission (IEC). This code gives basic safety guidelines when using lithium batteries such as making sure to test batteries for over discharge to avoid explosion. By following each of these standards and codes the team will not only be successful in competition but ensure safety throughout the duration of the project.

Table 3: Standards of Practice as Applied to this Project

Standard Number or Code	**Title of Standard**	**How it applies to Project**
AMA	Devices Academy of Model Aeronautics National Model Aircraft Safety Code [2]	Helps in ensuring safety while flying and prepping the plane before flight.
SAE	2020 Collegiate Design Series SAE Aero Design Rules [1]	All rules and regulations for competition.
IEC 60086-4 Ed. 5.0 b:2019	Primary Batteries - Part 4: Safety Of Lithium Batteries [3]	Gives precautions to ensure safety while using lithium batteries.

3 Testing Procedures

3.1 Testing Procedure 1: Thrust Test

The thrust test will be conducted to satisfy the thrust engineering requirement. Thrust is the force that moves the plane forward and in turn creates lift under the wing. This test will be conducted in 98 c well before any of the other tests are taken. This test will be the determining factor of whether or not the team needs a new motor or propeller.

3.1.1 Testing Procedure 1: Objective

The objective of the thrust test is to satisfy the engineering requirements for thrust which the team targeted at around 3 pounds of force. This test will be conducted using a scale and a mount which will be connected to both the scale and the motor with the propeller attached. After everything is mounted, the motor will be connected to the ESC and battery. Then the scale will be zeroed out. The motor will be actuated using the remote controller to full power thus rendering a negative value on the scale which is our max thrust. This value will then be inputted into our software ecalc as a known value for thrust which will then be used to calculate our potential lift.

3.1.2 Testing Procedure 1: Resources Required

The resources required for this test include; a scale, a mount for the scale and motor, the ESC, the battery, and the remote controller. Only two team members are necessary to be present for this test and it will be conducted in the machine shop on campus 98c.

3.1.3 Testing Procedure 1: Schedule

This test is scheduled to be within the first week of the second semester, so all of the resources as stated above will need to be either ordered or manufactured during winter break. After all the components are in the team's possession the test will be conducted January 15th.

3.2 Testing Procedure 3: Flight Test

The Flight test will be one of the final testing procedures conducted before the final demonstration because the aircraft's ability to be able to fly appropriately and accurately and land with limited damage inflicted is based upon the previous testing procedures. This testing procedure will test all of the engineering requirements and customer requirements, but more specifically it will test that the aircraft is capable of flying a 400 foot leg in the air and that the wheeled landing mechanism can be steered. This test will be conducted several times after each iteration or updated design, but the first scheduled test is February 21st.

3.2.1 Testing Procedure 3: Objective

The objective of the flight test is to reassure the team that the aircraft can fly properly. The aircraft will need to be completely constructed, and this includes the ailerons, drive system, and rudder actuates correctly in response to the remote controller. The fuselage, landing gear, wings, and electrical components will need to be completely finished and ready for the flight test.

3.2.2 Testing Procedure 3: Resources Required

The resources required to perform the flight test are few because the only requirement is the actual design to be fully constructed. The weather will be the most troublesome component to this test because it is the middle of winter in Flagstaff in February, so depending on the temperature, wind velocity, humidity, and snow, this will dictate our flight performance. If needed the flight can be performed indoors, i.e. the Health and Learning Center on NAU's campus. There will be little to no obstacles in comparison to the outdoor elements.

3.2.3 Testing Procedure 3: Schedule

February 21st will be the time when the first flight test will take place. This will give the team enough time to construct version 1 of the completed design in the spring semester.

3.3 Testing Procedure 4: Weight Test

Testing the weight of the completed design will be necessary because the design cannot exceed the max weight of 10lbs. The storage volume is another engineering requirement because the collapsed design of the aircraft must be able to fit in a 12.125 inches X 3.625 inches X 13.875 inch cubed cardboard box.

3.3.1 Testing Procedure 4: Objective

The objective of the weight test is to see whether or not our design exceeds the SAE competition rules of 10 lbs. This test will combine the storage volume and weight limit capacities in one test by disassembling the finalized design and placing it in the storage container to see if it can fit and then following this the components will be weighed. This will determine if the proposed dimensions of the components will satisfy the engineering requirements of the weight and the limited storage volume.

3.3.2 Testing Procedure 4: Resources Required

The resources required will be a box of the desired dimensions: 12.125 inches X 3.625 inches X 13.875. This will be made of cardboard as per the competition rules. In addition to the storage volume, the team will need access to a scale that can measure pounds, so we can be as accurate as possible. The location of where the weigh in is measured will be building 98C because it needs to be a hardwood or tile floor in order to register the correct reading.

3.3.3 Testing Procedure 4: Schedule

The schedule for this is dependent upon having the design completed. The flight test is scheduled for the third Friday of February, so the weight test will be conducted the week prior. The hard deadline that the weight test must be conducted by is February 21st, the same date as the flight test.

3.4 Testing Procedure 4: Assembly Test

Testing the time it takes to assemble the aircraft within our engineering requirement of three minutes is pertinent to the success of the team receiving high scores in competition. By doing this test the team will understand the components of the aircraft that need to be modified to both ensure structural integrity and speed of assembly which is a somewhat difficult trade to make. This test will be taken once the final design is complete.

3.4.1 Testing Procedure 4: Objective

The objective of the assembly test is to ensure that our SUAV will be able to be assembled out of our 12.125 inch X 3.625 inch X 13.875 inch box within 3 minutes. The first step of this test is to collapse the plane and fit it within our box. The next step is to start a stopwatch and begin assembling the plane as quickly and methodically as possible. The main components that will need to be assembled are the wings and tail. This test will be run through 10 times for practice and speed while working together with the team. The target for this assembly time is 1.5 minutes which is exactly half of the given time during competition.

3.4.2 Testing Procedure 4: Resources Required

The resources required for this test include the 12.125 inch X 3.625 inch X 13.875 inch cardboard box, a stopwatch, and the final design of the aircraft. The location of this test will most likely be done in the machine shop on campus 98c. All team members will be present while this test is taken.

3.4.3 Testing Procedure 4: Schedule

The schedule for this test is also dependent upon the completion of the final design. This test should be done after the flight test, to ensure that the team is not wasting time practicing assembly for an aircraft that does not even fly. This test will be done the same day as the flight test on the 21st of February just as long as it is done after.

4 DESIGN SPACE RESEARCH

The contents within chapter 3 includes; a literature review from each member of the group, benchmarking from previous designs, with multiple subsections, and a functional decomposition including a black box model and a functional model.

4.1 Literature Review

4.1.1 Corbin's Literature Review

Source 1: RC Basics: Introduction to how a RC radio system works [4]

This video gave clear definitions of the components of the radio control system which include the radio controller, radio receiver, binding tool, servo motors, and electric motors. Along with the components there are also different mode variations of the controller which outline the analog sticks axis to the outputs of the SUAV. There is also information on how to bind the human inputs of the controller to the outputs of the SUAV using the binding tool.

Source 2: Online marketplace for Radio Controller/Receiver [5]

This online marketplace gave the team a general understanding of remote controller/receiver prices to use for optimizing our budget. The review sections for each product is extremely useful to understand what consumers thought of different products which will help the team to weed out what is unreliable products.

Source 3: Understanding Radio control gear [6]

This resource is key in the teams design to understand the channels of a remote controller. Channels are the connection between inputs to the code within the controller and the outputs of the SUAV. Each channel has a distinct output including actuation of the propellor, ailerons, elevators and rudder.

Source 4: How to land your R/C model airplane [7]

This informational website gives explicit instructions on the landing of an SUAV. A useful tip learned was about adjusting power rather than the ailerons to increase/decrease the altitude of the vehicle. Another tip mentioned was to make the landing as gradual and flat as possible to ensure that all wheels come into contact simultaneously as possible following a guide slope.

Source 5: Fox and McDonald's Introduction to Fluid Mechanics, 8th ed [8]

The fluid mechanics textbook is a very essential tool in the calculations to be used for concepts such as lift and drag. Boundary conditions and airfoils for the teams design will be referenced through this book as well. When comparing the prototypes to the final design a non dimensionalized analysis approach will be using references from the textbook.

4.1.2 Eli's Literature Review

Source 1: CORENGR-V012200 [9]

A technical aspect that is beneficial to our overall design is a Computational Fluid Dynamics or CFD. This is important because we can simulate and view the flow vectors, the lift, and the overall airfoil. This foreshadows how our overall design of the fuselage and the wing will look like. The ANSYS Fluent software performs these tasks with ease. After setting up the boundaries of the airfoil and creating a C-Mesh domain the user can design a model of what airflow they want simulated.

Source 2: CORENGR-V012800 [10]

In ANSYS Fluent the user can start plotting the streamline function, which is very similar to plotting velocity vectors. After creating a mesh grid and clicking on the Stream Function tab in ANSYS Fluent and put in desired values. By changing the minimum mass flow rate, the maximum flow rate, and the levels, Fluent will create a graph shown in Figure 4.

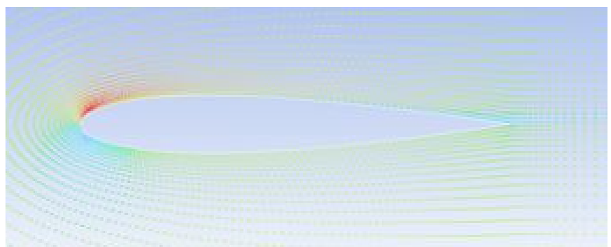

Figure 4: Streamline of Airfoil

In Figure 5, the fluid that the airfoil is submersed in at a certain angle of attack. It shows how the fluid (air in this case) molds around the airfoil at its' desired angle of attack. Without the use of CFD it would be possible to compute the velocity vectors, but in order to achieve the desired accuracy of an actual experiment, CFD is the ideal method.

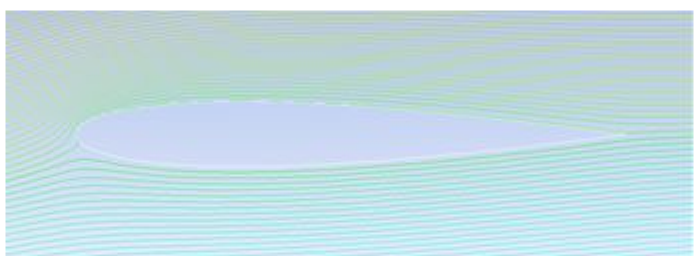

Figure 5: Flow of the Fluid around Airfoil

Source 3: Introduction to Aircraft and Stability Control [11]

This resource explains the importance of lift and drag of airfoils and how it dictates how well the aircraft will fly. The back of the envelope calculations introduced in the Academic text describe how to calculate the desired life and thrust in order for the aircraft to be successful. The most important criteria that this project details is that that aircraft must fly. Throwing an aircraft and letting it glide will not be efficient enough. The pilot of the aircraft must be able to control the design during the duration of the flight.

Source 4: How Ducting a Propeller Increases Efficiency and Thrust [12]

One of the important components of an aircraft and the flight. The propulsion of the aircraft is one of the deciding factors whether or not the aircraft will take flight. The use of a shroud or ducts will increase the thrust and efficiency of the aircraft.

Source 5: Cornell University Learning Modules [13]

This website that Cornell University created details the importance of modules; such as Matlab, ANSYS Aim, and Bladed learning modules. All of these modules are integrated with fluid mechanics, with each module has their own distinct advantages when dealing with fluid mechanics. ANSYS will plot the vectors a lot more efficiently than Matlab, but Matlab will calculate the drag and lift values more accurately.

4.1.3 Zach's Literature Review

One of the most important aspects of designing the plane is conducting structural analyses on various parts. For instance, the wing frame and foil must be able to support the lift that is being generated, and the fuselage must support the landing and payload. For these structural analyses, the team decided to use finite element analysis (FEA). Five sources of literature were identified to aid in FEA implementation.

Source 1: "What is FEA: Finite Element Analysis" [14]

The purpose of analyzing this source was to understand the basic fundamentals of FEA and the types of software that are used in FEA. This resource explained that ANSYS and SolidWorks are among the leading software used in FEA [14]. From this, the team decided to use SolidWorks for future FEA endeavors.

