SAE Aero (Regular) Competition Team
“Ponderosa Pilots”

Final Report

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2020

PONDEROSA
PILOTS
Northern Arizona University

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DISCLAIMER

EXECUTIVE SUMMARY

The following report will summarize the work and achievements of NAU's 2020 SAE Aero Competition Team (Regular Class). This team has completed a project that has fulfilled the NAU CEIAS capstone requirements of: research, design, analysis, prototyping, testing, and final product completion. This team, the "Ponderosa Pilots," undertook an annual project sponsored by the Society of Automotive Engineers- the Aero Design Competition. As participants in this competition, the team was tasked with the design and manufacture of a small-scale, payload-carrying aircraft. For the 2020 competition, the design challenge was updated to include "oversized payload" (soccer balls), and a shorter runway (100 feet). SAE provided a long rulebook that explained how designs would be scored (a ratio of payload to aircraft size) and documented various requirements and restrictions on size, power, etc.

The Ponderosa Pilots analyzed the scoring equation presented by SAE and determined a unique solution: building the smallest plane possible. Because the new scoring criteria rewards designs for payload capacity *and* small size, our team decided the easiest and most effective way to perform well at competition would be to minimize the size of our aircraft, while still carrying a moderate amount of weight. After preliminary research into aircraft design and aerodynamics, a preliminary design was drawn up. Using various analysis techniques, the design was modified and updated several times over to fully maximize payload capacity while maintaining the smallest size possible. The final design featured a 9.5-pound aircraft with a 60-inch wingspan. It accommodated one soccer ball and an additional 6 pounds of weighted payload.

Through a vigorous testing process that involved the testing of seven different prototypes, the team was able to further optimize their design for ease-of-manufacturing and flight success. Testing remained limited to indoor flights for the majority of this process, and by the time the team was ready to do full-scale, flight circuit testing, SAE announced that they would be cancelling the dynamic competition, instead opting for a "virtual" presentation competition, because of the circumstances surrounding the COVID19 pandemic. However; the Ponderosa Pilots were determined to see their project through, and were able to implement the final design at a private airfield in Maricopa county. This implementation saw the success of the aircraft in several areas: it could carry the expected payload of one soccer ball and 6 pounds of steel weights, it could take off in 100 feet, and it could land within 400 feet. However, the team's design was *not* able to complete a full flight circuit. Many straight-line flights yielded success, but the team found that their aircraft lacked the ability to turn effectively. This, we theorize, is attributed to the windy conditions of our testing environment, the undersizing of the aircraft's control surfaces, and a lack of rigidity in the ailerons.

While the team was disappointed at the turning failure of the design, we are, overall, very proud of the work we've been able to accomplish. Over the course of this project, we've gained valuable knowledge in the fields of aerodynamics and aircraft design, as well as insight into engineering processes such as design analysis and the prototyping process. Not only that, the team has also learned skills such as budget management, teamwork, and professional development. Our aircraft, Pine Patrol One, fulfilled nearly every engineering requirement laid forth at the start of the project, and we feel we would have represented NAU positively in a competition setting. This, combined with the skills and knowledge acquired over the course of the year, leads us to conclude that this project was a success.

ACKNOWLEDGEMENTS

The team would like to give a special thanks to some of the individuals and organizations that have helped us on our journey of aircraft design, manufacturing, and testing. In the early stages of design, we were fortunate to hear the advice of Ben Foster from Raytheon and Dr. Schafer from NAU, both of whom had worked on SAE Aero teams as undergrads. Dr. Schafer was also very courteous in his lending of a static thrust test bed that was used to determine propeller selection. Over the course of the design process for our aircraft, Professor David Willy was a bountiful source of information and advice. As NAU's current Aerodynamics instructor, Prof. Willy was able to explain aerodynamics concepts and point the team towards softwares and analysis techniques that eventually informed the team's final design. Our team was also very fortunate to have a line of communication with last year's Aero team. While their direct help was minimal, the examination of their old design and procedures was instrumental in our process. Finally, when it came time for testing, the team could not have carried on without the support of local airfields. Preliminary testing was done at the Flagstaff Flyers' airfield. We thank them for accommodating us. Final design implementation was done in Maricopa County at the RC Speedworld airfield after the SAE competition was cancelled. Al Pilon and his team were very generous in their offering of their facilities, their expertise, and even their pilots. We highly recommend that next year's Aero team develops a relationship with their organization.

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1 BACKGROUND

1.1 Introduction

The SAE Aero Design competition aims to challenge undergraduate and graduate engineering students to design, manufacture, and test a payload-carrying aircraft. As participants of this competition, this team has designed and constructed an electric, propeller-driven aircraft. This aircraft was ready to represent NAU in the annual SAE competition before its unfortunate cancellation due to the COVID19 pandemic. The objective of this competition was to successfully complete "flights," which encompass take-off, airborne flight, and landing- all while carrying a payload. This payload consists of "oversized payload" (soccer balls), and "regular payload" (weighted plates). Primary stakeholders of this project included the university, the NAU College of Engineering, project sponsors, and the student team members themselves. The importance of the team's project success cannot be understated. The team's participation in the SAE competition (now virtual) will be a representation of the NAU College of Engineering, as well as the university itself. To reflect positively on these stakeholders, the team must be successful. Through many successes and failures, this project has additionally proven to be one of self-enrichment. Not only have team members gained valuable insight into the engineering process, but they have also been subject to lessons about engineering application in the real world, and the consequences of engineering failure.

1.2 Project Description

Following is the original project description provided by SAE.

> *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.The Regular Class is an all-electric class intended to develop a fundamental understanding of aircraft design.* [1]

After the events surrounding the COVID19 pandemic began to unfold, SAE issued the following update:

> *For this competition season, SAE will transition all non-dynamic event participation to a virtual platform for the purpose of maintaining the significant educational components that participation in SAE Collegiate Design Series events provides.* [2]

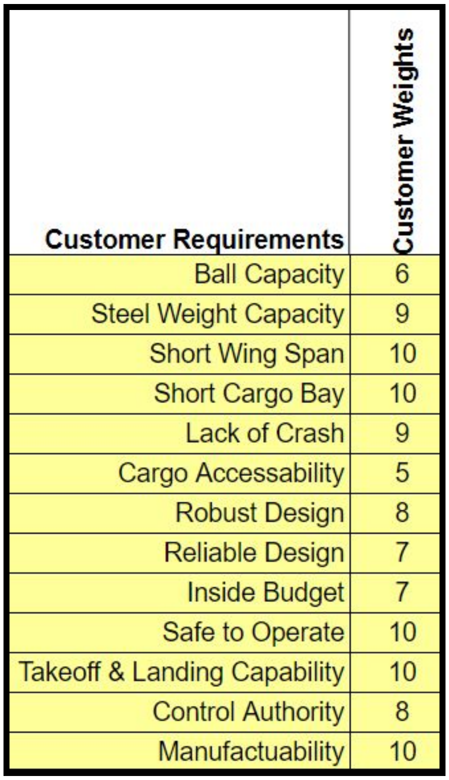
2 REQUIREMENTS

The first item that the team had to complete was to assess the requirements for this project. First, customer requirements were pulled in from class requirements, team goals, and SAE's rulebook. These customer requirements were converted into "Engineering Requirements." These are quantifiable requirements that the team could test and assess for fulfillment. With the above requirements formulated, the team organized them into a Black Box Model, a Functional Model, and a House of Quality. These organizational aids assisted the team in the design of their final product.

2.1 Customer Requirements (CRs)

As mentioned above, the first step in understanding the requirements of this project was to read in requirements from the "customer." In this case, the customer was the SAE Competition first and foremost, but additionally, the class instructor and the team itself. The following section will discuss the customer requirements that the Ponderosa Pilots adhered to, and the "weights" that ranked the importance of each of these requirements. **Table 1** below shows a summarizing table.

Table 1: Customer Requirements & Weights



Customer Requirements	Customer Weights
Ball Capacity	6
Steel Weight Capacity	9
Short Wing Span	10
Short Cargo Bay	10
Lack of Crash	9
Cargo Accessability	5
Robust Design	8
Reliable Design	7
Inside Budget	7
Safe to Operate	10
Takeoff & Landing Capability	10
Control Authority	8
Manufactuability	10

Before this report goes into detail about the specific requirements and weightings, it's important to take a closer look at SAE's scoring equation. This equation, shown below, gives an increase in score with an increase in payload capacity or a *decrease* in aircraft size.

$$FS = Flight\ Score = 120 * \frac{2 * S + W_{steel}}{b\ + L_{cargo}} \tag{1}$$

$S = Number\ of\ Spherical\ Cargo\ Carried\ on\ a\ Flight$

$W_{steel} = Regular\ Boxed\ Cargo\ Weight\ (lbs)$

$b = Aircraft\ Wingspan\ (inches)$

$L_{cargo} = Length\ of\ Cargo\ Bay\ (inches)$

Ball Capacity (6) & Steel Weight Capacity (9)

These are direct objectives of the flight vehicle. While these requirements are directly listed in the flight score, only one of them has high importance- Steel Weight Capacity. This is due to early analysis done by the team that revealed that ball capacity was not worth increasing if it meant increasing the length of the cargo bay. It was found that a one-ball design with a small cabin would score as well, or better, than a five- or ten-ball design with a larger cabin. This is why Ball Capacity is no longer as heavily weighted as it was previously.

Short Wingspan (10) & Short Cargo Bay Length (10)

These two criteria are also directly based on SAE's scoring equation. The team decided to maximize their importance after conducting the analysis that led to our decision to create a small aircraft. The team found that minimizing the size of the aircraft would be more beneficial to our score than maximizing payload. For this reason, requirements based on size were weighted heavily,

Lack of Crash (9)

According to the SAE Rulebook, a crash will result in a massive point deduction. It may also damage the plane beyond repair, rendering it impossible for further flights. These two reasons informs the high importance of this customer requirement.

Cargo Accessibility (5)

The rules state that the team will only receive points for payload that can be unloaded within two minutes. This informed the Customer Need of "Cargo Accessibility." This need has been weighted as moderate since it does not directly affect the end score. As long as the cabin is moderately accessible it will not have a negative impact on the score.

Robust Design (8)

The aircraft needs to be robust to survive unexpected conditions. After researching weather statistics at the competition field, the team found that conditions can vary widely. The aircraft needs to operate amid unexpected conditions in order to score points.

Reliable Design (7)

Reliability was of great importance to the team. Our design needed to be dependable so that we could accurately predict the payload capacity and fly the aircraft without worry of crashing or sustaining irreparable damage.

Inside Budget (7)

While this customer requirement is not explicitly noted by the competition, producing an aircraft to be able to compete to be able to score any points is a key requirement of the ME486C class. Because of this important role it has a high weight value.

Safe to Operate (10)
It is imperative that the aircraft is safe to operate, if the SAE staff deam the craft unsafe it will not be allowed to compete and earn points.

Take-Off and Landing Capability (10)
Take-off and Landing is an integral part of the flight process. It’s a crucial aspect of the competition, and because last year’s team encountered failures in these areas, our team made it a Customer Requirement of maximum importance.

Control Authority (8)
The aircraft must be capable of maneuvering predictably and reliably under varying conditions. This need is shown in the rules. It explains that the vehicle must be able to make a full 360 degree turn in the air before landing in order to obtain points for the payload it carried.

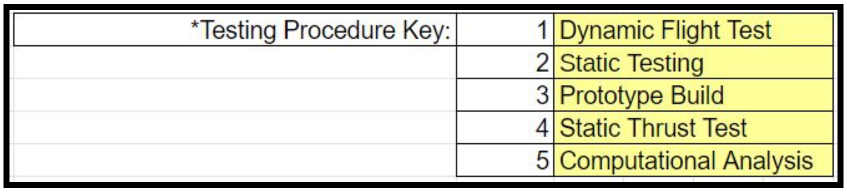
Manufacturability (10)
Manufacturability was a Customer Requirement that was devised by the team ourselves. In order to complete prototype testing and final product manufacturing on a short timeline, the team’s design needed to be highly manufacturable.

2.2 Engineering Requirements (ERs)

Once the above Customer Requirements were compiled, they were re-envisioned as “Engineering Requirements,” items that are quantifiable, and therefore test-able. Summarized in the chart below, these “ER’s” will be discussed along with their target values and how they’ll be tested.

Table 2: Engineering Requirements, Importances, Target Values, Testing Procedures

	Engineering Requirements												
	Weight	Power	Cost	Lift	Low Drag	Ease of Assembly/Repair	Velocity	Turning	Load/Unload Time	Cabin Length	Wing Span	Success Rate	Factor of Safety
Absolute Technical Importance	394	405	341	420	522	190	354	254	193	183	168	368	49
Relative Technical Importance	5	4	8	3	1	10	7	9	11	12	13	6	14
Technical Requirement Units	lbs	Kw	$/Unit	lb	lb	min	mph	rad/s	s	in	in	%	%
Technical Requirement Targets	17	1	500	18	4.23	15	15	0.8	60	8.75	60	95	115
Technical Requirement Tolerence (+-)	2	0	100	3	2.35	5	5	0.01	20	0.5	1	5	2
Testing Procedures*	3	4	3	1, 5	1, 5	1, 3	1, 5	1	2	3	3	1	1, 5



*Testing Procedure Key:	1	Dynamic Flight Test
	2	Static Testing
	3	Prototype Build
	4	Static Thrust Test
	5	Computational Analysis

Weight (lbs) Target Value: 17 lbs
This ER directly correlates to the CR's regarding payload capacity. Benchmarking last year's aircraft which had a wingspan of 10 feet and a loaded weight of about 35 pounds, our team decided the target value for our half-sized plane would be 17 pounds- about half the weight.

Power (kW) Target Value: 1 kW
Power is directly related to Take-off and Landing, which is one of the CR's. Competition rules limit power to 1 kW, so we have designated this value as our target, with no tolerance, as we intend to fly with max power.

Cost (USD) Target Value: 500 USD/unit
This ER correlates to the "Inside Budget" CR. While the budget provided by our sponsor W.L. GORE and Associates was a full $3,000, the team set a target value of $500/plane. This will leave room for the prototyping process and the construction of at least two final products after the $1,100 competition fee is subtracted from the initial budget.

Lift (lb) Target Value: 18 lb
Lift will determine the success of our aircraft across many CR's. Lift will need to be greater than or equal to the weight of the plane in order for it to fly, and we have assigned its target value accordingly.

Low Drag (lb) Target Value: 4.23 lb
This criterion is based off the amount of thrust our plane can generate. In order for the plane to continue on a forward trajectory, its drag will have to be less than or equal to its thrust. The value of 4.23 pounds was assigned after preliminary static thrust testing.

Ease of Assembly / Repair (min) Target Value: 15 min
Ease of Assembly / Repair is measurable in time and is related to the customer need of manufacturability. The time period of 15 min was chosen as the target value as it is the shortest potential time the team will have in between flights.

Velocity (mph) Target Value: 15 mph
The velocity is related to the gliding ratio which increases lift efficiency. Gliding ratio is the coefficient of lift over coefficient of drag. It also is related to the customer need of control authority and lack of crash. Essentially, if the aircraft velocity is close to the wind speed then the craft's intended direction will not be the major component of the aircraft's ground velocity (Ground velocity being the aircraft's velocity relative to the ground). The local average wind in Fort Worth is 11 mph [3] ; therefore it is ideal that the attainable velocity of the aircraft is slightly above this. This criteria is related to the lack of crash because if the pilot does not have control of the ground velocity component, it is more likely that the craft will collide with something.

