PENN STATE

Department of Mechanical and Nuclear Engineering

Final Report
Vertical Take-Off and Landing UAV for Military Applications

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Intellectual Property Rights Agreement- No
Non-Disclosure Agreement- No
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Executive Summary

Sikorsky tasked the group with designing and building a proof of concept prototype for a vertical take-off and landing (VTOL), unmanned aerial vehicle (UAV). The vehicle design and prototype must meet customer needs such as, ability to protect the aircraft's hardware, endure rigorous environments, and be compact for ease of transport. The UAVs main purpose will be for military applications. Sikorsky wants it to have a durable build so that it can withstand the harshest of environments, fly its own pre-planned mission, the ability to be transported easily, and have quick maintenance capability in the field.

To achieve each of these goals, the followed a detailed design process. The process started with research into different options for the vehicle itself. Currently, various final designs are being considered and proposed to the sponsor. Once a final design concept has been selected, manufacturing and testing of the prototype will be performed.

The detailed design report that follows will examine customer needs, state the problem the group will solve, and show early concept and design generation. A timeline is presented to complete various objectives. Charts and pictures showing the thinking behind the designs, and a preview of the model is also presented. Finally, this report provides the next steps that will be taken to create a working prototype of a VTOL UAV for military applications.

Contents

1.0 Introduction

1.1 Initial Problem Statement

Sikorsky is interested in creating a prototype Vertical Take-off and Landing (VTOL) Unmanned Aerial Vehicle (UAV) that could be used in military applications. However, current UAV designs lack the level of durability and reliability that is necessary for such applications. With this in mind, Sikorsky has provided the task of creating a functional VTOL UAV that could operate effectively in hostile environments. This UAV should be able to conduct advanced flight mission tasks (i.e. loitering), be easy to use, and have a significant focus on a rugged airframe design.

1.2 Objectives

The prototype design will demonstrate a fully functional UAV quadcopter that has the ability to conduct flight missions. The prototype must be easy to operate. The prototype will feature an optical element, allowing it to carry an on-board camera to monitor its surroundings. The majority of the airframe design will be constructed using carbon fiber to ensure a lightweight and durable assembly. The airframe will be inspired by that of the Tarot carbon fiber 600mm quadcopter airframe. This will provide an excellent initial design and help to generate ideas that will lead to a unique and rugged airframe that fulfils the goals set forth by Sikorsky.

2.0 Customer Needs Assessment

2.1 Gathering Customer Input

The team communicated with the project sponsors to help determine the most important attributes for the UAV quadcopter. These customer needs do not include the minimum requirements needed for the UAV to fly such as a flight controller, battery, speed controllers, motors, propellers, wiring for electronic parts, radio transmitter and receiver.

2.2 Weighting of Customer Needs

The team created an analytic hierarchy process (AHP) shown in Table 1, to weigh specific needs from the project sponsor for the UAV. It is important for the team to weigh the importance of the customer needs when considering the overall design and how to fit the most important needs into the budget. How the table works is each row has a customer need that is given an importance determined by the team and the feedback received from the project sponsor, relative to each other need by column. For example, the robust airframe in row 1 was given a value of 8 in column 8, meaning it is between strongly and extremely more important than the infrared camera. The Total column is the sum of all the values determining relative importance for each customer need. A higher total number gives more importance to the customer need. The weight of each need was also calculated from the sum of the total column divided by the number of customer needs that are listed.

Table 1: AHP Pairwise Comparison Chart to Determine Weighting of Important UAV Attributes

Customer Needs	Robust	Portable	Modular	FPV	Operate	GPS	Survey	Infrared	Total	Weight
Robust Airframe (impact resistance in harsh enviornment)	1	1	3	6	2	4	4	8	**29**	**0.203**
Portable (easy to carry/light)	1	1	3	6	2	4	4	8	**29**	**0.203**
Modular (replaceable parts)	1/3	1/3	1	4	1/3	3	3	8	**20**	**0.14**
FPV camera for flight (manual control)	1/6	1/6	1/4	1	1/3	1/4	1/4	8	**10.4167**	**0.073**
Easy to operate (minimal training needed)	1/2	1/2	3	3	1	2	3	8	**21**	**0.147**
GPS (for automated flight)	1/4	1/4	1/3	4	1/2	1	3	8	**17.3333**	**0.121**
Camera for surveillance	1/4	1/4	1/3	4	1/3	1/3	1	8	**14.5**	**0.101**
Infrared Camera	1/8	1/8	1/8	1/8	1/8	1/8	1/8	1	**1.875**	**0.013**
									143.125	1

Key:
1 = Equally important — **red = Airframe structure**
3 = Moderatly more important — **yellow = Electrical & flight control**
5 = Much more important — **green = Militarized applications**
7 = Strongly more important
9 = Extremely more important

3.0 External Search

3.1 Existing Products

Most of the major UAV drones readily available in the market serve the filmmaking and the agricultural industry. Currently, DJI is one of the leading manufacturers of drones that manufacture the Phantom 4, Mavic Pro, Matrice and others. Most drones cost between $1000 to $6000 and come with advanced features like return to home, anti-collision and can carry increased payloads.

Drones like Mavic Pro and Phantom are designed for general consumer market and therefore focus on the increased flight time and better picture/video recording features [1]. Some drones like Matrices focus on the enterprise market and therefore design the drone for surveillance purposes. They are more rugged and allow a more versatile payload.

UAVs can be used for a set of applications but due to the limited weight and flight duration, UAVs make trade-offs between speed, flight time and payload acceptance to complete the desired task.

Figure 1. Existing UAVS on the market; DJI Phantom 4 (left) and DJI Martice 600 Pro (right)

4.0 Engineering Specifications

4.1 Establishing Target Specifications

The UAV will be able to fly for 20 minutes for a standard payload. The frame and the propeller guards will handle minor accidents and the UAV, using Mission Planner Software and an on-board GPS, can complete pre-planned missions. The First-Person View (FPV) camera will enable easy handling and will provide a panoramic view. The UAV will have an on-board camera with live feed for surveillance and recording purposes.

5.0 Concept Generation and Selection

5.1 Problem Clarification

Upon receiving the project to create a robust military aircraft, the team used a flow process diagram to clarify the problem and more fully understand it. As illustrated in Figure 2, the team used a flow chart diagram to identify problems of designing, prototyping and testing a UAV quadcopter into the various components: the airframe, materials, propulsion, and electronics. This enabled the team to begin brainstorming and considering all possible options in terms of raw materials.

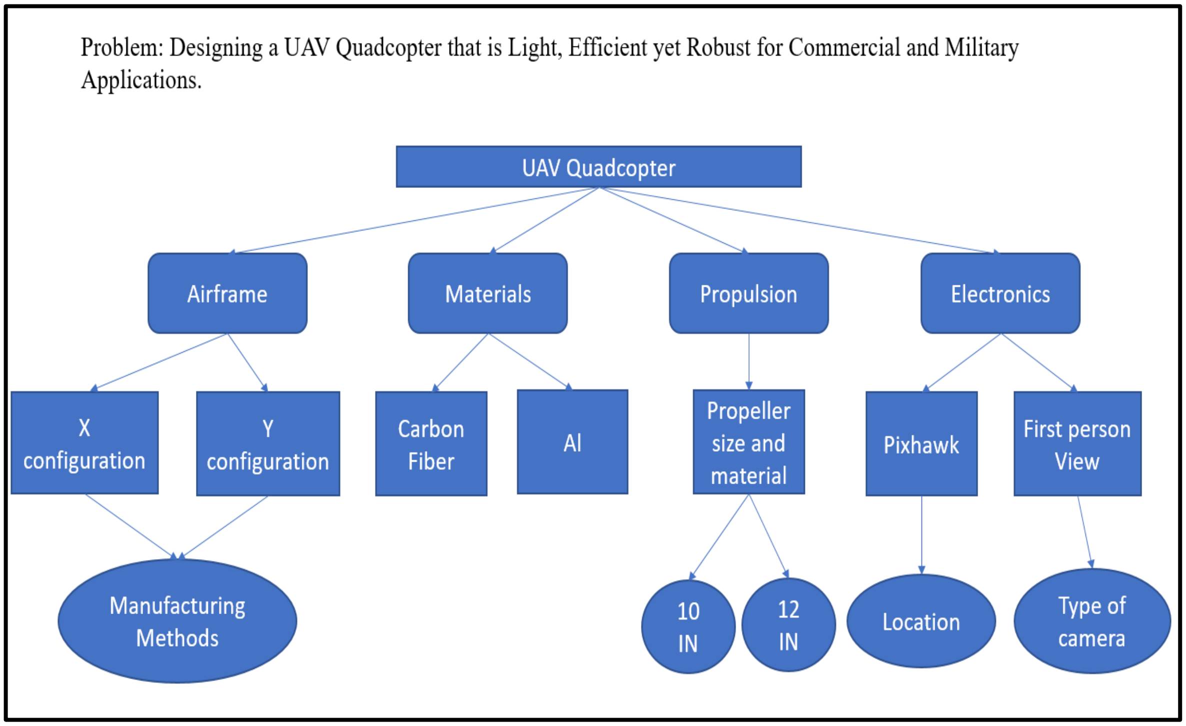

Figure 2. Flow Chart Identifying Problem and Key Characteristics

5.2 Concept Generation

The Sikorsky design team began brainstorming ideas after meeting with sponsor representatives and an initial design review. The robust airframe was paramount to the overall design. As shown in Figures 3 and 4 designs included several iterations. Initially the team considered several different materials, specifically aircraft grade aluminium, and fiberglass due to the low cost and machinability. The team decided to investigate an aluminium airframe first, as shown in Figure 3. From a design standpoint, the model looked acceptable, but upon further stress and weight analysis it was concluded that an airframe weighing in excess of 3 lbs was not feasible for the given scope. The team consulted with Brennan Holderman, a graduate student working on Lidar aircraft in the Forest Resource Laboratory for suggestions and experience [2]. After meeting with Mr. Holderman the Sikorsky team decided carbon fiber was a better material in regards to strength, mass and affordability. Considering tooling costs for aluminium, carbon fiber costs are virtually the same. The team then performed a redesign in SolidWorks with carbon fiber materials, shown in Figure 4. The Sikorsky team will buy carbon fiber in 6 x 6 in sheets and 1/2 in tubes and CNC waterjet cut the desired design from the SolidWorks files after they have been finalized.

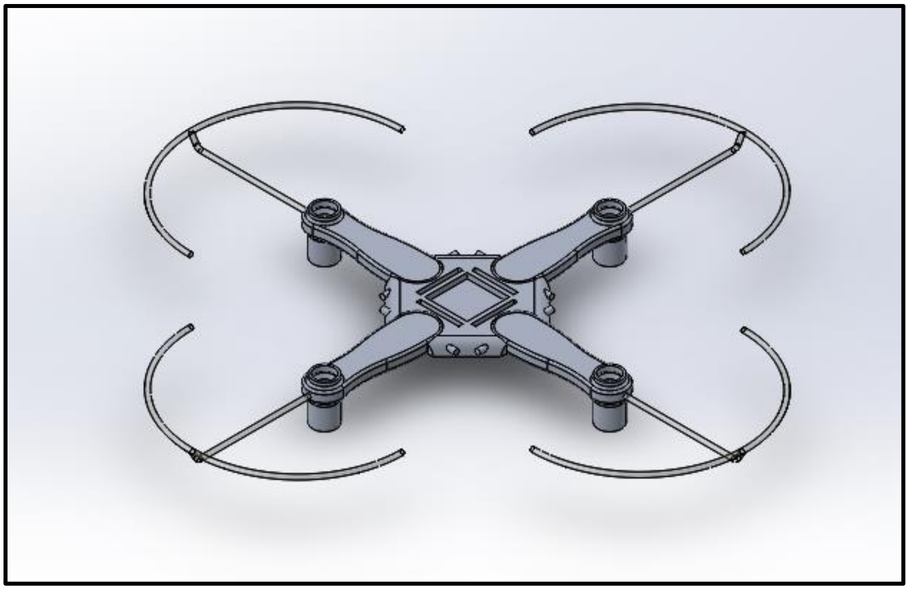

Figure 3. Preliminary SolidWorks Assembly of the UAV aluminium design

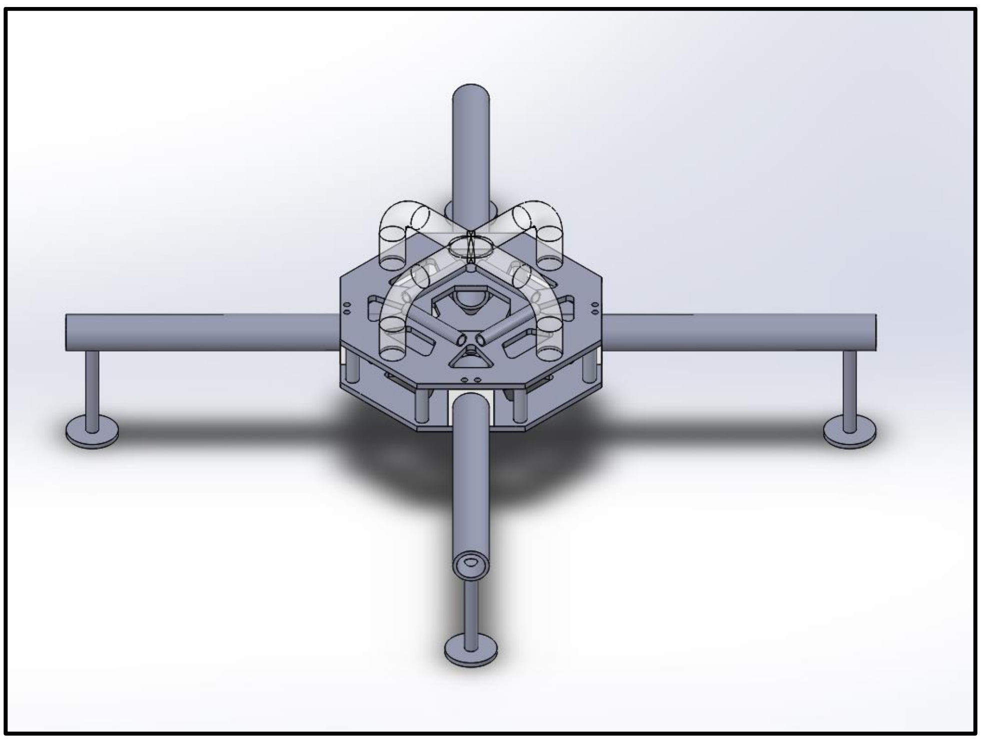

Figure 4. Carbon Fiber SolidWorks Assembly

5.3 Concept Selection

Initially, iterative designs were made in SolidWorks utilizing aluminium for the frame material. Later after meeting with Mr. Holderman the team began investigating carbon fiber [2]. When compared, the carbon fiber design, and the material itself, were superior to the aluminium design in cost, strength, weight, manufacturability, ease of repair, and the frame design was simplistic yet robust. In the end, the carbon fiber material and design were chosen to be used in the final product. Table 2 documents the scoring chart used to determine material/concept selected.

Table 2: Pugh Concept Scoring

		Concepts			
		Aluminium (ref)		Carbon Fiber	
Selection Criteria	Weight	Rating	Wgtd. Score	Rating	Wgtd. Score
Strength	0.15	**3**	0.45	4	0.60
Ease of Use	0.11	**3**	0.33	4	0.44
Ease of Mfg.	0.14	**3**	0.42	5	0.70
Cost	0.18	**3**	0.54	4	0.72
Weight	0.25	**3**	0.75	5	1.25
Portable	0.07	**3**	0.21	**3**	0.21
Repairability	0.10	**3**	0.30	4	0.40
	Total Score		3.00		4.32
	Rank		2		1
	Continue	No		Yes - Prim. Dsgn	

Relative Performance	**Rating**
Much worse than reference	1
Worse than reference	2
Same as reference	3
Better than reference	4
Much better than reference	5

6.0 System Level Design

For the project, the team has decided to focus on specific parts of the design to meet customer goals. The focus will be on protecting important parts of the aircraft's hardware, durability, and ability to be packed away. The team is designing a new airframe with protective guards around the hardware in the event of a crash, sturdier landing legs, and foldable arms. Improvements to the quadcopter design will add increased mission capability to permit use in military applications. By using carbon fiber as the main material, the drone will not be damaged or break as easily in the field. It will also be simpler to pack away in a bag for soldiers on the move. These design changes will be described in Section 6.1.

6.1 3D SolidWorks Model

The 3D model below represents the new airframe design that the team will manufacture using carbon fiber sheets and tube. The carbon fiber sheets are modelled as an octagonal shape to take advantage of using space more horizontally to store electronics rather than stacking devices (A). These pieces have various shaped holes in them to reduce weight where the material is unnecessary. This will help to increase flight time considering weight can significantly affect battery life [3]. Connecting the two sheets are simple screws that will allow for hardware to be stored in the middle protected from outside damage. On top of the airframe is a plastic covering (B). This covering will protect the electronic systems on the top of the airframe in the event of a crash, roll over, and some weather effects. The dome will be 3D printed for this project, but it will be recommended the customer have it made from a plastic mold. The other major design changes represented are the new landing legs (C). These will be manufactured using carbon fiber tubing and attached to the arm near the rotors. Many quadcopters use plastic landing legs under the center of the body. However, the team feels this outboard leg design will allow for better stability during landing and crashes, as well as having a sturdier material than plastic. For easier transport, the landing legs also fold upward towards the quadcopter arm. Other parts represented in the design such as screws, clips and the arms will be modified parts from a Tarot Quadcopter kit. Other modifications include a motor guard on the end of the arm (D), arms that have the ability to fold for easier packaging, and the ability to run the wiring and electronic speed controllers (ESCs) through the arms rather than along their outside. The motor guards, will protect the wiring from the motor as it enters the arm. See Section 8.5 for detailed images.

