SAE Micro Airplane

Final Report

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ME 486C Section 002 Fall 2019

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Executive Summary

The SAE Aero Design Competition is an annual competition between colleges and universities. Sponsored by the Society of Automotive Engineers, teams from around the country come together to compete to see who can design and implement the best airplane based on rules made by SAE. This year, Northern Arizona University students David Anaya, Frank Bendel, Wyatt Goddard, Sam Harsha, and Andrew Van Doren gave their best efforts to design a completely new airplane for the micro class competition. The airplane was designed to fit inside an 11.875’’ x 13.625’’ x 3.375’’ box disassembled, assembled in 180 seconds, under 60 seconds preferred. and flown with as much PVC pipe payload as possible. Although the team were not able to attend the competition this year due to a summer-fall schedule, these design requirements were followed strictly as if it was to be flown at competition. This year’s plane differs from previous teams due to being a twin boom design.There is no use of a hollow fuselage, instead the plane is simplified into carbon fiber rods, aluminum bayonet mounts, wooden ribs and tail sections, and 3D printed trailing edges, landing gear and electronics tray. The team chose a 2200 mAh battery to power 2 propellers working in parallel to achieve lift on 3 wing segments made from an S1223 airfoil. On December 6th, 2019 the plane underwent a flight test. Unfortunately, the results were not what was expected. The center of gravity was further back than anticipated after adding landing gear, therefore, the battery, wiring, and payload were moved forward to compensate. On a runway take off, the front landing gear broke and no lift was achieved. After removing the failed pieces, a throwing takeoff was attempted. The plane rolled and drove itself into the ground. Ideas for further improvement are detailed within.

Acknowledgments

The SAE Micro Aero Design team would like to acknowledge the students, faculty, and sponsor mentors that helped us along the way. First we would like to thank Dr. David Trevas for being our professor and allowing us to take the reins on our design project. We had full creative control and he pushed us along to meet our goals. We would also like to thank Dr. John Tester for being our client and a valuable mentor. He allowed us to use his RAPID Lab to 3D print our designs and directing us with his many years of experience. We would like to thank Tim Kelly, and the rest of the Flagstaff Flyers for being an invaluable resource for manufacturing our plane parts and advice. Perry Wood for allowing us to use the Fabrication Lab, Machine Shop, and Composites lab as well as his expertise on composites and manufacturing processes. Lastly, Rockwest Composites for sponsoring our team with discounts on their products.

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1 BACKGROUND

1.1 Introduction

SAE Micro Aero team designed and built a plane that meets the criteria of the SAE Aero Micro competition rules. The 2 major practical restraints are the box dimensions that the plane and payload must fit into, and the type of propulsion system must be electric with batteries that don't exceed a defined capacity. The scoring for the competition is based on 3 equations that we must maximize: Assembly Demo, Flight Score, and Final Flight Score. To maximize our score we carried as large of a payload through the air as we can. To do this we designed a 2 boom airframe, pulled by 2 electric motors with the payload hanging between and below the booms. By relying on a small flight time and a high velocity craft, we can carry more payload. The aircraft must also quick to assemble.

1.2 Project Description

The original project description was to build a mini airplane that follows the rules of the SAE Micro Airplane competition. This competition entails creating a lightweight airplane that has a high load capacity. Also taken into consideration is the amount of time the aircraft remains in flight and whether or not the aircraft can complete the course. The final requirement is that the aircraft fit into a predetermined box assembled or disassembled. There is a point system to determine which of the aircraft completes the course with the most weight for the longest time in the air and with low assembly time.

1.3 Original System

This project involved the design of a completely new micro-airplane. There was no original system when this project began.

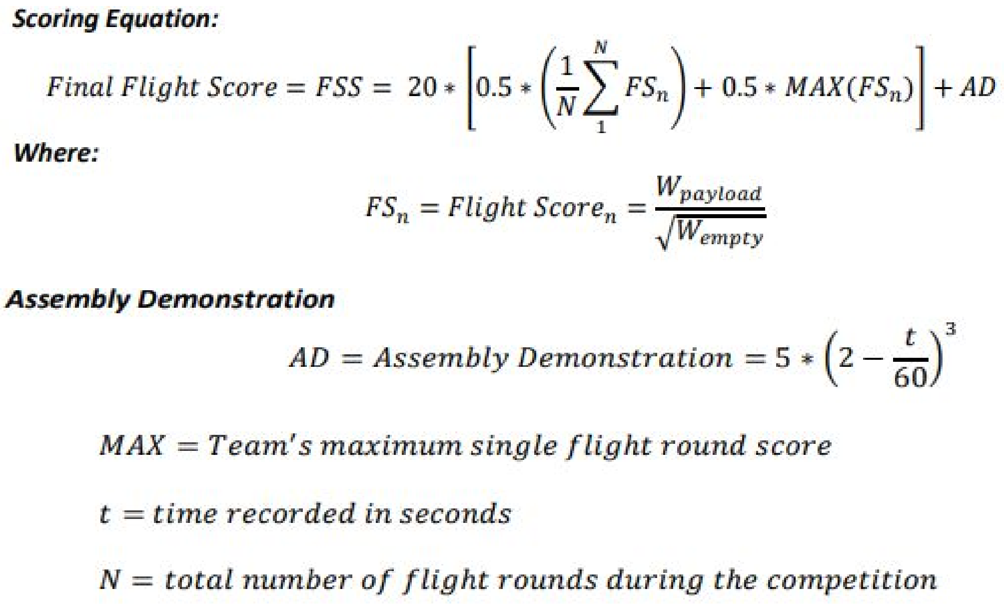
2 REQUIREMENTS

The necessities of this micro-airplane design are described in detail in the SAE Aero 2020 Rule Book. Because our customer is technically Dr Tester and the NAU Engineering department, instead of a third party, who didn't give us any specific requirements other than the SAE competition rules, we will describe the Customer requirements in terms of the rules and scoring criteria. The Engineering requirements will be in terms of the specific challenges the team accommodated for.

2.1 Customer Requirements (CRs)

Customer requirements for the Micro class of the Aero competition are described in section 9 of the rules. This includes several key requirements.

