MECHENG 450
Team 29
Winter 2021
Final Report

"We have fully abided by the University of Michigan College of Engineering Honor Code"

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Executive Summary & Problem Statement

Team 29 is tasked with designing an additively manufactured drone capable of picking up, transporting and depositing a specified cargo through the ASME IAM3D 2021 Course. Our problem statement is as follows: obtain a high scoring submission in the ASME IAM3D competition with a drone that makes use of additive manufacturing benefits will serve as validation of a successful design.The specifications of this project were to create a remotely operated flying drone manufactured from as many additively manufactured parts as possible, with a maximum motor to motor diagonal distance of 33 cm and a maximum height of 25 cm. This drone must complete a series of obstacles and pick up five 1 inch^3 cubes and drop them off at a specified 48 in. by 36 in. area right next to the pickup location within ten minutes.

Through several design iterations and concept generation processes, the final design of the drone was made which incorporated a split camera design and an electromagnet to pick up the cubes. To validate our design process, we made use of calculations and simulations to determine the electronic components needed, as well as the design of the drone frame. Once we had figured out the electronic components needed for our drone, we calculated the power draw from all the components and determined the correct battery to power our drone. This battery gave us a run time estimate of 5-6 minutes. After component selection, the design of the frame was created by first using static finite element analysis (FEA) modeling along with simulated drop tests of the drone to figure out which areas needed more support in order to protect the fragile electronic components on board. We also used the specification of the motors' thrust to determine the maximum weight of the drone frame.

The results from our simulations and battery draw calculations proved our drone was effective for meeting most of the specifications outlined. Due to several setbacks with software issues and non-functioning electronic components such as the video transmitter, we were unable to fully test our final design of the drone. This made us incapable of meeting the requirements pertaining to the obstacle course. We do believe however that this drone has effectively made use of additively manufactured parts to create unique structures otherwise impossible by current subtractive manufacturing methods and that with further testing and debugging a fully functioning drone can complete the obstacle course and other specifications outlined in the project description.

Due to an accelerated timeline, we were unable to fully test the flying capabilities and maneuverability of the drone in an obstacle course setting. Based on the calculations and simulations completed we are confident that the drone could satisfy all of the requirements outlined to us by our stakeholder and the ASME IAM3D competition rules. We have outlined some recommendations for a possible redesign or continued improvement of the drone if the project is resumed in the future.

Problem Definition

Requirements and Specifications

To further aid in our design process, a series of requirements and specifications have been generated to guide the provide guidance to our design. Requirements are taken from the stakeholders idea of what the design must and should be able to accomplish. From these requirements a set of engineering specifications that allow for the verification of the requirements will be used as a measuring tool to ensure that the design is meeting the expectations of the stakeholders.

As our project is based around the ASME IAM 3D competition, our group does not have a sponsor to provide us with the requirements for our design. Instead our stakeholders consist of the competition judges, Professor Saitou and our group members. The requirements for our design fall into three categories that range in importance. The first category are requirements from the ASME IAM3D 2021 ruleset must be met [1], defined in Table 1.1. The next set of requirements is grouped around scoring highly on the competition as dictated in Table 1.2. The final set of requirements outline the optimal operation and design of the drone outlined in Table 1.3.

Table 1.1: Requirements and specifications from ASME IAM3D competition rules.

Requirement	Specifications
Drone will meet size requirements for motor placement and height	33 cm max distance measured diagonally from motor center to motor center and 25 cm max height
Drone must be piloted remotely with first person view	At least 1 camera is mounted on the drone which allows a pilot to pilot the drone from outside the course.
Certain components must be commercially manufactured	Electronics, wire, electric motors, propellers, batteries, fasteners.
Drone is powered by commercial batteries	Maximum battery specifications: -4S battery pack -4.2 Volts per cell
Drone has required safety features	At least 1 arming switch is required on the drone controller.

The requirements in Table 1.1 are the highest priority. If we are not able to meet all competition rules, our entry will be ineligible and we will not be able to compete in the competition. Competition rules that standardize the size and operation method of the drone will constrain the geometry of our airframe as well as our method of piloting the drone. The drone safety requirement serves to protect the drone in case of a potential hazard in the flight path. These requirements are the highest priority and therefore will need to be included in the final drone design.

Table 1.2: Requirements and specifications from ASME IAM3D scoring guidelines.

Requirement	Specifications	Justification
As many parts of the drone as possible will be additively manufactured.	Airframe is designed from additively manufactured parts and has less than 10 manufactured parts (not including comercially manufactured parts listed in Table 1.1) in the total design.	Scoring is heavily weighted (5000/14000 points) on the percentage of parts that are produced through additive manufacturing.
Drone will be able to maneuver through all competition obstacles.	Drone will be able to slalom through 48” tall obstacles placed 120” apart as well as fly under 48” arch obstacles without touching the obstacles or ground.	3000 points are given for how well the drone is able to transverse through the course.
Drone will be able to pick up and drop off competition payload.	Drone will be able to pick up a 10 gram cube and deliver competition payload while maintaining hold of the payload throughout the course.	200 points are given for each block that is picked up and delivered through the competition course.
Drone will have enough battery to complete the course.	Drone will be able to complete 5 laps of the provided course in one battery charge.	Drone must complete all 5 laps in a 10 minute video so it should be able to complete the course in one battery charge.

Table 1.2 contains the requirements and specifications based on the competition scoring guidelines. As our primary goal is to score as high as possible in the competition, these requirements are the second highest on our priority list. Because the most amount of points come from the percentage of additively manufactured parts, we will be making our airframe entirely using additive manufacturing and limiting the total number of parts in our design. The remaining requirements have to do with completing the obstacle course provided by the competition. The competition course includes 5 laps of slalom and arch obstacles as well as pickup and drop off of a 1 inch PLA cube during each lap.

Table 1.3: Requirements and specifications for better design.

Requirement	Specifications	Justification
Parts purchased and manufacturing cost remain within budget	Purchased parts remain under $400 budget.	Our team was provided a $400 budget from the ME450 class to spend on manufacturing and design.
Drone will be easily serviceable	Motors and ESCs can be swapped out within ten minutes with two tools.	Easily serviceable drones limit service time and allow us to spend more time optimizing drone's controllability.
The drone will have a lightweight frame	The 3D printed frame will weigh less than **200** grams.	Our team decided to pursue more powerful motors which will allow us to have a heavier frame to support more robust components
Able to survive minor crashes	Drone will be able to withstand freefall from 48" without fracture of 3D printed components.	During competition the drone should fly no higher than the 48" obstacles. Being able to survive a fall from that height without breaking will be helpful during testing.

Table 1.3 contains requirements that our group members generated when considering best design practices as our group members make up the majority of stakeholders. As these requirements are intended to improve the performance and testability of the drone and are not requirements from the competition, they will remain at the bottom at our priority list. These requirements serve as a guideline and will help us accomplish our overall problem statement as we design, manufacture and test our drone.

Concept Generation

With our requirements for our design fully developed, our team set to generate a series of concepts that would best aid in accomplishing these requirements. Through brainstorming and the use of engineering design heuristics, we were able to produce a wide range of ideas for all different parts of our drone.

Brainstorming

We began our design generation with a couple of brainstorming sessions to obtain as many ideas as possible. By following the guidelines of brainstorming, which include deferring judgment and building on each other's ideas, we were able to come up with a large amount of ideas that we would eventually narrow down to our final design. We began our brainstorming by breaking up our drone design into four major subsystems: the gripper mechanism, the frame, the camera, and different mounting methods. To better visually show our thought process during our brainstorming session, a mind map was created to show our ideas. The section for the frame design is shown below in Figure 1.

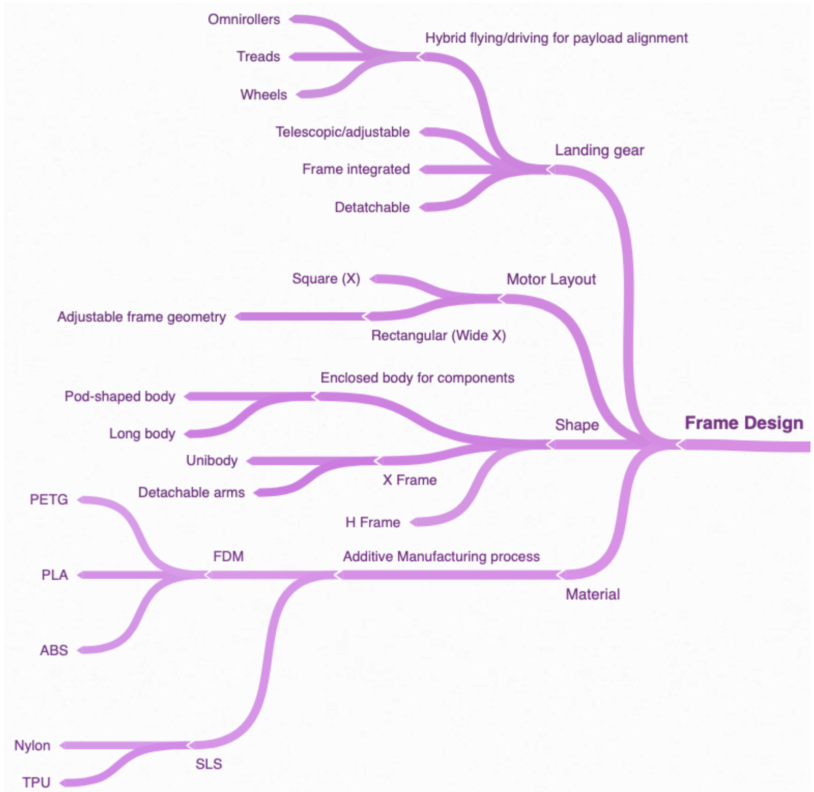


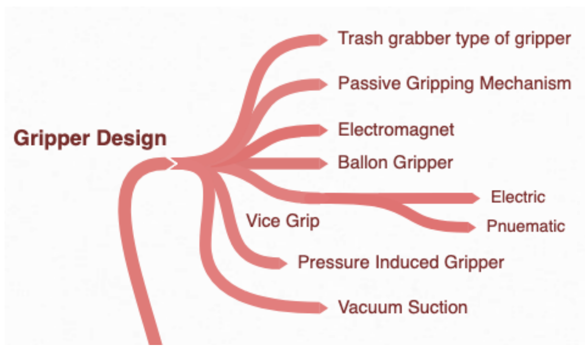
Figure 1: Mind map of frame design ideas.

Frame: As seen, brainstorming for the drone's frame design spanned a large range of design decisions, from the layout of the drone to the material and manufacturing process needed to construct the frame. For the layout of the drone, our group explored ideas for the location of the motors, where the components would be housed, as well as the motor layout. Based on the competition rules we were required to have our air frame made from additively manufactured materials. In our brainstorming we explored some of the additive manufacturing processes such as FDM (fused deposition modeling) and SLS (selective laser sintering), as well as the different materials available for use in both.

Gripper: The next subsystem that our team tackled was the gripper design. This gripper will be how our drone picks up and deposits the 1" payload for the competition. The mind map for the gripper is shown on the next page in Figure 2.A.

For the gripper design our team had to figure out a way for our drone to pick up and transfer a 1" PLA cube with a ferromagnetic washer attached to the top of the cube. During our brainstorming sessions, ideas of active mechanisms that would require some sort of power input, such as vacuum suction or a vice grip that could be either electric or pneumatic, were discussed. The options of having a passive mechanism that would be able to secure the cube without a power operated system, or taking advantage of the ferromagnetic washer on the cube with use of magnets was also considered.

Mounting Methods: Figure 2.B below shows the mind map for different mounting methods. As the frame of our drone will be additively manufactured we have the opportunity to explore many different mounting methods for our components such as our electronics, batteries, cameras, and motors. Some of the ideas that came up during our concept generation were generic solutions such as zip ties and screws that would have been used in many drone designs. Some other ideas that would take advantage of our 3D printing capabilities would be creating custom 3D printed housing for our components or heat staking components into the soft 3D printed material.



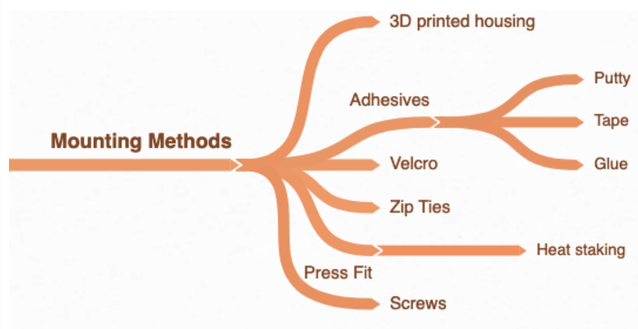


Figure 2.A: Mind map of gripper design subsystem. **Figure 2.B:** Mind map of mounting methods.

