Design for Manufacturing, Reliability, and Economics

Team 8: AUVSI Design Competition

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SUBMITTED TO: DR. GUPTA, DR. FRANK, DR. SHIH

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I. INTRODUCTION

Team 8's goal for the senior design project was to build an aircraft capable of vertical takeoff and landing. An important aspect to consider for the final aircraft design was manufacturing. Using proper design for manufacturing techniques, the cost and quality of the final product can be greatly improved. These techniques include, but are not limited to: reducing the number of parts, use of standard components, ease of fabrication, and minimizing assembly steps [1]. Reliability is another important feature of the final design. The aircraft must be able to withstand not only the forces being applied to the system, but also frequent use. It is crucial to chose reliable components for the design. Finally, design for economics is a critical part of the final design. It is important to stay within budget while also creating a design that is comparable to other products on the market. Team 8 has designed an aircraft in which all of these aspects play a major role.

II. DESIGN FOR MANUFACTURING

The first of the above design for manufacturing techniques is analyzing the total number of parts in the system. Our system can be separated into two subsections. The primary subsection is the Senior Telemaster plane. The plane will be treated as one part in our design, as it is pre-assembled for our project and is not being modified. This was very important to Team 8 as it insured the capabilities of the existing system and avoided any destructive modifications. Another reason to avoid any modifications to the plane is that successive senior design teams are expected to utilize the platform. The second subsection of the design is the multi rotor attachment. This subsection includes all new materials being added to the plane in order to achieve vertical takeoff and landing. The multi rotor attachment is comprised of the remaining parts listed in Table I.

It can be seen in Table I that the total number of parts in the final design is 46. Several steps could be taken to reduce this number, however with the given situation, Team 8 did an adequate job at keeping

Part	**Quantity**
Plane	1
Attachment Body Materials	
Plywood Base	1
Polyurethane Foam Pad	1
Industrial Strength Velcro	4
Aluminum 6061 Cross Bars	2
Carbon Fiber Arms	2
ABS Arm Mount Bottom	4
ABS Arm Mount Top	4
G-10 Motor Mount Bottom	4
G-10 Motor Mount Top	4
Quad Rotor Components	
6V Battery	1
Venom 22.2V Battery	2
Cobra 60A ESC	4
Cobra Multi Rotor Motor	4
APC Propeller 18x5.5"	4
Adrupilot APM 2.6 and GPS	1
3DR Telemetry Kit	1
Futaba R/C Receiver	1
Wiring	1
Hardware	n/a
Total Number of Parts	**46**

TABLE I
TOTAL PARTS LIST AND QUANTITIES.

simplicity an important design factor. If provided a larger budget, many of the parts could be exchanged or customized. For example, customizing the base of the attachment could incorporate the cross beams and reduce assembly time, but due to budget and time constraints, cheap and readily available plywood was laser cut to fit the design. Ideally the design should have as few parts as possible to achieve a fully functioning design.

The second aspect considered in the final design was to use standard and available components. By using standard components; complexity, cost, and assembly time are all decreased while repeatability is increased. For the quad rotor attachment, Team 8 chose to use as many standard components as possible. These include plywood for the base, standard 6061 aluminum, protruded carbon fiber, hardware and other parts readily available from local hardware stores or material suppliers. The non-standard components were crucial to the design and kept to a minimum. These components include the motors, propellers, battery packs, autopilot system, and a few others. While these parts are not available locally, they were delivered quickly and easily. Without these non-standard components, the resulting design would not work effectively.

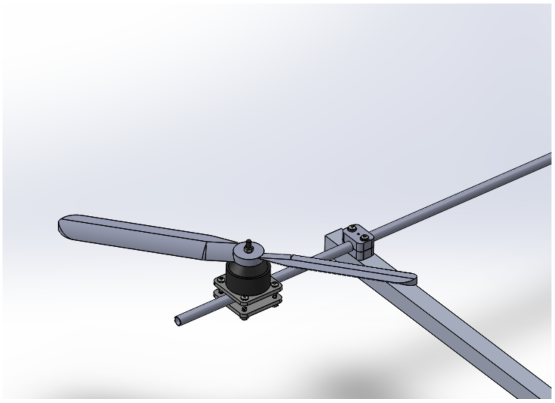
Another important aspect is to keep fabrication simple and to a minimum. For the final design, there are several components that require fabrication, but this fabrication is extremely simple. The plywood base was laser cut due to speed and ease, but could have also been fabricated by hand. The aluminum cross bars only required trimming and several holes drilled in them for attachment of other pieces. This fabrication can be done quickly as well. Next, the carbon fiber arms only required two small holes in each, for positioning purposes. These arms are held in place by two piece ABS plastic clamps. These clamps are fabricated with a combination of four holes and one final cut to separate the two halves. Finally the motor mounts are cut into a square shape with four holes in the bottom mount and five holes in the top mount. All of these parts can be found in Appendix A, with their corresponding drawings. This ease of fabrication requires less time and effort to produce the correct parts. In addition, it leaves less room for fabrication error, which can propagate into error in the final design.

