Unmanned Aerial Radio Tracking System for Monitoring Small Wildlife Species

Final Report

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EXECUTIVE SUMMARY

The Forestry department at Northern Arizona University (NAU) has been conducting research on bat colonies in the forests of Northern Arizona. Our mechanical engineering team was tasked with creating the fourth iteration of a drone that will be able to aid and simplify the bat tracking process. The past three iterations consistently had issues with the thrust to weight ratio, torsional rigidity, ability to transport, and flight stability. Therefore, the newest iteration's customer requirements were as follows; lightweight, rigid, collapsible, and stable during flight. Specifically, the drone needed to be under 1 lb, produce a minimum 2:1 thrust to weight ratio, be torsionally stable during flight, be able to sustain a 4 ft fall, be able to fit into a 30 L backpack, and have a center of gravity lower than the geometric center. Additionally, though not structurally important, the drone needed to be aesthetically pleasing for the purpose of product marketing.

Originally, the design constraints for the drone were based solely on the aforementioned customer requirements. After analyzing the past iteration's design flaws and conducting benchmarking of other existing drones, the team decided on a central hub focused design. The first central hub design featured thorough use of shelling and a double boom arm configuration to minimize weight and optimize the torsional rigidity, respectively. However, during a consultation our faculty advisor gave an additional constraint of enclosing all electronics and heavily advised against using the double boom arm, causing an extensive redesign. The second central hub design was larger and incorporated more features to allow for the proper connection and concealment of the electronics. This second central hub design was prototyped and used to finalize the design. After finalizing the design, the drone was put through a series of tests to ensure that the design fulfilled the requirements.

The testing procedures were as follows; weigh the drone and confirm it is under 1 lb, conduct a successful test flight, drop the drone from 4 ft and check for damage, disassemble the drone and fit it into a 30 L backpack, and use modeling software to calculate the center of gravity to ensure it is lower than the geometric center. When measured, the drone weighed 1.31 lbs, 0.31 lb above our target weight. However, it still produces a thrust to weight ratio well above 2, which is critical to the operation of the drone. Also, the drone was able to conduct a successful test flight, sustained minimal damage after a 4 ft drop, and fit into a 30 L backpack. Finally, the drone frame has a center of gravity that is 0.61 cm below the geometric center. This center of gravity will be even lower when the electronics are added, since the majority of the electronic weight is located in the lower compartment of the drone frame.

Although the drone did not pass the weight test, the team and our mentor consider the drone a successful design. Further iterations will be completed using this drone as a baseline. These iterations will focus on reducing the frame weight further and adding in new features such as a parachute system, an arm system that is easier to remove from the frame, etc.

ACKNOWLEDGEMENTS

The team would like to take this opportunity to acknowledge and thank individuals who were vital in the design and development process of the project. Dr. Michael W. Shafer, our faculty advisor, provided the team with invaluable advice during all stages of the project. Dr. Sarah Oman, our capstone professor, provided the team with professional, financial, and documentation advice. Finally, Chris Gass, a fellow student, provided the team with documentation and information about his experiences with the previous iterations of the project. Additionally, the team would like to thank the NAU machine shop and RAPID LAB employees for providing manufacturing services.

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1 BACKGROUND

1.1 Introduction

The Forestry department at Northern Arizona University (NAU) has been conducting research on bat colonies in the forests of Northern Arizona. This research requires bats to be captured and then tagged with radio frequency transmitters. During the day, when the bats are inactive in their roosts, the signal from these transmitters are tracked to determine the location of the bat colony. This is done by hiking into the mountains and following signal responses. To ease this process, several iterations of an Unmanned Aerial Vehicle (UAV) have been designed by engineering students at NAU. These UAVs were made solely for the purpose of assisting this research. The UAVs were designed to fly to a set height and travel in a programmed path that optimizes the telemetry between the transmitters and the receiver system carried on the UAV. Once a signal was found, the data collected was analyzed to determine the direction the signal was originating from. That direction would then be used to map a location for the next flight. By performing this flight in several places, the UAV could help triangulate the position of the roosts.

The team's client, Dr. Shafer, has been involved in projects that utilize telemetry and gained knowledge that was beneficial for the research on these bats [1]. He was approached by a professor in another department and informed about the trouble that the researchers were having. Dr. Shafer generated the idea of using a UAV for collecting the signal locations more efficiently. He then established the capstone team that would design the first model of this UAV, and continues to guide the teams that produce each iteration.

1.2 Project Description

The team was tasked with engineering the latest iteration of the drone by designing a new frame that could meet more requirements. The project description was defined as follows:

> "I would like your project to develop an improved UAV design capable of lifting the animal tracking antenna and associated electronics. The total payload capacity should be between 1 and 2 lbs. The UAV design should be robust to field deployments (not delicate or hard to assemble). The UAV should also be collapsible so that it can be packed and carried into the field."

In addition to this description, the team also considered the requirements for the previous iterations of the drone. These require the drone be able to:

- Execute a programmed flight path
- Collect signal locations at several points along the path.
- Return to operator
- Withstand drops from distances of three feet with no damage and up to six feet with repairable damage.

1.3 Original System

Three iterations of a quad copter UAV have been completed prior to this project. Each iteration added a feature that more closely satisfied the customer's needs.

The first version was an original design of the mechanical and electrical aspects of the project. This initial system had the required components of a multirotor set-up: Electronic Speed Controllers (ESC's), motors, batteries, and the flight controller board (3DRobotics Pixhawk). This electronics package was mismatched and wouldn't perform when it came to longevity.

The second iteration involved the design of a new frame using the existing electronic components, as well as new propellers of the proper size to remedy the compatibility issue. The frame was designed and built with no reference to the previous frame. Brackets were 3D printed to join carbon fiber arrow shafts to a central hub where each “arm” of the multirotor had a basic truss design for maximum strength in the vertical axis. This truss design became a source of problems with the torsional rigidity of the end of each “arm”.

Finally, the third iteration was designed to remedy these resonance issues that were present in Iteration 2, and was still in progress at the time of this writing. This iteration utilized many of the same design elements as Iteration 2; the use of trusses and 3D Printed parts. It added a more refined landing gear, stronger truss system, and a better layout of electrical components. There was a new electrical system implemented; these new electrical components raised the overall voltage from 12V to 16V, allowing for larger propellers to provide nearly twice the lifting force of the previous iterations, or ~2kg of thrust per motor.

The following sections outline these designs in order to show the development of the Quadcopter. A history of the design will show the concepts that have been kept/discarded to yield our current design.

1.3.1 Original System Structure

Iteration one was completed by Arjana et al. [2] and incorporated off the shelf materials which made the final product very sturdy but heavy. Square aluminum tubing was used for the arms and aluminum sheet metal was used for the electronics mounting plate. The landing gear assembly was constructed of PVC tubing. A CAD drawing and picture of the final design can be seen in Figures 1 and 2, respectively. Final cost of the frame materials was $202.75. An itemized cost list can be seen in Table 1.

Figure 1 - Iteration 1 CAD drawing [2].

Figure 2 - Iteration 1 final design [2].

Table 1 - Iteration 1 itemized costs [2].

Component	Description	Quantity	Price	Total
Frame	Hard High-Strength 7075 Aluminum, 0.125" Thick, 8" by 8"	1	$24.14	$24.14
Frame	Multipurpose 6061 Aluminum Rectangular Tube, 1/16" Wall	1	$15.56	$15.56
	Shipping			$26.51
Fasteners	Mach Screw 32x1-1/2	3	$1.18	$3.54
	tax		$0.29	$0.29
Plastic Box	Home organizer box	1	$9.94	$9.94
	tax		$0.89	$0.89
Fasteners	bolt, nut and screw mis box&bulk (4 invoices)	1	$9.33	$9.33
Fasteners	bolt, nut and screw mis box&bulk (4 invoices)	1	$13.82	$13.82
base plate	hard high strength 7075 Aluminum .09" thick 12"x12"	1	$38.68	$38.68
rectangular	Multipurose 6061 Aluminum Rectangular Tube 1/16" wall	1	$9.82	$9.82
rectangular	Multipurose 6061 Aluminum Rectangular Tube 1/16" wall	1	$9.02	$9.02
quick release	zinc-plated steel quick- release button connectors	2	$4.08	$8.16
frim gray f3 felt	1/8" Thick, 12" x 12" adhesive back	1	$13.51	$13.51
	shipping			$19.54
				$202.75

The goal of the second iteration was to decrease the weight of the UAV frame. It was constructed using carbon fiber arrow shafts and 3D printed junctions. The new design brought the frame weight down to approximately one pound. A SolidWorks model of Iteration 2 can be seen in Figure 3.

Figure 3 - SolidWorks model of Iteration 2.

1.3.2 Original System Operation

The original frame design incorporated spring-pin connections at the arms. This made the frame easy to disassemble and allowed it to be stored within a more compact volume. The arm junction was connected to the electronics baseplate using a nylon bolt (Figure 4). This bolt was designed to fail at approximately 10 lbf to prevent damage to vital components in the event of a crash. This system allowed the drone to survive a five foot drop while sustaining only field-repairable damage.