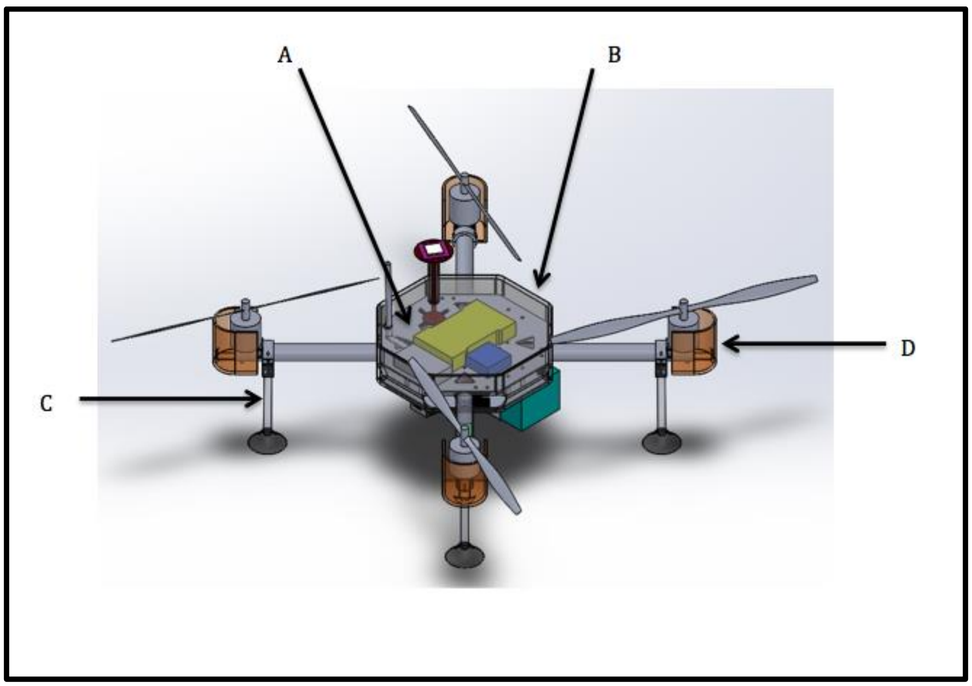

Figure 5. SolidWorks assembly of the VTOL UAV

7.0 Special Topics

7.1 Preliminary Economic Analyses

The estimations of the budget currently full under the $1000 limit. As expected, the majority of the budget is estimated to go towards the materials to build the quadcopter, approximately 60% of the budget. Table B1 describes the budget estimates for each category of expenditure, and Table B2 contains the bill of materials that make up the material costs, split into raw materials and electronics categories.

7.2 Project Management

To complete the project, the group was split into teams, each focusing on a particular sub-system. This way, each group could be an expert on their topic, given the size of the overall project. The groups are manufacturing, propulsion, and electronics. Each member was placed in their group based on their technical skills to ensure everyone was able to function within their designated sub-system. Management is delineated to all members so that everyone is held accountable by the others for their work and for deadlines. Figure 2 provides a Gantt chart for the project. All sequential and parallel tasks are listed, and it is updated as deadlines change and new tasks become apparent.

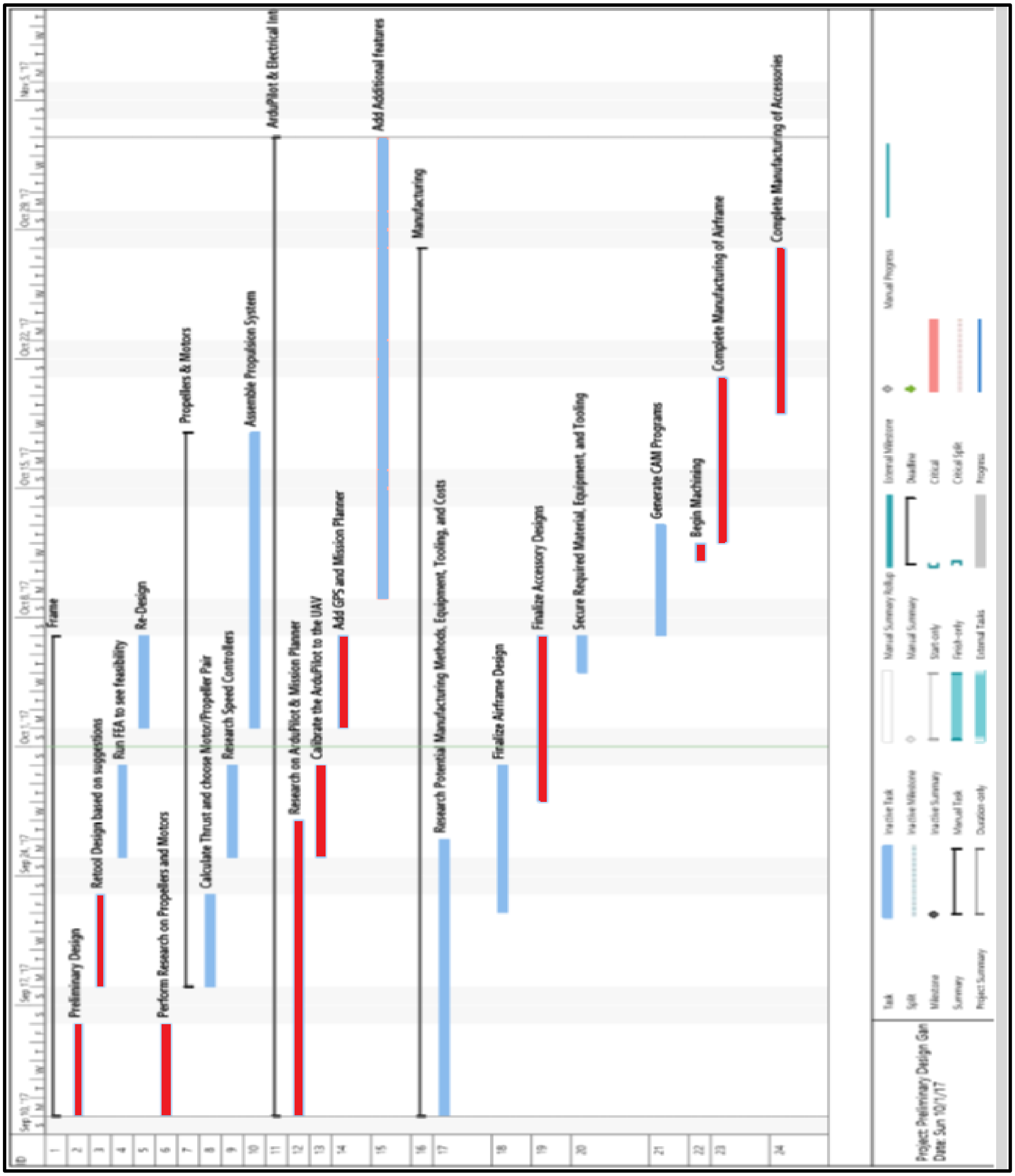

Figure 6. Team Gantt chart with critical path

7.3 Risk Plan and Safety

The key to satisfying the customer and avoiding all problems is constant communication, both within the group and with the customer. Open lines of communication will allow for tasks to be tracked, and expose possible hold-ups or problems that may arise. The critical path to designing and finishing the quadcopter is as follows:

Research materials to build quadcopter, including electronics; design frame of quadcopter and order other parts/materials; assemble/build frame and build subsystems like propulsion and electronics;

assemble the quadcopter; test the capabilities of the quadcopter; adjust, alter and troubleshoot issues that are revealed and retest until quadcopter meets expectations.

Table 3 identifies the foreseeable risks during the project. The likelihood of occurrence, actions that can and are being taken to alleviate the impact, and the responses to deal with the risks are listed. By far, the largest issues foreseen are schedule delays and an issue with the electronics not communicating properly. The listed actions are currently being employed to prepare in case of such incidents, but the setback they may cause would be serious. While not the most serious risk foreseen, delays in the delivery of materials can limit the project's progress severely. To avoid these delays, 3D printing will be utilized where possible to create parts. While not everything can be replaced by 3D printing, such as a motor, the raw materials like the carbon fiber can be replaced with 3D printing until the actual material arrives.

Table 3: Potential Risks and Contingencies Chart

Risk	Level	Actions to Minimize	Fall Back Strategy
Change in quadcopter specification	Low	• Constantly update customer on progress and decisions • Build above expectations to anticipate changes	• Make time for alterations
Schedule delays	High	• Check in with group to track progress • Plan milestones aggressively	• Have multiple members work on task
Delays in order placement or delivery	Moderate	• Purchase items in advance of needing them • If purchase is over $50, gather info for purchasing department	• 3D print or manufacture part
Quadcopter does not fly	Moderate	• Build propulsion system to over perform • Flight test after each addition/change	• Order new propulsion equipment • Try to reduce load where possible
Controller does not properly communicate with quadcopter	High	• Use the most up-to-date software • Purchase equipment that is easy to use and is compatible with one another • Test equipment often	• Consult with experts • Browse hobby forums • Purchase a better component, if possible
Customer not satisfied	Moderate	• Check in with customer often • Communicate with customer to know and be reminded of needs	• Alter design • Communicate to find solution
Delays in 3D printing	Moderate	• Design and submit parts ahead of schedule	• Find alternative part that can be rush ordered

7.4 Ethics Statement

In order to maintain ethical integrity, the group will cite all references compiled and research done, record all vendors used, and abide by current patent laws when designing the quadcopter. In addition, the group shall be upfront with all decisions and design choices to ensure the customer is satisfied with and approves of the direction the group is taking. The group is also approved to fly by FAA regulations and will follow established guidelines.

7.5 Environmental Statement

To meet environmental standards, the quadcopter will be designed using standard electrical components, eliminating any emissions or chemicals the quadcopter might produce. The quadcopter should have no other perceivable environmental impacts.

7.6 Communication and Coordination with Sponsor

Communications with Sikorsky occur every week, once on Monday and once on Thursday. Monday correspondence includes an email containing a memo that goes over the work and research done since the previous Monday. This memo is submitted as a Word document, and responsibility for creating and submitting the memo alternates between all group members. Communication on Thursdays is a Skype teleconference where all group members are present. During the conference, the memo from Monday is discussed, as well as any developments between Monday and Thursday. In addition, plans for the coming week are reviewed, and any questions the team might have are fielded and answered.

8.0 Detailed Design

8.0.1 Modifications to Statement of Work Sections

Revisions to the Detailed Design Report Sections 1 through 7 are listed as 8.0.1.X:

8.0.1.1. Introduction - no change
8.0.1.2. Customer Needs - no change
8.0.1.3. External Search - no change
8.0.1.4. Engineering Specifications - no change
8.0.1.5. Concept Generation and Selection - Clarified material selection and concept generation.
8.0.1.6. System Level Design - Inserted updated CAD design with current model, and updated explanation of the model
8.0.1.7. Special Topics - Risk and contingencies table added to

8.1 Manufacturing Process Plan

The first design the team created comprised of an aluminium alloy airframe and a plastic shell. However, after further investigation and research the team made the decision to rethink the design and look into another material. The result was carbon fiber. Carbon fiber is strong and light, two components vital to the design. The aluminium design weighted over 4 pounds fully laden, extremely heavy for a quadcopter, leaving little room for payload. Carbon fiber cuts this weight in half. To create the initial prototype the team will use 3D MakerBot printers to get a feel for size and shape and further refine the design before machining the carbon fiber. Finally, the team will use the Tarot Kit to test all subsystems and components before final assembly. Table 4 shows the final manufacturing process plan.

Table 4: Manufacturing Process Plan - Final Quadcopter

Assembly Name	**Material Type**	**Raw Stock Size**	**Operations**
Base	Carbon Fiber plate	2-6”x6” Plates 1.5mm thick	CNC Waterjet using CAD XTF File
			Drill holes with titanium bits need to fasten U-Joints that hold battery
Arm (4 times)	Carbon Fiber Tube	13” X 0.5” Diameter	Waterjet to length 6.5 in
Legs (4 times)	Carbon Fiber tube	7” X .5” Diameter	Waterjet to length 3 in
Landing Leg Stanchions	Plastic	1.5 In Diameter	3D Print using MakerBots
Motor Caps	Plastic	0.5 in Diameter	3D Print using MakerBots
Final Assembly			Screw base together, assemble airframe, add electronics and accessories.

8.2 Analysis

The battery and motor/propeller combo chosen was dependent on how long the quadcopter would be able to stay in the air. As given by the customer, the quadcopter should have a flight time between 20 and 30 minutes. Because the battery is one of the heaviest components, and the weight is proportional to the power that can be provided to the motors and the battery life, an analysis on the efficiency of the motors and the flight time was required to prove whether or not an 8000 mAh 4S battery was the proper choice. Calculations, tables, and figures can be found in Appendix B and Appendix C. For the mass of the quadcopter, the final weight is an estimation which tries to account for currently unknown additions that may be added to the frame later on. All values in the Table B3 are given by the specification sheet for the motor/propeller combo except for the thrust/weight ratio and the flight time. The thrust to weight ratio was calculated by dividing the thrust of all four motors combined in pounds by the weight of the quadcopter. The flight time was calculated by dividing the total capacity of the battery in amps by the current draw of the system and converted from hours to minutes. The current draw of the system was estimated as the drain from all four motors, and an extra 2 amps from the rest of the system. One additional data point was added to the chart through linear interpolation at a thrust/weight ratio of 1 to show data for when the quadcopter is hovering. This data point is red in the figures.

8.3 Material and Material Selection Process

The primary material consideration for the UAV was directed towards the construction of the airframe. Material selection is one of the most important aspects of the UAV design because it directly relates to Sikorsky’s principal needs of durability and ease of use. The final decision regarding the material was between aluminium and carbon fiber. A Pugh concept chart, shown in

Table 5, was utilized to make this decision. This chart details the criteria that drove the selection process and ultimately led to the decision to make the airframe using carbon fiber.

Table 5: Pugh Concept Chart

		Concepts			
		Aluminium (ref)		Carbon Fiber	
Selection Criteria	Weight	Rating	Wgtd. Score	Rating	Wgtd. Score
Strength	0.15	**3**	0.45	4	0.60
Ease of Use	0.11	**3**	0.33	4	0.44
Ease of Mfg.	0.14	**3**	0.42	5	0.70
Cost	0.18	**3**	0.54	4	0.72
Weight	0.25	**3**	0.75	5	1.25
Portable	0.07	**3**	0.21	**3**	0.21
Repairability	0.10	**3**	0.30	4	0.40
	Total Score		3.00		4.32
	Rank		2		1
	Continue	No		Yes - Prim. Dsgn	

Relative Performance	**Rating**
Much worse than reference	1
Worse than reference	2
Same as reference	3
Better than reference	4
Much better than reference	5

8.4 Component and Component Selection Process

For the propulsion systems, the initial choices were largely based on size of the quadcopter. It was decided initially that the frame size should be 16 inches, or about 400 millimeters, from one corner to its opposite corner. This size was nominally chosen to be within the customer's specification of between 12 and 18 inches. This meant that the space between adjacent motors was approximately 11.3 inches. To maximize lift of the quadcopter while reducing the potential between the propellers, 10x3.8-inch carbon fiber propellers were chosen. A lower pitch of 3.8 inches was necessary for the quadcopter to get enough lift to fly and helped to stabilize the quadcopter. Lower pitches can produce more lift at lower RPMs for larger quadcopters. This also serves the dual-purpose of making the quadcopter fly with more stability and respond slower to changes in speed and direction. This was a requirement listed by the sponsor for making it easier for beginners to fly. Carbon fiber was chosen over plastic as the material for its strength and ability to survive an impact. In addition, the price difference between plastic and carbon fiber was minimal. The motors chosen to work with these propellers were 2216-810 kV motors. These motors were rated to operate well with 10-inch propellers, and were the most efficient and powerful motors for the propellers. The cost of the motors was not significantly different from other motors. The ESCs were chosen based on the maximum current that could be drawn from the motors, which according to their data sheet is 15.4 amps. Therefore, 20-amp ESCs were chosen to be safe in case a spike occurred. Lastly, the battery was chosen to be an 8000 mAh 4S Lipo battery based on the specifications for the motors. The battery needed to be able to provide enough power for the quadcopter to stay in the air for approximately 20 to 30 minutes. This requires a delicate balance between the weight of the battery and the overall weight of the quadcopter, the power that can be achieved with the motors using the battery, and how much power the motors will drain from the battery. As shown in Section 8.2, Table B3 and Figures D1, D2, and D3 contain the analysis to prove the battery was a suitable and robust option.

The flight controller was chosen based on the budget, features and ease of use. The team chose Pixhawk AutoPilot as the flight controller due to its compatibility with Mission Planner software, GPS module support, features like dual accelerometer/gyros and its overall cost. The Pixhawk has the latest firmware and hardware design, and therefore can easily be upgraded for the latest technology. Additionally, the Pixhawk flight controller is compact in size and weighs only 38 g [4]. The GPS module was selected to be mRo GPS u-Blox Neo- M8N since it was readily available with the PixHawk as a bundle as shown in Figure 7and therefore was much cheaper. The bundle also included a buzzer, two telemetry radios and a switch. The buzzer and the switch ensure that the UAV is armed safely and only when it needs to be armed and the two 915 MHz telemetry radios help in sending the data from the UAV to the user. Considering the design of the UAV and the functionality of the GPS, the team chose to go with a foldable GPS mast.