Finally, Team 8 focused on minimizing assembly steps and difficulty. This concept follows the same as all of the others previously mentioned. By reducing difficulty in each step, the overall design is simplified. The final design is comprised of several steps, but most will be done by the end consumer, these are detailed in Team 8's Operation Manual. An overview exploded view of the assembly can be seen in Figure 1. The first of these consumer steps is attaching the base and aluminum cross beams using six 1/4-20 bolts, washers, and lock nuts. Once the aluminum cross beams are secured, the adhesive-backed foam pad is

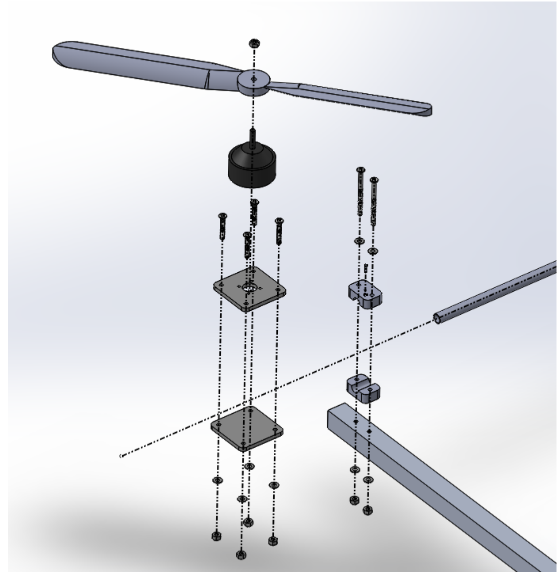
A: Assembled view of attachment

B: Exploded view of attachment

Fig. 1. Attachment assembled (A) and exploded (B) views to show how major pieces are assembled.



A: Assembled view of clamp and motor mounts



B: Exploded view of clamp and motor mounts

Fig. 2. Clamp and motor mounts assembled (A) and exploded (B) to show how parts are assembled.

stuck on to the top of the base. After that, the ABS plastic clamps are attached to the aluminum beam ends. Clamped on the ends are the carbon fiber rods, perpendicular to the aluminum beams. An exploded view of the clamps and arms can be seen in Figure 2.

One step that must be done by the manufacturer is epoxying the bottom motor mounts to the carbon fiber rods. The mounts must be a distance of 100 cm center-to-center, as well as being centered about the long axis of the carbon fiber rod. To do so, a template was made and secured to a level surface. An example of the template can be seen in Figure 3. This provides an outline of where to temporarily secure the two mounts using a removable adhesive (tape). Once the mounts are secured, high-strength epoxy (Team 8 used Double Bubble Orange Epoxy) can be applied to the area in which the carbon rods will rest on the mounts. This is the highlighted rectangular area in Figure 3. After the epoxy is applied, the carbon fiber rod should be placed on the mounts according to the template, it is important to keep the rod centered about the mounts. Next, the assembler should weigh down the rod and let the epoxy cure (the

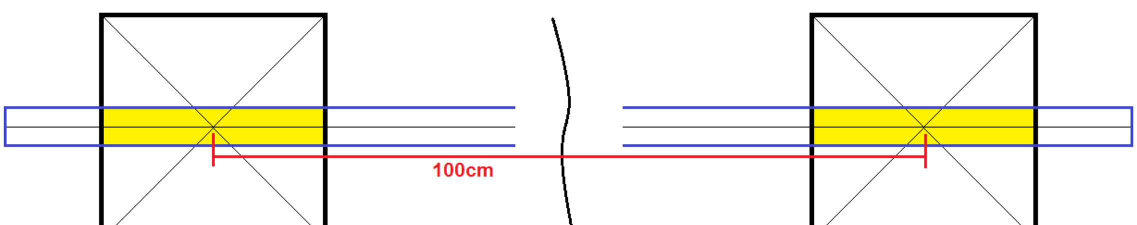


Fig. 3. An example template used to align and epoxy the motor mount bottoms to the carbon fiber rods. The centers of the mounts should be 100cm apart.