Turning (rad/s) Target Value: 0.8 rad/s
Turning is also related to control authority. It is another component of control. This turning refers to turning about an axis normal to the ground. This turning target value is derived from the need to turn a full 180 degrees in a reasonable amount of time. At this target value the aircraft should be able to turn around in under 4 seconds. This target value was developed in conversation with the team's pilot, whose

experience informed how quickly an aircraft should be able to turn around.

Load/Unload Time (s) Target Value: 60 s
This engineering requirement directly ties to the customer need of "Cargo Accessibility." The rules state that payload that must be loaded or unloaded in 120 seconds in order to be counted towards the flight score. In an attempt to ensure that this requirement is met, the team designated a target value of 60 seconds.

Cabin Length (in) Target Value: 8.75 in
This ER relates to the CR of "Short Cargo Bay Length." Once the team analyzed possible cargo configurations for scoring potential, it became clear that an ideal design would have a cabin length of one soccer ball, or 8.75 inches.

Wing Span (in) Target Value: 60 in
The wing span should be short to maximize the score but long to maximize the lifting capacity and therefore the score. After planform analysis was conducted with the help of NASA's openVSP software, it was determined that 60 inches was the optimum wingspan for our design challenge.

Success Rate (%) Target Value: 95%

This aircraft needs to be reliable. If you want to analyze how many points your aircraft will be capable of earning, you must also consider how reliably it can earn those points. If the craft can earn 10 points but only earn them 50% of the time, then on average it is really only earning 5 points. This Engineering requirement will be weighed against others to determine if certain design risks are worth it and ties into the reliability customer need.

Factor of Safety (%) Target Value: 115%
This requirement is based on the Customer Needs for Reliability, Robust Design, Lack of Crash and Safe to Operate. The target value is derived from our discussions with our project advisor and faculty advisors who recommended this factor of safety as it still allows for some error but does not conflict too heavily with engineering needs to have the aircraft too heavy.

As mentioned previously, all of these Engineering Requirements were chosen because they could be put to the test. Table ii lists those testing procedures which include Dynamic Flight Testing, Static Testing, Prototype Building, Static Thrust Testing, and Computational Analysis. More detail on these testing procedures will be discussed in Section 3.

2.3 Functional Decomposition

Using functional decomposition aided the team by outlining the main process of the product along with inputs, outputs, and the order by which objectives are accomplished. A black box model helped the team to identify the main process of the device as "transportation of payload" and a functional model outlines the functions of the aircraft from input to output while visually representing the different flows of energy in the system. Because the team's design was well-established at the time that the following models were created, no modifications have been made on the figures. However, as the team moved through the prototyping process, certain elements of the functional decomposition were updated. For example, in an effort to reduce the dry weight of the aircraft, the battery was replaced with a smaller-capacity, lightweight battery. This will affect the "Store Energy" and "Supply Electricity" elements of the Functional Model, but without altering the flow path at all.

2.3.1 Black Box Model

To help the team visualize the main process along with inputs and outputs of this system, a black box model was created. The main process required by the competition is transportation of the payload. Although there are multiple processes, reducing them down to the core function simplifies the understanding of this device.

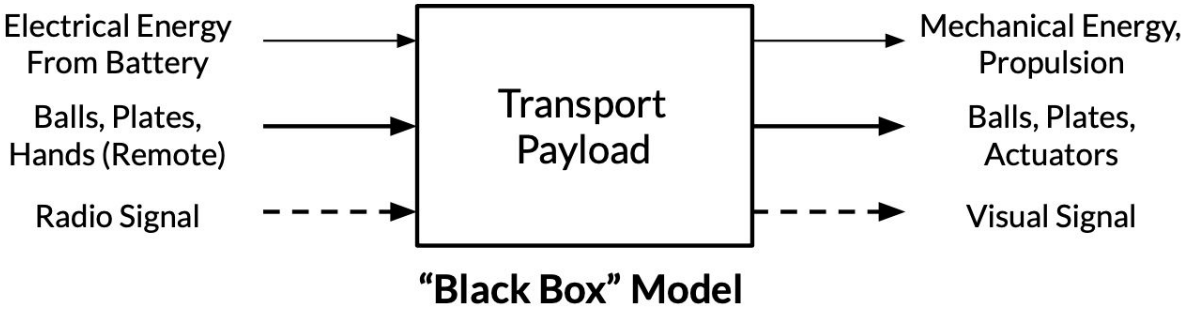


Figure 1: Black Box Model

Because the device in question is a plane, the team initially considered flight to be the main process. Upon further consideration, the team realized that flight was merely the method by which the payload was transported; thus, the main process to consider is the transportation of the payload. Energy input is simply identified as electrical energy from the battery. It is output as mechanical rotational energy that becomes propulsion. Moving forward, material input includes the payload itself: soccer balls and weight plates, as well as hands operating the remote control. Material output is modeled as the payload having been transported along with movement of the actuators. Finally, radio signal is the signal input that helps the main process occur and is output as visual signals such as visual observation of the plane responding to said inputs. Overall, the black box model helped the team realize the main process in tandem with its necessary inputs and outputs.

2.3.2 Functional Model

The below functional model graphically depicts the operations the aircraft performs on the input material, energy and signals to transform them into reactions that are applied to the aircraft to effectively transport payload. The material, energy, and signal flows are represented by bold lines, standard lines, and dashed lines respectively. This model shows how each task interacts with one another. As can be seen, energy from a human hand, electromotive force, and radio signals will be used to operate this design. Movement of the vehicle, heat, and auditory signal will be resultant of the workflow.

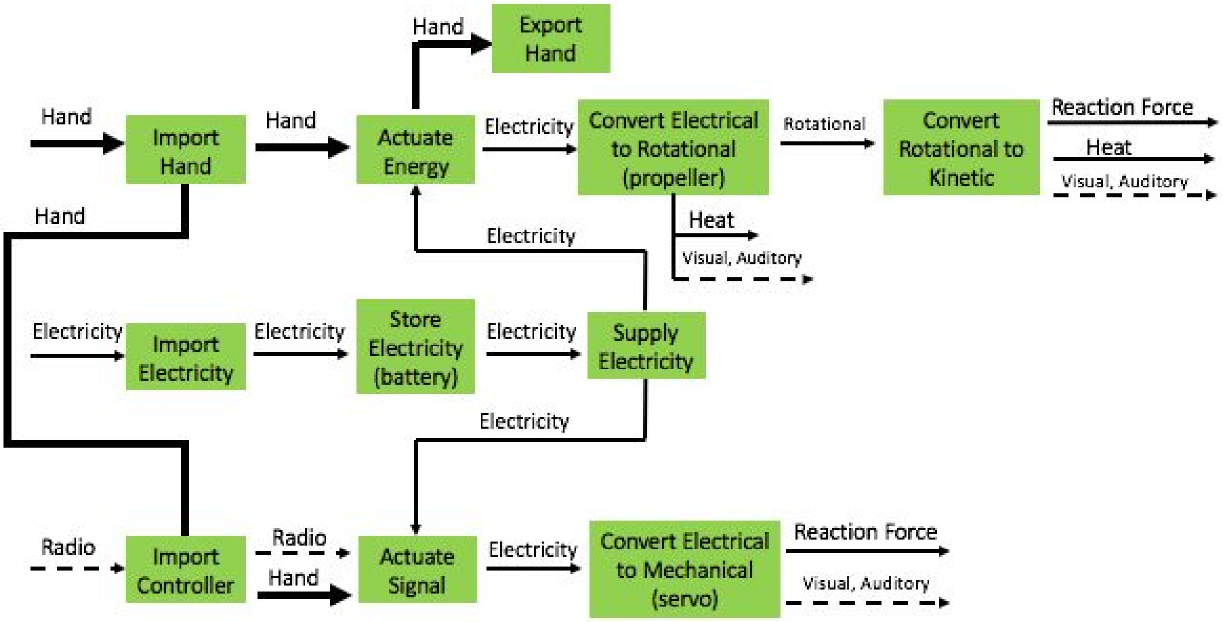


Figure 2: Functional Model

This graphical representation let the team easily visualize and clarify the way input flows are manipulated and converted into desired output flows. By breaking up the process into sub-functions that are easier to change, the overall operation can be more easily modified. Being able to visualize how the different types of energy in use by the aircraft will move through the system greatly aided the team in early concept generation as well. Initial designs were created and altered based on every component that utilized a form of energy.

2.4 House of Quality (HoQ)

The House of Quality is a matrix designed to outline Customer Needs and relate those needs to measurable aspects of a design. It also rates how important each Engineering Requirement is and references how each requirement will be tested to show the validity of our design.

*See **Appendix A** for **House of Quality***

The House of Quality helped our team through the design process in a number of ways. First, it forced us to spend a significant amount of time defining the problem statement and understanding the challenges posed by the customer. Initially, the team viewed the SAE Competition as the sole "customer," but after conversations with the professor about Customer Needs, the team realized we, the students, are also one of the customers. The team also has needs to meet before it can satisfy the SAE Aero competition needs; needs such as constructability. Making the House of Quality also helped the team understand another key Customer Need that is not explicitly listed in the rules: Reliability. Reliability is almost more important than the scoring capacity, since a large number of points can be lost. In addition, competition data reveals that more than 30% of the teams in the competition have problems with reliability. Every time the team worked on concept development, we could look to the House of Quality's "Importance" values to determine how much time and resources should be spent developing certain concepts.

As the team finished the Concept Generation phase of the project, the House of Quality became helpful in another field- prototyping and testing. By planning test procedures around being able to satisfy certain ER's, the team was well-prepared to validate our design when the time came.

2.5 Standards, Codes, and Regulations

If competition were to have taken place, the team would have needed to adhere to many standards. The Society of Automotive Engineers (SAE) provides some standards in the competition rule document. SAE requires that the 2D technical drawing submitted to them must be in compliance with ANSI-Y14.5 M 1994 on Dimensioning and Tolerancing. In addition to the standards from SAE, standards from the following organizations will also have to be followed. American Society of Mechanical Engineers standards pertaining to Aluminum will be used, Institute of Electrical and Electronics Engineers standard on aircraft electronics, and the American Welding Society standard of Aluminum welding. Generally flying objects would have to conform to Federal Aviation Administration (FAA) guidelines as well, but since this aircraft is being operated at the SAE competition, is less than 55 pounds in weight, will not be flown within five miles of an airport, and it is classified as a personal radio controlled device it does not have to abide by any FAA regulations. **Table 3** below shows these standards and the reasoning behind using them.

Table 3: Standards of Practice as Applied to this Project

Standard Number or Code	**Title of Standard**	**How it applies to Project**
ANSI-Y14.5 M 1994	Dimensioning and Tolerancing	2D Drawings must be submitted in this forma per competition rules.
ASME Y32.10 - 1967	Graphic Symbols for Fluid Power Diagrams	The team will need to implement the correct symbols so those in the industry can understand the teams deliverables.
SAE J429	Mechanical and Material Requirements for Externally Threaded Fasteners – Standard	The fasteners used on the aircraft must not yield during operation, and must stay in place.
SAE J452	General Information – Chemical Compositions, Mechanical and Physical Properties of SAE Aluminum Casting Alloys	Material properties for 6XXX series Aluminum need to be known since it will be the main structure of the design and will have to have high enough strength for the design.
IEEE 750-1947	AIEEE Report on Aircraft Electric System Guide	This will be a good guideline for how the electronics on board should be configured and operated.
SAE G-14	Americas Aerospace Quality Group	Good to use when designing the final plane, if the design conforms to this it should have minimal unforeseen issues.

SAE G-23	Manufacturing Management	This standard will be useful when building the final aircraft and manufacturing processes are very important.
AWS D1.2	Structural welding (aluminum)	This standard needs to be followed to ensure that the welded members of the main structure of the design are reliable.

3 Testing Procedures (TPs)

The following section contains the executed testing procedures. These tests were conducted to verify satisfaction of aforementioned customer and engineering requirements of the design. The two major categories of testing that will be discussed are prototype flight trials, and static power bench testing.

3.1 Testing Procedure #1: Prototype Flight Trials

With the preliminary calculations that were performed and analysis as a basis, the team began conducting flight trials to confirm or negate the validity of those calculations. The construction of the initial prototype was made modular, so that many different configurations could be set up quickly providing the team with data on a large number of variables to verify how well each configuration satisfies the following engineering requirements. These tests demonstrated the satisfaction of produced lift, low drag intensity, velocity, take off distance, maneuverability, loading time, success rate, and factor of safety. Additionally, in the event of a crash, these tests also demonstrated the satisfaction of ease of assembly/repair. This testing took many attempts and spanned January up until the end of March.

3.1.1 Testing Procedure #1: Objective

Flight tests were run at a large airfield controlled by the local hobby flight club the Flagstaff Flyers. Before flights took place, loading and unloading of various amounts of cargo were timed and confirmed that it could be done in the competition time constraint. These attempts also confirmed cabin length to be correct by fitting the needed payload inside of the aircraft correctly. A team member acted as the sole pilot of the aircraft throughout the tests so that there was no additional variation created due to differing pilot styles. For the current geometry of the modular design, a predicted lift and acceleration *with included* factor of safety was set as the assumed flight performance. By including the factor of safety the team confirmed a cushion so that if something were to go wrong during competition, there is a chance the aircraft can still operate correctly. Velocity and acceleration were measured using a handheld timer to record time, graduations on the dirt landing strip to record distance, and the kinematic equations. Accurate velocity and acceleration data was needed to confirm requirement satisfaction as well as prove future calculations. Satisfaction of the predicted lift for a measured plane weight (structure and payload) was confirmed by the plane becoming airborne at the given velocity calculated. The correct lift at a specified velocity is important so that the team could accurately predict possible payload and adjust speed as necessary for a needed lifting force. Once in flight, actuation of differing control surfaces was done to confirm that the plane is maneuverable and can be controlled with relative precision in flight, this will be proven by the plane banking to turn 90 degrees within ten seconds. Each test also validated general performance in crosswinds and landings showed that the landing gear structure was sufficient for use but could have been improved. To demonstrate success rate and the design's robustness, each preliminary configuration was tested for at least ten iterations, and the final design was tested 20 times so that the 95% success rate could be easily proven with 19 out of 20 successful flights. In practice, the final configuration took off easily 20/20 times and satisfied all of the above engineering requirements.

3.1.2 Testing Procedure #1: Resources Required

To complete the above test objectives the following was needed. An airfield and permission to utilize it before any testing could take place, this was done by contacting the Flagstaff Flyers. All team members needed to be present to operate the measurement equipment and fly the plane. A handheld timer as well as a walking measuring tape were needed for the velocity and acceleration measurements supplied by a team member’s mobile phone and home depot respectively. To document the testing and provide a method of evaluating the test at a later time, each test was recorded via a team member’s mobile phone. Due to the modularity of the design and team’s desire to test multiple configurations, hand tools were brought so that the attachment hardware (M8 bolts and nuts) could be removed and re-secured for each new configuration. To test the loading time steel plates and a soccer ball were needed. Additionally the aircraft and the radio controller (pre-programmed) were needed to communicate with the plane, along with that, the essential electronics such as the electronic speed controller, radio receiver, servo motors, and the battery.

3.1.3 Testing Procedure #1: Schedule

Before testing, the foam wing sections had to be wire cut and attached to each other. The team did the testing in segments spanning multiple months. Beginning in January, flight tests that resulted in crashes were followed by reconstruction and redesign and more testing. With each iteration, a growing number of flights could be done with each plane until reaching the final result that had a 100% take off rate. Due to the battery only having an estimated flight duration of six minutes, two extra batteries and a battery charger were brought to the test site. Each flight only took a short time, but the initial set up and taxiing took an appreciable amount of time, with modifications for each trial varying up to about 30 minutes each. The report for competition was due at the end of February, so agressive testing took place in the first weeks of February so that changes could be implemented before the report was due. After the final design was submitted, additional engineering change requests could be submitted to SAE, and so flight tests continued into mid-March to prove the best center of gravity and payload locations. After that, testing stopped because final product construction had to begin taking place.

