Howard University

Department of Mechanical Engineering

Senior Project II Final Report

MEEG-442-01

By:

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For:

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ACKNOWLEDGEMENTS

Team i-MAJHN would like to express sincere gratitude to our professors, Dr. Warner and Dr. Glakpe, without which, this project would not be possible. A big thanks also to Arielle Miller and Celeste Brown for sharing their research and expertise to help make our design possible as well as Ibukunoluwa Esan for his guidance and support. We would also like to thank Fabiola Clayton for making it possible for us to print a physical prototype of our design.

Executive Summary

The ASME IAM3D competition has tasked students to create an unmanned aerial racing cargo vehicle (UARCV) capable of picking up and dropping off a payload on each lap. i-MAJHN seeks to create a functional drone that meets the requirements to race in the ASME competition.

The competition requirements include:

- Picking up & dropping off a $1in^3$ payload (max weight 94g) with a ferromagnetic washer during each lap.
- Completing 5 laps in 15 minutes or less.
- The UARCV should be designed iteratively and manufactured using additive methods.

This report seeks to describe and evaluate the proposed design solutions, justify and analyze the chosen solution. This report also addresses the manufacturing of the drone and issues encountered and how they were resolved while the drone was being 3D printed. In order to create the best drone design to meet the requirements, the overall design was divided into five subsystems: Coding, Electronics & Propulsion, Gripping Mechanism and Frame.

Key accomplishments for the Fall Semester:

- Overall design of drone was completed as well as user-friendly and power efficient electronics were chosen to improve drone handling.
- Weight reduction of printed parts was done to increase the thrust-to-weight ratio. FEA analysis was done with Fusion 360 software on critical parts (arms, legs) to prevent yield.
- An electro-permanent magnet was chosen as the most efficient gripping mechanism

Key accomplishments for the Spring Semester:

- 3D Print of the drone was started, and edits were made to compensate for 3D printer errors/ quality and issues with support material chemical bath
- Assembly of printed parts and adjustment of the Purchasing List
- Proposed Redesign of Legs of the drone to allow for more strength and less support material
- Further Analyses on Landing Gear and Arms

Problem Statement

The objective is to design and manufacture an Unmanned Aerial Racing Cargo Vehicle (U.A.R.C.V.) using additive manufacturing and an iterative design process, including designing and developing a solution to all the requirements of the competition, while maintaining feasibility and efficiency. The UARCV will race in five team flights for five laps (under 15 minutes) through an obstacle course picking up and delivering one payload per lap. The vehicle must also stay within course boundaries and below an altitude of 10 feet throughout the duration of the competition. The payload that must be picked up is a 1-inch by 1-inch block with a small ferromagnetic steel washer smaller than one inch and larger than one half inch diameter attached to the top. Vehicle size constraints include a maximum of 33 cm measured diagonally from motor center to motor center and 25 cm in height. Maximum battery specifications, which must be purchased, include 4S and 4.2 Volts per cell.

Literature Review

Electronics & Propulsion

Review of literature has shown that the main electronic components of an Unmanned Aerial Vehicle (U.A.V) are the motors, propellers, electronic speed controllers, flight controller, cameras, radio transmitter system, and batteries. Key terms and component functions are defined in Appendix 1: Key Terms and Abbreviations. The components of this subsystem that drove decision making are the motors and propellers. There are many criteria to consider when selecting the motors and propellers of a U.A.V. [1] When selecting a suitable motor important factors to consider are the drone weight and frame size, thrust to weight ratio (TWR), motor size and efficiency. The propeller selected is dependent on the motor, as drone motors are manufactured to be operated with a specific size propeller to deliver the desired thrust. Once the motor is selected, other critical criteria to consider for propeller selection include propeller pitch, size, weight, number of blades, propeller material, thrust, and speed.

Further review revealed that the thrust to weight ratio (TWR) is the main dynamic characteristic that will determine the flight profile of the drone. To maintain steady flight, the TWR needs to be equal to 1 and for takeoff the TWR needs to be greater than 1. The motors that produce thrust must do so efficiently, in order to strike the correct balance between power drawn and thrust produced and maximize flight time. The maximum thrust of a given torque motor and propeller combination is achieved when the motor has reached maximum RPM. However, the torque of a motor determines how quickly the motor can vary the speed of the propeller. Torque is extremely important, especially in the context of a pick and place race such as the IAM3D competition.

Material, Manufacturing and Mechanical Design

For this competition, a 3D printed drone is expected to carry a payload, support thrust and the weight of components, and face possible collision. Suitable design and analysis must be done to prevent failure. The quadcopter design, with angular diameter between 90° and 120°, is known to be versatile, easy to construct and have better handling during flight [2].

In order to analyze the stresses and evaluate proposed design, Finite Element Analysis (FEA) was used for static stress in literature to determine the maximum stress and critical areas (which was determined to be the arms) [2].

Of the materials that are capable of being 3D printed, literature suggested that carbon Fiber, Aluminum and other fiber filament materials such as Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA) and Nylon are some of the most used. However, in order to maintain feasibility, as 3D printing can be 53 to 104 times more expensive than other manufacturing processes such as injection molding, PLA and ABS become the materials most accessible for this project [3]. According to research, between PLA and ABS, ABS does not have deterioration of its properties through time and most importantly it is lighter than PLA which is an ideal characteristic for this drone design [4].

In other research, however, it was found that the properties of 3D printed materials cannot be modelled using the same data as continuous, isotropic version of the same material [5]. Fused Deposition Modelling, a popular method of 3D printing, produces prototypes with anisotropic, specifically orthotropic, in contrast to the behavior of bulk material. Instead, the mechanical properties of FDM parts depend on raster angle, void density, build orientation, bonding between filaments, and continuity of filaments. Approximate values for Yield strength and Ultimate Tensile Strength was found in research by Hibbert, Warner, et al [6].

Despite this, literature review was done to guide the optimization of drone parts. Fatigue data was reviewed to assess the performance of the arms under the anticipated periodic up and down thrust of the propellers [7], [8]. This data will be supported with physical testing before assembly unto the drone.

Proposed Approach

Functional Requirements

Based on the requirements of the competition, the following functional requirements were derived:

1. Reach more than 10 feet altitude during the duration of the competition
2. Vehicle size constraint of 33 cm measured diagonally from motor center to motor center
3. Maximum 25 cm in height
4. Maximum battery specification of 4S and 4.2 Volts per cell
5. Drone made using additive manufacturing (3D printed)
6. Navigate through obstacle course at a maximum flight time of 15 minutes for all 5 laps
7. Gripping Mechanism to pick up and drop off Payload

From this design, a requirements matrix was derived using only the functional requirements and after, a specification table was derived to rate them, based on importance. This can be found in Appendix 5: Additional Criteria and Design Matrices. Based on the functional requirement matrix, other features were derived and added to the specification table. For example features such as, LED indicators (to inform user of height of drone), Cameras and Repositioning Programing were derived from the drone requirements that the drone must be able to pick up and drop off payloads and navigate through an obstacle course.

Early Design Approach

There were various design approaches that were taken into consideration. One of the early design ideas included having two 3D printed grippers attached to the bottom drone plate resembling arm like parts that would've been used to pick up the payload. The initial design sketch idea showing the grippers can be found in Appendix 11: Early Design Iterations. After analyzing the effect of the drone weight to the overall flight performance, we concluded that it would be better to attach something more lightweight to the drone base to pick up the payload which was the electro permanent magnet. Not only was the electro permanent magnet much lighter but it was also much more efficient in terms of the control factor for picking up the payload.

System Design

Figure 1: Rendering of drone modelled in Fusion 360

The proposed design is a quadcopter with four landing gears /legs. It will be 3D printed using ABS and features all necessary electronic components including 4S battery, motors, arms, propellers, landing gear, cameras, flight controllers, ESC etc. The drone was designed to minimize weight while reducing stress. Heavy components were strategically placed to ensure the center of gravity was central to avoid tipping or spinning. The overall design was 33cm from motor center to motor center diagonally and about 11cm in height, well within competition specification. Critical aspects of the system design were divided into the following subsections:

1. Drone frame
2. Flight Control Coding
3. Payload Engagement System
4. Propellers and Motors

Drone Frame

Camera Placement

In order to see the obstacles clearly, one camera is placed face front in between the two plates. There is also another camera on the bottom plate that will be used to view payload pickup. An additional electronic component called a camera switcher will be added to switch between cameras in flight. This is shown in Figure 2 The camera CAD models are approximately the same size as the real camera that we will be purchasing which is 2.8 cm in height. It is expected that a combination of printed slots and Velcro will be used to attach the camera to ensure that this hardware can be used in all frame iterations.

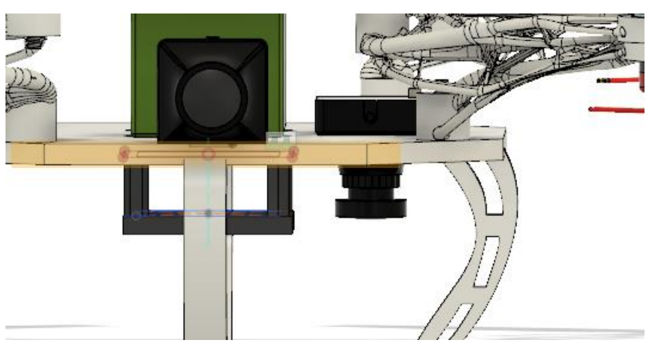


Figure 2: Front View of Cameras

Landing Gear/Magnet Spacing

Distance from the end of the electro-permanent magnet to the end of the landing gears needed to have a constraint of a maximum of 1.1 inch to ensure that the magnet will be able to effectively pick up payload without any interference. The current measurements for the distance between the two ends is 2.79 cm (1.0984 in) leaving a .0016 in tolerance as seen in Figure 3.

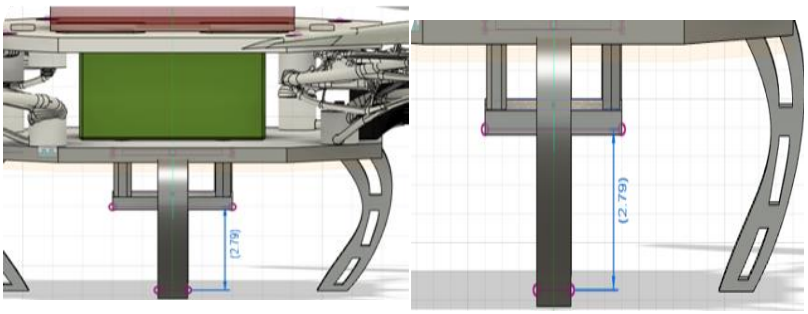


Figure 3: Front View of Landing Gears/Electromagnet holder

Thread Forming-Screws

The type of screws used for ensuring the components such as the arms were properly attached to the body of the drone were the Torx Rounded Head Thread-Forming Screw. The cad file for the screw was imported from McMaster Car to not only get a realistic idea of the drone design but most importantly to ensure that the holes were designed correctly for a correct screw fitting. Thread forming screws are ideal for 3D-printed ABS plastics because the threads on these screws are designed to cut further into the material, providing extra resistance to pull-out and can be inserted without nuts or inserts. McMaster Screw specifications can be found in Appendix 3: Assembly Documents and Renderings

The screws are positioned so that there are two aligned diagonally connected to two cylindrical holders that are connected via the arms (Figure 4). This design avoids the redundancy of a 4-screw design and will overall reduce the mass of the drone.

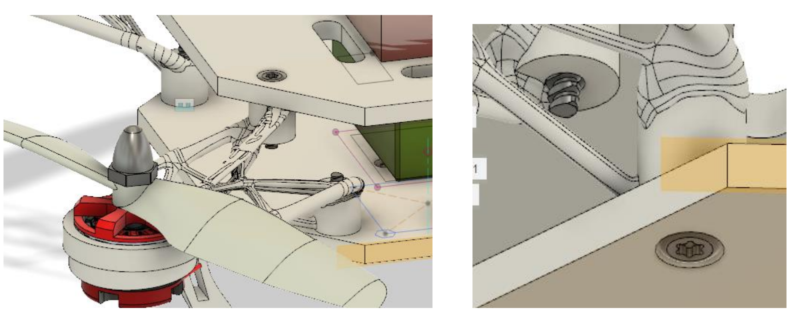


Figure 4: Screw placement

Using “Mechanicalc’s” bolt distribution calculator, the bolt forces and stresses for the Torx Rounded Head Thread-Forming, 18-8 Stainless Steel, M4.55 screw are calculated in Appendix 2

Drone Arm Transformation

The arms of the drone went through an extensive generative design process in which the mass was significantly reduced. Detailed images of this process can be found in Appendix 6: Generative Design Input. The results of modelling and printing are also discussed in Experimental Procedures section.

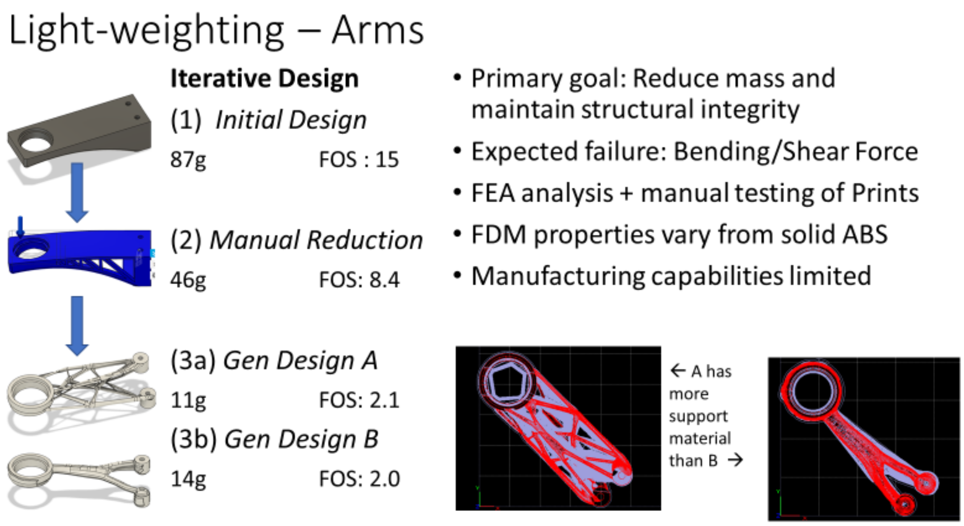


Figure 5: Summary of weight reduction process for arms using generative design

Flight Control Coding

The drone was to be programmed using a Pixhawk PX4 Flight controller, which comes preloaded with basic code. It is compatible with all other peripheral hardware. Additional information on this device is found in Appendix 3: Assembly Documents and Renderings.

Payload Engagement System

The gripping mechanism plays a key factor in the drone design, as a requirement of the competition is to pick up and drop off five payloads, one during each lap in the competition. The ideal gripping mechanism for the design will draw a low amount of current and power, have a high gripping/holding force and be light weight. At minimum the holding/gripping force must be more than or equal to the mass of the payload (max 94 g).

Between the mechanical gripper and electro-permanent magnet, a design matrix (Appendix 5: Additional Criteria and Design Matrices), revealed that an electro-permanent magnet has a higher holding/gripping force and is lighter than a mechanical gripper. Most importantly, the electro-permanent magnet was determined to draw less power from that battery, which is the most critical characteristic for the gripping mechanism selection, as an electro-permanent magnet only draws power when its being turned on or off (see Appendix 2). An electro-permanent magnet is also most likely to be easier to center on the drone, as well as it is compact and therefore more user friendly. In addition, an electro-permanent magnet has a wider surface area than grippers, which leads to a bigger tolerance when picking up the payload. Lastly, the expected modes of failure, like payload alignment with the magnet, are more predictable with the electro-permanent magnet when compared to the mechanical gripper. From these results, the electro-permanent magnet made by NicaDrone was chosen to be the ideal gripping mechanism. With a typical holding force 300N, it is found that the magnet can pick up the payload from an approximate maximum distance of 0.2 inches away (see Appendix 2). The drone design has an incorporated maximum distance, between the payload and electro-permanent magnet, of up to 0.1 inches away.

Propellers and Motors

The aircraft motor was chosen on the constraints of power for the least amount of weight. To improve efficiency, characteristics such as a brushless motor and non-ferrite magnets should be used. Criteria for motor selection include maximum thrust, current draw, weight and compatibility with propellers. By comparing options on the market, the best motor for the UAV was chosen to be the T-Motor F40 PRO III KV1600 Grey brushless Motor (Figure 6). It has improved Material selection, built-in fans as well as Präzisionsgewuchtete bell to ensure a high level of efficiency and long service life. The motor can spin as fast as 21,756 RPM. A decision matrix that informed this selection can be found in Appendix 5: Additional Criteria and Design Matrices

Figure 6: T-Motor F40 PRO III KV1600 Grey brushless Motor for FPV RC Drone

The propeller affects the thrust, speed and power requirements of a drone thus, impacting its endurance. Due to the requirements of our UAV, as well as the desire to keep development and acquisition costs as low as possible, existing model UAV propellers became the focus of the selection process. Since weight is a major consideration, choosing a lightweight propeller is of major importance. The lightest propellers are made of nylon, and are very flexible, which would aid in survivability on landing. However, the efficiency of a nylon propeller is very low, and would not achieve the necessary flight performance in order to operate. Composite propellers are both lightweight and efficient, but they are not very rugged and are more expensive than most other types of propellers. Aluminum propellers are efficient, but very heavy. A 2-bladed plastic propeller is the best choice for our UAV, as it has a good balance of efficiency, low weight, and durability. A two bladed propeller was chosen oven a three or four bladed propeller because it cruises faster and has better efficiency [9].

In conducting trade studies and analysis of different types of propeller geometry several variables were considered. These variables were propeller rotation speed, propeller pitch and diameter, thrust provided, power consumed, and propeller thrust. The chosen propeller has a pitch of 4.5 inch in addition to the 8-inch diameter. A plastic propeller of these dimensions is readily available from many different suppliers, costing approximately $0.75 – $3. Compared to the overall cost of the UAV, this is a small amount. The low cost also enables easy replacement of any propeller that may be broken on landing. A decision matrix that informed this selection can be found in Appendix 5: Additional Criteria and Design Matrices

Experimental Procedures

Generative Design

Initial iterations and experimentation were done using generative design in Fusion 360, an iterative design process that involves a program generating multiple outputs that meet specified constraints.

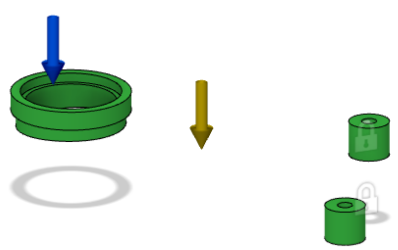


Figure 7: Preserve Bodies

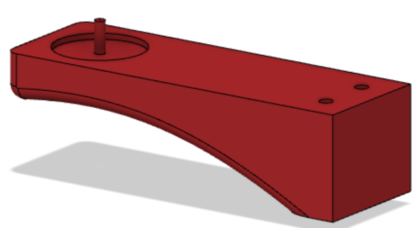


Figure 8: Obstacle Geometry

The screw holes and placement for motor were designated as preserve bodies since they were essential to the design. A bounding box to limit the size of the arms as well as geometry within screw holes were designated as obstacle geometry so that material would not be built in that area. The design was constrained by the 2 small cylinders (screw holes) shown in Figure 7Figure 36. In order to accurately represent the forces exerted on the arm during ascent and descent, calculations were done to determine the max thrust from propellers. 9.2N of downward force is expected to be exerted on the arms for max thrust, so the design was produced to bear 20N. Conditions for descent and impact were also specified and are further explained in Appendix 6: Generative Design Input.

Finite Element Analysis

In order to test theoretical designs, finite element analysis was done using Fusion 360 on the arms and legs of the drone, the load bearing components.

Analysis on Arms

During flight, it is expected that thrust from the propellers will exert an equal and opposite force on the arms, which are constrained by screw holes to the body of the drone. Based on data found in Appendix 2, the thrust and weight experienced by each arm is a maximum of 9.1N. Based on the results of these simulation, the factor of safety (based on yield) reduces to 1.6 for very high occurrences of stress (e.g. impact or flying at max velocity with most powerful propeller) in arm design 3a. Modal analysis suggest this design will experience resonance at 9900 RPM, which is below max motor RPM. The use of dampers as well as redesigning a stiffer arm were both discussed. A new generative study was done which improved the design in terms of modal frequency, by around 25%. Iterative improvements, along with dampening would remove the issue totally. Literature review suggests using earplugs to dampen vibration to critical areas, including the camera (which would transmit poor visuals with vibration) as well as the flight controller (which could be damaged). A 3D printed isolation mount, shown in Figure 9. for the flight controller, a critical area, was also explored. This would be mounted to the top of the drone and attached to the flight controller. These would all result in additional mass, so experimentation would need to be done to determine the most effective lightweight option. Some results of FEA are included in Appendix 7.

Figure 9: Isolation mount

Landing Gear Analysis

Figure 10: #1 Original Leg Design

Figure 11: #2 Enforced Leg Design

Landing gear analysis was performed to estimate the efficiency of the landing gear design. There are a variety of modes of drone failure and landing gear failure, and not all of them can be necessarily tested or predicted without physical testing. The purpose of the landing gear analysis was to test some potential forces that could be applied to the landing gear and some predictable scenarios, in which the landing gear will endure the most stress. Ultimately, three different analyses were performed for the two potential leg designs, both the original leg design made in the fall semester and the new leg designed made during the spring semester. During the manufacturing of the drone, it was found that the landing gear became very brittle and broke upon touch, once it emerged from the chemical bath (the chemical bath is used to soak off the support material of the 3D printer). The legs were thickened, and platforms were added to the gaps in the spaces of the original landing gear in hopes that this redesign would be able to withstand the bath. If time allotted, this new design would have been 3D printed and tested. If this new design also proved to be brittle two other potential leg designs were made that would reduce the overall support material necessary for the 3D print and/or would produce support material that could be easily removed. The three analyses performed were the following (Appendix 7: Additional Analysis):

Analysis #1: Force of the entire weight of the drone on one leg (8.50N)

Analysis #2: Force of drone following from 10 feet (maximum altitude allotted during the competition) and following on one leg (25.3446)

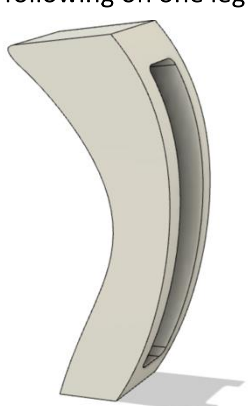


Figure 12: #3 Potential Leg Design for reduced support material

Analysis #3: Buckling Analysis with force of entire weight of the drone multiplied by 5 one leg (42.50)

Analysis of the potential leg designs proved that Leg Design #4 to be the strongest, with a minimum safety factor of 15, followed by Leg Design #2 with a minimum safety factor of 11.68, then Leg Design #3 with a minimum safety factor of 10.07 and the original leg design with an minimum safety factor of 3.069 (these safety factors are all from the analysis which simulates the weight of the drone on one leg). Ultimately, all the design reiterations are stronger than the original leg design however, the original design proved to weigh the least which is why it was originally chosen. Overall, the buckling analysis proved to show that each design had relatively significant buckling, which leg design #3 and #1 seemingly being the least significant with the least amount of shape deformation. In terms of the designs made to reduce support material, using only one hole in the design it is hoped that the support material could even possibly be manually removed by hand. In terms of leg design #4, the straight design would reduce the amount of support material needed significantly.

