Unmanned Aerial Radio Tracking System for Monitoring Small Wildlife Species

Final Proposal

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DISCLAIMER

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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 needed to be 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 drone for collecting the signal locations more efficiently. He then established the capstone team that would design the first model of this drone, 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 requirements 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. 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).

The second iteration involved the design of a new frame and used the existing electronic components. 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”. Iteration three was designed to remedy these resonance issues that were present in iteration two and was still in progress at the time of this writing. The following sections outline these designs.

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.

Figure 1 - Iteration 1 CAD drawing [2].

Figure 2 - Iteration 1 final design [2].

Final cost of the frame materials was $202.75. An itemized cost list can be seen in Table 1.

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.

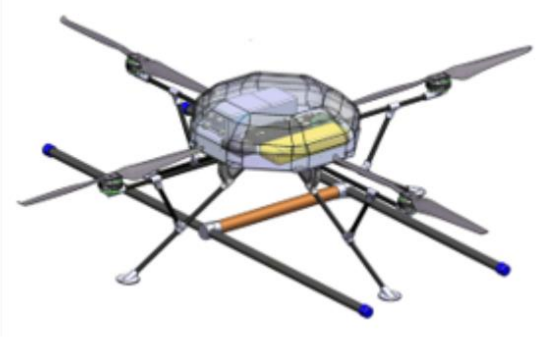


Figure 3 - SolidWorks model of Iteration 2.

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.

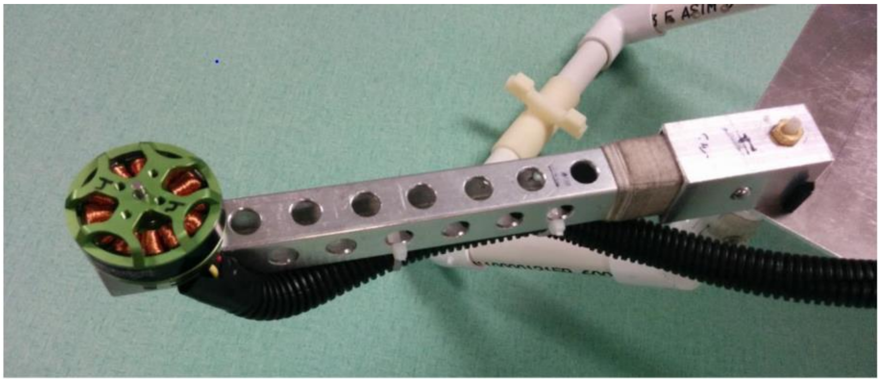


Figure 4 - Iteration 1 arm assembly [2].

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 include 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 of the multirotor, 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 multirotor 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 drone 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 the performance time of the drone. 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 drone flight.

If the drone 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 the structural integrity or performance of the drone. 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 quantities, some are just more precise 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 copter frame needs 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 is desired to a weight under one pound.
High Power to Weight Ratio	The drone, including the tracking equipment rig, should have a high power to weight ratio as a built in factor of safety. The team’s target is a 2:1 power to weight ratio, but would like to exceed that if possible to anticipate any other use our client has for the drone.
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.
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 should be able 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 will make any part less than 2 in connect to the body of the quadcopter by magnet or tether.
Payload Under Prop Height/	Both the 'Payload Under Prop Height' and 'Payload Attached to Underside of Platform' requirements are to lower the center of gravity and provide the drone with an inherent stability during flight.
Payload Attached to Underside of Platform	
Built from Easily Accessible 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 should be constructed of cheap and easily accessible materials.
Cheap Material	
Stable During Flight	The operators are not experienced with flying drones so the drone should 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 will be 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. In order to get the desired resolution, we will use smaller scales that have higher resolutions.

2. To test the thrust, each motor will be attached to an arm of the quadcopter with a weight attached that is known to be more than the theoretical thrust of each motor. The motor, arm, and weight combination will be placed on a scale and run to full throttle. The scale will be zeroed and the absolute value of the reading from the scale will be taken as the thrust of said motor being tested.
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 will drop the drone from 4 ft, and assess the damage. Weak points will be fortified and retested until the desired result is accomplished.