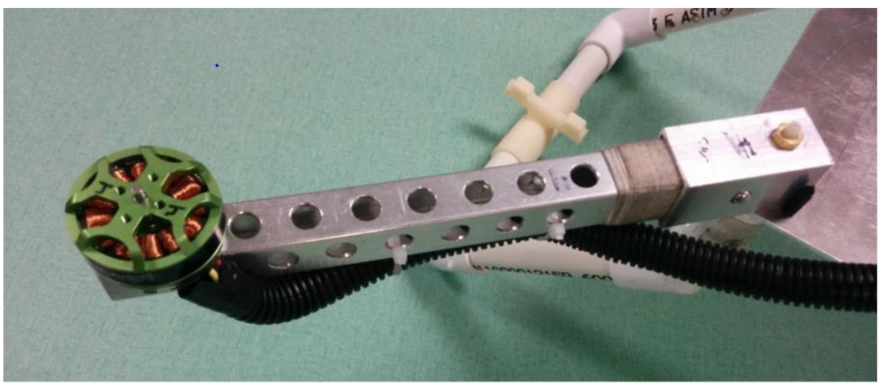

Figure 4 - Iteration 1 arm assembly [2].

Iterations 2 and 3 were neither collapsible nor designed for failure at a specific point. Both designs aimed to reduce the weight of the frame and test the viability of using carbon fiber arrow shafts as frame material.

1.3.3 Original System Performance

Exact specifications of the frame weight of Iteration 1 are unknown but were approximated by the designers to be five pounds. Lifting power was also not measured but was approximated to be 11 pounds, according to motor specifications [2]. The second iteration reduced the frame weight to approximately one pound and the third iteration is expected to be slightly heavier. The second and third iterations are expected to produce the same lift as the first.

1.3.4 Original System Deficiencies

The deficiencies associated with the first iteration included weight, stiffness, and component choice. The frame weighed approximately five pounds without the electronics mounted. This posed a huge power disadvantage because a 2:1 power to weight ratio is recommended for multirotor UAV's. At a weight of approximately five pounds and a lifting power of roughly eleven pounds, the frame alone was already close to this desired power to weight ratio.

The first iteration of the frame was made of aluminum. Although strong, aluminum carries vibrations through it easily because of its stiffness. There are an inherent amount of vibrations present in a multirotor due to imperfections in the manufacturing of moving components, each of which contributes to these vibrations. The accelerometers and gyroscopes that are imbedded within the flight controller board register these vibrations, causing unstable flight conditions. Carbon fiber and wood are great at dampening these vibrations, isolating the flight controller.

The components of the first iteration were poorly chosen. The motors chosen were designed to work with a propeller with a diameter of eleven inches and a pitch of five inches, however, the propellers that were fitted had a diameter of sixteen inches and a pitch of six inches. The oversized propeller drew more amperage from the batteries, overloading the motors and ESC's by 50%.

In the second iteration, these three main problems were fixed, however, a new torsional stiffness problem arose. The motors generated a torque when the aircraft yawed, creating a resonance vibration that forced the flight controller to read a false input. The flight controller reacted by changing the motor speed, causing the UAV to rapidly lose altitude.

2 Requirements

2.1 Customer Requirements (CRs)

The following Customer Requirements and weightings (out of 250) were developed to satisfy the customer needs:

- Lightweight (80)
- Strong/Rigid (80)
- Collapsible (50)
- Low Center of Gravity (30)
- Aesthetics (10)

The Lightweight and Strong/Rigid requirements were not only the highest weightings but also equal because they were the two main needs of the project. The UAV needed to be portable to the degree that it could be carried on long treks to data collection sites in rural and mountainous terrains without fatiguing the operator. Along with helping reduce operator fatigue, minimal weight was desired to extend operation time. For this project, lightweight is defined as under one pound. Additionally, the drone needed to be strong enough to sustain minimal damage in the event of a crash landing, as the wind conditions at the data collection sites are typically non-ideal for flight.

If the UAV was collapsible, it could be carried in a backpack, increasing the portability requested by the customer. Since collapsibility is a matter of convenience and not necessity, it has a lower rating than the aforementioned requirements.

The low center of gravity requirement was based on the customer request for stability during the drone flight. A low center of gravity provides inherent mechanical stability to the drone, before any aids need to be implemented electronically. Although this was important to the project, it was less intensive than the other tasks and, therefore, received a lower weighting.

Finally, the aesthetics requirement is not imperative to structural integrity or performance. However, the customer insisted this requirement be included. The drone is planned to be open-sourced but a professional frame design is more easily marketed for research grants.

2.2 Engineering Requirements (ERs)

Engineering requirements are technical measurements and goals that help further define the customer requirements. Not all engineering requirements can be quantified, some are more specific requirements for the design. All engineering requirements created for this project are described below.

Lightweight	To make the UAV easily portable over long distance hiking (where larger weights would cause great fatigue) the frame needed to be lightweight. Considering 6 lbs to be around the largest weight desired to avoid fatigue, and the fact that the operator has 5 lbs of tracking equipment, the frame was desired to weigh under one pound.
High Power to Weight Ratio	The UAV, including the tracking equipment rig, needed to have a high power to weight ratio as a built in factor of safety. The team’s target was a 2:1 power to weight ratio.
Durable	The customer requested that the UAV sustain minimal damage from a 4 ft fall. This is to prepare the copter for rough landings during operation.
High Rigidity	The motors create torsion during flight, requiring the adhesive affixing the joints to the arms must have a rigidity large enough to combat this effect.
Targeted Break Locations	To protect the parts made of expensive and/or difficult to access material, breaking points are going to be designed into the cheaper frame part.
Low Storage Volume	The backpacks used for these hikes are generally 50 L. However, the team is aiming for 25 L to account for the operator’s personal items (water, food, etc.).
No tools Required for Construction	To alleviate the amount of equipment the operators must carry on the hikes, the drone needed to be constructed without the use of extensive tools. Ideally, the frame would be able to be constructed without the use of any tools.
Small Parts Tethered to Copter	Small parts are easily lost, especially with excessive relocation. To avoid excess cost for replacing these small parts the team made any part less than 2 in connect to the body of the UAV by magnet or tether.
Payload Under Prop Height/ Payload Attached to Underside of Platform	Both requirements were to lower the center of gravity and provide the drone with an inherent stability during flight.
Built from Easily Accessible Material/ Cheap Material	The operators do not have large funding pools or access to advanced engineering materials. Therefore, in case of a fracture or break, the drone was constructed of cheap and easily accessible materials.
Stable During Flight	The operators are not experienced with flying drones so the drone was constructed to be as stable as possible.

2.3 Testing Procedures (TPs)

This section will discuss procedures developed by the team to test the Engineering Requirements described in the previous section. The numbers reference the TP numbers seen on the House of Quality in Section 2.5.

1. To test the weight of the drone and ensure it fits the weight requirement of under 1 lb, each of the landing feet were placed on small scales. The weights will be recorded and summed. The drone will have a large projected surface area and will only fully fit on a scale with low resolution. To get the desired resolution, smaller scales with higher resolutions were used.

2. To test the thrust, each motor was attached to an arm of the quadcopter with a weight attached that was known to be more than the theoretical thrust of each motor. The motor, arm, and weight combination were placed on a scale and run to full throttle. The scale was zeroed and the absolute value of the reading from the scale was taken as the thrust.

3. During landings, the drone will experience a free fall from between 1 and 4 ft. To ensure the drone is durable enough to withstand the landings, the team dropped the drone from 4 ft, and assessed the damage. Weak points were fortified and retested until the desired result was accomplished.

4. A torsion test was administered to find the relative torque that each arm can withstand. This test was performed by placing a weight on a moment arm of specified length. The arm was then attached to the motor mount to create a twisting force. A quadcopter utilizes an adverse torque between the motors in order to move to a desired yaw position. This torque in the xy plane also creates a torque in the zy plane. This torque needed to be calculated to create an arm able to withstand repeated use.

5. A maximum load and fatigue test was conducted on the frame to find the breaking points. Parts that broke but were not supposed to were redesigned to have a higher factor of safety.

6. The total spatial volume of the quadcopter was found by collapsing the frame and using the outermost dimensions in all three axes. This spatial volume is important to ensure that the quadcopter had the ability to fit inside a backpack of approximately 25-30L.

7. Each part was modeled in SolidWorks to get the exact dimensions and get the total volume, weight, and the location of the center of gravity (CG). The CG needed to be close to the center of the quadcopter to ensure good stability. If the CG is too far off, the motors on the side closest to the CG will be working harder, resulting in a loss of efficiency and stability.

8. While acquiring the parts for construction, research was conducted to ensure the parts can be easily and consistently found at a low cost. Additionally, the team searched for recycled material (such as arrows) that can be retrofitted for the drone. Cheap electronic replacements were found at hobby websites such as the 3D robotics website. Also it is assumed that the forestry research department will have access to a 3D printer for which SolidWorks files were provided.

9. The final test was a flight test of the quadcopter itself. This test was broken into 3 tests:
    a. Timed hover test
    b. Manual flight test (stability and flight time)
    c. Autonomous flight test (stability, flight time, and autonomous function)

    All of these tests were administered with a tether to abide by the FAA Rules and Regulations. They were also compared to theoretical values for the flight times and stability of the quadcopter.

2.4 Design Links (DLs)

Prior to creating a design based on the customer requirements, more specific engineering requirements were developed. These engineering requirements can be found in Section 2.2 and are used to provide more defined constraints and goals for the design. The following section describes how the engineering requirement goals satisfy corresponding customer requirements.