Camera: The rules for the ASME IAM 3D competition state the drone must be piloted using a first person view camera by a pilot outside of the course. Figure 3 shows the mind map our group created in our brainstorming session to figure out ideas for the camera that would be used to pilot the drone.

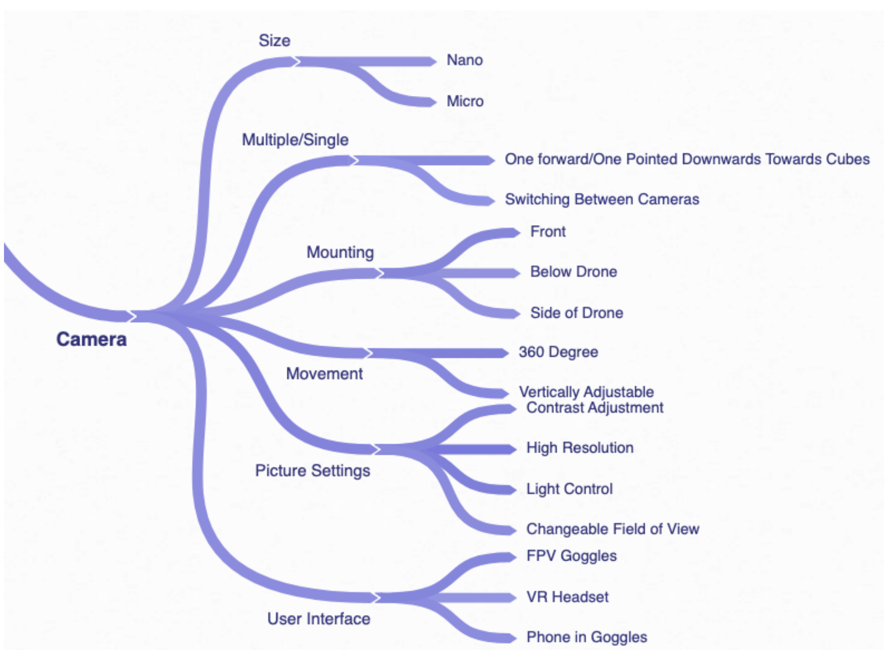


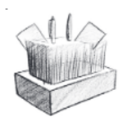
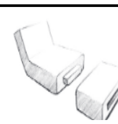
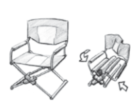
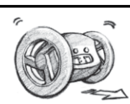
Figure 3: Mind map of camera ideas.

As seen in Figure 3 on the previous page, our group discussed both the camera itself as well as the mounting and possible movement of the camera on the drone. An important discussion was brought up during the brainstorming session about what the pilot should be able to see - although the number one priority is to be able to see where the drone is flying, it may also be helpful if the pilot is able to see the payload for pick up. This can be accomplished through having multiple cameras, or a singular camera that is able to change the direction it is facing.

Design Heuristics

In continuation of our team's concept generation, we utilized design heuristics to come up with ideas for all subsystems of our drone design. Table 2 below shows the 8 design heuristics that we decided to use, along with the solutions that were generated from their givin heuristics.

Table 2: Design heuristics and solutions for drone design.

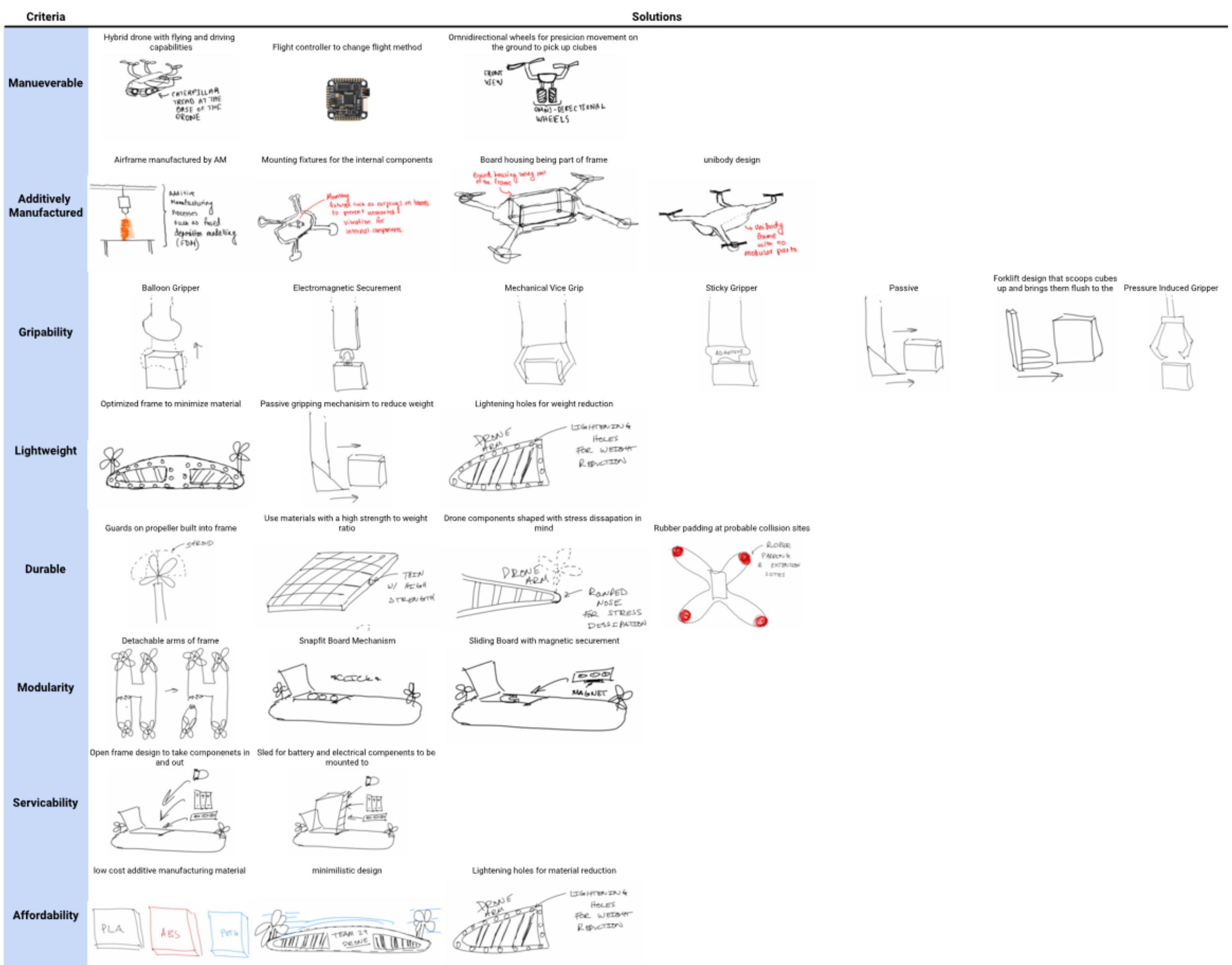
Design Heuristics	New Solutions	
Applying existing mechanism in a new way 	Trash grabber to pick up cubes	
Make components attachable/detachable 	Sled for electrical components and battery for easy access	Make propellor guards and arms detachable in case of fracture
Convert 2-D material to 3-D objects 	Make the arms of the drone 3-dimensional	Have multiple camera feeds to create a 3D image
Allow user to customize 	Change flight modes via controller	2 different modes of flying (Sport and Hover)
Telescope 	Telescopic landing gear	Telescopic arms for the drone
Reconfigure 	Change direction of motors to upside down	Multicell lipo battery split into individual cells to distribute weight about the Center of Gravity
Add motion 	Make motors tiltable to change direction of thrust in flight	Add treads or wheels to allow for movement on ground
Stack 	Put circuit board under the battery	

As we want to ensure easy serviceability, our group thought that the design heuristic of making components attachable/detachable would be important to consider as this allows us to easily fix or replace components. By taking advantage of additive manufacturing we can make custom parts that allow for this easy access and replacement of drone components.

Concept Development

Morphological Chart: Diving further into the concept exploration process, our team decided to construct a morphological chart with design specific design criterias that we expect our final design to accomplish. To construct the chart we divided it into eight different design criterias and determined a unique solution along with a sketch for the proposed solution. The morphological chart developed in the concept generation process is shown on Table 3 below.

Table 3: Morphological chart for drone design.



Criteria	Solutions					
Manueverable	Hybrid drone with flying and driving capabilities	Flight controller to change flight method	Omnidirectional wheels for presicion movement on the ground to pick up ciubes			
Additively Manufactured	Airframe manufactured by AM	Mounting fixtures for the internal components	Board housing being part of frame	unibody design		
Gripability	Balloon Gripper	Electromagnetic Securement	Mechanical Vice Grip	Sticky Gripper	Passive	Forklift design that scoops cubes up and brings them flush to the	Pressure Induced Gripper
Lightweight	Optimized frame to minimize material	Passive gripping mechanisim to reduce weight	Lightening holes for weight reduction			
Durable	Guards on propeller built into frame	Use materials with a high strength to weight ratio	Drone components shaped with stress dissapation in mind	Rubber padding at probable collision sites		
Modularity	Detachable arms of frame	Snapfit Board Mechanism	Sliding Board with magnetic securement			
Servicability	Open frame design to take componenets in and out	Sled for battery and electrical compenents to be mounted to				
Affordability	low cost additive manufacturing material	minimilistic design	Lightening holes for material reduction			

Our team generated many solutions for the gripping mechanism as it is one of the most vital design decisions for our final drone design. Our team also placed great emphasis on the importance on the manufacturability of the drone hence we came forth with a number of solutions exploring the utilization of additive manufacturing in our drone design. We also researched and came up with a couple of baseline solutions of what we expect from the material of the drone, shown in the "Lightweight" and "Durable" criteria. The criteria on the morph chart all come directly from our developed list of requirements and specifications.

Concept Evaluation and Selection

As the group is delaying frame development until a gripping mechanism and camera configuration is selected, this section details the evaluation and election of these subsystems.

Camera Evaluation

To decide which camera setup to use in our drone design, our team first consulted our developed list of requirements and specifications to construct criteria that could be used to rank camera ideas in a Pugh chart (Table 4). From the requirement "Drone must be able to pick up and drop off competition payload" we created two ranking criteria which used to subjectively evaluate the completion of this requirement, those being *Payload Visibility* and *Ease of Use* with the latter being a measure of how intuitive the setup is to operate. The *Lightweight* and *Cost* ranking criteria came directly from the requirements "Parts purchased and manufacturing costs remain within budget" and "Drone will have a lightweight frame". The *Course Visibility* ranking criteria came from the requirement "Drone will be piloted with first person view". The *Manufacturability* criteria is not outlined in our requirements and specifications, but serves as an important subjective measure of how easy the setup is to implement into our overall design.

Table 4: Camera design pugh chart.

	Manufacturability	Cost	Course Visibility	Payload Visibility	Lightweight	Ease of Use	Totals
Weight	1	3	5	5	4	3	
Singular Static Camera	1	1	1	-1	1	1	11
Singular Dynamic Camera	-1	0	1	1	-1	0	5
Multiple Cameras	0	0	1	1	0	1	13

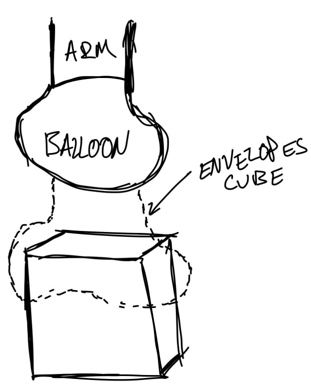
As seen in the Pugh chart above, we believe the multiple camera design to be the best option for our purposes and plan to integrate this design into our frame development. A singular dynamic camera would require a separate control for the positioning of the dynamic camera mount and hence was the least favorite amongst the three proposed camera designs.

Gripper Evaluation

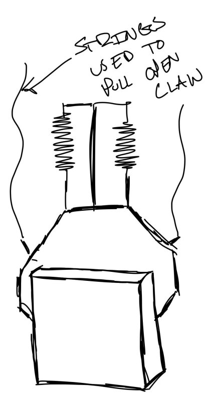
Again consulting our list of requirements and specifications, we surmised the most important features desired of a gripping mechanism in this context. The *Manufacturability*, *Lightweight* and *Ease of Use* ranking criteria were created for the same reasons outlined in our Camera Evaluation. The *Securdness* and *Reliability* ranking criteria came from the requirement "Drone must be able to pick up and drop off competition payload". The *Durability* criteria came from the requirement "Able to survive minor crashes"; *Additively Manufactured* came from the requirement "As many parts of the drone as possible will be additively manufactured" and *Power Usage* from "Drone will have enough battery to complete the course". From this list, we decided to rank the various gripping mechanism concepts with respect to chosen criteria (Table 5); Sketches of each concept can be seen in Figure 4.