4. A torsion test will be administered to find the relative torque that each arm can withstand. This

test will be performed by placing a weight on a moment arm of specified length. The arm will then be 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 needs to be calculated in order to create an arm that will be able to withstand repeated use.

5. A maximum load and fatigue test will be conducted on the frame to find the breaking points. If the part that breaks is a piece that should not break (because it is expensive or difficult to replace), it will be redesigned to have a higher factor of safety. The team will repeat the test until an acceptable part becomes the breaking point.

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

7. Each part will be modeled in SolidWorks to get the exact dimensions. This will get the total volume, weight, and the location of the center of gravity (CG). The CG needs 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 will be conducted to ensure the parts can be easily and consistently found at a low cost. Additionally, the team will be searching for recycled material (such as arrows) that can be retrofitted for the drone. Cheap electronic replacements can be 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 we can provide SolidWorks files for the joints.

9. The final test will be a flight test of the quadcopter itself. This test will be 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 will be administered with a tether to abide by the FAA Rules and Regulations. They will also be compared to the 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.

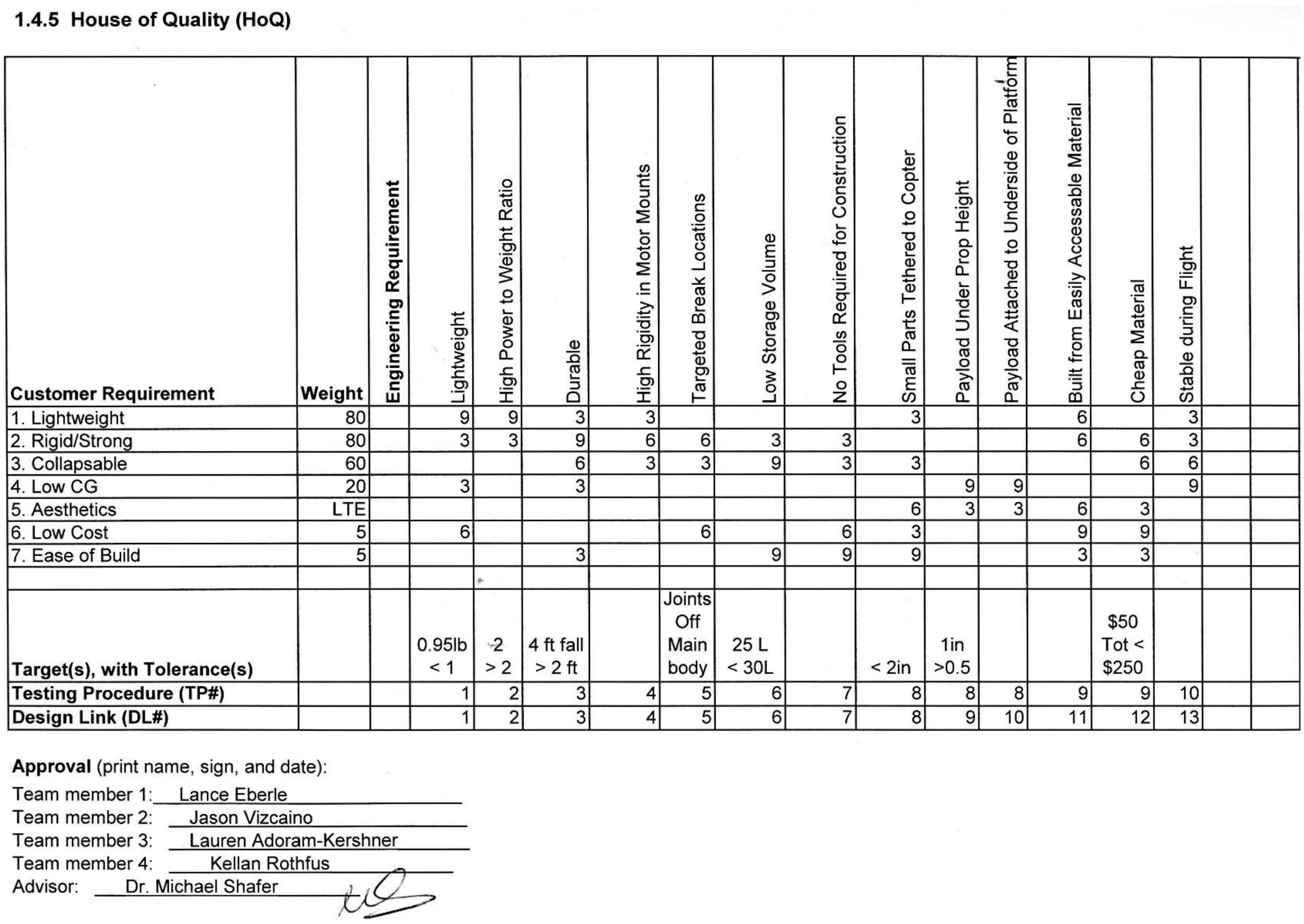
1. Carbon fiber arrow shafts are known to be lightweight. The extensive use of these shafts for the frame, as the skeletal structure, will yield a low mass per volume design. Additionally, the 3D printed joints, if made out of an appropriate material and reasonably dimensioned, will not add a substantial amount of weight.
2. The methods described above to reduce the weight will increase the power to weight ratio. This will provide better flight efficiency and increase flight time. A more efficient quadcopter will allow the use of the last iteration's electronics set up and decrease the current draw from the batteries which prevents overheating of electronic components.
3. The durability of the frame's design will be ensured by the use of trusses to create the arms and