Source 2: "Learn SolidWorks Simulation Tutorial" [15]

After identifying SolidWorks as the preferred (and free) method of FEA, the next step was to learn how to analyze a part or assembly using SolidWorks simulation. From this source, the team learned of the various inputs in SolidWorks, which include the geometry, material, connections, fixtures, external loads, and mesh [15]. Furthermore, the tutorial explains how SolidWorks simulations can analyze stress, strain, fatigue, and other metrics using said inputs.

Source 3: "FEA Explained for Beginners" [16]

Although the previous tutorial explained how SolidWorks FEA operates, it did not explain the theory behind how mesh and geometry interact. Basically, the overall geometry is broken into thousands of individual elements. Given boundary conditions, known material properties, and element-to-element interactions, the overall stress and strain can be solved for throughout the geometry [16].

Source 4: "Finite Element Analysis: Easy Explanation (YouTube)" [17]

This source served as supplemental information to the previous source, while also providing a video of SolidWorks FEA. The structure analyzed was a plane wing, where the user input various conditions and calculated the stress across the geometry [17].

Source 5: “Solidworks Simulation Tutorial: Steel Structure in Solidworks (YouTube)” [18]
The final source analyzed was a SolidWorks FEA simulation video, very similar to the previous video. However, this video explained ways of creating different meshes and fixtures for a simple beam [18]. This video was extremely valuable because it taught the team how to properly analyze loading within a beam, which will be used in both the wing and fuselage frame analyses.

4.2 Benchmarking

Table 4: Benchmarking

Legend	
A	SAE Aero Micro 2014-2015 NAU
B	SAE Aero Micro 2016-2017 NAU
C	SAE Aero Micro 2018-2019 NAU
D	SAE Aero Micro 2018 Puerto Rico Results
E	SAE Aero Micro 2019 University of Minnesota
F	SAE Aero Micro 2015 Montana State University
G	SAE Aero Micro 2019 Xi'an Jiaotong Univ First Place
H	SAE Aero Micro 2019 Acharya Institute of Technology
I	SAE Aero Micro 2019 Wright State Univ 6

Competitor Benchmarking

1 Poor	2	3 Acceptable	4	5 Excellent
E,C	D,B	F	H	G
C	E,B	D	H	G
D,E,C	F		H	G
D,E,C,B		F	H	G
D,E,C,B	D,F,H			G
E,C	D,B	H	F	G
E,C	D,B	F	H	G
E,C	D,B	F	H	G
H,C	E,B	D,F		G
C	D,B	E,F,H	G	
E,C	D,B	F,G		
H, B	F, C	G	E	I
H, B	F, C	G	E	I,D
H, B	F, C	G	E	D
F, H	C, B	G	E	
		A,B,C,D,E,F,G,H,I		
H	F, C, B	G	E	D
H	C, B	F, G	E	I,D
H	E, C	D, G, B		

In order to design, manufacture, and operate a functional prototype Engineers must compare their initial design to previous models that have been made; this is called benchmarking. The purpose of benchmarking is to create a more efficient and functional design than previous iterations. Observing why systems fail is part of being an engineer, so this process is designed to address the failure that occurred and then expand and improve upon the design. The best possible way to benchmark in a competition based Capstone, where each year there are various designs of the same criteria, was to look at previous competitors.

The three designs that will be benchmarked are the SAE Aero Micro 2014-2015 NAU, the SAE Aero Micro 2016-2017 NAU, and the SAE Aero Micro 2018-2019 NAU. The group found the most information regarding these designs, so this will make the benchmarking more precise and exact. The issues with benchmarking these specific designs are that none of these designs won the competition. They are average designs, but the main problem with these designs was not the design itself. It was that the members did not abide by the criteria that was set by SAE, i.e. not throwing the aircraft, not landing intact, or creating a invalid storage unit. Another problem that can occur with benchmarking is not reviewing all the information that is presented because some models are designed for a specific material, etc.

4.2.1 System Level Benchmarking

In our project we are abiding by the competition rules, which are also the customer requirements. The payload cannot aid frame integrity, gross weight limit, and a wheeled landing gear steering mechanism must be about of the assembly; these are a few examples of the criteria of the competition.

4.2.1.1 Existing Design #1: SAE Aero Micro 2014-2015 NAU

The first design that we benchmarked was the SAE Aero Micro 2014-2015 NAU [19]. The customer requirements for the SAE 2014-2015 Design competition were quite different, in that they had a 24 inch tube to place their components into. They would then limit the team in their wingspan and total aircraft chord length.

4.2.1.2 Existing Design #2: SAE Aero Micro 2016-2017 NAU

The second design that was benchmarked was the 2016-2017 NAU design. The customer requirements of their design are similar to the customer requirement of the 2020 competition. The design components like the aircraft must fit in a box like container, must land, and be controlled through hand launch still apply.

4.2.1.3 Existing Design #3: SAE Aero Micro 2018-2019 NAU

The final design that was selected for the benchmarking process is the SAE Aero Micro 2018-2019 NAU. The storage unit for this competition is very similar to the 2019-2020 Micro Aero competition 12x13.8x3.6 inches in volume.

4.2.2 Subsystem Level Benchmarking

The wing design, landing mechanism, and propulsion system will heavily decide on the effectiveness of the aircraft as a whole. Every year the design criteria will change, which will determine the effectiveness of the benchmarking process as a whole, but it still is relevant researching former teams designs. It will describe what are the positives and negatives of the design that will be implemented accordingly.

4.2.2.1 Subsystem #1: Propulsion

The propulsion of the aircraft is determined by the propeller, motor, and the force of drag. The increase of propeller blades will decrease the aerodynamic efficiency of the aircraft. The motor will determine the angular velocity of the propeller blades.

4.2.2.1.1 Existing Design #1: Basic Two Blade Propellor with No Shroud

The 2014-2015 NAU team were not limited in the battery power nor the size of the motor, but they did use a propeller with a width of 9.95 inches. This will generate enough thrust to continue the desired flight path. There was no shroud with the design, which would have increased the thrust, but it would have increased the weight.

4.2.2.1.2 Existing Design #2: Angled blades that have differential thrust

The propulsion concept of the 2014-2015 NAU's team revolved around the blade angle and number of blades on the propeller. The team decided that even though the number of blades in the propeller efficiency will decrease, they combatted since a Micro aircraft needs more surface area because the aircraft's velocity is not too high. The thrust generation is decided upon the angle at which the blades are formed. The outer edge of the blades have a greater velocity than the inner edges, so there will be a difference in thrust.

4.2.2.1.3 Existing Design #3: Scorpion SII servo motor

The motor that was selected by this team was the Scorpion SII-2212-1850, which then created a 2.28:1 thrust ratio, along with a 4.66:1 weight ratio. The design team decided the 7x4 APC Electric E propeller would be the best cost/thrust ratio. [20]

4.2.2.2 Subsystem #2: Wing Design

The wing design is based upon the airfoil that is selected. Every airfoil will calculate different coefficients of lift and drag, and based on the design/materials of the prototype design will dictate what airfoil is selected. In general the wings should have a high aspect ratio (AR). The aspect ratio is the ratio of the wingspan to the chord length. This creates a lot of efficient surface area, which in turn creates lift.

4.2.2.2.1 Existing Design #1: 54 Inch Wingspan

The 2014-2015 NAU team [19] created an aircraft that focused more on the AR than anything else. Shown below in Figure 6, the total wingspan is 54.00 inches or 4.5 feet long. In their customer requirements they were limited in their chord length. The maximum limit for the chord length is 5 inches, so their AR is 11.9.

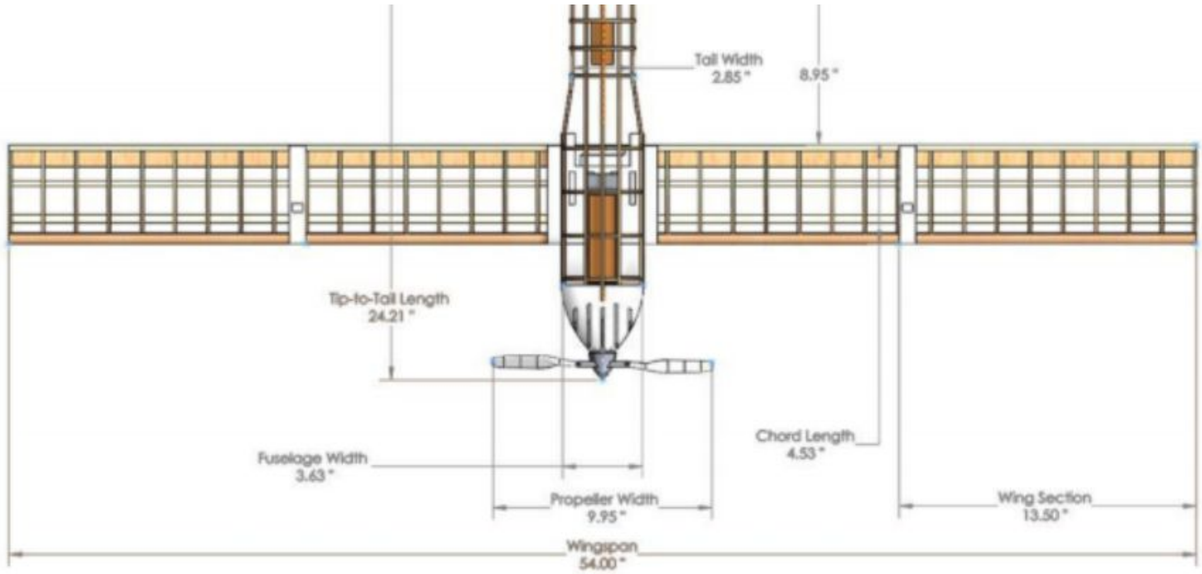

Figure 6: 2014-2015 Design model

4.2.2.2.2 Existing Design #2: Light Material with a higher Surface Area

The aspect ratio of the 2016-2017 NAU design is 8.4 [21]. The wingspan is 42 inches and the chord length is 5 inches. The material of the wing is housing insulation pink foam, which is light but unit volume.

4.2.2.2.3 Existing Design #3: Short wingspan with a low weight ratio and aspect ratio

The 2018-2019 NAU Design team [20] constructed a plane with an aspect ratio of 7.5 with the wingspan being 30 inches and then the wing chord length of 4 inches. This is the smallest AR that was researched, so overall observing the flight of the aircraft determines how well the AR contributes to the flight of the aircraft. The more surface area increases the lift, but it can also create drag and induced drag.

4.2.2.3 Subsystem #3: Landing Mechanism

The only requirement for the landing mechanism is that it lands. There are no limitations in the amount of wheels it has to be or if there even needs wheels. The updated customer requirements are that the landing mechanism has to be a steered landing mechanism.

4.2.2.3.1 Existing Design #1: Aircraft with little to no landing gear

The 2014-2015 NAU team did not focus heavily on the landing mechanism. They implemented small landing gear components that were calculated to have a high enough modulus of elasticity to handle the load of landing.

4.2.2.3.2 Existing Design #2: Tricycle Tail Dragger

This Micro team decided to use the reverse tricycle landing mechanism, which is two wheels in the front, connected to the mid-chord length of the wing, and a single wheel that balances the front and the back of the aircraft. This design shows the static representation of the aircraft which sits at a two degree angle from horizontal.

4.2.2.3.3 Existing Design #3: Two wheels in the front, One wheel in the back with Rudder Servo

The landing mechanism for the 2018-2019 NAU team was the same as the previous design. A reverse tricycle wheeled system with two wheels in the front to stabilize the tipping/rolling effect.

5 CONCEPT GENERATION

After benchmarking various Micro SUAVs, the next step was to generate concepts for an original design. Our team generated concepts by decomposing the overall design into 5 subsystems, where each subsystem had three subsystem variants. Sections 5.1 and 5.2 explain the full system designs and subsystem variants that our team generated and considered.

5.1 Full System Concepts

Sections 5.1.1-5.1.3 below explain the 3 unique full-system design concepts our team created. Each full-system design concept was generated using combinations of the 15 subsystem variants. Various pros and cons of each design are listed below.