- Must use electric motors
- Individual Batteries must not exceed 2200mAh 3s capacity
- Plane and Payload must fit into a 11.875'' x 13.625'' x 3.375'' medium sized shipping box
- The plane itself must be assembled in 180 seconds or less
- Must be hand thrown or launched
- Must fly around a closed course both with and without a payload



Scoring Equation:

$$Final\ Flight\ Score = FSS = 20 * \left[0.5 * \left(\frac{1}{N}\sum_{1}^{N} FS_n\right) + 0.5 * MAX(FS_n)\right] + AD$$

Where:

$$FS_n = Flight\ Score_n = \frac{W_{payload}}{\sqrt{W_{empty}}}$$

Assembly Demonstration

$$AD = Assembly\ Demonstration = 5 * \left(2 - \frac{t}{60}\right)^3$$

$MAX = Team's\ maximum\ single\ flight\ round\ score$

$t = time\ recorded\ in\ seconds$

$N = total\ number\ of\ flight\ rounds\ during\ the\ competition$

Figure 1: Scoring of Competition

The above scoring equations are the way that the SAE judges judge each team's performance during the competition. The Flight Score and the Assembly Demonstration are the 2 biggest determining factors toward our engineering requirements that can be designed for and built into the plane. The final flight Score and it's variables have much more to do with the skill of the launchers and the flyers as well as the overall quality of the design and its ability to fly in calm or austere conditions.

2.2 Engineering Requirements (ERs)

The 3 biggest CRs that inform the Engineering Requirements are the:

- Box Size
- Weight of the Payload Vs Weight of the Plane
- Assembly Time

Box dimensions are the biggest limitation that must be accounted for. In order to most efficiently use the space, the team decided to use the second longest dimension as the limiting width dimension. Meaning that no single part of the plane is longer than 11.75”. Our payload, boom sections and wing sections all fit into the box in that orientation. Minimizing the weight of the plane is highly critical but we also need the plane to be strong enough to survive minor crashes. Our original design utilized carbon fiber and we had intended to craft this all ourselves, however it proved to be too expensive to do so. Instead we decided to use pultruded rods, a cheaper and faster alternative to the long process of carbon fiber crafting. Pultruded rods offers almost identical results in terms of strength and weight, keeping the second requirement satisfied. This also will not affect our assembly time at the competition, nor the space in the box as compared to using the carbon fiber. The weight of the plane design is roughly 3.5lb, and we estimated 9lbs of lift. The difference in these values is where the payload is located. To maximize our payload, if we have exactly 9lb of lift, and the plane weighs exactly 3.5lb, we can add up to 5.5lb of payload with one catch. The payload must also fit inside the box, dimensioned 11.875” x 13.625” x 3.375”. The assembly time must be under 180 seconds to receive points in this category, but minimizing the time allows for maximum points.

2.3 Testing Procedures (TPs)

Testing procedures for each requirement are as follows. First for the box size, we are ensuring that each part will fit within the dimensions outlined, no part will exceed 11.75” in length. For the wing sections we plan to lay them on top of each other in the box, staggered a small amount to allow for more space on top of these sections. We also have two test boxes that we have cut the tops open on to test placing items in different orientations. Second, with the variable amount of payload, we are able to choose exactly what sections of tubing we will be using, and cut them to length for the correct weight. We will be placing these centered on the underside of the aircraft to balance the weight around the center of gravity. Third, we will test the assembly time with a stopwatch or timer and mimic the settings of the competition. Using the designed fittings, pre-assembled “in the box” items, and quick fasteners we will be able to test our assembly time under the same conditions and using the same parts that would be for competition. Fourth, being hand thrown or hand launched we will be testing this in a large field with ample space to throw the plane and fly in. It is preferable to have only one person throw the plane for every flight, and we will be testing as such, however it may be necessary to exchange throwers. Fifth, flying the aircraft is where almost all of our testing is focused. Through flight simulations we will decide who our best pilot is and they will be testing flying the real aircraft. They will be responsible for flying with and without the payload, following the route designed for the competition, and landing the plane.

2.4 Design Links (DLs)

Design link one will be for the box size. As mentioned the space allotted is only 11.875” x 13.625” x 3.375” so the longest any single part can be is 11.75”. To save space in the box, we placed items inside the tubes of the payload and the wings are staggered in the box to give more space to place something on top.

Design link two addresses the payload. Since this is variable, we can choose how much we carry depending upon our lift. We can cut sections of tubing to be shorter, allowing us to manipulate the payload weight in minor amounts. Only manipulating one section of tube (out of three) allows us to keep the other two balanced over the center of gravity, so that we only have to move one dependent on how much we remove.

Design link three is for the assembly time. We will meet the engineering requirement by imitating exactly the settings of the competition. Having all of our items in the box ready to assemble, then being timed during assembly, and calculated on the same scoring that will be in the competition will accomplish this.

Design link four will be testing different people who will be throwing. Those of us with a longer wingspan will be better to have throwing if we need to send it at a much higher speed. Also to have multiple people used to throwing the plane would be better, in case we have to exchange the current one for any reason. However this means that training more people to throw the plane could end up in a disaster when someone is learning.

Design link five will be for piloting the aircraft. This begins with training on the flight simulator, where determine who is likeliest to be our real pilot. From there we trained as much as possible with the Flagstaff Flyers and their training aircraft. This helped us learn to land the plane. Finally we will be testing with our own plane, with lots of replacement parts on hand.

2.5 House of Quality (HoQ)

The house of quality has been an important part of our design process. It allows us to evaluate the importance of different individual parts of the project, and compare them to each other. The main elements of the HoQ are the Engineering and Customer requirements. Those requirements as laid out above are compared to each other in the house of quality, allowing us to find our most important aspects. In this HoQ, the importance of each requirement as related to each other as we have found them are as follows. The most important is flying the aircraft, followed by the payload weight, then the aircraft weight, then the lift of the aircraft, then the volume of the box, followed by the throwing of the plane at takeoff, and finally ending with the assembly time. These importances of the engineering requirements are dependent upon how they relate to each other, the customer requirements, and not always the competition requirements. For example, the assembly time is a major priority in the competition, but does not directly relate to many of the other requirements. An image of the house of quality can be found in Appendix A.

3 EXISTING DESIGNS

There are quite a few designs for teams that competed in the SAE Aero Micro Competition. Many of the designs are similar to each other. Our team wanted to find a unique solution to this problem.

3.1 Design Research

Research began by watching videos on Youtube from the last several years of competitions and searching for different websites for the teams that scored highly. Unfortunately many of the team websites weren't well documented with their process or specifications, so most of the research on other competing teams is anecdotal. The winner of last year's Micro class was the Georgia Tech team. They achieved success with a unique flying wing design that had the payload incorporated into the airframe itself which maximized the allowable payload and minimize aircraft weight. Their design was powered by a single motor pusher prop.

3.2 System Level

By far the most prolific design for planes competing in the Micro division is the Single motor, Single Boom, Puller prop, Straight wing, design. Our team wanted to do something unique so in addition to trying to find out the other competition submissions we also just looked at the different kinds of unique airframes and propulsion systems of regular RC aircraft. Unfortunately there were no commercially sold RC planes that carry variable payloads.