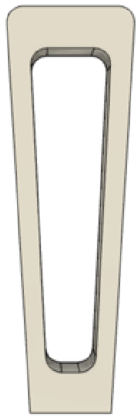


Figure 13: #4 Potential Leg Design for reduced support material

Overall, in order to determine which design would have been the most efficient for the drone design, as well as manufacturable using the 3D printer, a certain amount physical testing would have been necessary.

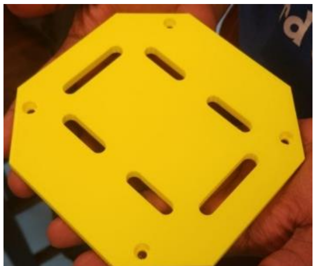
Printing Parameters

The raster angle, layer thickness, and interior fill style of 3D-printed Acrylonitrile Butadiene Styrene (ABS) were varied to test the mechanical strength as well as mass of the parts. Experimental plans were made to compare the weights and the amount of load (in the form of masses placed in load bearing areas) for each different build. Additional testing using the Object printer and new options for build parameters was also planned.

Results

Manufacturing

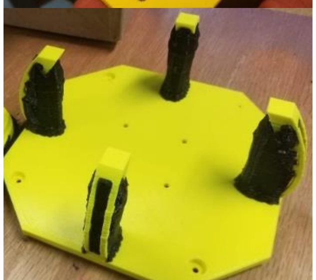
The entire frame of the drone will be 3D printed from commercially available ABS P430 filament using the Stratasys Dimension 1200es. Six separate bodies are being printed as follows:



(1) Upper Plate

Current Build Parameters : 0.3302 Filament | Low Density | 4545 Raster angle

Figure 14: Printed Upper Plate



(2) Lower Plate

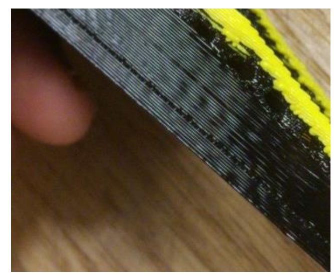
Current Build Parameters : 0.2540 Filament | Solid | 4545 Raster angle

Figure 15: Printed lower plate

(3) Four Arms

Current Build Parameters 0.2540 Filament | Solid | 4545 and 0/90 Raster angle

Figure 16: Printed Arms



It was found that many of the prints had very low resolution, which was expected to have an adverse effect on the mechanical properties of the drone. This was especially true for the drone arms, since the organic design required some precision. The parts were also lighter than predicted, due to infill settings.

Assembly

The parts were then assembled using thread forming screws to ensure a good fit and structural integrity. The thread forming screws allowed for sturdy assembly and fit flush in the design to limit drag. Minimal alterations had to be made to allow for assembly of drone frame.

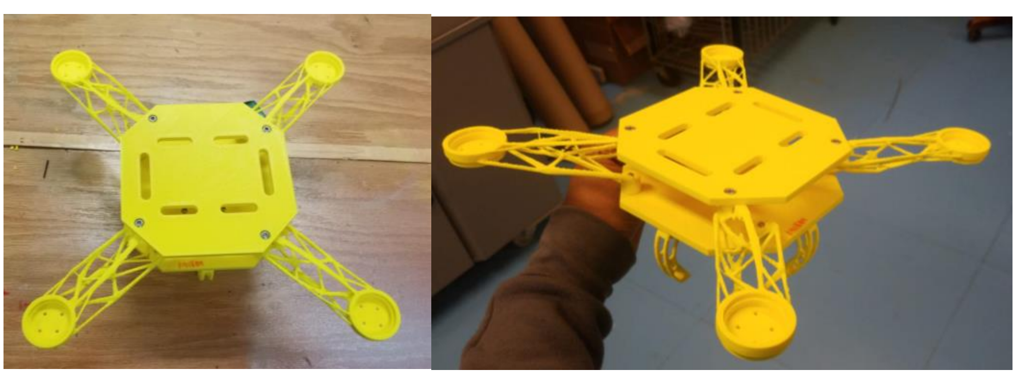


Figure 17 (a) and (b) : Assembled Drone

After removing support material in SCA 1200HT solution bath, however, the legs broke upon contact. Print parameters and duration of soaking time were also varied with no change to results. Further experimentation, including the updated design, would confirm whether this was due to the model material absorbing too much water or other non-design issue. If so, the design would have been altered to reduce the need for support material. Potential landing gear was designed to reduce the need of support material and aim to produce support material that can be more easily removed (see Appendix 7: Additional Analysis). These potential designs were also tested through the same analysis scenarios that the original two were tested in. If time allotted, these potential landing gear designs would have been tested and printed to determine which one can be 3D printed easily and effectively integrated into the drone design.

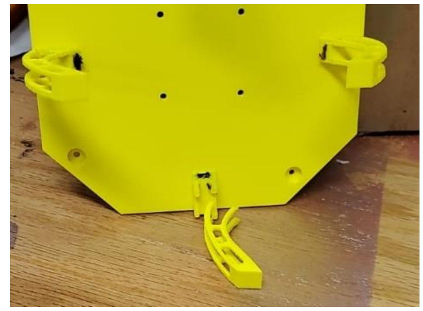


Figure 18: Failure in leg of lower plate

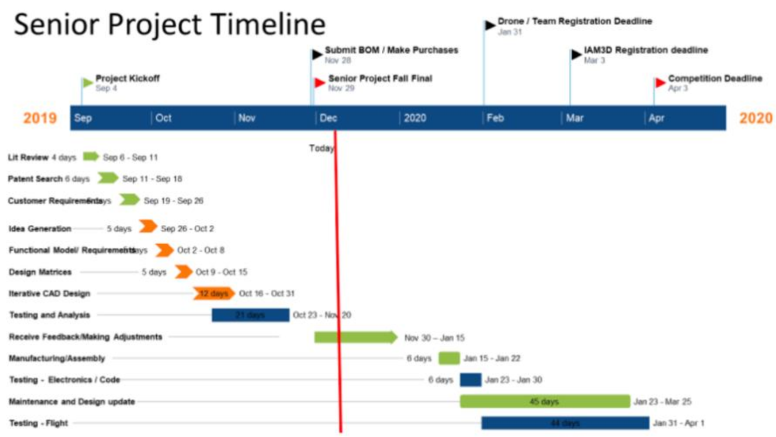
Support Material Removal

Figure 20: SCA 1200 HT Solution Bath

An integral part of the printing process is the use of the SCA 1200 HT Solution Bath to remove support material from printed parts of the vehicle framework. Team members became familiar with the operation of the SCA Solution Bath, which included the use of the Waterworks Soluble Concentrate. The Waterworks Soluble Concentrate dissolves the support material of the printed part leaving the designed model behind. While using the SCA 1200 HT team members had to take necessary safety precautions, which include wearing the proper safety gear, i.e. thermal rubber gloves and safety goggles. The operation of the bath was straightforward. First, the solution was prepared, then the model with support material was placed in the bath, and a timer was set for the cleaning process. Lastly, at the end of the cleaning process the model was removed from the bath and set to dry.

Figure 19: Waterworks Soluble Concentrate

Project Timeline



iMAJHN SENIOR PROJEFCT TIMELINE SPRING SEMESTER 2020

AT RISK	TASK NAME	SUB TASK NAME	STATUS	ASSIGNED TO	START DATE	END DATE	DURATION in days	COMMENTS
☐	3D Printing Trouble Shooting	Testing Parts in on different 3D pritners as well as fixing 3D printers	Completed	iMAJHN	01/13	02/28	46	
☐	3D Printing of Frame		Completed	iMAJHN	02/29	03/13	13	
☐	Assembly of 3D Printed Frame		Completed	iMAJHN	03/14	03/14	0	
☐	Adjustment of BOM		Completed	Jordan	03/24	03/26	2	
☐	CAD Change for Landing Gear	Editing existing parts to be strong enough to wistand 3D print and bath	Completed	Nefertari	03/26	04/01	6	
☐	Thurst Analysis and Calculations	Further analysis on thrust and its affect on the drone	Completed	Hanny	04/02	04/12	10	
☐	FEA Analysis on Arms	Vibrational and Stress Analysis on Arms	Completed	Melissa	04/02	04/12	10	
☐	FEA Analysis on Legs & Design for Minimal Support Material Legs		Completed	Ali	04/12	04/17	5	
☐	Final Report Development			iMAJHN	04/13	04/19	6	
☐	Final Presentation Development			iMAJHN	04/17	04/21	4	
☐	Final Presentation			iMAJHN	04/24	04/25	1	

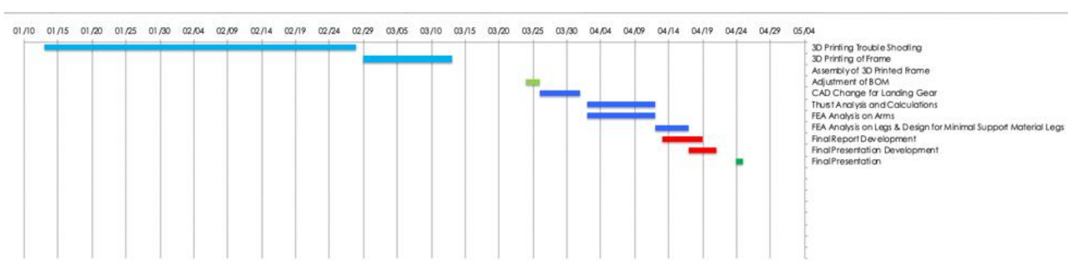


Figure 21: Project timeline for IAM3D competition

When comparing our original timeline to the new timeline there are some obvious changes. With the cancellation of the competition our finished project date was pushed back. We also originally planned to spend most of Spring Semester assembling and testing our drone which we did not get to do. Ultimately, some of the biggest setbacks for are projects would be issues with the with 3D printing. Not only did it take quite a while for us to get the 3D printer working, once we did get it working, we found some issues when it came to bathing our parts (specifically the landing gear), like previously mentioned above under "Landing Gear Analysis". With this, regardless, of the change of scheduled we would have had to spend significant time troubleshooting the 3D printer and our landing gear in order to find a leg design that will be able to be successfully 3D printed and used.

References

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Appendices

Appendix 1: Key Terms and Abbreviations

ASME – The American Society of Mechanical Engineers promotes the art, science & practice of multidisciplinary engineering around the globe.

Batteries: The power source of the drone. The Lithium Polymer battery was chosen due to its ability to store and deliver large amount of power and since our competition requires us to complete 5 laps in 15 minutes, our choice is the best option. LiPo (lithium polymer – rechargeable battery which uses a polymer electrolyte instead of a liquid electrolyte) batteries are the power sources of the quadcopters.

Electronic Speed Controllers (ESC): An ESC is a device that interprets signals from the flight controller (FC) and translates those signals into phased electrical pulses to determine the speed of a brushless motor.

Electro-permanent Magnet: An electro-permanent magnet or EPM is a type of permanent magnet in which the external magnetic field can be switched on or off by a pulse of electric current in a wire winding around part of the magnet. Before the electro-permanent magnet was invented, applications needing a controllable magnetic field required electromagnets, which consume large amounts of power when operating. Unlike electromagnets, electro-permanent magnets require no power source to maintain the magnetic field.

FPV: First Person View Camera. An FPV camera allows the pilot to view the flight path of the aircraft without being physically onboard. Our UAV has 2 cameras, one for real time video streaming, and the other for recording payload pickup and drop off. HD footage cameras don't have great video quality – they are designed for WDR (Wide Dynamic Range) and low latency, which is extremely important to FPV. WDR refers to a camera's ability to display changes in lighting conditions, and areas of shadow and light in the same image. Latency is the amount of time between the FPV camera capturing the image and display that image on a screen/ goggles. The FPV camera will connect to the VTX (Video Transmitter), often via the FC (flight controller) which then overlay's OSD (On-Screen Display) information of the image.

Generative Design: Generative Design is the capability of Mechanical Computer-Aided Design (MCAD) applications to autonomously generate one or more geometric designs to satisfy specific objectives and constraints.

Power Distribution Board (PDB): distributes the power on our drone and provides a neat and tidy way of connecting our battery to all our ESC's on the UAV. A PDB has positive pads/terminals which are all connected and negative terminals/pads which are all connected. This way when we solder all the red wires from our ESC's and battery to the positive pads on the PDB, and the black wires to all the negative pads, they will all become connected so that our battery can provide power to all of our ESC's as shown in the Appendix. The main safety aspect in terms of choosing a PDB for our drone is to make sure the PDB can handle the amount of current that is required to pass through it. The way to work this out is to check the ratings of the ESC's on the UAV to find the maximum total current draw. So, if we are building a UAV that uses 4x 20A ESC's we ideally need to have a PDB that can handle (4x20A) 80A. However, we will not be flying our UAV at max throttle so you could get away with a 60A PDB, but it's always best to use an overrated PDB as its worth the extra safety factor.

IAM3D - The ASME Innovative Additive Manufacturing 3D (IAM3D) Challenge is designed to give mechanical and multi-disciplinary undergraduate students around the world an opportunity to re-engineer existing products or create new designs.

Motors: Motors are electrical components which connect to propellers and cause them to spin around and generate thrust to enable drones to fly. The motors are the main drain of battery power on our UAV, therefore getting an efficient combination of propeller and motor is very important. Motor speed is rated in kV, generally a lower kV motor will produce more torque and a higher kV will spin faster, this however is without the propeller attached.

Propellers: These are the spinning blades that generate thrust and torque from the spinning motor. A heavier propeller will require more thrust from the motor than a lighter propeller, also blades with a higher AOA (Angle of Attack – aka "aggressive props") encounter more resistance from the air and require more thrust. When a motor must work hard to turn, it draws more Amps. Finding a balance between the thrust produced and the amperage used by the propeller and motor combination is a balancing act that every UAV pilot goes through, but we decided to purchase already balanced propellers to avoid that challenge. We will ensure our propellers are tight to avoid erratic behavior in flight. The pitch of the drone is the distance it moves in one full rotation.

UARCV – An Unmanned Aerial Racing Cargo Vehicle is a powered, aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely.

Appendix 2: Calculations

Thrust to Weight Calculations:

Quadcopter weight: 800gr

Actual drone weight: ~746gr

Propeller Characteristics:

Diameter = 8'' Pitch = 4.5

Motor Characteristics:

Kv = 1600 Volts = 14.8(4S battery)

RPM Generated by Motor:

RPM = Kv. Volts

=1600×14.8

=23,680 RPM

Motor Power Output Power = Power Absorption of Propeller:

Propeller Constant, K = 5.3×10^-15

Power = K. (RPM)^3. (diameter)^4. (pitch)

= (5.3×10^-15) × (23,680) ^3 × (8) ^4 × (4.5)

=1297.16W

Amp. Rating of Battery:

Amp Hours = 1.55 Discharge Rate = 100C

Amp Rating = Amp Hours × Discharge Rate

= 1.55 ×100

=155 Amp

Max. Motor Wattage:

Max. Wattage = Volts × Amp Hours

= 14.8 × 1.55

=22.94 W

Static Thrust in (N) produced by a Propeller:

Air density, ρ = 1.1839 @ 25C (77F)

Thrust, T = [pi/2(0.0254d) ^2 × ρ × (power)^2] ^½

= [pi/2(0.0254(0.2032)) ^2 × (1.1839) × (1297.16) ^2] ^½

= 9.13 N

Max Thrust = T × 4

= (9.13) (4)

= 36.52 N

Thrust to weight ratio:

= (Max thrust (grams) * Number of motors)) / Quadcopter Weight

= 3723.97/ 800

= 4.66

Below is a table showing our chosen motor with different propellers to determine the most efficient thrust. Our calculations indicate that the 1600Kv motor paired with a propeller with diameter of 8 inches and pitch of 4.5 is the best choice for our drone.

		Propeller		Motor/Propeller Combination		
Motor (Kv)	Motor power(W)	Diameter(inches)	Pitch	Thrust(N)	Max thrust(N)	TWR
1600	1729.55	8(2-bladed)	4.5	9.13	36.52(3723.97g)	4.7
	383.07	6(3-bladed)	4.2	2	8(815.773g)	1.0
	709.679	7(3-bladed)	4.2	4.99	19.98(2037.39g)	2.6

Maximum force on each arm

Max Thrust : 740g

Weight: 55g

Max Force = (Max Thrust + Weight) x g = 0.795 kg x 9.81 m/s^2 = **7.79 N**

Gripping Mechanism Power (function of Time) Calculations:

Assuming 3 minutes per lap of the competition (max of 15 minutes total, 5 laps, $\frac{15}{5} = 3\ minutes\ per\ lap$).

Electromagnet:

Assuming distance between dropping off previous payload and picking up new payload (at the beginning and end of each lap) is about 10-15 seconds (Appendix 8), the time needed for the electromagnet to be on is approximately 165 seconds per lap (2.75 minutes).

$$P = IxV = (0.6A)(5V) = 3\ Watts$$

$$1\ Watt = 60.00\ J/minutes$$

$$\frac{1\ Watt}{60\ J/min} = \frac{3\ Watts}{x}$$

$$x = 180\ J/minute$$

Total Joules per lap of race:

$$180\ x\ 2.75 = 495\ Watts\ per\ lap$$

Electro-permanent magnet:

Assuming magnet only needs to use power when turning off magnet to drop off payload and turning it back on once payload has dropped. Time needed to turn on = 0.75 seconds; time needed to turn off = 1.2 seconds. Adding up to approximately 2 seconds per lap, approximate 0.00111 minutes per lap.

$$P = IxV = (1A)(5V) = 5\ Watts$$

$$1\ Watt = 60.00\ J/minutes$$

$$\frac{1\ Watt}{60\ J/min} = \frac{5\ Watts}{x}$$

$$x = 300\ J/minute$$

Total Joules per lap of race:

$$300\ x\ 0.111 = 3.33\ Watts\ per\ lap$$

Mechanical Gripper:

Assuming motor for mechanical gripper only needs to be used when picking up and dropping off payload. Approximate time needed to pick up payload, 2 seconds, approximate time needed to drop off payload approximate 2 seconds. Adding up to approximately 4 seconds per lap, approximate 0.022222 minutes per lap.

$$P = IxV = (0.6A)(6V) = 3.6\ Watts$$

$$1\ Watt = 60.00\ J/minutes$$

$$\frac{1\ Watt}{60\ J/min} = \frac{3.6\ Watts}{x}$$

$$x = 216\ J/minute$$

Total Joules per lap of race:

$$216\ x\ 0.022222 = 4.8\ Watts\ per\ lap$$

Gripping Force for Mechanical Gripper:

Assumption: Calculations are assuming a basic gripping scenario with a friction grip (2-finger gripper) with flat gingers gripping at the parts center of gravity. Assuming that the payload is at a state off equilibrium, so all existing forces are counteracted by equal and opposite forces (Newton's 3rd law of motion). The vertical forces (FA, G) are determined by the product of the payload mass and acceleration (Newton's 2nd law of motion) and summed up.

$$Grip\ Force = m(g + a)S/\mu$$

Where m = mass of payload (kg), g = acceleration due to gravity (m/s^2), a maximum acceleration due to gripper (m/s^2), S = factor of safety, μ = coefficient of friction.

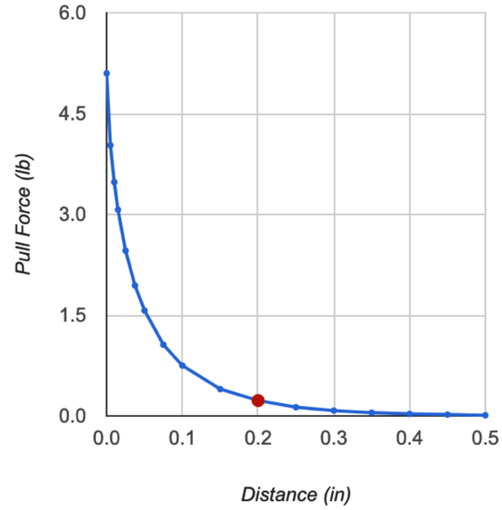
$$Grip\ Force\ = \frac{0.095(9.8 + 0.338)2}{0.75} = 2.56\ kg$$

*Note: A calculations were done using a Motor of about 0.6 Amps and 6.0 Volts; a stronger motor will lead to a stronger gripping force but will most likely also use more current.

Maximum Distance Electro-Permanent Magnet Pick up Payload From:

$$10\ grams\ (PLA\ Cube) + 85\ gram(Steel\ Washer\ 1\ inch\ diamter) = 95\ grams = 0.21\ pounds$$

$$0.21\ pounds = 0.21\ lbf$$



Grade = N40
Outer Diameter = 0.5"
Inner Diameter = 0.25"
Thickness = 0.125"
Distance = 0.2"
0.23 lb

Approximate Max Distance for magnet to be able to pick up Payload is approximately 0.2 inches

Note: Although maximum pull force at a distance of 0 is not necessarily necessary, it helps to have a stronger magnet as it has a larger magnetic pull from a further distance. Also, a strong magnetic pull will compensate for other acting forces on the payload while the vehicle is in flight.

Landing Gear Calculations

Below are all components that will contribute to the applied load on the bottom plate with landing gear attached. This mass total will be used in FEA analysis.