5.1.1 Full System Design #1: Single wing, full maneuvering devices, rear steer, single motor, and elliptical taper fuselage with payload snaps

Pros:

- Lightweight with single wing and single motor
- Higher maneuverability due to ailerons, rudder, and elevator
- Longer wheelbase due to tail dragger landing gear
- Decreased drag with elliptical taper
- Faster assembly time with payload snaps

Cons:

- Less surface area compared to dual wing results in less lift
- More difficult manufacturing due to more control surfaces such as ailerons, elevator, and rudder
- Posible rollover upon landing due to tail dragger landing gear
- Increased drag with payload outside of system

5.1.2 Full System Design #2: Single wing, dual aileron with rudder, front steer, single motor, and elliptical taper fuselage with internal storage

Pros:

- Lightweight with single wing and single motor
- Easier manufacturing with less moving parts due to deletion of elevator
- Decrease of rollover possibility with front steer
- Decreased drag with elliptical tapered fuselage and internal storage

Cons:

- Less surface area compared to dual wing results in less overall lift

- The range of the angle of attack is limited due to deletion of elevator

5.1.3 Full System Design #3: Dual wing, dual aileron with rudder, rear steer, single motor, and elliptical taper fuselage with payload snaps.

Pros:

- Increased lift with dual wings
- Easier manufacturing with less moving parts due to elevator deletion
- Faster assembly time due to payload snaps
- Decreased drag on aircraft due to elliptical tapered fuselage

Cons:

- Increased weight and moment of inertia with two wings results in less maneuverability
- Possible rollover upon landing due to tail dragger landing gear
- Less control and angle of attack due to elevator deletion
- Increased drag with payload outside of system

5.2 Subsystem Concepts

To arrive at the full system designs from above the team had to break down the SUAV into five subsystems, each having three different designs within the subsystems. Each design is described through short descriptions and figures.

5.2.1 Subsystem #1: Wing Design

5.2.1.1 Design #1: Bi-Plane

The bi-plane design shown in Figure 7 features a wing above and below the fuselage, which is designed to increase lift. The pros of a bi-plane design are greater lift, while the cons are decreased maneuverability and increased weight.

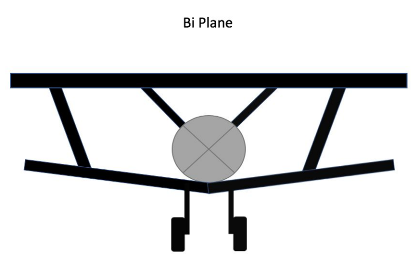

Figure 7: Bi-plane design

5.2.1.2 Design #2: Single Wing

The single wing design shown in Figure 8 features a single wing above the fuselage. The pros of a single wing design and increased maneuverability and decreased weight, while the only con is decreased lift.

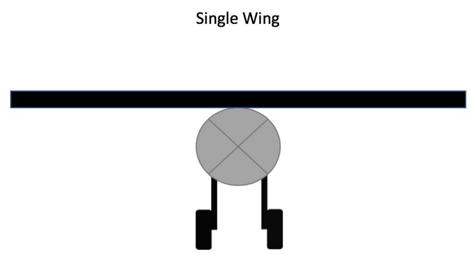

Figure 8: Single Wing Design

5.2.1.3 Design #3: Airfoil design

A specified airfoil design will be implemented on either the biplane or single wing design. A predetermined NACA airfoil design had not been selected at this point.

5.2.2 Subsystem #2: Maneuvering Devices

5.2.2.1 Design #1: Dual aileron, dual elevator, rudder

Having both elevators and ailerons allows for lift and drag to be better controlled in the wings and tail end of the plane. Furthermore, the angle of attack and turning are easily controlled with the rudder, ailerons, and elevator shown in Figure 9. However, the increase in moving parts will increase the difficulty in manufacturing.

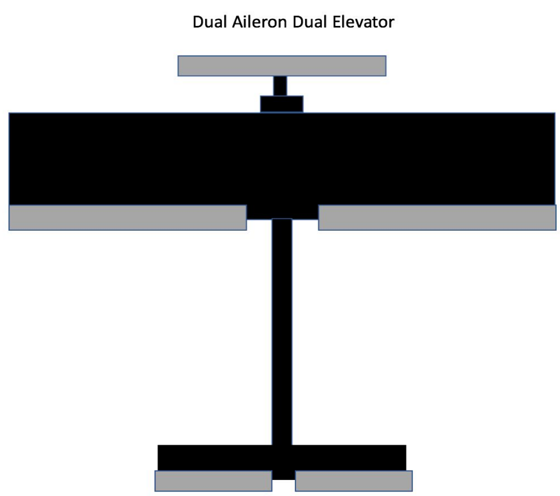

Figure 9: Dual aileron, dual elevator

5.2.2.2 Design #2: No aileron, dual elevator, rudder

With no ailerons, the airplane is unable to generate a roll turn in flight. However, the rudder and elevators allow for the angle of attack and yaw to be manipulated. So, the pros of this design are less weight and easier manufacturing, while the con is less maneuverability.

5.2.2.3 Design #3: Dual aileron, no elevator, rudder

With dual ailerons and a rudder shown in Figure 10, the plane can manipulate roll and yaw in flight, but the angle of attack cannot be manipulated. So, the pros of this design are less weight and easier manufacture, while the cons are decreased maneuverability.

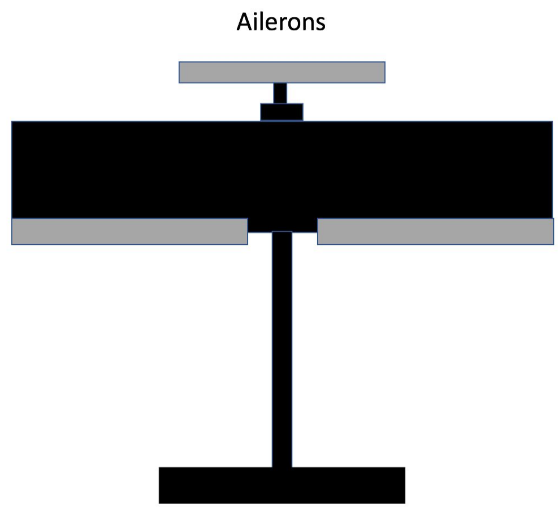

Figure 10: Dual aileron, no elevator

5.2.3 Subsystem #3: Landing Gear

5.2.3.1 Design #1: Skids

This design features pontoon-shaped skids that allow the aircraft to land on smooth surfaces. The pros of this design are ease of manufacturing and operation, while the cons are decreased maneuverability and increased chances of crash landing.

5.2.3.2 Design #2: Tricycle front steer

The tricycle landing gear features two wheels in the back and a steerable landing gear in the front, shown in Figure 11. The pros of this design are increased landing stability and maneuverability when taxying. The cons are increased drag and weight.

Figure 11: Tricycle landing gear [22]

5.2.3.3 Design #3: Two front wheels rear steer

The tail dragger landing gear features two wheels in the front and a steerable landing gear in the rear, shown in Figure 12. The pros of this design are increased angle of attack upon takeoff and maneuverability when taxying. The cons are increased drag and weight.

Figure 12: Two front wheels, rear steer [23]

5.2.4 Subsystem #4: Propulsion

5.2.4.1 Design #1: Twin motor

With a dual-motor system shown in Figure 13, two motors work in synchronization to generate twice the thrust. The pros of this design are increased thrust, while the cons are increased weight and manufacturing time.

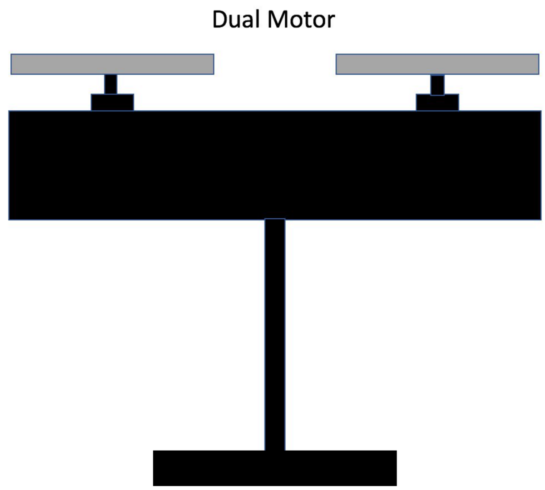

Figure 13: Twin motor

5.2.4.2 Design #2: Single motor

The single motor system shown in Figure 14 features one motor that generates thrust. The pros of this are decreased weight and manufacturing time, while the con is decreased thrust.

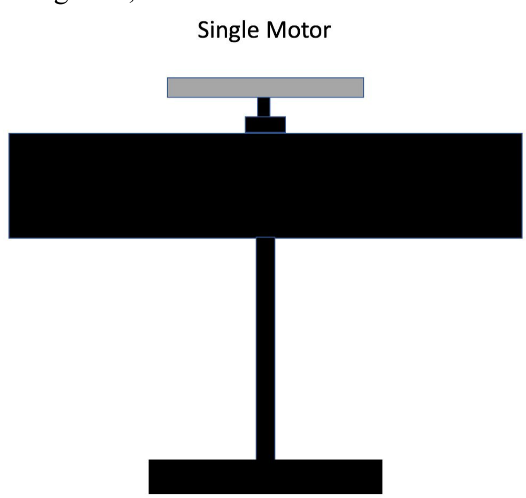

Figure 14: Single motor

5.2.4.3 Design #3: Singe motor with shroud

A shroud is a cylindrical tube that surrounds the propellor to guide more air into the propellor, which increases thrust. The benefit of this design is increased thrust, while the cons are increased weight and manufacturing time.

5.2.5 Subsystem #5: Fuselage/Payload

5.2.5.1 Design #1: Tapered cylinder with internal storage

For this design, the drive mechanisms and payload will be housed within the fuselage. To accomplish this, the fuselage will be a tapered cylinder. The pros are increased storage volume and decreased drag, while the con is added weight.

5.2.5.2 Design #2: Elliptical taper with fuselage snaps

The elliptical taper starts larger at the front of the plane and tapers down for the purpose of increasing aerodynamics. The payload is intended to be snapped into the fuselage with an undetermined fastening system but will in turn cause more drag, shown in Figure 15.

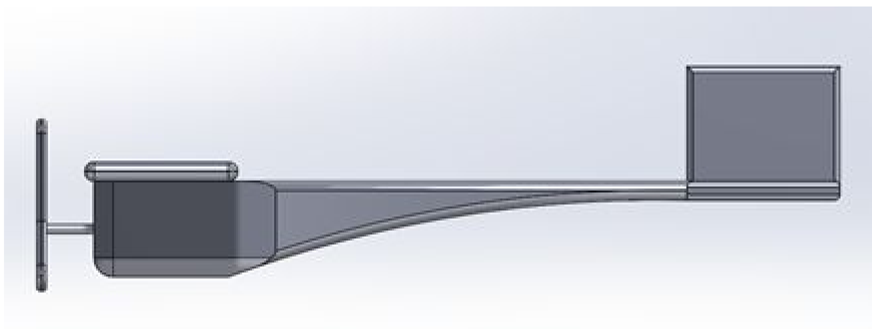

Figure 15: Elliptical taper

5.2.5.3 Design #3: Elliptical taper with wing snaps

The elliptical taper as shown in Figure 15 above starts larger at the front of the plane and tapers down for the purpose of decreasing drag. The payload is intended to be snapped into the wings with an undetermined fastening system. The pros of this are ease of manufacture and assembly, while the cons are added drag and decreased thrust.

6 DESIGN SELECTED - First Semester

This section details the design selection process throughout the first semester. The selection process begins with concept generation and selection conducted in the preliminary report. Then, the preliminary design is re-evaluated to provide the exact materials and dimensions for the final design. Finally, the preliminary design lacks the exact resources needed for final design. So, section 5 provides an in-depth implementation plan for the final design.

6.1 Design Description – First Semester

6.1.1 Preliminary Design

The preliminary report details the concept generation process, where each subsystem yielded unique concept variants to fulfill the subsystem requirements. The final product of concept generation combined one subsystem variant from each subsystem to produce three full-design variants. Each full-design variant is shown below in Table 4.

Table 4: Full-Design Variants

Subsystem	Full-Design Variant	Full-Design Variant 2	Full-Design Variant 3
Drive	Single motor	Single motor	Single motor
Fuselage	Unibody elliptical taper with external payload storage	Unibody with internal payload storage	Unibody elliptical taper with wing payload storage
Wings	Single wing	Single wing	Dual wing
Landing Gear	Tail-dragger	Tricycle	Tal-dragger
In-Flight Control	Dual aileron with elevator and rudder	Dual aileron with rudder	Dual aileron with elevator and rudder

Following concept generation, the next step was to compare each full-design variant and select the design that performs best given a unique subsystem combination. Designs were compared using a pugh chart and decision matrix, where the selection criteria are CRs and ERs. The Pugh Chart and Decision Matrix are provided in appendix Tables B1 and B2, respectively.