Table 5. Pugh chart ranking gripper concepts by desired criteria.

	Manufacturability	Lightweight	Securedness	Reliability	Durability	Ease of Use	Additively Manufactured	Power Usage	Totals
Weight	2	5	4	3	3	4	4	2	
Balloon Gripper (A)	-1	-1	1	0	1	-1	-1	-1	-10
Passive Spine Gripper (B)	-1	1	0	1	-1	0	1	1	9
Electromagnet (C)	1	0	1	1	1	1	0	-1	14
Motorized Vice Grip (D)	0	-1	1	1	1	-1	1	-1	3
Passive Gripping Mechanism (E)	-1	1	0	1	0	0	1	1	12
Passive Scoop (F)	1	1	0	1	-1	-1	1	1	9
Passive Gripping Mechanism w/ Magnet (G)	0	0	1	1	0	1	0	1	13



(A)



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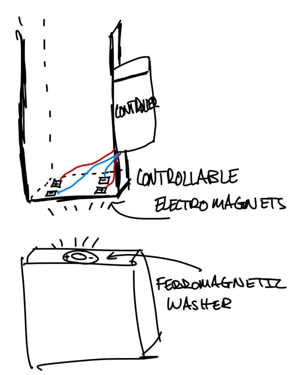

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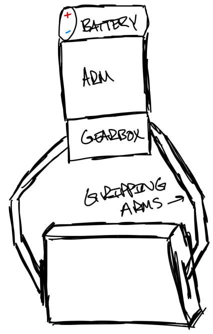

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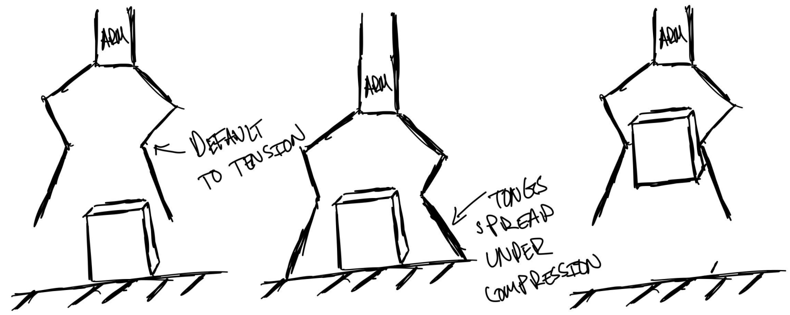
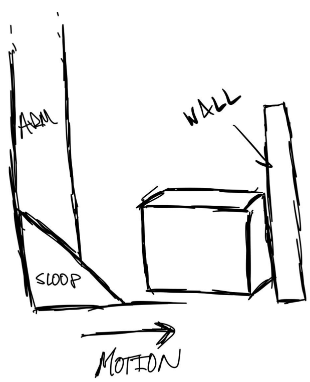
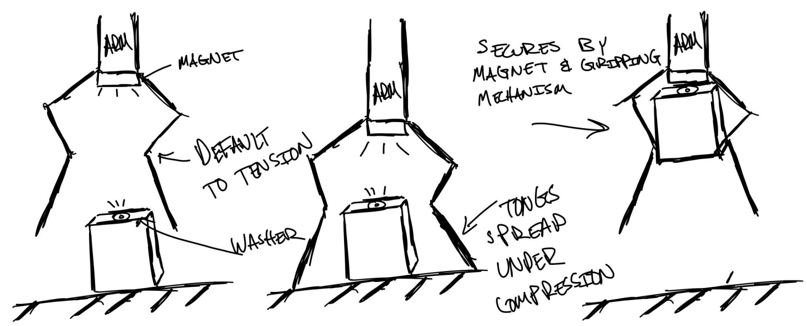


(E)



(F)



(G)

Figure 4. Various gripper sketches. Each sketch is referred to by its labeled alphabetical letter, corresponding to the Pugh Chart.

We weighed the eight criteria following Design Matrix Procedure, with criteria of “Lightweight”, “Securedness”, “Ease of Use” and “Additively Manufactured” being the heaviest [2]. The “Securedness” criteria refers to the probability of the payload being dislodged from the gripping mechanism during transport. ”Durability” refers to the amount of impact the gripping mechanism can sustain without becoming defective, “Reliability” refers to the probability of failure, and “Ease of Use” comprises how difficult the device is for the user to operate.

Gripper Selection

As seen in the Pugh chart, after the ranking process, winners were the Electromagnet and the Passive Gripping Mechanism with Static Magnet (PSM). With the concepts narrowed down, we created a Pros and Cons list to decide between the two concepts, shown in Table 6.

Table 6. Pros and Cons list employed to select a gripping mechanism.

	Pros	**Cons**
Passive Gripping Mechanism with Static Magnet	+ No user input is required to operate + Will be entirely additively manufactured, excluding the static magnet	− Requires complex design − Higher chance for failure when collecting/depositing payload − Takes more time to collect payload than electromagnet
Electromagnet	+ Easy to manufacture + Will be mostly additively manufactured + Make use of additive manufacturing benefits (integrated mounting, etc.) + Strong gripping force + Minimum user input required	− Needs power input − May need constant supply of power, potentially hurting drone performance − Additional weight relative to passive mechanism

Based on our given requirements and specifications, we believe the pros of the Electromagnet outweighs the cons and believe it to be the better design choice for our purposes. While the Electromagnet will add additional weight to the drone and require a larger power source to draw from during flight, we believe this will not hamper the performance significantly as we can use bigger motors to offset the weight - the larger power source allowing for use of these forceful motors. As it will be far easier to use than the PSM, the probability of meeting the competition requirements increases drastically. For example, the Electromagnet will have a less chance of knocking over cubes than a long PSM, due to its short height, which will allow us to successfully complete the obstacle course and deliver all of its payloads. Also, the Electromagnet will serve as a stronger option than the PSM as it is made from iron which will be more resistant to crashes than a 3D-printed material used for the PSM. Also, the Electromagnet holding force is known and if we wire it to the drone properly, we know it is going to hold up to a known amount whereas the PSM, the weight it can pickup is unknown and that is more time spent on trying to test the holding force, thereby leading to possible setbacks.

Landing Gear

The main purpose of the landing gear of a drone is to have a steady surface to minimize the shock upon impact of landing the drone from flight. Figure 5 showcases the designs we came up with for the landing gear for the drone design. Table 7 outlines the pros and cons of three different concepts our team thought of when designing the frame of the drone.

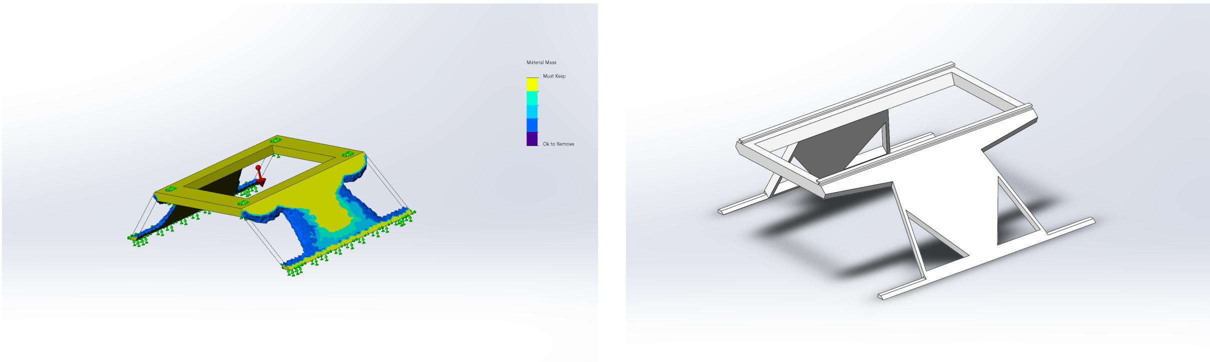


Figure 5. Sliding Landing Gear Design.

Table 7. Pros and Cons list employed to select the landing gear for the drone.

	Pros	**Cons**
Sliding Landing Gear	+ Modularity + Use of additively manufactured parts + Dispersion of weight	— Tight tolerances — Potential to knock cubes over when landing — Potential to not stay snapped into place mid-flight — Added weight
Individual Legs Underneath the Motors	+ Modularity + Use of additively manufactured parts + Dispersion of weight	— Potential to knock cubes over when landing — Added weight
No Landing Gear	+ No added weight + No obstacles in between the cubes and the electromagnet + Cheaper	— No use of additively manufactured parts — No dispersed weight

The first design we thought of was the sliding landing gear mechanism which came from the topology optimization feature in ANSYS. As shown in Figure 5, by starting from the body outline of the drone and using forces from the motors, ANSYS optimized the structure of the drone to get rid of mass and come up with a rough estimate of the shape of the supports of the drone. Then taking this model, we cleaned it up in Solidworks and produced a more realistic model from the optimization. This design would essentially slide into the bottom of the drone frame and snap into place. This design allowed for modularity in our design with being able to take the landing gear on and off, as desired and allowed for more use of additively manufactured parts. This sliding landing gear design, however, needed tight tolerances for the sliding slot and snap fit mechanism and with the process of 3D-printing, tight tolerances are hard to achieve. Also, this landing gear design would add extra weight to the drone, which could be problematic for the total drone flight time and battery life. Finally, this design had the potential to knock the cubes over when going in to pick them up as they are so close to the electromagnet and would stick further outward than the electromagnet.

The second design we came up with was individual peg-like landing gear mounted directly underneath the motor mounts by a single screw and nut. This design allowed the weight of the drone to be dispersed across four individual points as compared to the two points in the middle of the drone with the sliding leading gear mechanism. Also this design allowed for modularity and use of additively manufactured parts for the same reasons as the sliding landing gear design. As with the sliding landing gear design, the downfalls of this design are the added weight of the landing gear to the drone and a potential to knock the cubes over when coming in to pick up the cubes.

The final design we came up with was to eliminate landing gear and have the entire weight of the drone resting on the electromagnet. This design is simple, cheap, includes no added weight to the design, and allows for a clear path between the cubes and the electromagnet so there essentially no chance to knock the cubes over when coming down to pick them up. The downfalls of this design is that the entire drone would be resting on one point, but the surface area of the electromagnet is a large part of the total surface of the drone, with a 40mm diameter. Also, another con of this design is that it does not make use of additively manufactured parts. All in all when evaluating the landing gear design we decided that it was best to go with no landing gear as this was a cheaper option, as there were no extra parts to print, allowing for less added weight to the drone, plus it was less to design for the CAD model. All these pros of this design outweighed the cons of less use of additively manufactured parts and less dispersion of weight than the other designs.

Selection of New Components

Our decision to proceed with the dual camera configuration and the electromagnetic gripper mechanism will introduce additional mass and complexity to our design, which will ultimately require extensive revision of the electrical components previously purchased that power and control the drone. Since initial thrust with the purchased drone determined the maximum lift capacity to be approximately ~15g beyond its own weight, we do not believe it is feasible to utilize the given motors to include an electromagnet and an additional camera onboard and still be capable of pickup/delivery of the payload. Additionally, in order to remotely control the electromagnet and switchable camera feeds, we believe that purchasing drone components separately will give us a better chance of success due to the modularity, re-programmability, and plethora of documentation readily available.

Video Transmission Components
Two first person view (FPV) cameras were purchased to be mounted in the selected dual camera design. We selected the *RunCam Phoenix 2 Micro FPV* to be mounted in the front and the *RunCam Phoenix 2 Nano FPV* to be mounted underneath. While the micro FPV camera offers better camera quality, the nano FPV camera can be mounted such that the viewing angle is flush with the electromagnet while not hanging beneath it due to its smaller size.

We chose a *AKK Oscar's Backpack VTX 5.8GHz* video transmitter and a *XILO AXII Stubby SMA 5.8GHz* antenna for video transmission, as these components are compatible with the chosen *FatShark Recon V3 FPV* Goggles. If these goggles do not offer the desired level of resolution, we may switch to a monitor.