3.2.1 Existing Design #1: Flying Wing

The winning design from the last competition was a flying wing design. The problem with a flying wing is that it's difficult to attach a payload to it without messing up the aerodynamics of the airfoil. There is also a problem with making the wing collapsable in order to fit it in the regulation sized box. Because of these problems and the fact that getting a custom flying wing stable in flight, the team's confidence with solving these problems was not high enough for us to attempt this design.

3.2.2 Existing Design #2: Electric Ducted Fan Bi-plane

This design was promising but had the disadvantage of being relatively bulky and having a lot of drag in between the airfoils where the payload would have to go. The Biplane has a lot of lift for its size but isn't as stable in flight at such a small scale compared to airframes with wider wingspans.

3.2.3 Existing Design #3: Single Motor Monowing

By far the simplest and most ubiquitous design this plane is easy to assemble, and very lightweight for the lift that it provides. These planes are intuitive to fly and do so easily without a payload. The problem with this design is getting a secure and lightweight method of carrying a payload. Also since it's so simple and easy to build many different teams us this design but they are very difficult to make competitive since the design is so limited.

3.3 Subsystem Level

There are 3 major subsystems for our Airplane that needed to be considered for our design. The Airframe, which includes the airfoil, and superstructure of the craft, the Power and Propulsion system which involves the method of thrust and getting air to pass over the airfoil to create lift, and the Avionics and Stability which includes the control surfaces and methods for attitude adjustment.

3.3.1 Subsystem #1: Airframe

The Airframe is by far the biggest part of the aircraft and the most important part of that is the Airfoil that creates the lift for our craft and payload. In general the airframe of the aircraft can be considered as the aircraft structure itself. The airframe consists of the wing, fuselage, tail, and any other structural components, including control surfaces.

3.3.1.1 Existing Design #1: Flying wing design

Flying wings are a highly simplified airframe where as much of the aircraft is incorporated into the airfoil itself. There is a great deal of efficiency in this design if properly planned out and implemented. The biggest problem with this design is that there aren't many places to mount a payload to the aircraft without significantly affecting the performance of the airfoil. One of the previously winning teams got around this problem by incorporating the payload in between sections of the craft. Another consideration that must be taken into account with in implementing a flying wing is the stability and control of the platform. Normal control models do not apply to the flying wing as the control surfaces on board a flying do not compare directly to those on board a conventional platform.

3.3.1.2 Existing Design #2: Bi-Plane design

A bi-plane has a large amount of lift for its wingspan and overall size. More lift allows the design to carry a larger payload. However because the wingspan is shorter it's has less level stability in flight when being powered by an electric motor without a large rotational mass. Also the obvious place to put the payload and motors, in between the top and bottom airfoil, would require a more rigid and stable support structure requiring more weight. Placing the payload between the wings also creates the possibility of spoiling the lift created by the upper wing, thus defeating the advantage of a biplane altogether. This is, however, something that could be designed around by increasing the distance between the two wings, but would result in an increasingly complex design.

3.3.1.3 Existing Design #3: Monoplane design

This is by far the most common design for RC model airplanes. It can be easily attached to a wide assortment of different airframe configurations and payloads. Wider wingspan gives greater level stability in flight and also allows for greater effect on control surfaces on the airframe by having longer moment arms. The wings being by themselves and away from the rest of the aircraft also means that the fluid effects are less susceptible to secondary influences of the rest of the aircraft. Finally, the monoplane is a simple design. Incorporating a parasol wing allows the center of gravity of the plane to hang below the wing and contribute to the stability of the aircraft. In addition, the payload will be able to hang directly beneath the wing and avoid disturbing the flow of air below the wing at the sametime.

3.3.2 Subsystem #2: Power and Propulsion

Power and Propulsion (P&P) are the most important parts of powered flight and keeping the aircraft in the air longer than it could otherwise remain just by gliding. There are many different systems that can be used to power an aircraft but since the SAE rules only allow electric motors, we will focus on those.

3.3.2.1 Existing Design #1: Electric Ducted Fan

Electric Ducted Fans (EDF's) are typically used in high thrust applications. In the RC would they are used on scaled down airframes that have jet turbines in the full scale craft. A big limitation of these is that they are very power hungry and depending on the size, require large batteries with a high "C" rating. (The rated maximum discharge rate the battery can safely handle.) Those batteries are expensive and weigh more the higher their capacity is.

3.3.2.2 Existing Design #2: Single Motor Driven Prop

The great thing about this P&P system is its versatility. Any one of the components can be replaced to get more efficiency or endurance or power. It's very useful in fine tuning a design if you want to get the maximum amount of granularity in your system. You can design a system for maximum power output or a happy medium between the 3. Most of the RC Airplane Hobby is centered around this P&P for these very reasons.

3.3.2.3 Existing Design #3: Multiple Motor Driven Propellers

A Multi Motor Driven Propeller (MMDP) design gives you just as much versatility as a single motor but with some added benefits and a few drawbacks. It's more complex and therefore more that can break and that needs to be maintained. The extra complexity adds weight to the airframe but that is typically offset by the added thrust and increase in airspeed which creates more lift. The biggest drawback is that the added motor or motors draws a proportionate amount of current from the battery, possibly requiring a higher "C-rated" and more expensive battery.

3.3.2.4 Subsystem #3: Avionics and Stability

Simply put, Avionics and Stability are the sub-system that allow you to get the plane to do what you want it to do... To head in the direction that you want, in the way that you want, and with enough repeatability to make it predictable. The stability of the aircraft is influenced by its overall geometry and mass locations. In creating a design that is stable, it is important to consider what forces will be acting on the aircraft and where they will be acting. An example of the importance of this is to consider an aircraft on take off that has it center of mass behind the mean aerodynamic chord. As the aircraft begins to create lift, the lift will begin to create a pitch up moment around the center of gravity. Once the center of gravity becomes airborne, the pitch up moment created at the mean aerodynamic chord and the rearward center of gravity will create an increasing pitch up couple. This increasing pitch up couple will have to be trimmed by the elevator, and if it is not possible to trim for this couple, the aircraft will stall immediately upon take off. Creating sufficient control surfaces and locating the center of gravity in the correct location will allow the aircraft to be a controllable platform.

3.3.2.5 Existing Design #1: 3 Channel

One of the most simple RC airplane avionics systems is a 3 channel system. One channel for the throttle signal, and the 2nd and 3rd channels are for controlling individual servos that affect the elevator and rudder. While it doesn't give the airplane the ability to do a lot of maneuvers, it is simple and removes many of the variables in flying a plane. They are typically used for beginner pilots to allow them to get used to the basics of flying without over complicating the options that the pilot has to choose from. This design is typically used in tandem with a dihedral wing to add stability to level flight.