As shown in appendix Table B1, all three designs scored the same as the datum when compared to most competition requirements. However, design 1 had the highest positive score compared to the datum. The rear steering mechanism allows for greater control upon landing, so the radio control and reliability CRs scored higher with design 1. Next, the elliptical tapered fuselage with external fasteners allows for payload storage on the fuselage rather than wings, providing more area to store weight and greater durability. Thus, design 1 scored higher in durability, flight characteristics, assembly time, and weight CRs. Design 2 scored the second highest in the Pugh chart evaluation. The tricycle front steer prevents rollover landings, making design 2 more durable and robust. The deletion of elevators simplifies the control system while also limiting the weight of actuators, so design 2 also scored higher in weight and control CRs.

As shown in appendix Table B2, the decision matrix also scores design 1 as the highest. The main differences between designs 1 and 2 were the fuselage and landing gear designs. Design 1 features external payload storage with a rear wheel steering mechanism. This allows for decreased assembly time, increased landing capability, increased payload capacity, and less drag. The most important considerations are the decreased assembly time and decreased drag. Equations for payload assembly time and drag are shown in equations 1 and 2, respectively.

$$t_{assembly} = C_{fastener}N$$

$$Drag = C_D(0.5\rho v^2 A)$$

In equation 1, the assembly time is dependent on the fastener coefficient and the number of fasteners. Design 1 features external payload snap-on fasteners while design 2 features internal payload storage. Therefore, design 1 has a lower assembly coefficient and the same number of fasteners as design 2. Thus, the assembly time for design 1 is lower than design 2. Finally, the drag equation is dependent on the coefficient of drag and the cross-sectional area. Design 1 features a smaller fuselage with external storage, resulting in a smaller area and drag coefficient than design 2. Therefore, design 1 has a lower drag force than design 1. Thus, from the Pugh Chart and decision matrix comparison, design 1 was selected as the preliminary design. The rough CAD with various views for design 1 is shown below in Figure 16.

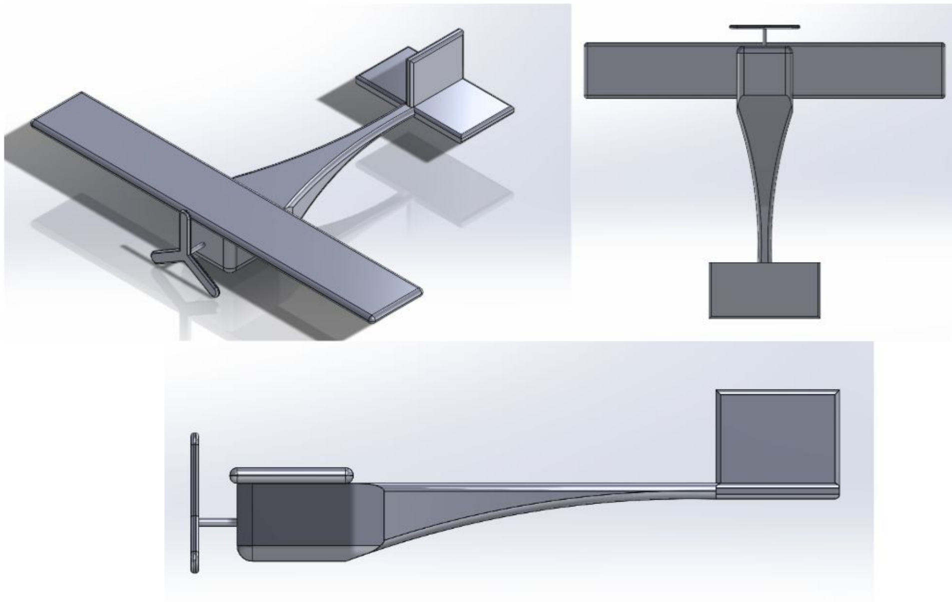

Figure 16: Preliminary Design CAD Model

6.1.2 Final Design Changes

Following the preliminary design, the next step in generating a final design was determining any necessary changes to the preliminary design. Two major changes were made for the final design: deleting the elevator and replacing the unibody fuselage with a tadpole design. First, the elevator design was deleted to simplify manufacturing and decrease the weight, assembly time, and cost. Our design features ailerons that operate independently to turn the plane and operate in unison to land the plane. Furthermore, the rudder steers the back end of the plane upon landing, so that the plane will land straight despite any form of cross wind. Thus, the elevator was deemed unnecessary and the final design will proceed with no elevator.

Second, the unibody fuselage design shown above in Figure 16 internally houses the drive components (motor, speed controller, battery, and receiver) and tapers down, eventually connecting to the tail wing. This design cannot work for two reasons: manufacture and size constraints. After determining the drive specifications, the square portion of the fuselage frame must be approximately 6 inches in length. In order to balance the plane, the tapered portion of the fuselage must be approximately 10 inches in length. Given the size constraints, a 16 inch unibody fuselage will not fit within the box. So, the solution to this is a tadpole design, where the 6 inch fuselage frame that houses the drive components is connected to a 10 inch carbon fiber rod. The tadpole design is shown below in Figure 17, and is discussed in further detail in the design specifications section.

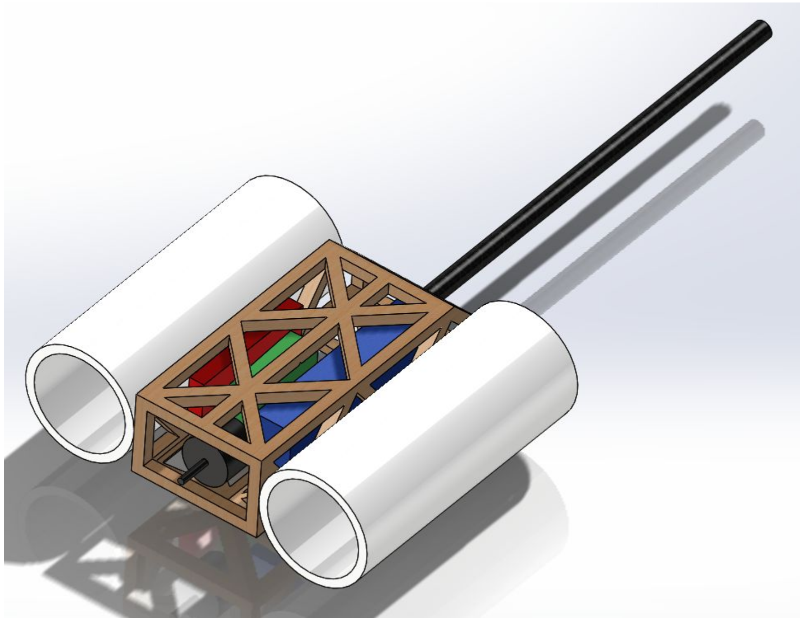

Figure 17: Fuselage Tadpole Design

6.1.3 Design Specifications

Once the final design changes were determined, the next step was to develop the exact specifications for each subsystem of the design. The specifications include dimensions, make/model, and material used to fulfill each subsystem. Subsystem specifications are described below.

6.1.3.1 Drive Specifications

The drive subsystem is broken down into four main components: propeller, electric motor, electric speed controller (ESC), and the battery. The first step was to select a propeller fit for our plane size. If the total weight of the plane is assumed to be 4 lb, and approximately 100W/lb is needed to fly, then approximately 400W of power is needed to fly [24]. 400 W of power is equal to 0.2 glow equivalent, a measurement of gas engine displacement in cubic inches [24]. So, given the propeller chart in Figure 18, the team selected an APC Electric 8"x4.7" SF propeller. This propeller has an 8 inch diameter with a 4.7 inch pitch, and is designed for slow-fly planes.

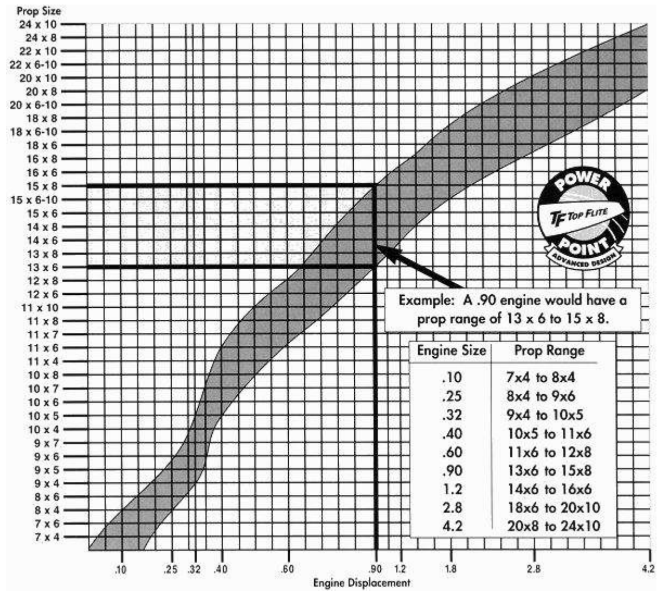

Figure 18: Propeller Selection

Next, there were thousands of motors that could work for our airplane. So, we narrowed our search by choosing from one manufacturer: Scorpion Propulsion. Of Scorpion's hundreds of motors, the Scorpion HK-2520-1880 motor was selected due to its high energy-to-weight ratio, brushless technology, and 800W max power. Furthermore, this scorpion motor is compatible with a Scorpion ESC.
When combined with the APC Electric 8"x4.7" SF propeller, the motor generates a thrust-to-weight ratio of 0.94 under ideal output and 1.20 under max output. These thrust-to-weight ratios suggest desirable flight performance [3].

The final step in drive selection was to select an ESC and battery. The main consideration when selecting an ESC was that the motor will not draw more current than the max rating of the ESC. At max output, the motor draws 41A of current. From this, we selected a Scorpion brushless ESC with a 45A rating. Finally, the battery selection was contingent upon the max electric load and flight time. The max battery discharge the drive will draw is 23C, and desirable flight time is approximately 3-5 minutes. From this, the team selected an 1800mAh 3-cell 35c lithium polymer battery. This battery not only meets the rules, but also can supply up to 50C discharge and a flight time of 4 minutes. All of the drive specifications are listed below in Table 5. Pictures of each component are shown in Figures 19-22.

Table 5: Drive Specifications

Drive Part	Brand/Model	Size	Weight (oz)	Cost ($)
Prop	APC Electric SF 8x4.7	8" dia x 4.7" pitch	0.25	2.45
Motor	Scorpion HK-2520-1880KV	1" dia, 0.8" length (0.63 in^3)	3.64	80.00
ESC	Scorpion Commander 15V 45A ESC SBEC (V3)	2.83"x1.18"x0.32" (1.06 in^3)	1.55	60.00
Battery	Lumenier 1800mAh 3s 35c Lipo Battery	4.1"x1.34"x0.79" (4.34 in^3)	4.94	20.00

Total		6.03 in^3	10.38	162.45

Figure 19: APC Electric 8x4.7 SF

Figure 20: Scorpion HK-2520-1880KV

Figure 21: Scorpion Commander 45A ESC

Figure 22: Lumenier Battery

6.1.3.2 Fuselage Specifications

As shown in the drive specifications Table 5, the fuselage frame must internally house all of the drive components. From this, the required length, width, and depth of the fuselage frame is 6.5”x2.75”x2.5”, respectfully. The 6.5 inch length of the fuselage frame means that the 6 inch chord length of the wings will mostly cover the frame. Also, the 6.5 inch length provides enough support to fasten the external PVC payload. The fuselage frame will be comprised of ¼” thick ABS members and 3D printed to ensure rapid prototyping. The final design of the fuselage frame is shown below in Figure 23.