3.2 Testing Procedure #2: Static Power Test

The test consisted of connecting the battery, engine speed controller, power limiter and propeller to a load cell. This load cell measured static force produced by the power train. Simultaneously an amp meter will be attached in line with the system to assure the power limiter is indeed limiting the power to 1 Kw as per our engineering requirements. This engineering requirement is noted in the House of Quality. (*See **Appendix A** for **Table A1: House of Quality)***

3.2.1 Testing Procedure #2: Objective

This test was run by hooking up the electronics of the propulsion system and testing it while measuring power draw. By doing this test it was proven that the power limiter and propulsion system are in compliance with the competition rules, and meets the House of Quality technical requirements (*See **Appendix A** for **Table A1: House of Quality).*** With accurate power readings, the requirements of possible weight and resultant wingspan could be calculated, and then satisfaction of them could be confirmed qualitatively by making sure that the wingspan was less than 120 inches, and the total weight did not exceed 55 pounds.

3.2.2 Testing Procedure #2: Resources Required

The resources required to do this test were the propulsion system, one team member and an amp meter. The load cell that measured the thrust is consistent with preliminary static tests done by the team was requisitioned from Dr. Shafer. A large array of propellers were also needed to find the best performing geometry for the limited power usage.

3.2.3 Testing Procedure #2: Schedule

The team had this procedure completed over the span of a single day and required the efforts of a single team member. This test occured in November when the new competition compliant power limiter was acquired by the team. Early testing had to be done so that the team had an accurate measurement for the power engineering requirement. With this number, the requirements pertaining to total weight and wingspan needed could be calculated.

4 DESIGN SPACE RESEARCH

Perhaps the longest maintained process during this project was research. Most team members entered this capstone project with little to no aeronautical design experience. A preliminary literature review brought the team to an initial level of competence on the matter, and ongoing research was needed to deepen understanding and make more challenging design decisions. Additionally, the high amount of physical testing conducted by the team needed to be supported with specialized depth research.

4.1 Literature Review

The team produced a preliminary literature review that encompassed a number of sources and mediums, but maintained research throughout the design year. One of the first sources considered was the technical report from last year's Aero team. Though the objectives of their design varied from this year's, their design process was still very pertinent to our team's challenge. Additionally, after the team had developed a firm understanding of the design challenge and the rules that came with it, the project advisor Dr. Tester was interviewed. This interview established realistic expectations for our design, as Dr. Tester had overseen many successful (and unsuccessful) Aero design attempts. The team's most consulted textbook was Aircraft Design by Scholtz. It provided detailed equations and design processes for all aspects of aircraft design and was used throughout the design process. For browsing various airfoils, the team used Airfoiltools and compared the characteristic charts. This source was also useful as it provided DAT files of each airfoil that were later imported into SOLIDWORKS. Chapter 9 of *Aircraft Design: A Systems Engineering Approach*, written by Dr Mohammad H. Sadraey; an associate professor and aeronautical engineer, proved useful for any landing gear considerations and calculations.

4.2 Benchmarking

Rather than starting the design process from scratch, it was useful to first survey what other designs have been used. The process of surveying existing designs and evaluating their successes and shortcomings is known as "Benchmarking." Ideally, this would involve on-site visits to organizations, observation, and interviews with employees to see how others have approached this design problem. Because of the team's lack of access to previous designs, much of the benchmarking so far has been done online through extensive research. We were; however, able to perform a dissection of the NAU Skyjacks existing design (see "Existing Design #1).

System Level Benchmarking

The following designs in the benchmarking process are full-system designs that completed similar objectives to the 2020 SAE Aero competition. Designs chosen include the aircraft from NAU's 2016, 2018, and 2019 Aero teams. These aircraft were designed with similar objectives in mind, and with similar resources available. For these reasons, they are the perfect candidates for full-system benchmarking.

Existing Design #1: NAU Skyjacks (2019 Team)

NAU's 2019 team "Skyjacks" produced the aircraft seen below in **Figure 3**. This craft features: shoulder-mounted wings, a conical nose cone, a U-shaped fuselage, and tail-dragging landing gear [4]. Because this craft was built for similar objectives to our competition, it is important to understand this design's successes and failures. The 2019 competition was broken into three rounds. During the first round, the Skyjacks' craft was successful in transporting its payload through one 360^{o} loop. However, upon landing, the landing gear was critically damaged. The Skyjacks accidentally contributed to electrical failure during the repair process and were unable to compete in the second round. During round three, the aircraft was taken by a gust of wind and was forced to crash. The design of this aircraft was used as a baseline design due to its early success, but in order for a new design to succeed, more research and design had to be conducted in areas of flight stability and landing gear.

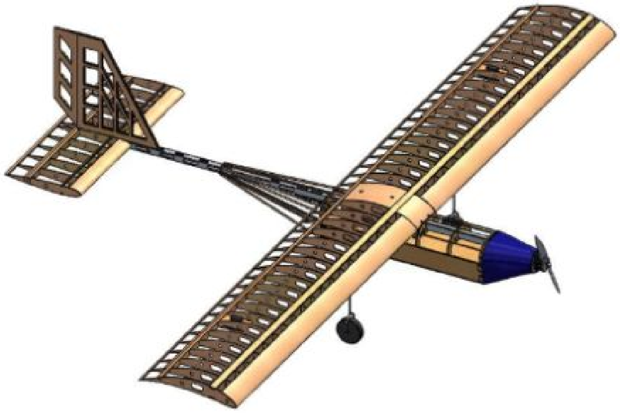


Figure 3: Team Skyjacks' Final Design without Monokote

Existing Design #2: NAU In Thin Air (2018 Team)

NAU's 2018 team "In Thin Air" produced the aircraft seen below in **Figure 4**. This craft features: body-mounted wings, a truncated pyramid nose cone, a rectangular fuselage, and a tricycle-style landing gear. Just like the previous existing design, the "In Thin Air" aircraft was designed for an SAE Aero competition with similar objectives to ours. Although competition data isn't available like it was for the previous design, a video of a test take-off reveals that this craft was hard to control in the face of wind. Team member Alex Klausenstock volunteered to help this team two years ago. He recounted that the primary problems facing the "In Thin Air" craft were low speed capability and imperfect airfoil fabrication. Luckily, our team was able to make the necessary strides in those areas to ensure success.

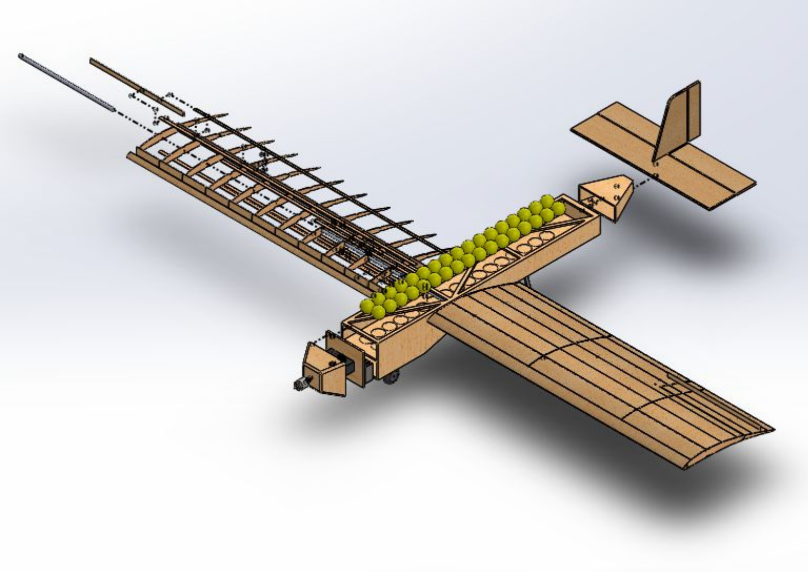


Figure 4: Team In Thin Air Final Design [4]

Existing Design #3: NAU Aero (2016 Team)

NAU's 2016 Aero team produced the aircraft seen below in **Figure 5**. This craft features: shoulder-mounted wings, truncated pyramid nose cone, rectangular fuselage, and a tricycle-style landing gear. Like the existing designs mentioned before, this craft was constructed to fulfill the needs of a SAE Aero competition. Because this competition took place several years ago, it is unclear whether or not the objectives were exactly the same. It is clear, however, that this plane was designed to transport some kind of payload in a 360 degree loop; very similar criteria to the other competitions. While competition data is not available, the 2016 team did document their testing process, which ended catastrophically. During the flight testing, the ailerons on the wings became damaged and the pilot lost control of the craft. Testing ended with a nosedive crash. This existing design influenced our team to take special care in designing control surfaces and the ways they are attached.

Figure 5: Aero 2016 Final Design [6]

Subsystem Level Benchmarking

In addition to analyzing full-system designs, benchmarking can also be used to evaluate subsystem designs. If a full system can be thought of as a sum of its parts, then it is critical that the best subsystems are chosen as parts. The following sections will aim to understand and analyze several subsystems: General Wing Shapes, Empennage Designs, and Landing Gear Configurations. An understanding of each of these systems will be vital to our team's design process.

Subsystem #1: General Wing Shapes

There exist many types of general wing shapes, including: rectangular, elliptical, tapered, delta, trapezoidal, and others. The amount of lift an aircraft generates, control at different operating speeds, stability and balance all change as the aircraft wing's shape is changed. Removing wing types used for supersonic and transonic flight, the following section will compare existing wing types and analyze the successes and shortcomings of each.

Existing Design #1: Rectangular Wing

The Rectangular Wing is the easiest-to-manufacture wing type. It is most often seen on small aircraft, like the Piper PA-38 pictured below. While it may be the easiest wing to manufacture, it is far from the most efficient in terms of aerodynamics [7]. Manufacturability is one of the team's customer needs, but aerodynamic success is more important. Evaluating the risks associated with this wing will be crucial in the wing type selection process.

Figure 6: Piper PA-38

Existing Design #2: Elliptical Wing

In contrast to the rectangular wing, the elliptical wing is the most efficient straight wing for subsonic flight, but the hardest to manufacture. Low drag is induced due to elliptical spanwise lift distribution. The elliptical wing was used on WWII aircraft that required the thinnest possible wings [11]. One example of these aircraft is the Supermarine Spitfire pictured in **Figure 7**. While this type of wing fulfills aerodynamic goals, our team will have to be mindful of our ability to manufacture complex wing types such as this.

Figure 7: Supermarine Spitfire with Elliptical Wings

Existing Design #3: Tapered Wing

The compromise between the two previous wing designs is the tapered wing. This wing most closely resembles a rectangular wing, but its tapered trailing and/or leading edges allow for a near approximation of an elliptical wing. While this approximation does not meet or exceed the aerodynamic efficiency of the elliptical wing, tapered wings provide a compromise between manufacturability and efficiency [7]. This style of wing will be an important consideration in our decision process.

Figure 8: Tapered Wings on the P51 Mustang

Subsystem #2: Empennage Designs

Equally important as wing design is empennage design. The "empennage" or "tail" of the aircraft consists of vertical and horizontal (pitch and yaw) stabilizers located at the rear of the aircraft. These stabilizers can take on various configurations. The most prevalent of these configurations are: conventional, t-tail, and cruciform. The following sections will study and analyze those designs in relation to our team objectives.

Existing Design #1: Conventional Tail

As given by the name, the conventional tail is the most common arrangement of aircraft empennage, with an estimated 75% of all planes using this configuration [12]. This configuration consists of one vertical stabilizer that sits atop the fuselage, and one horizontal stabilizer which is split on either side of the fuselage. The reason this configuration is so widely used is because it offers adequate stability control at the lowest structural weight. As the project progressed, this design was considered first and foremost in our team's design process.

Figure 9: Conventional Tail

Existing Design #2: T-Tail

The second-most popular tail design is the "t-tail." This design is similar to the conventional tail, except it places the horizontal stabilizers at the top of the vertical member. In doing this, those stabilizers are placed far out of the way of engine exhaust or wing wake. With these stabilizers free from aerodynamic obstructions, they become more efficient and can be made smaller [12]. However, their placement puts a larger moment on the vertical member. To combat this, t-tails often have to be produced from stronger, heavier materials. Upon simulation, the team found that a conventional tail is not effective enough in our application to outweigh its weight detriment.

Figure 10: T-Tail

Existing Design #3: Cruciform Tail

Similarly to what was seen in the wing shape benchmarking, there is again a compromise solution. The

Cruciform Tail, though rarely used in industry, offers a balance between tail efficiency and weight [8]. The main design follows closely the very-manufacturable Conventional Tail design, but raises the horizontal stabilizers slightly, as to remove them from the wing wake. If done properly, this design will prove an efficient, yet manufacturable solution. That being said, the midsection mounting of the horizontal stabilizers is *less stable* than the fuselage-mounting seen in a Conventional Tail. Due to limited literature on Cruciform Tail dimensioning, along with the added manufacturing difficulty and loss of stability, this setup was not implemented.

Figure 11: Cruciform Tail

Subsystem #3: **Landing Gear Designs**

The third and final subsystem that this benchmarking analysis will look at is *landing gear*. Landing gear is an integral part of the full system, and as mentioned before in the Original System Section, faulty gear has been the downfall of previous NAU teams (See Section 1.3). The following sections will detail the three standard landing gear layouts: tricycle, conventional (taildragger), and tandem.

Existing Design #1: Tricycle

Tricycle landing gear is the most common form of landing gear for small aircraft. This style of gear places its primary gear in the rear, and its secondary, turning gear in the front. This allows for a very stable and very controllable aircraft on the runway [13]. The downside to this design is that it places the propeller low to the ground. Any “tipping” could damage the propeller.

Figure 12: Tricycle Landing Gear on a Cessna 172

Existing Design #2: Conventional (Taildragger)

The other most common type of landing gear is the conventional, or “taildragger” configuration. This configuration is especially interesting to the team because it is often used on bush planes. This layout puts its main gear in the front and its secondary, turning gear in the rear. This design elevates the propeller which eliminates the possibility of damage due to tipping. However, this design is far less controllable on the runway due to its rear-placed turning gear.

Figure 13: Conventional (Taildragger) Landing Gear on a Piper J-3 Cub

Existing Design #3: Tandem

Another design for landing gear is the tandem design. This design utilizes two or more *rows* of wheels. This design is usually only used on large, heavy planes as a means to distribute the load. While load distribution would have been beneficial to the team’s aircraft design, it was not necessary. Tandem-style landing gear would have added more weight to the overall system and additional complexity to ground-steering capabilities [13]. This layout would have only been considered if weight distribution became a bigger challenge than control and it did not.

Figure 14: Tandem Landing Gear on an Antonov AN225

5 CONCEPT GENERATION

After completing its background research and analyzing the dynamic test flight scoring equation, the team produced three initial concepts. These concepts implemented various wing shapes, two landing gear configurations, and three payload size options. These ideas helped direct the team towards a single ball carrying design that focussed on reliability, but final design elements can be seen in both of the first two designs. These concepts that were purely based on knowledge derived from text evolved through further understanding of flight attributes and real world testing.