3.3.2.6 Existing Design #2: Aileron Controlled

An aileron controlled plane is more complicated than a 3 channel aircraft. Ailerons are control surfaces that are on the trailing edge of the wings and they allow the plane control over the roll attitude. Aileron means little wing in french and behaves in a realteable manner. The ailerons on the trailing edge of the wings rotate up and down, and cause the camber of the wing as a whole to change. By changing nature of the camber of the wing, the total lift force that the wings generates can be controlled. By deflecting an aileron upward, the lift that a wing creates will fall. Thus a wing that has an aileron is deflected upward will fall. A wing that has an aileron deflected downward will rise. This allows the plane to bank and to climb and dive more dramatically. These add more unpredictability in the capabilities of the craft and more things to keep track of. These added controls are best used by experienced pilots. In application to our design, we opted for a three channel aircraft due to the design constraints placed upon us by the competition rules. We found that it would be easier to create a three channel aircraft that would assemble and disassemble quickly rather than a four channel aircraft with operating ailerons.

3.3.2.7 Existing Design #3: Gyroscopic Stabilization

One option for adding stability and predictability to an RC plane is adding a gyroscopic unit to the airplane. This device will help keep the aircraft from drifting so much from its course and heading. They are allowed in the rules but the effectiveness of having something like this on a bare bones aircraft at the cost of losing some payload may not be worth it.

4 DESIGNS CONSIDERED

The designs that the team considered are basically different combinations of the various subsystems that we've broken down the problem into. There are also different ways of associating those subsystems, whether it be a hollow fuselage or a skeletonized airframe.

4.1 Design #1: Single Boom Single Motor Monoplane

The typical plane thats used for the SAE Aero Micro competition is the skeletonized single motor mounted to the end of a single boom that has a single airfoil attached to the boom and very simple rudder and elevator controls. Major limitations of this design are that there is no special design considerations to the specific ERs of the problem at hand other than perhaps the box size limitation. This solution is effectively taking and existing flying craft and trying to adapt it, ex post facto, to the problem. Unfortunately this means that the plane won't be able to carry a significantly large payload because there isn't much of a place to attach it to. On the positive side, many of the previous NAU teams attempted to use this design so there are lots of parts and components left over from the previous planes that our team can use so we can allocate a larger portion of our budget to other things.

4.2 Design #2: Dual Boom Pusher Prop Monoplane

A pusher prop aircraft isn't uncommon at the competition but it's still a little more unique than design #1. The dual boom design allows for a little more stability in the airframe which means that it will be capable of carrying a larger payload. While the design has an aesthetic quality there isn't really a great advantage to a pusher prop vs a puller prop design, other than shifting the center of gravity further back which would allow for the payload to be situated further toward the front. Control surface actuation and other components that have been used on previous NAU designs would also be usable for this design.

4.3 Design #3: Dual Boom Overhead EDF Monoplane

An overhead EDF is similar to a pusher prop in that it shifts one of the heaviest parts of the plane closer to the center of gravity. One of the benefits of an EDF is that it's fully enclosed (in the duct) and generates a large amount of thrust for the size of the motor in the assembly. Because of this, EDF's brings a high power to weight ratio which means that more of the lift capacity of the aircraft can be allocated to the payload. There are no spare EDFs available in the NAU SAE Aero cabinet so that would mean that we would have to buy extra components taking away from the room in our budget that we could use for strong and light-weight aircraft.

4.4 Design #4: Single Hulled Multiple EDF Monoplane

Instead of doing a skeletonized airframe that we attach components and the payload to a custom designed aircraft body that would incorporate dual ducted fans under the airfoil next to the fuselage. Using EDFs in this manner would allow the vertical profile of the plane to be much lower since the landing gear doesn't need to be tall enough to keep the propellers from hitting the ground during landing. The fuselage could be designed to contain the payload to keep it from contributing to aerodynamic drag and would be able to carry more and faster than a single EDF design due to the multiple motors. However that would put a large draw on the battery requiring a higher costing high C-rating. Also the NAU SAE Aero supplies don't have any spare EDF's so this design puts more strain on the budget than other designs.

5 DESIGN SELECTED – First Semester

After some extensive research and analysis the team came to a decision for a final design at the end of the first semester. We believe this design performs to the best capacity and earn the team the best ranking in the competition

5.1 Rationale for Design Selection

The team came to the conclusion that using a two boom aircraft with the S1223 airfoil style for the wing would be the best design for the competition. The two boom design was selected as it gave the team the chance to use two motors meaning two propellers allowing the team to get more thrust and lift more weight. The booms are made of carbon fiber which is lightweight but extremely strong. The S1223 airfoil gives the team the best lift to drag ratio meaning that there is a high coefficient of lift with a low amount of drag. This allows the airplane to move up and forward with a low amount of force pulling back on the plane. The airplane wing will be constructed of balsa wood ribs with balsa wood spars with a monocoat cover to add structure and surface area. This will provide a lightweight wing with a strong structure allowing the team to lift heavy weight with a light wing. With this design, the team will have a lightweight plane that will lift a heavy load which is ideal for the conditions of the competition.

5.2 Design Description

As described above, the design is a two boom airplane. The booms will be two feet in length with two propellers attached to the front to give plenty of thrust. In the rear there is an elevator to help create lift for the airplane and a rudder to allow us to steer the airplane left or right. These were made of balsa wood for the lightweight material. The wing is approximately three feet in length with a 6.75 inch chord. There is also a 15 degree dihedral to add stability in flight. The airfoil design is a S1223 airfoil which gives a high lift to drag ratio. Each of these design specifications can be seen in the CAD model included in the appendix. Unfortunately the team was not able to complete the prototype over the summer but we are confident that the model designed during the summer will perform the way we want it to. We do look forward to building a prototype and testing the design to learn what we can improve upon.

6 PROPOSED DESIGN – First Semester

The proposed design was built during the second semester of capstone due to the short summer semester. The booms were ordered in four foot lengths allowing the team to cut them down to size as needed. The balsa ribs, rudder, and elevator were laser cut hopefully by Tim Kelly of the Flagstaff Flyers. The team will assemble the plane using custom bayonet mounts.