Upper Plate + Arms + Screws = 134.372 g

Ow Motors = 2,880 g

Propellers = 220 g

Camera = 5.5 g

Microcontroller = 38 g

Battery = 192 g

Total = 3,469.872 g = 34.03 N

Bolt Stress

The Bolt Load Diagram below shows the tensile load on the bolt as a function of applied tensile load on the joint. The dark blue line gives the nominal bolt load, and the light blue lines account for preload uncertainty and relaxation. The knee in the curve shows the point at which the joint separates.

Before joint separation, only a portion of the applied load is carried by the bolt, and the other portion acts to relieve compression in the clamped parts. The bolt load line in this region has a constant slope equal to the joint constant. After separation, all applied load is taken by the bolt and so the bolt load line has a slope of 1.

Results Summary

Summary tables of results are shown below. These tables give the factors of safety for the joint and for the clamped parts. Any factors of safety of at least 1 are shown in green, and below 1 are shown in red. It is up to the discretion of the engineer to determine the appropriate factor of safety to use in design.

Joint Summary

The table below summarizes the factors of safety for the joint corresponding to the nominal, maximum, and minimum bolt load (the bolt load varies based on preload uncertainty and relaxation).

	$FS_{separation}$	$FS_{bolt\ yield}$	$FS_{thread\ shear\ bolt}$	$FS_{thd\ shear\ internal}$
Nominal:	1.14	1.97	1.88	2.26
Max Bolt Load:	1.42	0.97	---	---
Min Bolt Load:	0.74	1.32	---	---

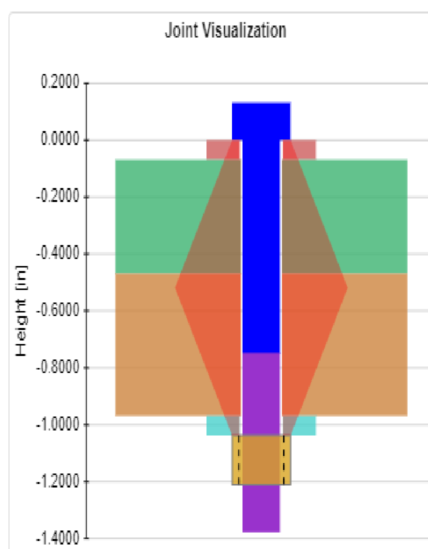


Figure 22: Result of Online Bolt Load Software

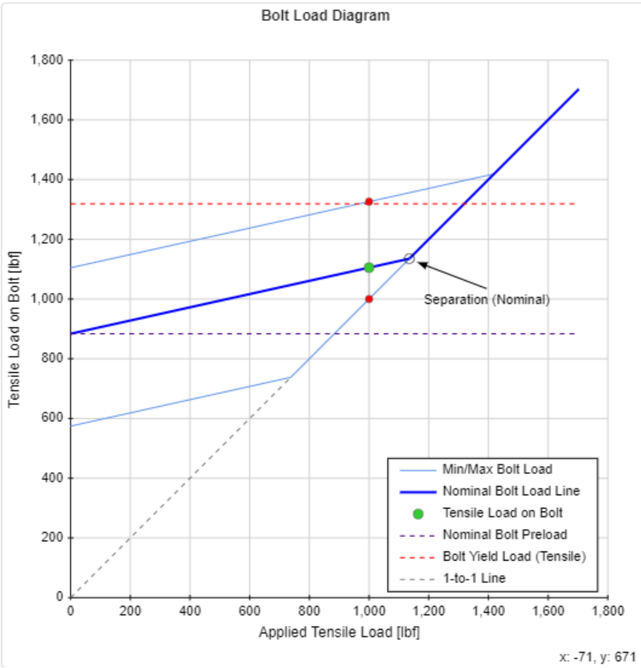


Figure 23: Bolt Load Diagram

Bolt Forces & Stresses

This section details the force and stress analysis on the bolt itself.

Preload Force

The nominal preload force is calculated as:

$$F_{PL.nom} = \%_{yld} \cdot S_{ty} \, A_t = \text{ 883.7 lbf}$$

Reference Values

$\%_{yld}$ = 67%
S_{ty} = 60,000 psi
A_t = 0.02198 in^2

Due to preload uncertainty, the actual preload applied to the bolt may be more or less than the nominal value. Due to preload relaxation, there will be some loss in the preload after the joint is installed.

The maximum value of preload accounts for the preload uncertainty, and is calculated as:

$$F_{PL.max} = (1 + \%_{uncrt}) \cdot F_{PL.nom} = \text{ 1,105 lbf}$$

The minimum value of preload accounts for the preload uncertainty as well as relaxation, and is calculated as:

$$F_{PL.min} = (1 - \%_{uncrt} - \%_{relax}) \cdot F_{PL.nom} = \text{ 574.4 lbf}$$

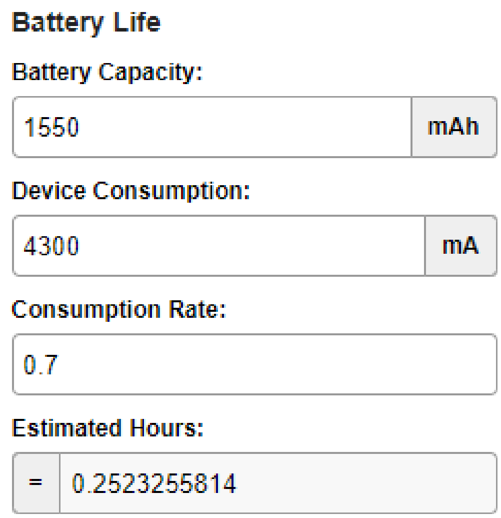
Reference Values

$F_{PL.nom}$ = 883.7 lbf
$\%_{uncrt}$ = 25%
$\%_{relax}$ = 10%

Figure 24: Bolt force equations

Motor Requirement Calculations

Component	**Current Draw (mA)**
Electro-permanent Magnet	10
Camera x2	80
Motor x 4	Unknown
Pixhawk	175
GPS	55
Compass	5
Telemetry Radio	35
Safety Switch	10



To ensure the battery that was selected would be able to support all electronic hardware onboard the craft, the above calculations were performed. Results showed that with the battery specifications of the 4S 4.2 Volts per cell and a given flight time of 15 minutes, with the use of the main electronic components of the craft we will achieve a consumption rate of 0.7.

		Propeller		Motor/Propeller Combination		
Motor (Kv)	Motor power(W)	Diameter(inches)	Pitch	Thrust(N)	Max thrust(N)	TWR
1600	1729.55	8(2-bladed)	4.5	9.13	36.52(3723.97g)	4.7
	383.07	6(3-bladed)	4.2	2	8(815.773g)	1.0
	709.679	7(3-bladed)	4.2	4.99	19.98(2037.39g)	2.6

Table 1: Thrust Calculation

Appendix 3: Assembly Documents and Renderings

The drone design can be accessed here: https://a360.co/2XOy6wA

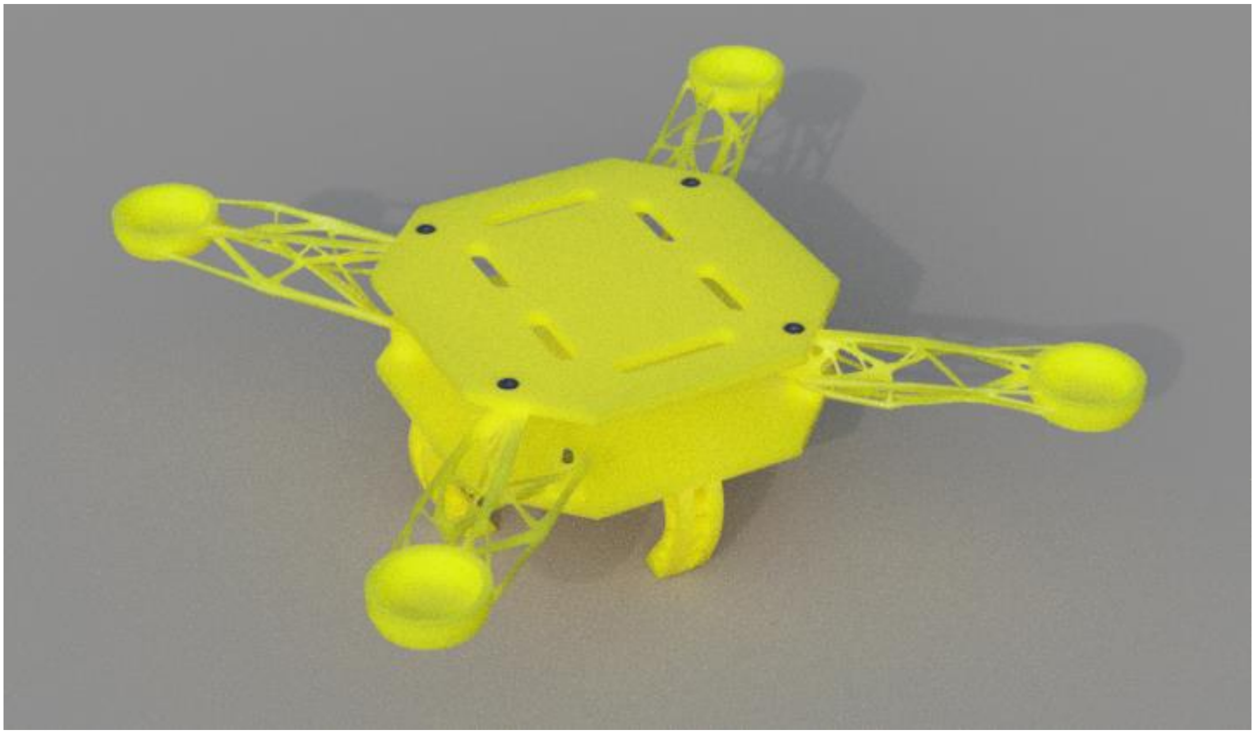


Figure 25: Render of 3D printed drone parts using Fusion360

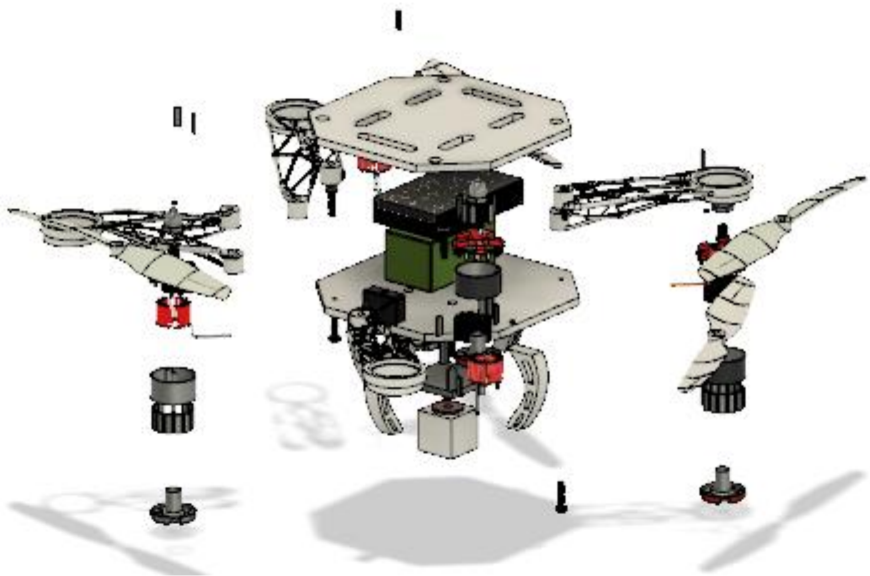


Figure 26: Exploded View of Drone

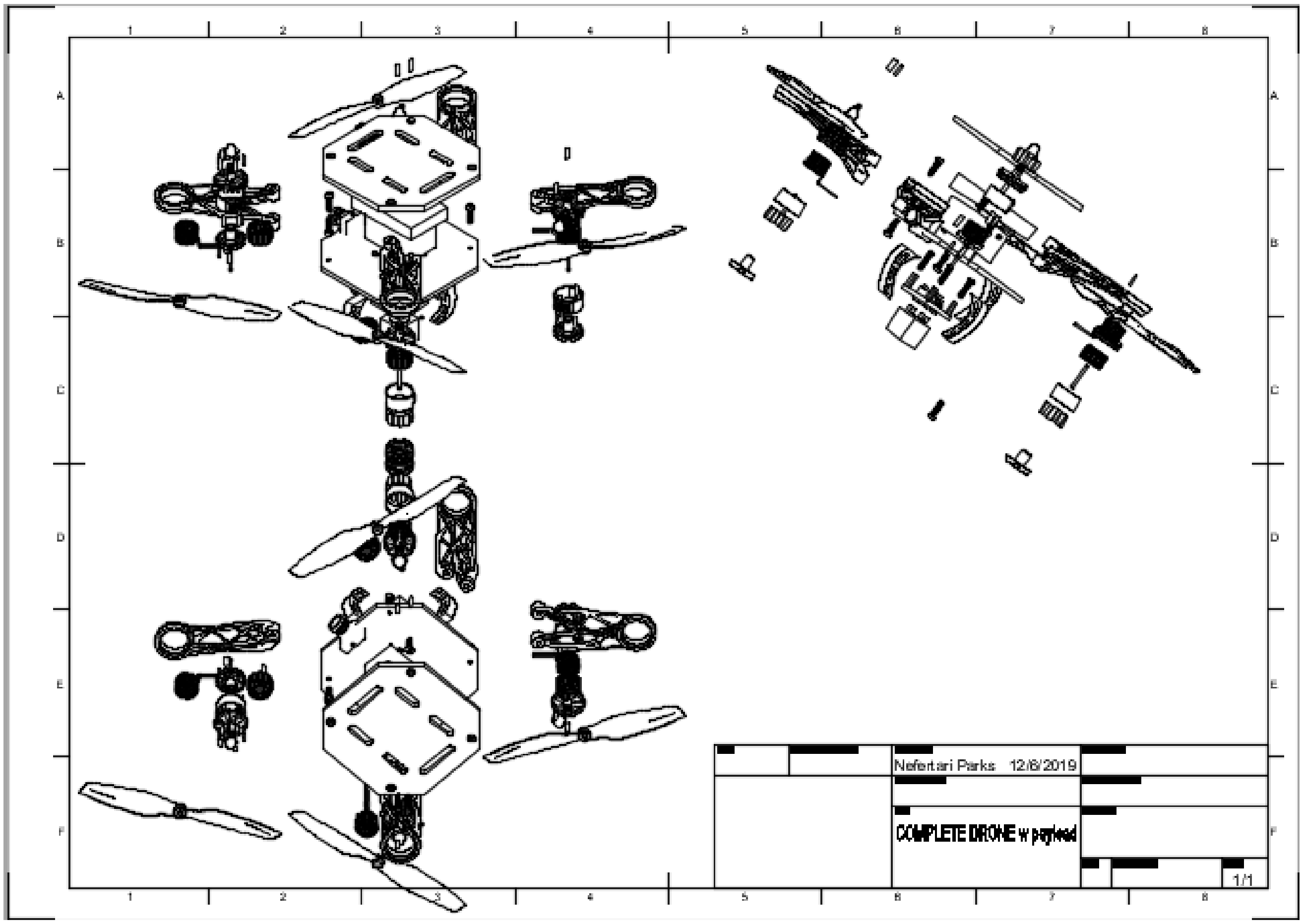


Figure 27: Drawing of Drone

This shows the detailed CAD model referenced throughout the report.

pixhawk® 4 mini

The power of Pixhawk® 4 in a compact form

Product Features

- Half the footprint of the *Pixhawk® 4*
- The same FMU processor and memory resources as the *Pixhawk 4*
- Aluminum casing for great thermal performance
- Easy to connect to commercial ESCs
- The latest sensor technology from Bosch® and InvenSense®
- Redundant IMUs for reliable performance
- NuttX real-time operating system
- Pre-installed with the most recent PX4 firmware

The *Pixhawk® 4* Mini autopilot is designed for engineers and hobbyists who are looking to tap into the power of *Pixhawk 4* but are working with smaller drones. *Pixhawk 4 Mini* takes the FMU processor and memory resources from the *Pixhawk 4* while eliminating normally unused interfaces. This allows the *Pixhawk 4 Mini* to be small enough to fit in a 250mm racer drone. The *Pixhawk 4 Mini* is easy to install; the 2.54mm (0.1in) pitch connector makes it easier to connect the 8 PWM outputs to commercially available ESCs.

Pixhawk 4 Mini was designed and developed in collaboration with Holybro® and Auterion®. It is based on the Pixhawk FMUv5 design standard and is optimized to run PX4 flight control software.

pixhawk® 4 mini

Technical Specifications

- FMU Processor: STM32F765
  - 32 Bit Arm® Cortex®-M7, 216MHz, 2MB memory, 512KB RAM
- On-board sensors
  - Accel/Gyro: ICM-20689
  - Accel/Gyro: BMI055
  - Mag: IST8310
  - Barometer: MS5611
- GPS: ublox Neo-M8N GPS/GLONASS receiver; integrated magnetometer IST8310

Interfaces

- 8 PWM servo outputs
- 4 dedicated PWM/Capture outputs
- Dedicated R/C input for CPPM
- Dedicated R/C input for Spektrum / DSM and S.Bus with analog / PWM RSSI input
- 3 general purpose serial ports
  - 1 with full flow control
  - 1 with a separate 1A current limit
- 2 I2C ports
- 3 SPI buses
  - 1 internal high speed SPI sensor bus with 4 chip selects and 6 DRDYs
  - 1 internal low noise SPI bus dedicated for Barometer with 2 chip selects, no DRDYs
  - 1 internal SPI bus dedicated for FRAM
  - Supports dedicated SPI calibration FLASH located on sensor module
- 1 CANBuses for CAN ESC
  - CANBus has individual silent controls or ESC RX-MUX control
- Analog inputs for voltage / current of battery
- 1 additional analog inputs

Electrical Data

Voltage Ratings

- Power Brick Input: 4.75~5.5V
- USB Power Input: 4.75~5.25V
- Servo Rail Input: 0~24V
- Max current sensing: 120A

Mechanical Data

- Dimensions: 38x55x15.5mm

Environmental Data, Quality & Reliability

- Operating temp. -40~85C
- Storage temp. -40~85C
- CE
- FCC
- RoHS compliant (lead-free)

McMASTER-CARR 99397A772

Torx Rounded Head Thread-Forming Screws
for Plastic, 18-8 Stainless Steel, M4.55 Size, 16 mm Long

Packs of 50 | In stock
$15.28 per pack of 50
99397A772

ADD TO ORDER

Material	18-8 Stainless Steel
Screw Size	M4.55
Length	16 mm
Head, mm	
Diameter	8
Height	3.1
Drive Size	T20
Drive Style	Torx
Drill Bit Size	No. 23
Drill Bit Size Decimal Equivalent	0.154"
Approximate Thread Pitch	1.59 mm
Thread Direction	Right Hand
Threading	Fully Threaded
Tapping Method	Thread Forming
Tapping Screw Type	TRS

Appendix 4: Manufacturing Results

Ph.D. candidate, Arielle Miller, suggested running simulations using CatalystEX, the associated 3D print slicing software. As seen in Figure 28 there was a lot of support material in the center of the arms. Figure 29, on the other hand only showed support material below the design.

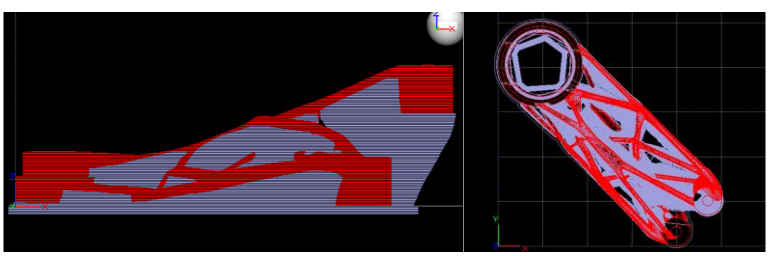


Figure 28: Support material (Grey) and Model Material expected for Arm Design 3

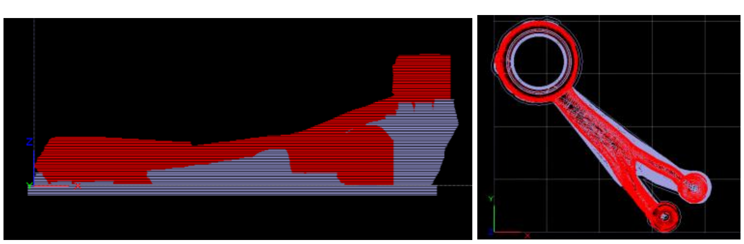


Figure 29: Support material (Grey) and Model Material expected for Arm Design 4

Figure 30: Removing support material causing damage

Figure 30 shows the effect of removing support material manually, breaking of some model material filaments. This may negatively impact the performance of the drone arms and should be avoided. Future manufacturing iterations will be more included to printers that have support materials that can be dissolved or more easily removed.

Appendix 5: Additional Criteria and Design Matrices

Design Specifications / Criteria

REQUIREMENT #:	DESCRIPTION OF REQUIREMENT:	RELATED FACTORS:	SUBSYSTEM:
1	4S Battery, 4.2 Volts Per Cell	Electronics	Electronics
2	Be able to pick up and drop off payload	Code Frame Gripping Mechanism	Gripping Mechanism
3	Use of Additive Manufacturing for Drone	Propulsion Frame	Frame
4	Dimensions: 33 cm measured diagonally from motor center, no taller than 25 cm height	Propulsion Electronics	Frame
5	Finish Competition/Laps in under 15 minutes	Speed Weight Electronics	Propulsion
6	Navigate through obstacles in competition	Code	Code
7	Reach no more than 10 feet in amplitude during competition	Code Propulsion	Code

Figure 31 Functional Design Matrix

Specification Table

D or W	Requirements	Importance (1- 10)
D	Dimensions: 33 cm measured diagonally from motor center	10
D	Dimensions: no taller than 25 cm height	10
D	Fast enough to finish 5 laps in 15 minutes	10
D	Drone made using additive manufacturing	10
D	Be able to pick up and drop off payload	10
W	Repositioning Programing	7
W	LED indicators (to inform user of height of drone)	4
W	Camera	9
W	Making additive manufacturing majority of parts of drone	5
D	Gripping Mechanism	10
D	Battery Specs: 4s and 4.2 Volts per cell	10

Figure 32 Specification Table

Physical Specifications

- Any LED's on Handheld Controller should be easily visible.
- Handheld controller should be adjustable or be able to fit various size hands.
- Handheld Controller should be comfortable to control.
- Exposed wiring should be kept to a minimum on the Handheld Controller.
- PCB encasing for Handheld Controller should be kept light weight to avoid strain on the user.
- Drone should ideally be able to lift around 2-3 lbs. worth of cameras and batteries.
- Any components attached to the drone should be easily removable and modifiable.
- Drone size should be capable of meeting racing requirements.