body of the quadcopter; these trusses will be made from carbon fiber shafts. The shafts are strong in the axial direction and trusses are the strongest member configuration, both these components ensure a durable and strong frame.

4. Obtaining a high rigidity in the motor mounts is related to the 3-D printed part as well as the quadcopters arms. The arms will consist of two horizontal shafts vertically stacked to minimize the bending and torsion imposed by the motor/propeller system. The motor mounts will be 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 will have designed 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 will be comparable to the average laptop. When collapsed this minimal volume and relatively flat structure will reduce transportation constraints.
7. The arm configuration (press fit joints with cotter pins) will minimize the amount of tools required for construction. Additionally, the support shafts will be held in by slightly bending the arms allowing the support shafts to be held in with a compressive force. This setup will not require any tools for construction, under normal conditions.
8. The only parts on the drone 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 is made out of recycled carbon fiber arrows and the joints are 3-D printed. This minimizes 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 will also feature a square motor configuration to increase stability.

2.5 House of Quality (HoQ)

The House of Quality is 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 to date. Customer requirements and the resulting engineering requirements are subject to change until the completion of 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

3 EXISTING DESIGNS

There are a plethora 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 multirotor.

3.2 System Level

Several existing designs were used for inspiration towards the latest iteration of the multicopter 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 5 - 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.

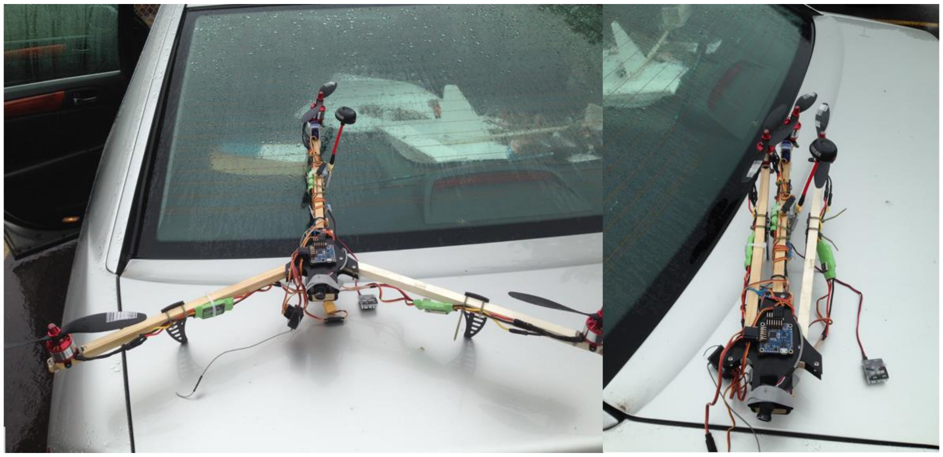


Figure 6 - RCExplorer tricopter.