Since the UAV is required to complete pre-planned missions, Mission Planner software was chosen because of its functionality of ground control and ease of use. Mission Planner can easily connect to the Pixhawk firmware and the user can set the desired waypoints for the UAV. Furthermore, Mission Planner uses common geographical mapping systems like Google maps/Bing/Open Street Maps [5]

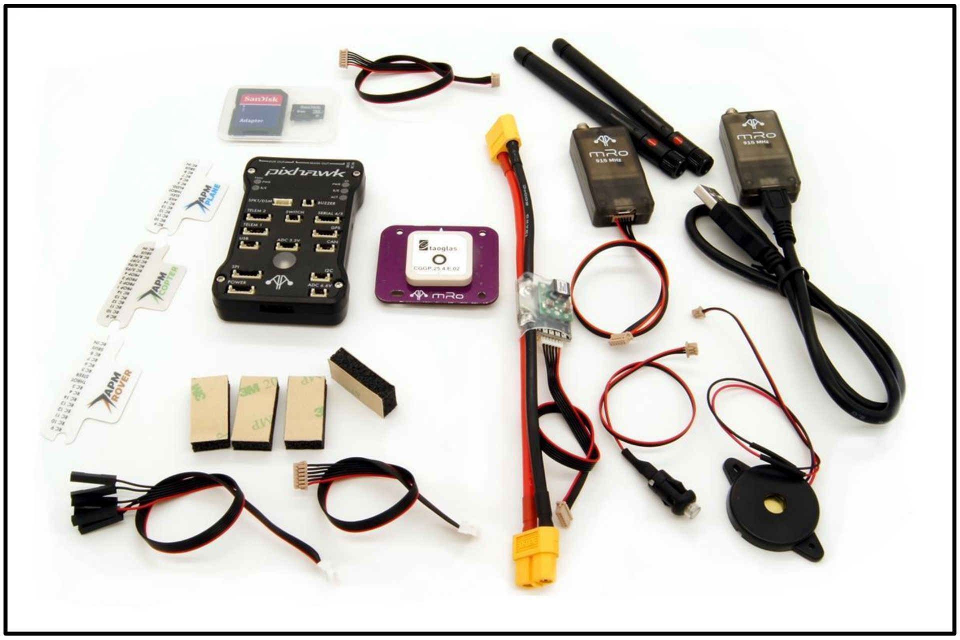

Figure 7. Pixhawk kit with GPS

The Spektrum DX7 7 channel transmitter was given to the group outside of the budget. The 7-channel transmitter will allow the user to manually control the UAV through the use of different channels through a receiver attached to the UAV. The different buttons, switches and sticks on the radio controller can be set to any channel the user wants. Each channel can control a specific movement such as throttle, yaw, roll and pitch. The throttle would move the UAV up and down while yaw would let it rotate to change direction. Roll will let the UAV move in the left or right direction and finally pitch allows the UAV to move forward or backward. Two channels can be used for gimbal control such as on the pitch and tilt axis and the last channel can be used for changing flight modes through Mission Planner. The Spektrum remote receiver that comes with the Spektrum DX7 can be directly connected to the Pixhawk as seen in the circuit diagram on Figure C2.

The FPV camera was given to the group along with a 5.8 GHz transmitter, on screen display (OSD) and Black Pearl screen display receiver. The team was also given a battery converter to convert to voltage from the power distribution board to an acceptable voltage for the FPV. These components allow FPV for the UAV for easier manual control when flying. The FPV will be fixed to the quadcopter facing forward towards the front of the UAV.

The group currently has a GoPro 4 silver available for testing. In order to have a downward view intended for surveillance on the UAV, a gimbal will be purchased to control and hold the GoPro. The team has decided to buy a 2-axis gimbal since it is lighter and less costly compared to a 3-axis gimbal. It allows for stabilization of a pitch and tilt axis and can be controlled by the radio controller.

A comparable camera in size to a GoPro that can be used for infrared in a gimbal is the FLIR Duo. The FLIR Duo allows for a Bluetooth connection with an App on a tablet or phone to watch an infrared video feed. The FLIR Duo will not be purchased for our team since it does not fit within our budget costing approximately one thousand dollars.

The components are connected and set up according to the diagrams as seen in Appendix C.

8.5 CAD Drawings

This section is comprised of various views for the quadcopter. The first picture displayed is a 2D drawing front view for the quadcopter assembly. The 2D view shows details on important dimensions of the vehicle. The next three images are an isometric, front, and top view of the quadcopter SolidWorks assembly. In these images, locations of all components are included, to show how they will be assembled in real life. Using the SolidWorks assembly to size and place components helps to streamline the final manufacturing and assembly process. The final images are the assembly of the landing legs. These images are shown separately because they are an integral part of the design, and an innovation on current models. The images show the landing legs standing and folded, with a transparency added to the parts to show the locking mechanism. In Appendix E, individual pictures of components to be manufactured are included.

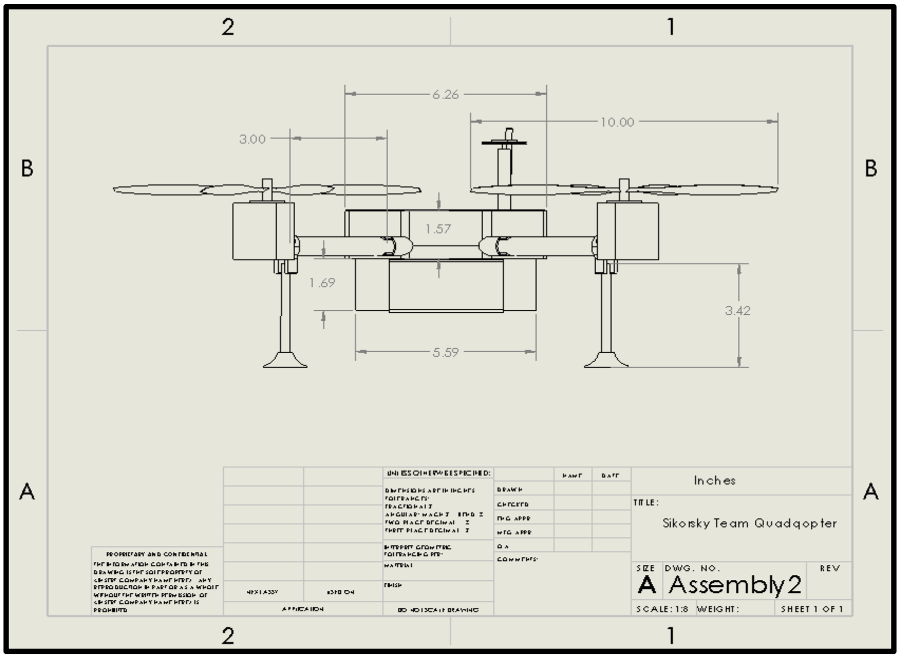

Figure 8. Dimension drawing of the front view of the quadcopter

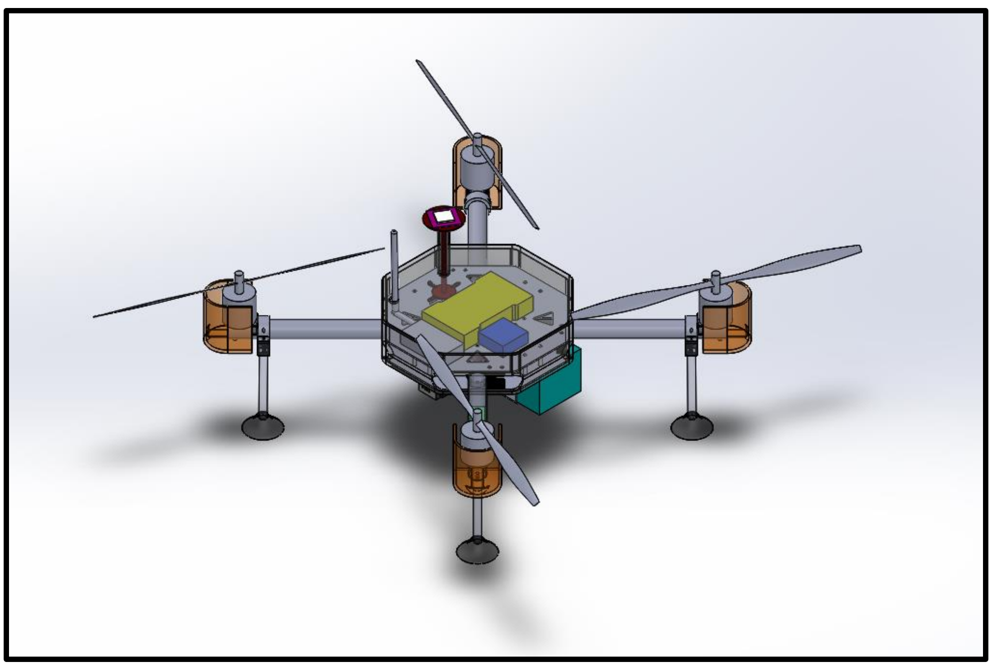
Figure 9. Isometric view of the quadcopter with representations of components

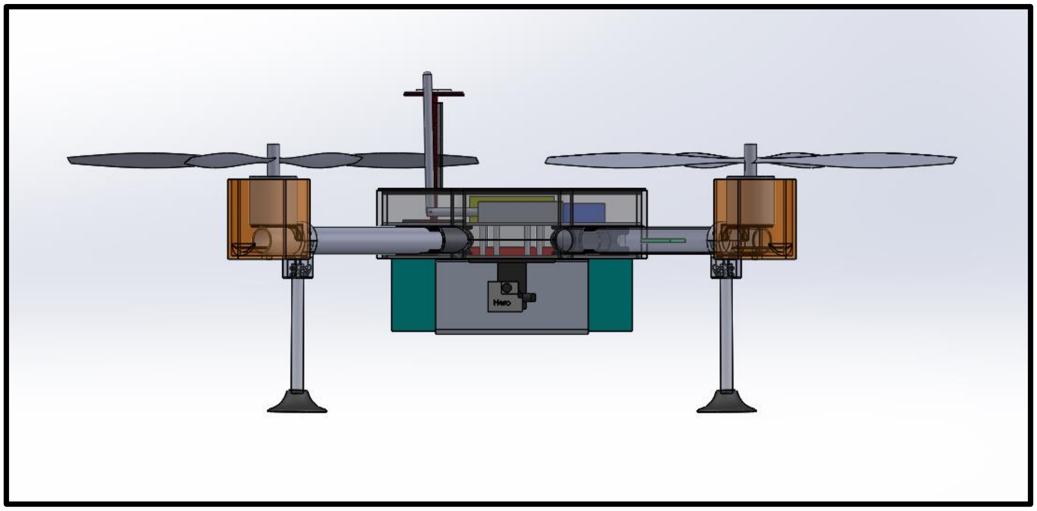

Figure 10. Front View of the quadcopter with representations of components

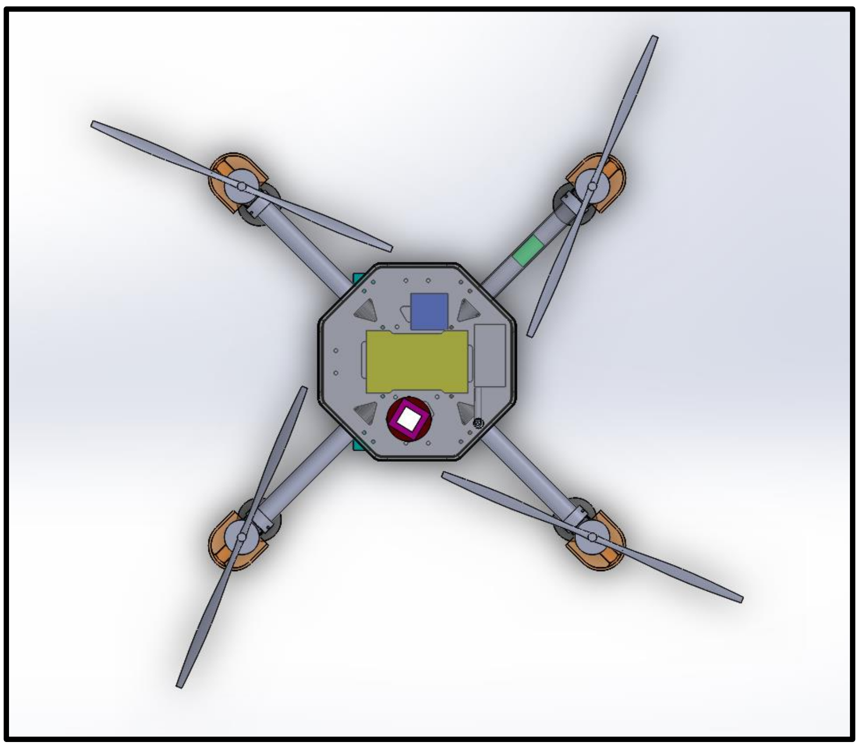

Figure 11. Top view of quadcopter with representations of components

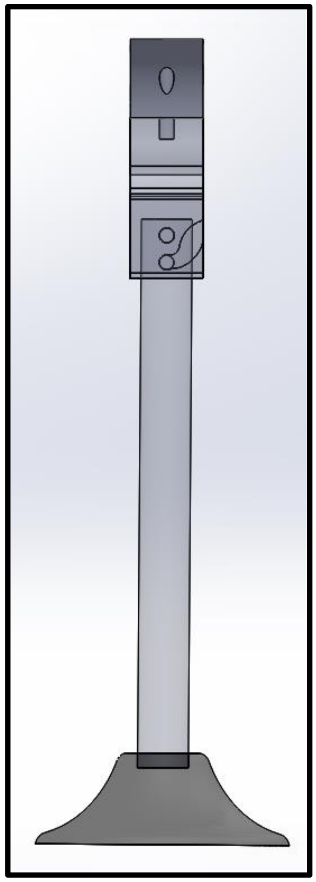

Figure 12. Assembly of the landing leg

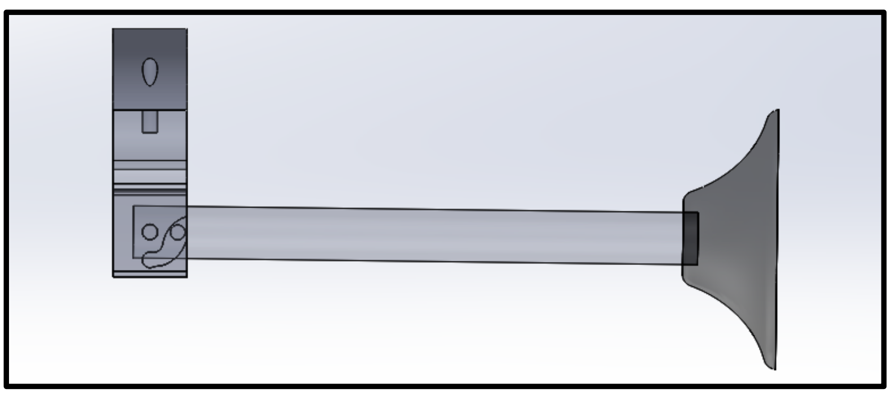

Figure 13. Landing leg in folded position for carrying

8.6 Test Procedure

Initial testing will be carried out using the Tarot airframe. This will provide a basis for making sure all of the electronics are fully functional. This model will be tested by each member of the group to ensure everything is operational and easy to use.

A prototype of the airframe will be 3D printed. This will be used to test the physical assembly of the UAV, ensuring a proper fit. Once the fit is finalized, the final iteration of the airframe will be cut from carbon fiber and assembled. This model will be tested for its ability to idle and carry out missions. It will also be flown by each member of the group because it must be easy to operate, and this will provide a larger sample size in analysing ease of use.

8.7 Economic Analyses - Budget and Vendor Purchase Information

Table 6 provides the current state of the team's budget. The total amount of funds allocated to this project was $1000. The team tried to find vendors that were affordable given the budget, and stocked the quality parts needs for the build. Several vendors were selected, HobbyKing, mRobotics, Rock West Carbon Fiber Composites, Banggood, and Amazon. The team also took shipping cost and delivery date into consideration, the team wanted to get the parts in a timely fashion to begin design review, and testing components.

Table 6: $1000 Budget

Material	*Vendor*	*Number Purchased*	*Unit Price*	*Ship & Hand*	*Total Cost (Already puchased)*
6 x 6 x 1/16" Carbon Fiber Sheet	Rock West Composites	3	$ 10.99	$ 10.49	$ 43.46
6 piece 10 x 3.8" Carbon Fiber Propellers	Amazon	1	$ 29.99	$ -	$ 29.99
2216 KV810 Motors	Banggood	4	$ 18.38	$ -	$ 73.52
20A ESC	Banggood	6	$ 9.99	$ -	$ 59.94
Pixhawk AutoPilot kit	mRobotics	1	$ 237.40	$ -	$ 237.40
UBEC Distribution Board	Amazon	1	$ 26.45	$ 4.50	$ 30.95
Battery Connectors	Amazon	1	$ 11.55	$ 6.18	$ 17.73
Quanum E4 Cube 50W Balance Charger for LiPo 100~240V AC	Hobby King	1	$ 21.53	$ 9.84	$ 31.37
Multistar High Capacity 8000mAh 4S 10C Multi-Rotor Lipo Pack XT90	Hobby King	1	$ 43.68		$ 43.68
another 4S battery	Hobby King	1	$ 41.54	$ 8.45	$ 49.99
GPS mast	Amazon	1	$ 7.44	$ -	$ 7.44
poster	Penn State	1	$ 62.24	$ -	$ 62.24
materials		1	$ 83.72	$ -	$ 83.72
manufacturing (water jet)		1	$ 19.21	$ -	$ 19.21
2 axis brushless gimbal for GoPro	Amazon	1	$ 49.99	$ -	$ 49.99
AR7700 Serial Receiver with PPM/SRXL/Remote Receiver Output	Horizon Hobby	1	$ 59.99	$ 9.99	$ 69.98
Grand Total Spent:					$910.61
Remaining Budget (From $1000):					**$89.39**

9.0 Final Discussion

9.0.1 Modifications to Statement of Work and DDR Sections

Revisions to the Proposal and DDR Sections 1 through 8 are listed as 9.0.1.X:

9.0.1.1. Introduction - no change
9.0.1.2. Customer Needs – no change
9.0.1.3. External Search – no change
9.0.1.4. Engineering Specifications – Updated components selection
9.0.1.5. Concept Generation and Selection – no change
9.0.1.6. System Level Design – no change
9.0.1.7. Special Topics - Updated budget and BOM
9.0.1.8 Detailed Design – Updated manufacturing plan and analysis

9.1 Construction Process

The Sikorsky team used a wide array of manufacturing techniques and raw materials to prototype and build a robust and innovative unmanned aerial vehicle (UAV). The main components and details can be seen in Table 4. The team used several raw materials found in the Tarot Ironman 650 kit, such as .05" carbon fiber tubes, and miscellaneous spacers and screws. First the team finished the final design. Then the team purchased raw 6"x6" .05" thick carbon fiber sheets that served as the base of the quadcopter. The design was put into a CNC waterjet and machined to specification. The plates were then drilled with a titanium drill bit for the additional required holes for screws. Next the team cut the carbon fiber tubes to size for the arms and legs with a diamond coated jigsaw blade. Then the team soldered the electronics. The Electronic Speed Controllers (ESC) were soldered to the electric motors. These ESC's were then soldered to the Power Distribution board. The two carbon fiber case plates were then screwed together using .5" spacers and .07" or M2 screws. This allowed the team to rough fit all the electronic and necessary equipment. Once this was complete the Power Distribution board was screwed to the bottom base, and the arms were screwed into place. Moreover, the battery box was secured, this allowed the team to test all electrical components before final assembly. All the drawings for the 3D Prints for the shroud, motor guards, and landing leg bases were submitted and printed. The two base plates were secured with screws. The team then began the final stages of the construction and assembly process. The Pixhawk, Receiver, First Person Camera and GPS were secured with Velcro. The final step was to screw the protective plastic shroud around the base. See appendix F, for figures of components and subcomponents before the quadcopter was assembled to show how all the parts were manufactured. There were a few minor design changes in the end. The battery slot was turned into a battery box with tray to further protect the battery from the elements. Additionally, the screw locations for the gimbal and battery box moved for increased clearance and fit. Finally, the team made an executive decision to use straight landing legs, as the designed foldable legs were not able to be manufactured with the available 3D printers given their imprecision. Sikorsky with more advanced and precise additive manufacturing capabilities would be able to manufacture these parts with more exacting precision and tolerances that are required for this application.