Hardware Specifications

- Components must run off (Insert planned battery voltages) or less.
- Drone should be able to run for at least 15 minutes per race requirement.
- Handheld Controller should be able to run off powered USB connection.
- Drone must have a physical kill switch located on the vehicle or controller for safety.
- All batteries must be stored in a LiPo safe bag for safety.

Software Specifications

- Source Code should be written using a Pixhawk series controller.
- Pixhawk series controller should be flexible in terms of hardware peripherals that can be attached.
- Programming should not exceed given memory space on chosen Microcontroller and similar variants.
- Should be able to upload to microcontrollers through USB connection.
- Should be kept on an easily accessible repository and properly maintained.

Gripping Mechanism

Gripping Mechanism	Size & Mass:	Holding Force	Current Draw & Nominal Voltage:	PixHawk Compatibility	Cost	Power Requirement:
Mechanical Gripper	Size: Drone will likely have to be modified to accommodate Mass: Approximately 2.15 ounces (based on inspiration gripper)	Design Dependent. Using Specified Motor = 2.56 kg	1.2 Amps 4.8- 7.2V (Voltage/ Amps from Gripper similar to one that may be used)	Can be Compatible	Unknown/ Low (Printable) + Additional Motor / Servo ($12.99)	Ideally would only draw power when opening gripper, or to change gripper position Power Draw: Medium
Electromagnet	Diameter: 1.5" Center Diameter: 0.7" Height: 0.8" Mass: Approximately 2.88	25 Kg/55 lbs Weight of Object: 5 kg/ 10 lbs max	0.6 Amps at 5V	Compatible with a Raspberry Pi (Ubuntu) So everything will have to be adjusted for Pixhawk	$19.95 + cost of Cricket Board ($29.95)	Must Draw Power when Electromagnet is on. Meaning the entire time the drone is carrying the payload, the magnet will be drawing power: Power Draw: High
Electro Permanent Magnet	40 x 40 mm Magnet Plate: 4.30 mm Secondary Plate: 0.80 mm 4x M3 x 0.5 Mass: Approximately 3 ounces	15 Kg/30 lbs Weight of Object: 3 kg/ 6 lbs max	0.6 Amps at 5V	Completely Compatible with Pixhawk	$159.99	Magnet draws power to turn magnet "off" so it will only draw power when turning dropping payload Power Draw: Low

Criteria	Weighting	Mechanical Gripper		Electromagnet		Electro Permanent Magnet	
		Score	Total	Score	Total	Score	Total
Size	3	3	9	5	15	4	12
Weight	5	3	15	5	25	4	20
Holding Force	4	3	12	5	20	4	16
User Friendliness	4	2	8	3	12	4	16
Pixhawk Compatibility	5	3	15	1	5	5	25
Power Requirement	5	3	15	1	5	4	20
Cost	3	3	9	5	15	1	3
	Total		83		97		112

Tab[1]le 2 (a and b): Design Matrix for Gripping Mechanism Subsystem

Table 2 shows the justification for choosing the electro-permanent magnet. It scored the highest overall and is a good choice for the project requirements.

Symbol	Parameter	Minimum	Typical	Maximum	Unit
$T_{cycle(ON)}$	Time to complete one cycle		0.75		s
$T_{cycle(OFF)}$	Time to complete one cycle		1.2		s
F_{max}	Max holding force	200	300		N
V_{supply}	Operating voltage	4.75	5.0	6.5	V
I_{steady}	Steady state current draw		10		mA
I_{peak}	Peak current draw during cycle execution			1000	mA
m	Mass of the device		65		g
$t_{operating}$	Operating temperature	-40		+70	°C
$RH_{operating}$	Operating humidity (non-condensing)	0		75	%

Figure 33 Electromagnet Specifications

1

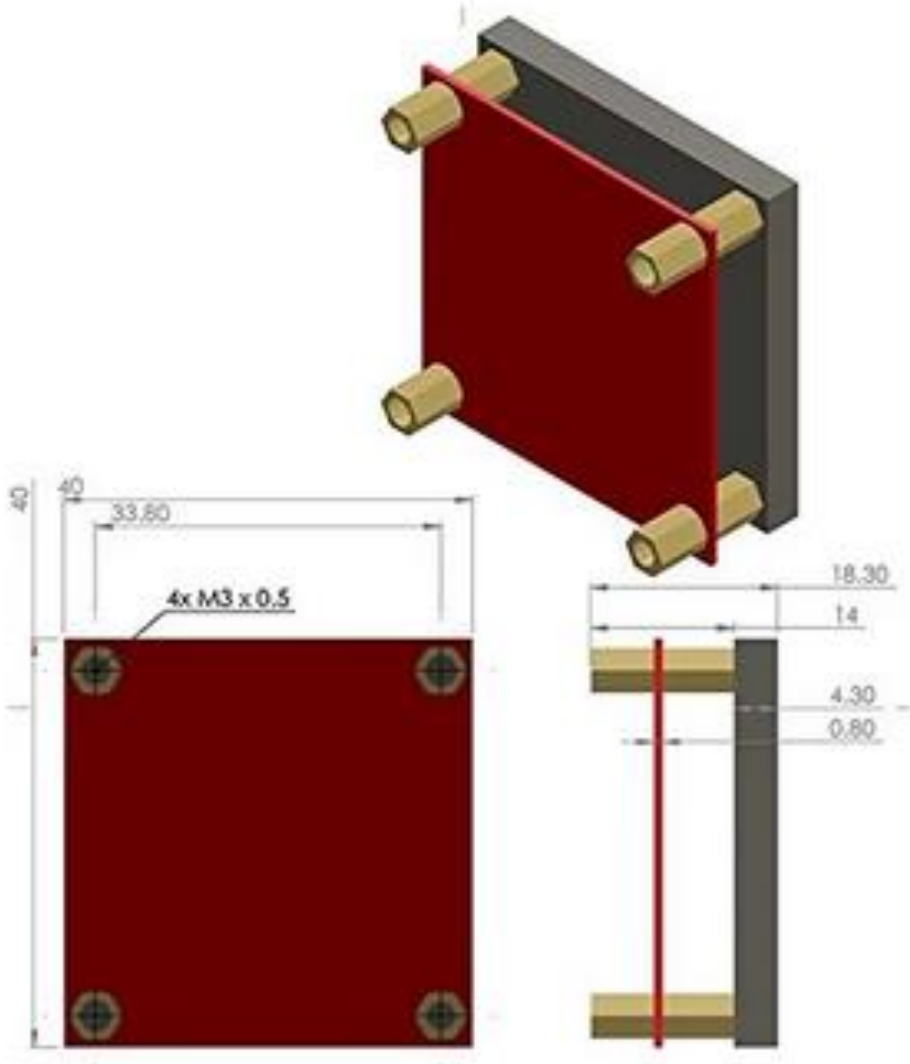


Figure 34 Electro-permanent magnet size

Coding Requirements and Design Matrix

Topic	Weight (/5)	Unacceptable (1)	Mediocre (2)	Marginal (3)	Acceptable (4)	Exceptional (5)
Compatibility	5	No compatibility between other electrical / RC components	Custom software/hardware will need to be obtained to allow compatibility between components	Flight controller has been cited by 50% other components as compatible hardware	Flight controller has been cited by 75% of other components as compatible hardware	Flight controller has been cited by all other components as compatible hardware
Available Documentation / Ease of use	5	No Doc. available online	Doc. minimal or available at a price	Doc. Is available but difficult to follow or incomplete	Doc. Is available for general purposes but not for our specific application	All Doc. Is available for nearly identical applications
Price	3	Flight controller and telemetry are most expensive				Flight controller and telemetry are least expensive
Lightness	1	Flight controller and telemetry are heaviest	-	-	-	. Flight controller and telemetry are lightest
Compactness	1	Flight controller and telemetry are bulkiest				Flight controller and telemetry are most compact

Figure 35: Criteria for Concept Selection for Coding Subsystem

			
Option	A: Pixhawk PX4	B: Qualcomm Flight Pro	C: Raspberry Pi 2 Navio2
Price	$180-300USD	$949.00 USD	$213 USD
Weight	15.8g	40	54.6 g
Dimensions	44x84x12mm	75x36mm	55x65mm
Software	Linux, Mac, Windows	Linux	Linux
Connection	Wifi / Radio: ESP8266 external	Wi-Fi, Radio, Bluetooth 4.2	Wifi Radio
Notes	Open hardware flight controllers that run PX4 on NuttX OS. For hobbyists and amateurs	Requires advanced level of software, electronic and mechanical assembly	

Engineering Design Matrix

					Options	
Topic	Multiplier		A	B	C	D
				5	3	3
Compatibility	5	x		25	15	15
Available				5	2	4
Documentation /	5	x		25	10	20
				5	1	4
Price	5	x		25	5	20
				4	5	5
Compactness	1	x		4	5	5
				5	3	2
Lightness	1	x		5	3	2
		Total		84	38	62

Table 3a: Design matrix for Coding subsystem

Table 3 shows the comparison between flight controllers available for purchase. Based on the criteria for concept selection, Figure 35, Pixhawk Flight controller received the highest score in all categories and thus was chosen.

Electronics and Propulsion Design Matrix

In the meticulous decision process of choosing a suitable motor and propeller pair the design matrix below was created to weigh the best options found on the market. The matrix considered the most important criteria as it relates to the overall design of the drone. Each criterion is weighed according its importance to the functionality of the remaining hardware components of the UAV. The motor and propeller combination with the highest score was chosen for the initial prototype.

Engineering Design Matrix							
Category	**Multiplier**		Option				
			T-motor F40 Pro III 1600KV 4-6S CW Thread Brushless Motor	EMAX RS1408 Performance Brushless Motor 3600KV	EMAX RS1108 Performance Brushless Motor 5200KV	EMAX RS1606 - Brushless Racing Motor	EMX-MT-1534- EMAX Multicopter motor MT2213
Max Thrust *Max Thrust of 642.59g needed for take-off*	5	x	634.33 g **Score: 5 = 25**	667 g **Score: 5 = 25**	456 g **Score: 2 = 10**	670 g **Score: 5 = 25**	670 g **Score: 5 = 25**
Weight	4	x	33.5 g **Score: 2 = 8**	14 g **Score: 3 = 12**	8.2 g **Score: 5 = 20**	15.8 g **Score: 3 = 12**	53 g **Score: 1 = 4**
Recommended Propeller Compatibility *Whether or not the manufacturer recommended propeller is compatible with the airframe of the UAV*	5	x	German Fan 6042 Diameter: 6" Pitch: 4.2" Price: $3.39 **Score: 5 = 25**	AVAN 3.5x2.8x3 Diameter: 3.5" Pitch: 2.8" Price: $2.99 **Score: 3 = 15**	German Fan 3020 Diameter: 3" Pitch: 2" Price: $5.99 **Score: 3 = 15**	GF 4052 Diameter: 4" Pitch: 5.2" Price: $2.92 **Score: 4 = 20**	EMAX 1045 Diameter: 10" Pitch: 4.5" Price: $1.06 **Score: 0**
Max Current *Current required at Max Thrust*	5	x	7.48A **Score: 5 = 25**	15.2A **Score: 3 = 12**	17.5A **Score: 3 = 12**	25.1 A **Score: 2 = 8**	9.6 A **Score: 5 = 25**
Price *Per unit in USD*	3	x	$26.90 **Score: 2 = 6**	$12.99 **Score: 4 = 12**	$12.99 **Score: 4 = 12**	$12.99 **Score: 4 = 12**	$15.50 **Score: 3 = 9**
Efficiency *The ratio of mechanical output to electrical input*	5	x	4.36 **Score: 4 = 20**	2.09 **Score: 3= 15**	1.56 **Score: 2 = 10**	2.12 **Score: 3 = 15**	6.3 **Score: 5 = 25**
		Total	**109**	**91**	**79**	**92**	**88**

Table 4: Design Matrix for Propeller and Motors

** Thrust calculations (see Appendix 2) revealed that due to the design's changing weight, the propeller selection would have to be modified to obtain a satisfactory thrust to weight ratio. The team selected the same type of propeller (German Fan 6042), just with an increased pitch of 4.5 inches instead of 4 inches.

Appendix 6: Generative Design Input

Generative Design is an iterative design process that involves the use of Fusion 360 to generate a certain number of outputs that meet certain constraints. The constraints set up for this generative design are listed below.

Goal: minimize mass / light-weighting

Safety factor minimum : 2.0

Manufacturing: 3D printing max overhang 60

Material: ABS

The preserve bodies, the volume that needs to be maintained, was set up as shown in Figure 36. The area that needs to be kept clear for the arm to function as needed is shown in Figure 37, including the space for the screw holes and motors. The optional starting shape shown in Figure 38 highlights the initial design provided as a guide to the program.

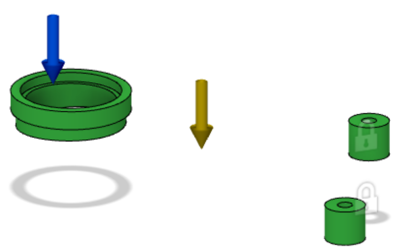


Figure 36: Preserve Bodies

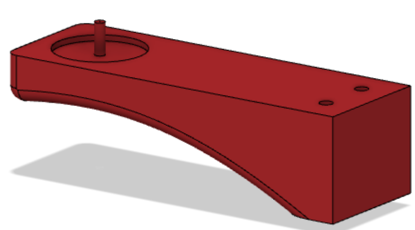


Figure 37: Obstacle Geometry

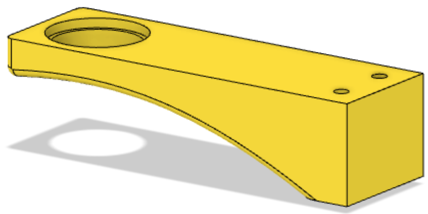
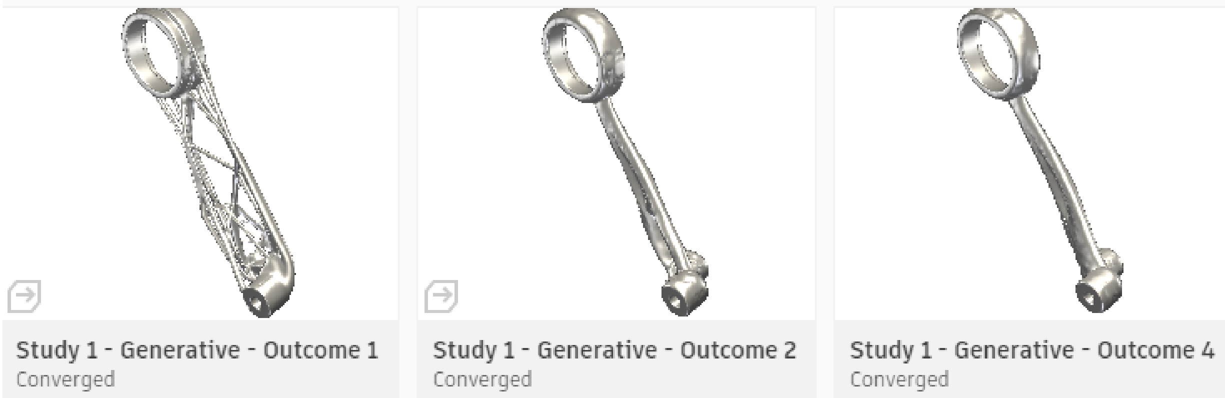


Figure 38: Starting Shape

Results are shown below in Figure 39. The designs chosen were selected based on weight and factor of safety.



Properties	Study 1 - Generative - Outcome 1	Study 1 - Generative - Outcome 2	Study 1 - Generative - Outcome 4
Status	Converged	Converged	Converged
Material	ABS Plastic	ABS Plastic	ABS Plastic
Orientation	-	X+	Z+
Manufacturing method	Unrestricted	Additive	Additive
Volume (mm^3)	1.001e+4	1.341e+4	1.445e+4
Mass (kg)	0.011	0.014	0.015
Max von Mises stress (MPa)	9.6	10	10
Factor of safety limit	2	2	2
Min factor of safety	2.07	2	2

Figure 39:A few results from generative design input

Appendix 7: Additional Analysis

From research by Hibbert et al, the Yield strength of 17MPa and ultimate tensile strength of 22MPa was used for the FEA. The strengths vary on build parameter, strain rate and other factors as shown in

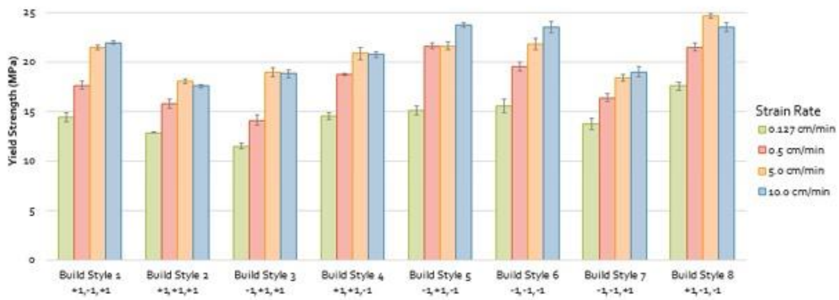


Figure 3.18: Effect of Strain Rate on Yield Stress

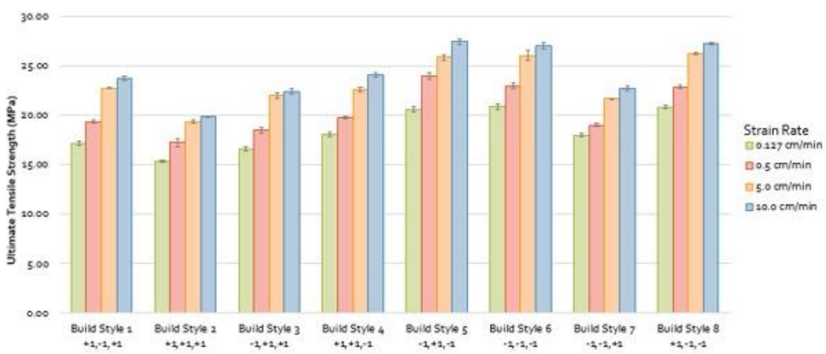


Figure 3.19: Effect of Strain Rate on Ultimate Tensile Strength

Figure 40: Properties of 3D printed ABS

ABS Plastic

Static Load

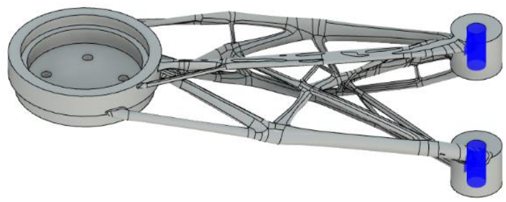
Constraints

Fixed1

Type	Fixed
Ux	Yes
Uy	Yes

Uz	Yes

Selected Entities

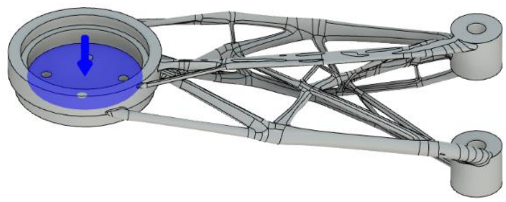


Loads

Force1

Type	Force
Magnitude	10 N
X Value	0 N
Y Value	-10 N
Z Value	0 N
Force Per Entity	No

Selected Entities



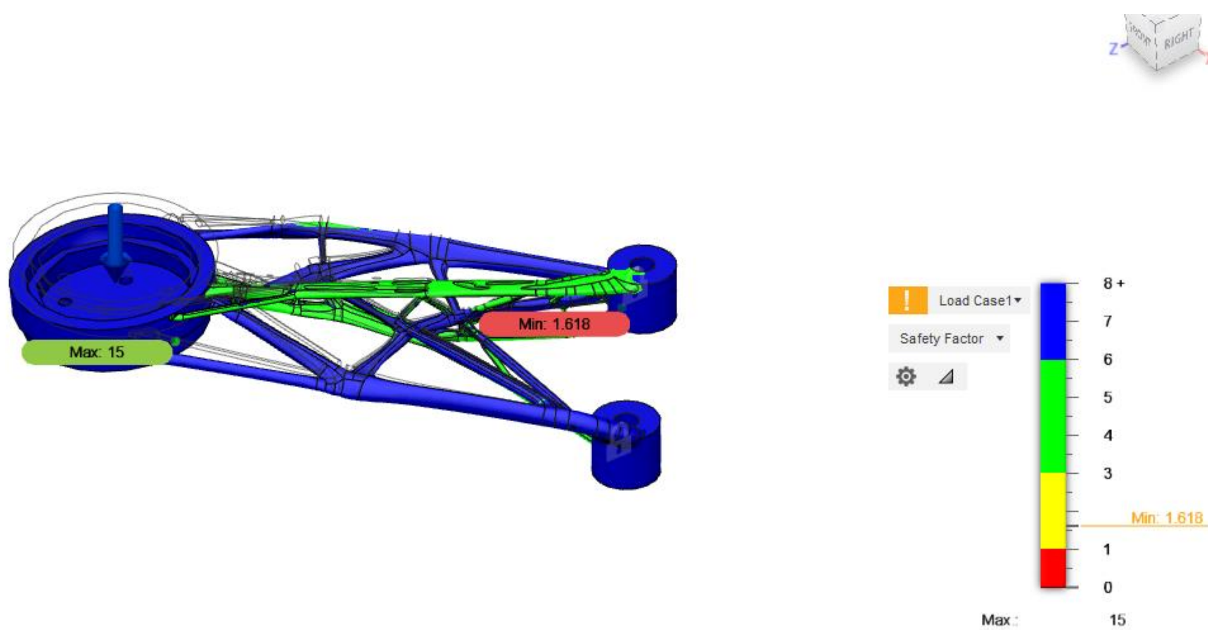
Results

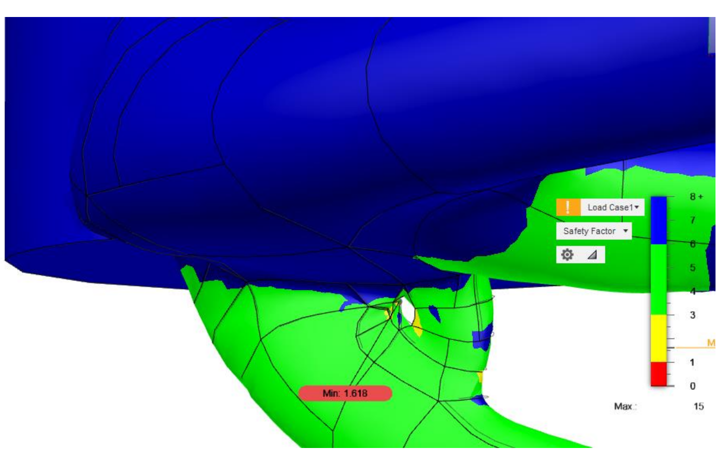
Result Summary

Name	Minimum	Maximum
Safety Factor		
Safety Factor (Per Body)	1.618	15
Stress		
Von Mises	0.01029 MPa	12.36 MPa
1st Principal	-1.803 MPa	18.22 MPa
3rd Principal	-9.757 MPa	5.262 MPa
Normal XX	-6.762 MPa	6.768 MPa