1. Carbon fiber arrow shafts are known to be lightweight. The extensive use of these shafts for the frame, as the skeletal structure, yielded a low mass per volume design. Additionally, the 3D printed joints did not add a substantial amount of weight.
2. The methods described above to reduce the weight increased the power to weight ratio. This provided better flight efficiency and increased flight time. A more efficient UAV allowed the use of the last iteration's electronics set up and decreased the current draw from the batteries which prevented overheating of electronic components.
3. The durability of the frame's design was ensured by the use of trusses to create the arms and body of the quadcopter; these trusses were made from carbon fiber shafts. The shafts are strong in the axial direction and trusses are the strongest member configuration, making a durable and strong frame.
4. Obtaining a high rigidity in the motor mounts was related to the 3-D printed part as well as the quadcopters arms. The arms consisted of two horizontal shafts vertically stacked, with the bottom boom at an appreciable angle to minimize the bending and torsion imposed by the motor/propeller system. The motor mounts were connected to the arm using a press fit, and then secured with a pin to eliminate slip.
5. The legs and arms of the frame were designed with break points within the shafts. The shafts are cheaper and easier to replace in the field whereas the 3D printed joints and flight components are more expensive and take time to replace.
6. With the arms removed and legs folded, the storage volume was comparable to the average laptop. When collapsed this minimal volume and relatively flat structure reduce transportation constraints.
7. The arm configuration (press fit joints with cotter pins) minimized the amount of tools required for construction. Additionally, the support shafts were held in by slightly bending the arms allowing the support shafts to be held in with a compressive force. This setup did not require any tools for construction, under normal conditions.
8. The only parts on the UAV that will require tethering are the cotter pins, due to their size and removable design. As a precaution it will be recommended that replacement cotter pins be carried by the operator.
9. The major payload for any of the designs is the antenna used to detect the signals. In all cases, the antenna is mounted on the underside of the frame (but above the feet). This configuration also helps lower the center of mass.
10. See Design Link #9
11. The majority of the frame was made of carbon fiber arrows and the joints were 3-D printed. This minimized the cost of materials. The arrows can found at many hobby shops or archery retailers and it is assumed that 3-D printing is easily accessed by a researcher.
12. See Design Link # 11
13. The efforts made to lower the center of gravity and attach the payload under the propellers will increase the UAV's stability. The design also featured a square motor configuration to increase stability.

2.5 House of Quality (HoQ)

The House of Quality was used to ensure that all customer requirements are accounted for in the project's engineering requirements. Additionally, it shows the importance each engineering requirement has to the corresponding customer requirements. Figure 5 depicts the House of Quality created for the project.

1.4.5 House of Quality (HoQ)

Customer Requirement	Weight	Engineering Requirement	Lightweight	High Power to Weight Ratio	Durable	High Rigidity in Motor Mounts	Targeted Break Locations	Low Storage Volume	No Tools Required for Construction	Small Parts Tethered to Copter	Payload Under Prop Height	Payload Attached to Underside of Platform	Built from Easily Accessable Material	Cheap Material	Stable during Flight		
1. Lightweight	80		9	9	3	3				3			6		3		
2. Rigid/Strong	80		3	3	9	6	6	3	3				6	6	3		
3. Collapsable	60				6	3	3	9	3	3				6	6		
4. Low CG	20		3		3						9	9			9		
5. Aesthetics	LTE									6	3	3	6	3			
6. Low Cost	5		6				6		6	3			9	9			
7. Ease of Build	5				3			9	9	9			3	3			
Target(s), with Tolerance(s)			0.95lb < 1	2 > 2	4 ft fall > 2 ft		Joints Off Main body	25 L < 30L		< 2in	1in >0.5			$50 Tot < $250			
Testing Procedure (TP#)			1	2	3	4	5	6	7	8	8	8	9	9	10		
Design Link (DL#)			1	2	3	4	5	6	7	8	9	10	11	12	13		

Approval (print name, sign, and date):

Team member 1: Lance Eberle

Team member 2: Jason Vizcaino

Team member 3: Lauren Adoram-Kershner

Team member 4: Kellan Rothfus

Advisor: Dr. Michael Shafer

Figure 5 - House of Quality

3 EXISTING DESIGNS

There is a vast number of multirotor designs on the market today for both commercial and personal use. These multirotors are well over $3000.00 or do not have the size requirements specified by the customer. The team has taken into account aspects of many of these multirotor designs in order to build a vehicle that meets all of the aforementioned requirements.

3.1 Design Research

The online community has been a core resource for benchmarking. As there are very few designs for this specific application, a combination of designs from individuals across the internet have been invaluable to the progress of this UAV. By combining aspects of several different designs, the team was able to visualize a large quantity of different arrangements during concept development explained in Section 4. Sections 3.2 and 3.3 describe the system and subsystem level design concepts that were researched and used as inspiration for this UAV.

3.2 System Level

Several existing designs were used for inspiration towards the latest iteration of the UAV frame. Some of the most pertinent are presented below, as well as the relevance each has towards the current design.

3.2.1 Jimustanguitar Quadcopter

The Jimustanguitar Quadcopter fits the design criteria for using the carbon fiber arrow shafts (Figure 6). This quadcopter was built using a series of 3D printed plates and brackets which sandwich the arrow shafts. By not cutting the arrow shafts, the risk of failure during the cutting process is decreased. This also reduces the replacement time of the arm if one were to break in the event of a crash. The dual arrow design increases the torsional strength of each arm. This is important because these motors create a torque that, when yawing, can create an undesired oscillation, as seen in the second iteration of the frame design.

Figure 6 - Jimustanguitar quadcopter [3].

3.2.2 RCExplorer Tricopter

The RCExplorer Tricopter (Figure 7) fits the design criteria of collapsibility. When fully deployed, the multirotor has a radius of thirty-four inches, allowing for stable flight with a GoPro and/or other recording devices. When folded, the multirotor easily slips into, or is strapped to, a backpack. The arms are held from pivoting by friction. A friction fit allows the arm to fold backwards as opposed to breaking in the event of a collision. This tricopter was built by team member Kellan Rothfus and currently has a lifting power of four pounds and a flying weight of 1.4 pounds. This was inspired and modified from its original creator, David Windestål of RCExplorer [4], to fit the needs of the builder and pilot. Modifications include arm dimensions/material, electronics selection, and layout.

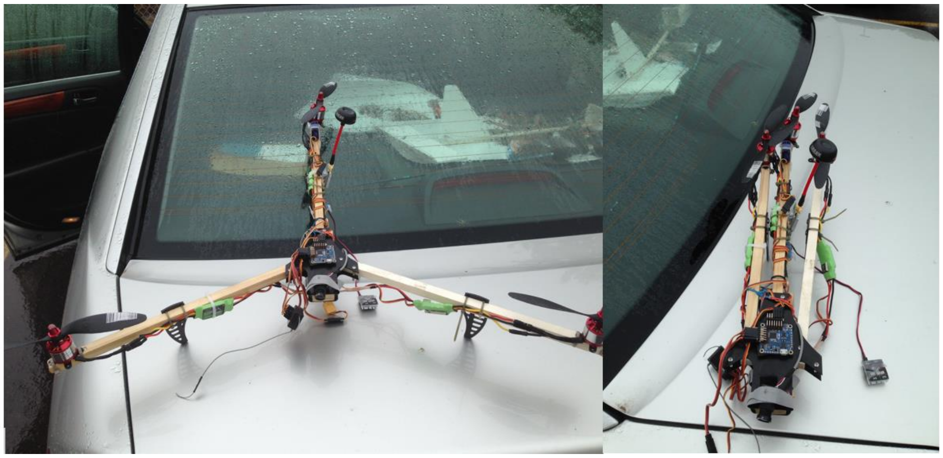

Figure 7 - RCExplorer tricopter.

3.2.3 Flite Test ElectroHub

This design uses wooden beams to obtain torsional rigidity in the arms (Figure 8). This design is too small for the application of the current design, however, it can be scaled up to allow for larger motors and more area to mount the hardware needed.

Figure 8 - FliteTest ElectroHub [5].

3.3 Subsystem Level

The three main subsystems of any multirotor frame are the motor mounts, arm material/geometry, and central hub design. All subsystems have a main purpose but the execution of each is undetermined.

3.3.1 Motor Mount

Motor mounts are affixed to the end of each arm of a multirotor. Their purpose is to transfer the force generated by the motor and propeller combination to the frame and, ultimately, the payload of the multirotor.

3.3.1.1 Jimustanguitar Motor Mount

The Jimustanguitar Motor Mount design (Figure 9) sandwiches the arm members with three 3D printed parts that use the motor mounting screws to apply the pressure needed to hold the members in place. There are also rubber O-rings in place at the interface of the arrow shafts and the 3D printed parts for vibration reduction.

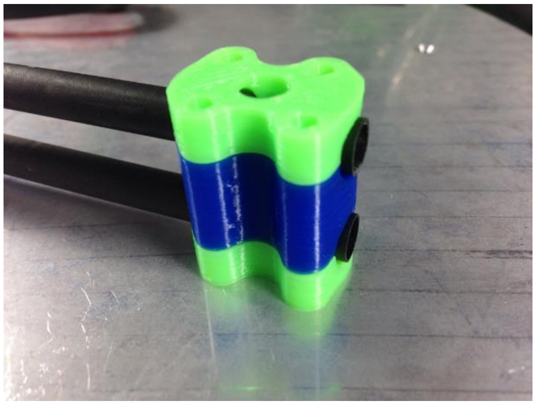

Figure 9 - Jimustanguitar motor mount [6].

3.3.1.2 Preformed Plastic Motor Mount

Several preformed plastic motor mounts are available for purchase. One such example can be seen in Figure 10. This design requires drilling through the arm and then screws are used to affix it. The motor is mounted to the outside of the reach of the member. This mount allows for a shorter member to be used in each arm and can allow for a designed weak point in a collision.

Figure 10 - 12mm plastic motor mount for multirotors [7].

3.3.1.3 Zip Tie Method

Using the mounting bracket that comes with each hobby motor, one is able to zip tie the motor to the arm member. This technique works well with wooden booms, as seen in Figure 11, and is able to be a calculated point of failure to save the motor in the event of a crash. This meets the design requirements in making the motor mount as cheap as possible and easily repairable.