Full System Design #1: Straight Wing, Tricycle Gear, One Ball

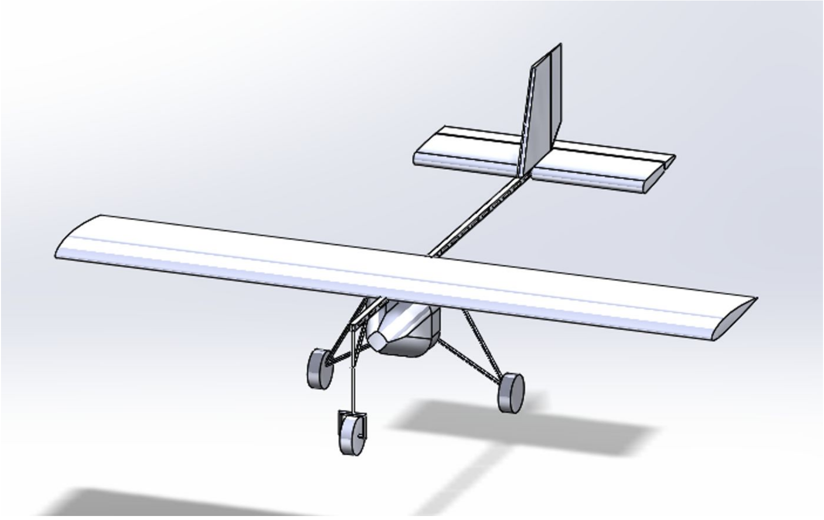


Figure 15: Straight Wing, Tricycle gear, One Ball System CAD Model

The first design that was considered was the base scoring option. It was an aircraft with a straight (rectangular) wing, tricycle landing gear, and a cabin designed to accommodate 1 ball and additional weighted payload. This design was conceived while designing the simplest and potentially most reliable aircraft. Its benefits were that it would have been very easy to combine the selected systems since the cabin was relatively small and structurally negligible. The tricycle gear would have born some negatives such as a shorter wheelbase. Another downside of this design was that it would have been prone to forward and diagonal tipping had it encountered a bump during landing due to its high center of gravity. The team knew initially that a straight wing design would be easiest to manufacture compared to a tapered wing or a wing with washout features. The lightweight, base-scoring design was expected to be the easiest to design and manufacture, with its reduced structural member complexity and weight.

Full System Design #2: Tapered Wing, Tail Dragger, Two Ball

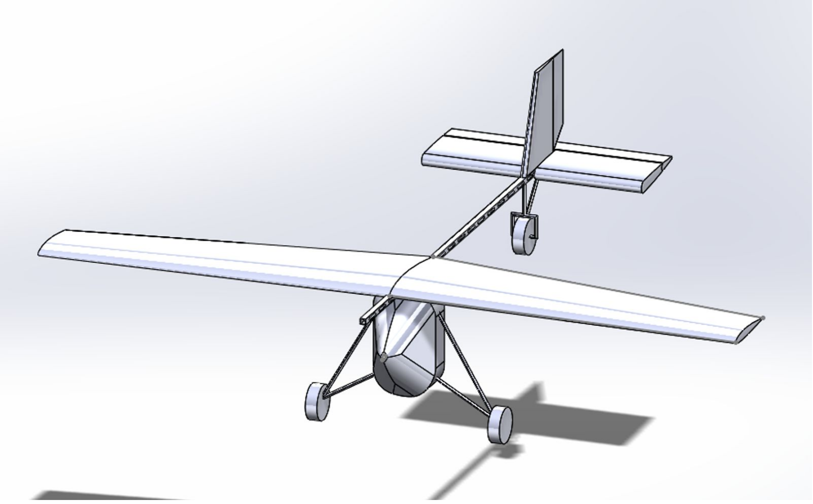


Figure 16: Tapered wing, Tail Dragger, Two Ball

The team's second design explored a higher scoring option and combined the tapered wing layout with a tail dragger landing gear and featured a two ball payload cabin. The advantages of this design were the landing capabilities of the tail dragger configuration, higher scoring potential, along with improved structural mounting of the front gear that would mitigate the landing impact difficulties the 2019 team faced. The tapered wings would have less drag than straight wings and mitigate downwash effects. Additionally, the high angle of attack resulting from tail dragger landing gear would allow higher lift production on the ground. Foreseen disadvantages of this design were the difficulty of manufacturing wing taper. The two ball configuration would have increased score by one point, but incurred higher drag. Lastly, the tail dragger was known to be the most difficult to control on the ground during takeoff.

Full System Design #3: Tricycle, Suspension, Three ball

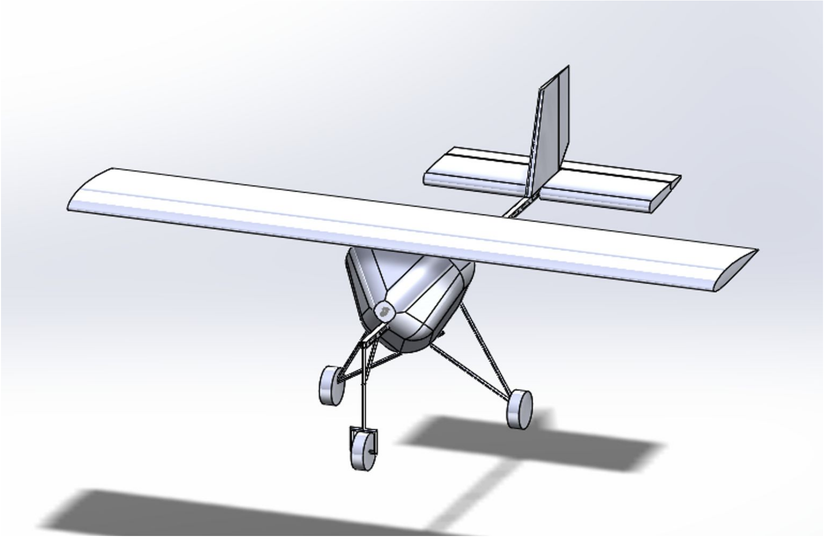


Figure 17: Straight Wing Planform, Tricycle landing Gear, Three Ball

The third original concept design was conceived with the highest scoring potential in mind . It detailed the combination of a straight (rectangular) wing, tricycle landing gear, and a three ball payload cabin with additional weighted cargo. The benefits of this configuration included: the highest scoring potential presented by the team as a result of more balls, high stability and effective control on take-off, as well as a suspension system to dampen the landing (suspension not pictured). This design came with its own list of drawbacks. Having three balls would have induced even more drag and made the plane significantly less aerodynamic. Additionally, the suspension system would have greatly increased the frame's weight. This design was rejected as it suggested the least chance of reliable and repeatable success.

6 DESIGN SELECTED – First Semester

Our selected design, affectionately nicknamed "Pine Patrol One," features many of the components outlined in our preliminary report, including: rectangular wings, Conventional-style empennage, and tricycle landing gear. However, several significant changes have been made since filing the last report. Most notable was a scoring revelation. Recall that the scoring equation represents a ratio between carrying capacity and size (the smallest plane with the most payload wins). Our team's earlier designs tried to maximize carrying capacity by considering three-, five-, or even ten-ball designs. What we have discovered is that we can score as good, or better, by focusing on the *size* aspect of the scoring. By building a smaller plane that can carry a fair amount of payload, our team can score exceptionally. This is why the team's final design will employ a small, five-foot wingspan, and carry a singular soccer ball. Another change since the preliminary design is the cabin design. The team has begun work on an aerodynamic solution to the drag imposed by our earlier cabin designs: an airfoil-shaped cabin, nicknamed "Ballfoil." Paired with an all-aluminum frame and a powerful thrust system, the short wingspan and the Ballfoil will come together to create a successful aircraft.

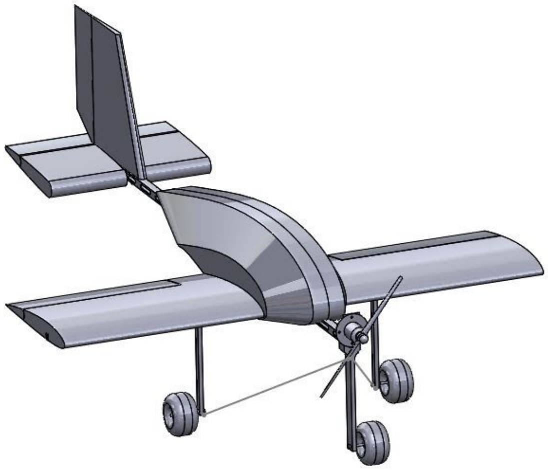


Figure 18: CAD Model of Final Design (First Semester)

Design Description – First Semester

Frame

The first major subsystem of our design will be the frame. An all-aluminum frame will run through all members of the plane and supply support and rigidity to the system. All components- wings, cabin, thrust system, empennage, and landing gear- will be mounted to this frame. Some components, such as the wings and the cabin will be modular across the frame, as different mounting positions have already been drilled.

Thrust System

The thrust system was the first system to be designed. Similar to the "drive-train" of an automobile, our thrust system is a system of moving power. Power will start in a 6-cell LiPo battery as specified by SAE, and move into a brushless, electric motor. Before reaching the motor, the power will be limited by a 1kW power limiter, which is mandated from SAE. The motor will use the 1kW of power to turn a size 16x6 propeller at a speed regulated by an ESC controller. This propeller was selected based on the results of two static propeller tests.

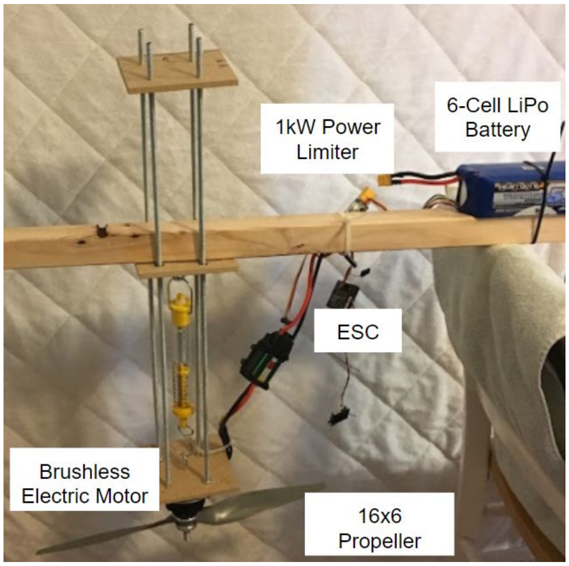


Figure 19: Thrust System (In the Context of the Team's First Static Thrust Test)

Aerodynamic Surfaces (Wing, Tail)

Since the preliminary report, the design of the plane's aerodynamic surfaces has not changed much. We will still employ a Conventional-style empennage, the sizing of which will be governed by industry-standard equations (See Appendix C) and a rectangular wing. Our wing will have a span of five feet, and a chord length of eighteen inches. The team has narrowed airfoil selection down to three airfoils: Eppler 61, NACA 2412, S1223. We've determined that these airfoils will provide us with adequate aerodynamic properties and will test each during the prototyping process before making a final selection.

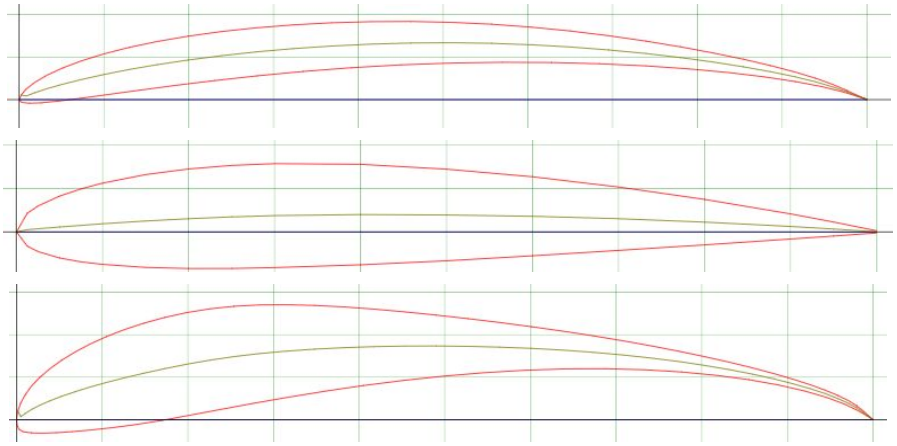


Figure 20: (From Top to Bottom) Eppler 61, NACA 2412, and S1223 Airfoil Diagrams [9][10][11]

All aerodynamic surfaces will be cut from EPS foam using a nichrome wire cutter that we have begun to assemble. EPS foam is extremely lightweight, and will serve us better than wooden wings, so long as the foam is properly supported by the aluminum frame.

Cabin

The team's cabin design is arguably the most creative aspect of our design. Once the team realized that only one soccer ball was necessary to score well, alternative cabin designs began to be formulated. The problem with designing a cabin was that most designs incurred a large amount of drag. Large drag forces will slow the aircraft down and render its lift and thrust forces inadequate. The problem of drag was solved when a team-member discovered the NASA Langley airfoil. This airfoil was thick enough to house a soccer ball, and aerodynamic enough to conserve the aircraft's lift and thrust forces. Thus, the "Ballfoil" cabin was designed. In addition to its reduced effect of drag, preliminary simulations show that the Ballfoil will provide the aircraft with some additional lift.

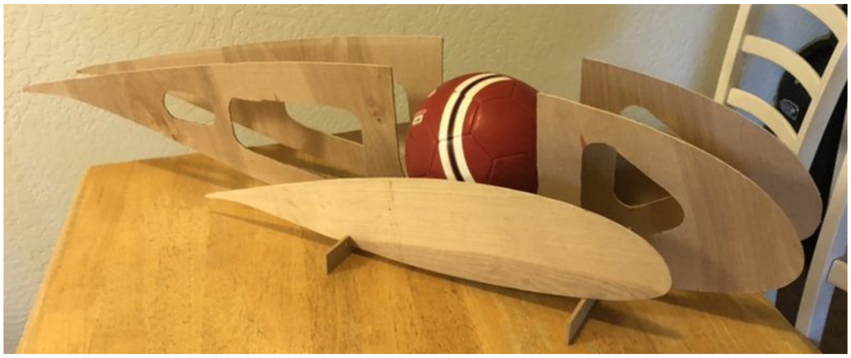


Figure 21: Ballfoil Prototype

Ideally, the Ballfoil will be constructed using the lightweight EPS foam that makes up the wings. However, the team has begun construction on a *wooden* cabin, due to the inaccessibility of large foam blocks.

Landing Gear

As explained in the Preliminary Report, our aircraft will best be served by Tricycle-Style landing gear. This type of gear places two, stationary wheels under the wings, and one, turning wheel under the nose. These wheels will be mounted to the aluminum frame for strength and will be tensioned into position with steel cable for stability. A team member is currently analysing the landing gear system for bending and yielding stress failures, but drop tests on our working prototype have shown us that the system is viable.

Justification

The justification for this design is three-pronged. The team's analysis draws from simulated results, hand calculations, and physical testing. Hoping to get a head start on our project, we conducted thrust testing very early on- within the first few weeks of the semester. Additionally, we have already begun to build our first prototype- months ahead of schedule. The data we've collected from these processes, along with the computer-simulated and hand-calculated results has shown us that our final design will be successful.

Thrust Testing

As aforementioned, the team conducted static thrust tests early in the semester. By building our thrust system and measuring the thrust output of several different propellers, we were able to deduce which propeller would benefit our system the most, as well as discern as an estimate for the thrusting force we'll have available during flight. It was these tests that informed our decision to select a 16x6 propeller. With this propeller, we estimate that our thrust system will deliver eight pounds of thrust on the ground, and at least two pounds of thrust in the air.