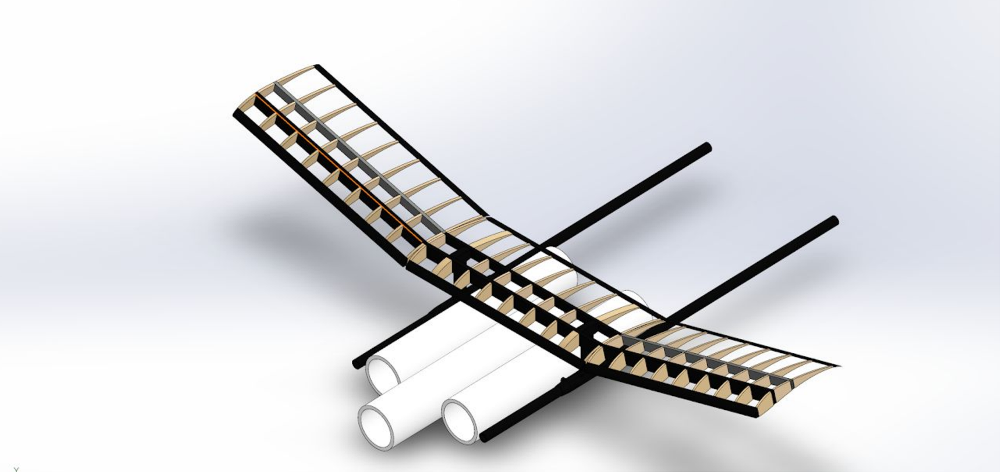


Figure 3: CAD model of Preliminary Design

Assembly Name :	Micro Airplane
Pieces :	46
Total Cost :	$61.36

Category	Part #	Part Name	Color	Qty	Units	Unit Cost	Cost
Wing	1	Ribs	Tan	27	each	$ -	$ -
Wing	2	Spars	Tan	1	each	$ 10.00	$ 10.00
Wing	3	Monocoat	Any	1	each	$ -	$ -
Booms	4	Booms	Black	2	each	$ 14.68	$ 29.36
Propulsion	5	Motors	N/A	2	each	$ -	$ -
Propulsion	6	Propellers	Orange	2	each	$ 7.00	$ 7.00
Tail	7	Rudder	Tan	2	each	$ -	$ -
Tail	8	Elevator	Tan	1	each	$ -	$ -
Tail	9	Flat Plate	Tan	2	each	$ -	$ -
Landing Gear	10	Wheels	Black	3	each	$ -	$ -
Landing Gear	11	Wheel Supports	N/A	3	each	$ 5.00	$ 15.00
			Total Pieces	**46**		**Total Cost**	**$ 61.36**

Figure 2: Bill of Materials, First Semester

7 IMPLEMENTATION – Second Semester

7.1 Manufacturing

In order to manufacture all the components and subsystems of the micro airplane we divided each system into components and fasteners. Due to the nature of the modular design being implemented, each fastener must be reliable, efficient, and quick to assemble. The goal is to assemble the airplane in under 30 seconds, with 60 seconds maximum. Each component, subsystem, and the manufacturing processes will be discussed below.

Carbon Fiber

The use of carbon fiber was a novel design decision that was made early on in the decision making process during the first semester. After research into composites used in the aerospace industry, the team decided to use this material for the structural components in the wings as well as in the framing of the fuselage booms.

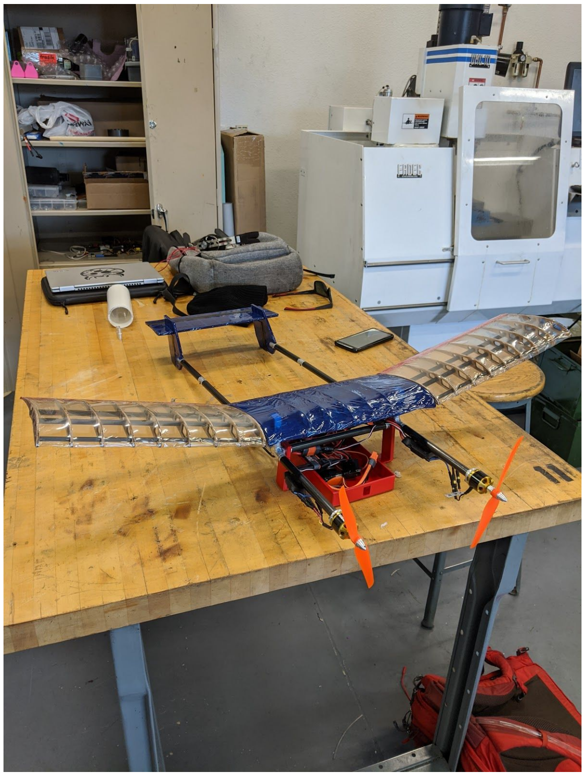


Figure 4: Carbon fiber rods shown in position

The carbon fiber chosen was to be manufactured in two ways. The first was to use premade, off the shelf, pultruded, unidirectional carbon fiber tubes for the spars and booms as this was the most reliable way to acquire consistent results from composites in both fiber moduli and correct geometries. This includes round booms and spars, as well as square spars mounted in the wings for rigidity. These pultruded tubes have tensile strengths 33 Msi.

Laser Cutting Wing Ribs and Tail Sections

The team found a local resource that generously let them use their laser cutter to cut out ribs and tail sections up to .005 millimeter precision. In order to save some money, ⅛ inch utility ply was used instead of more expensive alternatives such as balsa or spruce that were also considered. Below is a picture of the ribs.

Figure 5: Wing Rib

Aluminum Fasteners

To assist in mounting and assembly time of the modular wing, boom, motor, and tail sections, aluminum bayonet mounts were CAD'd and machined in the machine shop in 98C. Aluminum was chosen due to its strength to weight ratio and it's deeply understood manufacturing processes. Aluminum was readily available and inexpensive. Below are figures describing the motor mounts. They were machined using a lathe and mill. They are inserted into the booms, epoxied in place, and the motors were mounted in place.

Figure 6: Motor Mount

Next, Bayonet mounts were chosen to be made of aluminum for the same reasons as described above. The ease of manufacturing these parts were also a large part of the decision to make these as opposed to previous designed discussed in later sections. Below are figures describing the implementation of such devices as well as the geometries. It is important to note that the custom cross shaped part was built on a lathe in three sections then tack welded together, while the male sections are simpler to lathe out and a pin inserted for the annular fit. In order to ensure proper tension in the connection, pin springs are inserted in the male ends.