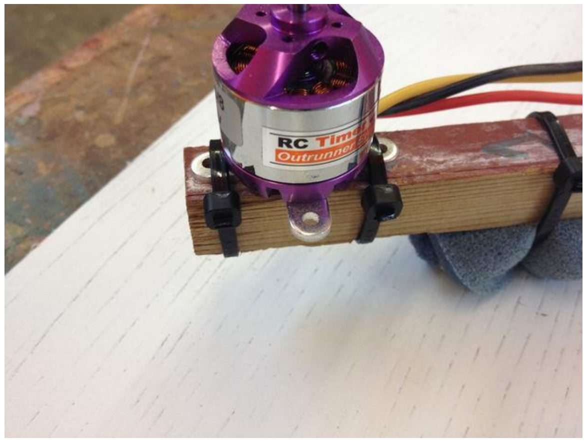

Figure 11 - Zip-tie motor mount.

3.3.2 Arm Design

The arm design comes in many shapes and sizes. Each arm assembly takes the force produced by the motors/propellers and transfers it from the motor mount to the rest of the multirotor. Several potential designs are presented below.

3.3.2.1 Dual Boom Arm

As seen in Figure 9, a dual boom design can be used to create a stiffer boom in torsion. A quadcopter yaws, or rotates, in the xy-plane by speeding up two motors that are diagonal from each other and slowing down the other two motors. This creates a torque in the xy-plane, yawing the vehicle. A torsional stiffness is needed to absorb the torque created by the moment of the propellers' RPM change.

3.3.2.2 Square Wooden Arm

A square wooden boom, as seen in Figure 8, allows for a cheap and easily replaceable member that still gives the torsional rigidity and strength a multirotor needs. Wood absorbs vibrations that are inherent in the motors and propellers when at their operating speed of 10,000-20,000 RPM.

3.3.2.3 Truss Design

A truss design, as seen in Figure 12, can help reduce the weight of the multirotor, increase torsional rigidity, and allow for a multitude of materials to be used, such as wood, carbon fiber, and fiberglass. This fits the design requirements of low weight and oscillation reduction.

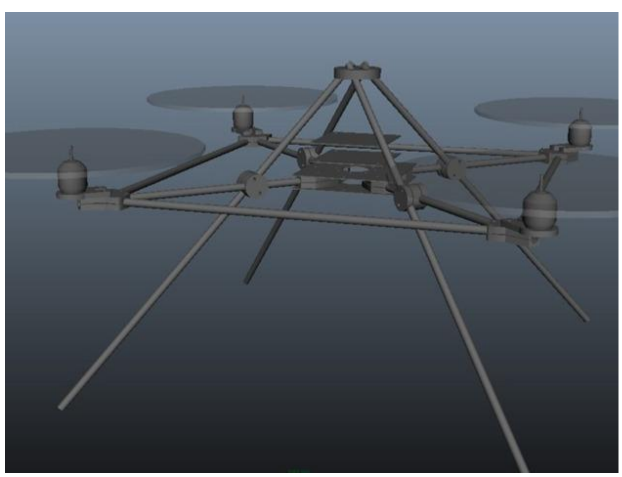

Figure 12 - Carbon fiber quadcopter frame [8].

3.3.3 Central Hub

The central hub is what ties the arms together. This is where all of the main electronics, including the battery and flight controller, are placed. The Capstone Quadcopter required a large platform to store the main electronics, recorders, and radio receiver for the bat transmitters.

3.3.3.1 Stackable Hub

A stackable design allows for a small form factor in terms of area but allows for a large volume to house the electronics needed. Figure 6 shows how this can be integrated into the system with relative simplicity.

3.3.3.2 Long Central Hub

A long central hub, used in an H style UAV (Figure 13), allows for a large area to place the electronics. This design allows for a folding arm design, which satisfies the collapsibility requirement.

Figure 13 - MultiRotor H quadcopter [9].

3.3.3.3 Large Central Hub

A large central hub has a lot of area in order to accommodate all of the electronic components. Figure 14 shows the current version of the quadcopter built by Dr. Shafer. This hexagonal design is common and is a modification of the round central hub used by many UAV's.

Figure 14 - Capstone quadcopter.

4 DESIGNS CONSIDERED

This section will briefly discuss 9 feasible designs that were created during brainstorming. The top three designs are defined in more detail in sections 4.1-4.3. First, the team generated 21 new design concepts for the UAV. Several Pugh charts were used to focus on viable ideas. The original Pugh chart with all 21 ideas and can be reviewed in Table 3. The concepts were reduced to 9-targeted ideas. The advantages and disadvantages for the 9-targeted ideas were the deciding factors leading to construction consideration. Table 2 outlines the 9 ideas and provides advantages and disadvantages for each. A final Pugh chart was then used to choose the three designs for more thorough discussion. Table 3 displays the final Pugh chart.

Table 2 – Design concepts.

Concepts	**Description**	**Advantages**	**Disadvantages**
Expanding Body	The body will be able to collapse using a series of scissor jacks within the frame.	• Collapsibility is maximized	• Expensive to manufacture • Not repairable in the field • Complications with stability
Hinge Propeller	Propellers utilize rotational inertia to extend to full length.	• Expensive parts are protected while inactive	• Complex design • Loss in maneuverability
Pipe Body	H-style quad frame that has a tube as the central body of the copter. This is to aid in transportation as the arms and motors will be able to slide into the central body and thrown into a backpack.	• High Collapsibility • High Portability	• Hard to repair in the field • Complicated build process
Airplane	Small prop plane that would circle the target location and collect signal data to be later analyzed.	• Most stable option • Reliable	• Hard to manufacture • Expensive
H Body Swivel	The drone body would be constructed of carbon fiber sections in the shape on a capitol H and would swivel/collapse at the two main intersections.	• Easy to build • Cheap to manufacture	• Stability issues can occur
Angled Props	Props are built with a slight angle of attack that provides stability during flight	• Stable Flight	• Not collapsible • Complex design
Folding Arms	Prop arms fold in to allow easy storage.	• High collapsibility • Cheap to manufacture	• Hard to repair in the field • Expensive repairs
Tri Body Fold	The main body of the drone would be split into three parts that can be folded in on itself to make a pyramid.	• High collapsibility • Cheap to manufacture	• Stability issued can occur • Expensive to repair
Dragonfly Inspired Copter	“Wings” (arms that held the propellers) would fold into the body above or below, like a dragonfly folding in its wings.	• High collapsibility • Stable flight • Cheap to manufacture	• Complex design

Table 3 – Initial Pugh Chart

Criteria	Expanding Body	Pendulum -> goes into pipe	Blimp/Weather Balloon	Telescope arms	Hinge propeller	Pipe Body	Air Canon with parachute	Bowl Body (arms slide into)	Airplane	Slingshot	Periodic payload drop	H body swivel	x-8 motor	Props pushing in	Props double as legs	Folding arms	Tri body fold	Falcon with GPS	Dragonfly ornathopter	Spider	Flying Squirrel
Cost	D	+	-	+	-	+	-	+	-	+	-	+	-	s	+	+	+	-	+	+	-
Ease of Build		+	+	+	+	+	-	+	-	+	-	+	s	+	s	+	+	-	+	-	-
Reliability	A	-	s	s	s	s	-	s	+	-	-	s	s	s	s	-	s	-	s	-	-
Efficiency		-	s	-	+	-	-	-	+	-	-	+	s	+	+	s	s	-	+	-	-
Stable	T	+	-	-	+	+	-	-	+	-	-	+	s	-	+	+	+	+	s	-	-
Portable		-	-	-	s	+	-	-	-	+	-	+	-	s	-	s	-	-	-	s	-
Σ+	U	3	1	2	3	4	0	2	3	3	0	5	0	2	3	3	3	1	3	1	0
Σ-		3	3	3	1	1	6	3	3	3	6	0	2	1	1	1	1	4	1	4	6
ΣS	M	0	2	1	2	1	0	1	0	0	0	1	4	3	2	2	2	0	2	1	0

Table 4 – Final Pugh chart.

Criteria	Expanding Body	Modified-Hinge propeller	Pipe Body	Airplane	H Body Swivel	Angled Props	Folding Arms	Tri Body Fold	Modified Dragonfly Ornathopter
Cost	-	-	+	-	+	s	D	-	+
Ease of Build	-	s	+	-	+	s		-	+
Reliability	+	+	s	+	s	+	A	s	s
Efficiency	s	+	+	-	s	s		s	+
Stable	s	s	s	+	-	-	T	-	+
Portable	s	s	+	-	+	+		+	s
Σ+	1	2	4	2	3	2	U	1	4
Σ-	2	1	1	4	1	1		3	0
ΣS	3	3	1	0	2	3	M	2	2

The Pipe Body, H Body Swivel, and Dragonfly Inspired Copter were chosen to be analyzed. These designs and their subsystems are described below.

4.1 Dragonfly Inspired Copter

This design features removable, carbon fiber arrow, dual-boom arms and Jimustanguitar, or repurposed, 3D printed motor mounts. The central hub would be rectangular and consist of carbon fiber arrow skeleton with a lightweight platform to house the electronics. All junctions between the arrow shafts would be 3D printed at Northern Arizona University, minimizing cost. In addition to removable arms, the legs would have the ability to be folded flat against the bottom of the frame. Removable support shafts would be included between arm pairs and between the legs to enhance rigidity and assist with resonant vibration through the shafts. When collapsed, this design would be very compact and flat, minimizing the amount of volume required during transport. A rough sketch of the Dragonfly Inspired Copter can be seen in Figure 15.