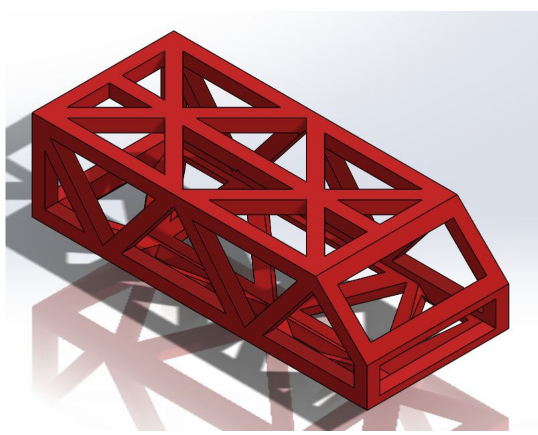

Figure 23: Fuselage Frame

6.1.3.3 Wing Specifications

In order to generate the thrust and lift necessary to fly the plane, the airfoil, wingspan, and chord length must be selected. First, the Clark Y airfoil will be used to generate the lift. The Clark Y is widely used for RC planes and provides a smooth stall entry and sufficient lift. The airfoil is largely flat on the bottom, making it easier to manufacture. The wing shape will be a rectangular platform with a uniform chord length of 6 inches and a wingspan of 52 inches. The long, rectangular wingspan maximizes the lift area and stability of the aircraft. However, in order to fit within the box, the wings must be segmented into four sections of 13 inches. The wings will be constructed out of a balsa wood frame and exterior. The airfoil and wing design is shown below in Figure 24.

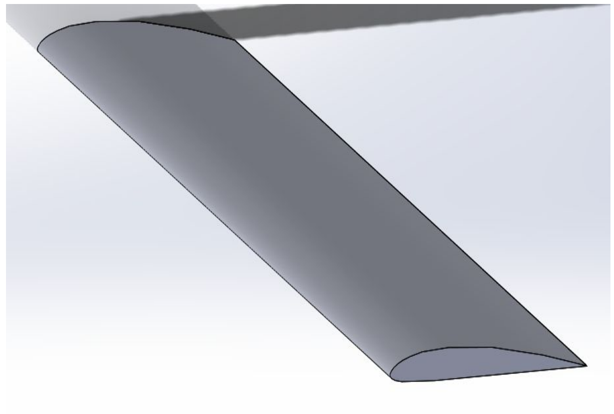

Figure 24: Wing Design

6.1.3.4 Landing Gear Specifications

The landing gear will feature two independent front wheels and a rear wheel that steers the plane upon landing. In order to support landing, the selected wheels are 1.5 inches in diameter and supported by thin aluminum rods 5 inches in length. The 5 inch length of the rods ensures the propeller will not strike the ground upon landing. The rear wheel is 1 inch in diameter and supported by a rod-and-spring suspension approximately 2 inches in length. The front and rear wheels are shown below in Figure 25 and 26.

Figure 25: Front Landing Gear

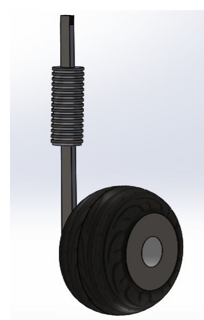

Figure 26: Rear Landing Gear

6.1.3.5 Control Specifications

The fixed-wing plane is operated by a controller and receiver. The controller sends a signal to the receiver, which then sends input to various channels. Our design has a motor, two ailerons, rudder, and rear wheel that will be actuated by the receiver. Each of these components operates on a unique channel within the receiver. This means the design must incorporate a 5-channel controller and receiver pair into the design. Furthermore, the two ailerons, rudder, and rear wheel need an electric motor and linkages to convert rotational energy to linear motion. For this, the team will use four servo motors externally mounted using control horns on the wings, rudder, and tail wing. For example, the rotary motion of the servo motor will push/pull a rod which is fastened to control horn on an aileron. This, in turn, pushes or pulls the aileron, essentially steering the plane while in flight. The servo motors, push/pull rods, and control horns are shown below in Figures 27-29.

Figure 27: Servo Motor

Figure 28: Push/Pull Rods

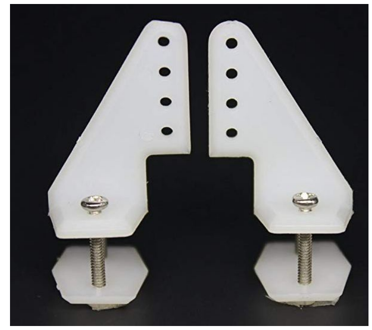

Figure 29: Control Horns

6.1.4 Prototype

The current-state low fidelity prototype features the 3D printed fuselage frame, which successfully houses the receiver, ESC, and battery. The prototype is shown below in Figures 30 and 31. Some key learnings from creating the prototype include mounting procedures for the carbon fiber rod, motor, and landing gear. The next iteration of the fuselage frame will have built-in mounting points for all of the components previously mentioned.

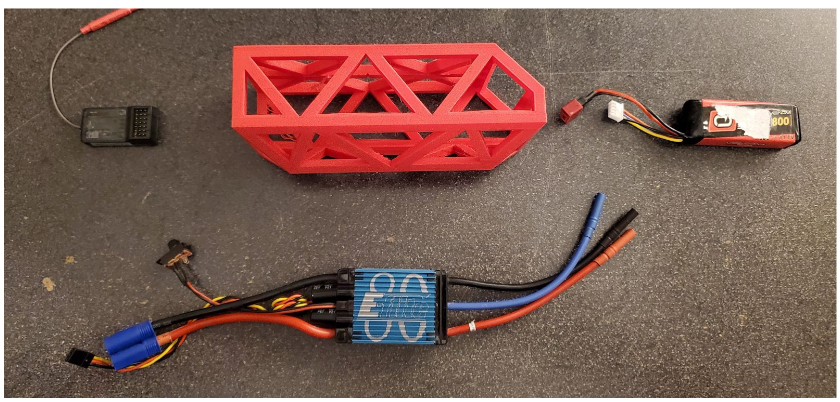

Figure 30: Prototype Exploded View

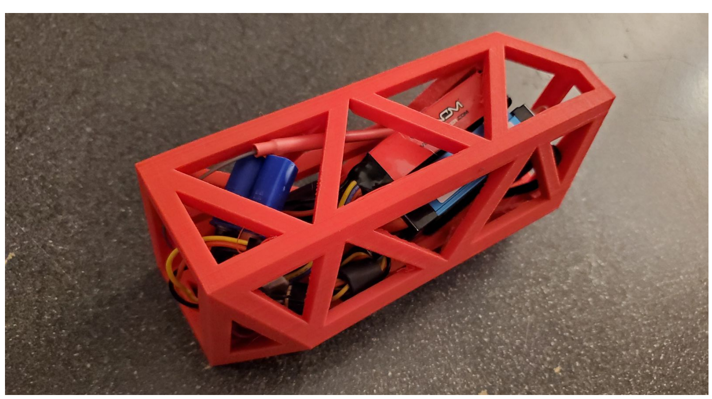

Figure 31: Prototype Housing

6.2 Implementation Plan – First Semester

This section provides a complete description of how we plan to implement our design. The team has already purchased software necessary to calculate flight data, meaning there is no need to write code or program simulations to predict the thrust and lift required or generated for our design. Furthermore, in-flight operator procedures will be purchased along with the controller and receiver. So, the remaining implementation steps include constructing a prototype, conducting test procedures, and iterating the prototype once completed. A complete list of the implementation plan is provided in Table 6 below. The implementation plan includes the dates, description, and resources needed to carry out the design.

Table 6: Implementation Plan

Start	**Finish**	**Description**	**Resources needed**
11/18/19	12/13/19	Purchase all materials	$475 total cost. Use purchasing links to buy items and request refunds through Karine Story
12/16/19	1/10/20	Fabricate base plane prototype (fuselage, wings, landing gear)	Manufacture in-house using purchased materials. Utilize laser cutter and machine shop in bldg. 98C
1/13/20	1/17/20	Weight/center of mass test and assembly test	Weigh in machine shop. Balancing COM test kit and assembly box are available in bldg. 98C.
1/13/20	1/17/20	Conduct drop test	Grass field and yardstick needed for drop test
1/20/20	1/24/20	Re-calculate thrust and lift given exact weight and COM	Use E-Calc software to program exact dimensions and weight to find true thrust and lift desired
1/20/20	1/24/20	Conduct propeller thrust test	Static thrust test in Dr. Schafer's lab
1/27/20	2/7/20	Fabricate and install plane drive mechanisms	Drive materials, base plane, mounting materials, and bldg. 98C needed to install drive
1/27/20	2/7/20	Fabricate and install plane control mechanisms	Control materials, base plane, mounting materials, and bldg. 98C needed to install servos and linkages
2/10/20	2/14/20	Conduct ground check and flight test	Complete plane assembly, safety equipment, and open field (South Fields)
2/17/20	2/28/20	Evaluate design based on flight test and make changes	E-Calc software, research articles, extra materials, Dr. Tester, and bldg. 98C are required for design iteration
3/2/20	3/13/20	Finalize design and prepare for competition	E-Calc software, extra materials ($200), bldg. 98C, and the south fields are needed for design finalization

As shown in the implementation plan, the only costs associated with implementing the design are in purchasing the complete bill of materials and purchasing any extra materials needed for design iteration. All fabrication, installation, and testing will be conducted in-house at NAU for zero cost. Thus, the total implementation cost is $675, assuming $200 for extra materials and $475 for BOM materials. The complete bill of materials is provided in Appendix Table C1. When factoring in registration expenses of $1100, the total project cost becomes $1775. When compared to the $2000 budget, this leaves an extra

$225 for unforeseen expenses.

With the implementation plan in place, the CAD model provides a basic understanding of what the plane will look like. The current-state CAD includes the drive, fuselage, wings, and landing gear subassemblies. However, CAD is missing control components: namely the ailerons, control horns, push/pull rods, and servo motors. Furthermore, the mounting hardware for the payload and the fuselage cover material are not included. The final assembly for the fall semester is shown below in Figure 32. The exploded view of the assembly is provided in Figure 33.

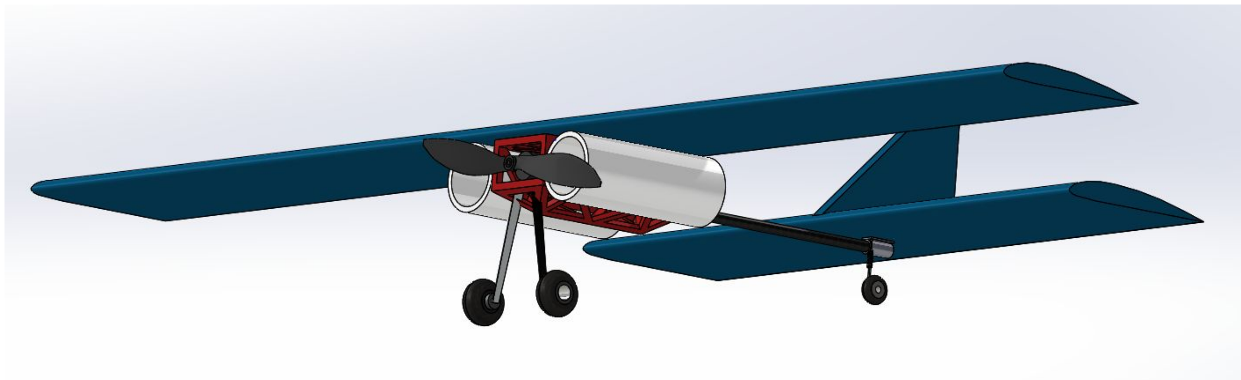

Figure 32: Final CAD Assembly Fall Semester

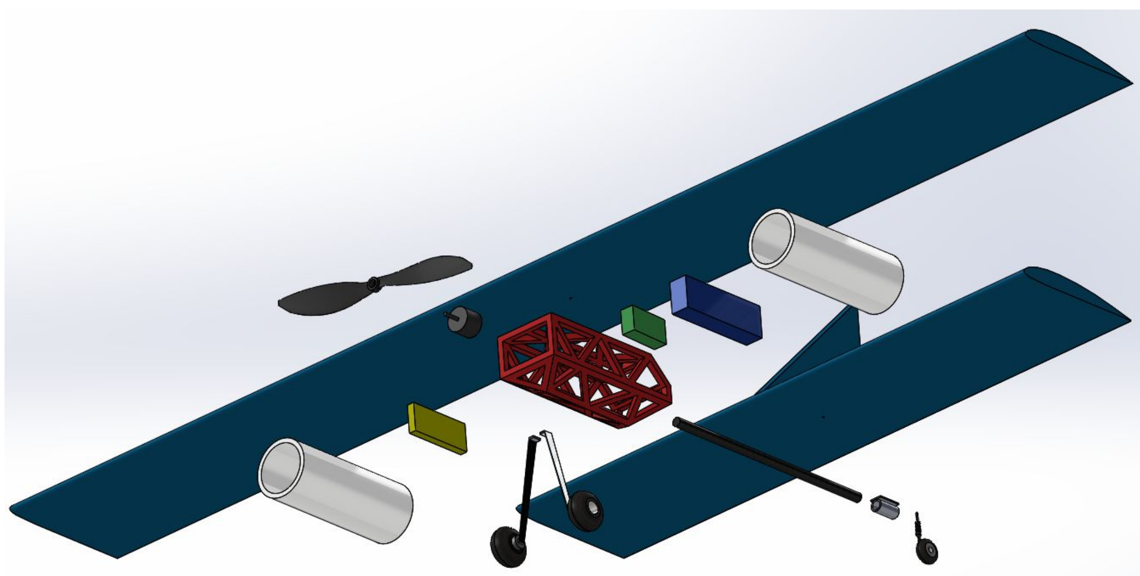

Figure 33: Final CAD Exploded View Fall Semester

7 IMPLEMENTATION – Second Semester

7.1 Manufacturing

Prototyping

The team created one minor non-functional prototype for the plane to further understand the dimensions of the plane to be able to fit it inside the box used in competition. The prototype was constructed out of materials including an abs fuselage, cardboard wings, and a wooden dowel in place of the carbon fiber rod as shown in Figure 34 below.