3.2.3 Flite Test ElectroHub

This design uses trusses to obtain the torsional rigidity of the arms. Each member of the truss is made of wood and connected via 3D printed brackets. This truss 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 7 - FliteTest ElectroHub [9].

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 8) 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.

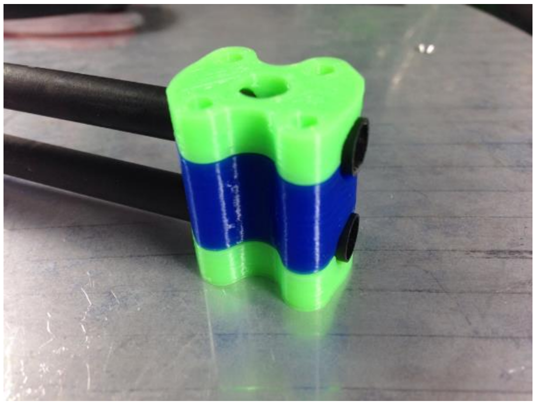


Figure 8 - Jimustanguitar motor mount [5].

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 9. 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 9 - 12mm plastic motor mount for multirotors [6].

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 9, 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.

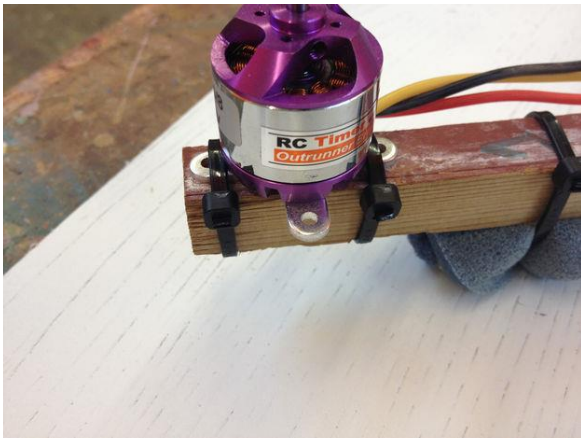


Figure 10 - Zip-tie motor mount.

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 6, 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 7, 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 11, 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.

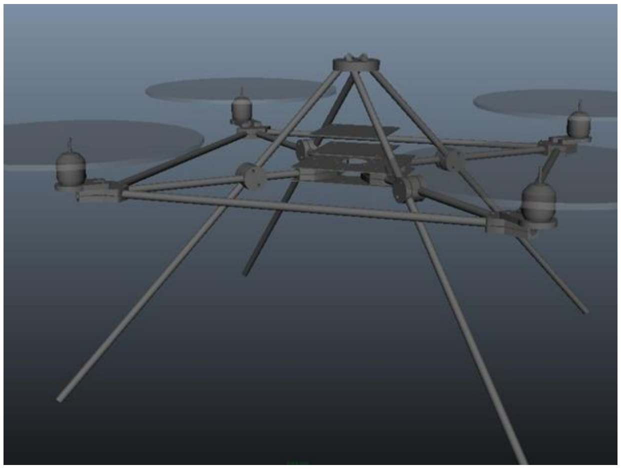


Figure 11 - Carbon fiber quadcopter frame [7].

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 requires 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 11 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 12), allows for a large area to place the electronics. This design allows for a folding arm design, which satisfies the collapsibility requirement.

Figure 12 - MultiRotor H quadcopter [8].

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 13 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 multirotors (Figure 14).

Figure 13 - Capstone quadcopter.

4 DESIGNS CONSIDERED

This section will briefly discuss 10 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 drone. Several Pugh charts were used to focus on viable ideas. The original Pugh chart with all 21 ideas and can be reviewed in the Appendix. The concepts were reduced to 10-targeted ideas. The advantages and disadvantages for the 10-targeted ideas were the deciding factors leading to construction consideration. Table 2 outlines the 10 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 – 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.