Double Bubble Orange Epoxy had a cure time of twelve hours). This process is repeated for the second carbon fiber rod. The result is a simple way to insure the level attachment of the bottom mounts. The level attachment of the motors can be further adjusted in a later step.

The four motors can be attached to the four top motor mounts using the M3 screws provided. These mounts are then attached to the bottom motor mounts that were epoxied to the carbon fiber rods. The top mount is bolted to the bottom mount, but is placed on the other side of the carbon fiber rod, compressing around the rod. The mounts use size 10-24 bolts, washers, and lock nuts at each corner. The motor mount assembly can be seen in the exploded view in Figure 2. These four bolts can be adjusted to ensure the motor is attached level to the plane, as previously discussed.

The basic wiring of the aircraft needs to be done by the manufacturer. The process consists of supplying power to the motors and control to the ESCs. First, solder 3 mm male bullet connectors to all wires coming from motors. Next, solder 3 mm female bullet connectors to all ESC wires that will connect to the motors. These can then be connected safely. After the motors and ESCs have been connected, create a wiring harness by connecting two batteries in parallel. The wiring harness combines the two batteries in parallel, and can then be attached to the four ESCs. As a result, the motors are plugged into the ESCs, then ESCs are plugged into the wiring harness, which is then attached to the two batteries. Finally, the signal wire from ESCs are connected to the Adrupilot, this allows the Adrupilot to control the ESCs and in turn the motors.

In conclusion, the final design takes about 3 hours to assemble, not including the cure time for the motor mount epoxy. More detailed and clear instructions can be found in Team 8s Operational Manual, and all part drawings can be found in Appendix A. Team 8s final design took into account many aspects of design for manufacturing in order to promote simplicity, accuracy, and consistency.

III. Design for Reliability

To examine the reliability of the hybrid aircraft, many different components need to be considered. This includes the multi rotor motors, ESCs, carbon fiber tubes, aluminum beams, and the wood frame base. Each part has a different life cycle and different determining factors. The length of each part's life cycle will govern when it needs to be replaced in order to avoid overall system failure. It is important to analyze the failure modes of each part, the factors that caused the failure, and the effect of the failure on the system. To organize these failures and rate their severity; a Failure Mode, Effects, and Analysis (FMEA) was created and can be seen in Appendix B. In the FMEA, a failure would be considered a high risk if the Risk Priority Number (RPN) was over 100. As seen in the FMEA, there were three failure modes that were identified as high risk. The three failures were the large shear stress in the G-10 motor mounts, the vibrations in the wood base, and the large moments that could be created in the frame. Recommended actions have been assigned to address the issues and lower the RPN to acceptable values. These actions are currently being addressed by Team 8. Along with the three failure modes above, a recommended action was assigned to flying the plane in horizontal flight, even though the RPN was less than 100. This was because Team 8 decided this was of high importance, since only authorized pilots are legally allowed to fly the plane. The FMEA helped identify the risks involved in the system and work on correcting them before a problem occurred. In addition to the FMEA, Team 8 has done further analysis on the system.

The hybrid attachment design, uses four Cobra 4510 420Kv brushless DC motors. These are used to provide vertical lift to the aircraft. The motors are rated to withstand up to 900 W for maximum power input. Pairing this with APC 18x5.5 propellers at 84% throttle, the motors will draw 832.3W of power [5]. In this range of power, the manufacturer recommends that the motors be run at short burst of up to 15 seconds. This will keep the motors from overheating or burning out. Team 8 can monitor power delivered to the motors using the Mission Planner software to ensure the power limitation is not exceeded for longer than 15 seconds during the vertical takeoff and landing. By limiting large power usage, Team

Max Current (A)	Max Power (W)	Battery	Volts (V)
40	900	6 Cell	22.2

TABLE II
ADDITIONAL MOTOR SPECIFICATIONS FOR COBRA 4510 BRUSHLESS DC MOTOR.

8 is able to extend the life of the motors. This will be an important factor in increasing the life cycle of the motors. More specifications for the motor can be seen in Table II.