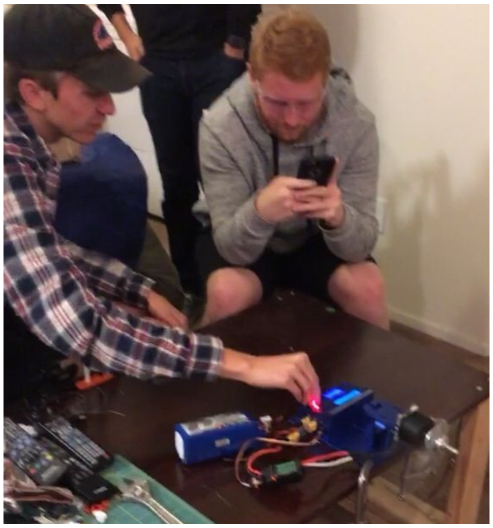


Figure 22: Thrust Testing

Lift

Plenty of hand-calculated lift-force values were evaluated, but after Ballfoil was created, the most effective way to determine lift came from Solidworks Flow Simulations. By imposing a 12-degree, 10 m/s airflow across our CAD model, we were able to analyze the aircraft's interaction with the air and determine lift forces. The simulation gave us an estimated 12.1 pounds of lift, which is more than the 11.3 pounds we need to combat our weight.

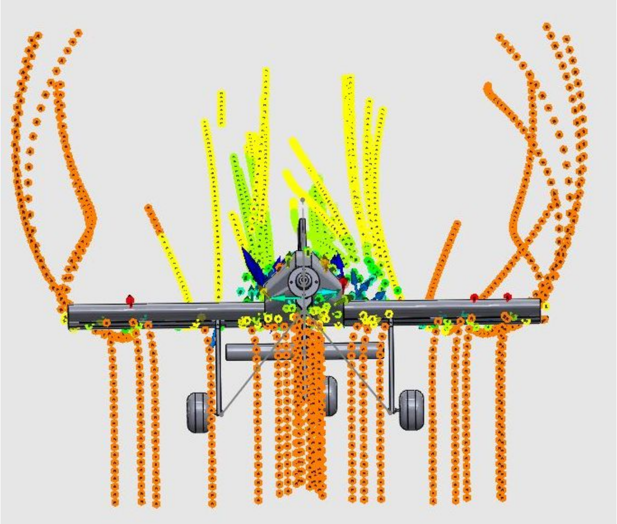


Figure 23: Streamline Figure Output from Flow Simulation

Weight

As mentioned in the section above, the weight of our plane is an estimated 11.3 pounds. The team weighed all of the components we currently have, and estimated or researched the weights of the materials we don't have. The tabulated weight data can be seen in Appendix D. This low value for weight works hand in hand with our lift value to justify our design. Because the aircraft weight is less than the aircraft lift, it *will* fly.

Drag Hand Calcs

The simulations detailed earlier also provided the team with estimations for drag. These estimations varied between 1 and 2.5 pounds of force. For an aircraft as small as ours, *induced drag* is a primary concern. To validate the results given by the simulations, hand calculations for induced drag were produced. These calculations can be seen in Appendix E and show an overestimated induced drag value of 2 pounds and a direct drag value of 0.3 pounds. The total value of our drag is less than our predicted thrust, so this design will accelerate.

Prototype

In an effort to acquire palpable results in all the previously-mentioned categories, the team has begun to construct a prototype. Currently, the prototype features the aluminum frame, the thrust system, and half the landing gear. It also is equipped with last year's empennage as a placeholder while we acquire the materials needed to construct a new one. The Ballfoil has begun to take shape, though it will not be completed until Monokote wrap is purchased. The team plans to cut the wings over the next few days. Through the course of this process, the team has learned how to operate many of the machines in the campus machine shop, and have become well-versed in precision hand-cutting. Over the next couple days, we expect to learn the foam cutting processes necessary for the manufacture of our wings. So far, the aircraft has been designed with easy manufacturing in mind. If any manufacturing processes turn out to be easier than anticipated, the team has a few designs that we'd like to try, including: tapered wings, trimmable stabilizers, etc.

Figure 24: Current State of Prototype

Implementation Plan – First Semester

As far as implementing our design, the primary mode of implementation will be the prototyping process. As a team, we've already conducted simulations and calculations for most aspects of our design. As our sponsor mentor told us, "Calculations will only get you so far. You need to prototype early to get a grasp on your project" [12]. The time has come for hands-on analysis.

Plan: Prototype and Testing

Because our competition takes place in early April, and we have to provide SAE with technical documents by February, our prototyping schedule is accelerated, as compared to other capstone teams. The schedule is as follows:

- November 1st: Begin Construction of First Prototype
- November 16th: Book Field Time with Flagstaff Flyers
- November 22nd: Complete Construction of First Prototype
- November 22nd: Static Testing of First Prototype
- November 23rd-30th: Flight Testing of First Prototype on Flagstaff Flyers Field
- December 1st: Begin Construction of Second Prototype
- December 19th: Complete Construction of Second Prototype
- December 19th: Static Testing of Second Prototype
- January 11th-25th: Flight Testing of Second Prototype on Flagstaff Flyers Field
- January 20th: SAE Technical Documents Due
- February 1st: Begin Construction of Final Design
- March 7th: Complete Construction of Final Design
- March 7th: Static Testing of Final Design
- March 7th-31st: Flight Testing of Second Prototype on Flagstaff Flyers Field
- April 3rd-5th: SAE Competition

7 IMPLEMENTATION – Second Semester

Plan: Prototype and Testing

Because our competition was planned to take place in early April, and we had to provide SAE with technical documents by February, our prototyping schedule was accelerated, as compared to other capstone teams. The schedule proceeded as follows:

- November 1st: Begin Construction of First Prototype
- November 16th: Refine Manufacturing Processes
- November 22nd: Complete Construction of First Prototype
- November 22nd: Static Testing of First Prototype
- December 19th: Flight Testing of First Prototype on South Field
- January 8th: Begin Modify Second Prototype
- January 12th: Complete Construction of Second Prototype
- January 12th: Static Testing of Second Prototype
- January 13th: Modify for third Prototype
- January 13th: Test Indoors at Field House
- January 14th: Flight Testing of Second Prototype on Flagstaff Flyers Field
- January 20th: SAE Technical Documents Due
- February 1st: Begin Construction of Final Design (Version 4)
- February 16th:Finish Construction of Final Design
- February 17th: Test Final Design at Flagstaff Flyers Field (Crashed)
- February 18th: Revise Pitch Equation
- March 1st: Begin Manufacture of Final Design
- March 7th: Complete Construction of Final Design
- March 7th: Static Testing of Final Design Indoors
- March 10th: Order back up components
- March 18th:University closes & SAE competition is canceled
- April 24th: Start Modification for Final Test
- April 25th: Fullscale Test at Altitude at Speedworld Maricopa County

Manufacturing

The team found themselves with a calculation-proven and prototype-tested design. The following section will detail the manufacturing process, both for the prototypes and for the final design.

Discussion

A materials analysis led to the team's decision to craft their aircraft's aerodynamic surfaces from foam. EPS foam is easily accessible and has an incredibly low density of 15-50 kg/m^3. Because of EPS' tendency to fracture, all of the plane's foam surfaces are supported by a lightweight aluminum frame. All other aircraft components are fabricated with PLA plastic. All members are held together with adhesive or aluminum bolts.

Prototype

Construction of the aluminum frame and landing gear components was simple, fortunately. Most members of the team had been trained in aluminum fabrication at the University's machine shop, and the team had access to the required equipment (drill presses, band saws, end mills, lathes) in their or the University's possession. Members for the plane's frame were cut to size using a horizontal band saw, and aluminum flat beams were bent to shape using vices and mechanical advantage. These aluminum components had all mounting holes drilled with a drill press.

The EPS foam aerodynamic surfaces took more time to construct. The most effective and easiest way to shape EPS foam is with a hot-wire cutter. Because the team did not have access to a professional-grade hot-wire cutter, one was constructed by the team. The hot wire cutter features a tensioned, nichrome wire, through which an electrical current is run from an off-the-shelf power supply. By manipulating the voltage and amperage through the wire, the team could heat the wire to the necessary temperature to melt foam.

Figure 25: Homemade Hot-Wire Cutter in Use

Other parts, such as the motor mount and the battery compartment were modelled in Solidworks and submitted to the University's "Maker Lab" for 3-D Printing. Tapered wing tip sections were also constructed using 3D printed template sections.

Finally, all components were assembled. Most connections were established with nut-and-bolt fasteners. All nuts were positive locking or coated in Lock-Tite to prevent slipping due to vibration. Foam connections were made with adhesives. After finding that many glues melted the EPS, the team discovered that JB Weld epoxy successfully held foam members together.

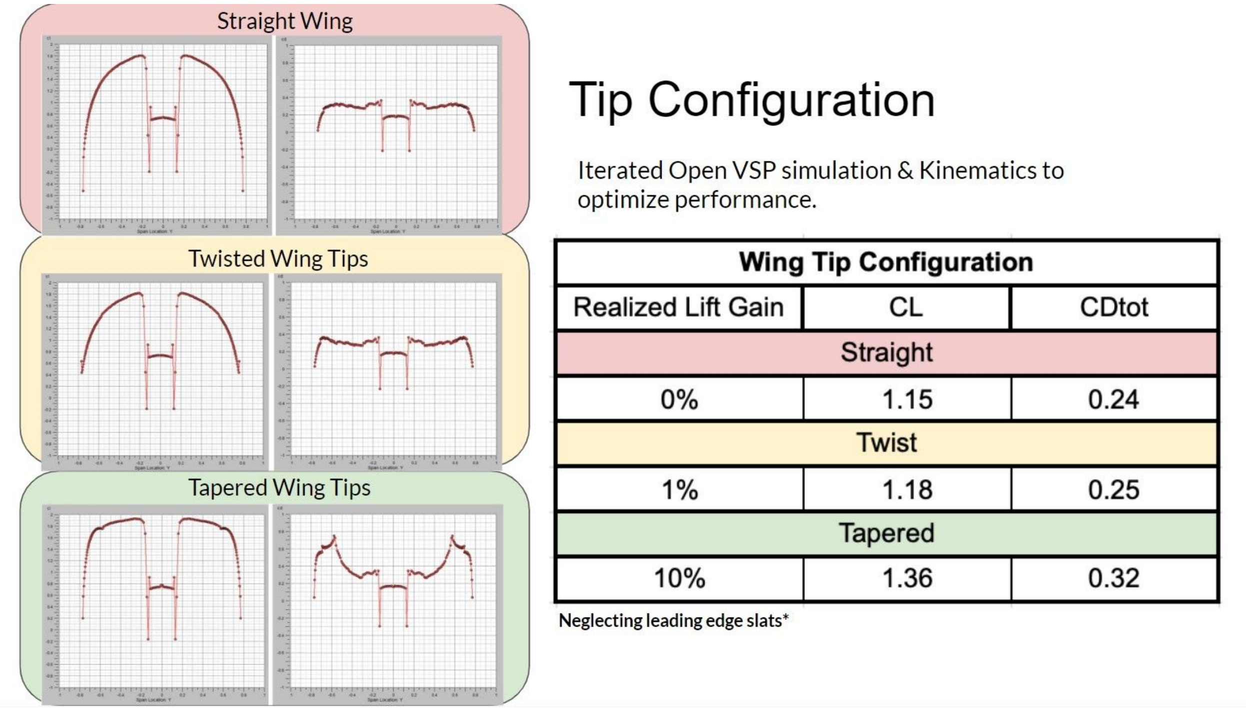
Final Product

The team's final product was manufactured using similar methods to the ones for the prototype described above. Due to the Corona Virus Outbreak many added features were not added which were planned like a carbon fiber landing gear which would be purchased as per SAE Aero rules, and a magnetically sealed cargo enclosure.

Design Changes

The aircraft had pitch moment issues. The issues would not allow the aircraft to take off or would cause the craft to uncontrollably pitching up one in the air. To resolve these problems the team tested a number of payload positions. We also tried to make the elevator bigger in two seperate ways. One, we increased the size of the actuating flap. Two we made the whole elevator surface actuate. The first method proved to not be powerful enough to overcome the pitch moment issue. The second faced serious structural and actuation issues. On take off when the full horizontal stabilizer elevator was actuated down, the air sucked it down and caught on the ground, resulting in the plane flipping on the runway, the moment was calculated to make sure this did not happen ahead of time but we did not account for ground effect. Finally the team went back and completed some detailed calculations to understand the moment in the pitch direction. It was found that our default angle of the elevator was too high, it was moved to a zero angle and the payload was moved to a new location to set the moment to net neutral. This worked and the elevator was moved to a default zero angle of attack and returned to a normal hinged actuator design. Testing proved that it resolved our issues. The moment calculator is included in appendix C (See Figure C2).

Additionally flow simulations showed that changing the wing tips to be a taper showed that it would increase lifting performance by 10% and they were added. See the appendix C Figure C1 for the flight characteristics based on simulation results example excel sheet.



Straight Wing

Twisted Wing Tips

Tapered Wing Tips

Tip Configuration

Iterated Open VSP simulation & Kinematics to optimize performance.

Wing Tip Configuration		
Realized Lift Gain	CL	CDtot
Straight		
0%	1.15	0.24
Twist		
1%	1.18	0.25
Tapered		
10%	1.36	0.32

Neglecting leading edge slats*

Figure 26: Wing Tip Configuration Simulation Results

8 RISK ANALYSIS AND MITIGATION

In order to prepare the best functioning final design, potential critical failures were considered through FMEA. Forseeing the product's potential shortcomings helped the team during the design process. Scoring these possible failures on the basis of severity, likelihood of occurrence, and detectability has allowed the team to identify potential critical failures of greatest concern.

8.1 Critical Failures

In order to prepare the best functioning final design, potential critical failures were considered through FMEA. Forseeing the product's potential shortcomings helped the team during the design process. Scoring these possible failures on the basis of severity, likelihood of occurrence, and detectability has allowed the team to identify potential critical failures of greatest concern.

The selection of subsystems for this product includes functions, structural, objectives, and components. This is because the team fears failures that result in damage to the plane as well as failures that result in loss of points during competition. The highest RPN ranking possible critical failures come most notably from the structural subsystem and are listed in order below.

See Appendix X: Graphs 1-4 of FMEA

Potential Critical Failure 1: Airfoil Frame (Structural)

This member lies in the structural critical subsystem. The airfoil's purpose is to produce a pressure differential across the top and bottom control surfaces; producing lift. This means that there is a force gradient across the wing and that this member is loaded in shear. The team's initial foam airfoil reinforcement member was planned to be wooden, but vetoed in favor of an aluminum beam.

Potential Critical Failure 2: Landing Gear (Structural)

Because the competition requires the regular class to take-off from the ground and land post-circuit, the landing gear is an essential component. It also receives high impact forces on landing and must also act as a spring to dampen the momentary upwards acceleration on touchdown. The main gear was constructed from aluminum to keep the weight low and was bent to shape to save on manufacturing costs. The team's research and FEA proved that a carbon fiber gear should be implemented, but cancellation of the SAE event terminated further progress on that ground.

Potential Critical Failure 3: Airfoil (Foam)

The surface of the airfoil receives pressure from lift production and must be capable of resisting translation. Because the team has selected EPS foam airfoils, a potential critical failure is more likely. A failure by this method would be shearing at some point along the wingspan. The cause would likely be a lack of support and ability to transfer forces. The foam sections were supported with a hollow square aluminum tube inside the entire wingspan.

Potential Critical Failure 4: Lift Production (Functions)

This failure scored the highest in the functions subsystem. The team fears that the plane wouldn't be able to produce enough lift force to overcome gravity. This failure comes in the form of airfoil damage or unpredictable weather conditions. Indoor testing showed lift to be sufficient, but outdoor testing struggled under all dynamic flow conditions.