Table 7: Manufacturing Process Plan - Final Quadcopter

Assembly Name	Material Type	Raw Stock Size	Operations
Base	Carbon Fiber plate	2-6"x6" Plates .05 thick	CNC Waterjet using CAD XTF File
			Drill 12(1/8") holes with titanium bits needed to fasten Battery Box, Power Distribution Board and Gimbal.
Arm (4 times)	Carbon Fiber Tube	13" X 0.5" Diameter	Cut with Diamond Coated Jigsaw to length 6.5"
Legs (4 times)	Carbon Fiber tube	7" X .5" Diameter	Cut with Diamond Coated Jigsaw to length 4"
Landing Leg Stanchions	PLA Plastic	1.5 In Diameter	3D Print using MakerBots
Motor Caps	PLA Plastic	0.5 in Diameter	3D Print using MakerBots
Base shroud	PLA	6.5" x 6.5"	3D print using MakerBots
Electronics	-	-	Solder Power Distribution Board to Battery, Solder Electronic Speed Controllers to Motors. Secure PDB to base with four screws. Secure Gimbal to Base with four screws.
Final Assembly	-	-	Screw Base together, Assemble Airframe, Battery Box and add Electronics and Accessories

9.2 Test Results and Discussion

The team tested all the electronics separately and they worked correctly. The voltages on the power distribution board were tested using a multimeter and the outputs were 13 V for the ESC output and 6.3 V for the Pixhawk port. The team successfully tested the Pixhawk through the use of Mission Planner software downloaded on a laptop. The Pixhawk can communicate with the laptop either through a USB connection or through the 915 MHz telemetry radios. The team then successfully binded the receiver to the radio controller. As seen in Figure 13, each channel was tested by giving a command with the radio controller in the radio controller calibration on Mission Planner thus changing the values of each of the green bars. Since it is a 7-channel transmitter, the radio controller was able to move seven of the bars indicating that the radio controller was working. The radio transmitter was calibrated such that the throttle, pitch, roll and yaw had high of 2000 and low of 1000. The pitch was reversed for easier control.

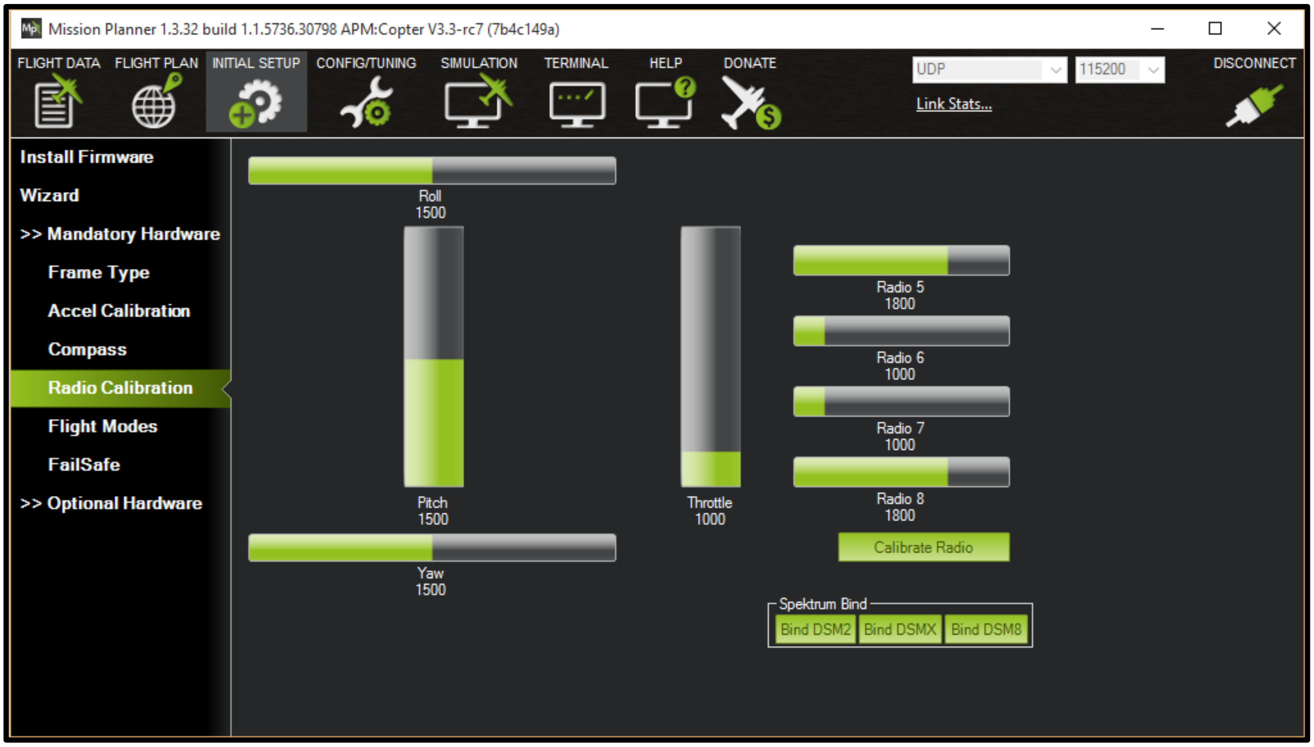

Figure 14. Radio calibration on Mission Planner [5]

The motors were then successfully spun with the ESC calibration in Mission Planner. The accelerometer calibration was performed when the Pixhawk was mounted on the UAV and was stable. The FPV camera was connected to the OSD module and was tested successfully on the Black Pearl screen. The team also tested each of the manufactured parts but due to the limited manufacturing machinery and equipment, some of the 3-D printed parts did not match the 3-D CAD model.

The team then tightened the propellers on the respective motors and strapped the UAV to a heavy block of wood in order to test the thrust of the propellers as seen in Figure 14.

Figure 15. Preliminary flight test, UAV strapped down

The first test flight crashed due to incorrect calibration of the Pixhawk and the spin direction of one of the motors. As seen in the appendix, Figure C4, the way the ESCs or electronic speed controllers are connected to the brushless motors determines their spin direction. As seen in Figure C5, the quadcopter the team programmed through Mission Planner for the Pixhawk follows the QUAD X configuration. With one motor spinning the wrong way, this will not allow the quadcopter to fly and they must follow the configuration set with the Pixhawk. After re-calibrating the Pixhawk and reversing the spin direction of motor number two, the team had a successful flight of the UAV as seen in Figure 15.

Figure 16. The UAV during flight

Due to time constraints, the team was unable to calibrate the sensitivity of the controls for a smoother flight control along with testing of the GPS and its different flight modes.

10.0 Conclusions and Recommendations

In the beginning of the semester, representatives from Sikorsky tasked the team with designing a quadcopter that had various criteria. The most prominent of these criteria were to make a quadcopter that was robust, compact, modular, and weather resistant. In sections 6.0 and and 8.5, the description of the original design can be found.

To design a robust quadcopter, the main decisions made focused around the various materials that would be used. The design focused on making two base plates, four arms, and landing legs out of carbon fiber. Using the carbon fiber would allow for strong material that wouldn’t damage during a crash.

One of the most important criteria was to make the quadcopter compact. Its main use would be on military missions, which meant that soldiers would have to carry it on their back, sometimes for miles at a time. Most quadcopters on the commercial market for similar surveillance use were around 24” along its axis. Our team decided to design a quadcopter that was 16” along its axis. The center base plates were made 6” in width, and the drone arms were made 6.5” long, but the edge was set 1.5” inside the base. Parts were also designed to fold when not in flight. The arms would swing on a singular pivot point and lock into snaps for flight. this ensured that they would remain secure and not move when being flown, but could be made small when flight was needed. The landing legs would also fold upwards as to not stick out during transportation.

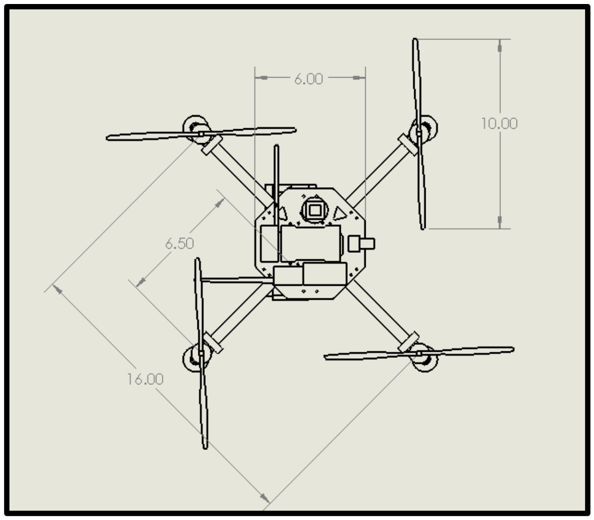

Figure 17. Drawing showing current dimensions of the quadcopter sizing

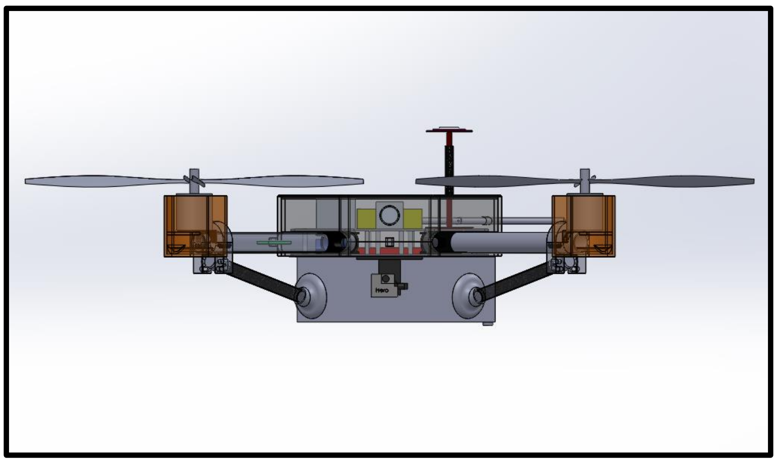
Figure 18. Image of quadcopter with legs folding demonstrating its ability to be more compact

Modular components were needed to ensure for quick fixing in the event something broke. Our sponsors said that soldiers would treat the quadcopter like a five-year-old treats their toys, and the quadcopter would also face many crashes. The landing legs were built so the connection to the arms could be slid in and out easily. The dome was made in two pieces, and held together by screws, so that it could be removed easily to fix any components inside. The arms only needed one screw, so they could be removed with easy in the event the esc inside needed to be replaced.

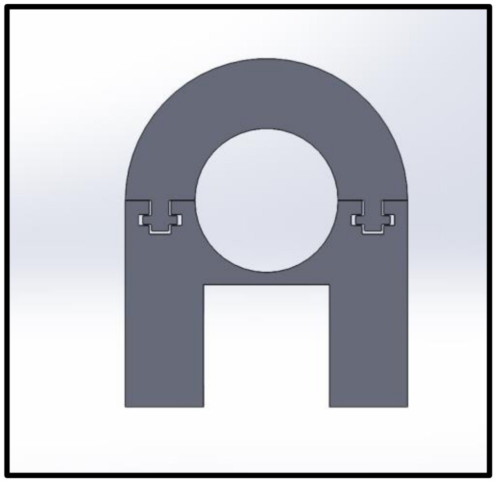

Figure 19. Connection of landing legs that go around the arm

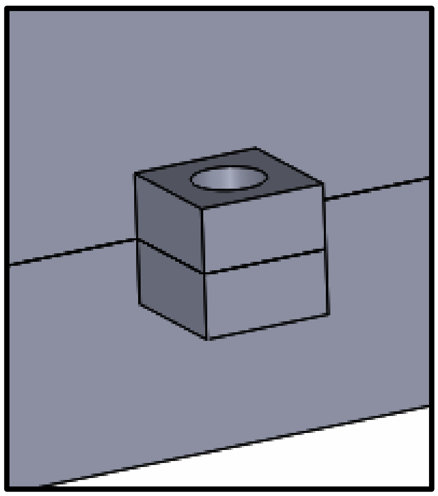

Figure 20. Screw hole on dome where the top and bottom pieces will connect together

Finally, multiple protective parts were used to make the quadcopter weather resistant. Due to its use in harsh military environments, with a focus on Iraq and Afghanistan as the theaters of battle, parts were designed to keep dust and water out, as best as possible. To ensure protection, the bottom base plate had most of its holes removed except ones necessary for wires to go through, and the dome was designed to have rubber gaskets placed in its holes so that dust and water would be kept out. While it was not dust and waterproof, it will be resistant so that electronics will be protected. the battery for the quadcopter was also rather large, and would sit outside of the dome, under the quadcopter. A design was made using a slider, that would allow the battery to be moved in and out of a metal protective housing. This way the battery could be protected on all six sides.

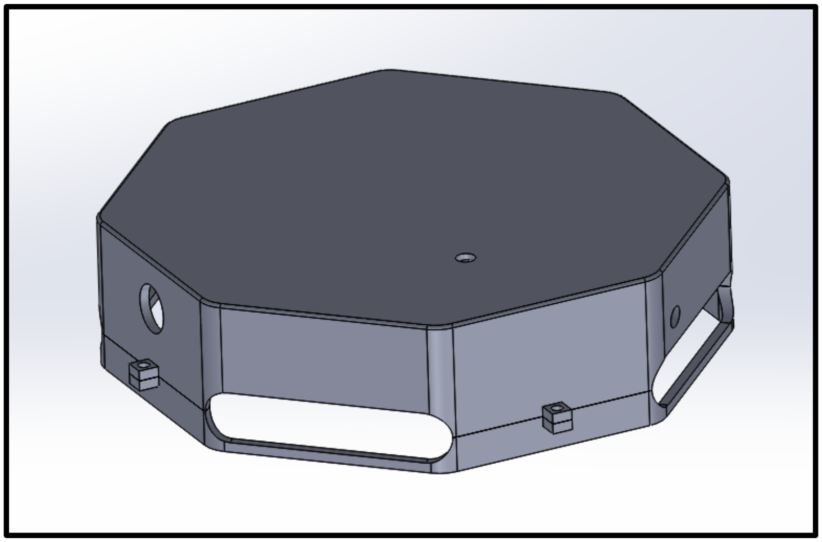

Figure 21. Protective dome placed around center body of airframe

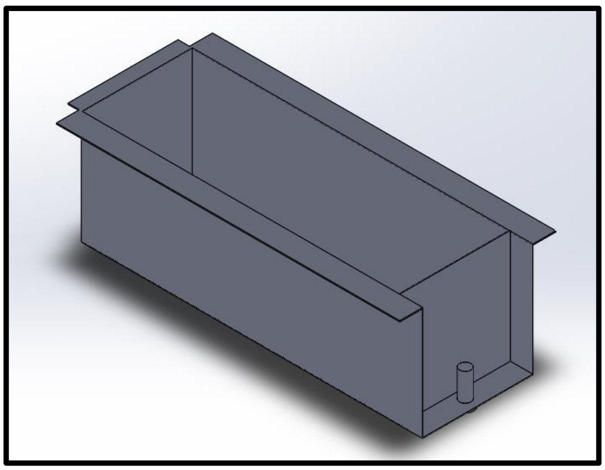

Figure 22. Battery box designed to provide protection on all sides of the battery

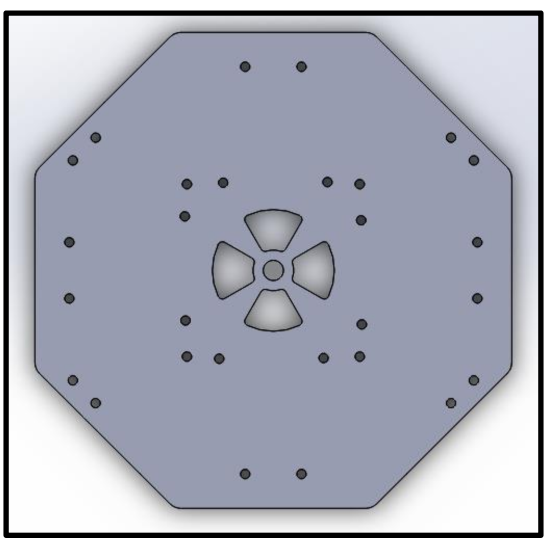

Figure 23. Bottom carbon fiber base with minimal holes to allow for best possible protection from dust and water

As with any prototype there were a multitude of changes that can be made for the next or final iteration. Two small design changes that could made that would make a huge difference relate to the sizing of the quadcopter. First, the height of the quadcopter could be raised. The space between the two base plates and between the top plate and the dome could each be made a ¼” larger. This would allow for a more room to place the components without placing stress on the wiring. Along with creating a little more vertical space, the width of the quadcopter should be bumped up by about 2” total, with a ½” being added to the width of the base plates and ¾” added to each arm of the quadcopter. These changes will have two big impacts. Making the base wider will allow for the power distribution board to fit better between the connections of the arms and supports. Making the arms wider will allow for the quadcopter to utilize the next size bigger in props and motors. This means more thrust and a longer flight time while using the same battery. The extra weight from increasing the size would also be negligible because the components are carbon fiber which is extremely light weight.