Other components that need to be taken into account are the raw materials used to build the base of the attachment. This includes 1/2 inch carbon fiber rods, aluminum 6061 1 inch hollow square beams, and the plywood base. All of these components will experience loads when the vehicle is in flight. The aluminum beams have an ultimate tensile strength of 45 ksi [2]. Since this is much larger than any thrust force applied, it was obvious the beams would not fail. From there, Team 8 needed to be determine how far the beams would deflect. The maximum displacement of the aluminum beams can be seen in Figure 4. This is using the maximum thrust force (49 N) created from the motors placed 100 cm apart from each other, where the carbon fiber rods will attach. From the Finite Element Analysis (FEA), it can be seen that the maximum displacement is 0.2026 cm. This amount of deflection is considered acceptable for our design and will not cause failure in our system.

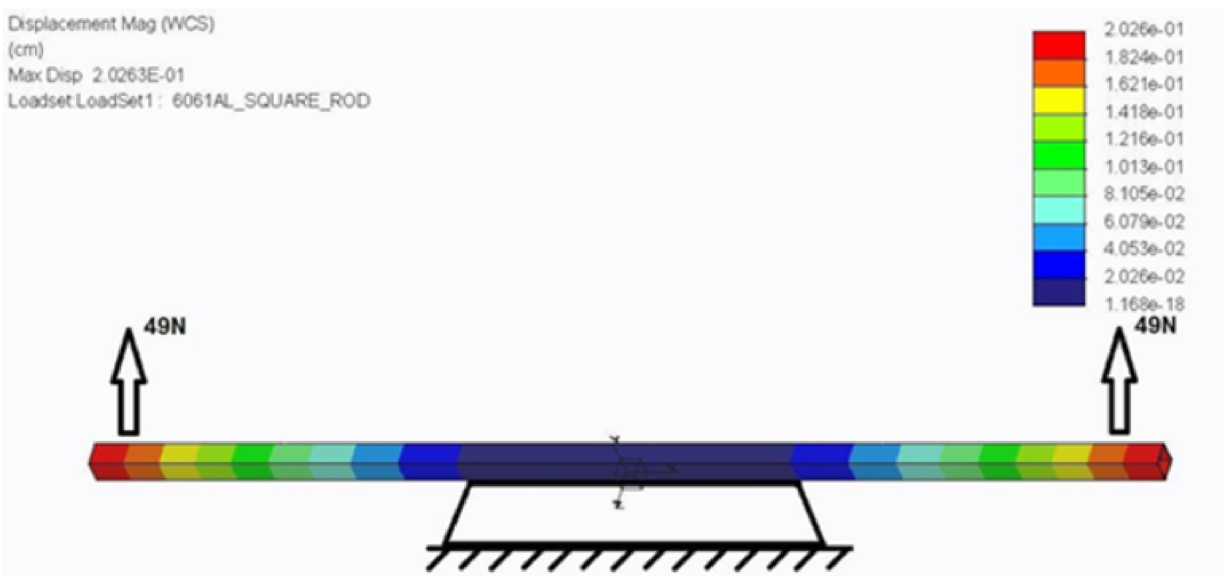


Fig. 4. Finite Element Analysis (FEA) conducted on the aluminum 6061 cross beams. A force of 49N, the maximum resulting force from the motors, was applied 50cm from the center in each direction. The result was a maximum deflection of 0.2026cm.

Another concern that can affect the reliability of the hybrid design is fatigue in the aluminum beams or the carbon fiber rods. For the aluminum beams, the fatigue strength is 14 ksi after 500 million cycles [4]. Therefore, fatigue in the aluminum rods is not a concern because of the relatively low stresses applied compared to the fatigue strength of the material. The mechanical properties of the other materials can be seen in Table III.

The carbon fiber rods fatigue strength also needs to be considered for the extended use over time. Carbon fiber fatigue limits and strengths are not readily available like other materials (steel, aluminum, etc.), so to ensure long life for the components, strength needs to be much larger than applied forces. For the selected carbon fiber rods, they have a flexural strength between 89 ksi and 174 ksi [3]. This is significantly larger than the applied load of around 100 psi or 0.100 ksi. For these reasons, fatigue will

Material	Ultimate Tensile Strength (ksi)	Ultimate Flexural Strength (ksi)	Fatigue Strength (ksi)
Aluminum 6061	45	40	14 @ $5x10^8$ cycles
Carbon Fiber	120	89 - 174	n/a
Plywood	4.5	n/a	0.363 @ 10^6 cycles

TABLE III
VARIOUS MATERIAL MECHANICAL PROPERTIES.

not be a concern in the carbon fiber rods.

With these factors considered, the hybrid aircraft attachment can last about as long as the operator desires during normal operation. Normal operation is defined as flight within motor limits, without any catastrophic crash. A catastrophic crash would be any kind of crash landing from high altitudes that causes damage to multiple components. This is the main concern for failure in the system. Without crashing, during normal operation, the attachment will maintain all of its capabilities.