Figure 34: Prototype

The prototype was able to bring up many problems with our design including how to fasten components like the fuselage and wings with something other than duct tape.

Manufacturing Tasks

For the manufacturing of the plane you can see in Table 7 each of the implementation tasks followed to build the plane.

Table 7: Manufacturing Tasks

Task	Description	Team Member Assigned
Purchases	Purchasing all materials and keep all	All team members

	invoices for later reimbursement	
Wing ribs	Laser cut balsa wood into Clark Y airfoil profile	Zach: G code Corbin/Eli: Laser cutting
Wing frame segments	Connect ribs using ¼ inch wooden dowels	Eli/Corbin
Ailerons/Elevator	Trim ends of wing sections and pin ailerons/elevator and glue servo and control horns in place connected with push pull rods	Ailerons: All team members Elevator: Corbin
Fuselage	Using solidworks 3D model fuselage to be able to fit drive components; motor, ESC, Battery, and receiver which are all held in place using velcro and motor mount	Solidworks: Zach
Mount wings to fuselage/empennage	Using nuts and bolts connect base plate of center members of	All team members
Mount fuselage/empennage to carbon fiber rod	Drill holes through shaft collar at rear of fuselage and front of empennage with carbon fiber rod in place and pin using nuts and bolts	Eli/Zach
Landing gear	Bolt front landing gear with two bolts to bottom of fuselage and bolt rear steerable landing gear to empennage connector with servo embedded in empennage connector	All team members
Rudder	Cut vertical stabilizer & rudder profile; attach both using a hinge, glue servo and control horn in place	Eli/Corbin
Controller Setup	Solder ESC and motor and connect ESC to both battery and receiver. Set up controller to actuate servo motors	Corbin/Zach
Monokote	Wrap the wing sections with monokote using sealing iron and heat gun to remove wrinkles	All team members

The manufacturing processes included; laser cutting, 3D printing, wood gluing, and the use of dremels, drill presses, vertical band saws, and heat guns. The process of manufacturing the plane took about two weeks with each team member working for an average of two hours a day in the machine shop on NAU's campus.

7.2 Design Changes

With any design, the first iteration of components almost always are going to go through various changes. For the rib design, the team did not initially realize that wiring was going to have to run from the servo motors to the receiver through the wing. With the use of a dremel the team was able to create holes for the wiring to pass through as shown in Figure 35.

Figure 35: Original wing rib to modified rib to allow wiring to pass through

Another design change that had to be made was the team's rudder design. Initially the team was using duct tape to act as a hinge. This duct tape design was helpful when seeing the actuation of the rudder on the ground but for in-flight controls it did not seem like a reliable design. The team ended up using an actual hinge for the rudder and also included 3D printed tabs to fasten the vertical stabilizer to the empennage as shown in Figure 36.

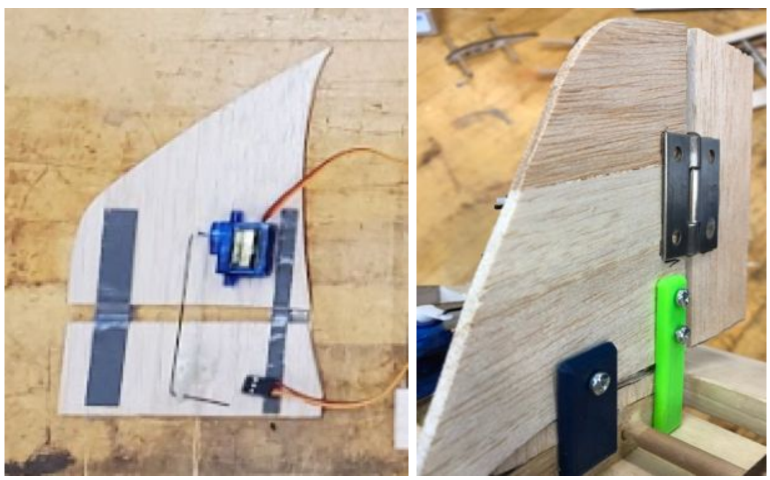

Figure 36: Original rudder to modified rudder with hinge and 3D printed tabs

The fuselage also went through multiple iterations. Realizing that the lightweight design, as shown on the left of Figure 37, was weak after breaking it in the prototyping stage as well as realizing there was not a proper surface to mount the carbon fiber rod the fuselage a new iteration was necessary. To alleviate these problems, the fuselage was updated to a box design with a shaft collar as shown on the right of Figure 37.

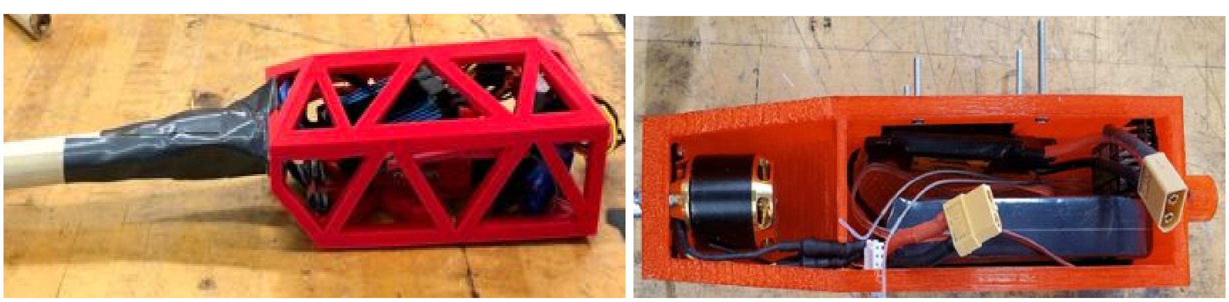

Figure 37: Original rudder to modified rudder with hinge and 3D printed tabs

The last design change the team encountered was updating the empennage connector which was used to fasten the empennage to the carbon fiber rod. As you can see to the left Figure 38, the original iteration used a 3D printed shaft collar between two sheets of balsa. This design proved to allow some vibration in the rear of the plane. To stiffen the design the empennage connector was composed entirely of ABS as shown to the right of Figure 38.

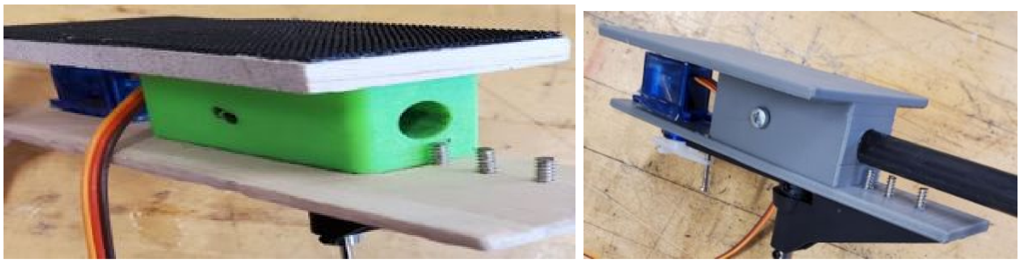

Figure 38: Original rudder to modified rudder with hinge and 3D printed tabs

8 Risk Analysis and Mitigation

The risk analysis and mitigation is pertinent in any engineering project. It allows the group to perform more efficiently in the final result and when performed properly can withstand conditions that are unexpected. If the material or component of the design fails during the testing procedures the team must create a solution to reduce the risk of that part failing before the competition. If risk analysis and mitigation does not occur during the design process than when that component fails there will be no solution to that problem. The overall benefit of performing a risk analysis and mitigation is to maximize the progress rather than the digress in the manufacturing stage; this will also minimize the amount of materials that are purchased/used.

The potential failures in our project range from buckling to fracturing and then to multiple wiring connection failures. The designed aircraft is not a large object; it is a fairly small device that must be able to withstand its own weight, but maintain flight. The small components of the aircraft: wings, propeller, landing gear are very prone to failure because of the material properties and the result of the external force that is applied. We will mitigate the testing procedures by selecting the appropriate materials that will withstand the desired force, stress, and strain, but are also cost efficient.

8.1 Critical Failures

8.1.1 Potential Critical Failure 1: Frame of Landing Gear

The top potential failure occurs in the frame of the landing gear; this occurs when the strength of the aluminum alloy fails and buckles when the aircraft lands. This failure can simply be caused by the stress and strain of the material itself. If these aluminum connectors cannot withstand the force of the aircraft landing then buckling will occur. This failure can be mitigated by testing the material of the landing gear before constructing the finalized design. The RPN is 120 and this is higher than all other potential failures because of the occurrence factor; based on previous designs, due to benchmarking, the frame of the landing gear fails more often than any other component.

8.1.2 Potential Critical Failure 2: Motor in the Drive system

The next potential failure is the motor in the drive system and this is due to improper discharge of voltage from the battery. The cause of this is due to the motor being too powerful. The detection factor is high because it is hard to detect the discharge of the battery to the motor. There are no physical observations that can be used to determine whether or not there is a failure. The RPN is 105, which is the second highest.

8.1.3 Potential Critical Failure 3: Propeller - Landing Gear

The propeller in terms of landing gear can fail if the propeller comes into direct contact with the ground before the landing gear. This coincides with the first failure; if the frame buckles then the propeller will break upon impact. The severity of this failure is high because there will be two main components of the aircraft that will fail. The RPN is 100, with the severity, occurrence, and detection to be 5, 5, and 4 respectively.

8.1.4 Potential Critical Failure 4: Ailerons - Wings

The ailerons are an important subsystem to the aircraft design because it steers and turns the aircraft. The wiring from the servo motor to the ailerons systems must work appropriately in order for the aircraft to turn. The cause of this failure would be assembly/user error. The team would test the ailerons before the initial flight to be sure that the wings function properly.

8.1.5 Potential Critical Failure 5: Rudder - Wings

The rudder is another component that steers the aircraft, but it performs this is the tail of the aircraft. This failure is identical to the failure of the ailerons because it is due to the manufacturing of the wiring system from the servo motor. Both the rudder and ailerons have a 96 RPN.

8.1.6 Potential Critical Failure 6: Battery - Drive

The battery is an essential component to the aircrafts design because it powers the propeller and the servo motor. If the battery does not comply with the motor or servo motor then there is a potential of an improper discharge. The detection factor is the highest for this failure because the battery will be over exerted or work improperly in a flight test. The only resolution is to test the battery with the proper electrical components and make sure the battery does not overcharge.

8.1.7 Potential Critical Failure 7: Main Cabin Landing Gear - Fuselage

The landing gear connection to the main cabin (fuselage) would be due to a fastener failure. As long as the fasteners work initially the only concern would be tolerance buildup. If testing the aircraft so many times can affect the fastener strength over a period of time. The RPN is not too high at a value of 48, which the ideal failure RPN is 30. In order to mitigate this failure is to double check the fasteners that contribute to the landing gear.

8.1.8 Potential Critical Failure 8: Propeller - Drive

The propeller is one of the most critical components of the aircraft, but it is the most exchangeable part because the propellers are so readily available. There is still a potential failure that the propeller might crack or fracture, and the cause of this is due to tolerance buildup. If the propeller begins to show any sign of ware then it will be evaluated and tested to see if the propeller needs to be replaced.