Normal YY	-7.723 MPa	17.52 MPa
Normal ZZ	-7.11 MPa	8.083 MPa
Shear XY	-4.191 MPa	3.583 MPa
Shear YZ	-4.401 MPa	3.871 MPa
Shear ZX	-3.659 MPa	3.255 MPa
Displacement		
Total	0 mm	1.789 mm
X	-0.3666 mm	0.006733 mm
Y	-1.752 mm	0.01082 mm
Z	-0.2401 mm	0.01434 mm
Reaction Force		
Total	0 N	5.068 N
X	-2.054 N	3.494 N
Y	-0.4944 N	0.8141 N
Z	-4.155 N	1.418 N
Strain		
Equivalent	7.95E-06	0.007389
1st Principal	5.231E-06	0.007573
3rd Principal	-0.006287	-5.327E-06

Normal XX	-0.002653	0.002259
Normal YY	-0.003003	0.005666
Normal ZZ	-0.002983	0.002841
Shear XY	-0.005165	0.004415
Shear YZ	-0.005422	0.00477
Shear ZX	-0.004508	0.004011





Modal Frequency

General

Contact Tolerance	0.1 mm
Number of Modes	8

Component	**Material**	**Safety Factor**
Body1	ABS Plastic	Yield Strength

ABS Plastic

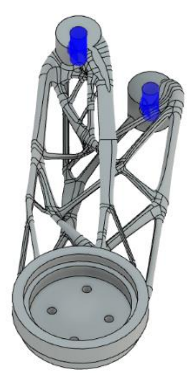
Density	1.06E-06 kg / mm^3
Young's Modulus	2240 MPa
Poisson's Ratio	0.38
Yield Strength	20 MPa
Ultimate Tensile Strength	29.6 MPa
Thermal Conductivity	1.6E-04 W / (mm C)
Thermal Expansion Coefficient	8.57E-05 / C
Specific Heat	1500 J / (kg C)

Type	**Nodes**	**Elements**
Solids	88355	48995

Constraints

Fixed1

Type	Fixed
Ux	Yes
Uy	Yes
Uz	Yes



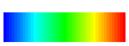
Results

Result Summary

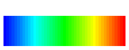
Frequency	Participation X	Participation Y	Participation Z
Mode 1: 165 Hz	4.88119982	44.4362998	2.56629996
Mode 2: 190.3 Hz	1.23150004	8.2487002	1.30329998
Mode 3: 358.7 Hz	26.9811988	1.92910004	22.0765993
Mode 4: 460.2 Hz	0.816200022	6.95189983	3.79099995
Mode 5: 731.2 Hz	0.062599999	1.85349993	0.689700013
Mode 6: 851.4 Hz	0.627700007	0.521899993	0.0132
Mode 7: 1202 Hz	6.77819997	3.23060006	2.31410004
Mode 8: 1312 Hz	0.0055	0.298699993	1.50030004

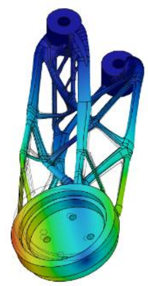
Total Modal Displacement

Mode 1: 165 Hz Total Modal Displacement

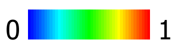
0  1

Mode 2: 190.3 Hz Total Modal Displacement

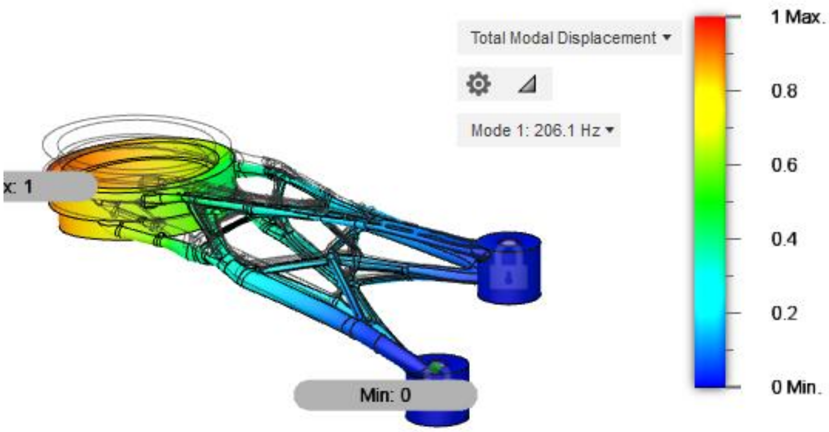
0  1



Mode 3: 358.7 Hz Total Modal Displacement



Design 2 to reduce modal frequency



Mode	Frequency	Participation X	Participation Y	Participation Z
1	206.1 Hz	5.38679995	42.1407014	2.59249993
2	284.2 Hz	2.14869995	0.226600002	1.72300003
3	385.5 Hz	20.3254998	5.53539991	20.5201998
4	479.9 Hz	1.39619997	13.0269006	0.548399985
5	828.6 Hz	0.578300003	0.094	0.226400001
6	919.1 Hz	1.97800007	0.192099996	1.73390005
7	973.5 Hz	2.88050007	2.00880002	1.32929999
8	1181 Hz	0.471000001	0.514299981	0.0741
Sum		35.1649998	63.7388019	28.7477998

Static Load on leg – Unilateral Compression

The figures below demonstrate the iterative design process in light weighting the legs.

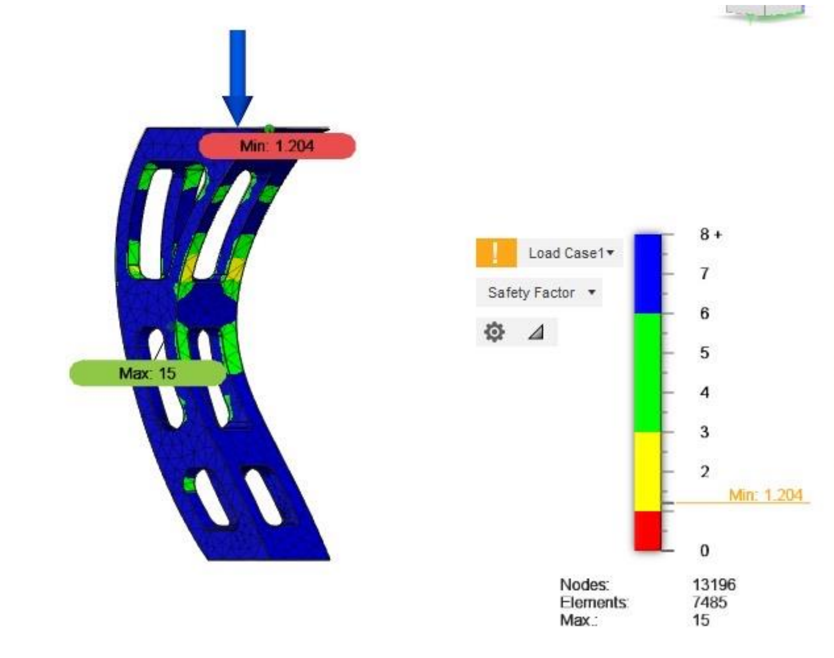


Figure 41: Load applied with sharp edges

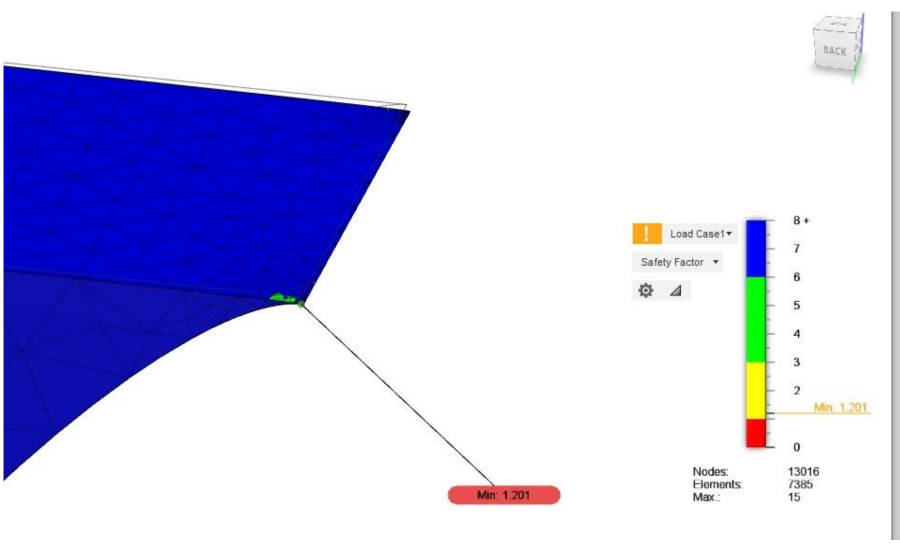


Figure 42: High Stress Concentration/Inefficient Safety Factor with sharp edges

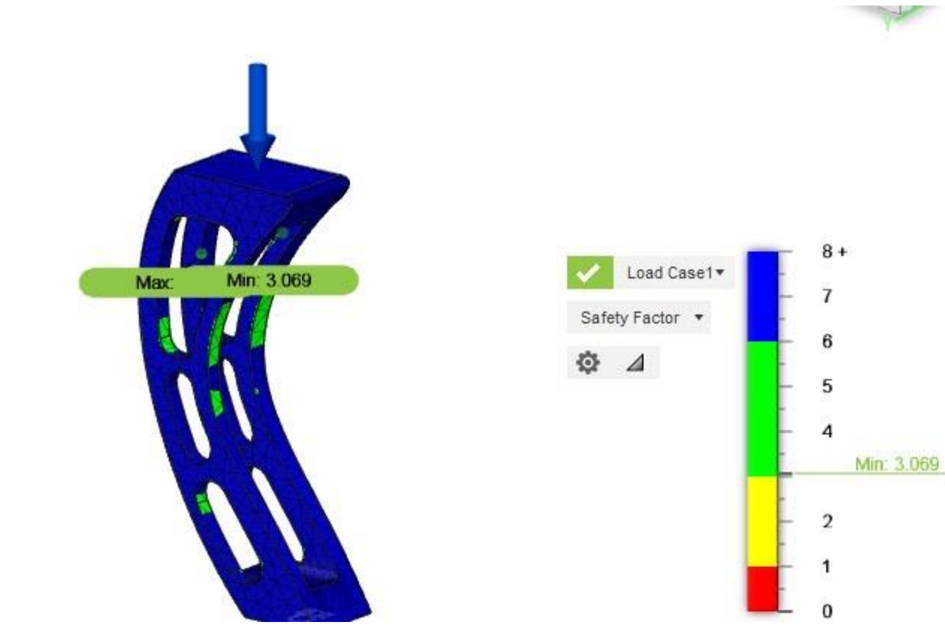
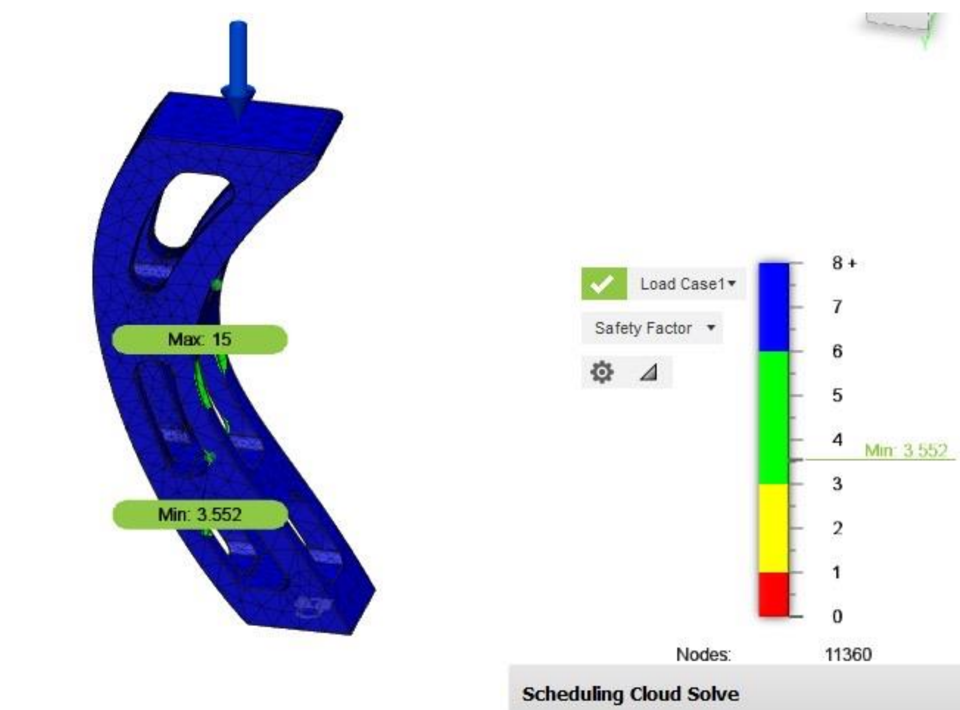


Figure 14.3: Figure 13: Updated Efficient Safety Factor with rounded edges



Complete results for final iteration

Loads

Force1

Type	Force
Magnitude	8.5 N
X Value	1.434E-06 N
Y Value	0 N
Z Value	-8.5 N
Force Per Entity	No

Selected Entities

Results

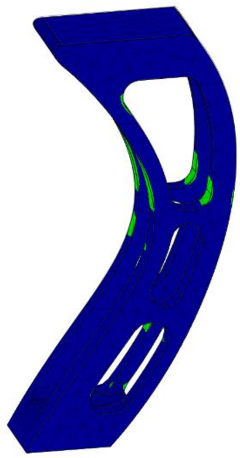
Result Summary

Name	Minimum	Maximum
Safety Factor		
Safety Factor (Per Body)	3.069	15
Stress		
Von Mises	9.318E-04 MPa	5.539 MPa
Displacement		
Total	0 mm	0.1947 mm

Safety Factor

Safety Factor (Per Body)

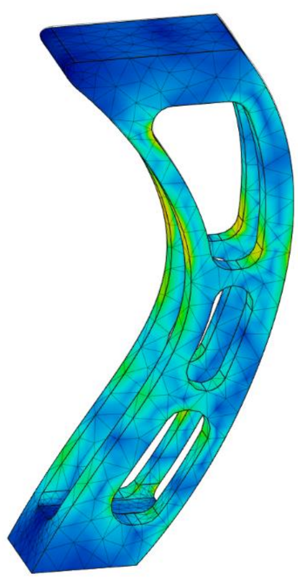
0 [color scale] 8



Stress

Von Mises

[MPa] 0.001 [color scale] 5.539



An Additional study was done on this design to model the landing of the drone on 2 legs at a 20 degree angle to the x direction instead of 4 with some acceleration. Figure 43 shows the result of this set up with reference to ultimate tensile stress. It was found that it will not fail under these conditions but has a low factor of safety (min 1.16).

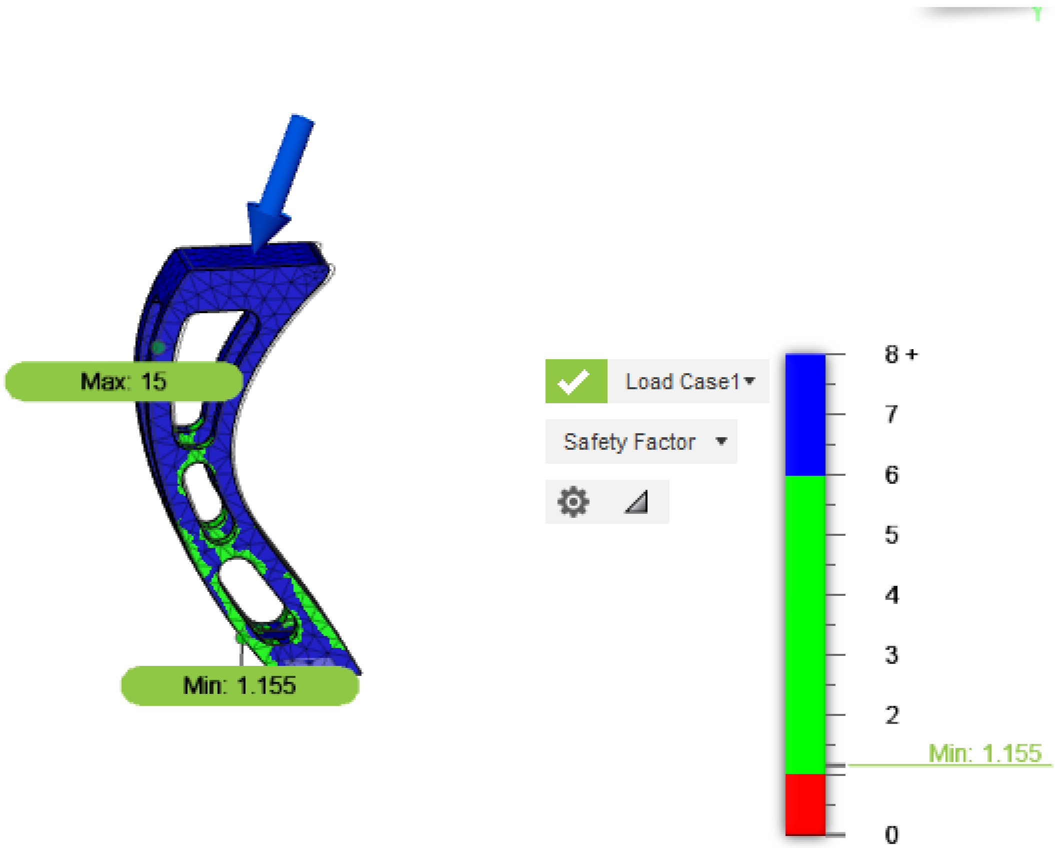


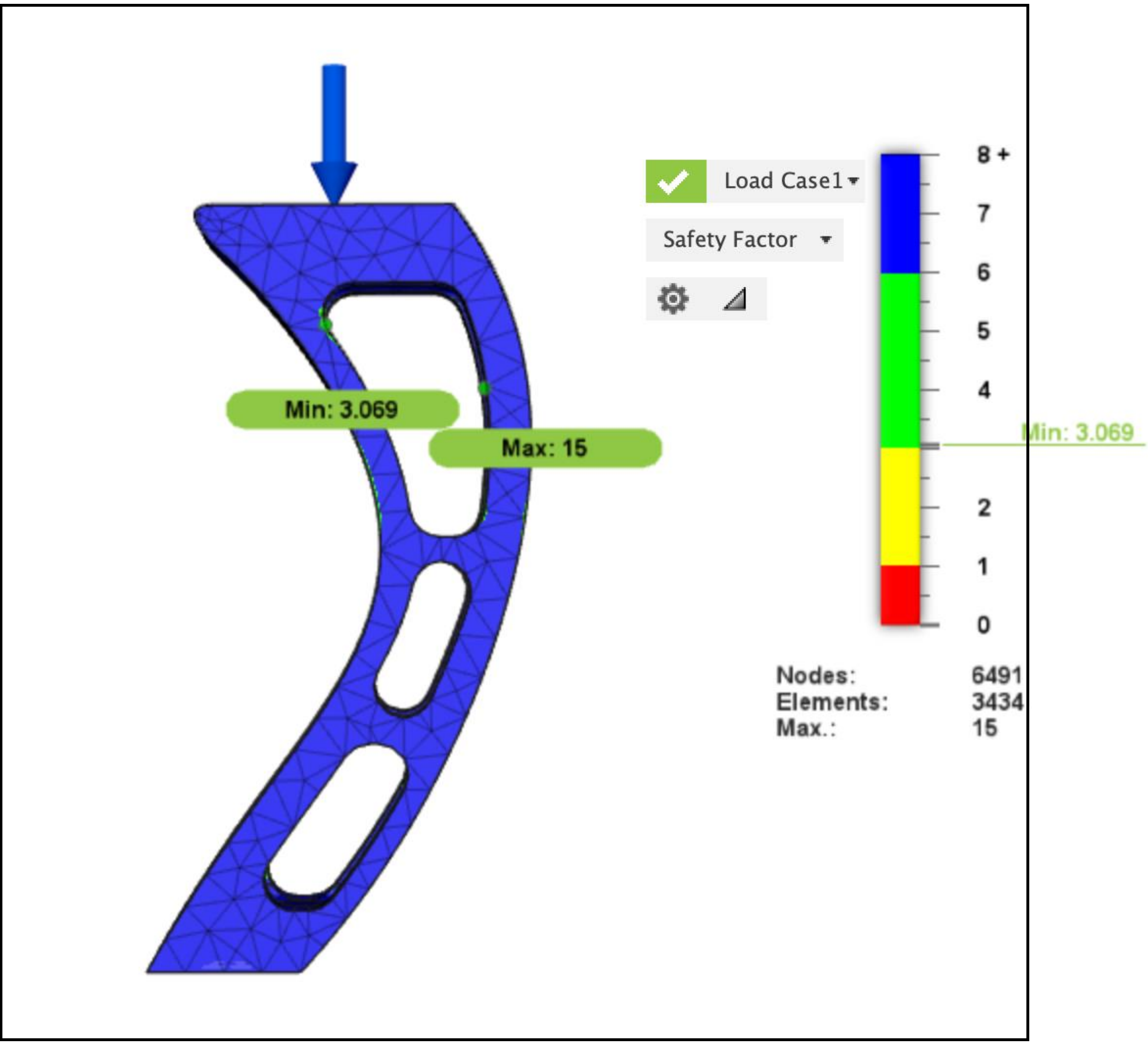
Figure 43: Results of 17N at 20 degree to the x axis