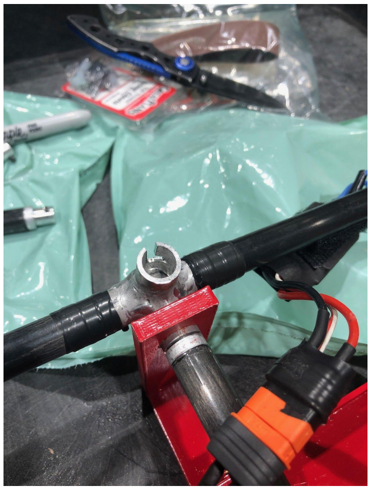


Figure 7: Cross Bayonet Mount

Figure 8: Bayonet Mount

7.2 Design Changes

This section will discuss problems encountered with previous methods of manufacturing, previous designs that were not chosen, why they were not chosen, and the ways in which they were improved.

Foam Wings

A large part of the changes to the design were due to materials not being suitable or reliable enough for the stresses that will be experienced during assembly and flight. Foam wings were considered early on in the design phase as they were inexpensive to make and had been used in other planes built by hobbyists. A hot wire cutter was used to attempt to cut out the wings from dense closed cell XPS foam bought off the shelf. This method was unreliable due to the tension in the hot wire being difficult to stay consistent, and the complex geometry of the airfoil. Also, the resolution that was being produced during the hot cutting was large which led to voids being produced in the cuts. We later decided on ribs as they were dense, easier to manufacture, still inexpensive, and reliably reproducible.

Figure 9: Foam Wing Cross Section

Snap fits

The team spent a large amount of time designing snap fits made from 3D printed ABS plastic. A few iterations were designed, but only one was selected at the end. These included cantilever snap fits meant to fit into the spars of the wings in order to provide quick assembly of the 15 degree dihedral designed to provide stability during flight. These were kept although redesigned a few times to fit the changing geometry of the spars during the design phase. Below is a table detailing the design parameters of the cantilever snap fit geometry meant to fit inside the penultimate design of the spars.. A dihedral shell and cantilever snap fit was also considered. This allowed a rib with cantilever snap fits to fit into a shell that would provide the 15 degree dihedral for the wing sections. The complexity and unpredictability of the shell manufacturing method was what lead us to a different design. It was 3D printed, however the tolerances weren't meeting the standards that we needed for it to be reliable. The cantilevers failed during small deflections and the idea was scrapped.

Table 1: Cantilever Snap Fit Geometry and Forces

Givens		
Alpha (inclination angle)	30	degrees
Length (assumed)	0.5	in
Undercut	0.025	in
Height (assumed)	0.1	in
Base	0.3	in
Permissable deflection	0.0125	1.25%
Secant Modulus, Es	280000	psi
Friction Coefficient, U	0.6	

Final Forces		
Deflection force(constant)	3.5	lbs
Mating Force (constant)	6.295872	lbs

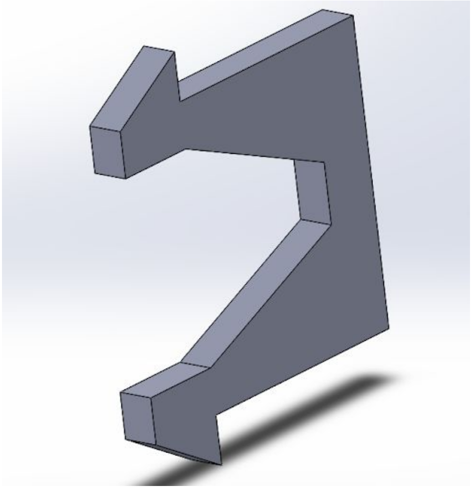


Figure 10: Cantilever Snap Fit

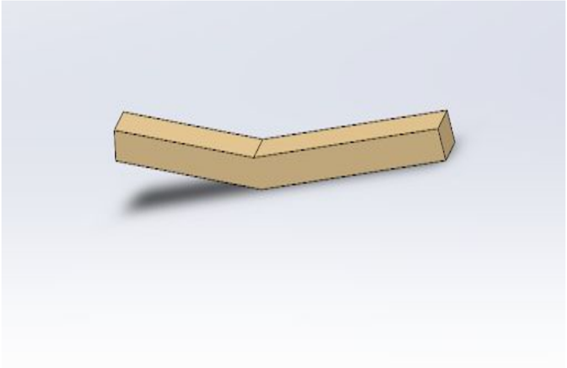


Figure 11: Dihedral Part

Elbow spars replaced the dihedral shell. Originally there 3D printed, but the plastic was too weak to handle the stresses during flight. Therefore, new ones were CNC'd out of aluminum. They go inside the spars within the wings and quickly assemble the wings together.

Figure 12: Aluminum dihedral elbows

Annular Snap fits were determined to be too unreliable in mating forces as well as difficult to design correctly. Below are a few iterations that were printed. The bayonet mounts discussed in previous sections were chosen due to their superior strength to weight ratios as well as the reliability of the resolution in the 3D prints.

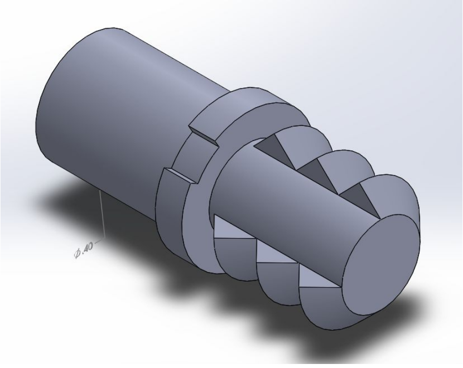


Figure 13: Male Annular Connector

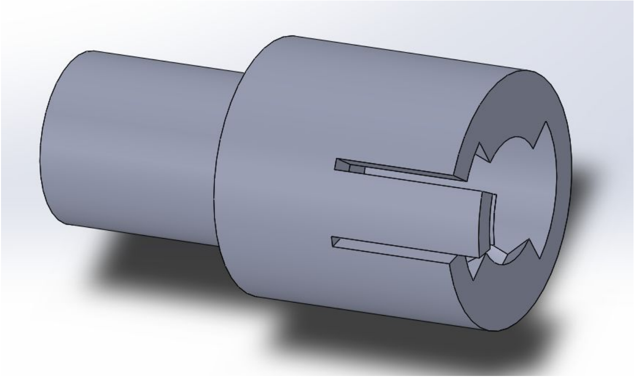


Figure 14: Female Annular Connector

Bayonet Mounts vs Custom Hanger design

A custom hanger was discussed for a length of time during the design phase. This hangar was going to be a custom part meant to be a sleeve that went over the booms, connecting the front and rear sections to the cross members holding the payload, as well as snap the wing sections into place. The hanger also provided a 7 degree angle of attack needed for maximum lift on the airfoil surfaces. Although this idea was novel, it fell into the same traps as the other complex geometries that were considered before. It was difficult to reliably manufacture, was expensive due to the use of the CNC machine that only one person in the department could operate, and could be simplified to the bayonet mounts discussed before. The bayonet mounts provide the same functions that the hanger could, except for the angle of attack..