8.1.9 Potential Critical Failure 9: Rear Tail - Wings

The rear tail or the empennage is critical for flight. 70-80% of the weight of the aircraft is in the front or the nose of the plane. This means that the rest of the weight is in the rear of the plane. The potential failure for the empennage would be that cracks will occur. This is due to tolerance buildup, but in order to mitigate this failure the team would need to document how the rear tail performs and how the structure is impacted after each flight test. The last two potential failures have a relatively low RPN of 48.

8.1.10 Potential Critical Failure 10: Tail Dragger and Front Landing Gear

The tenth and final critical failure mode is the landing gear in its entirety to fail during landing. The cause of this is due to the fracture of the landing components and/or the flexion of the components laterally. This is dependent on how 'soft' landing is because the more force that is exerted vertically downward the more weight the landing gear must be able to hold. This critical failure's RPN is 45, which is a nice value based on or target value of 30. We must test the landing gear appropriately to feel confident that the landing gear will remain intact.

8.2 Risks and Trade-offs Analysis

The critical failures that were observed and calculated were based upon the four systems: drive, fuselage, wings, and landing gear. The majority of the failures do correlate to one another because there are so few components in this aircraft. All of the ailerons, rudder, and propeller mechanisms are based upon the battery and drive system. If there is an issue with the wiring of the aircraft then both the ailerons and rudder will not work properly. Besides the potential failure of the propeller cracking, the failure of the propeller is based upon the motor, drive, or the landing gear buckling or flexing. The overall mitigation would be to perform flight checks before each trial and during the testing procedures to ensure that every potential failure will be accounted for and observed by all the members of the team. The failures for the landing gear and wings are dictated by the materials that the team will use. If the testing procedures are performed properly then the analysis of the overall subsystem will be able to be analyzed through small checks and observations before the trial period. In regards to the risk and tradeoff analysis, the components that are readily available and replaceable are the propeller, battery, and parts of the landing gear assembly, because these components are cheap and available there is very little severity to the system, but the occurrence is a higher value, so in the end the risks and trade-offs are taken into account.

9 TESTING

In Section 2, the customer requirements (CRs) for the project were established using the SAE Aero Micro 2020 competition rulebook [1]. Furthermore, the engineering requirements (ERs) for the project were established to evaluate the CRs. Benchmarked data was used to provide a rationale for a target design value and target tolerance for each ER [25,26]. To ensure project success, each ER was proven to be met through testing or purchasing. Table 8 below shows the complete list of ERs, their target values, if the requirement was met, and whether or not testing was required to meet the ER.

Table 8: Engineering Requirements

Engineering Requirements	Target	Tolerance (+-)	Target and Tolerance Rationale	Requirement Met? (Y/N)	Test Required? (Y/N)
Control Frequency (GHz)	2.4	0.1	Exact competition requirement	Yes	No
Motor Power (Watts)	350	50	Power limited by 2200 mAh	Yes	No

			battery		
Total Weight (lbs)	5	1.5	Benchmarked weights approx. 4-5 pounds [25,26]	Yes	Yes
Assembly Time (min)	2	0.5	Competition requires assembly under 3 minutes	Yes	Yes
Battery Capacity (mAh)	1000	250	Optimize weight, max battery capacity 2200 mAh	Yes	No
Storage Volume (in^3)	72.3	20	Calculated for 2-lb payload given PVC density	N/A	No
Storage Length (inch)	16.3	5	Calculated for 2-lb payload given PVC volume	N/A	No
Current (Amperes)	15	5	Benchmarked value for aero micro planes [25,26]	Yes	No
Launch Angle (deg)	5	1.5	Benchmarked value [25,26]	N/A	No
Launch Acceleration (ft/s^2)	1.3	0.3	Benchmarked average overhand acceleration [25,26]	N/A	No
Propeller Velocity (m/sec)	Varies	Varies	Variable motor rpm	N/A	No
Motor Speed (rpm)	Varies	Varies	Variable motor rpm	N/A	No
Lift (lb)	2	0.5	Benchmarked value [25,26]	Yes	No
Thrust (lb)	3	0.5	Benchmarked value [25,26]	Yes	Yes
Cost ($)	550	100	Calculated given budget and prototype materials	Yes	No
Frame Yield Strength (psi)	145	15	Known yield strength of balsa wood	Yes	No

Shown above in Table 8, all of the engineering requirements were satisfied through either purchasing or testing. Some of the original design requirements were ambiguous or did not apply to the project once the manufacturing had finished. Thus, these ambiguous requirements shown in orange did not need to be tested or were not relevant to the success of the design. The ambiguous requirements included storage volume, storage length, launch angle, launch acceleration, propeller velocity, and motor speed.

Also shown above in Table 8 are the engineering requirements that were met through purchasing. The complete list of purchased parts is shown in the Bill of Materials in Appendix C1. The requirements met through purchasing are shown in green and include control frequency, motor power, battery capacity, current, lift, cost, and frame yield strength. The 2.4 GHz control frequency target was met by purchasing a 2.4 GHz controller and receiver. Next, the 300W motor power target was met/exceeded by purchasing an 800W max motor. Third, the 1000 mAh battery capacity target was met/exceeded by purchasing a 1800 mAh battery. Fourth, the 15A current target was met by purchasing a battery with a 70C max discharge rate. Fifth, the 2 pound lift requirement was met through assuming a speed of 30 mph given the tested thrust. Sixth, the cost target of $550 was met by having a total cost of $666. Finally, the frame yield strength target of 145 MPa was met by using balsa wood for the frame.

Lastly shown above in Table 9, the three rows of ERs highlighted in blue required experimental data to prove the ER was satisfied within the design. These three ERs include total weight, assembly time, and thrust. Two other experimental tests were conducted for the center of gravity and overall flight test. The exact testing procedures for each test are described in detail above in Section 3. The results for each of the experimental tests are shown below in Table 9.

Table 9: Testing Results

Test	**Result**
Assembly	Assembly time = 2 min 36 sec
Center of Gravity	CG = 5.5" behind wing tip
Weight	Weight = 2.07 lbs
Thrust	Max Thrust = 30 oz at 75% throttle
Flight	Crash upon takeoff

Thus, all of the non-ambiguous project ERs were proven to be met through either direct purchasing or testing. Furthermore, the flight and center of gravity tests were not successful, but these were not engineering requirements, so the data for each does not affect the success of meeting each ER. The results of the experimental tests negatively affected the overall flight performance, such as the center of gravity being too far back from the wing tip. The implications of the center of gravity and flight test are discussed in detail below in sections 10 and 11. Thus, the results of the flight test yielded future work and conclusions for next years' competition.

10 FUTURE WORK

After taking the aircraft for a test flight the team was not successful in flying or landing the plane. There were some components that broke due to a crash landing and some components that need to be modified to ensure a successful flight and landing. One of the most obvious adjustments that the team found was necessary for successful flight was to correct the center of gravity because the plane was tail heavy and performed a back loop. Other components that broke due to the crash and needed to be reconstructed included redesigning; fuselage rod connector, flange-shaped rear empennage connector to hourglass shape, and rear landing gear. Repair Rudder and left wing segment; we will also need to repair the center wing base plate (bolted connection to fuselage). After each of these components have their adjustments made, another flight test will be performed to see whether or not more modifications will have to be made.

11 CONCLUSIONS

A capstone project should be applied to the bigger picture in this large engineering world; that is what the SAE program wants to implement, a mindset to create something that will potentially benefit the world. The SAE Aero Micro capstone project has many applications such as being used as SUAVs in the military or for NASA, but these ideas can be applied to other devices outside of the SAE program. For our capstone project the aircraft is devised into five separate subsystems: wings, fuselage, landing gear, propulsion, and control mechanisms. All of the subsystems were selected through different engineering methods, but once the team decided upon the designs of each subsystem then the next step was to manufacture these components, while adhering to all of the engineering requirements. After six weeks of manufacturing the testing phase began because the aircraft has a weight limit, a volume capacity, and of course, it must fly. The aircraft complies with all the engineering requirements, so the final challenge that the team must strive for is to maintain flight. In the initial flight test, we hand launched the aircraft and it crashed but what repairable. The final flight test achieved a greater distance, but crashed, fracturing the fuselage. The team has later revised a beneficial plan that future Aero Micro teams can use.

11.1 Contributors to Project Success

The purpose of our team stated in the team charter is as follows:

> "This SAE Aero Micro design team seeks to represent NAU in good standing at the undergraduate research symposium on April 24th, 2020. Our team's purpose is to gain a deeper understanding of engineering research and design during the capstone project, while showcasing engineering abilities gained during the undergraduate progression."

Our team successfully completed our purpose during the fall semester. The team's primary focus was to represent NAU in good standing at UGRADS, and at the end of the fall 2019 semester, our team was on track for presenting at UGRADS. In order to achieve our primary focus, the team's purpose was to gain a deeper understanding of engineering research and design during the fall semester. Through individual learning exercises and technical analyses, we successfully gained deeper knowledge for engineering research and design. Examples of self-learning and technical analysis include finite element analysis (FEA) and computational fluid dynamics (CFD). Finally, by applying previous knowledge and learning new skills, we successfully prepared our team to showcase our engineering abilities at UGRADS.

Next, the goals of our team stated in the team charter are as follows:

> "The goals that our team has agreed on are to design and manufacture a functioning aircraft that abides by the rules of the competition. The quality goals are to meet requirements such as Customer Needs and SAE Competition Requirements. The manufacturing goals are to construct the plane within budget, while also demonstrating an ethical design that does not endanger others."

Most of the goals stated in the team charter are in regards to manufacture, which did not take place in ME 486C. However, our design from ME 476C successfully meets the rules of competition and customer needs. Furthermore, our design strictly adheres to the budget and safety concerns. Thus, upon the manufacture of our Fall 2019 design, the plane will also meet the manufacturing goals stated in the team charter.

The four major ground rules set in the team charter are for each team member to attend all meetings, communicate in a timely manner, to contribute fairly, and complete his share of the work. These ground rules were met throughout the semester and therefore contributed to the overall success of the project. The most important ground rules were for each teammate to contribute fairly and complete their work. Without exception, these two ground rules were met during ME 476C. As a direct result, the team completed all reports and presentations successfully.

The main coping strategy to avoid the barriers to success in the team charter was simply to communicate any issues. This coping strategy was used effectively throughout the semester. Rather than the entire team experiencing problems in ME 476C, it was often one person. When this person communicated their problems, the team always solved the issue.

When it came to aspects of project performance such as time management, the team was able to always have a finished project the night before the due date for reports and presentations. Zach was also able to run meetings smoothly by always informing other teammates of what was going to be covered in the meeting as well as having action items for each team member to accomplish for the upcoming meeting. Accompanying the great time management skills, the team also was able to submit quality reports by having each of the team members read over and edit before submission. This did not only help with grammar errors and understandable writing but also kept the team up to date on other members parts of the project.

11.2 Opportunities/areas for improvement

In any engineering problem or manufacturing team there will be difficulties that the group must handle, this could be due to lack of understanding, lack of cooperation, among various other factors. Throughout the semester, there were many individual problems and group problems that surfaced. This section will cover what difficulties the team as a whole had to address during the semester and why did those problems occur.

The SAE Micro Aero rules are different each year, so benchmarking because a task because were needed to compare the design that we created and compare it to designs that had several modifications because of previous rules. For example, in 2015 the SAE Micro Aero teams aircraft was required to fit into a cylindrical tube, but now our aircraft must fit into a box that is 12x13x4 cubed inches. This can create massive differences in the final result. We combatted this specific example by examining the drive components (i.e. prop, motor, esc, and battery) because the thrust generated by these components were the most critical engineering requirements for our design. The most significant problem that the team needed to handle was the uncertainty behind the SAE guidelines. We were never informed whether or not we were competing based on the waitlist. No emails or notifications were sent stating the status of our registration as a team. We understood that we would not be representing NAU if we did not attend the competition, but we did not expect the level of dubiety that registering for the competition would have on us.

From the start of the semester the group created a google drive and were able to communicate very effectively. We later learned that separating certain documents, creating folders, and labeling the documents is the most efficient way of becoming organized. For example, the creation of Presentation 1 consisted of QFD charts, engineering requirements, benchmarking, among other documents that we would need to copy for Presentation 2 (another folder in the drive). When a task begins it is very simple and not overwhelming, but after more developments continue that task is complicated. Being organized in a google drive, whether that is purchase receipts, CAD models, or presentations can be very forward thinking into benefiting the team later on.