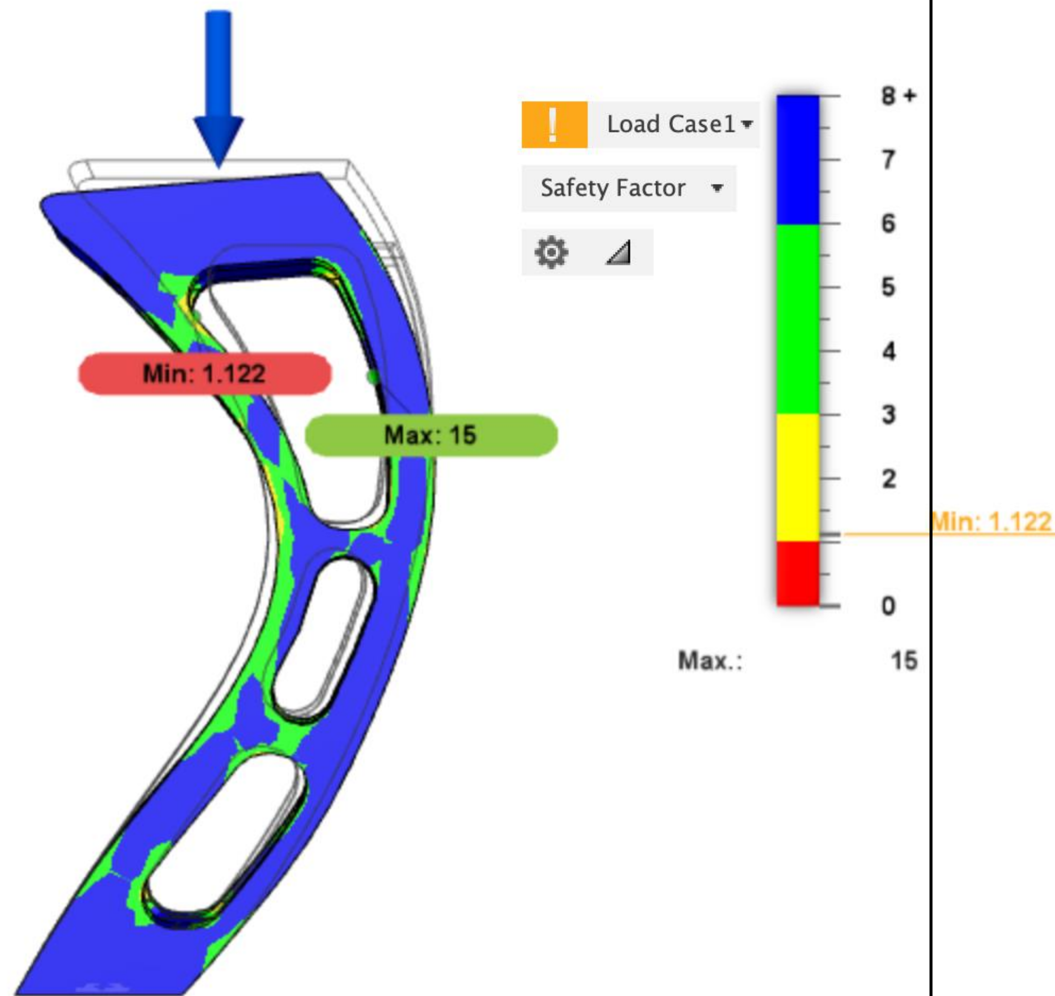
Spring Semester Landing Gear Analyses

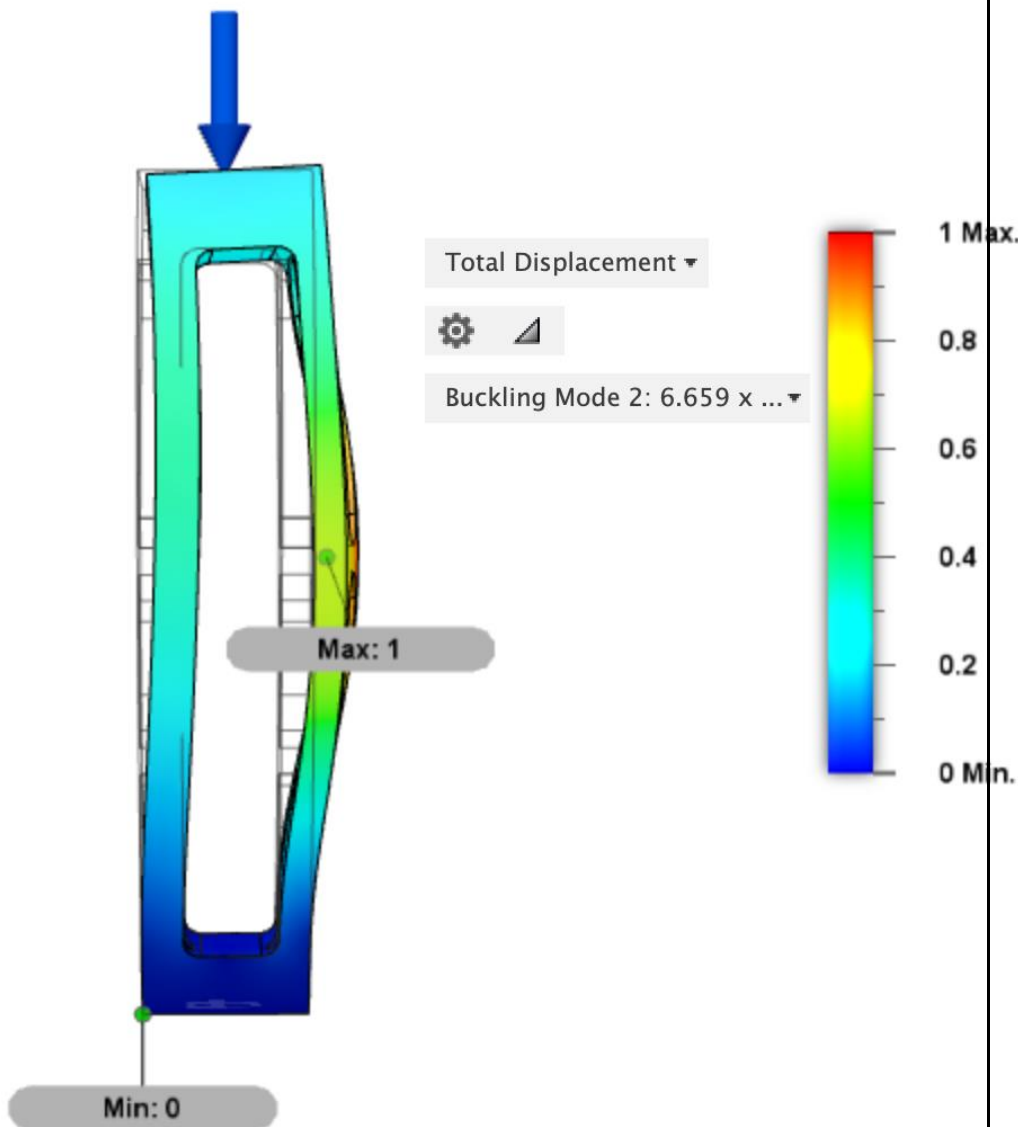
Leg design was altered during the second semester in order to increase strength. However, due to issues that arose when printing the legs, with regards to the support material and the support material chemical bath, new designs were created that could potentially be used. These designs are specifically made to both reduce the potential support material needed to 3D print them, as well as possibly produce support material that can be easily removed with or without the chemical bath.

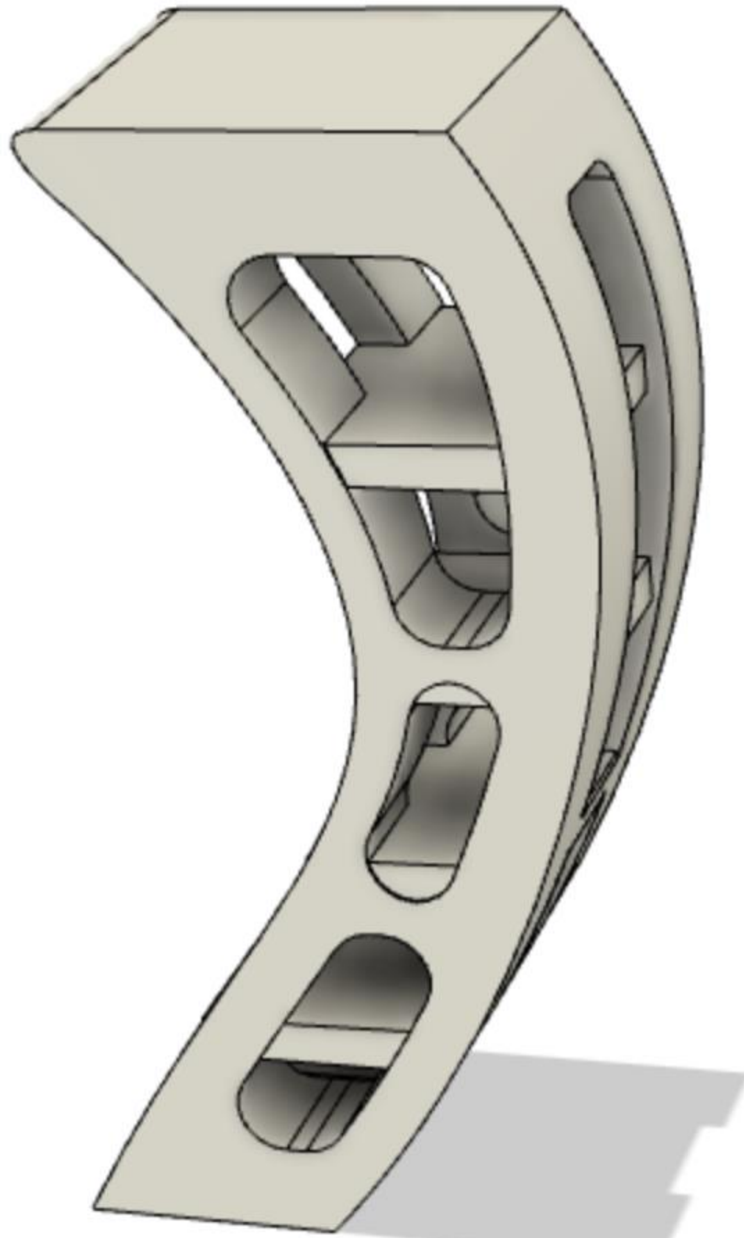
Ultimately, four potential leg designs were created and multiple analyses were performed for each design. Analysis 1 is a static analysis of the full weight of the drone on one leg. Analysis 2 is a static analysis of the force of the drone falling on one leg from the 10 feet in the air (the max altitude for the competition). Analysis 3 is a buckling analysis done using the force of the drone's weight on one leg multiplied by 5, in order to identify the worse buckling case for each design iteration.

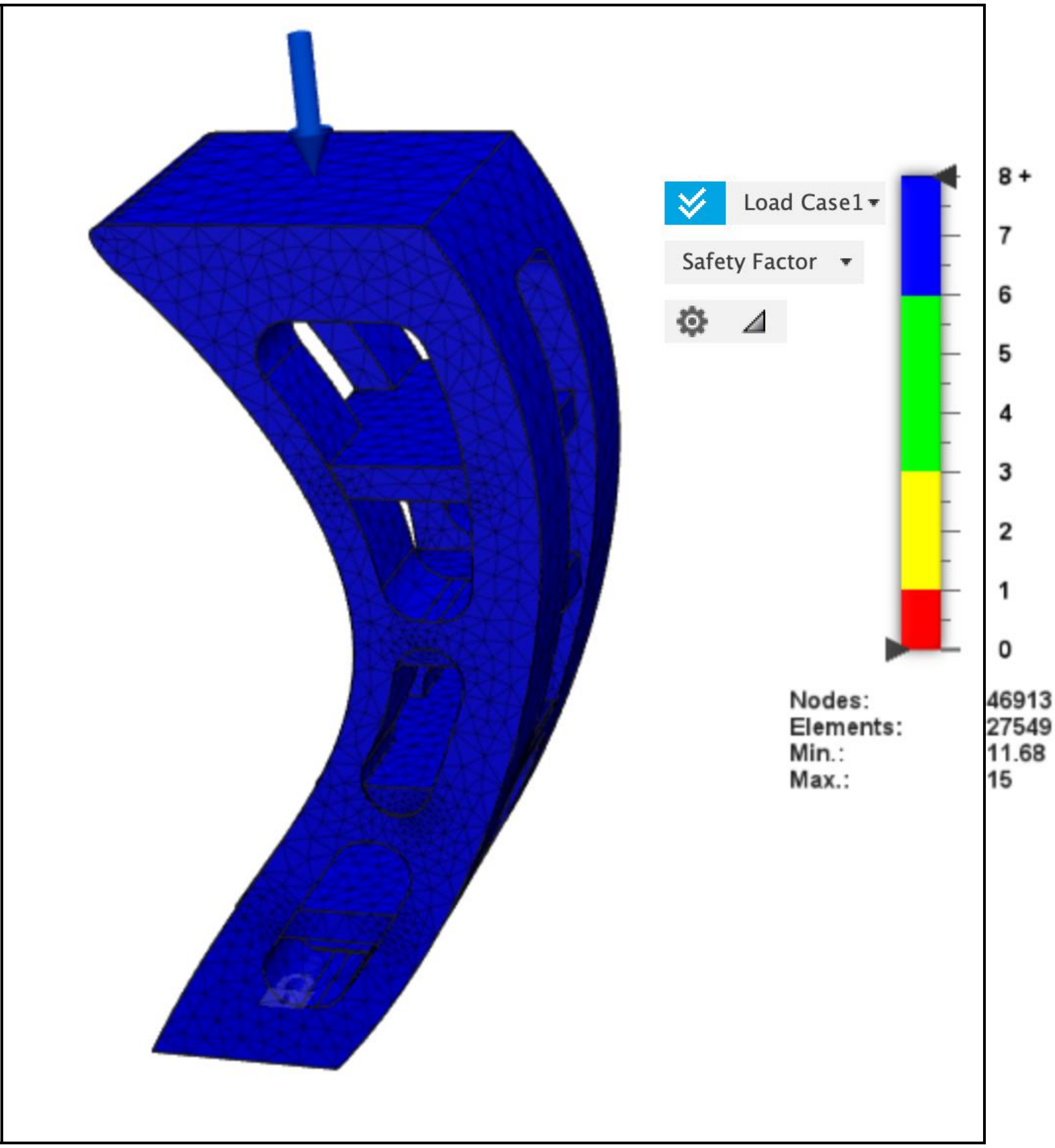
Leg Iteration: Original Design	

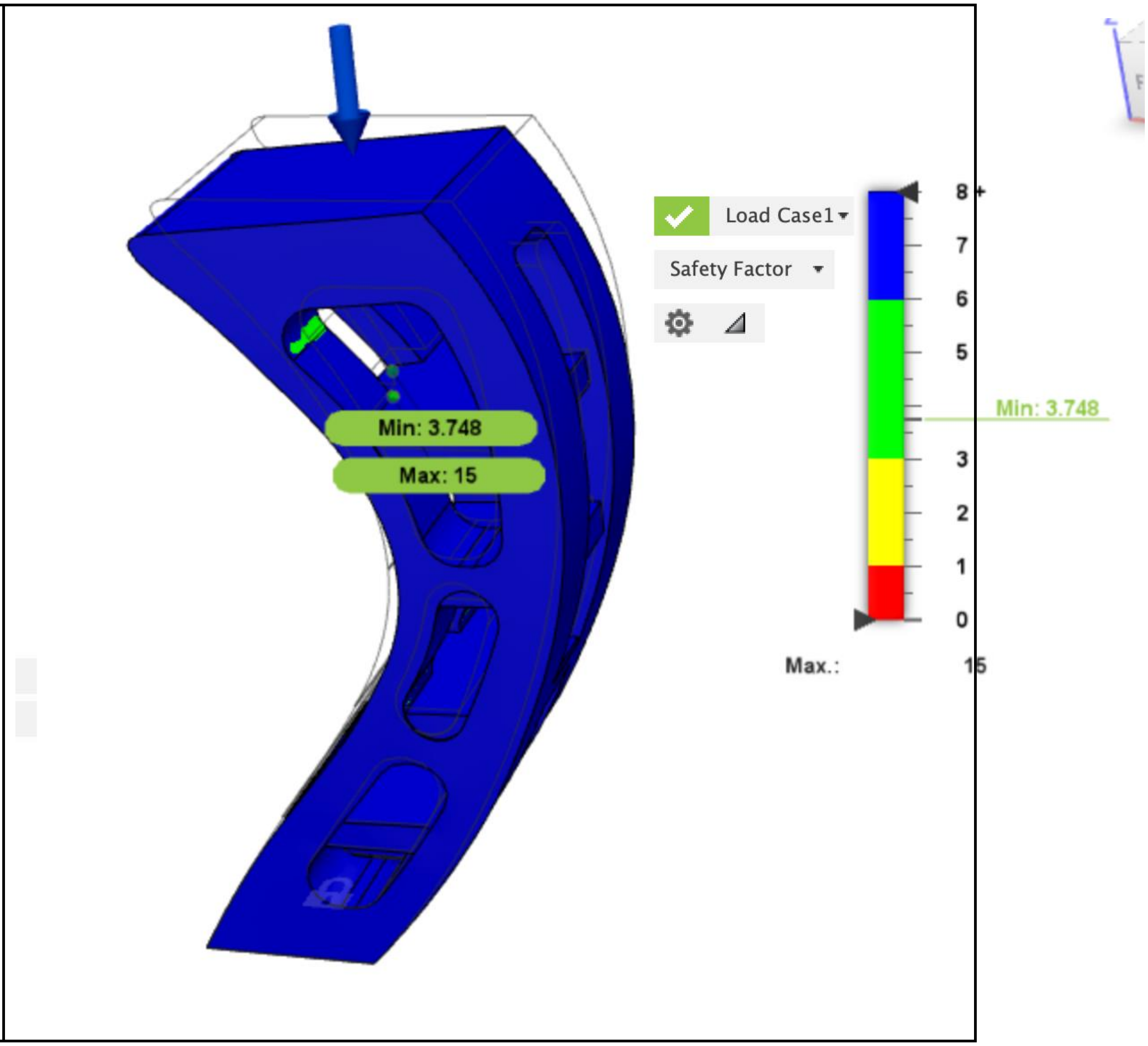
Analysis 1: Static Analysis with 8.50 N force to simulate the force of the entire weight of the drone on one leg.	

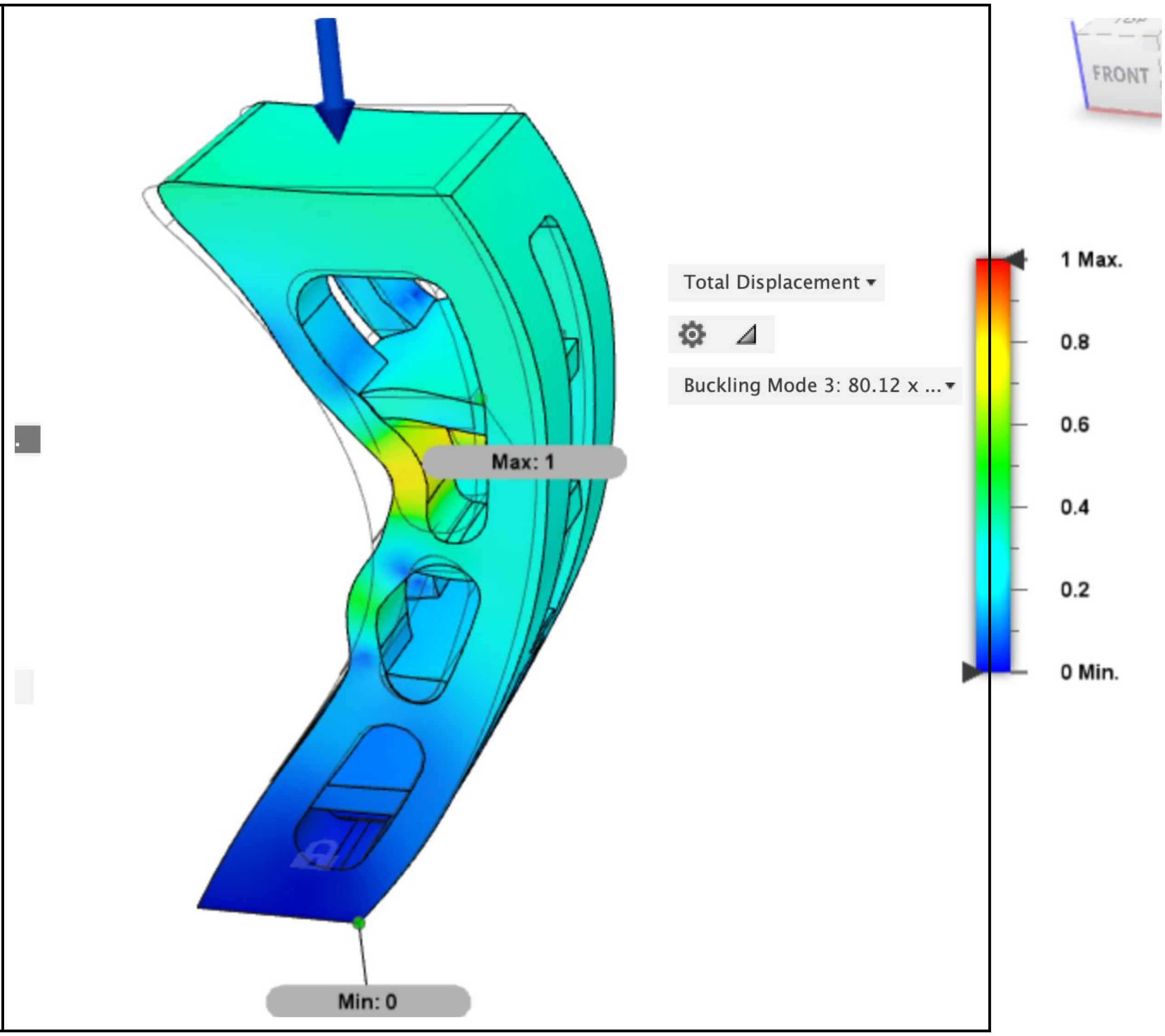
Analysis 2: Static Analysis with 25.3446 N force to simulate if the drone fell from a height of 10 feet (maximum altitude for the competition) and fell on one leg	