Potential Critical Failure 5: Landing (Objectives)

Competition requirements dictate that the aircraft must land within 400 feet. A failure to complete this requirement is deemed to be semi-critical in fear of point loss either by exceeding 400 feet or stepping out of bounds. This failure would be prompted by the plane landing with excess energy or having too low of control authority. This was addressed with the tail-dragger configuration as it is the easiest to land.

Potential Critical Failure 6: Ground Steering (Functions)

During the competition, the plane must stay within the specified runway during take-off and landing procedures to prevent penalization. The ground steering gear will require more force to change direction considering the weight of the plane. The simple servo and linkage implemented in the design proved successful during testing.

Potential Critical Failure 7: Empennage (Structural)

The empennage design requires deliberate balancing of lift forces. Should this member be poorly designed it would reduce control authority over the craft and could compromise the effectiveness of the design. A critical failure would be classified as an empennage that alters the angle of attack in a negative way. The team struggled with this aspect in the middle stages of design, but after moment the equation of lift forces was computed and zeroed, the plane was proven to function properly.

Potential Critical Failure 8: Wingspan (Objectives)

One of the team's greatest fears was a potential critical failure by reducing the wingspan too short. One of the most notable competition scoring rules this year is that a shorter wingspan merits a higher score. The team feared that in effort of scoring the most possible points; the wingspan would be reduced to an inoperable point. An iterative excel calculator and extensive testing mitigated this fear.

Potential Critical Failure 9: Aerial Steering (Functions)

The purpose of the ailerons, elevator, and rudder are to provide aerial steering. A potential critical failure would result from the loss of any one of these steering components. Potential effects of this failure include flying out of the safe flying zone and being forced to cut power and crash the plane. This would likely result in a total loss of aircraft. In an attempt to reduce the likelihood of this occurrence, the team has redesigned the servo placement and linkage to prove more reliable.

Potential Critical Failure 10: Remote/Receiver (Functions)

The remote and receiver communicate the actions and inputs of the user to the plane. Loss of control authority, even momentarily, would result in the inability to compete or crash. The team has begun addressing this shortcoming by retiring the old faulty controller and purchasing a new one in addition to replacing the plane's receiver.

8.2 Risks Mitigation and Trade-offs Analysis

The above critical failures rarely conflict with each other and together lead to a more effective design. The main conflict arose from increasing the factor of safety on all structural components due to the increasing weight. This meant that the mitigation of structural subsystem potential critical failures directly conflicted with lift production of the functions subclass as higher lift would be needed. Methods of mitigating risks included usage of strong aluminum support members, lift force calculations, cabin shape to reduce drag, and foam wings. Additionally, early examples of prototyping and testing can be viewed proving that these fears were addressed with the various iterations of the craft.

9 TESTING

The team carried out more than 100 tests with far too much detail and changes to go over here so we will discuss a few of the tests that resulted in design changes rather than just manufacturing tweaks like adding loctite.

Mark I did not take off. At the time we did not have strong calculations to prove it would take off but rough approximations that indicated that it would. We theorised that the plane did not take off because the elevator was not strong enough to push the tail down and create the angle of attack needed to generate lift. Therefore we decided to add a default angle of attack by increasing the length of the front landing gear.

Mark II had these changes incorporated and managed to take off. However it could not carry as much weight as the team anticipated. It was also unstable due to the long front steering landing gear. It also did not seem stable in flight.

Mark III. By this time full simulations had been carried out to prove that the craft not only could fly but that its aerodynamic shape was optimal. Therefore we continued by adding leading edge slats which would increase the velocity of the air over the top surface and further optimize the lift. It worked and the plane took off in a shorter distance.

Mark V. Since we had proof the plane would fly, it was decided to reduce weight. The team moved to change the landing gear to a taildragger to maintain the default angle of attack on the ground, but cut down the steering landing arm and place it in the rear instead. This improved ground stability and increased payload capacity, however at this stage the team moved to full scale flight tests and it was discovered that the plane could not pull up when in full flight, this resulted in a crash. To reconcile this problem, the team created a pitch moment calculator (see Appendix C) to determine how to fix the problem.

Mark VII. It was determined based on pitch moment calculations that the payload would need to be moved backward and the elevators default angle of attack would have to be decreased from 15 to 0 to make the moment equation equal zero. These changes were implemented and this indoor test showed that it was capable of stable flight and carrying a significant payload. Later tests would show us that while it was stable indoors with no wind, that the wind could roll it over and the control surfaces were not powerful enough.

Table 4: Testing Status

Iteration	Mark I	Mark II	Mark III	Mark V	Mark VII
Pros	Learned manufacturing techniques	Could take off unloaded in 100 feet	Leading edge slats allowed 30ft take off	Lighter, tail dragger holds optimal angle of attack	Can take off loaded within the 100 foot limit
Cons	Couldn't take off at all, very heavy	Couldn't handle payload well	Not enough pitch control in flight	Elevator set to incorrect angle	Harder to taxi and take off

10 FUTURE WORK

In the end the wind could push the plane over and cause it to crash. Control and dynamic stability need to be improved. The plane was dynamically unstable because the cargo weight CG was above the center of lift, so as soon as the plane rolled, the length between these two points became a moment arm pulling the plane upside down. In fact the plane landed upside down a number of times during final testing. The Pitch control was sufficient. However the yaw and roll controls could be enhanced to help combat wind forces. They could be enhanced by either increasing the speed by decreasing payload weight or decreasing drag. They also could be increased in size slightly, though according to some rules of thumb, our aleron size was almost at its limit, alternatively the control surface could be made more rigid or the boundary layer could be manipulated to enhance control surface performance, either by employing vortex generators or dynamically variable gaps between the aleron and the wing.

11 CONCLUSIONS

The preceding report has documented the entirety of the Ponderosa Pilots' project process, from research, to design, to analysis, to testing, and finally the presentation of a final product. An analysis of our implementation performance will show success across many of the primary engineering requirements, such as payload capacity, size minimization, and short take-off/landing. The design also fulfilled all secondary requirements, such as manufacturability, load/unload time, cost, and robust design. While it failed to establish control authority and turn successfully, the team views the design as a success. It was successful in fulfilling nearly all engineering requirements, and it would have represented NAU positively in a competition setting. The team's unique answer to the design challenge would be fully effective with minor improvements to mitigate known failures. The following sections will detail contributors to the success of the project as well as areas for improvement.

Contributors to Project Success

The first large contributor to success was that the team adhered to the purpose and goals stated in the team charter. The primary purpose set by the team was to attend competition with a working aircraft. This remained the primary purpose, and the team positioned itself well with meeting deadlines even though the competition was canceled. The original understanding of goals was simplified, but they detail overall successfulness in meeting competition requirements as well as a positive representation of NAU. Again, the team believes this was maintained throughout the project. Primary ground rules set by the team outline team meeting requirements such as specific meeting days of the week along with set times. The team quickly changed its meeting schedule to Tuesdays, Thursdays, and frequently on weekends during manufacturing intensive portions of the semester. Additionally, members not present for any of those meetings were required to stay active in the Aero group chat should questions arise during the meeting. Set meeting dates and expectation of team member attendance helped the team throughout the design process. The charter was less specific about responses to divergent team members, as all members agreed that verbal confrontation about issues was the best method for resolving issues. This method worked sufficiently, and team members were generally on track. The successes of the team were due to several methodologies and practices. As far as overarching themes of the team go, one could attribute team cohesion to two areas: Organization and Drive. The team was able to stay very organized and on-schedule. This was due to the multi-weekly meetings mentioned above and instant communication through a group messaging system. Minutes, notes, and lists of action items were compiled and stored in an online sharing platform; all members were on top of the "to-do" lists. Drive was also an integral part of the team's success. Every member of the team wanted to work hard and perform well. It was this determination that informed the team's decision to stay in Flagstaff over the winter break and continue work on the project. These work-weeks often translated to 30-40+ hour week loads. The team would not be where it is today without that drive to push the design process hard. More specific elements of the team's success include the practices of specialized knowledge and shared knowledge. In order to expedite the design process, the team decided to have each member specialize in different subsystems. One member specialized in aerodynamics and became well-versed in flow simulations; another specialized in control surface sizing and became the lead on ratio-based CAD design; etc. By the time the team members each finished their sub-systems, it was possible to piece together a full-system design efficiently and effectively. When it came time for manufacturing, however, the team found it beneficial to share all knowledge. By making sure that each team member knew how parts of the plane were manufactured and mounted, it was ensured that the team wouldn't have to solely rely on one person to make certain parts. Everyone knew the basics of wire cutting, everyone knew how the landing gear was mounted, etc. Because of this distribution of knowledge on assembly, the team was able to keep the manufacturing process moving along smoothly. The team performed exceptionally in terms of cohesion, efficiency, and collaboration when regarding manufacturing matters. This is especially relevant because a large amount of effort and time went into figuring out how to manufacture with the desired material, EPS foam. There were a number of hurdles that the team overcame in this department. Time management also went quite well and the team stayed on schedule over the course of last semester, though some minor deviations were required moving from initial plans. The gantt chart was a fairly accurate model of how progress preceded. With the original setup, dates were created to meet deadlines set by SAE, but due to some late changes in their dates, the team had a somewhat difficult time adjusting to new deadlines. Although since physical full scale prototyping began so early, the team was ahead of schedule and able to accommodate changes.

While working on the accelerated timeline of the project team members quickly learned about 3D wing flow effects, thrust calculations, flow simulations and 3D printing manufacturability which were useful late in the process. These were all new technical concepts to most of the team members, and grasping them was instrumental to the team's design success. 3D flow effects are an important consideration when designing a wing of finite span. These effects can induce lower lift and higher drag characteristics near the tips of wings. Thrust calculations are also a pivotal part of the flight dynamics equation, and therefore important to our team. While working with these equations the team learned a lot about the relationships relating propeller metrics to dynamic thrust performance. Flow simulations were a key component of the design process. Flows around lifting bodies are complicated and could not have been analytically determined in the given time frame. Therefore, having conceptual understanding of lifting phenomena paired with simulation data helped guide the overall design of the aircraft. Finally 3D print manufacturing concepts were important because they led to shorter prototype turnaround time and allowed for lightweight functional mounting components to be made in less time than if these components were to be made by hand or out of harder materials such as aluminum.

Opportunities/areas for improvement

There a large number of areas our aircraft could improve on, and pure lifting potential is not one of them. It is quite likely despite all its failings that our aircraft was as effective as it could be in pure lift per span performance as it could ever be.

The landing gear durability, control authority, propeller optimization and the dynamic stability could all be improved. First let's discuss the control. Control authority was the largest issue our team faced. Our aircraft had enough control to maneuver in flight indoors, but not enough to mitigate wind which would cause the plane to roll uncontrollably. Our ailerons were as large as we could make them. We believe the airspeed and dynamic instability were responsible for these issues. The aircraft had a low airspeed. This was by design, drag increases with velocity squared, and with a limited 100 ft long runway and 1 kilowatt of power it did not make sense to make the craft fast or we would risk taking too long to take off. More speed gives more flow that the control surfaces see that they can convert into pressure and then moment to exert control. Our final test had a cross wind of about eight miles per hour, we expected as much as fifteen mile per hour of wind at competition. To overcome these issues next year's team could utilize the control surfaces analysis tool in Open VSP. In last year's competition (2019) about 75% (61 out of 80) of the aircraft did not get a flight score above zero because they crashed before completing their first full flight loop. A team could place in the top 15% just by carrying the smallest payload and being reliable. Therefore we recommend next year's team should focus on control first and payload capacity second, carry less to fly faster and have more control. Another aspect of control is dynamic stability. Our cargo was carried above the wings, it became apparent during our final tests that whenever the plane was not perfectly upright it wanted to flip itself over as the weight acted as a moment arm. This resulted in a number of upside down landings. There are two things that can be done to help make the craft stable rather than inherently unstable. First move the cargo under the wing, even if it means adding structure weight. Secondly adding dihedral or anhedral, depending on where the wings are relative to the body. This may help with cross wind.

The next opportunity for improvement would be in propeller optimization. We believe there are tools in Open VSP or J-blade that can help the team optimize the propeller for the specific designed aircraft.

Finally the landing gear we manufactured was a bent aluminum bar and was used like a leaf spring, it was very easy to repair in the field, but it would be better if it simply never bent. Our team believes a carbon fiber spring landing gear in the same configuration would improve landing gear reliability.

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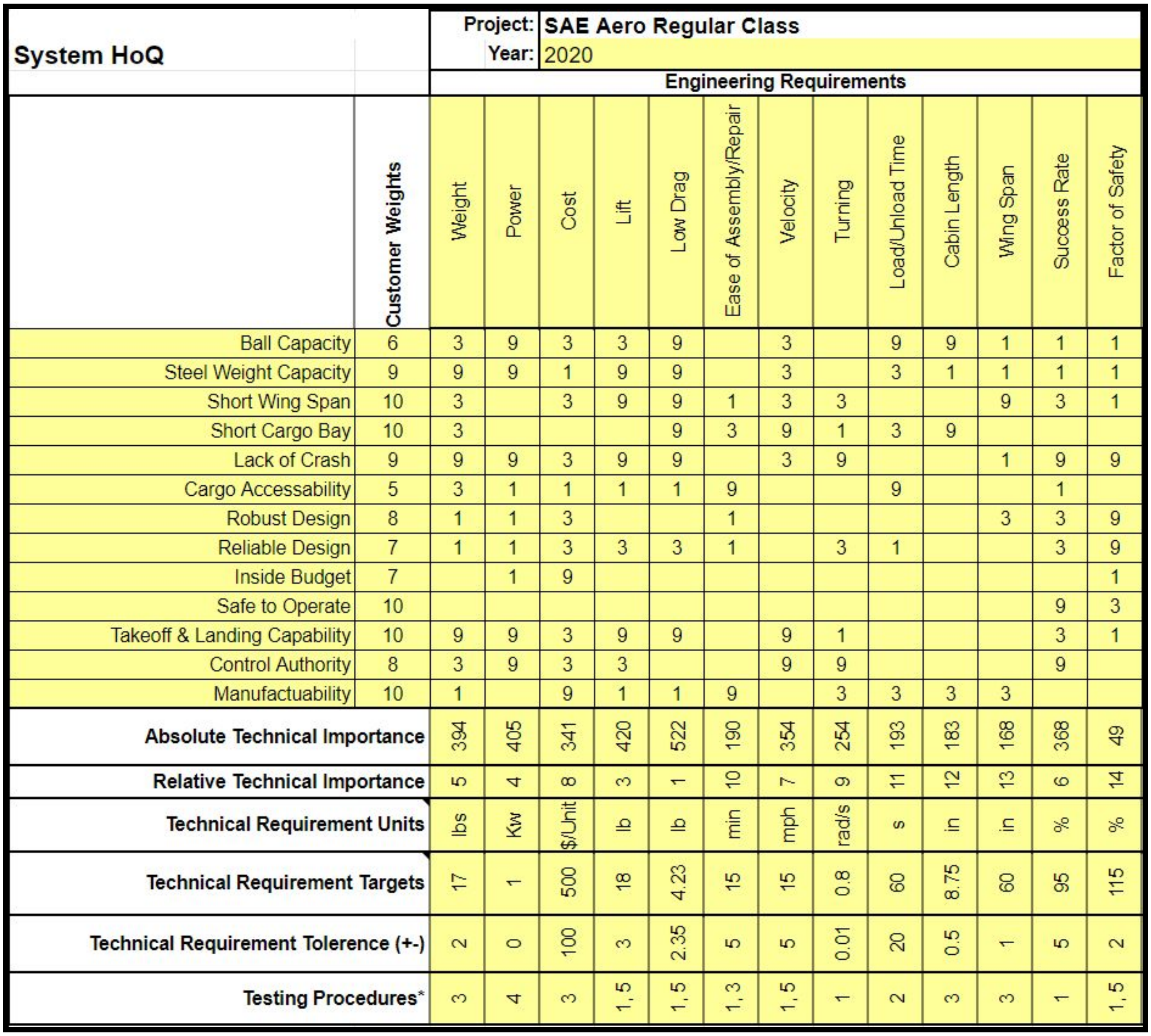
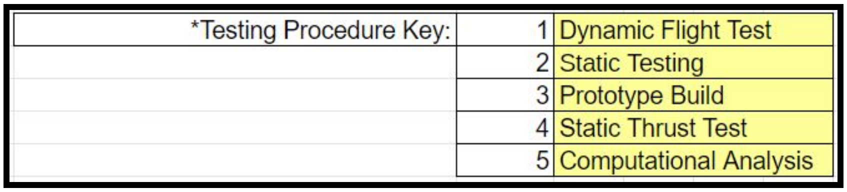
APPENDICES