Control Boards
In order for the drone to receive user inputs, detect orientation during flight, and operate the drone motors with the correct amount of power, two important control boards are needed. The first board is called an Electronic Speed Controller (ESC) which controls the amount of power that is provided to each motor. Certain drone designs utilize individual ESCs for each motor, while others use specialized 4 in 1 ESCs that are able to provide power throttling to all four motors from one ESC. We decided to go with the later setup and chose the *T-Motor Velox V2 V45A 4-in-1 ESC*.

The control board that is utilized in most drones is the flight controller. Flight controllers process multiple series of data to ensure proper operation of the drone. Flight controllers take in the user inputs, sent to the board through the *Frsky R-XSR Micro Receiver*, that are used to fly the drone along with data obtained from its accelerometer and gyroscope to determine what speeds to run each of the motors. Software packages such as *Betaflight* can be used to change how the flight controller reacts to user input and sensory inputs and can even create multiple flight modes such as a hover mode that automatically stabilizes the drone in flight. For our drone we decided to use the *Flywoo GOKU F722 Flight Controller* and it will be mounted on top of the T-Motor ESC. The flight controller will send the desired speed of the motors to the ESC which determines how much power to supply to the motors to achieve the desired flight. The flight controller will also allow us to switch between which video feed we will be transmitting to our receiver from one of our two cameras.

Electromagnet
We intend to use an electromagnetic gripper mechanism for the pickup and delivery of the cubes, we have purchased an electromagnet in addition to the components required for remotely controlling its operation. The electromagnet we purchased is a 5V 50% duty cycle electromagnet with a holding force of 10kg. While 10kg is likely significantly heavier than required, we believe that the surface area of contact will be the limiting factor of the magnet's effectiveness rather

than the holding force, due to the 0.5” diameter hole in the center of the ferritic washer. In order to remotely power the magnet on/off from the drone’s radio transmitter, Using a similar method to the switchable FPV cameras above, the *Betaflight* flight controller software will be used to assign a switch on the drone’s radio transmitter to an available AUX channel, which will allow us to manipulate the power status of the electromagnet.

Motors

In order to make select motors capable of providing adequate thrust, we assumed the drone to weigh roughly 700g, which is a conservative estimate encompassing the weight of the drone frame, electrical components and cargo. We wanted the ability to fly the drone at a 2:1 thrust to weight ratio, as this is a racing drone standard [3]. This necessitates 350g of thrust per motor.

As the efficiency of the propellers mounted to the motors exponentially decreases as the drone motors reach their maximum thrust, we looked for motors that provided 350g of thrust at a low percentage of their maximum thrust [4]. We found the *Emax ECO II Series 2207 2400KV Brushless Motor* is capable of producing 350g of thrust at roughly thirty percent of its maximum thrust. There are motors that provide this thrust at a lower percentage of their maximum, however as we need to ensure we remain in budget, these motors provide the best value.

Power Analysis

After selecting components that make the drone functional, we performed a power analysis to select a battery capable of supplying the necessary amount of power. To do this analysis, some assumptions had to be made.

The first assumption was that the drone would have a final weight of roughly 700g. This is a safe assumption to make as similar racing drones weigh roughly 300g without the battery, standard batteries weigh 200-300g and the electromagnet weighs roughly 100g. Small electrical components were assumed to have negligible weight and power draw. We also assumed the drone to require thrust at a ratio of 2:1.

After these assumptions were made, calculations were able to be performed. Below is the derivation of the required battery capacity to power our drone for roughly five minutes, where P is power in watts, I is operating current in amperes, V is nominal battery voltage, T is flight time in minutes, C is the c-rating of the battery, and U is the battery capacity in milliamp-hours.

Required Current

$$P = I \times V = 4 \times 94\,W = 376\,W$$

Standard Drone Batteries are 14.8 V

$$376\,W = I \times 14.8\,V$$

$I = 25.4\,A$ Operating Current Draw

Desired Battery C-Rating

Desired Flight Time of 5 Minutes

$$T = 60min/C \rightarrow 5min = 60min/C$$

$$C = 12$$

Required Battery Capacity

$$U/1000 \times C = I$$

$$U/1000 \times 12 = 25.4$$

$U = 2116$mAh

Utilizing this calculated battery capacity, we purchased a *Auline 4S 2000mAh 120C LiPo* battery as it provides the amount of storage required at a relatively low cost.

Solution Development and Verification

Material Selection

The material that was chosen for manufacturing the drone was *HP 3D High Reusability Nylon PA 12*. One of the core requirements of the project was that the drone frame had to be additively manufactured. In order to choose the right material we initially considered our design requirements to guide our decision. The additively manufactured frame would have to weigh less than 200 grams and that the drone will be able to withstand freefall from 48" without fracture of the airframe while also maintaining the integrity of the aerial vehicle assembly. We decided not to opt for the option of metal and rather decided to choose a polymer, mainly due to the high expenses involved in metal printing processes. The mechanical properties of the additively manufactured part is greatly influenced by the additive manufacturing process used. While there are quite a few companies that offer additive manufacturing services that suited our manufacturing goals, factoring in all the variables including lead time, shipping and also quality of finished part we decided to outsource our printing job to a company called *Jawstec*. The density of the parts printed with this material is 1.01g/cm^3[5]. Some of the important mechanical properties of the selected material is shown on Table 8.

Table 8. Important mechanical properties of the selected material HP MJF Nylon PA 12 [5].

Mechanical Properties	Value
Tensile strength, max load	48MPa
Elongation at break, XY, XZ, YX, YZ	20%
Elongation at break, ZX, ZY	15%
Flexural Strength (@5%)	70 MPa

Drone Airframe Design and Development

During our time benchmarking previous competition submissions, we noticed that most utilized a boxed x-frame along with a top shell that protected the inner components of the drone and housed the camera. We drafted an initial frame and top-shell design utilizing this information, shown in Figure 6. These preliminary designs served as a good starting point to run analysis on and determine what aspects of the design could be improved by benefits unique to additive manufacturing.

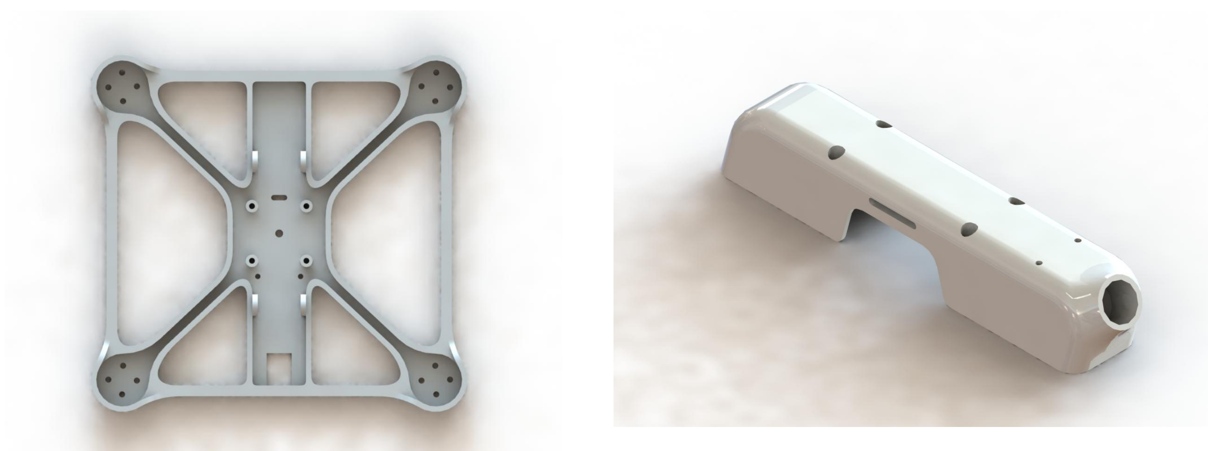


Figure 6. Frame (left) and top shell (right) initial design concepts with no electrical components attached.

Finite Element Analysis

In order to verify that our initial design concepts were able to meet the specification that the drone be able to withstand a freefall of 48 inches, finite element analysis was employed. After simulating impact forces at various locations on the drone frame and top shell, two weak impact locations were identified.

As drop tests are computationally expensive to run, these impact stresses were modeled in static tests. The impact force was estimated as the weight of the drone, $783.6\ grams\ \times 9.81\ m/s^2$, equalling roughly 10 N multiplied by an impact factor of 50, yielding an impact force of 500 N. This impact factor widely varies depending on the context, regularly ranging from 1 to 1000 depending on the elasticity of the colliding materials [6]. As our drone would be colliding into grass, a lower impact factor of 50 N was assumed. While this assumption may make our impact force be significantly different than the real world impact load felt by the drone during a free fall drop, this simulation still allows us to identify and reinforce weak points in the structure. The tests were performed with the fixed geometry setup shown in Figure 7.

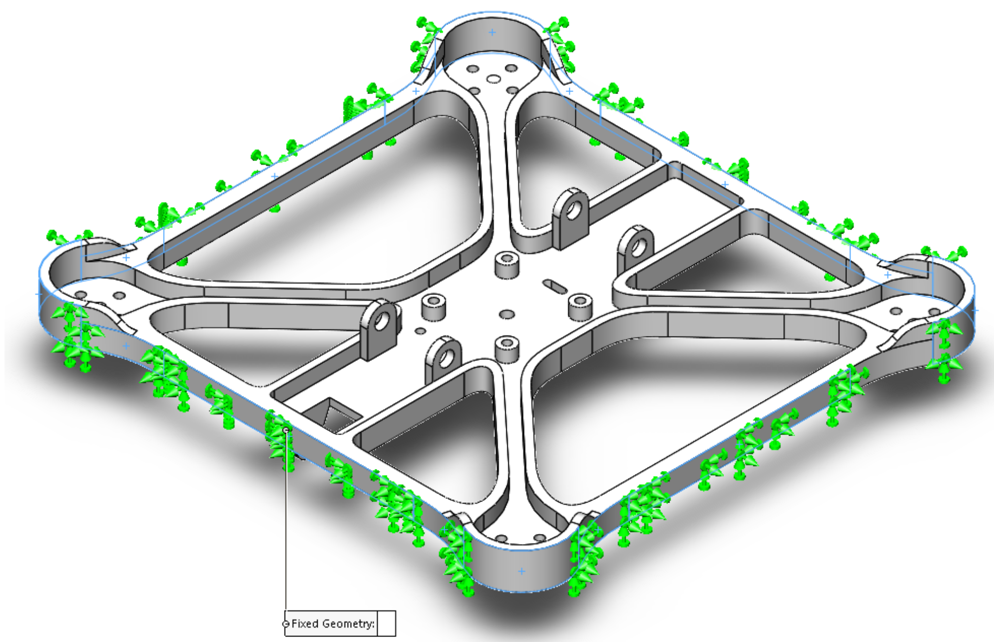


Figure 7. Initial frame design showing the general fixture setup employed when performing finite element analysis static tests.

If the drone is dropped from a height of 48 inches directly onto the electromagnet, it was apparent that fracture of the frame would be occurring on top of the electromagnet and frame mating site as shown by the simulation shown in Figure 8.

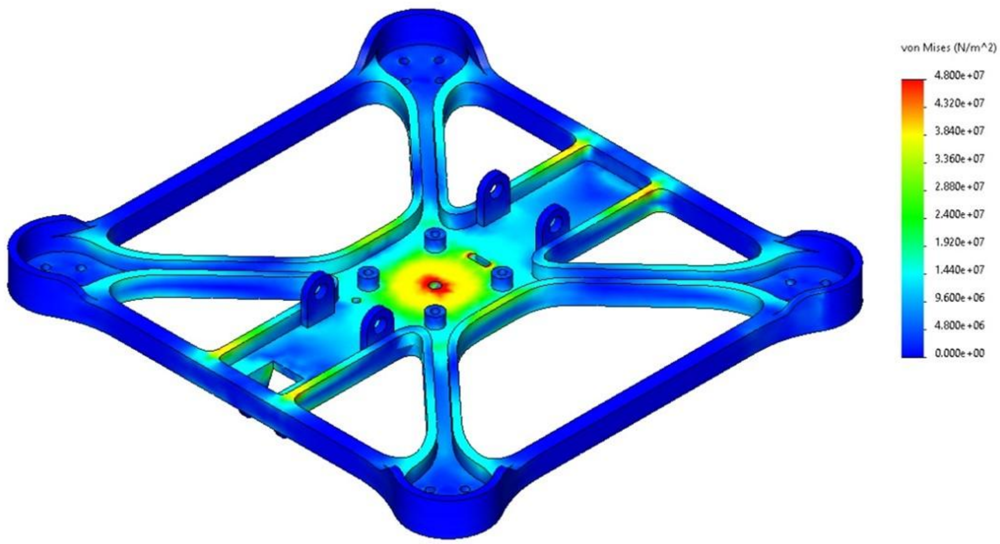


Figure 8. Initial frame design simulation showing fracture occurring on top of where the electromagnet is mounted at an impact force of 500 N (red indicates applied stress exceeding fracture strength of 48 MPa).