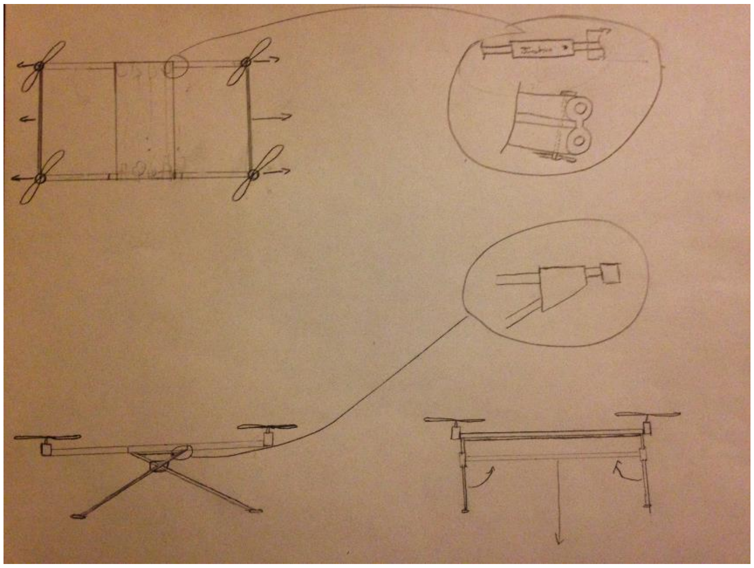


Figure 14 – Dragonfly Inspired Copter sketch.

Pros:

- Compact when collapsed
- Rigid
- Lightweight

Cons:

- Intricate part design

May be more costly than other designs

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.

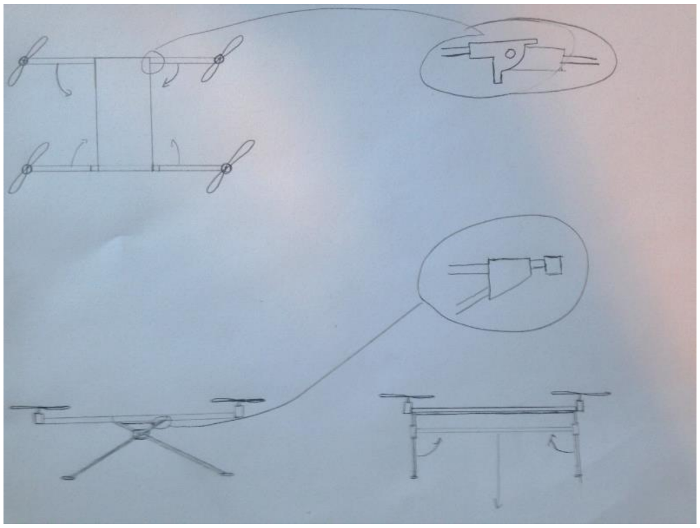


Figure 15 – H-body swivel.

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 copter is a pipe. The pipe houses all of the electronic components, except the motors, and will be the main structure for the multirotor. 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 copter 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 copter 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.

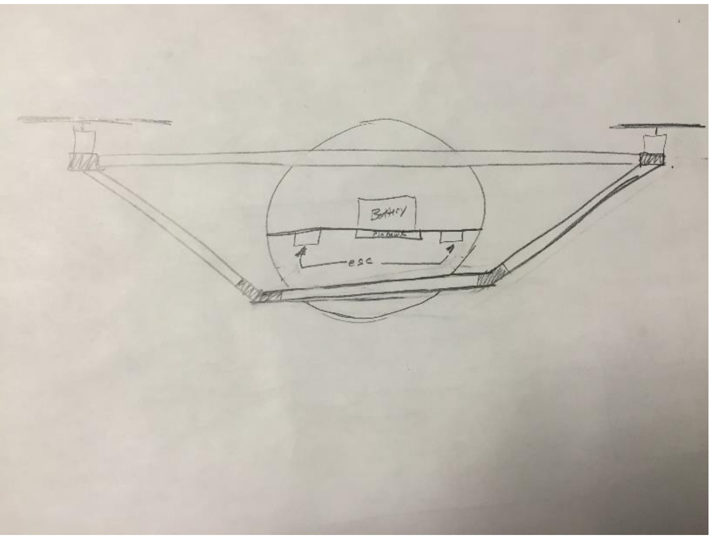


Figure 16 – Front view of pipe body design.