1.1 Appendix A: House of Quality



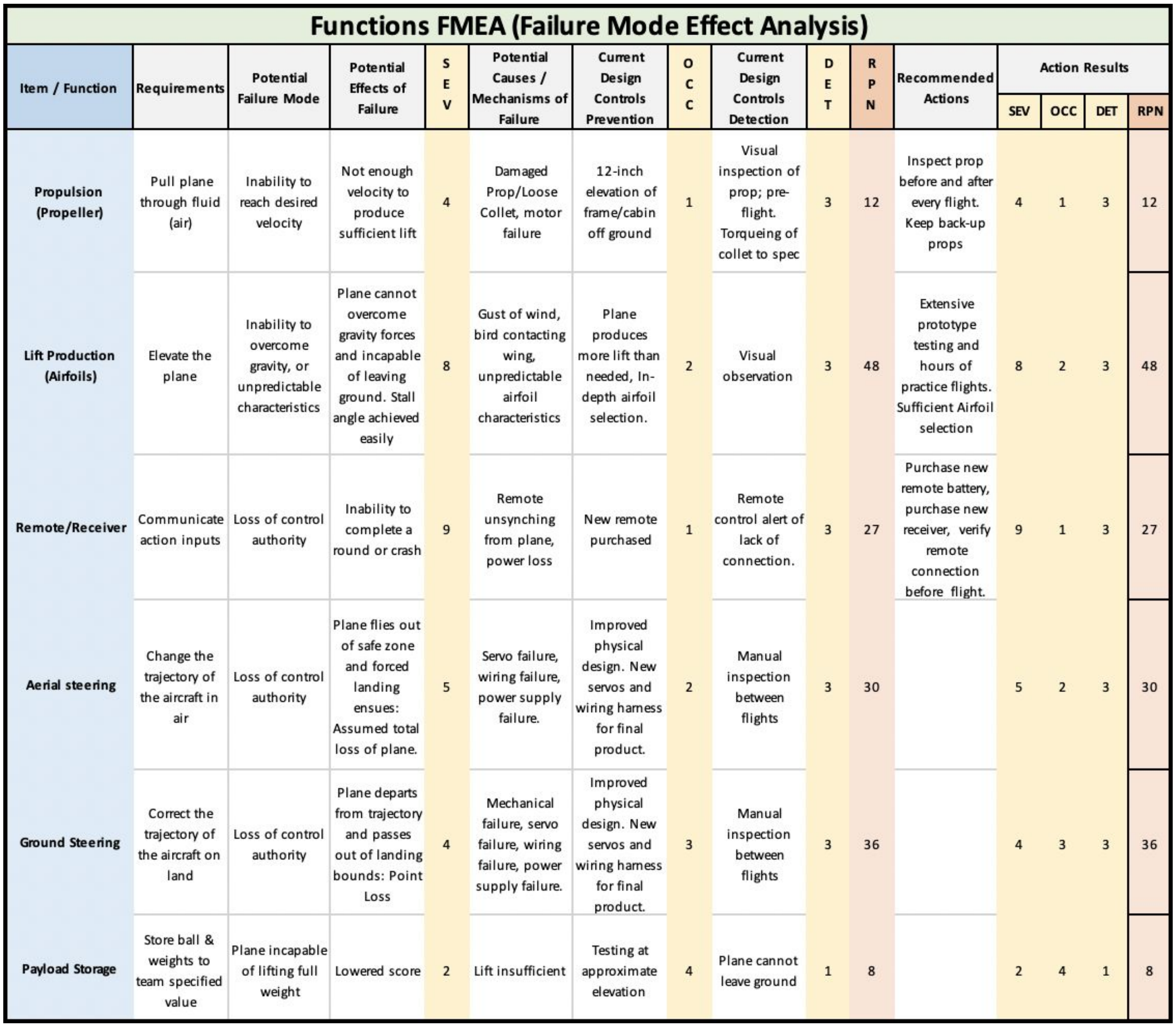
System HoQ		Project:	SAE Aero Regular Class											
		Year:	2020											
		Engineering Requirements												
	Customer Weights	Weight	Power	Cost	Lift	Low Drag	Ease of Assembly/Repair	Velocity	Turning	Load/Unload Time	Cabin Length	Wing Span	Success Rate	Factor of Safety
Ball Capacity	6	3	9	3	3	9		3		9	9	1	1	1
Steel Weight Capacity	9	9	9	1	9	9		3		3	1	1	1	1
Short Wing Span	10	3		3	9	9	1	3	3			9	3	1
Short Cargo Bay	10	3				9	3	9	1	3	9			
Lack of Crash	9	9	9	3	9	9		3	9			1	9	9
Cargo Accessability	5	3	1	1	1	1	9			9			1	
Robust Design	8	1	1	3			1					3	3	9
Reliable Design	7	1	1	3	3	3	1		3	1			3	9
Inside Budget	7		1	9										1
Safe to Operate	10												9	3
Takeoff & Landing Capability	10	9	9	3	9	9		9	1				3	1
Control Authority	8	3	9	3	3			9	9				9	
Manufactuability	10	1		9	1	1	9		3	3	3	3		
Absolute Technical Importance		394	405	341	420	522	190	354	254	193	183	168	368	49
Relative Technical Importance		5	4	8	3	1	10	7	9	11	12	13	6	14
Technical Requirement Units		lbs	Kw	$/Unit	lb	lb	min	mph	rad/s	s	in	in	%	%
Technical Requirement Targets		17	1	500	18	4.23	15	15	0.8	60	8.75	60	95	115
Technical Requirement Tolerence (+-)		2	0	100	3	2.35	5	5	0.01	20	0.5	1	5	2
Testing Procedures*		3	4	3	1, 5	1, 5	1, 3	1, 5	1	2	3	3	1	1, 5



*Testing Procedure Key:	1	Dynamic Flight Test
	2	Static Testing
	3	Prototype Build
	4	Static Thrust Test
	5	Computational Analysis

1.2 *Appendix B: FMEA*

Table B1: Functions FMEA



Functions FMEA (Failure Mode Effect Analysis)

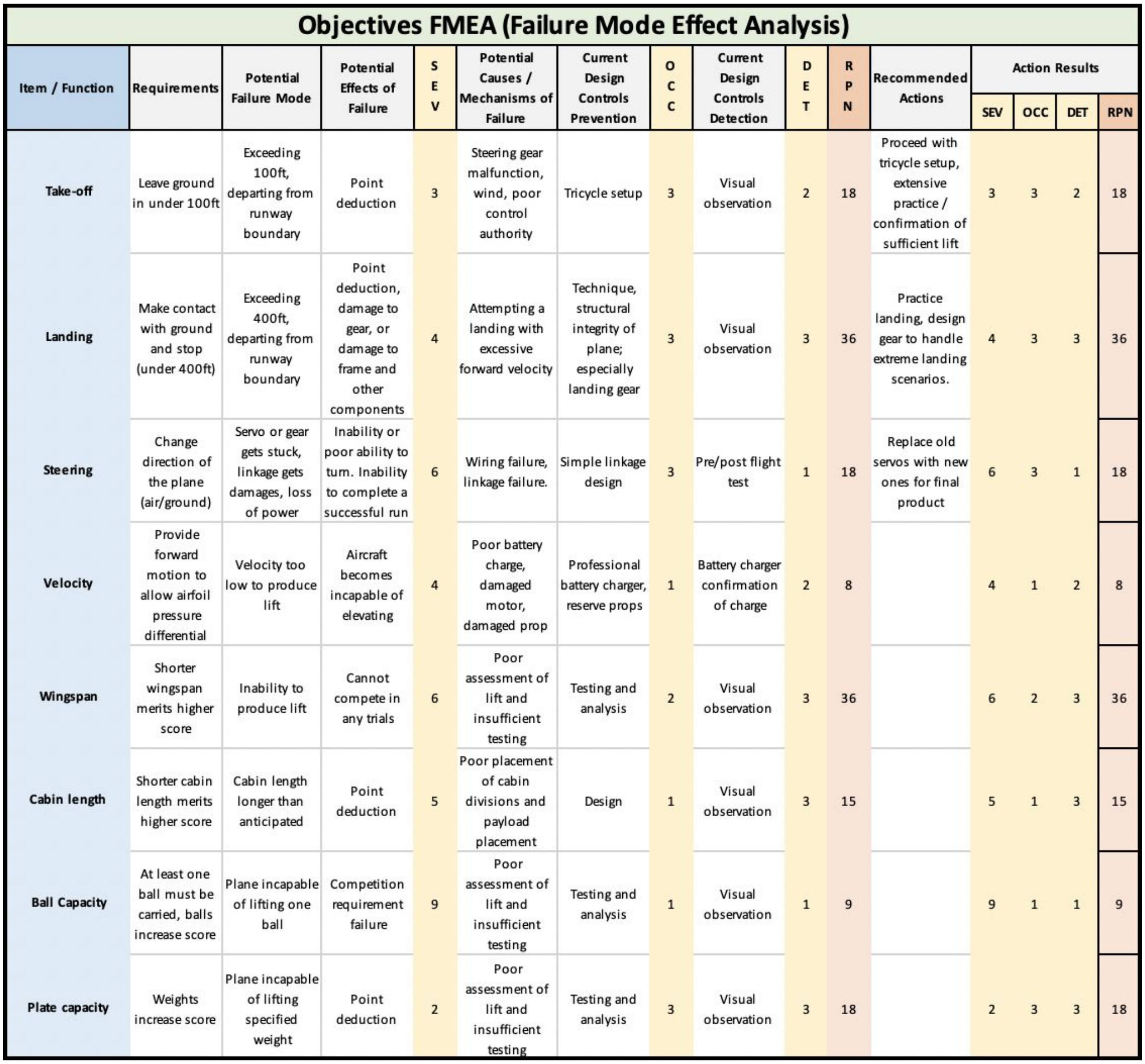
Item / Function	Requirements	Potential Failure Mode	Potential Effects of Failure	SEV	Potential Causes / Mechanisms of Failure	Current Design Controls Prevention	OCC	Current Design Controls Detection	DET	RPN	Recommended Actions	Action Results			
												SEV	OCC	DET	RPN
Propulsion (Propeller)	Pull plane through fluid (air)	Inability to reach desired velocity	Not enough velocity to produce sufficient lift	4	Damaged Prop/Loose Collet, motor failure	12-inch elevation of frame/cabin off ground	1	Visual inspection of prop; pre-flight. Torqueing of collet to spec	3	12	Inspect prop before and after every flight. Keep back-up props	4	1	3	12
Lift Production (Airfoils)	Elevate the plane	Inability to overcome gravity, or unpredictable characteristics	Plane cannot overcome gravity forces and incapable of leaving ground. Stall angle achieved easily	8	Gust of wind, bird contacting wing, unpredictable airfoil characteristics	Plane produces more lift than needed, In-depth airfoil selection.	2	Visual observation	3	48	Extensive prototype testing and hours of practice flights. Sufficient Airfoil selection	8	2	3	48
Remote/Receiver	Communicate action inputs	Loss of control authority	Inability to complete a round or crash	9	Remote unsynching from plane, power loss	New remote purchased	1	Remote control alert of lack of connection.	3	27	Purchase new remote battery, purchase new receiver, verify remote connection before flight.	9	1	3	27
Aerial steering	Change the trajectory of the aircraft in air	Loss of control authority	Plane flies out of safe zone and forced landing ensues: Assumed total loss of plane.	5	Servo failure, wiring failure, power supply failure.	Improved physical design. New servos and wiring harness for final product.	2	Manual inspection between flights	3	30		5	2	3	30
Ground Steering	Correct the trajectory of the aircraft on land	Loss of control authority	Plane departs from trajectory and passes out of landing bounds: Point Loss	4	Mechanical failure, servo failure, wiring failure, power supply failure.	Improved physical design. New servos and wiring harness for final product.	3	Manual inspection between flights	3	36		4	3	3	36
Payload Storage	Store ball & weights to team specified value	Plane incapable of lifting full weight	Lowered score	2	Lift insufficient	Testing at approximate elevation	4	Plane cannot leave ground	1	8		2	4	1	8

Table B2: Structural FMEA

Structural FMEA (Failure Mode Effect Analysis)

Item / Function	Requirements	Potential Failure Mode	Potential Effects of Failure	SEV	Potential Causes / Mechanisms of Failure	Current Design Controls Prevention	OCC	Current Design Controls Detection	DET	RPN	Recommended Actions	Action Results			
												SEV	OCC	DET	RPN
Airfoil Frame	Support pressure differential	Shearing from poor loading, distribution of weight, or design	Loss of airfoil, total loss of aircraft	10	F.O.S too low: gust of wind or landing force	Structural analysis	2	Visual inspection only	7	140	Sufficient analysis & testing	10	2	7	140
Cabin (Ballfoil)	Contain Payload (Weight)	Poor loading, distribution of weight, or design	Damage to entire structure	6	Unsecured payload, bad transfer of forces through members	Structural analysis	1	Visual inspection only	3	18	Sufficient analysis & testing	6	1	3	18
Landing Gear	Allows plane to take-off from ground and land	Poor loading, distribution of weight, or design	Damage to number of members, total destruction of craft.	8	Bad transfer of forces through members, hard impact, poor damping	Structural analysis	4	Visual inspection only	2	64	Sufficient analysis & testing	8	4	2	64
Main Frame Bar	Support all forces and resist all moments	Yielding or stripping of a bolt hole	Lift angles altered or other structural members become compromised	5	Poor placement of forces or mounting holes	Structural analysis	1	None	2	10		5	1	2	10
Empennage	Stabilize flight, provide balancing lift, steering	Failure to stabilize or provide functions	Difficult to control aircraft	6	Poor lift force analysis	Lift force balancing	2	None	3	36		6	2	3	36
Steering Gear servo linkage	Change direction of plane on ground	Servo detaches from gear	Inability to control direction	7	F.O.S too low, damage on landing	Simpler design	1	Visual inspection only	2	14		7	1	2	14
Airfoil servo linkage	Change direction of plane in air	Servo linkage damaged	Inability to steer in air	7	F.O.S too low or gust of wind	Increased F.O.S	2	Visual inspection only	1	14		7	2	1	14
Elevator	Change angle of attack	Servo damaged	Unable to alter angle of attack and loss of altitude	5	Poor empennage analysis	Lift force balancing	2	None	1	10		5	2	1	10
Motor Mount	Secure motor to main frame, resist moments and forces	Yielding or stripping of a bolt hole	Motor is free to translate, damage of motor, propeller, or wiring harness	4	F.O.S too low	Structural analysis	1	None	3	12		4	1	3	12
Airfoil (Foam)	Support pressure differential	Shearing from poor loading, distribution of weight, or design	loss of airfoil performance, possible destruction of craft	6	Foam incapable of transferring forces to airfoil frame	Structural analysis	3	Visual inspection only	3	54		6	3	3	54