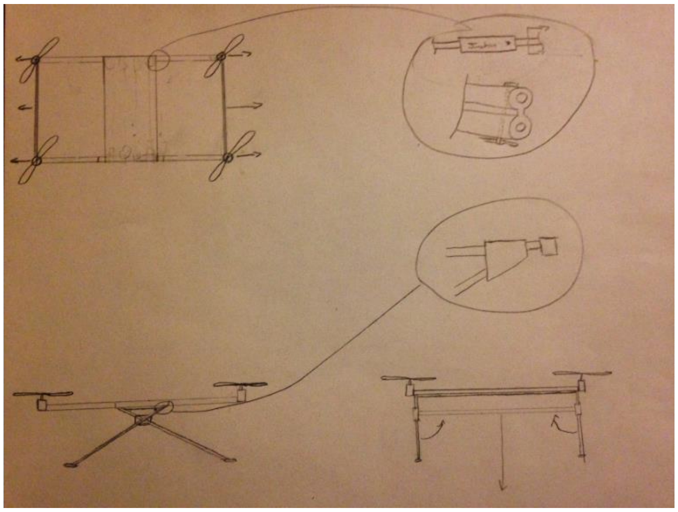

Figure 15 – Dragonfly Inspired Copter sketch.

Pros:

- Compact when collapsed
- Rigid
- Lightweight

Cons:

- Intricate part design
- More expensive

4.2 H-body Swivel

The H-body aspect of this design is not a new concept in the world of multirotors; however, the swivel aspect is a frontier that is still in the preliminary stages. The team's design would allow for the arms to pivot in the x-y plane, which would "fold" the arms towards the center of the quad copter. A schematic of this design can be seen in Figure 16.

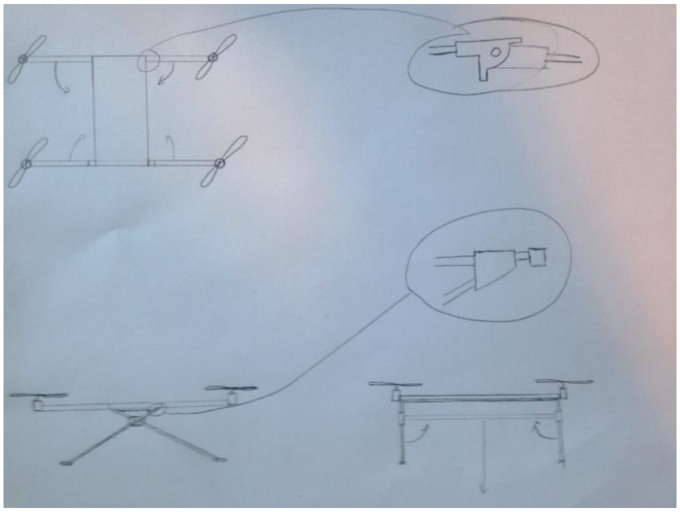

Figure 16 – H-Body Swivel.

Pros:

- Compactable
- Rigid
- Lots of electronics space

Cons:

- Not strong in transport (arms folded)
- Complicated Manufacturing of Hinges
- Heavy
- Exposed Electronics

4.3 Pipe Body

The Pipe Body design is an H-style multirotor where the main “fuselage” of the UAV is a pipe. The pipe houses all of the electronic components, except the motors, and will be the main structure for the UAV. When the multirotor is in transportation mode the arms will be removed from the pipe and by using foldable propellers one will be able to put the arms inside of the pipe body. Putting the arms inside of the pipe will allow for the pipe to double as a protective carrying case for transport. Schematics of this design can be seen in Figures 17-19.

Using a plastic or fiberglass pipe, as found in fishing pole travel cases, will keep the UAV light, rigid, and low cost. This design will protect the electronics in both flight and transport modes. Transport mode, when coupled with friction fit end caps, will enclose all of the gear into a water resistant case, and flight mode, when coupled with said end caps, will enclose all of the electronics in a water resistant package. The UAV is still able to be water resistant in flight mode even though the motors are exposed. The motors are inherently waterproof because they are brushless motors that have thee windings of the motor coated in order to mitigate shorts. Brushless motors have wires that are wound around “poles” which use a magnetic field to move magnets that spin the propeller providing lift.

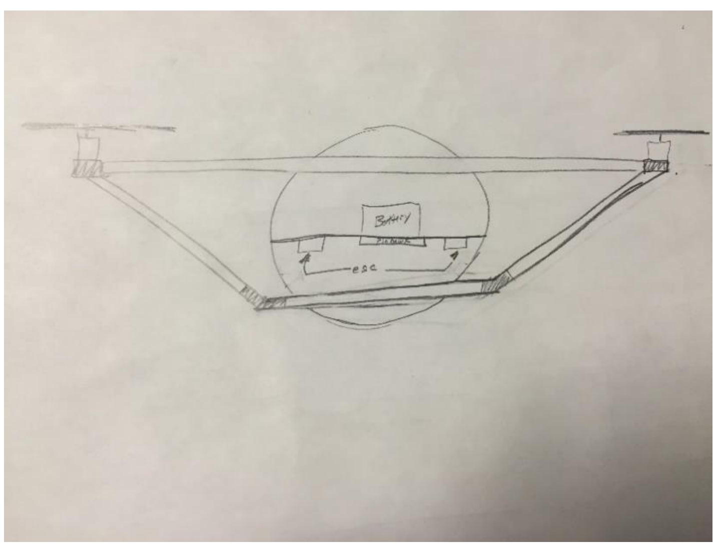

Figure 17 – Front view of pipe body design.

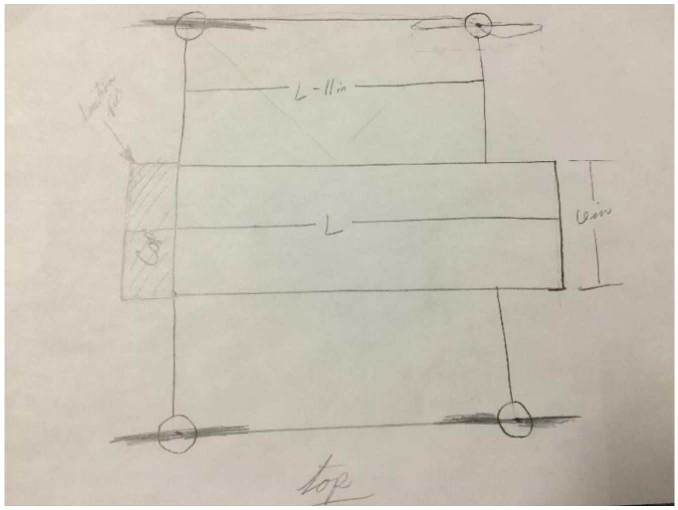

Figure 18 – Top view of pipe body design.

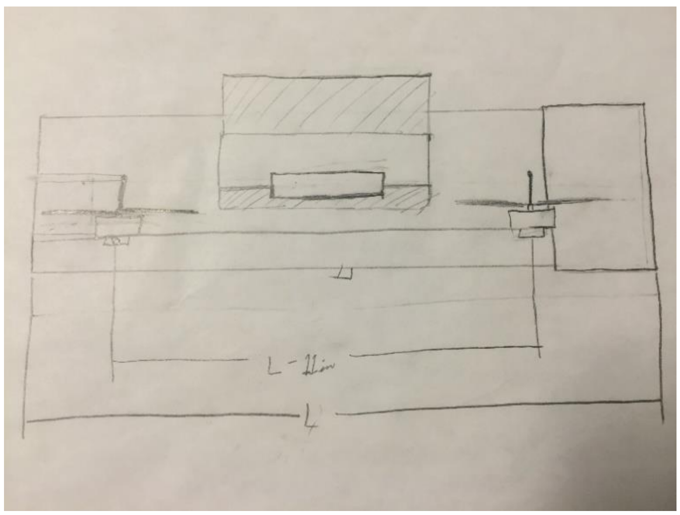

Figure 19 – Side view of pipe body design.

Pros:

- Light
- Strong/Rigid
- Water resistant
- Collapsible
- Packable
- Low Center of Gravity

Cons:

- Electronics not easily accessible
- Specialty brackets
- Less electronic real-estate

5 DESIGN SELECTED

The three highest scoring designs described above were taken to the client for input. A final brainstorming session was performed where old design concepts were combined into a final design. The designs were discussed and combined into a new design that the team chose to model and is presented below. Further changes were made during the implementation process and are discussed in Section 6.

5.1 Rationale for Design Selection

Changing the design of the frame to make it more collapsible, lighter, and more rigid was the end goal. Utilizing a combination of the considered designs, a frame was decided upon by the team in conjunction with the sponsor, Dr. Michael Shafer.

A frame that has multiple layers, such as the FliteTest ElectroHub (Figure 8 in Section 3.2.3), was chosen because it gave the ability to maximize the utility of the quadcopter, design a failure point that could be easily replaced, and increase the rigidity of the frame. This layered design coupled with the dual boom design increases the torsional rigidity and changing the resonance of the frame to mitigate the amount of resonant vibrations. The dual booms reduced the amount of 3D printed joints, which decreased the overall weight of the quadcopter by approximately a half of a pound.

Finally, the manufacturability of the new frame design is much better. Cutting two plates of carbon fiber and 3D printing half the amount of parts decreases the build time. The ability to build a frame have fewer parts in less time will save greatly on money; money is lost in manufacturing *and* when the quadcopter is unable to fly because a part that was not taken to the field becomes broken in transit.

5.2 Design Description

The final design takes aspects of the previous designs and ideas that came about from the benchmarking stated previously.