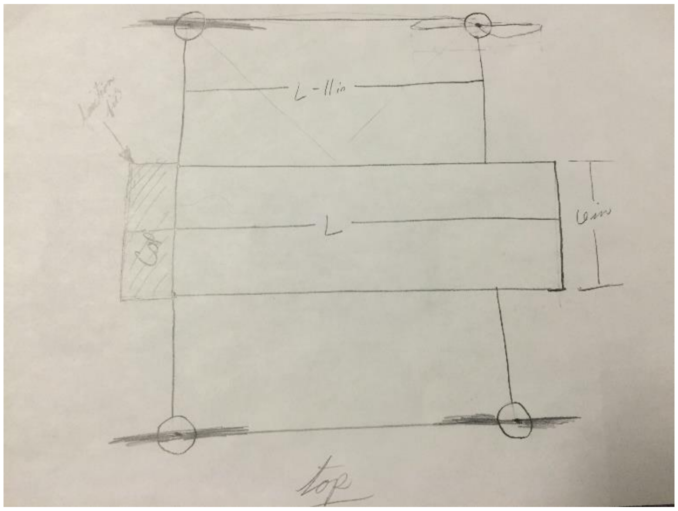


Figure 17 – Top view of pipe body design.

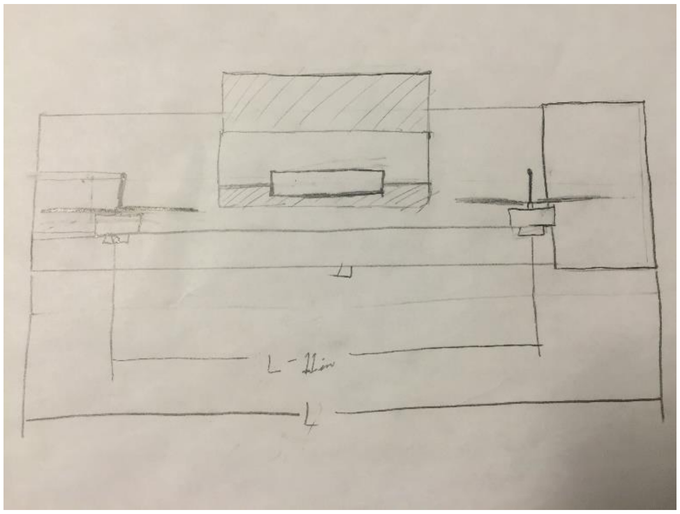


Figure 18 – Side view of pipe body design.

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 the team's final design presented below.

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 our considered designs, a frame was decided upon by the team in conjunction with our Sponsor, Dr. Michael Shafer.

A frame that has multiple layers, such as the FliteTest ElectroHub (Figure 13), 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 wasn't 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 19), from our (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.

In order to reduce the overall weight of the quadcopter and keep the overall rigidity of the frame, a layered design will be implemented. Two carbon fiber plates that are both 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 19).

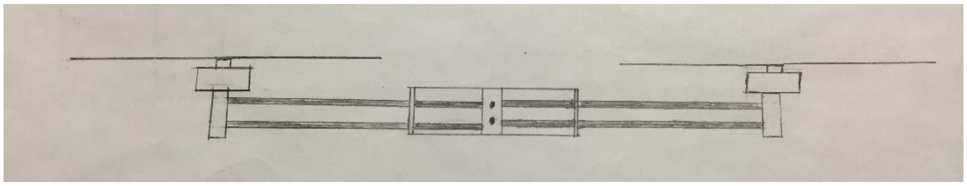


Figure 19 – Sketch of Dual Boom/Dual Plate design.

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 20) showed some pitfalls 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; also, 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 20 – Prototype of final design.

6 IMPLEMENTATION

In consideration of the final design, the team has made a full scale prototype out of cardboard and wooden dowels to gain perspective on dimension adjustments that need to be made. The team plans to prototype the docking plates to ensure there are no electrical component sizing constraints. Additionally, the team is currently refining the CAD models for the joints that will connect the arrow shafts.