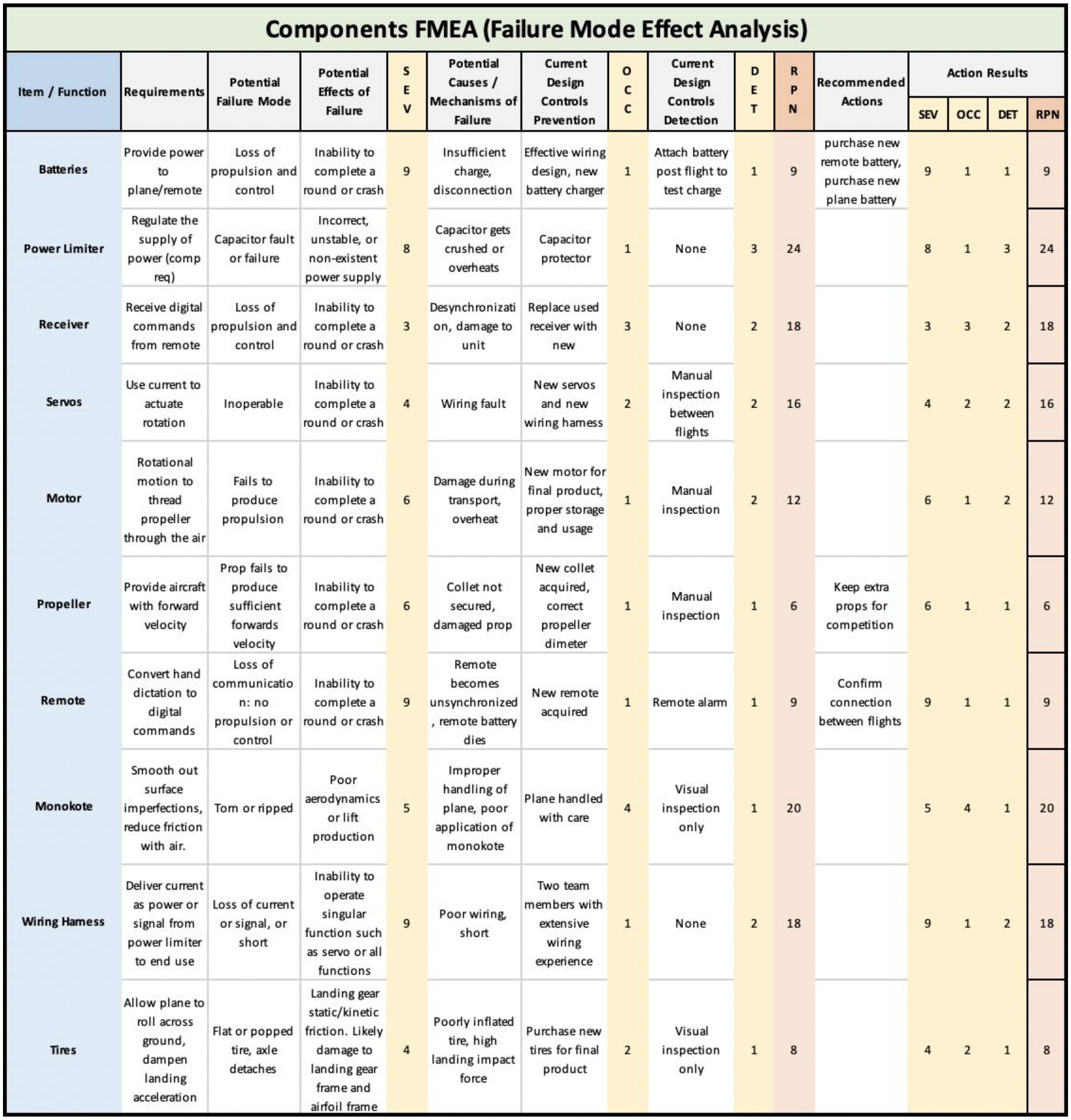
Table B3: Objectives FMEA



Objectives FMEA (Failure Mode Effect Analysis)

Item / Function	Requirements	Potential Failure Mode	Potential Effects of Failure	S E V	Potential Causes / Mechanisms of Failure	Current Design Controls Prevention	O C C	Current Design Controls Detection	D E T	R P N	Recommended Actions	Action Results			
												SEV	OCC	DET	RPN
Take-off	Leave ground in under 100ft	Exceeding 100ft, departing from runway boundary	Point deduction	3	Steering gear malfunction, wind, poor control authority	Tricycle setup	3	Visual observation	2	18	Proceed with tricycle setup, extensive practice / confirmation of sufficient lift	3	3	2	18
Landing	Make contact with ground and stop (under 400ft)	Exceeding 400ft, departing from runway boundary	Point deduction, damage to gear, or damage to frame and other components	4	Attempting a landing with excessive forward velocity	Technique, structural integrity of plane; especially landing gear	3	Visual observation	3	36	Practice landing, design gear to handle extreme landing scenarios.	4	3	3	36
Steering	Change direction of the plane (air/ground)	Servo or gear gets stuck, linkage gets damages, loss of power	Inability or poor ability to turn. Inability to complete a successful run	6	Wiring failure, linkage failure.	Simple linkage design	3	Pre/post flight test	1	18	Replace old servos with new ones for final product	6	3	1	18
Velocity	Provide forward motion to allow airfoil pressure differential	Velocity too low to produce lift	Aircraft becomes incapable of elevating	4	Poor battery charge, damaged motor, damaged prop	Professional battery charger, reserve props	1	Battery charger confirmation of charge	2	8		4	1	2	8
Wingspan	Shorter wingspan merits higher score	Inability to produce lift	Cannot compete in any trials	6	Poor assessment of lift and insufficient testing	Testing and analysis	2	Visual observation	3	36		6	2	3	36
Cabin length	Shorter cabin length merits higher score	Cabin length longer than anticipated	Point deduction	5	Poor placement of cabin divisions and payload placement	Design	1	Visual observation	3	15		5	1	3	15
Ball Capacity	At least one ball must be carried, balls increase score	Plane incapable of lifting one ball	Competition requirement failure	9	Poor assessment of lift and insufficient testing	Testing and analysis	1	Visual observation	1	9		9	1	1	9
Plate capacity	Weights increase score	Plane incapable of lifting specified weight	Point deduction	2	Poor assessment of lift and insufficient testing	Testing and analysis	3	Visual observation	3	18		2	3	3	18

Table B4: Components FMEA



Components FMEA (Failure Mode Effect Analysis)

Item / Function	Requirements	Potential Failure Mode	Potential Effects of Failure	SEV	Potential Causes / Mechanisms of Failure	Current Design Controls Prevention	OCC	Current Design Controls Detection	DET	RPN	Recommended Actions	Action Results			
												SEV	OCC	DET	RPN
Batteries	Provide power to plane/remote	Loss of propulsion and control	Inability to complete a round or crash	9	Insufficient charge, disconnection	Effective wiring design, new battery charger	1	Attach battery post flight to test charge	1	9	purchase new remote battery, purchase new plane battery	9	1	1	9
Power Limiter	Regulate the supply of power (comp req)	Capacitor fault or failure	Incorrect, unstable, or non-existent power supply	8	Capacitor gets crushed or overheats	Capacitor protector	1	None	3	24		8	1	3	24
Receiver	Receive digital commands from remote	Loss of propulsion and control	Inability to complete a round or crash	3	Desynchronization, damage to unit	Replace used receiver with new	3	None	2	18		3	3	2	18
Servos	Use current to actuate rotation	Inoperable	Inability to complete a round or crash	4	Wiring fault	New servos and new wiring harness	2	Manual inspection between flights	2	16		4	2	2	16
Motor	Rotational motion to thread propeller through the air	Fails to produce propulsion	Inability to complete a round or crash	6	Damage during transport, overheat	New motor for final product, proper storage and usage	1	Manual inspection	2	12		6	1	2	12
Propeller	Provide aircraft with forward velocity	Prop fails to produce sufficient forwards velocity	Inability to complete a round or crash	6	Collet not secured, damaged prop	New collet acquired, correct propeller dimeter	1	Manual inspection	1	6	Keep extra props for competition	6	1	1	6
Remote	Convert hand dictation to digital commands	Loss of communication: no propulsion or control	Inability to complete a round or crash	9	Remote becomes unsynchronized, remote battery dies	New remote acquired	1	Remote alarm	1	9	Confirm connection between flights	9	1	1	9
Monokote	Smooth out surface imperfections, reduce friction with air.	Torn or ripped	Poor aerodynamics or lift production	5	Improper handling of plane, poor application of monokote	Plane handled with care	4	Visual inspection only	1	20		5	4	1	20
Wiring Harness	Deliver current as power or signal from power limiter to end use	Loss of current or signal, or short	Inability to operate singular function such as servo or all functions	9	Poor wiring, short	Two team members with extensive wiring experience	1	None	2	18		9	1	2	18
Tires	Allow plane to roll across ground, dampen landing acceleration	Flat or popped tire, axle detaches	Landing gear static/kinetic friction. Likely damage to landing gear frame and airfoil frame	4	Poorly inflated tire, high landing impact force	Purchase new tires for final product	2	Visual inspection only	1	8		4	2	1	8

1.3 Appendix C: Calculations

Table C1: Flight Characteristic Calculator Based off Simulation Results

Propeller Properties	
Prop	Tested
Pitch	8
Diam	16
RPM	7484

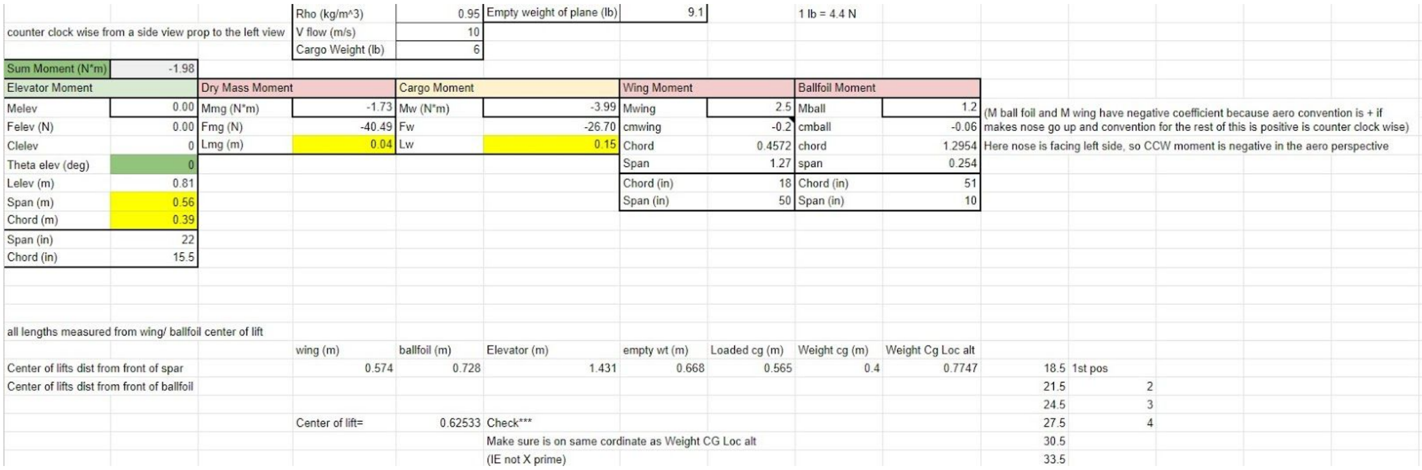
Airfoil Properties	
Airfoil	S1223
Planform Area (m^2)	0.95128842
CD	0.32002
CL	1.44472

Misc Parameters	
Weight (lbs)	11.00
Mass	4.99
Air Density	0.97
Time Interval (s)	0.50

Planform Area Calculator			
Part	Span (m)	Chord (m)	Total
Main Foils	0.635	0.4572	0.580644
Ball Foil	0.127	1.1303	0.1435481
Empenagge HS	0.2794	0.4064	0.22709632
		Total	0.95128842

Time (s)	Distance (dx)	Velocity (m/s)	Thrust (N)	Drag	Acceleration (m/s)	Lift (N)	Lift (Lb)	Score
0	0.00	0.00	38.22	0.00	7.66	0.00	0	-7.322834646
0.50	0.00	3.83	32.44	2.17	6.07	9.78	2.197758113	-3.861798247
1.00	1.91	6.86	27.87	6.96	4.19	31.40	7.059457861	3.794421828
1.50	5.35	8.96	24.71	11.85	2.58	53.50	12.02811529	11.6190792
2.00	9.83	10.25	22.77	15.51	1.46	70.00	15.73603662	17.45832538
2.50	14.95	10.98	21.67	17.78	0.78	80.29	18.04973463	21.1019443
3.00	20.44	11.36	21.08	19.07	0.40	86.08	19.35243066	23.15343412
3.50	26.12	11.57	20.78	19.75	0.21	89.17	20.04556921	24.24499088
4.00	31.90	11.67	20.62	20.10	0.10	90.76	20.40350231	24.80866505
4.50	37.74	11.72	20.54	20.28	0.05	91.57	20.58550579	25.09528471
5.00	43.60	11.75	20.50	20.37	0.03	91.98	20.6773282	25.23988693
5.50	49.47	11.76	20.48	20.42	0.01	92.18	20.72347033	25.3125517
6.00	55.35	11.77	20.47	20.44	0.01	92.29	20.74661133	25.34899422
6.50	61.23	11.77	20.47	20.45	0.00	92.34	20.75820533	25.36725248
7.00	67.12	11.77	20.47	20.46	0.00	92.36	20.76401119	25.37639558
7.50	73.00	11.77	20.47	20.46	0.00	92.38	20.76691783	25.38097297

Table C2: Pitch Moment Calculator



counter clock wise from a side view prop to the left view

Rho (kg/m^3)	0.95	Empty weight of plane (lb)	9.1
V flow (m/s)	10		
Cargo Weight (lb)	6		

1 lb = 4.4 N

Sum Moment (N*m)	-1.98

Elevator Moment		Dry Mass Moment		Cargo Moment		Wing Moment		Ballfoil Moment	
Melev	0.00	Mmg (N*m)	-1.73	Mw (N*m)	-3.99	Mwing	2.5	Mball	1.2
Felev (N)	0.00	Fmg (N)	-40.49	Fw	-26.70	cmwing	-0.2	cmball	-0.06
Clelev	0	Lmg (m)	0.04	Lw	0.15	Chord	0.4572	chord	1.2954
Theta elev (deg)	0					Span	1.27	span	0.254
Lelev (m)	0.81					Chord (in)	18	Chord (in)	51
Span (m)	0.56					Span (in)	50	Span (in)	10
Chord (m)	0.39								
Span (in)	22								
Chord (in)	15.5								

(M ball foil and M wing have negative coefficient because aero convention is + if makes nose go up and convention for the rest of this is positive is counter clock wise)

Here nose is facing left side, so CCW moment is negative in the aero perspective

all lengths measured from wing/ ballfoil center of lift

	wing (m)	ballfoil (m)	Elevator (m)	empty wt (m)	Loaded cg (m)	Weight cg (m)	Weight Cg Loc alt		
Center of lifts dist from front of spar	0.574	0.728	1.431	0.668	0.565	0.4	0.7747	18.5	1st pos
Center of lifts dist from front of ballfoil								21.5	2
								24.5	3
	Center of lift=	0.62533	Check***					27.5	4
			Make sure is on same cordinate as Weight CG Loc alt					30.5	
			(IE not X prime)					33.5	