In order to manufacture a fixed wing aircraft the members must be proficient in CAD, such solidworks, and with that software students must be able to do analyses as well. These analyses can be as simple as whether or not the parts with become a full assembly or as advanced as a Finite Element Analysis. Members of the group are required to understand the mathematics of lift, thrust, and drag. These variables dictate whether the aircraft will maintain an angle of attack, and if not it will lose control. The group gained access to the machine shop in 98C, which is critical to the manufacturing of this capstone project.

When it came to project performance team had a few areas to improve upon including ordering parts, creating prototypes, and solutions for fastening parts of the plane. The team procrastinated ordering parts during the first semester. By doing this the team is left without being able to begin manufacturing until the parts come in about two weeks after the beginning of the spring semester. When it came to prototyping the team was only able to accomplish physically seeing the dimensions of the plane and how it would fit in the box as well which is helpful, but it does not help with the success of flying the aircraft. One of the biggest challenges that the team has faced is to fasten each of the components such as the wings and fuselage to each other. This is difficult because these components are made of different materials so they cannot be welded like you would with steel or aluminum. The team has left that solution to be solved during this semester leaving little time to complete the task.

The team used different methodologies and practices to arrive at our final design with most of these methods being successful and others not exactly accomplishing much. For our design selection the team came up with three different designs for our five different subsystems which included the wings, landing gear, propulsion, maneuvering devices, and the fuselage design. Three different final design concepts were created but the problem the team had with this method of selection is that we already had in our heads what would be the best design and deemed this process useless. An improvement that the team should have done to speed up the process of designing the plane would have been creating the design of the wings, fuselage, and empennage before designing the drive system. The team selected the drive design prior to designing the plane itself which made calculations somewhat backwards and the team had to retrace our steps elongating our process.

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13 APPENDICES

13.1 Appendix A: House of Quality

Table A1: QFD

	Control Frequency (GHz)	Motor Power (Watts)	Total Weight (lbs)	Assembly Time (min)	Battery Capacity (mAh)	Storage Volume (in^3)	Storage Length (inch)	Current (Amperes)	Launch Angle (deg)	Launch Acceleration (ft/s^2)	Motor Velocity (degrees/sec)	Motor Speed (rpm)	Lift (lb)	Thrust (lb)	Cost ($)
Control Frequency (GHz)															
Motor Power (Watts)	1														
Total Weight (lbs)	1	9													
Assembly Time (min)	1	3	1												
Battery Capacity (mAh)	1	3	1	3											
Storage Volume (in^3)	1	1	3	1	3										
Storage Length (inch)	1	1	3	1	1	9									
Current (Amperes)	1	3	1	1	9	1	1								
Launch Angle (deg)	1	1	1	1	1	1	1	1							
Launch Acceleration (ft/s^2)	3	9	9	3	1	9	3	3	1						
Motor Velocity (degrees/sec)	1	1	3	3	1	3	3	1	3	1					
Motor Speed (rpm)	3	9	1	3	3	1	1	3	1	1	1				
Lift (lb)	1	9	3	1	1	3	3	1	9	9	1	1			
Thrust (lb)	1	9	9	1	1	3	9	1	9	9	1	3	9		
Cost ($)	1	3	9	3	9	1	1	1	1	3	1	1	1	1	
Yield Strength (psi)	1	1	9	1	1	3	3	1	1	9	1	1	1	1	3

Customer Requirements	Customer Weights	Control Frequency (GHz)	Motor Power (Watts)	Total Weight (lbs)	Assembly Time (min)	Battery Capacity (mAh)	Storage Volume (in^3)	Storage Length (inch)	Current (Amperes)	Launch Angle (deg)	Launch Acceleration (ft/s^2)	Motor Velocity (degrees/sec)	Motor Speed (rpm)	Lift (lb)	Thrust (lb)	Cost ($)	Yield Strength (psi)
Gross Weight Limit (10 lbs)	5	1	3	9	1	1	3	3	1	1	1	1	1	1	9	3	3
In-flight radio control (2.4 GHz) w/ fail safe	5	9	1	1	3	1	1	1	3	1	1	3	1	1	1	3	1
wheeled landing gear steering mechanism	4	1	1	1	1	1	1	9	1	3	1	1	1	1	1	3	3
Payload cannot aid frame integrlty	3	1	1	9	1	1	9	3	1	1	1	1	1	1	3	1	9
Payload attached w/ metal hardware	3	1	1	9	1	1	3	3	1	1	1	1	1	1	3	1	1
Electric motor/Servo	4	3	9	9	1	9	1	1	9	1	9	9	9	9	9	3	3
Red arming plug	5	1	9	1	1	1	1	1	9	1	1	1	1	9	9	1	1
3 cell 2200mAh lithium polymer battery	5	1	9	9	1	9	9	3	9	1	1	1	1	3	3	3	1
gyroscopic assist allowed	2	1	1	3	1	1	3	3	1	9	1	9	1	1	1	3	3
2" dia schedule 40 ASTM D1785 PVC Payload	4	1	1	9	1	1	9	9	1	1	1	1	1	1	9	1	3
Hand launch	4	1	9	9	3	1	1	9	1	9	9	9	9	9	9	1	3
12.125 in X 3.625 in X 13.875 in container	5	1	1	3	9	1	9	9	1	1	1	1	1	3	3	1	3
3 min assembly	4	1	1	3	9	1	3	3	1	1	1	1	1	1	1	1	9
1 min to energize, check, and launch	4	1	1	3	9	1	1	3	9	1	1	1	1	1	1	1	3
fly for 400-foot leg of a flight circuit	3	1	9	9	3	3	9	9	1	9	3	3	9	3	3	1	1
cost within budget	3	3	9	9	1	3	1	3	1	1	9	1	3	9	9	9	3
durable and robust design	4	1	3	9	1	1	3	3	1	1	3	1	1	3	1	9	9
reliable design	5	9	9	3	3	9	3	9	9	9	9	3	3	9	9	1	3
safe to operate	5	9	9	1	1	9	1	3	3	1	3	1	1	3	3	1	1
Absolute Technical Importance		211	367	421	215	241	283	353	281	197	229	183	181	289	365	183	245
Relative Technical Importance		12	2	1	11	9	6	4	7	13	10	15	16	5	3	14	8
Target Value		2.4	350	5	2	1000	72.3	16.3	15	5	1.3	N/A	N/A	2	3	550	145
Tolerance(+-)		0.1	50	1.5	0.5	250	20	5	5	1.5	0.3	N/A	N/A	0.5	0.5	100	15

13.2 Appendix B: Design Charts

Table B1: Pugh Chart

Design Criteria (CR's)	Design Alternatives Datum (2018-2019)	1	2	3
Gross Weight Limit (10 lbs)	DATUM	+	+	+
In-flight radio control (2.4 GHz) w/ fail safe		+	+	+
wheeled landing gear steering mechanism		S	S	S
Payload cannot aid frame integrlty		S	S	S
Payload attached w/ metal hardware		S	S	S
Electric motor/Servo		S	S	S
Red arming plug		S	S	S
3 cell 2200mAh lithium polymer battery		S	S	S
gyroscopic assist allowed		S	S	S
ASTM D1785 PVC Payload weights		S	S	S
Hand launch		S	S	S
12.125 in X 3.625 in X 13.875 in container		S	S	S
3 min assembly		+	S	-
1 min to energize, check, and launch		S	S	S
fly for 400-foot leg of a flight circuit		+	S	S
cost within budget		S	S	S
durable and robust design		+	+	+
reliable design		+	S	-
safe to operate		S	S	S
TOTAL	(+)	6	3	3
	S	13	16	14
	(-)	0	0	2

Table B2: Decision Matrix

Criteria (ERs)	Weight (%)	Design 1 Score(1-5)	Weighted Score	Design 2 Score(1-5)	Weight Score	Design 3 Score (1-5)	Weighted Score
Frequency (GHz)	5	5	25	5	25	5	25
Power (Watts)	9	5	45	5	45	5	45
Weight (lbs)	8	3	24	4	32	4	32
Time (seconds)	5	4	20	3	15	3	15
Capacity (mAh)	4	3	12	3	12	3	12
Storage Volume (in^3)	5	3	15	5	25	4	20
Length (inch)	4	4	16	4	16	4	16
Current (Amperes)	4	5	20	5	20	5	20
Angle (deg)	6	4	24	4	24	4	24
Acceleration (feet/second^2)	7	5	35	3	21	3	21
Angular Velocity (degrees/sec)	5	4	20	3	15	4	20
Angular Speed (rpm)	8	4	32	4	32	4	32
Lift (lb)	8	4	32	3	24	4	32
Thrust (lb)	9	5	45	5	45	5	45
Cost ($)	6	5	30	4	24	5	30
Toughness (in*lb/in^2)	7	4	28	5	35	4	28
Total	100		423		410		417

13.3 Appendix C: BOM

Table C1: BOM

Part #	Part Name	Qty	Description	Functions	Cost ($)
1	Luminier Battery	1	Lumenier 1800mAh Lipo Battery	Stores Power	28.81
2	Ovonic Battery	1	Ovonic 2200mAh Lipo Battery	Stores Power	19.64
3	XT-60 Connectors	4	XT-60 connectors battery to ESC	Connects battery wires to speed controller	7.99
4	XT-60 adapter	10	XT-60 to deans plug adapter	Connects deans battery plug to xt60	10.55
5	Jewelry box hinges	10	Stainless steel butt hinges	Connects rudder to tail wing	11.40
6	Heavy duty velcro	4	Heavy duty j-hook velcro	1st attempt at wing connections	5.36
7	Propeller adapter	4	Mulit-diameter, dome-shaped linkage	Connects 3.5mm motor shaft to propeller	7.63
8	RayCorp 9x4.7 SF propeller	8	Plastic slowfly propeller	generates thrust	11.99
9	APC 8x4.7 SF propelller	1	Plastic slowfly propeller	generates thrust	5.85
10	Enegitech battery charger	1	Charges LiPo batteries	Recharges energy supply to fly and steer plane	30.02
11	Front landing gear	1	Twin-wheeled A-frame landing gear	Translates flight speed into rotational motion	15.99
12	Tail landing gear	1	single-wheeled, springed landing gear	Translates flight speed into rotational motion	10.19
13	Controller and Reciever	1	FlySky 6-channel RC controller and reciever	Programs speed controller and servo motors	45.00
14	Push-pull rods	10	small diameter steel rods	pushes/pulls control surfaces	9.99
15	Control horns	10	triangle-shaped plastic pieces with holes	Mount to control surface and connect to push/pull rods	7.99
16	Servo motors	10	Small electric motors	Convert electrical energy to rotational motion	25.42
17	Carbon Fiber rod	1	3/8"x48" carbon fiber rod	Connect fuselage to rear connector	39.18
18	Motor mount	1	16mmx19mm steel x-mount	mounts fuselaage frame to motor	7.20
19	Scorpion motor	1	HK-2520-1880KV electric motor	Converts electrical energy into rotational energy	121.99
20	Scorpion ESC	1	Commander 15V 45A speed controller	Powers reciever, programs variable speeds to motor	59.99
21	Scorpion Prop adapter	1	Mulit-diameter, dome-shaped linkage	Connects 3.5mm motor shaft to propeller	8.99
22	ECalc Subscription	1	Online flight calculator	Predicts flight charachteristics given drive components	6.99
23	Fuselage prototype	1	Fuselage frame prototype Fall 2019	Provides visual for housing drive components	8.35
24	Hardware	N/A	M3 machine screws,nuts at various lengths	fastens plane components together	20.00
25	Fuselage Frame 1	1	Square-bodied ABS frame	1st attempt at connecting wing, landing gear, and CF rod	12.62
26	Fuselage Frame 2	1	Square-bodied ABS frame	Final attempt at connecting wing, landing gear, and rod	19.45
27	Rudder tabs	4	Rectangular ABS segments	Connect rear wing to rudder	2.34
28	Rear connector	1	I-beam shaped ABS connector	Connects CF rod to tail wing and rear landing gear	5.59
29	Monokote	2	Thin airfoil material	Conforms to wing rib shape, generates lift	30.00
30	Balsa Sheet	1	Thin balsa sheet to cut out wing ribs	Wing ribs have airfoil profile and generate lift	43.29
31	Monokote Iron Sock	1	Cotton cover for monokote iron	Protects monokote from melting	4.00
32	Monokote Iron	1	Small clothes-iron shaped heat applicator	Heat shrinks monokote to balsa	23.00
			Total Cost:		**666.80**
			Overall Budget:		**2000.00**