A dual Carbon Fiber Arrow Shaft arm design (Figure 20), from the first considered design will be utilized to keep the weight low and increase the torsional rigidity of the arms; the downfall of the previous iterations. The dual booms also solve a resonance issue that the motors induced on previous iterations by limiting the movement of the torsional and vertical degrees of freedom.

To reduce the overall weight of the quadcopter and keep the overall rigidity of the frame, a layered design was implemented. Two carbon fiber plates 2 – 3 mm thick will be placed horizontally and 3 inches apart. The plates will be supported by a cylindrical 3D printed tube, which will house the PixHawk flight controller and the receptacles for the arms, as well as either aluminum or plastic stand offs (Figure 20).

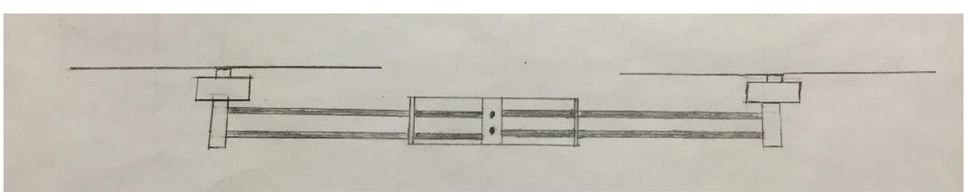

Figure 20 – Sketch of Dual Boom/Dual Plate design.

The standoffs will also be able to hold supports that will give another point of contact for the arms to be supported. These standoffs will be needed in order to transfer the forces properly through the carbon fiber plates that make up the majority of the frame's strength.

A larger power system will be fitted to increase the power to weight ratio. This increase in power to weight ratio is needed to handle the longer duration flights that will occur for collecting the needed data to track the bats. This power system includes a lower kV motor that will allow for a larger propeller to be use, Electronic Speed Controllers with a higher amperage rating to handle the higher voltage battery (14.8 Volts or 4S), and a larger capacity battery to help accommodate the longer duration flights.

The prototype built (Figure 21) showed some flaws in the rigidity between the upper and lower plate. Adding the standoffs at the vertices of the octagonal plates will greatly increase the stiffness of the quadcopter and increasing the support at the outer edges of the plates will spread out stress that would normally by focused at the central hub where the booms are attached. These standoffs are a relatively cheap way of increasing the stiffness/rigidity to handle the amount of flight times and forces the frame will be subjected to in the event of a crash.

Figure 21 – Prototype of final design.

6 IMPLEMENTATION

Implementation issues forced the design to go through significant changes. Section 6.1 outlines Design A, which was the design that was selected for prototyping. This design was submitted to the client and, after some deliberation, a new boom and central-hub design were developed. This new design (Design B) is described in Section 6.2. Motor mounts were then modified from past designs. This process is outlined in Section 6.3 and the overall manufacturing process is described in Section 6.4. Finally, a design of experiment was created to test the torsional stiffness of the arm configurations between the two iterations. The test plan is outlined in Section 6.5.

6.1 Design A

Design A was the first design selected to be modeled in SolidWorks and was based off the prototype shown in Figure 21 in Section 5.2. This design utilized a dual cantilever beam design as the booms, and a central hub to contain all the electrical components. This SolidWorks model can be seen in Figure 22.The main complication of this design was the central hub. Efforts were made to minimize the mass of the hub without affecting the structural integrity. The central hub is modeled in Figure 23. This model allowed the team to make some preliminary calculations of the weight of the frame as a whole. These calculations created some concerns about the force distribution through the booms from the thrust required to maintain a 2:1 thrust to weight ratio. The standoffs between the plates were designed to double as supports for the booms. This added unexpected weight to the design.

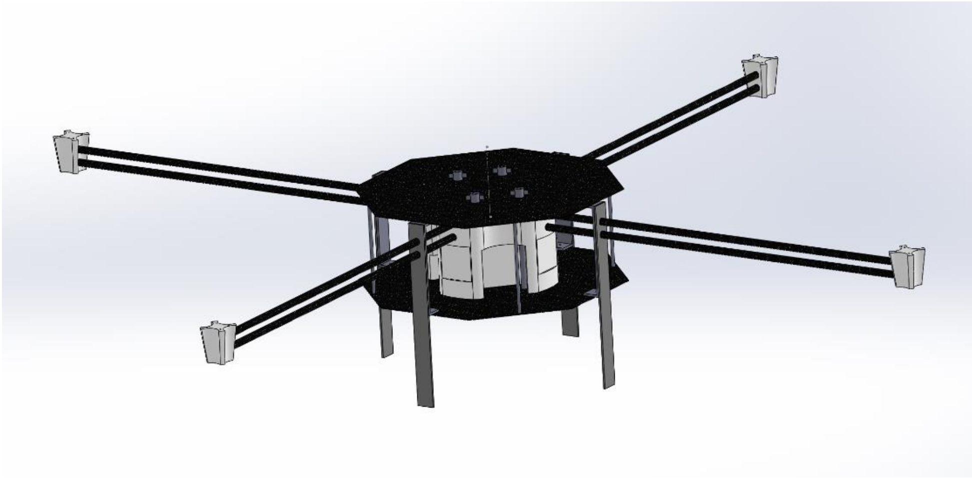

Figure 22 - Design A assembly.

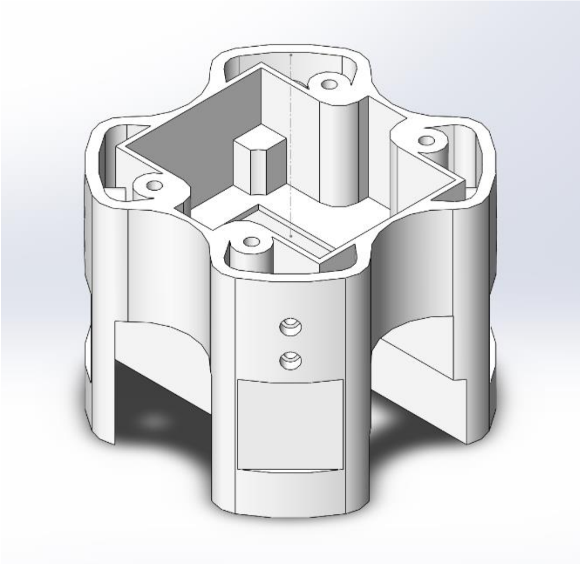

Figure 23 - Design A central hub.

6.2 Design B

After discussions with the client, it was decided that the boom configuration would be more appropriate with a truss design than a cantilever beam design. This decision was made due to the need to use carbon fiber arrow shafts as the frame material. The truss design would eliminate the need for the standoffs between the plates. This design also allowed for both carbon fiber plates to be reduced in size which significantly decreased the cost and weight of the design. The central hub was lengthened to compensate for the new truss design and increased in diameter to allow the battery to be completely enclosed. The revised assembly and central hub can be seen in Figures 24 and 25, respectively. The carbon fiber plates have been hidden in Figure 24 to display details of the inner compartment.

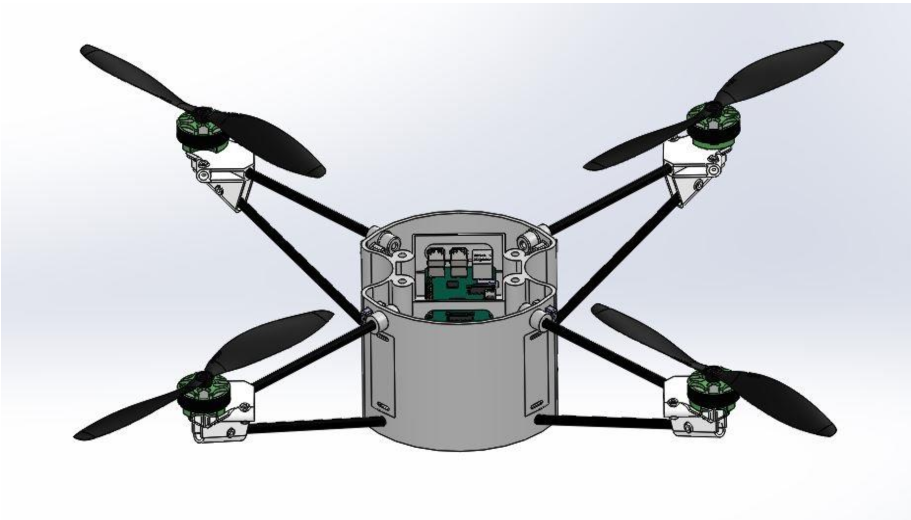

Figure 24 – Design B assembly.

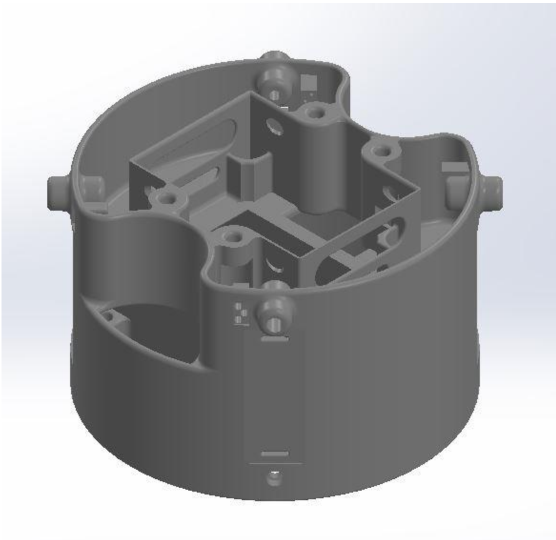

Figure 25 – Design B central hub.