The final changes that should be focused on are the production of certain parts during manufacturing. Parts such as the connections for the landing legs, dome, and motor guards were created using 3D printed parts. While this allowed the team to keep manufacturing costs low and within budget, they also led to low quality. Parts many times printed incorrectly, such as the landing leg connections. the pars would not fit into each other many times, and the pivots would not come out correct. Using precision manufacturing such as a CNC, the parts would’ve had a better chance to work, or at the very least, it would’ve been easier to identify design flaws. Overall the designs and manufacturing worked for this initial prototype of the quadcopter. Taking time to analyze the design and manufacturing procedures will allow for a better product in future iterations.

11.0 Self-Assessment (Design Criteria Satisfaction)

The was able to come together and work well in completing the project, though the team performed better in some areas than others. The team’s strongest quality was its knowledge and resourcefulness. Given the range of backgrounds within the group, there was always at least one person with information or experience with a particular piece of the project. In cases where the group hit a wall and could not figure out an issue, a solution was developed with the help of multiple members. A great example of this is the usage of aluminum shaped into landing legs to be used for test flights so the actual landing legs would not be damaged further and could be used in the design showcase.

One area where the group struggled was communication. This issue did not arise till later one when it was realized that ideas were not being conveyed or interpreted correctly, and things were being overlooked when it was thought they were being addressed. The lack of proper communication became evident when problems in the design started to show up that others thought were fine. There was also an issue with basic communication in scheduling meetings and dividing work. Members would sometimes not respond to the messages for various reasons. This created confusion and concern in certain situations.

Another area requiring improvement was punctuality. On more than one occasion the team was working on an assignment right up to the deadline, and in some cases the assignment was not completed to the best of the team’s ability because of this. The group was frequently told it was behind schedule, and this was the direct result of that, to the point where testing was done only about a week before the design showcase. In addition, the lack of committing to deadlines led to members not showing up to meetings on time, with or without a legitimate excuse.

11.1 Customer Needs Assessment

The prototype quadcopter was able to meet most of our customer needs fairly well, though it struggled to meet others. Table 7 lists a score out of 10 for each of the ten customer needs. The customer needs in green were ones that were fully tested and met with varying levels of room for improvement. The needs in yellow were unable to be thoroughly explored due to the limitations of the prototype. With a final version of the quadcopter based on the design, it is believed that these needs would have been fully tested. The customer needs in red are ones that were fully tested and were found to be a failure for the quadcopter. To meet these needs, changes to the design would be required.

Table 8: Customer Needs Scoring Table

Customer Needs	Score out of 10
Robust airframe (impact resistant)	9
Portable (easy to carry and light)	9
Modular (replaceable parts)	10
Surveillance camera with a gimbal	8
Fixed FPV camera for flying	9
Easy to operate (minimal training required)	6
GPS (for automated flight)	6
Weather resistant (dust/water)	6
Limit disassembly	7
Longer flight time (20 to 30 minutes)	4

Through the multiple flight tests and resulting crashes, the quadcopter was shown to be extremely robust. The crashes, while not extremely hard, placed pressure on sensitive components and areas that managed to withstand the crash. The only part of the quadcopter that was not as robust as necessary was the landing legs. Due to the shallow spaces in the 3D printed parts, the carbon fiber landing leg would snap out of the fixtures every time, despite being reinforced with epoxy. The UAV was quite compact and light, capable of folding and weighing under five pounds. The arms could successfully fold, and the landing legs would be capable of folding with more precise manufacturing. The folding joints were 3D printed and the MakerBots used were not precise enough to make the joint work. If the joints were instead made using CNC machines with solid stock, the landing legs would be able to fold. The modular nature of the quadcopter was tested with each flight as some parts either broke or flew off and were lost. The lost or broken parts were replaced with ease and did not impact the performance of the quadcopter in subsequent flights. The final design was able to incorporate a gimbal underneath the quadcopter towards the front of the frame. When the gimbal was wired to the flight controller and powered, it was possible to operate the gimbal successfully using the radio controller. The gimbal, while designed for GoPro cameras, can be used with any camera that is of a relatively similar size with only minor modifications to how the gimbal holds the camera. Currently the camera is held in using a Velcro strap with a hole to fit the lens of a GoPro; this strap could be replaced with a regular Velcro strap to hold a different camera. As for the FPV camera, it was attached to the quadcopter and worked properly. However, the camera was not actually used to fly the quadcopter, and the range at which the camera could operate was not tested. Unfortunately, the UAV struggled during successful test flights to stay in one place and operate as intended. This was primarily caused by poor dimensioning and tolerancing when designing the body and arms of the quadcopter. With more testing and improvements, it is believed that the UAV would be able to fly as intended. From the few successful flights, the UAV responded slowly and gently to the input commands as desired. In its current state however, the quadcopter is difficult to fly from the errors. The GPS was not actually tested in conjunction with the quadcopter, though there is no foreseen reason as to why it would not work. The GPS was operational on its own, and seemed to communicate with the computer well. Testing of the GPS would see how accurately the quadcopter could relay its current position and follow a preset path using Mission Planner. The protective dome was designed to make the UAV both water and dust resistant while flying. There was never an attempt to test the effectiveness of the dome for fear of damaging parts within the body. From the design, a final version of the quadcopter would incorporate rubber gaskets on the bottom and the holes for the arms to make the entire body water and dust tight. In addition, using a better material than that of the MakerBots would be recommended to test how weather proof the cover is. With all of the different parts, pieces, and fixtures, it was important to limit how much assembly and disassembly the quadcopter needed to start and end flights. When all together the prototype only require the propellers and landing legs to be attached for flights. The propellers would always need to be removed, but a final version of the quadcopter would have landing legs that do not need to be removed due to the foldable design. The last customer need of flight time is one that was not able to be met. The originally estimated weight suggested that the quadcopter would be able to meet the 20 to 30-minute interval. However, the actual weight was much greater than anticipated and ate into the flight time. The current estimates place the time between 24 and 12 minutes. While the upper range would satisfy the customer need, it is unlikely that the analytical model accurately predicts the flight time of the quadcopter, and it is less likely that the model predicts conservatively. It was not possible to test the flight time of the UAV due to the aforementioned issues with flying, so the analytical model is the only way to judge the flight time.

Overall, the most important customer needs were either met or should be met with a final version of the quadcopter based on the design and performance of the prototype. This does not mean the quadcopter is without faults, and improvements should be made on the current design to better meet the customer needs.

11.2 Global and Societal Needs Assessment

In terms of global and societal needs, on a scale of 1 - 10, it would be fair to award the quadcopter a score of 6. While it helps to further certain needs, it fails to effectively address others. Depending on the point of view, the quadcopter does fulfil the need of safety. The intended use of the quadcopter is in a military application. The primary goal of the military is supposed to be to keep its representative nation safe. In this sense, the quadcopter will aid in this effort. In addition, as this is a remotely controlled vehicle, it could provide safety to soldiers as well by preventing some of the necessity of sending members of the military into potentially dangerous areas. However, while the quadcopter is successful in its applications toward safety, it fails when analyzed in terms of its sustainability and environmental impact. While many of the materials used in the making of the quadcopter are technically recyclable, the process in making the materials, specifically the carbon fiber, uses a large amount of energy. This process is not environmentally friendly. In addition, while carbon fiber can be recycled, the recycling process weakens the material, meaning it would be unlikely to use it again in the making of a drone, especially after several recycling processes. This means that it is also not very sustainable. The battery used is also a lithium ion battery, the creation of which involves a very environmentally harmful process. This again takes away from its contributions to sustainable and environmental needs. The quadcopter does not have an appreciable positive or negative effect in terms of bioethics or basic human needs. With this said, it seems fair to award the quadcopter a score of six. This is because it is positive in terms of safety and negative in terms of the environment and sustainability. The score is weighted more towards 10 because the primary goal of the quadcopter is safety, and it therefore effectively seeks to contribute to this global need.

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Appendix A: Budget Estimate

Table A1: Budget Projections

Expenses	**Estimated Cost**
Materials	$730
Equipment	$80
Poster	$62
Repairs	$20
Manufacturing	$19
TOTAL	$911

Table A2: Bill of Materials

Material	Vendor	Number Needed	Cost Per	Total Cost
Raw Materials				
Tarot Carbon Fiber 600mm Frame	Amazon	1	$110.00	$110.00
72 x 3/4” Carbon Fiber Tube	Grainger	1	$13.19	$13.19
6 x 6 x 1/16” Carbon Fiber Sheet	Rock West Composites	1	$10.99	$10.99
6 pc 10 x 3.8” Carbon Fiber Propellers	Amazon	1	$29.99	$29.99
TOTAL:				$164.17
Electronics				
2216 KV810 Motors	Banggood	4	$18.38	$73.52
20A ESC	Banggood	6	$12.82	$76.92
Pixhawk AutoPilot	mRobotics	1	$250	$250
UBEC Distribution Board	Amazon	1	$26.45	$26.45
Battery Connectors	Amazon	1	$12.52	$12.52
Multistar High Capacity 8000mAh 4S 10C Multi-Rotor Lipo Pack XT90	Hobby King	2	$43.68	$96.78
OSD Module	Quad Questions	1	$21.99	$21.99
Black Pearl- FPV display	Amazon	1	$147.99	$147.99
Spektrum DX7- Radio controller w/ Ar8000 receiver	Spektrum	1	$299.99	$299.99
GoPro HERO4 Silver	Amazon	1	$347.00	$347.00
Boscam 5.8 GHz transmitter	Banggood	1	$14.19	$14.19
FPV camera	-	1	~	$0
Battery Converter	-	1	~	$0
TOTAL:				$1117.65
Miscellaneous				
Drill kit	Amazon	1	$15.00	$15.00
TOTAL:				$15.00
FINAL TOTAL:				$1296.82

Appendix B: Data Tables

Table B1: Quadcopter Weight Estimation

Part	**Weight (lbs)**	**Number**	**Total (lbs)**
Frame	0.386	1	0.386
Motors	0.136687	4	0.546748
ESCs	0.0132277	4	0.0529108
Flight Controller	0.0837757	1	0.0837757
Power Board	0.02557362	1	0.02557362
Battery Connector	0.0194007	1	0.0194007
Battery	1.41757	1	1.41757
Battery Box	0.2	1	0.2
FPV Camera	0.0220462	1	0.0220462
Surveillance Camera	0.185188	1	0.185188
Gimbal	0.286601	1	0.286601
Motor Guards	0.05	4	0.2
Protective Dome	0.2	1	0.2
Landing Legs	0.05	4	0.2
Misc Electronics	0.25	1	0.25
Misc Materials	0.25	1	0.25
		TOTAL (lbs)	**4.32581402**

Table B2: Battery Properties

Capacity (mAh)	8000
Voltage (V)	14.8
Constant Discharge (A)	80
Peak Discharge (A)	160

Table B3: Motor/Propeller Data Sheet and Flight Time Calculations

Current (A)	Thrust (G)	Thrust (lbs)	Power (W)	Efficiency (G/W)	Speed (RPM)	Thrust/Weight Ratio	Flight Time (min)
1.00	160.00	0.35	14.80	10.81	3420.00	0.33	80.00
2.00	270.00	0.60	29.60	9.12	4340.00	0.55	48.00
3.00	360.00	0.79	44.40	8.11	4950.00	0.73	34.29
4.00	450.00	0.99	59.20	7.60	5540.00	0.92	26.67
4.45	490.54	1.08	65.87	7.46	5553.51	1.00	24.48
5.00	540.00	1.19	74.00	7.30	5570.00	1.10	21.82
6.00	600.00	1.32	88.80	6.76	6100.00	1.22	18.46
7.00	670.00	1.48	103.60	6.47	6340.00	1.37	16.00
8.00	730.00	1.61	118.40	6.17	6540.00	1.49	14.12
9.00	780.00	1.72	133.20	5.86	6810.00	1.59	12.63
9.45	802.50	1.77	139.86	5.74	8079.00	1.64	12.09
10.00	830.00	1.83	148.00	5.61	9630.00	1.69	11.43
11.00	890.00	1.96	162.80	5.47	7130.00	1.81	10.43
12.00	930.00	2.05	177.60	5.24	7310.00	1.90	9.60
13.00	960.00	2.12	192.40	4.99	7480.00	1.96	8.89
14.00	1010.00	2.23	207.20	4.87	7580.00	2.06	8.28
15.40	1070.00	2.36	227.90	4.70	7730.00	2.18	7.55

Appendix C: Configuration Diagrams

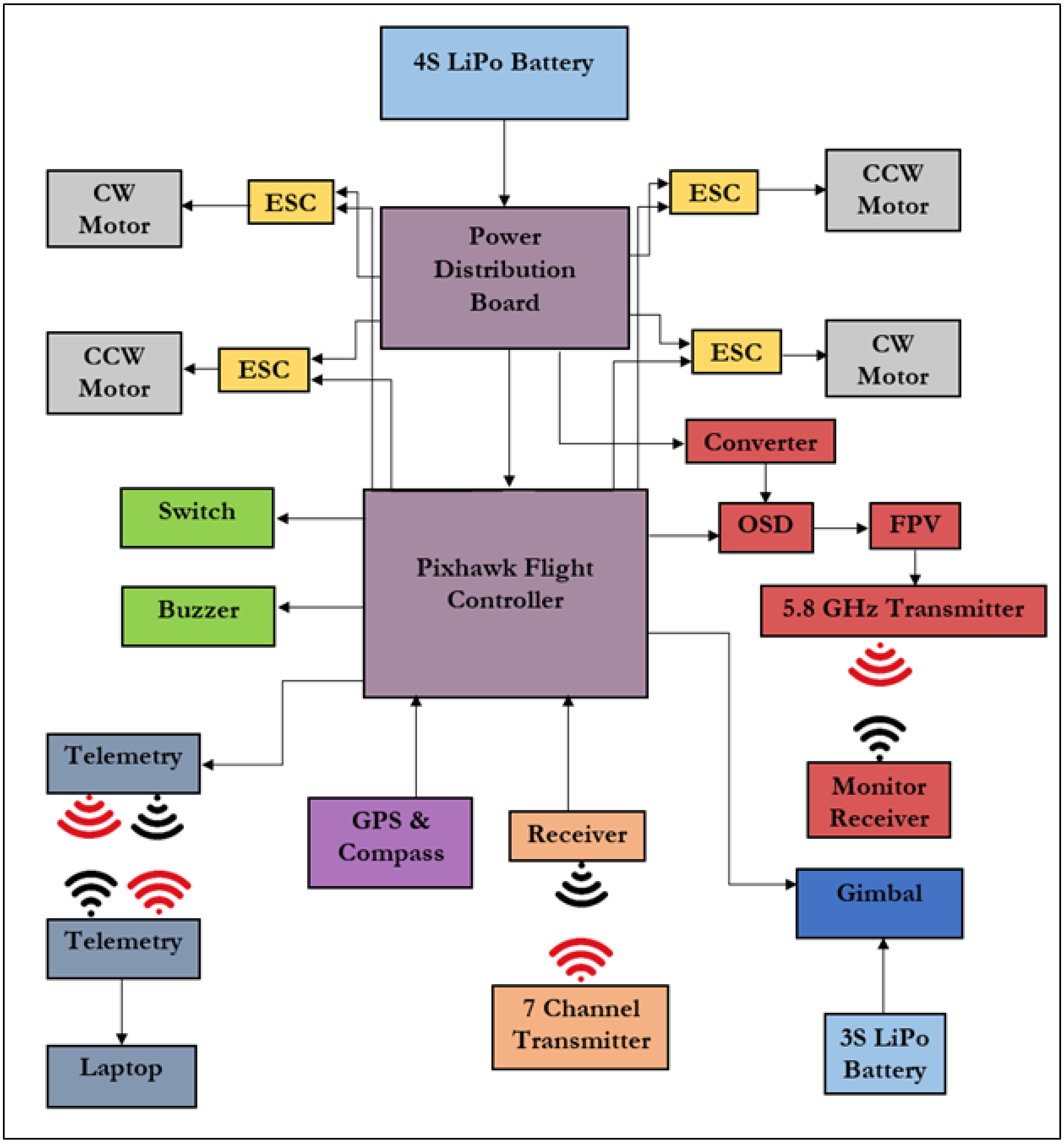

Figure C1. Block diagram for electrical components. CW is Clockwise, CCW is Counter Clockwise, ESC is Electronic Speed Controller, OSD is On Screen Display, and FPV is First Person View camera, Converter is the Battery converter, Telemetry is a 915 MHz telemetry radio. A red signal indicates a transmission while a black signal indicates a receiving signal.