We needed to reinforce this structure in order to prevent fracture of the frame. This was done by added bracing at the impact site as well as other locations in the drone frame. The addition of bracing at the impact site increases the area that the impact force is applied to, which decreases stress applied to the frame at the impact location. The addition of bracing at the front and back of the drone stabilizes the frame, preventing excessive displacements [7]. These added reinforcement structures can be seen in Figure 9.

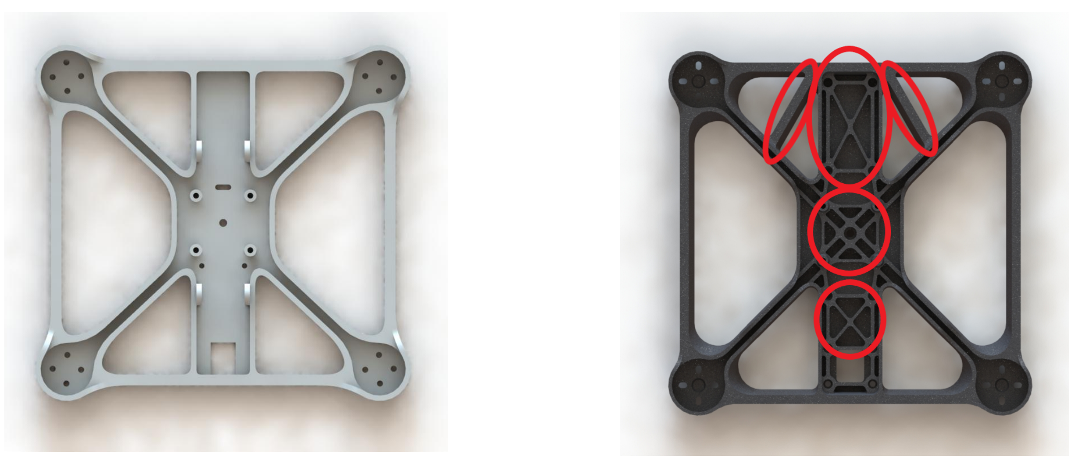


Figure 9. Initial (left) and final (right) frame designs. Bracing additions are denoted in red.

An impact loading simulation run with these modifications can be seen in Figure 10. As seen, this added bracing dissipates the impact force away from the frame itself onto the bracing, decreasing impact stress. This allows the frame to still be operational in the event of a crash as fracture would no longer occur.

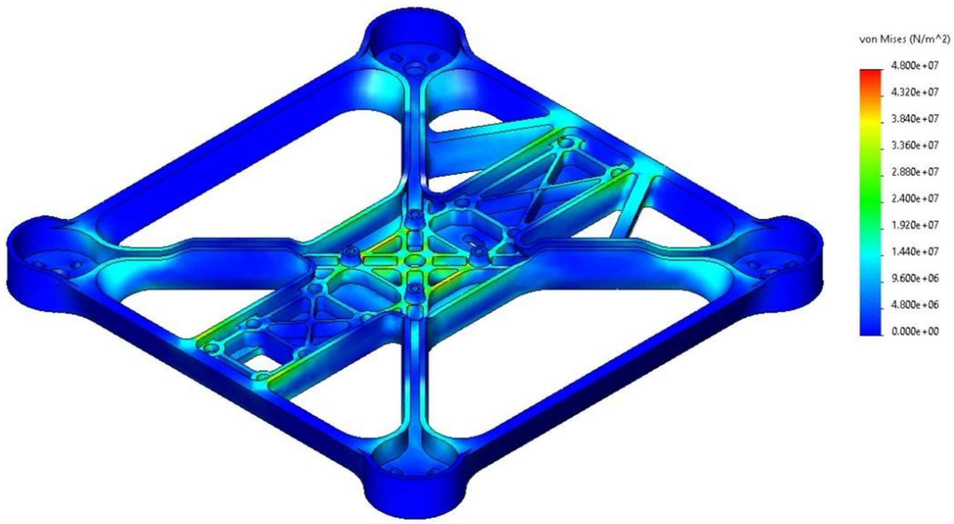


Figure 10. Final frame design simulation demonstrating the addition of bracing leads to better stress dissipation and no fracture at an impact force of 500 N.

On the flip side, another impact site that could be improved was found at the interface between the battery and the top shell (battery-shell interface). If the drone is dropped directly onto the battery, applying the impact force of the weight of the drone to the top shell, we found large stress being applied as seen in Figure 11.

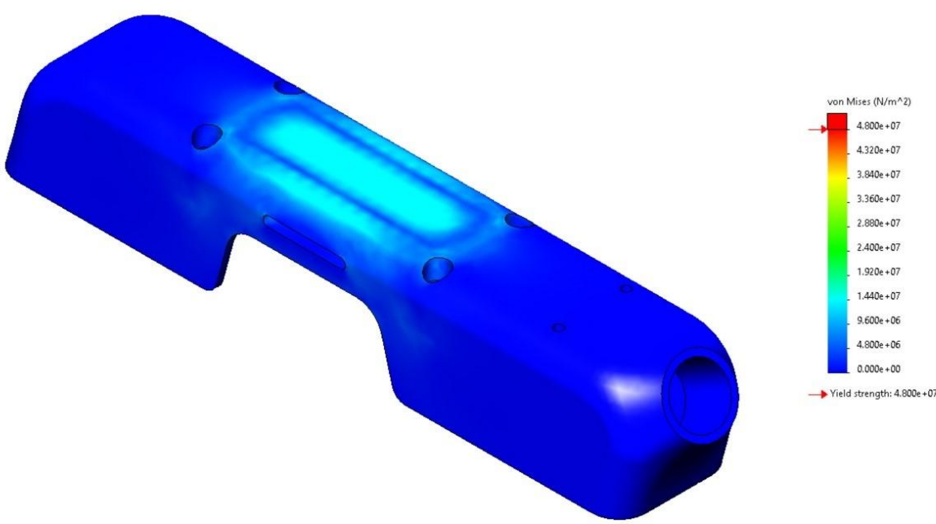


Figure 11. Initial top shell design simulation at an impact force of 500 N.

While the stress applied to the top shell does not exceed the fracture strength of 48 MPa when dropped from a height of 48 inches, we saw the opportunity to easily modify this structure to better dissipate stress in the event that it is dropped from a higher height. To do this, we implemented beam reinforcement, as seen in Figure 12. This reinforcement better dissipates the stress applied to the top shell at the battery-shell interface, as well as limits deflection. We also implemented a hexagon pattern on the interior of the top shell, further aiding in the dissipation of stress.

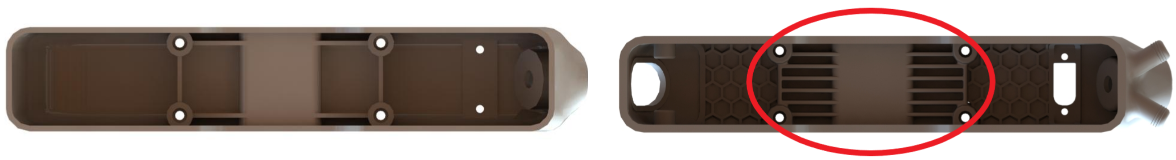


Figure 12. Initial (left) and final (right) top shell designs. Final top shell includes beam and hexagon reinforcement to lower the effect of impact force at the battery-shell interface.

An impact loading simulation was run with these modifications made and is seen in Figure 13. This simulation shows the effect that additional reinforcement has on the dissipation of stress across the battery-shell interface during this impact load.

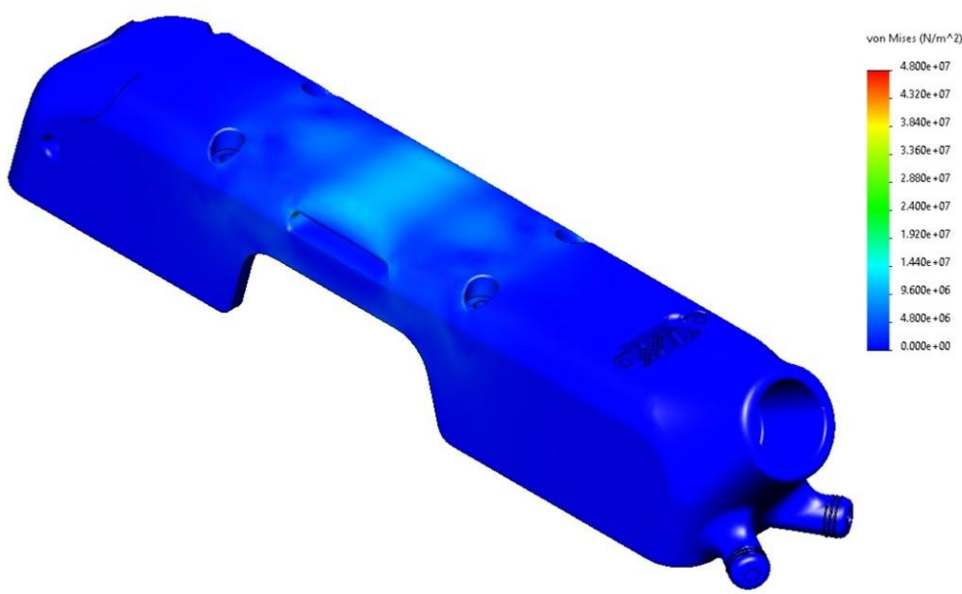


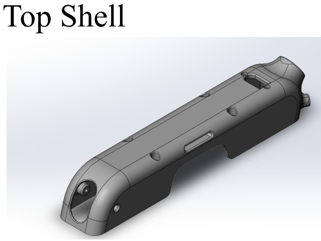
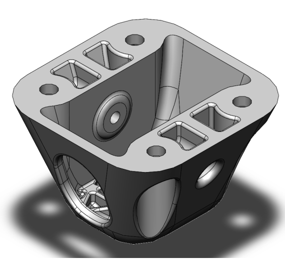
Figure 13. Final top shell impact load simulation ran with a 500 N impact force demonstrating the addition of reinforcement leads to better stress dissipation at the battery-shell interface.

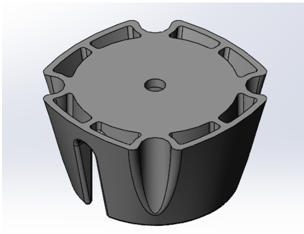
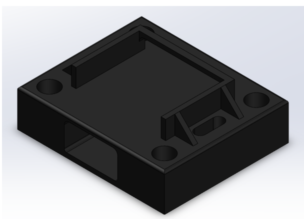
Finalized Drone Design

Manufacturing

The additive manufacturing process that was used to manufacture the drone is called *Multi Jet Fusion* (MJF) and it is *HP*'s proprietary 3D printing process. MJF can also be categorised under Selective Laser Sintering (SLS) printing processes. In this particular printing process, the parts are built by jetting a binding agent onto thin layers of polymer powder particles and then sintering them using an infra-red heat source. The tolerance for the MJF printing process would be +/- 0.30 mm in the *x* and *y* direction and +/- 0.40 mm in the *z* direction. The printer that is used to print with the *HP MJF Nylon PA 12* by *Jawstec* is *HP 5210 MJF* and has a build volume of (380 x 280 x 380) mm in the corresponding x,y, and z axes. The manufacturing process chosen utilizes powdered Nylon PA 12 that is 80% recycled [5]. The parts that were additively manufactured using MJF printing process along with their volume, surface area, build volume and also the cost of manufacturing (excluding shipping and taxes) is shown on Table 9.

Table 9. The parts to be additively manufactured with their build information and the cost of printing.

Parts to Manufacture	Part Information	Cost ($)
Base Plate 	Volume: 126299.89 mm^3 Surface Area: 89169.46 mm^2 Build Volume: 203.90 mm x 16.01 mm x 203.90 mm	80.19
Top Shell 	Volume: 55753 mm^3 Surface Area: 43274.07 mm^2 Build Volume: 203.02mm x 36.02 mm x 36 mm	31.95
Camera Pod 	Volume: 7050.87 mm^3 Surface Area: 7043.91 mm^2 Build Volume: 36.00 mm x 24.00 mm x 36.00 mm	5.16

Electromagnet Sleeve 	Volume: 9267.72 mm Surface Area: 9698.72mm^2	6.64
	Build Volume: 42.90 mm x 23.00 mm x 42.91 mm	
VTX and RX Mount 	Volume: 4342.73 mm^3 Surface Area: 4219.45 mm^2	(Not outsourced) Printed using a basic home 3D printer with PLA material
	Build Volume: 27.00 mm x 8.00 mm x 32.00 mm	

Overall Drone Dimensions

The overall height of the drone was 10.7 cm and the diagonal distance from motor to motor was 24.04 cm which were both well under maximum size allotments of 25 cm height and 33 cm diagonal distance. Also the battery we incorporated to power our drone is a 4S 14.8V battery which means there are 3.7 volts per cell which are within the specification. These dimensions are outlined in Figure 14.