IV. Design for Economics

To achieve success in this years senior design project, Team 8 was allocated a budget of $1,500. The budget is supplied by the Aero-Propulsion, Mechatronic, and Energy (AME) building funds at Florida State University, in conjunction with the Fund for the Improvement of Postsecondary Education (FIPSE). The overall goal of this project was to create the best possible aircraft for the future success at the 2016 AUVSI SUAS design competition. With this goal in mind, the funds were used to purchase necessary new parts and to replace many damaged parts from previous projects. These parts were used to modify the existing Senior Telemaster plane into a hybrid vertical takeoff and landing aircraft. All of the required parts needed to redesign and achieve this years goal have been purchased and shipped, leaving Team 9 with an excess of $11.91. Team 8 was able to stay under budget. This was accomplished by planning which parts were needed, comparing cost to find the best price, and lastly, setting aside a percentage of the funds that would be used to replace previously damaged components. Using this approach, Team 8 was also able to purchase extra parts in case damage was caused to the exposed parts of the aircraft. These extra parts included two extra multi rotor propellers, an extra aluminum beam, and an extra carbon fiber rod. A breakdown of the cost of each component purchased by Team 8 along with the quantity for

Part	Qty.	Unit Price	Subtotal
Carbon Fiber 0.5” Arms	3	$41.05	$123.15
Industrial Strength Velcro	1	$30.39	$30.39
Double Bubble Orange Epoxy	1	$11.99	$11.99
APM 2.6 Adrupilot	1	$239.98	$239.98
12 AWG Silicon Wire	16	$2.74	$43.78
12 AWG Silicon Wire for ESC	1	$10.04	$10.04
12 AWG Male Wire Connectors	1	$10.58	$10.58
12 AWG Female Wire Connectors	1	$8.92	$8.92
Cobra 4510 420Kv Multirotor Motor	4	$74.99	$309.96
Cobra 60A Multirotor ESC	4	$48.86	$195.46
Venom 22.2V LiPo Battery	1	$119.99	$119.99
APC 18x5.5” Propellers	6	$12.83	$76.98
Resilient Foam Base	1	$40.44	$40.44
Aluminum 1x1” Beams	3	$28.57	$85.71
3DR Telemetry Kit	1	$110.36	$110.36
Hardware & Misc.	1	$70.36	$70.36
		Total	**$1488.09**

TABLE IV
LIST OF EXPENSES FOR EACH PURCHASED PART AND THE CORRESPONDING COST.

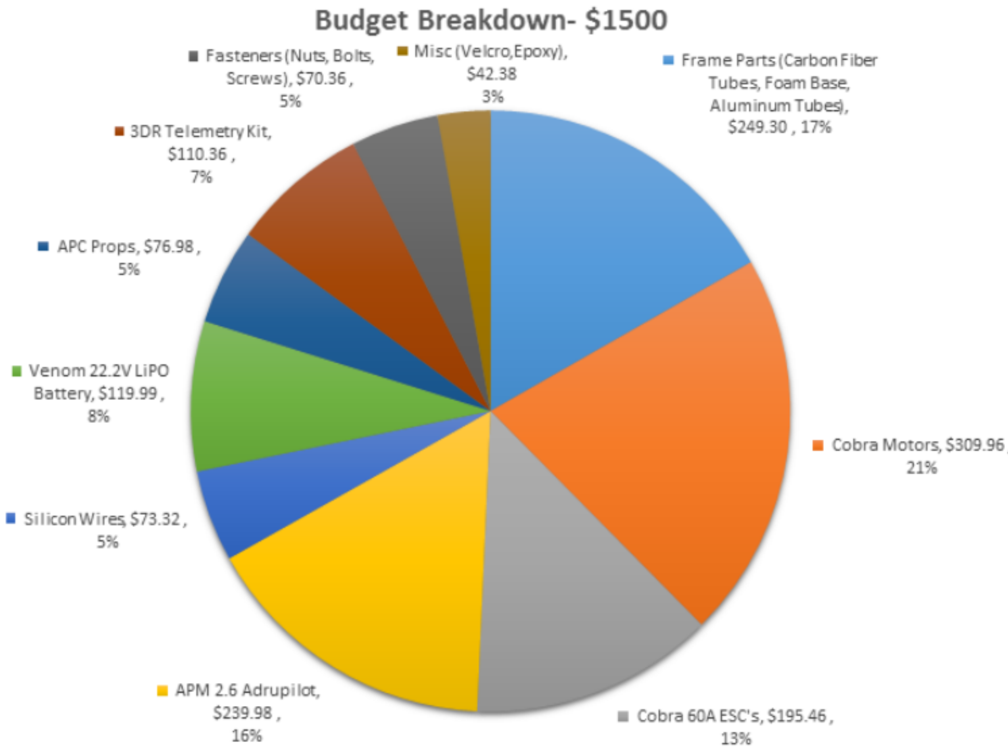


Fig. 5. Breakdown of expenses along with percentage of total $1500 budget.