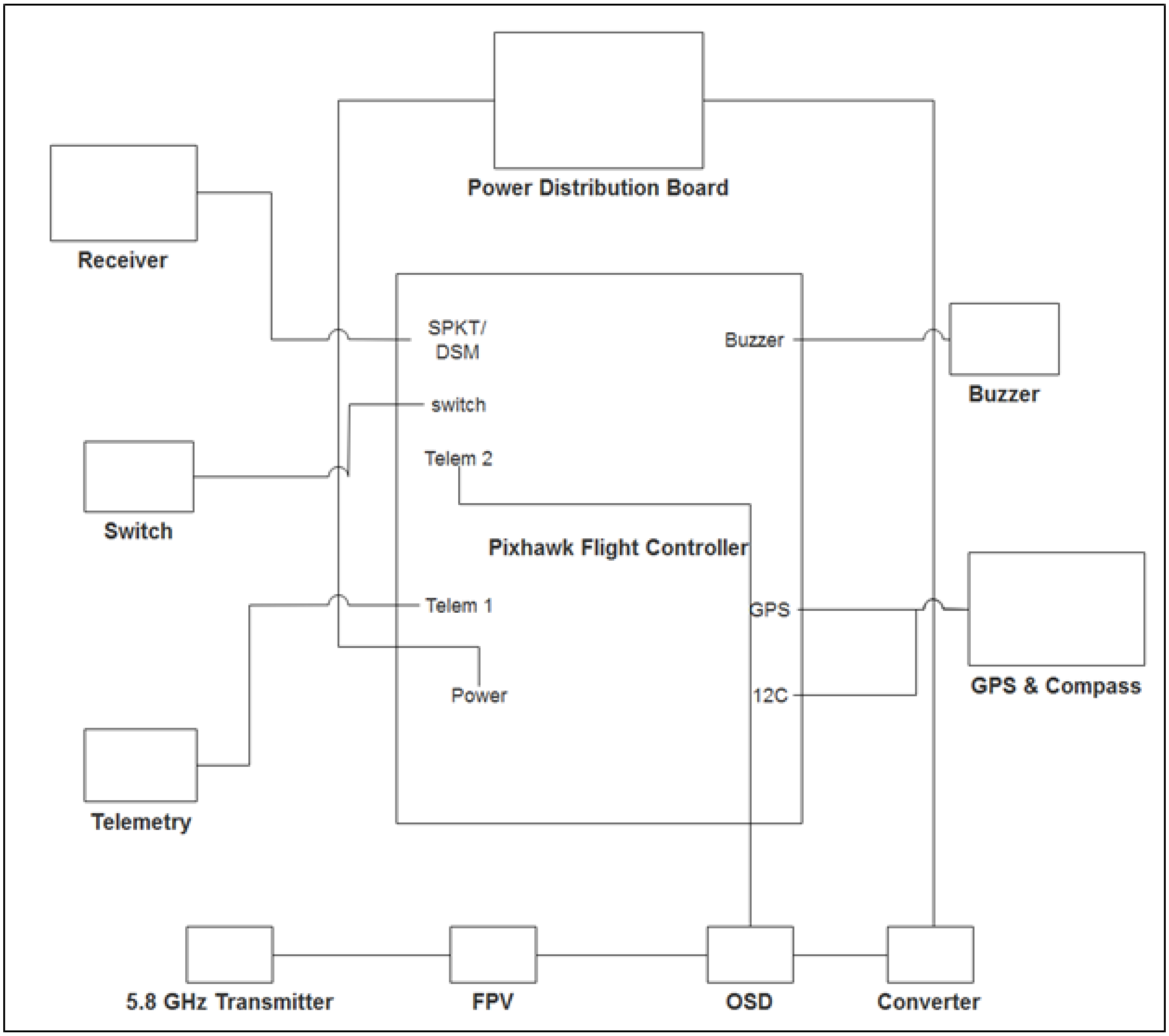

Figure C2. Blown-up section of circuit diagram for the Pixhawk Flight Controller.

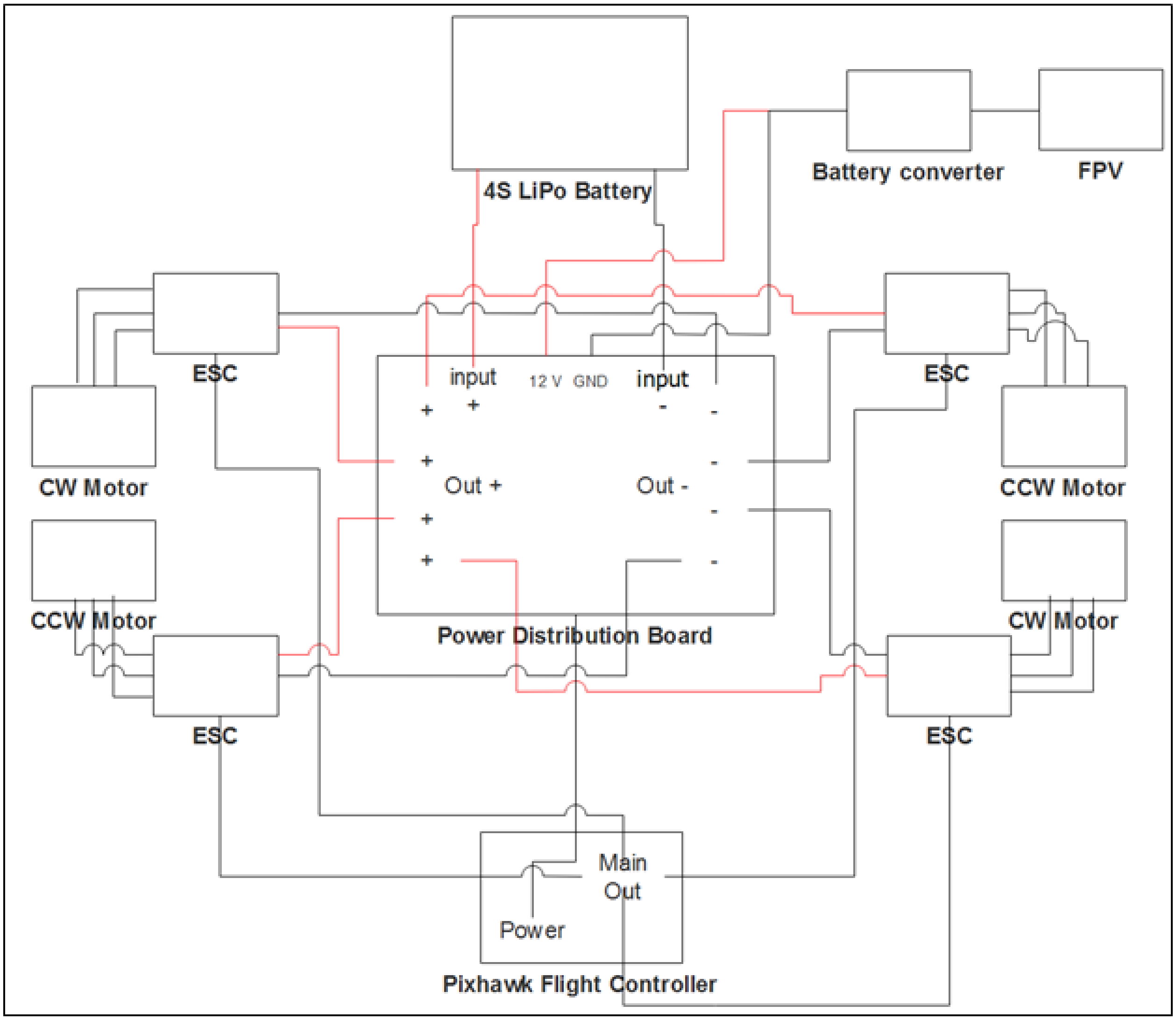

Figure C3. Blown-up section of circuit diagram for the Power Distribution Board

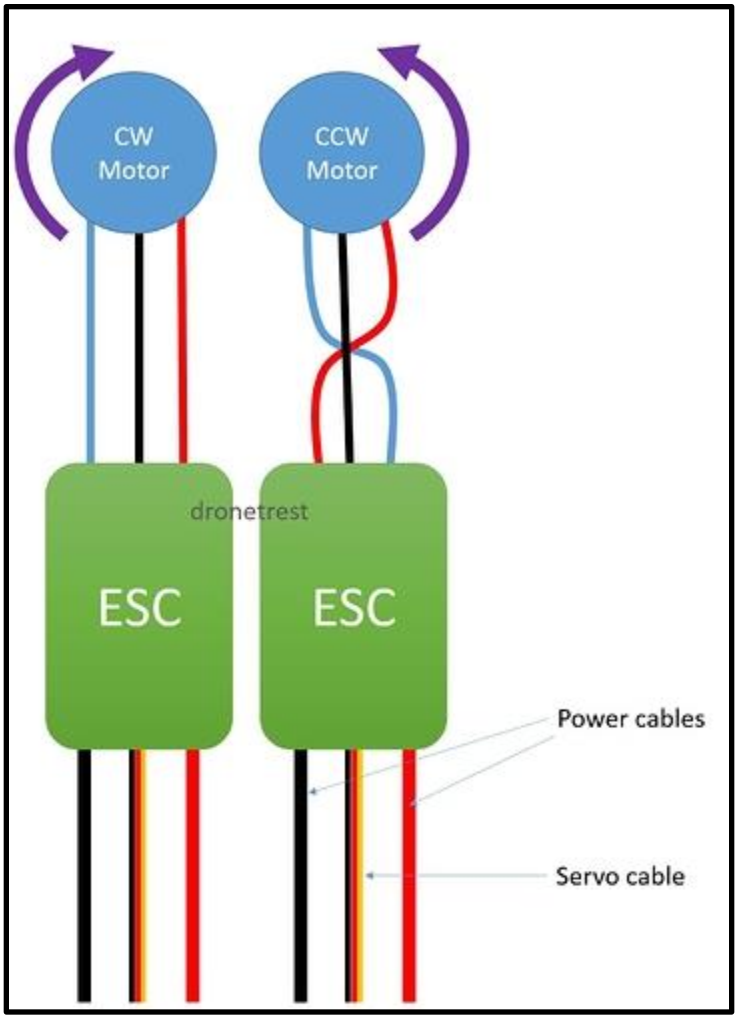

Figure C4. ESC connections to brushless motors [6]

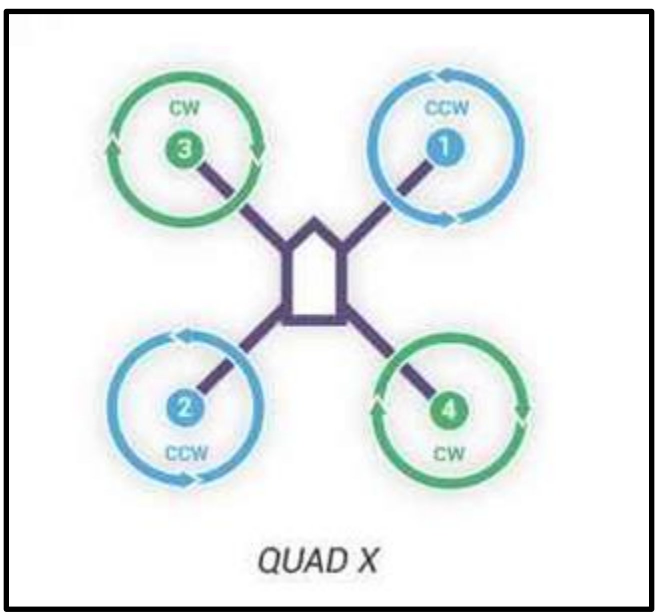

Figure C5. The QUAD X frame type is used for the team's quadcopter through Mission Planner [5]

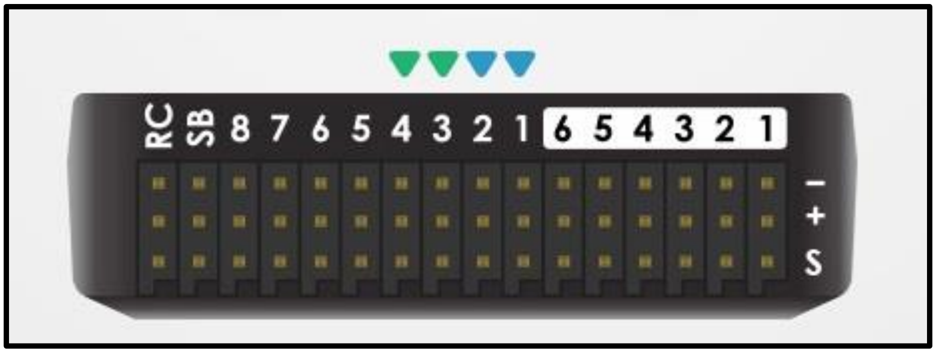

Figure C6. ESC connections to Pixhawk Main Out pins with numbers based on QUAD X frame in Figure C5. The team's ESC'S signal wires were white [5]

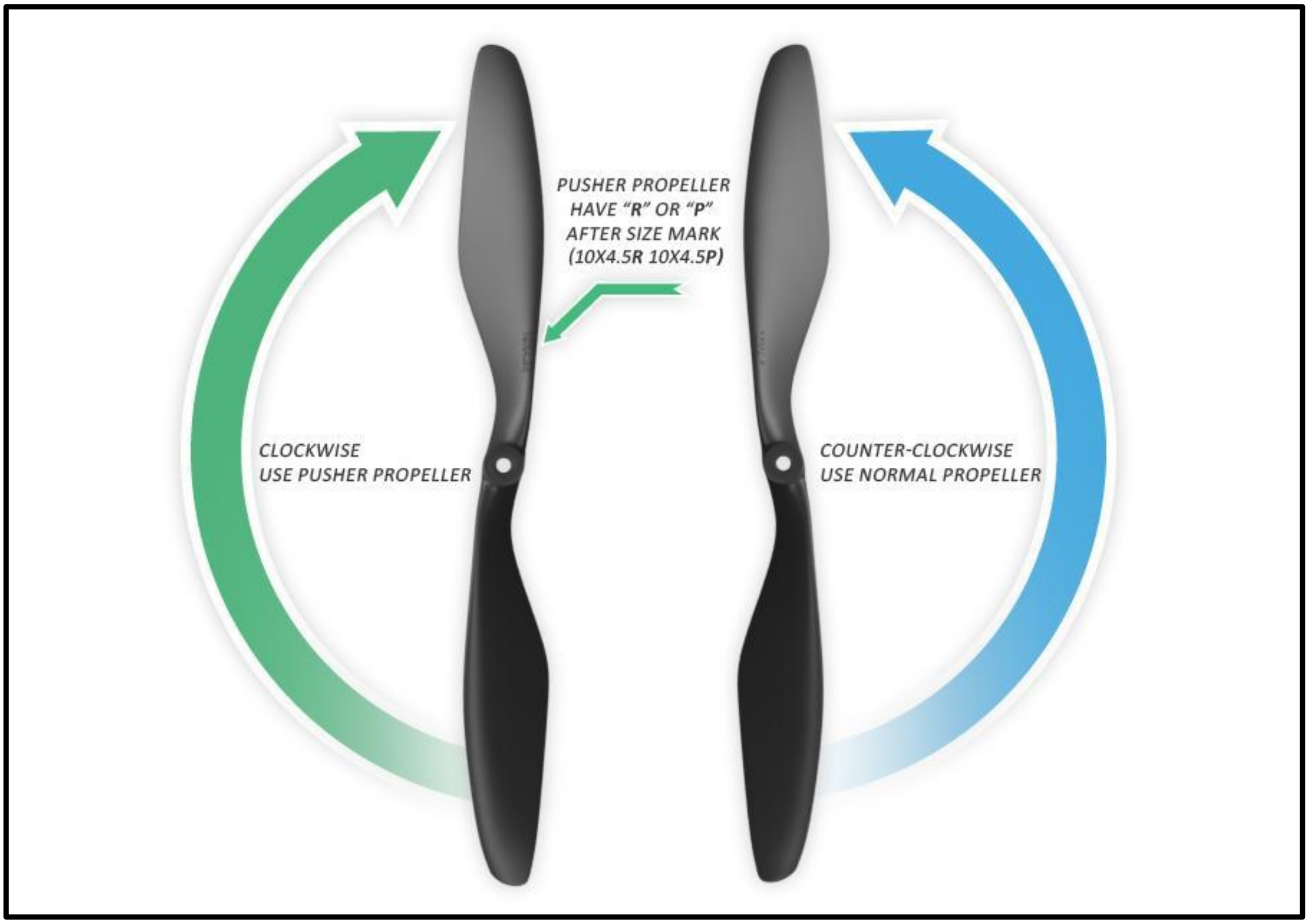

Figure C7. Propeller selection is determined by their motor rotation [7]

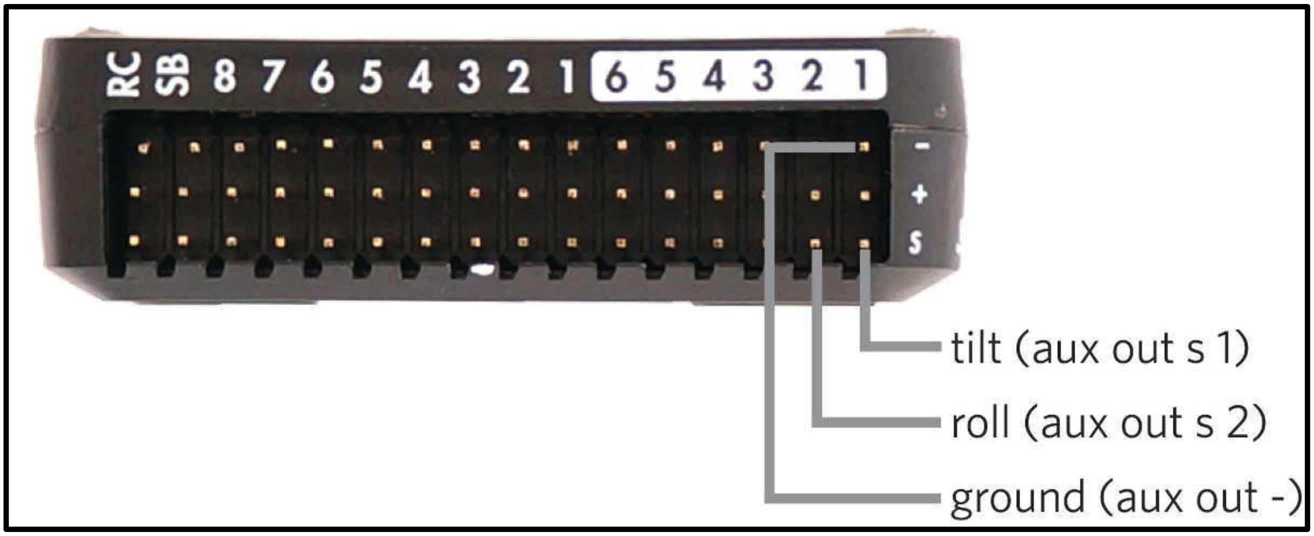

Figure C8. Gimbal connection on Pixhawk [5]