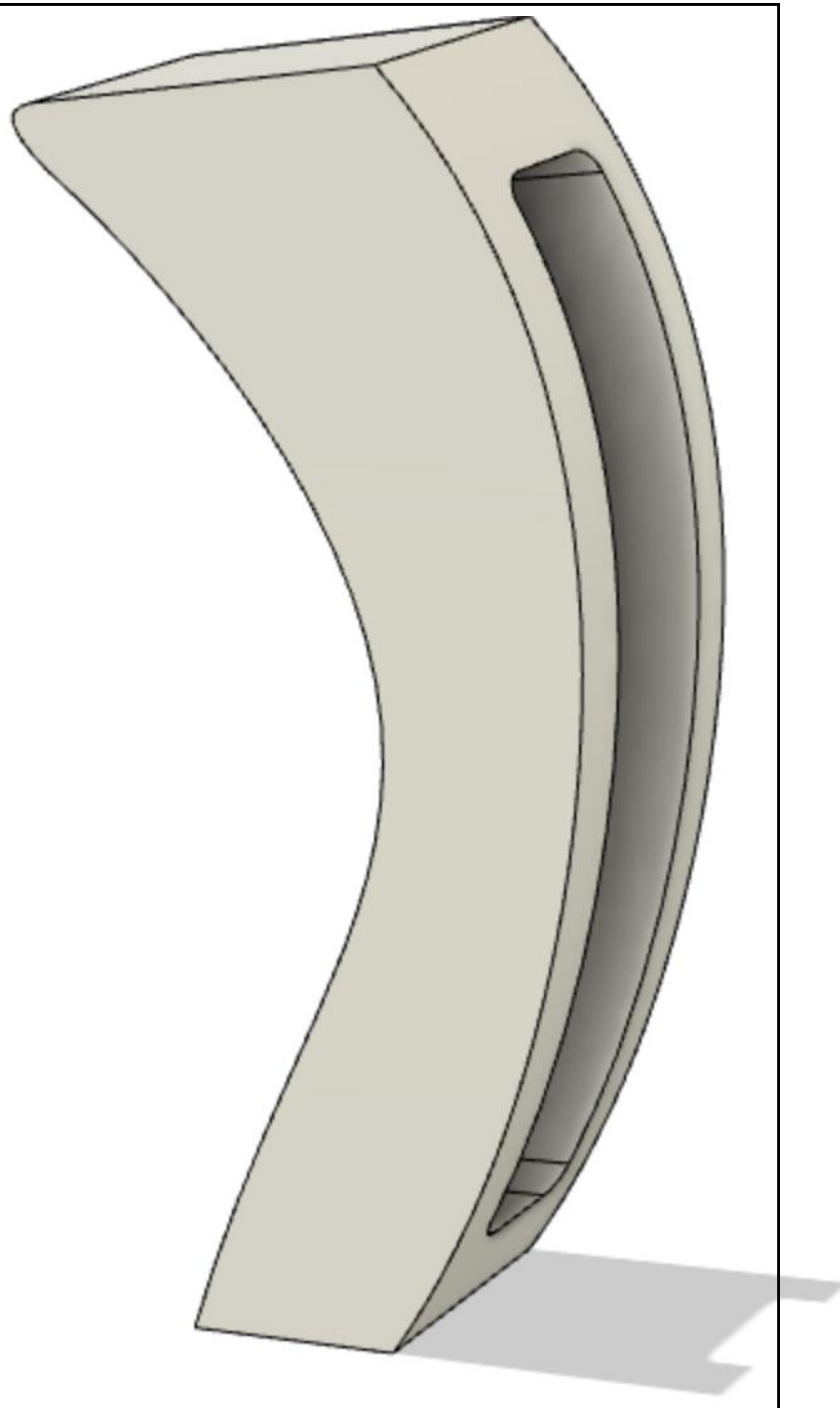
Analysis 3: Force chosen was 42.50 N (5 times the weight of the drone). Buckling Mode 2 proved to be the worst buckling failure with the most displacement and shape deformation.	

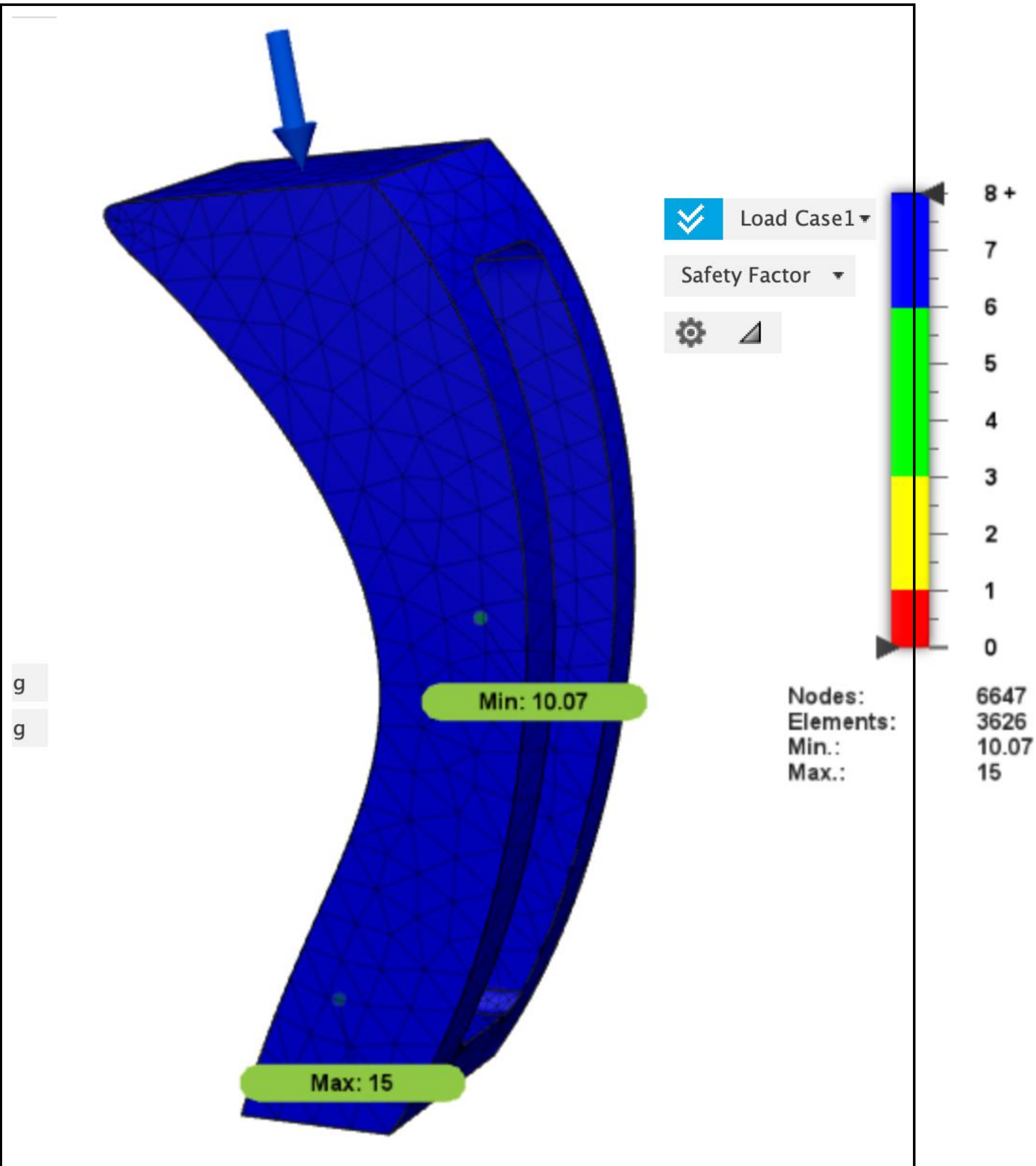
Leg Iteration: Final Leg Design Added to Drone (platforms in leg added to strengthen leg design)	

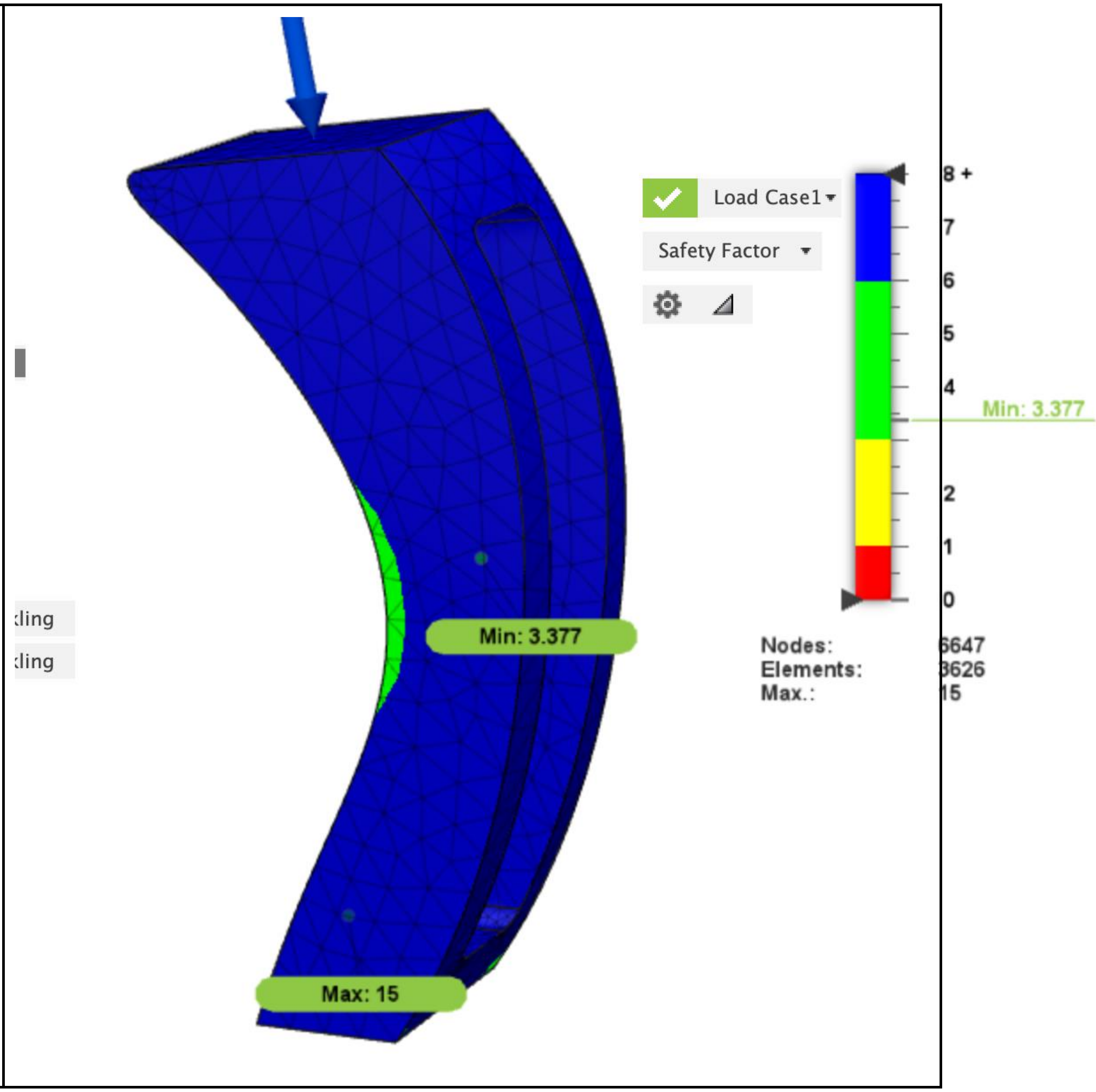
Analysis 1: Static Analysis with 8.50 N force to simulate the force of the entire weight of the drone on one leg.	

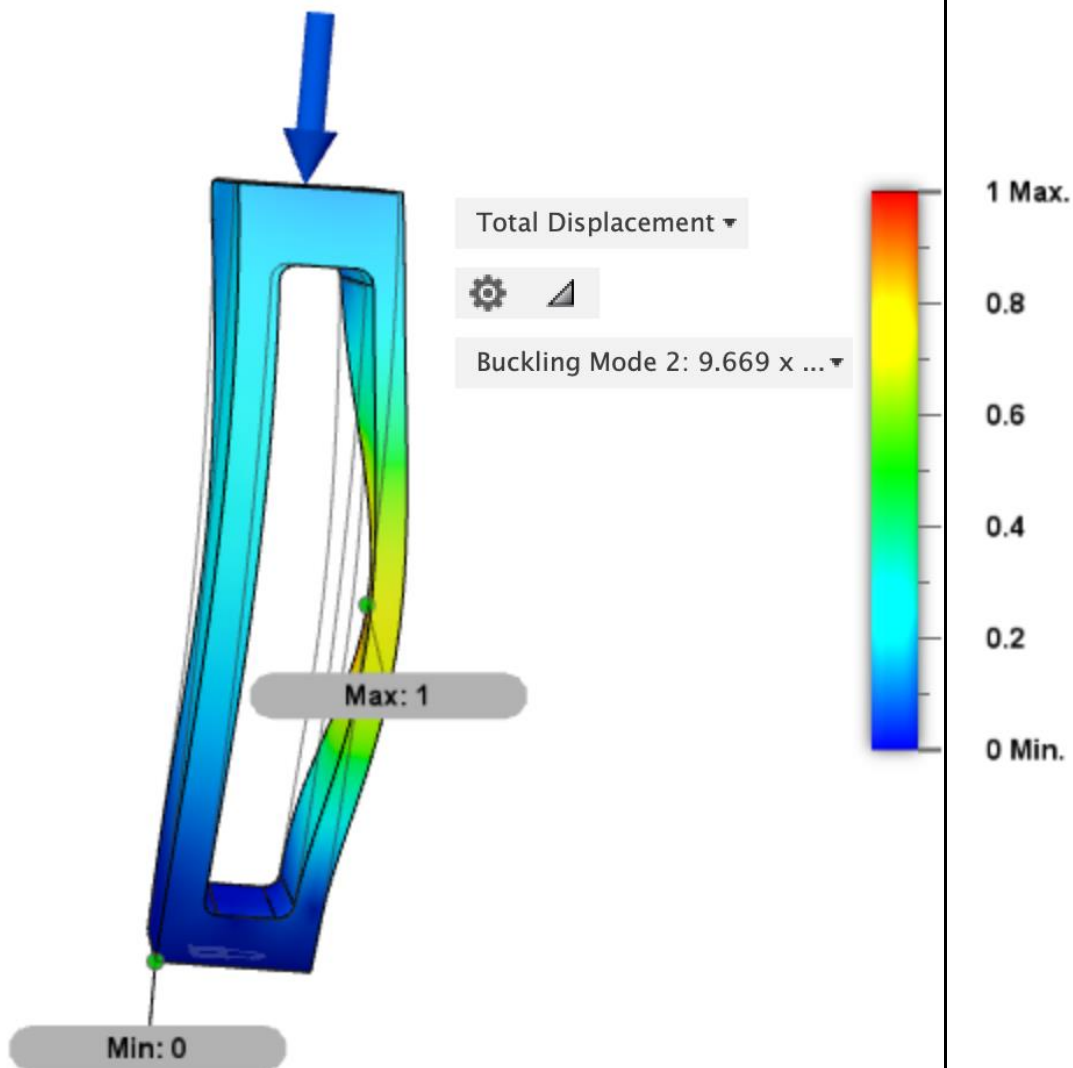
Analysis 2: Static Analysis with 25.3446 N force to simulate if the drone fell from a height of 10 feet (maximum altitude for the competition) and fell on one leg	

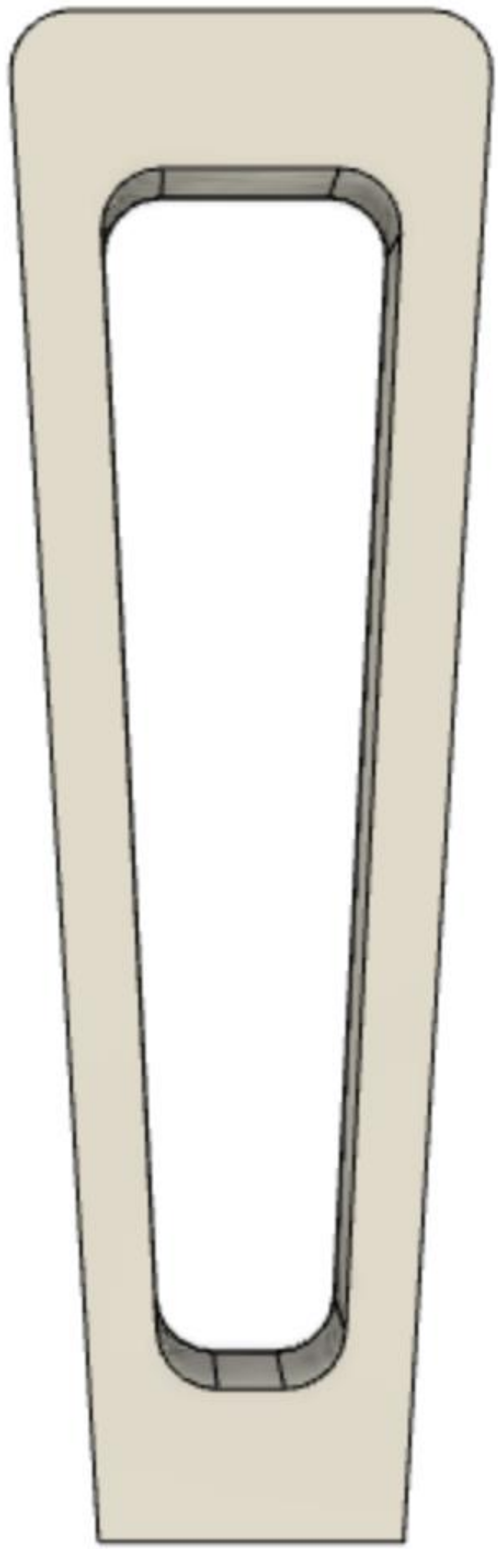
Analysis 3: Force chosen was 42.50 N (5 times the weight of the drone). Buckling Mode 3 proved to be the worst buckling failure with the most displacement and shape deformation.	

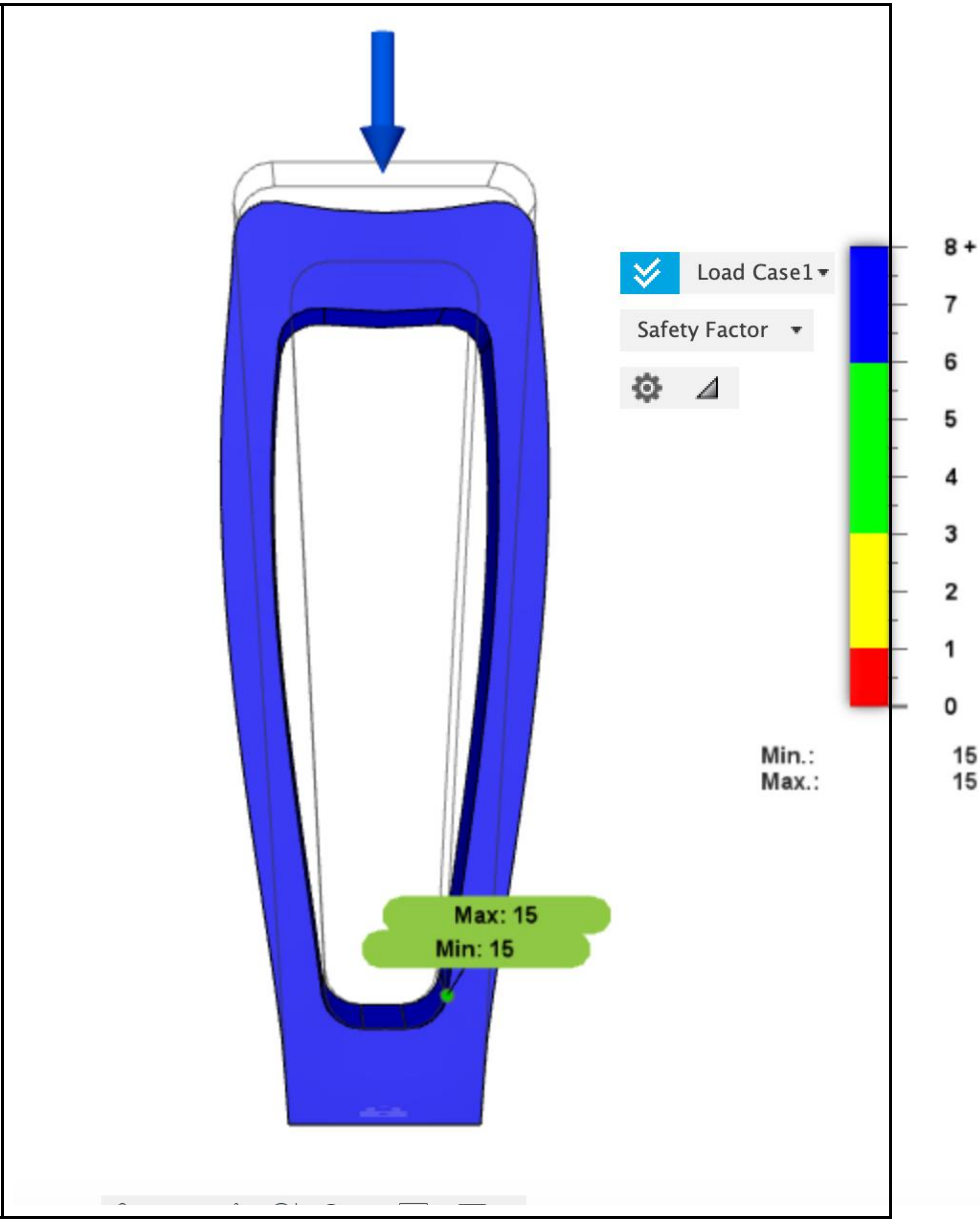
Leg Iteration: Potential Leg Design #1 that minimizes need for support material. Ideally support material would be able to be physically removed by hand or will be more easily removed in the chemical bath.	