each part can be seen in Table IV. The total cost spent on parts for this project totaled $1488.09. The budget breakdown is shown in the pie chart in Figure 5.

With the cost of each component defined in pie chart above, it can be seen that 50% of the total budget was spent on the four cobra motors, four ESCs, and the APM 2.6 Adrupilot. The four Cobra 4510 DC motors were the most expensive parts that were purchased. While being budget conscious and comparing other motors, the Cobra 4510 DC motors provided the required thrust needed for aircraft at the most reasonable price. A comparison of similar products on the market will be displayed in Figure 6. Team 8 was focused on using the budget wisely and being cost efficient. Purchasing a new Adrupilot and 3DR Telemetry Kit was not in Team 8s original budget plans, but needed to be done after discovering that the Adrupiot APM 2.5 and 3DR Telemetry Kit from last year were both damaged and not working properly [6]. Overall, purchasing all of the necessary parts will prepare next years team to focus on completing the objectives of the design competition, instead of the design and build for the newly remodeled hybrid aircraft.

Team 8's aircraft was first designed and built last year as only a fixed wing aircraft. Since redesigning as a hybrid VTOL aircraft, comparing the cost of the aircraft to other fixed wing or multi rotor aircraft has become unrevealing. Instead, in Figure 6, the most expensive components that were purchased using the allocated budget have been compared to similar products on the market. Looking at autopilot systems which allows the multi rotor to become autonomous, the purchased APM 2.6 Adrupilot at $239.98 was compared to another product on the market called the Pixhawk at $319.98 allowed us to save $80.00 [7]. In relation to the four DC motors that were needed, going with the Cobra 4510 420kV at $74.99 per motor compared to a similar Tiger motor MN4120 at $129.90 per motor allowed Team 8 to save $219.64 [8]. Lastly, four ESCs were needed, and the purchased Cobra 60A ESC at $48.86 per ESC in comparison to an on the market T-motor 60A ESC at $59.99, saved Team $44.52 [9]. To summarize, 50% of Team

8s budget was spent on four motors, four ESCs, and an autopilot system that totaled $745.40. Similar on the market products of the four motors, four ESCs, and an autopilot system totaled $1089.56. Thus, Team 8 saved $344.16 by researching which components were needed for the success of the aircraft and what was the best possible price.

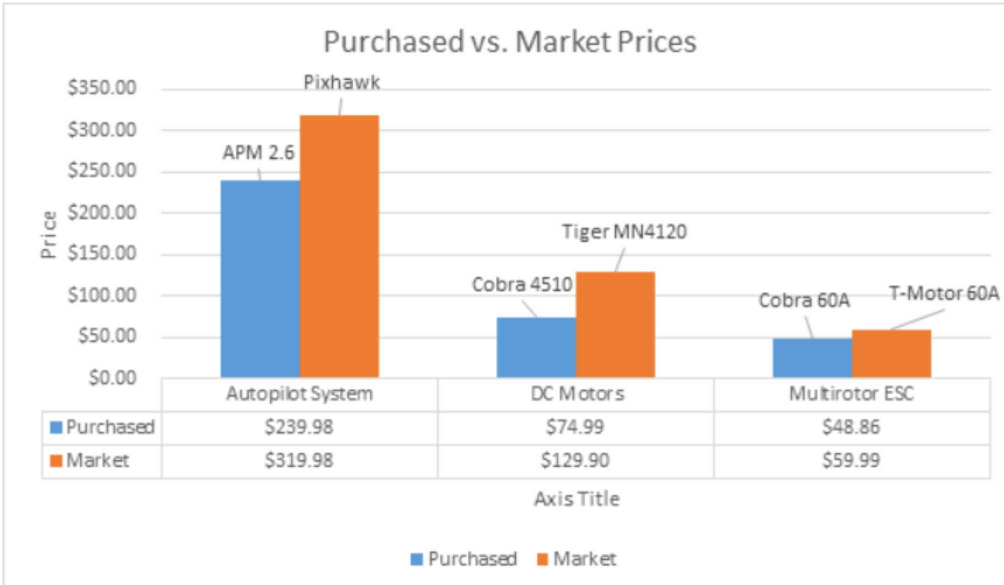


Fig. 6. Cost comparison of purchased components with similar products.