Appendix D: Motor Calculation Graphs

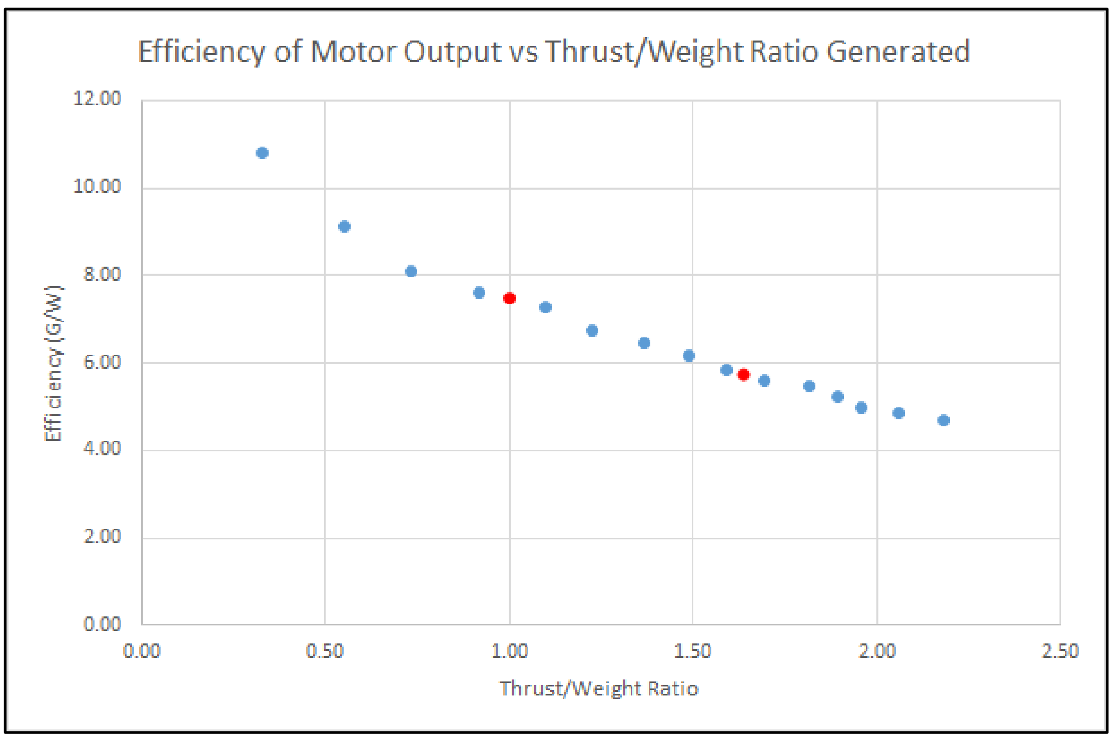

Figure D1. Plot of the efficiency of the motor/propeller pair against the thrust to weight ratio. The efficiency is defined as the amount of thrust in grams over the power required by each motor. The Thrust to weight ratio is based on the thrust of all four motors. The red dot represents hovering.

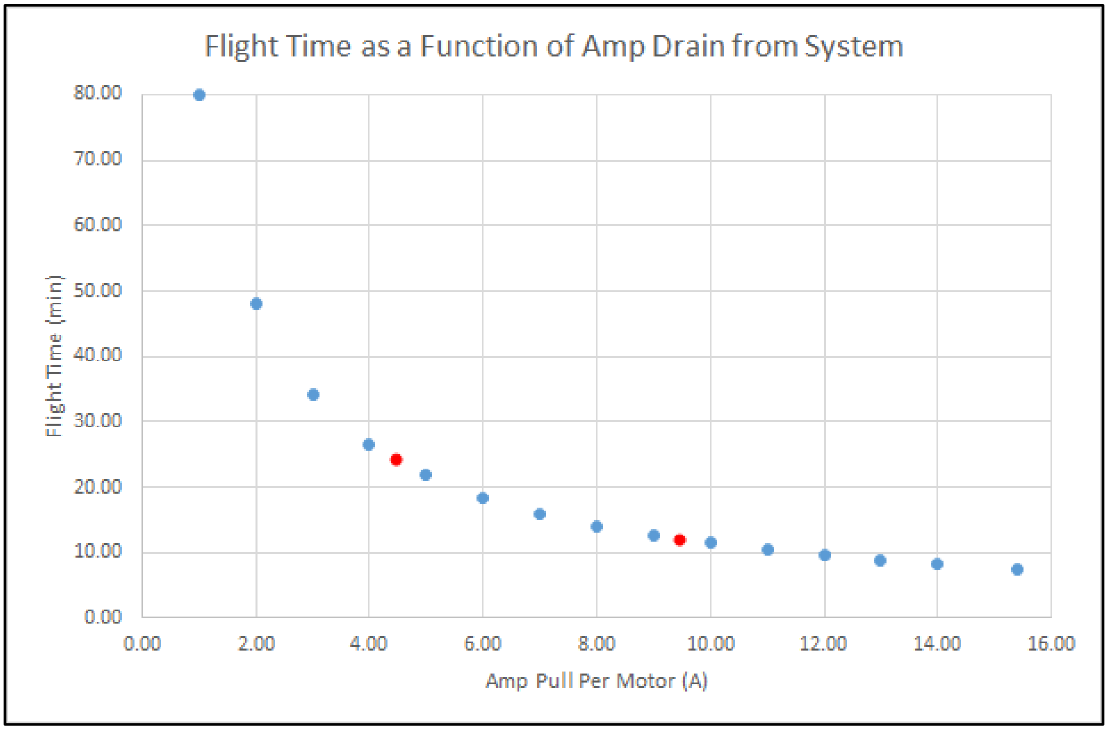

Figure D2. Plot of the estimated flight time against the current drawn from each motor. The flight time is calculated by estimating the total current drawn from the battery by the system at various thrust to weight ratios. The red dot represents hovering

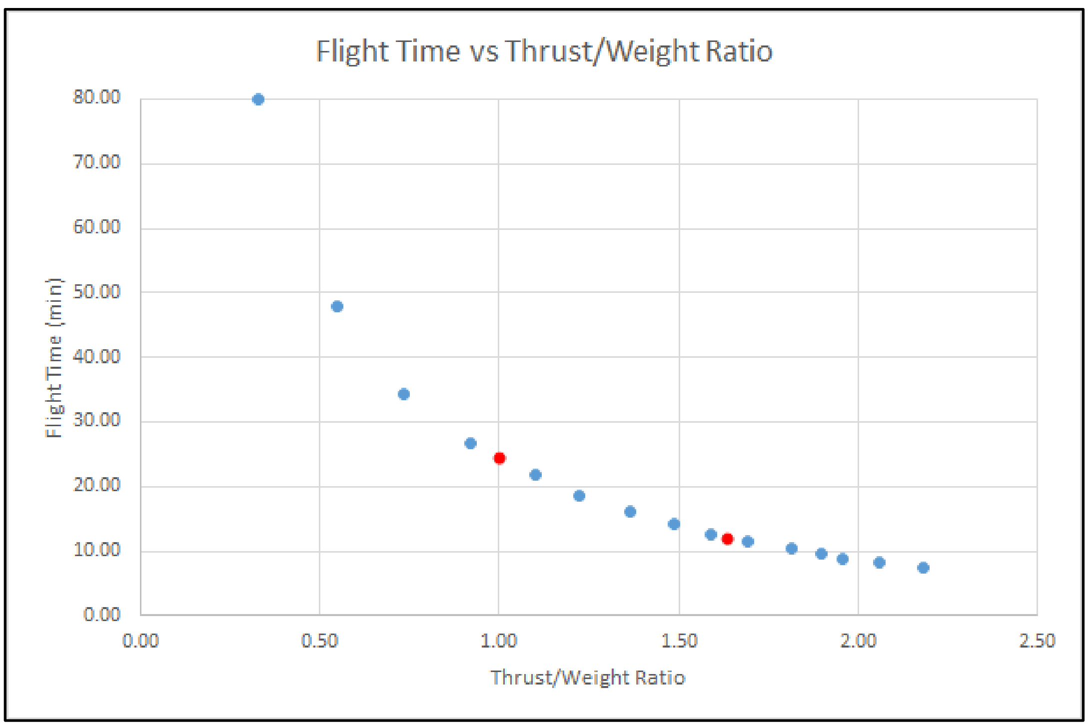

Figure D3. Plot of the estimated flight time against the thrust to weight ratio. The Thrust to weight ratio is based on the thrust of all four motors. The red dot represents hovering

Appendix E: SolidWorks Components

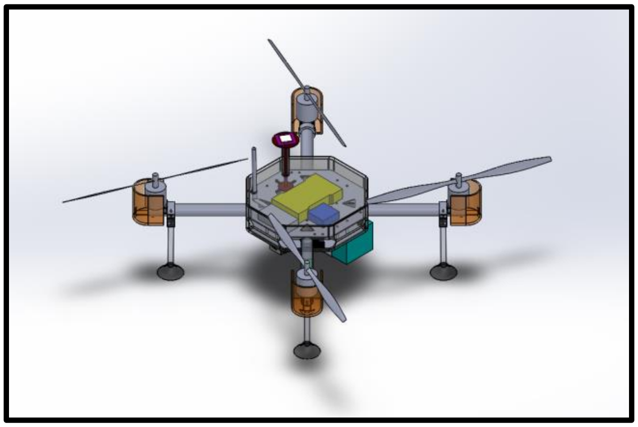
Figure E1. Design from DDR

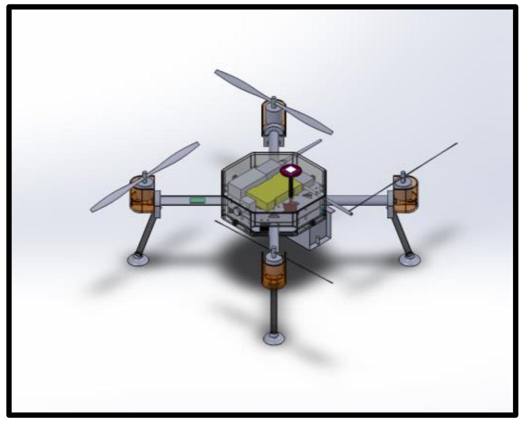
Figure E2. Final Design

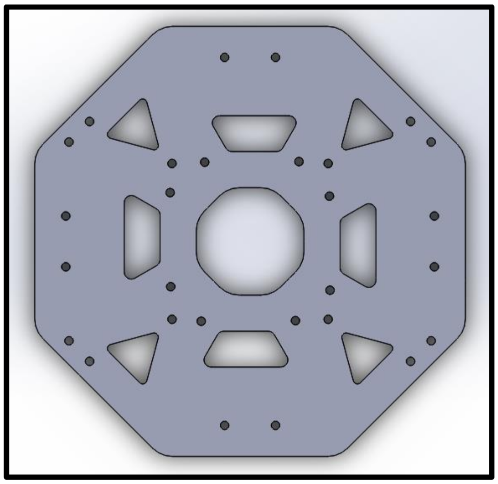
Figure E3. Top base plate of the airframe

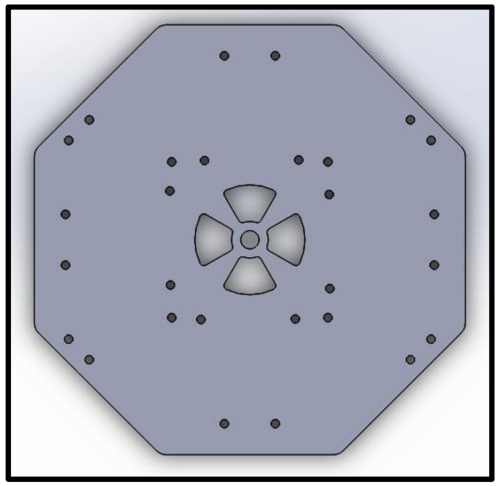
Figure E4. Bottom base plate of the airframe