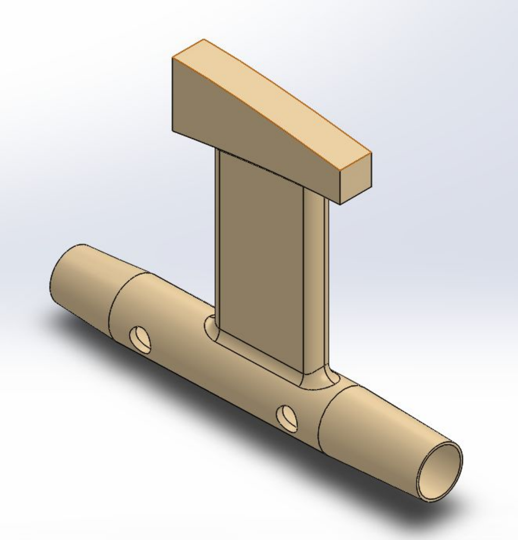


Figure 15: Hanger

Leading and Trailing Edges

The use of prepreg carbon fiber was going to be used for the leading and trailing edges. Prepreg carbon fiber is made of sheets of carbon fiber that is already impregnated with the epoxy used to cure into a hard, light, material. The molds were 3D printed to the correct geometry of the airfoil design. The prepreg carbon fiber was laid up along the surface of the molds after applying release wax and film to assist in removing the composites after curing. To reliably conform to the shape, a vacuum bag method was implemented and cured in the oven in the Composites Lab. We also decided not to attempt the leading edges as it was unnecessary. It was easier to monokote over the wooden rib than to make new leading edges. Below is an example of the process used in manufacturing these parts.

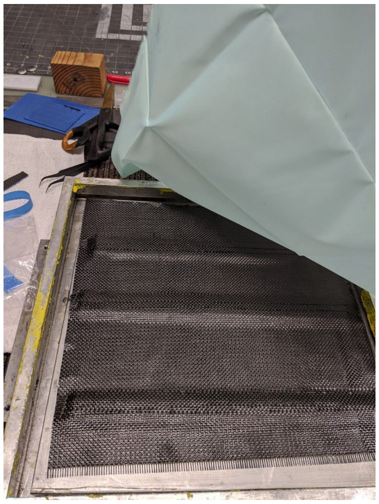


Figure 16: Carbon Fiber Leading and Trailing Edges

Although we were able to successfully make the parts, they were not good enough. The prepreg carbon fiber was thinner than expected and it proved to be too brittle and elastic to withstand the loads in flight. Therefore the team decided to use the 3D printed Leading edges, laminated with enamel spray paint, and covered in Monokote in order to get the smooth surfaces needed for lift.

8 Testing

The team took the plane out to Hebestreit Field with Tim Kelly from the Flagstaff Fliers and took it for a flight test. When it was first inspected by the Fliers, it was noticed that with all the landing gear on, the center of gravity was behind the wing. The center of gravity was designed to sit just below the center rib of the plane so as to provide the most balanced lift force. In order to compensate for this, we removed the rear wheels and moved the electronics as far toward the nose as possible. This balanced the weight of the aircraft better and we attempted a runway takeoff. During this attempt, the front landing gear was not getting the correct rotation that it should have and caused the plane to nose forward into the ground. This resulted in destruction of the propellers, and the landing gear breaking off entirely.

For a second attempt, the team decided to remove the rest landing gear and fly the plane from a thrown take off. Here we were testing to see if we could get a better lift off. The rules state that this is how the plane was to take off anyway, but we had hoped that it would be easier to try a runway takeoff first. Upon throwing the aircraft there was a moment where the plane was able to fly flat, before beginning a barrel roll which it completed before landing flat on the Earth. This was likely caused by either the rotation of the propellers, an uneven weight, or the dihedral shape of the craft not controlling the roll. It is important to mention however, that when the plane completed its roll it may have been able to stabilize if it had more altitude in flight, and was also able to maintain a straight, direct path forward in the direction it was thrown.

9 Post Mortem

9.1 Contributors to Project Success

There are a few things that contributed to the success of manufacturing the plane, however there are many more contributors to what did not. First, the biggest contributors to the assembly of the plane had to be the bayonet mounts and the off the shelf carbon fiber parts. The bayonet mounts made assembly less than a second for each connection, and the pultruded carbon fiber tubes drastically reduced the amount of time the team needed for structurally strong support for all the components of the plane, including the wing. Next, the use of a laser cutter on the wooden ribs, the horizontal and vertical stabilizers, rudders, and elevator helped immensely. The team, with the help of the fliers, were able to make those parts in just over 3 hours with only a CAD file.

Unfortunately, the plane cannot be called a complete success. Some of the bayonet mounts yielded in manufacturing, meaning that they became loose after a few cycles. We were forced to tape them down for reinforcement which means they cannot reliably be assembled in the time that was estimated. Also, the plane crashed twice. It was unable to fly for any period of time, which means it was unsuccessful in meeting that requirement.

The only thing that the plane did succeed in was in that it remained mostly intact after it crashed. Although it most of the important components broke, they did not shatter and explode into multiple pieces. One of the bonus point criteria in the rules is that if the plane remains intact or in as few pieces as possible it can keep points towards it's score.

9.2 Opportunities/areas for improvement

The forward landing gear did not sufficiently adhere to the boom sheared off. The propellers fell forward and broke on impact. Things to improve here are better position and material of the landing gear. The landing gear added a lot of weight, mostly due to the rubber wheels. The next iteration of the plane would make due with lighter foam wheels, these reduce the density without losing out on the ability to roll, steer, and control using the servos.

The next thing to improve is the position of the servos. Since we were tail heavy, removing any amount of weight off of the servos is paramount to the CG being in it's optimal position. By moving the servos towards the center of the plane and providing longer linkage, we contribute more towards the center of gravity for more optimal lift.

After removing the landing gear entirely, and adding a small section of payload, the center of gravity was better positioned. The next step was to attempt the throwing takeoff described in the rules of the competition. After a few steps, the throttle was fully open and the plane was thrown to give a positive angle of attack. After a second or two, the plane began to roll and crashed after one full revolution. This left the carbon fiber rods used as hangars, connecting the wing to the airframe in pieces. They broke in shear upon impact, as did the screws used to mount the motors. Another set of propellers were also broken on impact. Pictures of the damage can be seen below. The tray shattered at the flanges.