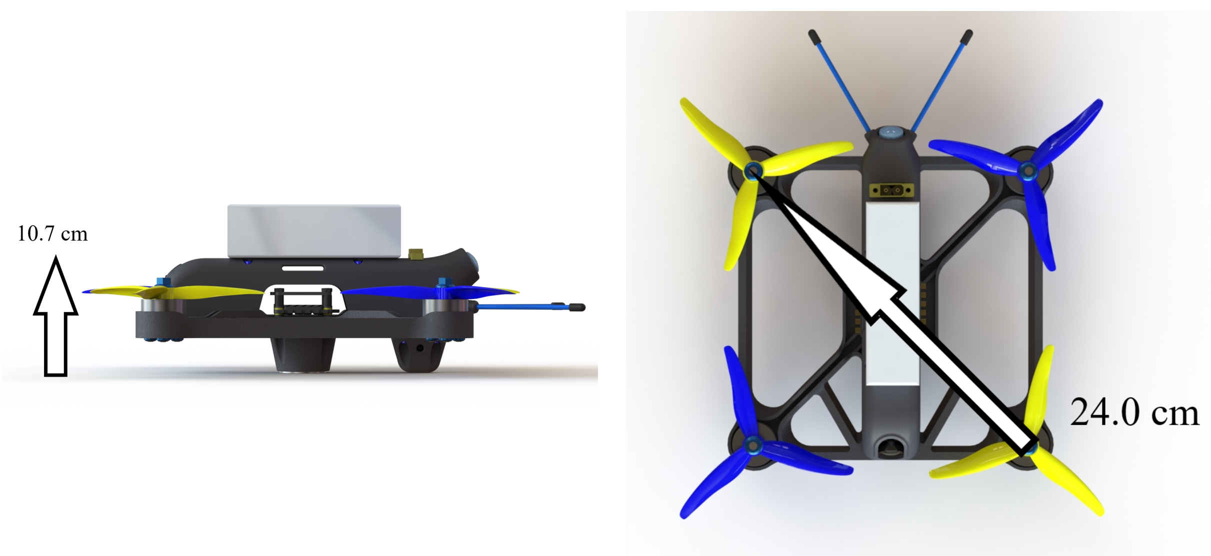


Figure 14. Side and top profile of the drone rendered in Solidworks.

After the CAD model of the drone was finalized we were able to print the drone using selective laser sintering (SLS). We decided to outsource the printing of this drone body to a company called Jawstec as the dimensional tolerances required for this design were too tight for any process on the University of Michigan's campus. Figure 15 shows the comparison between the finalized CAD model in SolidWorks and the finalized drone fully assembled.

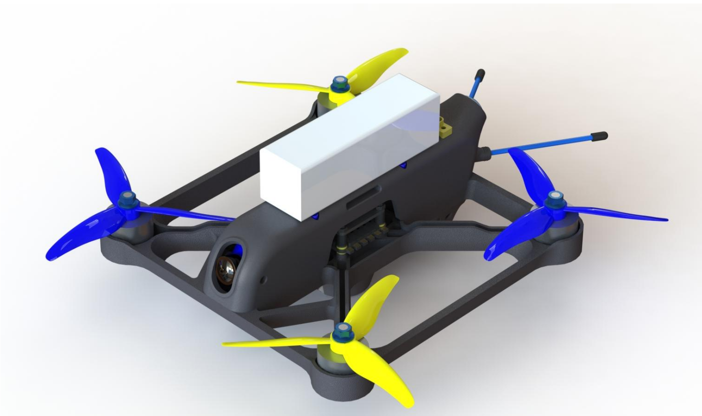


Figure 15. Side-by-side comparison of the drone in Solidworks versus assembled.

Component Mounting

In order to ensure all electrical components were mounted in an accessible manner to the drone, we decided to split the drone design into two pieces: a frame and a canopy. All components are to be mounted to the frame, and the canopy would be installed after the components are secured. This design modularity allows for easy serviceability of the electrical components.

Canopy

The canopy is secured to the frame itself using four M3 screws and two anodized aluminum 30mm threaded spacers. The design of this canopy was not needed directly based on the specifications of our design, however since we were planning to test this drone outside we wanted to protect the electronic components on board from getting damaged from any environmental elements like water, dust, dirt or other possible contaminants. In addition to protecting the electronic components and confining the battery the canopy also housed the front camera mount, held the antenna protectors and the antenna for the VTX transmitter as shown in Figure 16.

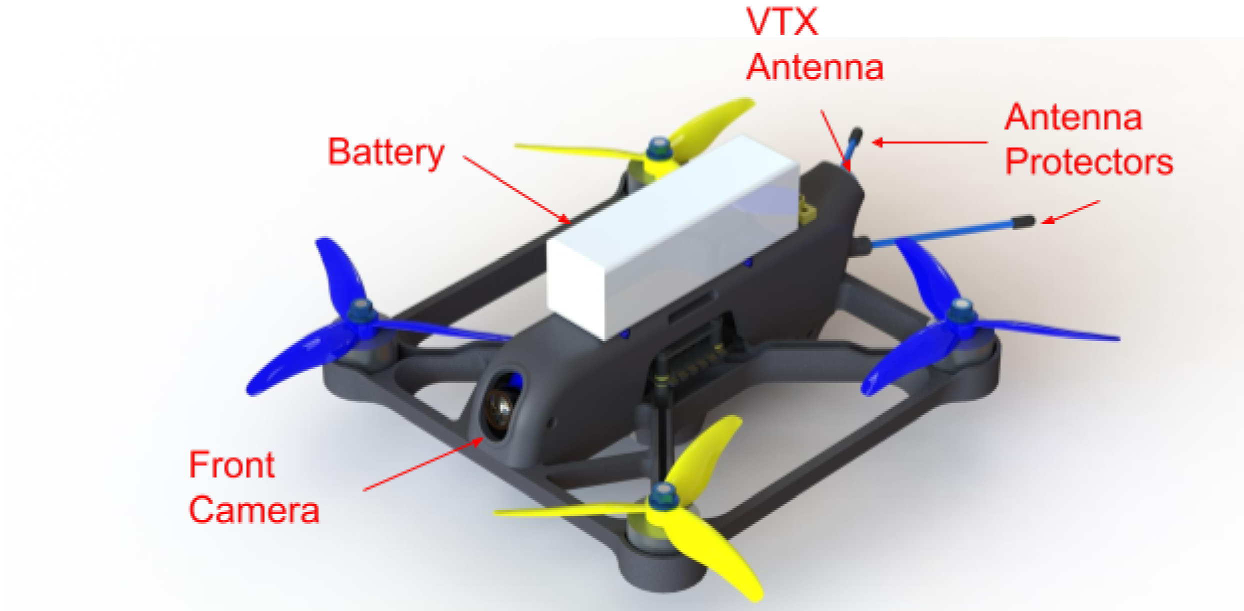


Figure 16. Frame with the canopy attached.

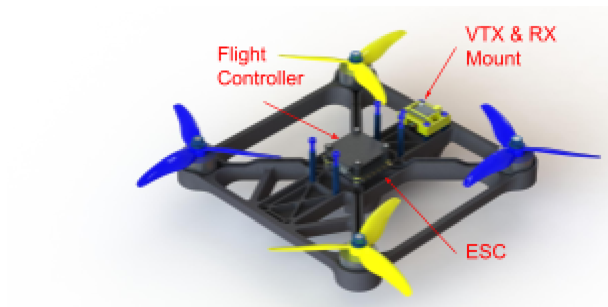
These aspects of the canopy allowed for weight reduction in the design as an additional camera mount was not needed. Also, the implementation of antenna protectors for the VTX transmitter protected the antennas from getting damaged from a possible crash or any environmental elements as specified previously. Overall the canopy acts to protect and hold critical components in a weight and structure efficient manner.

Electronic Components On Top of the Base Plate

The electronic components of this drone serve to carry out critical functions based on the specifications of our drone and are placed strategically on top of the base plate as shown in Figure 17. The ESC and flight controller are stacked together on top of each other in order to employ efficient spacing within the drone, especially with wire management. The flight controller is crucial to remain as close to 0° to the horizon as possible in order to accurately control the drone with respect to the ground while flying, so we decided it was necessary to mount the flight controller on top of vibration isolation mounts which are made of rubber to dissipate any vibration or unexpected shocks while flying.

For the cameras we needed to position them such that one is looking in front of the drone for flying and maneuvering purposes and the other one is purely for looking at the electromagnet to easily pick up the five cubes.

Regarding the VTX transmitter and RX receiver these components needed to be right next to each other and preferably in the back of the drone as the room in the front of the drone was already occupied by the camera, so we decided to create a separate mount that allowed us to securely hold these components. Since these components did not have any screw holes we decided to make the 3D-printed mount a close fit so that you can just press the components in place. This mount is screwed right on top of the bottom camera pod using m3 screws on top of 10 mm standoffs and was made using a PLA printing process.



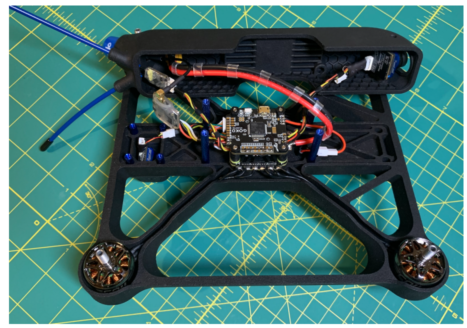


Figure 17. CAD Model of the frame loaded with electrical components versus the assembled frame with electrical components.

Electronic Components Beneath the Base Plate

In order to balance out the center of gravity for this drone design we needed to spread the components of the drone out. As seen in Figure 18, the camera looking at the electromagnet was more exposed than the front camera so we decided to incorporate a separate mounting mechanism in order to protect it from any possible crashes.

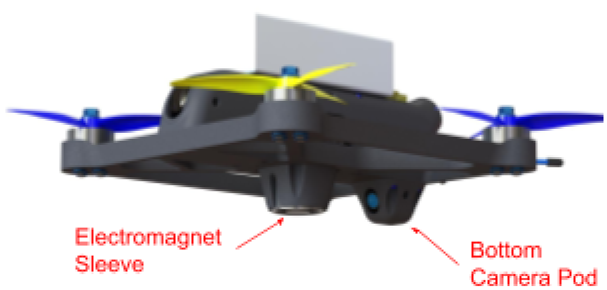


Figure 18. Finalized CAD model highlighting the electromagnet sleeve and bottom camera pod.

For the gripper mechanism we decided to utilize an electromagnet since we wanted to take advantage of the ferromagnetic washers on top of the cubes. By repeatedly testing the distance at which the electromagnet could pick up the cubes, we determined that the max distance the electromagnet had to be from the washer in order to pick up the cubes was 6 mm which gave us ample room for error when coming down from flight mode to pick up each individual cube.

Since no landing gear was incorporated into this drone design, we decided to use the electromagnet as our landing mechanism. In order to protect it from possible head-on collisions, we decided to protect the electromagnet using a detachable, additively manufactured shroud. This protective component acts as both a barrier against collisions while being lightweight.

Benefits of Additive Manufacturing

Our design benefits from additive manufacturing in multiple ways, the first of which being that it allows us to create lightweight structures that are not structurally compromised. We can strip away material that is unnecessary and retain only that which is vital to the structure's integrity, or we can add structural integrity by applying as little material as possible in a structurally efficient manner. The unique hexagon structure implemented in the top top shell of the drone takes advantage of this, it allows for us to drastically reinforce the top shell without adding much additional weight. Furthermore, all components shown in Table 9 also take advantage of this feature unique to 3D printing as it allows us to fabricate small parts tailored for our application that are weight efficient.

The overall design of the drone is practically unable to be manufactured in any other way. It can be argued that these structures could technically be injection molded, but this is impractical for a number of reasons. Additive manufacturing does not require custom tooling to manufacture components. Injection molding requires custom built molds that need to be fabricated and are extremely costly. They also regularly take eight to ten weeks to be fabricated [8]. Even more, for every design change, the molds would need to be refabricated, adding huge lead times at an extreme cost. This mode of manufacturing could only be argued as viable if your design was not going to change in the foreseeable future and you are looking to manufacture the drone in very large quantities, justifying the exorbitant setup costs.