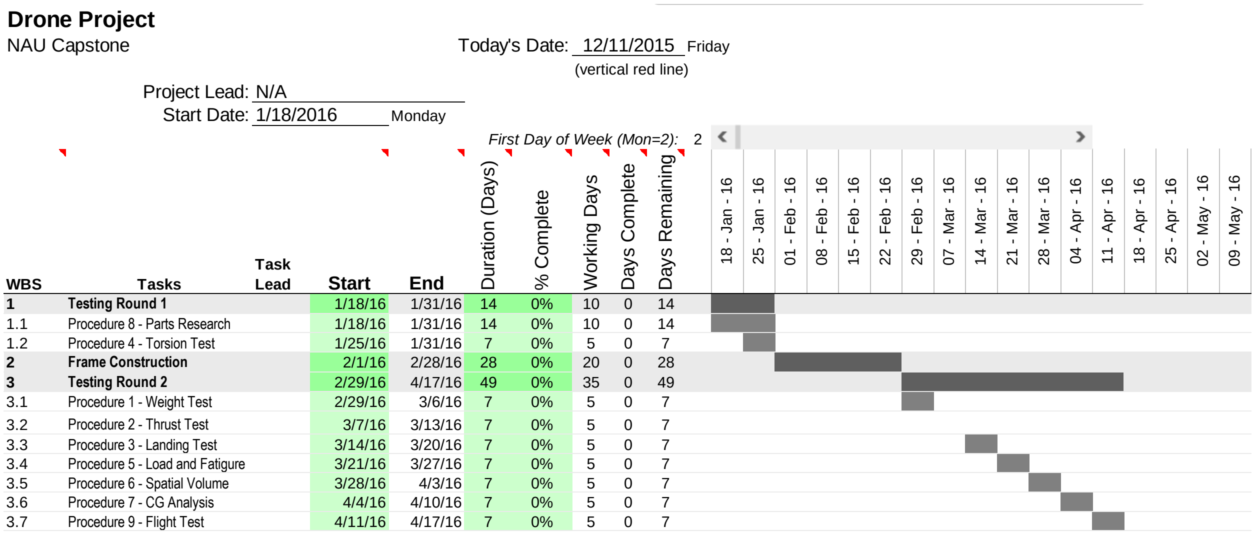
To effectively test the design, the team plans to gain permission to use equipment present in the machine shop. The possibility of using a personal lab of a faculty member is also an option that is being explored. If testing equipment is not confidently reserved for use by the end of December, campaigns to local shops will be made to find a viable testing location. The team will also proposition archery retailers for sponsorships or donations of arrow shafts to partially fulfill the material requirements. All other materials that have been projected to be used will be school funded (3-D printed joints) or bought at retail. The electrical components that will be used once the frame is complete will be harvested from the previous iterations. Any of the electrical components that fail or need to be upgraded will be bought by

Dr. Shafer. A complete projected bill of materials is displayed in Table 6.

Table 4 – Projected Bill of materials.

Component	Description	Quantity	Price	Total
Base Plate	28X28 cm Carbon Fiber or Fiberglass Square Plate	2	$10-$50	$20-$100
Shafts	Carbon Fiber Arrows 12pk	1	$0-$31	$31
Fasteners	Cotter Pins and random fasteners	n/a	$15	$15
Joints	3-D Printed	8	$0	$0
				$35-$146

Due to the ambiguity of the budget for this project the team has created a worst-case-scenario analysis for the cost of production. If the budget remains zero dollars then the team will have to provide finances of up to [blankity blankity blank] dollars through sponsorships or out of pocket. This situation will need to be resolved by January 20th to maintain the structure of the building/testing schedule. This schedule can be reviewed in Figure 21.



Drone Project

NAU Capstone

Today's Date: 12/11/2015 Friday
(vertical red line)

Project Lead: N/A
Start Date: 1/18/2016 Monday

First Day of Week (Mon=2): 2

WBS	Tasks	Task Lead	Start	End	Duration (Days)	% Complete	Working Days	Days Complete	Days Remaining
1	**Testing Round 1**		1/18/16	1/31/16	14	0%	10	0	14
1.1	Procedure 8 - Parts Research		1/18/16	1/31/16	14	0%	10	0	14
1.2	Procedure 4 - Torsion Test		1/25/16	1/31/16	7	0%	5	0	7
2	**Frame Construction**		2/1/16	2/28/16	28	0%	20	0	28
3	**Testing Round 2**		2/29/16	4/17/16	49	0%	35	0	49
3.1	Procedure 1 - Weight Test		2/29/16	3/6/16	7	0%	5	0	7
3.2	Procedure 2 - Thrust Test		3/7/16	3/13/16	7	0%	5	0	7
3.3	Procedure 3 - Landing Test		3/14/16	3/20/16	7	0%	5	0	7
3.4	Procedure 5 - Load and Fatigure		3/21/16	3/27/16	7	0%	5	0	7
3.5	Procedure 6 - Spatial Volume		3/28/16	4/3/16	7	0%	5	0	7
3.6	Procedure 7 - CG Analysis		4/4/16	4/10/16	7	0%	5	0	7
3.7	Procedure 9 - Flight Test		4/11/16	4/17/16	7	0%	5	0	7

Figure 21 – Tentative schedule.