6.3 Motor Mounts

The motor mounts in Figure 26 were taken from Iteration 3. A few changes were made to them in order to fit into our design. The lower arm mount was elongated downward in order for the lower arm to reach the mounting hole. Next, the hole to pin the lower arm in place was moved upwards, this allows the lower arm to be folded when removed from the multirotor. Finally, fillets were placed on every edge to allow for a stronger part when manufacturing via 3D printing. The motor mounts were designed such that each carbon fiber arrow was the same length, 21cm (8.3in), easing the manufacturability of each boom.

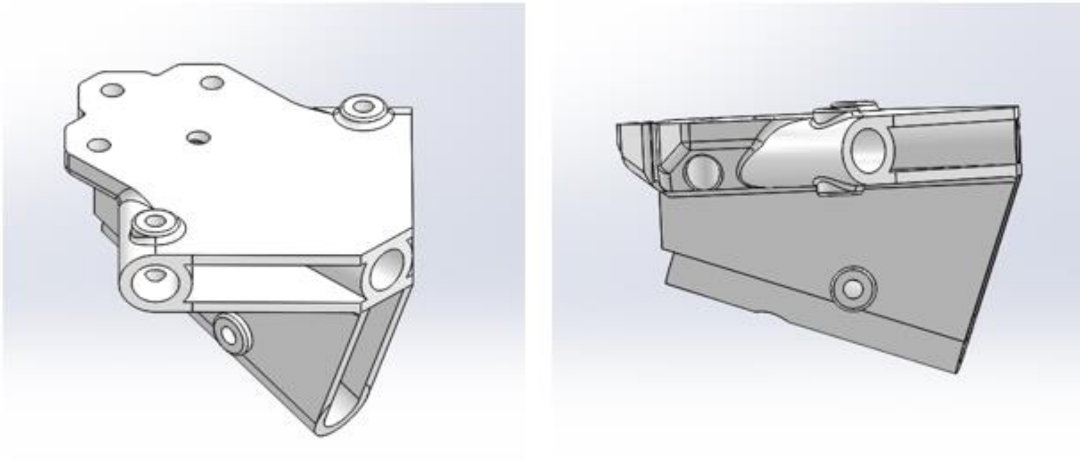

Figure 26 – Redesigned motor mounts.

6.4 Design of Experiment

A Design of Experiment (DOE) was set up to test the torsional rigidity of the arm configuration. Three variables were tested to determine the best setup; arm length, arm angle, and lateral support. Each variable was tested in a high (+) and low (-) configuration. Details of the variables and configurations can be seen in Table 5.

Table 5 - DOE variables and configurations.

Variable	High Configuration (+1)	Low Configuration (-1)
Arm Length	8.3 inch booms to make the max propeller size 14 inches	Longer 10 inch booms to increase the max propeller size to 16 inches
Arm Angle	Lower arm will create a 70 degree angle with the central hub (from vertical)	Parallel boom configuration of Design A; the booms go from the Central Hub to the Motor Mounts at an angle of 90 degrees from the vertical (Section 6.1)
Lateral Support	Lateral supports will be added between the adjacent Motor Mounts (i.e. supporting cross members between booms)	Lateral supports will be removed between the adjacent motor mounts so there is no additional lateral support

Each possible arm configuration was set up (8 total configurations) and a 1 kg weight was attached to the motor mount laterally to create a torque on the arm setup (Figure 27). The resulting deflection at the edge of the motor mount was recorded for each test to determine the optimal setup. It is worth noting that the two tests with 90˚ boom orientation and lateral supports were not able to be tested without a significant time investment by the rapid prototyping lab. To test the lateral supports, a central hub with at least two booms was needed. To attain the parallel boom setup, the booms were placed into a test print of ¼ of the Design A hub and tested the same. The DOE results can be seen in Table 6.

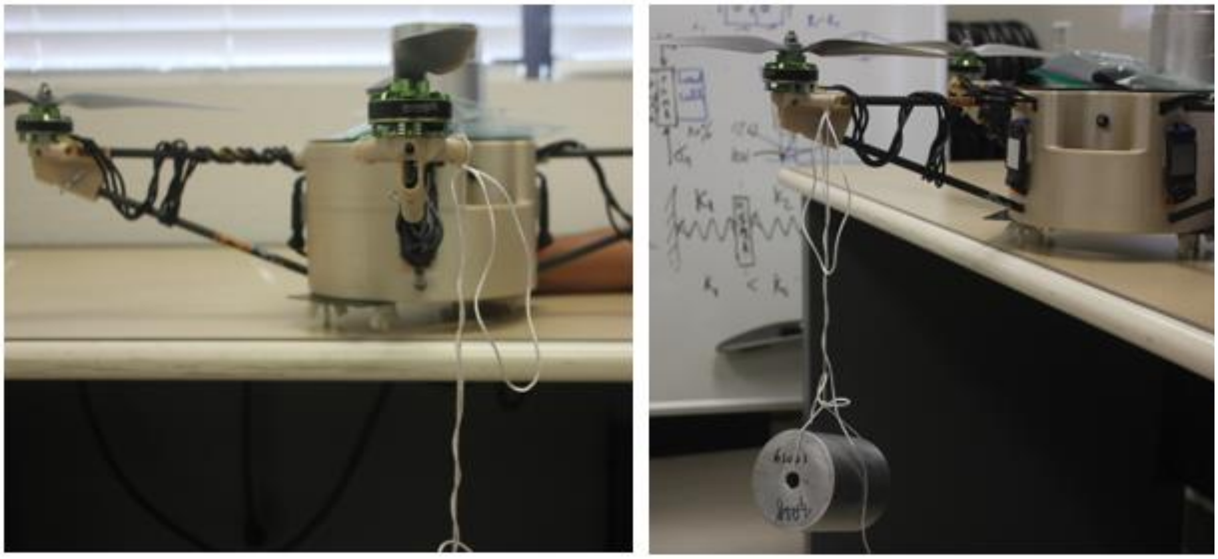

Figure 27 – DOE test setup.

Table 6 – DOE results.

Trial	Description	X1 – Boom Length	X2 – Boom Angle	X3 – Lateral Boom Support	Y1(d)
1	D_1 - long Boom, No angle, no support	-1	-1	-1	4 mm
2	D_2 - short boom, no angle, no support	+1	-1	-1	4 mm
3	D_3 - long boom, 70˚ angle, no support	-1	+1	-1	3 mm
4	D_4 - short boom, 70˚ angle, no support	+1	+1	-1	3 mm
5	D_5 - long boom, no angle, with support	-1	-1	+1	-
6	D_6 - long boom, no angle, with support	+1	-1	+1	-
7	D_7 - long boom, 70˚ angle, with support	-1	+1	+1	1 mm
8	D_8 - short boom, 70˚ angle, with support	+1	+1	+1	1 mm

The above results showed that the optimal configurations were both of the angled boom configurations with the supports in place. However, the deflection was acceptable without the supports in place and the repurposed motors did not have the power to accommodate 16 inch propellers. Therefore, it was decided that the optimal boom setup was D_4.

6.5 Manufacturing

Once the above hub and motor mount designs were finalized, they were 3D printed using PPSF plastic. Three materials were readily available for printing; all-temp, PPSF, and ABS plastics. The PPSF material was chosen due to its material properties. Its melting point is lower than the all-temp but it has the same strength whilst only increasing the weight of the components by approximately 25%.

Once printing was complete, assembly was started. The arrows were cut into eight pieces at 8.3 in. length for the boom assembly. Threaded metal inserts were then epoxied into one end of each arrow (Figure 28) and nylon inserts were epoxied into the other end before setting them aside to cure. The metal inserts were added to attach each arrow to the central hub (Figure 29) while the nylon was added to increase the cross-sectional area of the ends that needed to be drilled through. The arrows were then slid into the motor mounts and the cotter pin holes were drilled for assembly. The assembled motor mount/boom assembly can be seen in Figure 30. The entire assembly was then attached to the central hub.

Figure 28 – Threaded metal inserts.

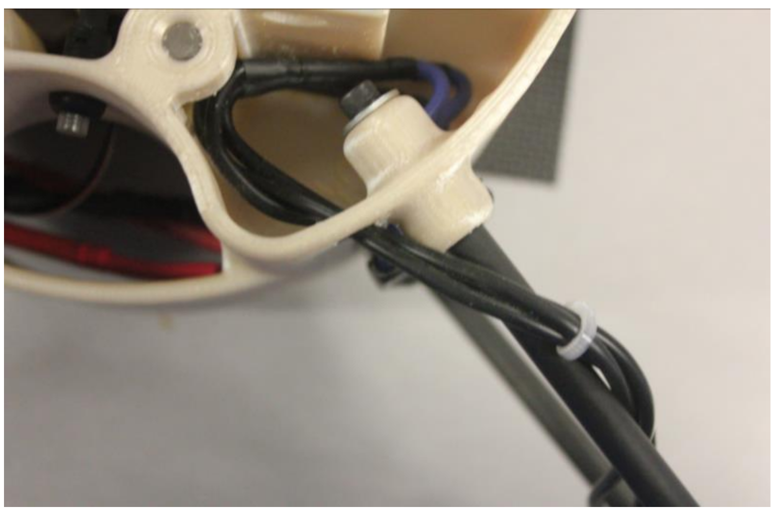

Figure 29 – Boom attachment setup

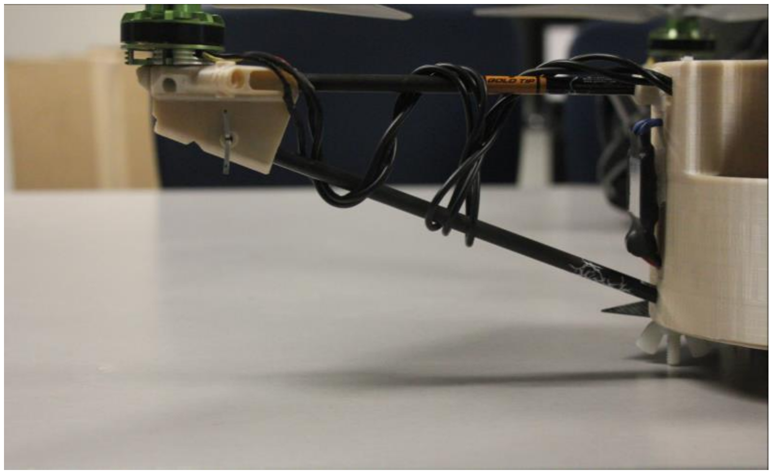

Figure 30 – Motor mount/boom assembly.