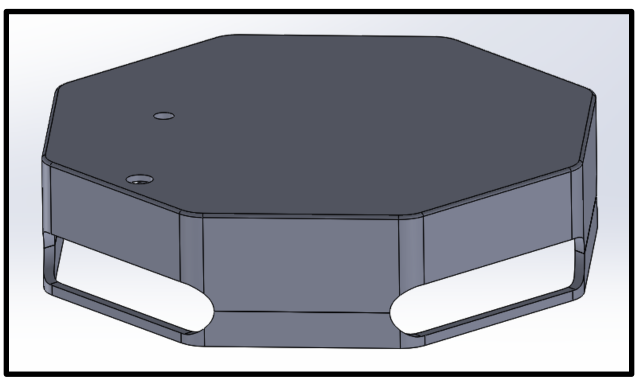
Figure E5. Dome design from the DDR

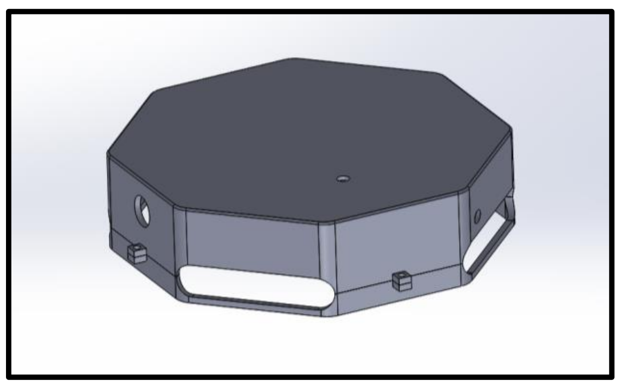
Figure E6. Final dome design

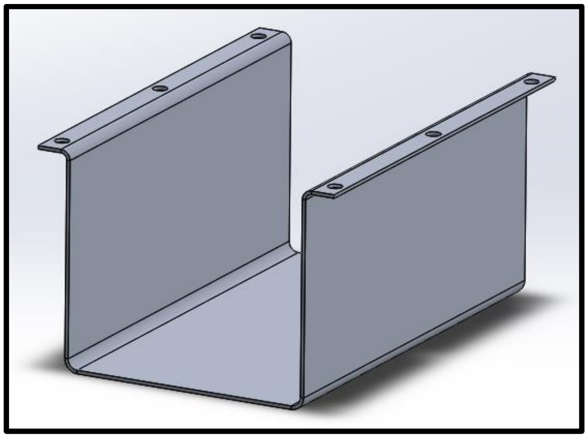

Figure E7. Battery box design from DDR

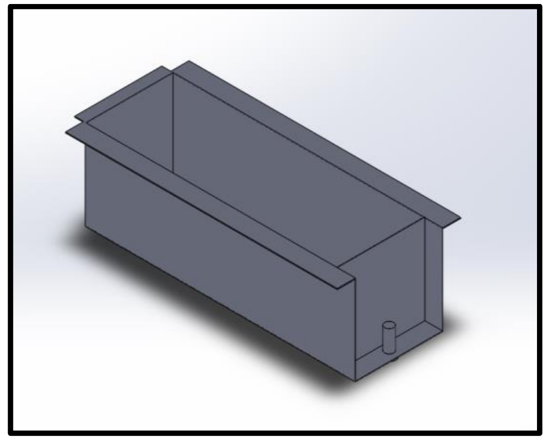

Figure E8. Final battery box design

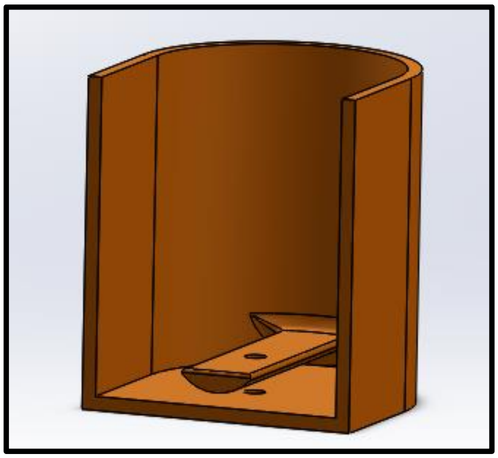

Figure E9. Motor guard design from DDR

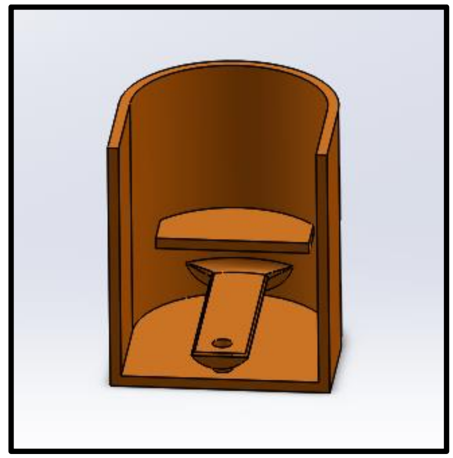

Figure E10. Final motor guard design

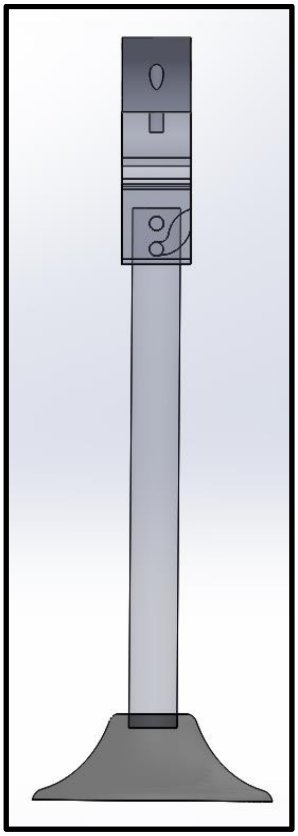

Figure E11. Landing leg design from DDR

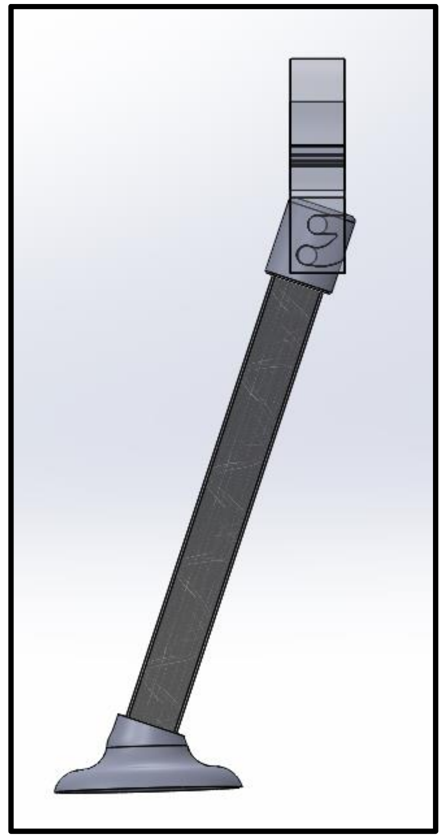

Figure E12. Final landing leg design

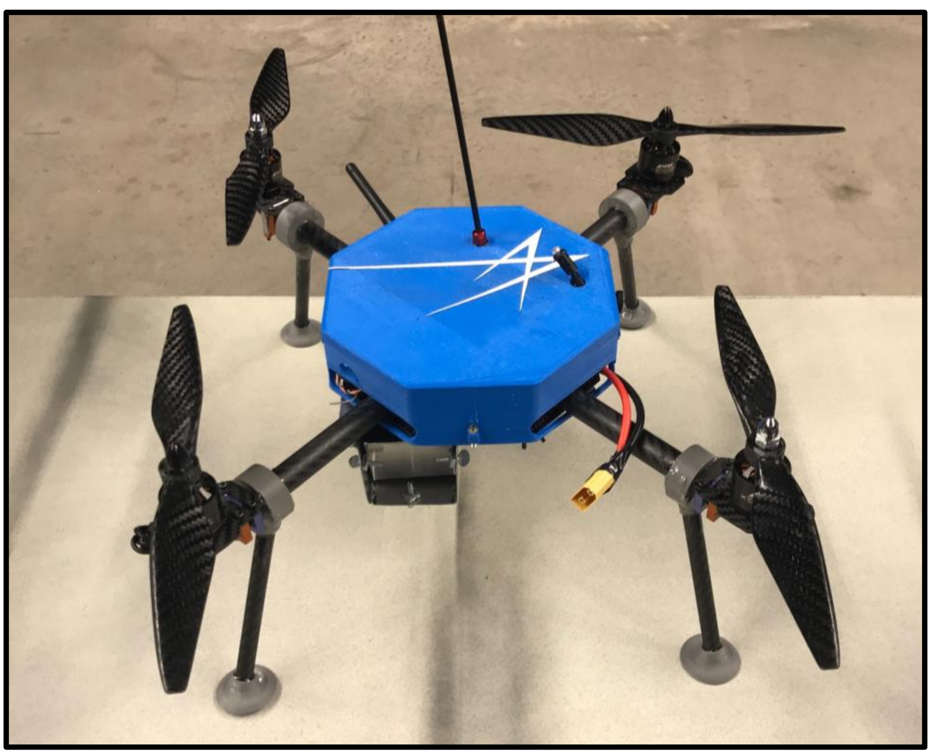

Figure E13. Final assembled product made from the solid works designs

Appendix F: Manufactured Components

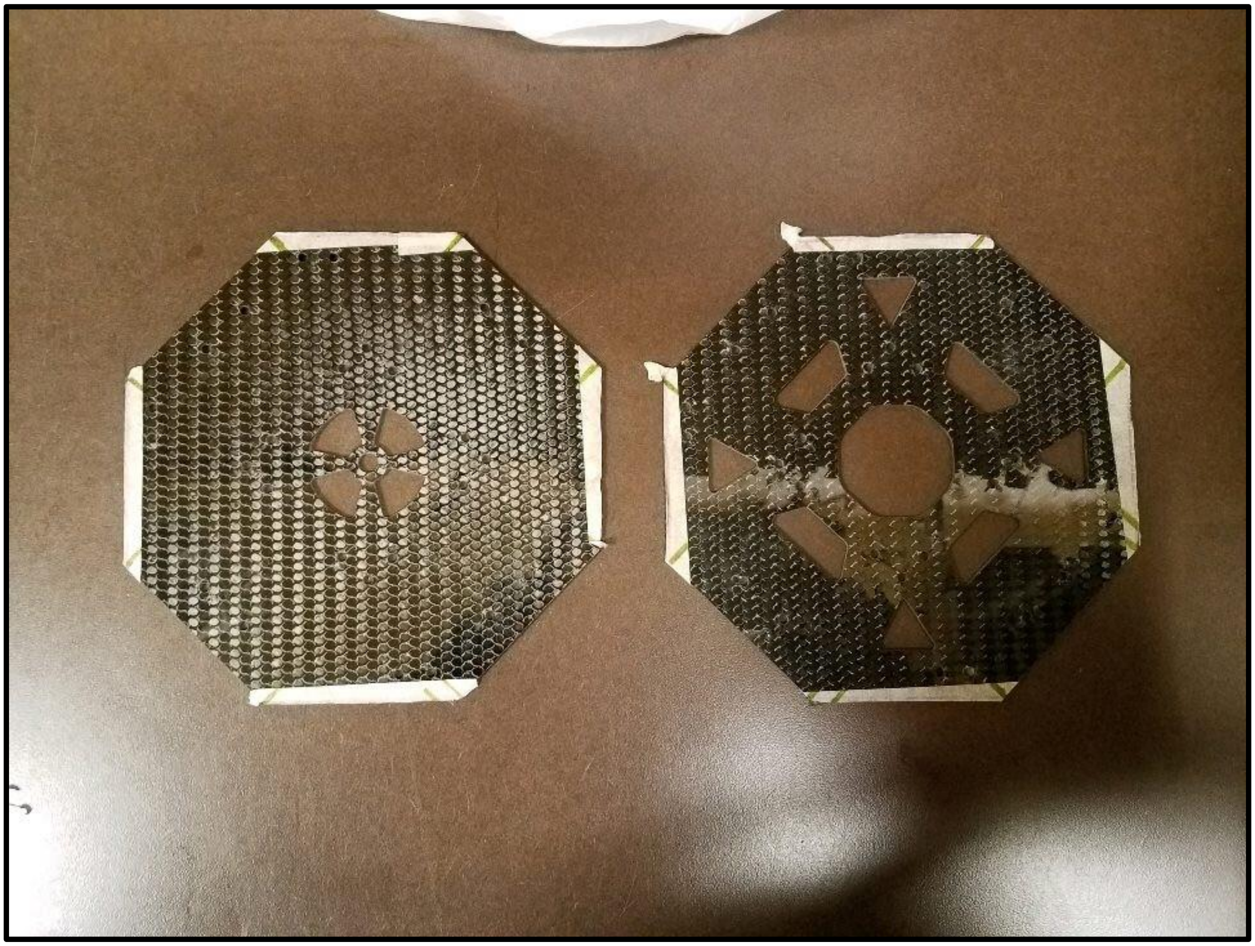

Figure F1. Carbon Fiber Sheets Machined to Size

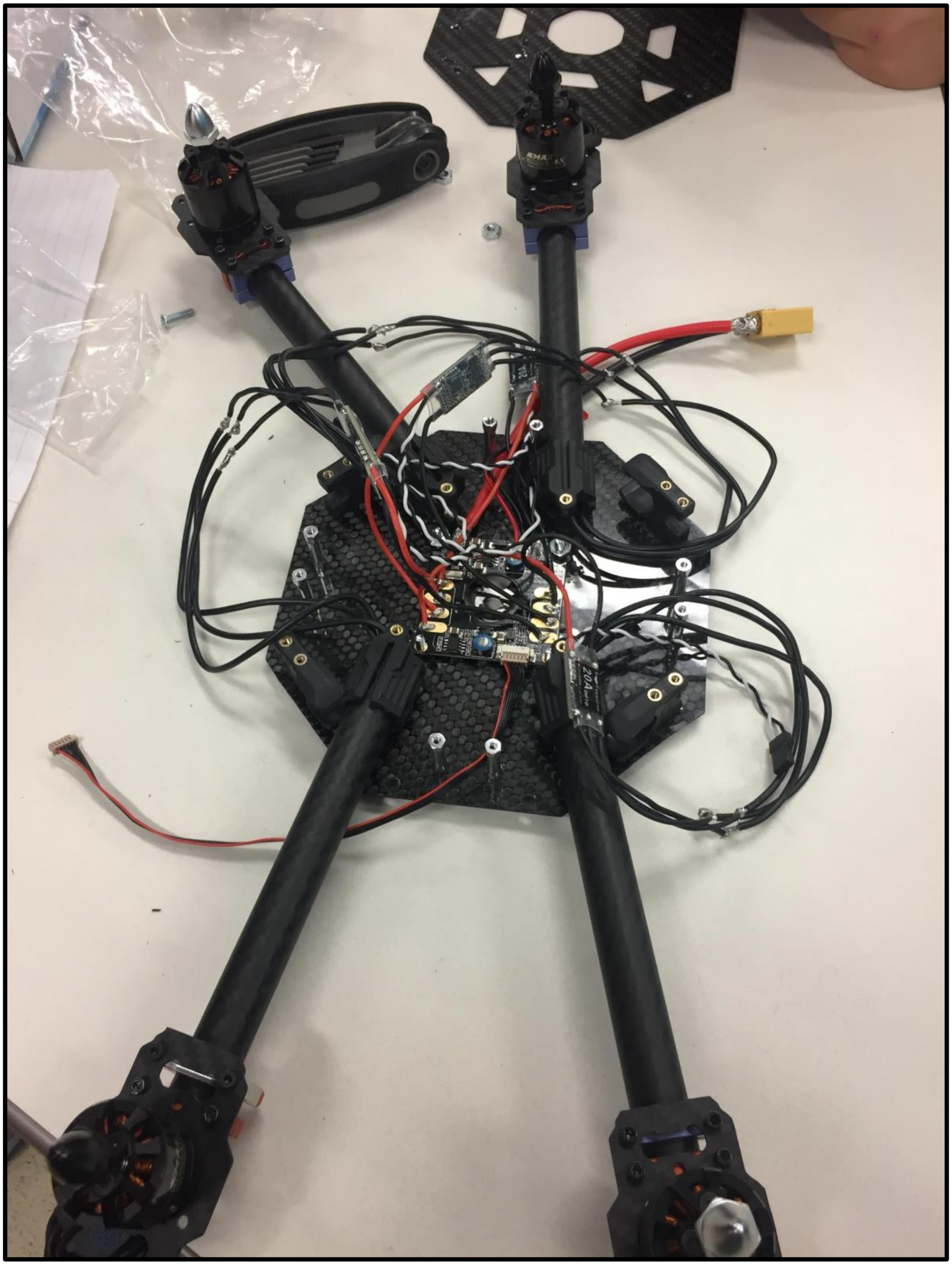

Figure F2. The Inner Base housed the Power Distribution Board and Essential Wiring

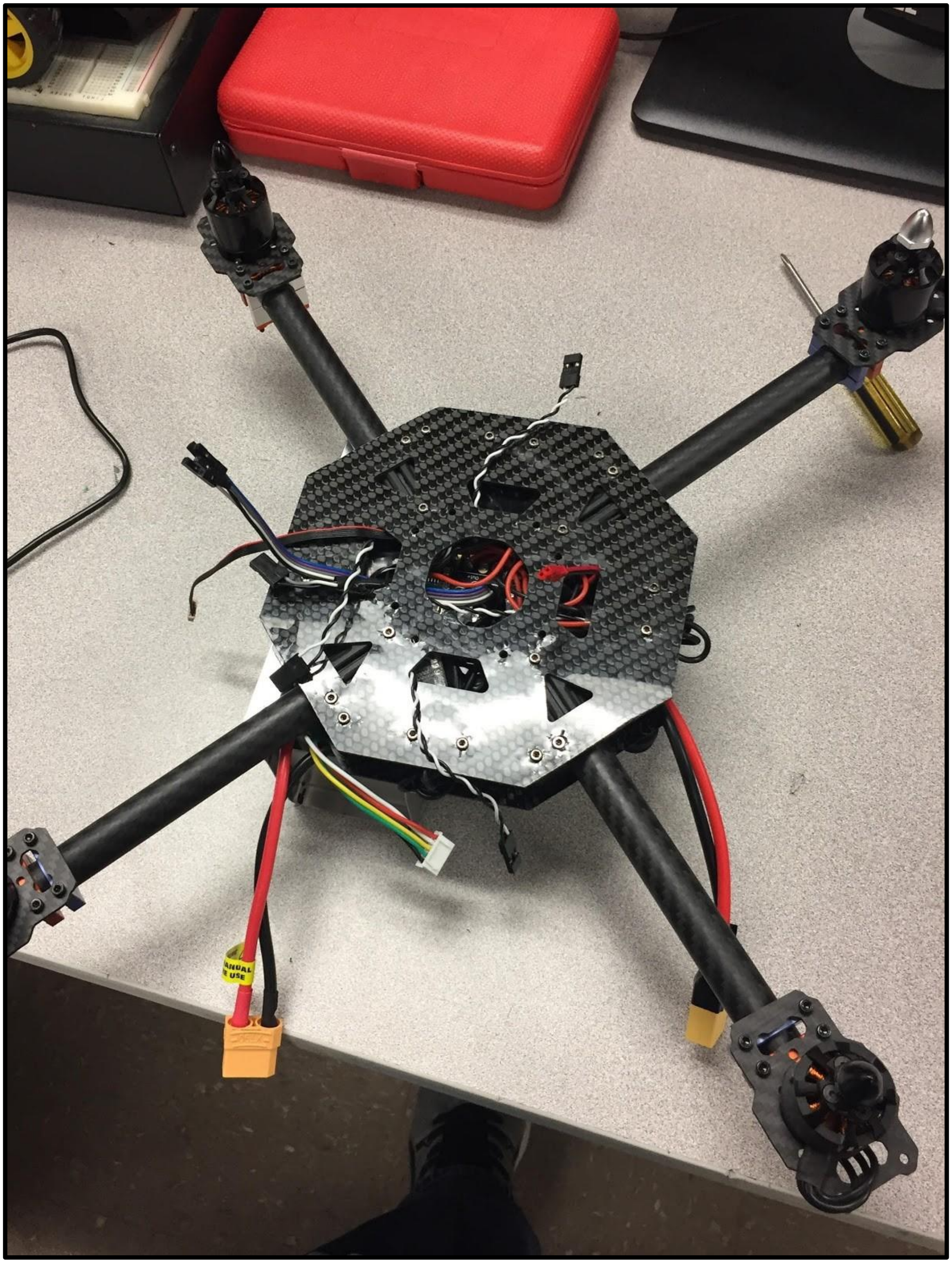

Figure F3. The two waterjet carbon fiber plates protected and housed all the main components

Figure F4. 3D Print of Base Shroud

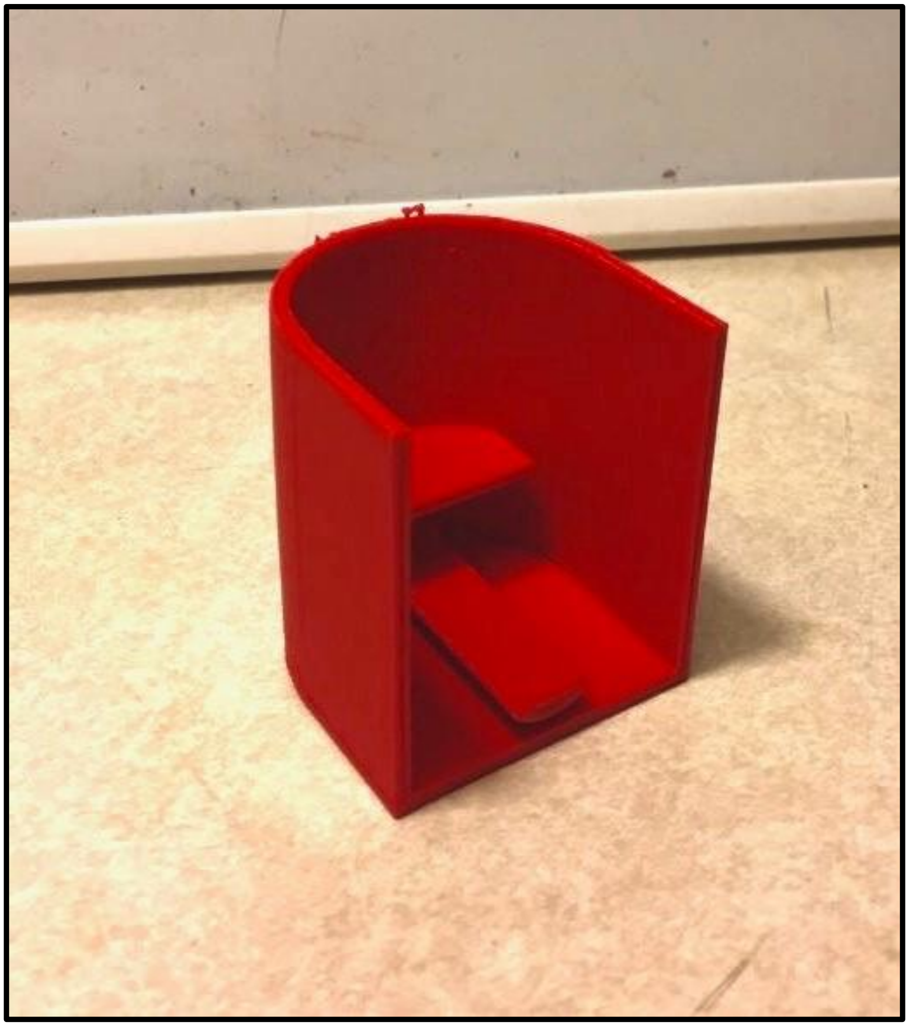

Figure F5. 3D Print of Motor Guard

Figure F6. Cut Carbon Fiber Arms