Overall, additive manufacturing allows for greater creative freedom in design, as well as a relatively low setup cost and quick time to bring those designs to life. This makes additive manufacturing the obvious choice for intricate designs, prototypes, and a contender for mass manufacture if the design changes on a semi-regular basis.

Risk Assessment

Our drone design consists of multiple electrical and mechanical systems that have created risk of safety and failure of the drone. To further evaluate the failure modes of our drone, we constructed a Failure Mode and Effects Analysis table (FMEA) to evaluate the severity and likelihood of failure for the different components in our design. The completed FMEA for each of the drones components can be found in Table A.2 in Appendix A.2 at the end of this report.

As seen in the FMEA table, our component with the highest risk were the drone motors. Loss of proper function of the drone motors would result in a loss of control in the air, which would most likely result in a crash. An unintended crash of the drone could lead to damage of the drone frame or any of the many electrical components within the drone. To mitigate any risk of drone motor failure we have taken two approaches. The first is to make sure we are not overloading the motors above what they are rated for. We picked our motors ensuring a 2:1 thrust to weight ratio. This ensured that we would not be pushing our motors to their maximum output and providing a longer motor life. To reduce the risk associated with the loss of control we have designed our drone frame to survive crashes from its maximum flying height of 48" and have ensured that all electrical components are covered by the airframe to avoid any damage.

When evaluating the majority of our failure modes, the end result of most failures is lack of proper control of the drone. Most of these failures can be fixed with a replacement or reconfiguration of electrical components. This would be a reasonably quick fix. Because these failure modes are not too consequential to the actual drone, we have decided that with proper process controls, the overall risk of our failure modes is low.

Discussion and Recommendations

After fully testing the drone and going through the full design process, there are several recommendations and redesign options that would allow for a smoother process and better drone design. With less time constraint, we would have liked to test our drone more than once on the obstacle course in order to gather accurate information about the drone including overall flight time, accuracy in picking up the cubes utilizing the electromagnet, and fastest obstacle course time. We were able to build a fully functional prototype of the drone based on our final design and have outlined recommendations for a better design and additional information that would allow for a smoother design process if this were to be redesigned.

Assembly Process

For the assembly of our drone, there are several recommendations that could be made to allow for a faster assembly process. The soldering of the drone was long even with our wiring diagram as we had to individually solder each wire to the ESC and flight controller. To alleviate this hassle, for the ESC, there are bullet connectors that directly solder onto the ESC and the wires just snap into the connectors, as seen in the TBS Oblivion drone design, in our case we would have one for each motor [10]. These connectors would allow the user to easily swap the motors by just disconnecting the wires from these connectors, therefore solidify our modularity requirement better.

Additionally, when putting the propellers onto the motors, the user has to grip the motor housing with a special pair of pliers with plastic cylinder grippers in order to not damage the motor housing. The part of the frame design where the motor sits at, the lip is too high and we had to unscrew the motor from the frame every time to put the propellers on which was time consuming. To alleviate this problem, the lip should be dropped by 1 mm to provide sufficient room for the pliers to grip the housing of the motor while also providing a sufficient constraint for the motor during flight.

The last recommendation regarding the assembly process of the drone is to split the top shell of the drone into two pieces because with the current top shell, caution has to be taken when removing the top shell because the antennas from the RX receiver and the wires from the front camera are short and could be damaged if too much strain is exerted on them. For example, the sides of the current top shell would be one piece and would include the piece where the RX antennas reside and the front camera mount and the other piece would be the top of the current top shell and would just include the X-T60E1-M connector housing for the battery and the VTX antenna housing. The advantage of this design is faster access to the flight controller, ESC, RX receiver and VTX transmitter because you just have to disconnect the battery from the X-T60E1-M connector and unscrew the VTX antenna from the SMA connector.

With regards to the overall functionality and design of the drone we were confident that given our requirements and budget that we chose the best design, however we did not have enough time to significantly test the drone to see if all of the subsystems would come together and work. We tested each individual subsystem and through small scale testing we were able to determine each subsystem worked on its own. However due to several unforeseen electronic and software issues that were not anticipated by our group, we were not able to test our drone fully. For example, we accidentally fried two VTX transmitters due to the fact that they were receiving power without the antenna plugged in, so in the future make sure the antenna is always connected to the VTX transmitter to ensure this will not happen. Also resoldering of the camera wires had to be completed due to damage caused by the entanglement of wires. In the future this can easily be eliminated using PET sleeving which organizes and protects all the wires. With further debugging using the Betaflight software we believe a lot of these electronic issues can be solved - we did not have enough time to fully dive into debugging these issues due to our low prior experience with this software.

The accelerated timeline of the semester did not give us the ability to fully test and verify our design. We planned to do multiple testing days of flying the drone which we felt were required to do in order to validate our design but those fell through due to unforeseen electronic issues. The prototyping and simulations for this design presented in this report, however, will be able to fulfill most of the goals of this project. With continued testing in the future we believe this drone design to be fully capable of completing the obstacle course and all of our predefined requirements and specifications.

Conclusion

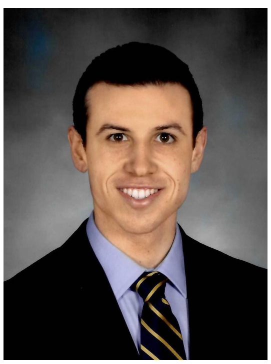
The aim of this project is to design and manufacture an additively manufactured first person view (FPV) drone that meets all the requirements of participating in the ASME IAM3D Competition. Using these requirements outlined from the competition rules, some input from our stakeholder, and benchmarking of existing drones, our team finalized a CAD model of the drone, determined the exact electronic components needed to be successful in achieving all of our predetermined requirements, and successfully manufactured the drone. Through validation procedures using calculations and simulations we were able to say that our drone could theoretically complete the obstacle course in the allotted time of ten minutes though we were unable to physically test the drone. Overall, this project served to show off the advantages of additive manufacturing as it made use of intricate design in the top shell and other components on the frame, rendering these parts unmanufacturable using regular subtractive machining methods. This completed design suggests that additive manufacturing offers the ability to create a better drone than any other form of manufacturing when taking into consideration lead time and cost to manufacture.

Biographies

Alex Bennett

Alex was raised in Jackson, Michigan and began his passion for engineering and design while being in the engineering program at the Jackson Area Career Center while in high school. After high school, he attended Jackson College for two years to obtain an Associate's degree in Science while tutoring English and writing for a year. After Jackson College, he transferred into the mechanical engineering program here at the University of Michigan where he got experience in design and manufacturing and is currently working as a mechanical intern at Tetra Tech, an engineering consulting firm. Alex is set to graduate in December of 2021.

Holden Chevalier



Holden was born and raised in Agoura Hills, California. He became interested in mechanical engineering and design early in high school through his experience in automotive courses and passion for modifying cars. Through his past and current project experience at the University of Michigan, he has a strong background in design for manufacturing and mechatronics. He plans to graduate in April 2021 and will be pursuing a career in manufacturing processes for prefabricated construction.

Elijah Paparella

Elijah was raised in Grand Rapids, Michigan. He became interested in engineering when working on various vehicles and industrial equipment in his teenage years. After graduating from high school, Elijah spent two years studying engineering courses at Grand Rapids Community College, where he tutored Math and English, before transferring to the University of Michigan in the Fall of 2018. He currently works in the Killian Orthopaedic Research Laboratory performing mechanical research on tissue. Elijah is set to graduate in December of 2021.

Mohammad Naimur Rahman

Mohammad was raised in Dhaka, Bangladesh. He completed his high school education from Dhaka where the school followed The University of Cambridge curriculum and after completing his Cambridge IGCSE O-Level, AS and A Levels he started his undergraduate studies at The University of Michigan - Ann Arbor beginning in the fall semester of 2017. Mohammad is interested in mechatronics particularly in mechanical engineering. Besides doing his undergraduate studies in mechanical engineering he explored his interest in Computer Science and Entrepreneurship at UofM. Mohammad worked as a remote data science intern during the summer of 2020 for Luminate of South Africa. Mohammad is set to graduate in December of 2021.

Andrew Urban

Andrew was born in Auburn Hills, Michigan, however was raised in Plymouth Minnesota. Most of his free time in high school was spent playing hockey and tennis for his local high school. In freshman year Andrew was a member of the Michigan Hyperloop team and was a lead designer of the systems chassis. In college Andrew has spent time with Atlas Copco LLC and TEL Manufacturing and Engineering of America as a mechanical engineering intern. Andrew is set to graduate in April of 2021.

Acknowledgements

Professor Kazu Saitou

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Appendices

Appendix A

Table A.1 Bill of Materials

Part Type	Part Name	Quantity	Price ($)	Weight (g)	Dimensions (mm)
4-in-1 ESC	T-Motor Velox V2 V45A 4-in-1 ESC	1	39.99	21	44.6 L x 41 W x 7 H
Battery	RDQ Series 14.8V 4S 2200mAh 80C LiPo Battery - XT60	1	36.99	245	110 L x 32 W x 34 H
Brushless Motor	Emax ECO II Series 2207 1700KV 1900KV 2400KV Brushless Motor for RC Drone FPV Racing	4	47.96	113.2	30.2 L x 27.7 D
Electrical Cables	4 mm Expandable PET Sleeving	1	4.17	1	1000 L
	14 AWG Silicone Insulated Wire	2	1.99	5	-
	26 AWG Silicone Insulated Wire	2	2.00	2	304.8 L
	Extension Cables	1	1.06	1	-
	Heat Shrink	1	9.99	-	-
	JST EH 2 Pin Cable	1	1.00	1	-
	MMCX-SMA Pigtail	1	1.99	4	71 L
	X-T60E1-M Connector	1	0.99	3.7	-
Electromagnet	5V Electromagnet 10 kg Holding Force 3874	1	14.95	90	22 H x 40 D
ESC Wiring Harness	DIY SH Silicone Cable Kit	1	4.99	5	-
Flight Controller	Flywoo GOKU F722 Flight Controller (MPU6000)	1	34.99	7.3	36 L x 39 W x 6 H
FPV Goggles	FatShark Recon V3 FPV Goggles	1	94.34	-	-
Frame (3D Printed Parts)	Baseplate	1	84.06	127.56	203.90 L x 203.90 W x 16.01 H
	Camera Pod	1	4.78	7.12	36 L X 36 W X 24 H
	Electromagnet Sleeve	1	3.78	9.36	42.90 L X 42.91 W X 23 H
	Top Shell	1	33.50	56.31	203.02 L x 36 W x 36.02 H
	VTX and RX Mount	1	0.00	4.39	27 L x 32 W X 8 H

Front FPV Camera	RunCam Phoenix 2 Joshua Bardwell Edition Micro FPV Camera	1	29.99	9	20 L x 19 W x 19 H
Gripper FPV Camera	RunCam Phoenix 2 Nano FPV Camera	1	29.99	5	22 L x 14 W x 14 H
Hardware	35 mm Aluminum Standoffs	4	0.75	1.2	35 L x M3 X 5 OD
	10 mm Aluminum Standoffs	4	0.75	0.34	10 L x M3 X 5 OD
Nuts	M3 Nylon Nuts	4	0.99	1	M3 x 1.5 H
	M5 Aluminum Nylock Nuts	4	3.29	0.5	M5 1.5 H
Power Switch	TinysLEDs RealPit VTX Power Switch	1	2.99	3.8	12.5 L x 10 W x 2.5 H
Propellers	Gemfan Hurricane Durable 51477 3-Blade Propeller (Set of 4) (Black)	1	2.99	4.15	129.5 D
RHCP Antenna for FPV Goggles	XILO Pagoda 2 Antenna	1	4.99	-	-
RX Antenna Protector	Forever Antenna Tubes (Black/Black)	1	2.99	0	-
RX Receiver	FrSky R-XSR 2.4GHz 16CH ACCESS/ACCST Micro Receiver w/ S-Bus & CPPM	1	20.99	1.5	16 L x 11 W x 5.4 H
Screws	M2 x 4mm Button Head Screws	4	2.99	0.5	M2 X 4 L
	M2.5 x 8mm Socket Head Screws	2	2.99	1	M2.5 X 8 L
	M3 x 6mm 7075 Aluminum Button Head Screws	20	8.99	4.4	M3 X 6 L
	M3 x 12mm 7075 Aluminum Button Head Screws	8	8.99	1.04	M3 X 12 L
	M3 x 14mm 7075 Aluminum Button Head Screws	4	8.99	1.2	M3 X 14 L
	M3 x 18mm TI-6Al-4V Button Head Screws	4	5.49	2.16	M3 X 18 L
Vibration Isolation Mounts	M3 x 7mm Anti-Vibration Flight Controller Soft Mount Standoff 4 Pack	4	2.99	3.5	M3 X 7 D X 7 H
VTX Antenna	XILO AXII Stubby SMA 5.8GHz Antenna (RHCP)	1	1.99	4.63	80 L
VTX Transmitter	AKK Oscar's Backpack VTX	1	14.99	2.8	19 L x 19 W x 4 H

Washers	uxcell Nylon Flat Washers M3 6mm OD 3mm ID 1mm Thickness	4	5.49	0.4	M3 X 1 H
	M3 Head Washers Gaskets Aluminum Alloy	16	5.99	2.72	M3 X 1 H
		96	564.14	751.66	

A.1 Circuit Diagram

The 4S Lipo Battery connects to the 4-in-1 ESC which will in turn power all the electronic components of the drone. The four motors connect individually to the 4-in1 ESC. The ESC is connected to the Flywoo GOKU F722 Flight Controller. The two FPV cameras of the drone are connected in series for the power supply and then connected to a single 5V port on the flight controller, the two cameras are also connected to the flight controller's camera ports *C1* and *C2* as shown on the wiring diagram depicted in Figure A.1. The flight controller also has a built-in VTX port and so the transmitter is connected directly to it. The micro receiver is also connected to the flight controller directly. The electromagnet is connected to a power switch which connects the electromagnet to the flight controller. The two FPV cameras and the micro receiver are connected to a 5V port on the flight controller, while the electromagnet is connected to a 9V supply. The only two components that use battery voltage are the flight controller and the transmitter.