7 CONCLUSIONS

The success of the project is impart to meetings with the project sponsor and the experience the team had with the previous iteration of the drone. During meetings with the team's sponsor, Dr. Michael Shafer, the design was refined and simplified. This allowed for easy analyzation and optimization of each element's effectiveness. Additional success was due to the team's involvement with the design of the 3rd iteration. Understanding the thought process behind the design helped the team avoid previously encountered obstacles and focus on the improvement of the newest iteration.

Proceeding with the design development, a more in depth analysis of the member rigidity, joint and central hub structure, and landing gears will be conducted. The analysis of the double boom arm design will validate its ability to properly counteract the torsion of the motors. Additionally, the analysis on the joints and central hub will allow excess material to be remove and ensure a lightweight yet still structurally sound design. Finally, the landing gears are not developed for the newest iteration. Plans to use the landing gears from the last iteration would be acceptable, however, a more light weight and intelligent design can be developed. The central hub and arm assembly design went through numerous iterations making the development of the landing gears difficult to complete. Therefore, this element of the final design will be completed during the first part of the next semester.

8 REFERENCES

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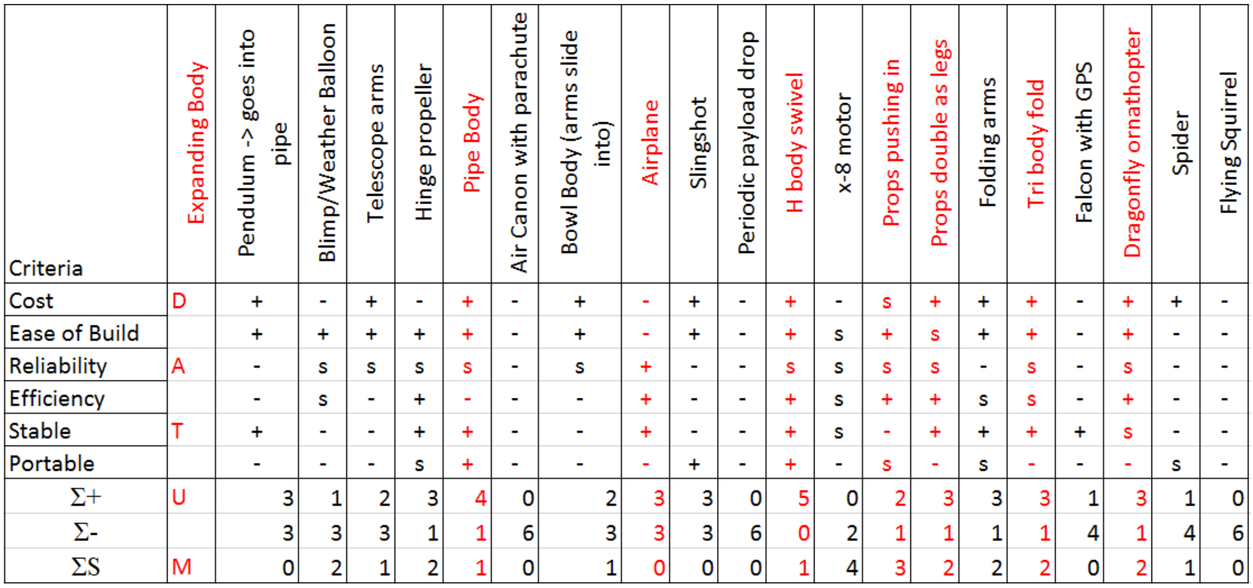
APPENDIX

Table A.1- Pugh chart encompassing 21 original design concepts.



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