Figure 17: Failed Carbon Fiber Hanger

Figure 18: Sheared Motor Mount Screws

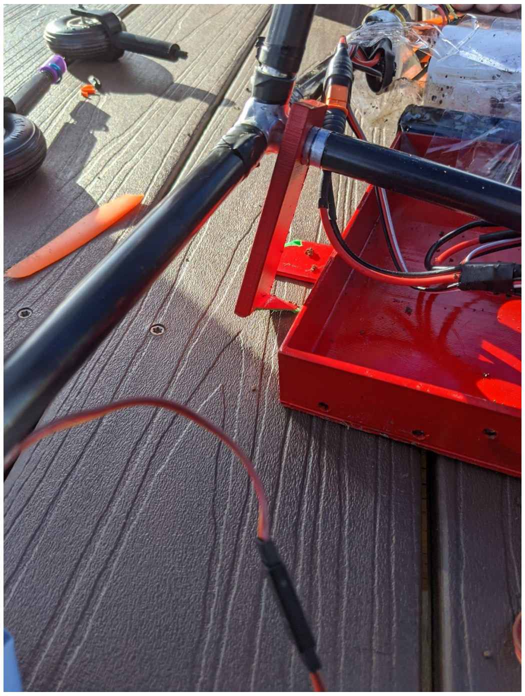


Figure 19: Broken Electronics Tray Flanges

A few things happened that lead to this failure. The first is that when manufacturing the cross-shaped bayonet mount, a second slot had to be made in order to fit the orientation of assembly. This lead to a point of stress concentration where it failed on impact. Next, tail had some flex, which led to twisting when in the air. On further inspection, it was noticed that it could have been fixed by adding more rigidity in the frame. Adding a second cross member to fight the twist that was being created in flight could have stopped the plane from rolling on takeoff.

Last, the propellers were not in the correct orientation. In order for the double propeller design to work, the propellers would have to be oriented so that they spun in opposite directions. This way, when they spin, the moments caused by each other propellers cancels out the lateral motion. This too could have caused the plane to roll the way it did. Since the propellers were oriented to spin in the same direction, all of the momentum caused by the rotation added together and caused the plane to tilt to one side.

Figure 20: The remains of the plane

10 REFERENCES

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Rockwest CF Tubes:

https://www.rockwestcomposites.com/shaped-tubing/square-tubing/t-sqr-236

Plastic Snap Fit Design Resource

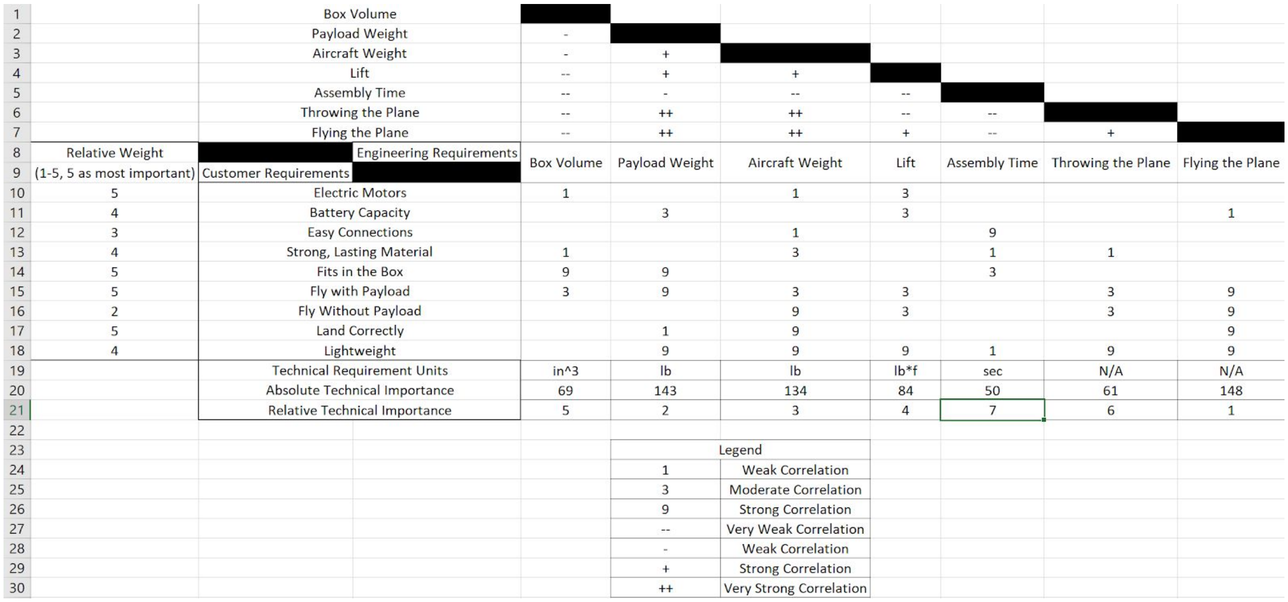
http://fab.cba.mit.edu/classes/S62.12/people/vernelle.noel/Plastic_Snap_fit_design.pdf

SAE Aero Micro 2019 winner page:

https://ae.gatech.edu/news/2019/03/ae-design-build-fly-team-wins-big-sae-aero-design-east-competition

11 APPENDICES

11.1 Appendix A: House of Quality



1		Box Volume		■						
2		Payload Weight		-	■					
3		Aircraft Weight		-	+	■				
4		Lift		--	+	+	■			
5		Assembly Time		--	-	--	--	■		
6		Throwing the Plane		--	++	++	--	--	■	
7		Flying the Plane		--	++	++	+	--	+	■
8	Relative Weight	■	Engineering Requirements	Box Volume	Payload Weight	Aircraft Weight	Lift	Assembly Time	Throwing the Plane	Flying the Plane
9	(1-5, 5 as most important)	Customer Requirements	■							
10	5	Electric Motors		1		1	3			
11	4	Battery Capacity			3		3			1
12	3	Easy Connections				1		9		
13	4	Strong, Lasting Material		1		3		1	1	
14	5	Fits in the Box		9	9			3		
15	5	Fly with Payload		3	9	3	3		3	9
16	2	Fly Without Payload				9	3		3	9
17	5	Land Correctly			1	9				9
18	4	Lightweight			9	9	9	1	9	9
19		Technical Requirement Units		in^3	lb	lb	lb*f	sec	N/A	N/A
20		Absolute Technical Importance		69	143	134	84	50	61	148
21		Relative Technical Importance		5	2	3	4	7	6	1
22										

	Legend	
24	1	Weak Correlation
25	3	Moderate Correlation
26	9	Strong Correlation
27	--	Very Weak Correlation
28	-	Weak Correlation
29	+	Strong Correlation
30	++	Very Strong Correlation