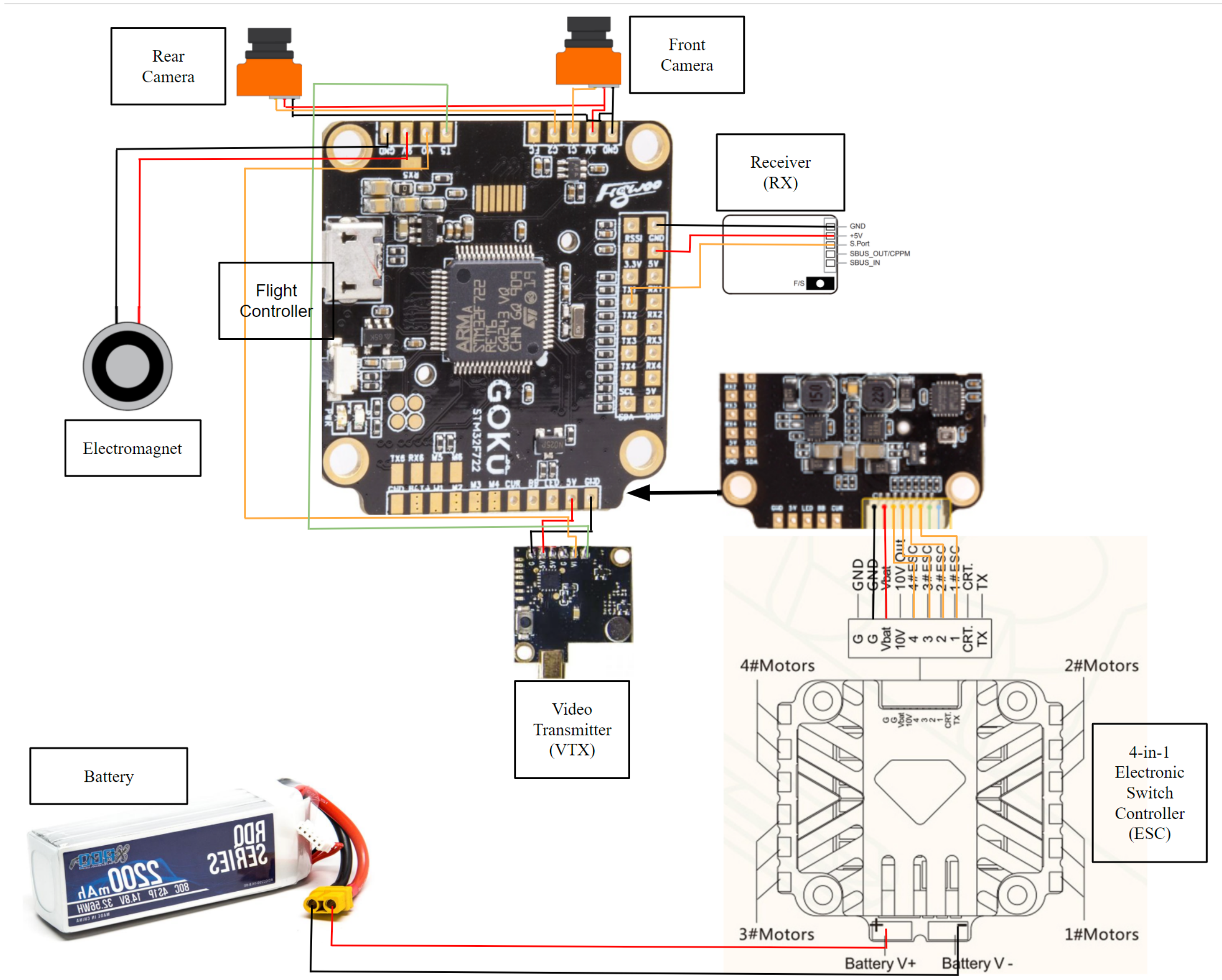

Figure A.1 Wiring Diagram/Schematic of all the electronic components.

A.2 FMEA Table

Table A.2 FMEA of Drone Components

Component	Potential Failure Mode	Potential Failure Effect	Sev	Potential Causes	Occ	Current Process Controls	Det	RPN	Action Recommended
Frame	Frame breaks due to crash impact	Frame is unable to hold components or achieve liftoff	10	High impact crash, imperfections in printing process	2	Testing in areas with soft landing areas and visually inspecting the frame	2	40	Test in areas with soft landing areas and visually inspecting the frame
Video Transmission	VTX is fried or wires are disconnected	VTX is unable to transmit video to controller	7	Soldered wires become disconnected or vtx is powered without antenna connected	2	Practice proper wire soldering procedures and ensure antenna is connected when vtx is powered	3	42	Check that wires are connected properly with multimeter
RX Antenna	Antenna is unable to receive data	Drone is unable to receive controls from pilot	9	Damage to antenna, interference in the environment	2	Protective shroud for the RX antennas are built into the drone frame with antenna covers	2	36	Test in open areas and ensure antennas are properly protected
Motors	Mechanical malfunction or bearing failure	Loss of control likely resulting in a crash	8	Fatigue from long term use or high impact crashes	2	Not running the motors at their maximum output to mitigate motor damage	3	48	Visually inspect motors and test at low speeds before flight
Battery	Lack of battery power	Loss of power to certain components, resulting in loss of control and functionality	6	Battery degradation from overuse	3	Using a battery alarm to make sure battery does voltage does not drop below a dangerous level	2	36	Make sure battery is charged and does not drop below acceptable levels
ESC and Flight Controller	Overheating or loss of connection to on board components	Loss of control and functionality of the drone	7	High impact crashes, overuse of components in confined area	3	Monitor PCB temperatures through Betaflight software, visually inspect connecting to PCBs	2	42	Monitor PCB temperatures through Betaflight software, visually inspect connecting to PCBs
Propellers	Fracture or loss of propeller	Loss of control likely resulting in a crash	6	High impact crash or motor nuts being improperly tightened	4	Visually inspect propellers for any damage and replace damaged propellers before a fracture occurs. Make sure motor nuts are properly tightened before each flight	1	24	Visually inspect propellers for any damage and replace damaged propellers before a fracture occurs. Make sure motor nuts are properly tightened before each flight

In the table above there are four categories associated with number values used to quantify the failure modes and risk associated with each component. *SEV* is the severity on a scale of 1-10 of the failure mode of the component with 1 being insignificant and 10 being catastrophic failure. *OCC* is the chance on a scale of 1-10 that the failure mode will occur over the lifetime of the component with 1 being very unlikely and 10 being almost certain. *DET* is the ability for the user to detect the failure mode using the current process controls on a scale of 1-10. Finally the *RPN* (Risk Priority Number) is the product of Severity (*SEV)*, Occurrence (*OCC*), and Detection (*DET*) ratings to provide a numerical value for ranking which failure modes need to be addressed.

Appendix B

B.1 Engineering Standards

Overall, the usage of engineering standards were not used throughout the process. Engineering standards were not used during this project because all the requirements were outlined from the competition rules and from our stakeholder so we used those to guide the design of our project. The proposed solution for this project was open-ended and that was also another reason engineering standards did not fit for our project.

B.2 Engineering Inclusivity

Our design process, being an American Society of Mechanical Engineers (ASME) sponsored drone competition, did not lend itself to a large amount of identifying social power and engineering inclusivity as a research of commercial product would have. For our project our stakeholders were composed solely of the ASME IAM3D competition organizers, Professor Saitou, and the members of our design team. Our design space was very limited in its sphere of influence due to our lack of stakeholders and the lack of influence our stakeholders had in our design. Professor Saitou was our lead contact point for our project, however he wished to remain out of our design process in the hopes of allowing us to create our own design. Our stakeholders at the ASME had a large part in guiding our design, as we were responsible for following the guidelines set forth in their competition rules. However, there was no communication between us and ASME aside from a couple questions clarifying the rules for the competition. This lack of meaningful discussion between stakeholders to promote inclusivity left us to create discussion within our own design group. With five members of the team with varying levels of experience in drone design we promoted discussion sessions to allow all members to propose and debate ideas that would aid our design process.

B.3 Environmental Context Assessment

The goal of our design project is design and build a single additively manufactured drone to compete in the ASME IAM 3D design competition. When selecting the material and manufacturing process used for the air frame of the drone, one of the factors we weighed into our decision was the environmental impact the manufacturing process would have. The material we ended up using is *HP 3D High Reusability Nylon PA 12.* Nylon PA 12 is a powder based material used in SLS additive manufacturing. Nylon PA 12 has a very high rate of powder recovery rate of 80%. The unused powder during prints can be collected and reused for future prints. This reuse allows for less material waste and provides a smaller impact on the environment than other material and manufacturing processes.

Although we made selections to try and reduce our impact on the environment, our design does not meet the conditions for sustainable technology. Our competition is built to show the benefits of additive manufacturing processes through the creation of a first person view piloted drone. This does not lead itself towards a design that makes progress towards an unmet and important environmental or social challenge. Furthermore, as the social and environmental benefits of the design are non existent, the electricity needed to charge the batteries along with the environmental cost from manufacture and disposal will outweigh any benefit this drone may have had during its lifetime.

B.4 Social Context Assessment

When evaluating the social context of our design project in the real world it is important to realize that this drone is a high cost luxury item that does not provide reasonable benefits outside of entertainment value. With the current budget of $700 dollars this drone would be reserved for individuals with a sizable amount of spending money. One of the positives of this high price tag in the current design is avoiding the rebound effect. This effect occurs when a product which should give a positive benefit to the environment is overproduced and actually has unintended consequences that harm the environment. In the future, with large scale manufacturing processes and more cost efficient technology the price may be reduced enough to make the drone more readily available, but for now it remains a luxury item. Another effect of the high price point is that this drone would not be resilient to changes in the economic market. As a luxury item used for entertainment purposes, if the economy were to struggle and peoples' extra spending cash was limited then drone users would decline. All of the previously mentioned reasons illustrate that our drone design does not meet the criteria for a sustainable technology.

B.5 Ethical Decision Making

As a small drone not meant for widespread commercial usage there were not many ethical dilemmas we faced while designing and deciding on our final proposed solution. While designing the drone we were primarily concerned with the functionality of the drone over any safety features. If this drone was meant for commercial usage, we would have installed some safety features within the drone design like propeller guards, a battery disconnect switch, and more PET sleeving throughout the drone, which protects the wires from getting damaged and could cause potential electric shock. Also, while designing this drone we did assume that whoever would be controlling the drone would have to have good hand-eye coordination as they had to physically control the joysticks on the flight controller and be able to make quick decisions based off of the view they are receiving from the first person view goggles. This was justifiable, in the scope of this project, as our group were the only people that were ever going to use this drone. If this drone were designed for commercial usage, this decision indirectly left out a large group of disabled people however that was not in the scope of our project.