The carbon fiber plates were purchased in square pieces and then machined to fit the top and bottom shapes of the central hub. Nylon bolts were also purchased and then fit into their designated bolt holes on the bottom of the central hub. These bolts were used to secure the bottom plate to the central hub, enclosing the battery and wiring. The top plate was attached using ¼ inch neodymium magnets. With all of the frame components assembled, the team then transferred the electrical components that were used in Iteration 3 to this UAV. The final assembly of Iteration 4 and a complete bill of materials for the frame components can be seen in Figure 31 and Table 7, respectively. The schedule for the implementation can be seen in Table 8.

Figure 30 – Iteration 4 completed assembly.

Table 7 – Final bill of materials.

Component	Description	Quantity	Price ($)	Total ($)
Carbon Fiber Plate	(200 x 500 x 1)mm plate for top and bottom plates	1	31.98	31.98
Magnets	Fastening system for top plate	1	13.53	13.53
Carbon Fiber Arrow	Booms (arms) for UAV	4	5.34	21.36
Nylon Bolts and Nuts	Nylon hardware for fastening bottom plate	6	1.42	8.50
Epoxy	Epoxy to set inserts and finish arrow ends	1	5.44	5.44
Velcro	Velcro for mounting ESC's and other electronics	1	3.24	3.24
Arrow Inserts	Inserts for mounting arrows to central hub	12	0.82	9.81
			Total	**93.86**

Table 8 – Implementation schedule.

WBS	Tasks	Task Lead	Start	End	Duration (Days)	% Complete	Working Days	Days Complete	Days Remaining	18 - Jan - 16	25 - Jan - 16	01 - Feb - 16	08 - Feb - 16	15 - Feb - 16	22 - Feb - 16	29 - Feb - 16	07 - Mar - 16	14 - Mar - 16	21 - Mar - 16	28 - Mar - 16
1	**Modeling**		2/1/16	3/5/16	34	0%	25	0	34											
1.1	Design A		2/1/16	2/16/16	16	0%	12	0	16											
1.2	Design B		2/17/16	3/5/16	18	0%	13	0	18											
2	**Frame Construction**		3/21/16	3/31/16	11	0%	9	0	11											
3	**DOE**		4/3/16	4/4/16	2	0%	1	0	2											

7 TESTING

The testing procedures outlined in Section 2.3 were completed and compared to the targets with tolerances in the HoQ (Section 2.5). Results are summarized in Table 9. Details for each test can be found in the following sections.

Table 9 - Testing summary.

Test	Outcome
Weight	Fail
Thrust	Pass
Drop	Pass
Torsion	Pass
Max Load and Fatigue	Ambiguous
Volume	Pass
Center of Gravity	Pass
Low Cost	Pass
Flight	Pass

7.1 Weight

The frame was assembled and weighed without electronics. The total weight was found to be 1.31 lb (595 g). The target weight was 1 lb (454 g) or less, yielding a final weight which was 31% heavier than desired. This test was failed but there are several places within the central hub and motor mounts where additional weight can be removed. The motor mounts could be printed using ABS plastic instead of PPSF. This would remove approximately 0.1-0.2 lb. The rest of the weight could be cut from within the central hub via windows and ports designed into the inner walls.

7.2 Thrust Test

A single motor and propeller were tested as described in Section 2.3. The test setup can be seen in Figure 32. The motor tested produced 1.2 kg of thrust, yielding a total thrust of 4.8 kg for the entire UAV. The total weight of the UAV with electronics was found to be 1.63 kg, yielding a power to weight ratio of 2.95. This is well above the desired 2:1 power to weight ratio.

Figure 31 – Thrust test setup.

7.3 Drop Test

The UAV frame (with electronics) was dropped from 2 ft and 4 ft to replicate a crash landing. No damage was sustained from either test.

7.4 Torsion

The torsion test was outlined in the DOE (Section 6.4). A flight test was also performed to determine torsional stiffness and is covered in Section 7.9.

7.5 Max Load and Fatigue

This test was intended to find the weakest frame component by loading the arms until something breaks. However, due to the low budget associated with this project, this test was not conducted. Funds were not available to replace parts broken during the test.

7.6 Volume

Each component was modeled as a simple geometric shape using its outermost dimensions to determine the total volume of each. The central hub was modeled as a cylinder with a diameter of 19 cm and a height of 11 cm. Each arm was modeled as a rectangular prism with dimensions of 6 cm x 4 cm x 23 cm. These dimensions yielded a total volume of 5.33 L which was lower than the target volume (25 L) by a factor of 4.7.

7.7 Center of Gravity

The frame was modeled in SolidWorks to determine the center of gravity. The CG was found to be 0.61 cm below the geometric center for the frame alone. The battery and antenna are both mounted at the bottom of the central hub, dropping the CG further. The results can be seen in Figure 33.

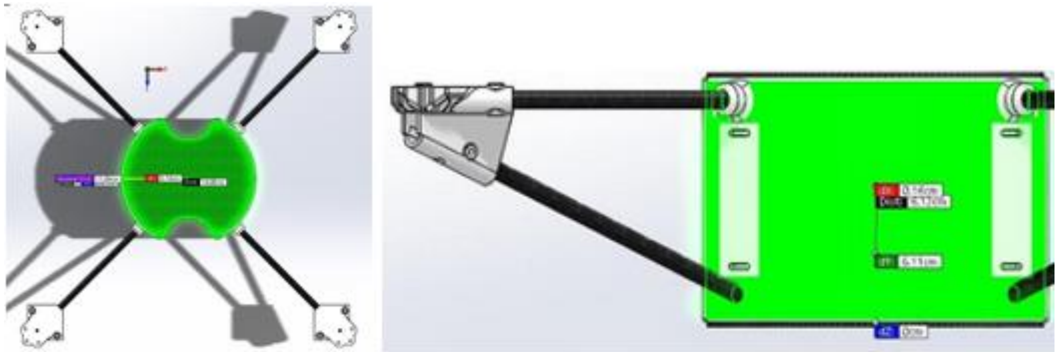

Figure 32 – CG SolidWorks model.

7.8 Low Cost

As previously mentioned, this project had an extremely low budget, making the low cost requirement inherent to the design. Total cost of the frame was $93.86 (Table 7) which was lower than the $250.00 target by a factor of 2.66.

7.9 Flight Test

A flight test was performed and deemed successful for all maneuvers performed. The high power to weight ratio allowed the UAV to hover at less than 50% throttle but a timed test was not performed. The pre-programmed flight was a feature of the flight controller used from Iteration 3. Tests were previously performed successfully with this iteration nut not with the current iteration.

8 CONCLUSIONS

As defined by the project description, the team was to redesign the frame of the previous drone iteration to make it lightweight, rigid, collapsible, and have a low center of gravity. The team completed Iteration 4 by salvaging the electrical components from Iteration 3 and creating a central hub focused design to minimize weight. Although the drone did not pass the weight test, exceeding our goal by 0.3 lbs, it passed the all other tests and drew admiration from our client. This leads the team to believe we completed our mission.

The manufacturing process and product quality were the most positive aspects of the project. Extensive effort went into the modeling stage of the design process, so in the manufacturing process there were minimal obstacles to overcome. Additionally, since the central hub design went through numerous iterations and thorough analyzation the final product was high quality. However, the team did struggle with time management and staying on schedule because of budget uncertainty. This budget uncertainty was the only negative aspect of the project.

Although the budget was the only negative aspect of the project, the team did experience additional problems throughout the project. For example, the first full prototype of the frame was printed out of PPSF which is denser than ABS, the team's original material choice. This material selection added unnecessary weight to the design and was too brittle for our applications. This created some issues during the manufacturing process and required the team to reprint the central hub for the final design. Additionally, the team experienced issues when we outsourced the manufacturing of our carbon fiber cover plates. We provided the parasolid model to the shop, expecting them to map the HAUS coding based off the two separate cover plates. However, the bottom plate was model off of the design of the central hub's top, which produced holes in the wrong locations. Since the group did not have a budget and all the material was used in manufacturing those plates, the team had to retrofit the bottom plate to work with the design.

The organizational actions that could have been taken to improve the team's efficiency were improvement in communication and holding more frequent meetings. However, the team learned a more valuable technical lesson that will improve productivity in the future. A large portion of the issues experienced during the manufacturing process were due to miscommunications and the team not being specific enough when outsourcing our manufacturing. The team learned they must be very clear with the specifications of parts being manufactured.

Through all the problems, the team completed a successful design that will serve as a baseline model to be updated and improved in future iterations. During these future projects additional features will be added to make the drone more efficient in the field. One of these features could be an emergency parachute in case of power loss during flight. Another feature could be a slide in boom configuration and bottom plate, this would alleviate the need to secure these parts with screws or wing nuts. These features along with others are going to bring this design closer to being field operational.

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