Analysis 1: Static Analysis with 8.50 N force to simulate the force of the entire weight of the drone on one leg.	

Analysis 2: Static Analysis with 25.3446 N force to simulate if the drone fell from a height of 10 feet (maximum altitude for the competition) and fell on one leg	

Analysis 3: Force chosen was 42.50 N (5 times the weight of the drone). Buckling Mode 2 proved to be the worst buckling failure with the most displacement and shape deformation.	

Leg Iteration: Potential Leg Design #2 that minimizes need for support material; specifically here that is done with a straight leg design instead of a curved one. Ideally support material would be able to be physically removed by hand or will be more easily removed in the chemical bath.	

Analysis 1: Static Analysis with 8.50 N force to simulate the force of the entire weight of the drone on one leg.	

Analysis 2: Static Analysis with 25.3446 N force to simulate if the drone fell from a height of 10 feet (maximum altitude for the competition) and fell on one leg	

<table>
<tr>
<td>Analysis 3: Force chosen was 42.50 N (5 times the weight of the drone).

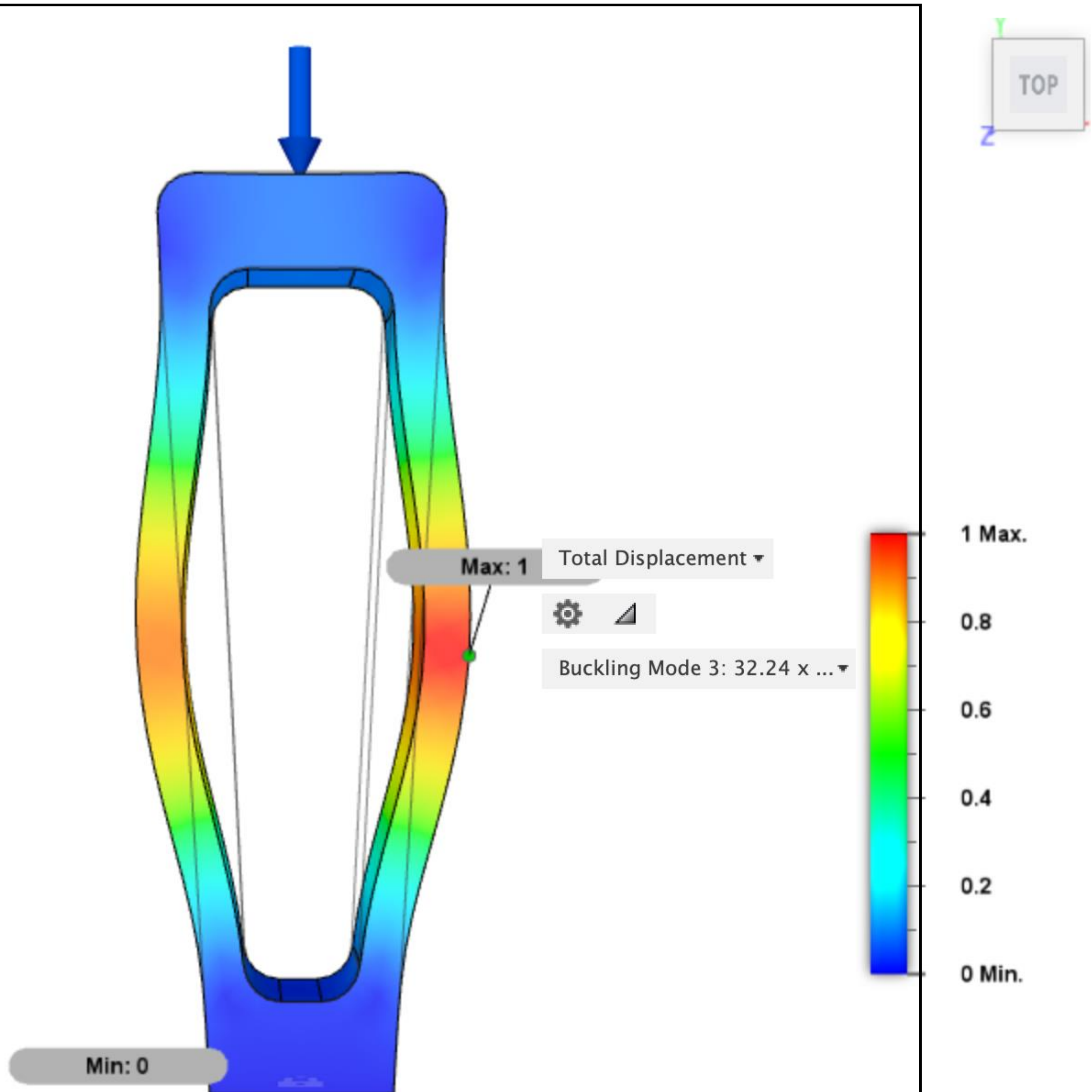
Buckling Mode 3 proved to be the worst buckling failure with the most displacement and shape deformation.</td>
<td>
</td>
</tr>
</table>

Figure 44: Screenshot and sample code from SITL flight simulation

imulation is a quick, easy, and most importantly, safe way to test changes to PX4 code before attempting to fly in the real world. It is also a good way to start flying with PX4 when you haven't yet got a vehicle to experiment with.PX4 supports both Software In the Loop (SITL) simulation, where the flight stack runs on computer (either the same computer or another computer on the same network) and Hardware In the Loop (HITL) simulation using a simulation firmware on a real flight controller board. Figure 44 shows sample SITL simulation done with the code. This was obtained from the PX4 Open source Autopilot documentation. [10]

Appendix 8: Additional Competition Details

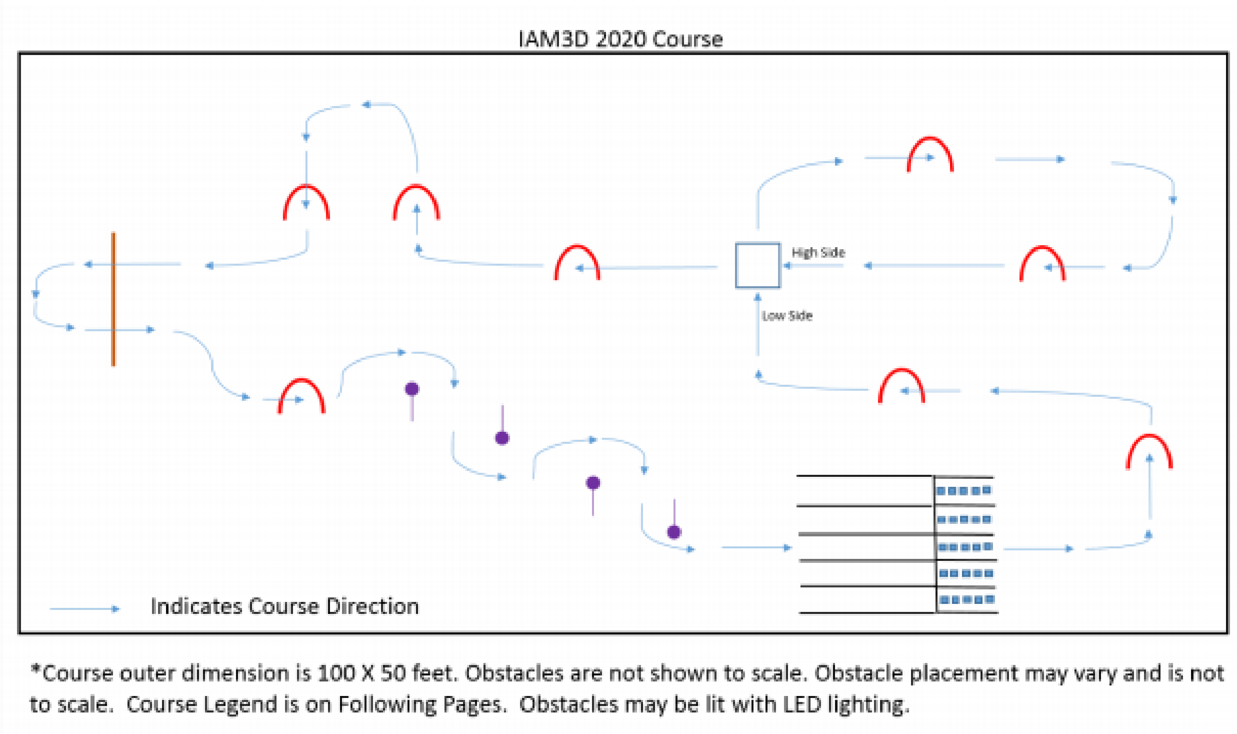


Figure 45: ASME IAM3D 2020 Course outline

Course Requirements:

- Reach no more than 10 feet amplitude during flight
- Vehicle Size: max of 33 cm measured diagonally from motor center to motor center and 25 cm in height
- Maximum battery specifications 4S and 4.2 Volts per cell
- Maximum 15 minutes of flight time for 5 laps

Competition scoring (point system)

- Design Report (/2500)
- Use of additive manufactured part (/5000)
- Obstacle course (/2000) + 200 per payload
    - 1st place in the competition 1000 points, 2nd place is 500 points and 3rd place is 250 points.

Appendix 9: Standard Operating Procedure

For safe operation of the U.A.V the following procedures must be followed in the stages listed below.

Pre-Flight

- **Before arrival at airfield**
    - Review relevant ASME IAM3D competition documentation to ensure rules are adhered.
    - In an unfamiliar airfield, review local regulations and permissions including the need to file a NOTAM (notice to airmen), and take note of the proximity of airfield to an airport.
    - Check weather conditions to ensure they are suitable for flying.
    - Ensure all batteries are sufficiently charged.
    - Check flight gear.

- **Upon arrival at airfield**
    - Scan area for obstacles.
    - Perform wind check.
    - Assemble UAV, ensuring screws are tight and propellers are properly secured.
    - Perform camera check.
    - Ensure battery is securely mounted.
    - Ensure GPS is fixed.
    - Confirm flight/training plan.
    - RC remote check
    - Perform final airframe inspection.
    - Flight crew briefing, i.e training plan for the day and safety.
    - Perform final wind check before launch.

Flight

- **Post Departure**
    - Ensure aircraft is at a suitable altitude.
    - Confirm flight crew has the aircraft in sight.
    - All systems are green.
    - Perform satellite and GPS check.
    - Check status of battery.
    - Perform training exercise.
- **Pre-Landing**
    - Ensure training exercise was completed successful.
    - Scan landing area for obstacles.
    - Perform wind check.
    - Observer briefing for landing.
    - All systems green.

Post Flight

- **Post Landing**
    - Power down UAV.

- Remove and safely store batteries.
- Perform airframe inspection.
- Check camera.

- **Post Exercise**
  - Discuss training exercise with flight crew, taking note of any improvements that can be made for the competition.

Appendix 10: Bill of Materials

Number	Quantity	Item (generic)	Item Full name	Price each	Total Price	Link to Vendor(s)
1	1	Microcontroller	Pixhawk PX4 PIX 2.4.8 Flight Controller NEO-M8N GPS 3DR 915Mhz Radio Wireless Telemetry Set OSD Module PPM Module I2C Splitter Expand Module Power Module for FPV Quadcopter	$ 128.86	$ 128.86	Amazon
2	1	Remote Control	Flysky FS-i6X 10CH 2.4GHz AFHDS RC Transmitter w/ FS-iA6B Receiver	$ 48.99	$ 48.99	Amazon
3	4	ESC	Hobbypower SimonK 30A ESC Brushless Speed Controller BEC 2A for Quadcopter F450 X525 (Pack of 4 pcs)	$ 24.97	$ 99.88	Amazon
4	1	Balanced propellers	GEMFAN 6042 6'' 2-BLADE PROPELLERS (8 Pack)	$ 3.26	$ 3.26	Amazon
5	2	FPV Camera	RunCam Racer 2	$ 15.40	$ 30.80	Amazon
6	1	Camera Switcher	VIFLY Dual FPV Camera Switcher	$ 6.99	$ 6.99	Amazon
7	1	4S Battery	Ovonic 14.8V 1550mAh 100C 4S LiPo Battery Pack with XT60 Plug for FPV Racing RC Quadcopter Helicopter Airplane Multi-Motor Hobby DIY Parts	$ 18.99	$ 18.99	Amazon
8	1	Video Transmitter	TS832 48Ch 5.8G FPV Transmitter	$ 15.89	$ 15.89	Amazon
9	4	Brushless motors	T-motor F40 Pro III 1600KV 4-6S CW Thread Brushless Motor for RC Drone FPV Racing	$ 25.49	$ 101.96	Amazon
10	1	Proximity Sensor	Ultrasonic proximity sensor, EZ, MB1013	$ 35.00	$ 35.00	Amazon
11	1	Video Receiver	FPV Receiver, EACHINE ROTG01 UVC OTG 5.8G 150CH Full Channel FPV Receiver for Android Mobile Phone Tablet	$ 29.99	$ 29.99	Amazon
12	1	Camera Switcher	VIFLY Dual FPV Camera Switcher	$6.99	6.99	Amazon
13	1	Charger for 4S battery	Tenergy TN267 1-4 Cells Li-Po/Li-Fe Balance Charger for Airsoft & RC Car Battery Packs with 1S to 4S XH Type Balance Connector	$24.99	24.99	Amazon
14	1	LiPo Safe Bag	LiPo Fireproof Explosionproof Safety Bag |ExpertPower|for Lithium Battery & DJI Mavic & DJI Phantom 3 Battery|Guard Charging and Storage Safe Bag (7.3 x 3.0 x 2.5 Inches)	$ 7.99	$ 7.99	Amazon
15	1	Alkaline Batteries	AmazonBasics AA 1.5 Volt Performance Alkaline Batteries - Pack of 20	$ 8.48	$ 8.48	Local Store / Amazon
16	1	Power Distribution Board	HOBBYMATE XT60 PDB Power Distribution Board - Support 3-6S Input, 5V/12V Output Support The LC Filter, w/Current Sensor	$ 12.90	$ 12.90	Amazon
17	1	Insert Screws	QLOUNI 330Pcs M2 M3 M4 M5 Female Thread Knurled Brass Threaded Insert Embedment Nut Assortment Kit	$ 12.99	$ 12.99	Amazon
18	1	Nuts Volt Screw Kit	DYWISHKEY 360 Pieces M3 x 6mm/8mm/10mm/12mm/16mm/20mm, 12.9 Grade Alloy Steel Hex Socket Head Cap Bolts Screws Nuts Kit with Hex Wrench	$ 10.69	$ 10.69	Amazon

Figure 46: Bill of Materials

Appendix 11: Early Design Iterations

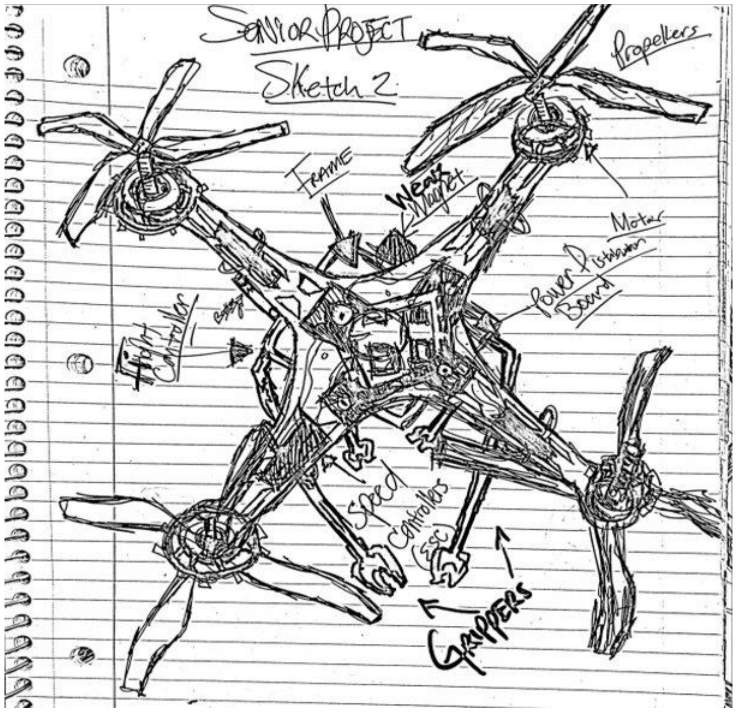
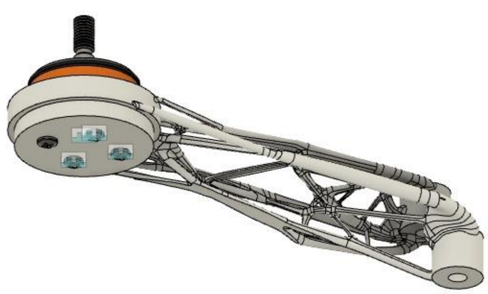
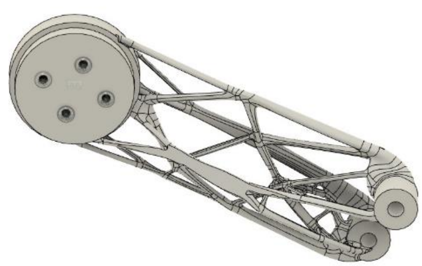
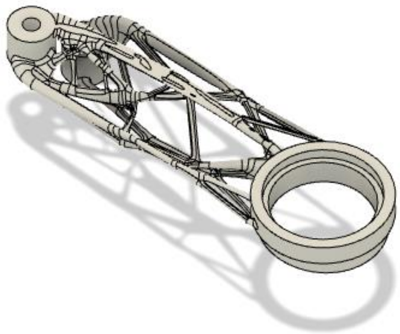


Figure 44: Early Design Iteration with Initial Gripper Concept

Other updates to design

New design



Old design

The arms were updated to reflect the dimension and screw of the rotors being currently used. The holes on the arms were also resized to accommodate screw inserts for reusability.

Screw updates

Initially, a thread forming screw was chosen because they're ideal for plastics due to the fact they can slice through with minimal stress and have low installation torque. However, we found that once our parts were manufactured and a fit test was conducted, the screw isn't quite long enough in length to ensure that the arms stay firmly connected to the upper and bottom plates. The new screws, found on McMaster, are 22 mm long, 6mm longer than the original screw. The hole in the drone plates are also adjusted to ensure that the screws have a secure and tight fit ensuring that the arms don't fall apart during flight. Therefore, the m3x 0.5 thread size is adjusted accordingly. Updated screw specifications are seen below.

McMASTER-CARR

Find

Button Head Hex Drive Screw

Passivated 18-8 Stainless Steel, M3 x 0.50 mm Thread, 22mm Long

Packs of 50

ADD TO ORDER

In stock
$4.74 per pack of 50
92095A473

Thread Size	M3
Thread Pitch	0.5 mm
Length	22 mm
Threading	Fully Threaded
Head Diameter	5.70 mm
Head Height	1.65 mm
Drive Style	Hex
Drive Size	2 mm
Material	Passivated 18-8 Stainless Steel
Hardness	Not Rated
Tensile Strength	70,000 psi
Thread Type	Metric
Thread Spacing	Coarse
Thread Fit	Class 6g
Thread Direction	Right Hand
Head Type	Rounded
Rounded Head Style	Button
Rounded Head Profile	Standard
System of Measurement	Metric
Specifications Met	ISO 7380

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We also decided to install M3 x 10 mm 12.9 Grade Alloy Steel Hex Socket Head Cap Bolt Screw Nuts to fasten the electromagnet enclosure to the plate securely. The electromagnet must stay in a stagnant position to ensure that the payload is picked up efficiently and doesn't deviate from its pickup and dropoff positioning.

Appendix 12: Memo of Individual Contribution per Member

Alli Ashby

Technical Contributions include the following:

- Full Analysis and development of the Payload Gripping Mechanism Subsystem (including calculations and design matrix which ultimately resulted in the chosen and most effective gripping mechanism for our needs: the electro-permanent magnet)
- FEA Analysis of altered drone legs/landing gear (iterations #2, #3, #4)
- Designing landing gear iterations #3 and #4 in order to minimize the need for support material/ aim to have support material that can be more easily removed (the need arose after the beginning of 3D printing and testing and the affect it was having on our original landing gear)
- 3D Printing Responsibilities: Taking shared responsibility, along with other teammates, to split up designated times to 3D print frame of drone
- Learning and setting up support material bath (along with other teammates) as well as taking shared responsibility to bathe 3D printed parts

Melissa Douglas

Technical contributions include the following:

- Completing generative design input, evaluation and post-processing for drone arms
- FEA Analysis on drone arms and previous builds of drone legs including static load, event simulation, and modal analysis.
- Assisting with creating CAD assembly in Fusion 360
- 3D printing responsibilities including
    - Setting up builds for 3D printed parts of drone based on print parameters
    - Training teammates on using splicing software and basic 3D printing techniques
    - Maintenance of 3D printer for multiple builds
    - Assembling existing parts and doing preliminary GD&T of printed parts

Jordan Fraser

Technical contributions include the following:

- Gathered technical specifications of recommended motors and propellers.

- Placed motor and propeller combinations into a design matrix to determine the most suitable combination.
- Worked closely with fellow team member Hanny Kourani to ensure the electronic components selected would be suitable as it relates to thrust calculations.
- 3D printing responsibilities including: setting up the solution bath to dissolve supporting material.

Hanny Kourani

Technical contributions include the following:

- Technical contributions include the following:
- Choosing efficient motors and propellers
- Performing calculations to determine the thrust to weight ratio required for takeoff
- Decision matrix tables informing our choice selection
- Design for concept selection (for drone)
- Assisting with soaking 3D printed parts in bath
- Assisting other subsystems as needed.

Full details for each task are explained explicitly in the final report.

Nefertari Parks

Technical contributions include the following:

- Created Initial Sketches of Drone Design
- Designed drone airframe/initial iteration of arms/specific iterations of landing gears using CAD (Fusion 360)
- Completing Bolt Force Distribution Calculations to ensure the most efficient screws were ordered for the Drone frame
- Created CAD assembly in Fusion 360
- Analyzed landing gear (specific iterations) using Finite Element Analysis
- Assisted with assembly of 3D printed parts