V. Conclusion

Team 8 has designed a multi rotor attachment for the Senior Telemaster plane inherited from previous senior design groups. With this aircraft, Team 8 was careful to create a design that not only met their objectives, but also kept in mind design for manufacturing, reliability and economics practices. The final design was as simple as possible without substituting quality. Team 8 was able to keep the complexity and amount of parts to a minimum, while also avoiding difficult assembly. The components chosen for the design were robust, ensuring strength and a long lifetime of the system. Also, cost was a major factor in finalizing the design. Team 8 was able to stay under budget throughout the project. The design effectively uses simple, inexpensive, but strong components to create a final product capable of vertical takeoff and landing.

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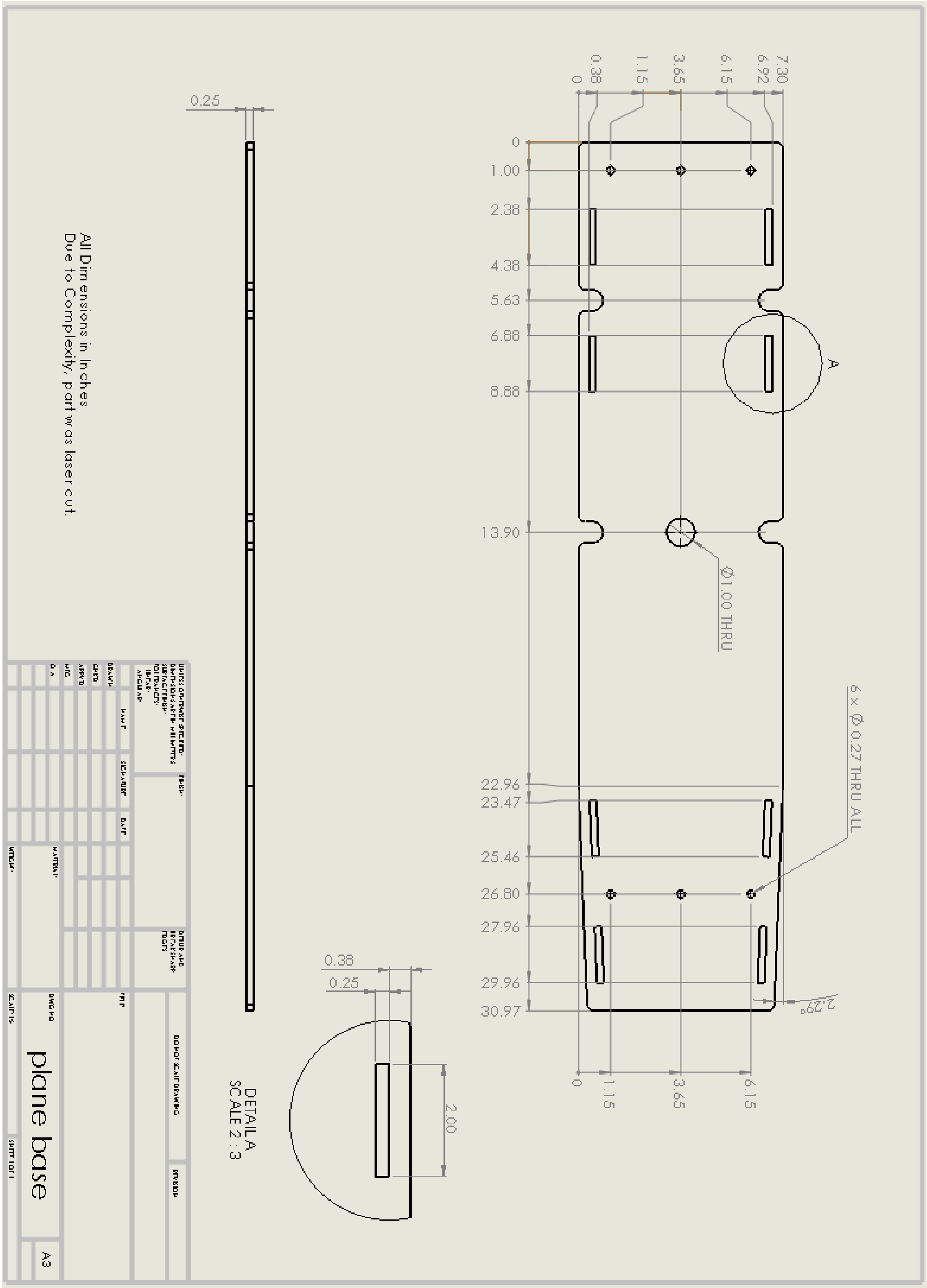
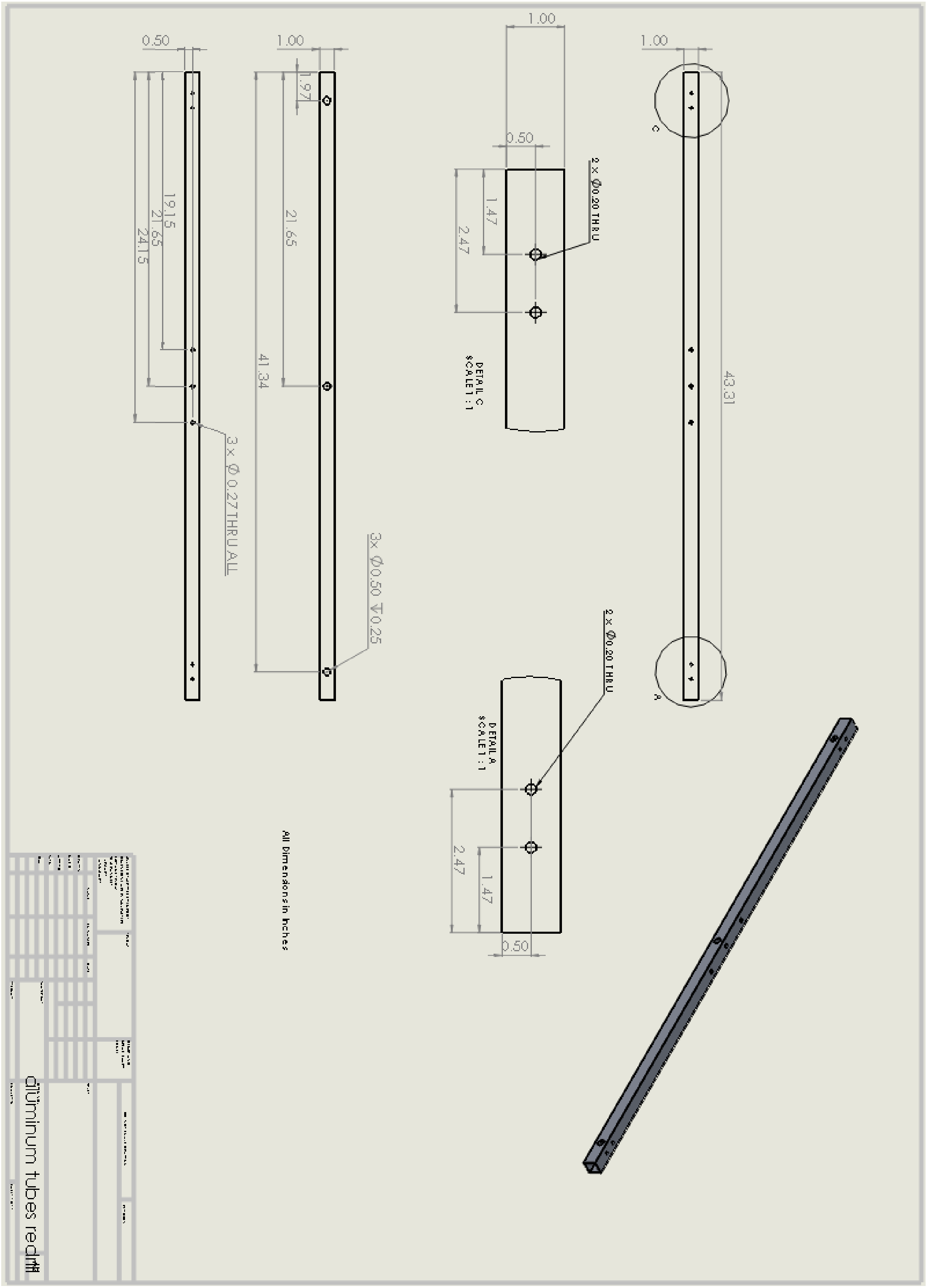
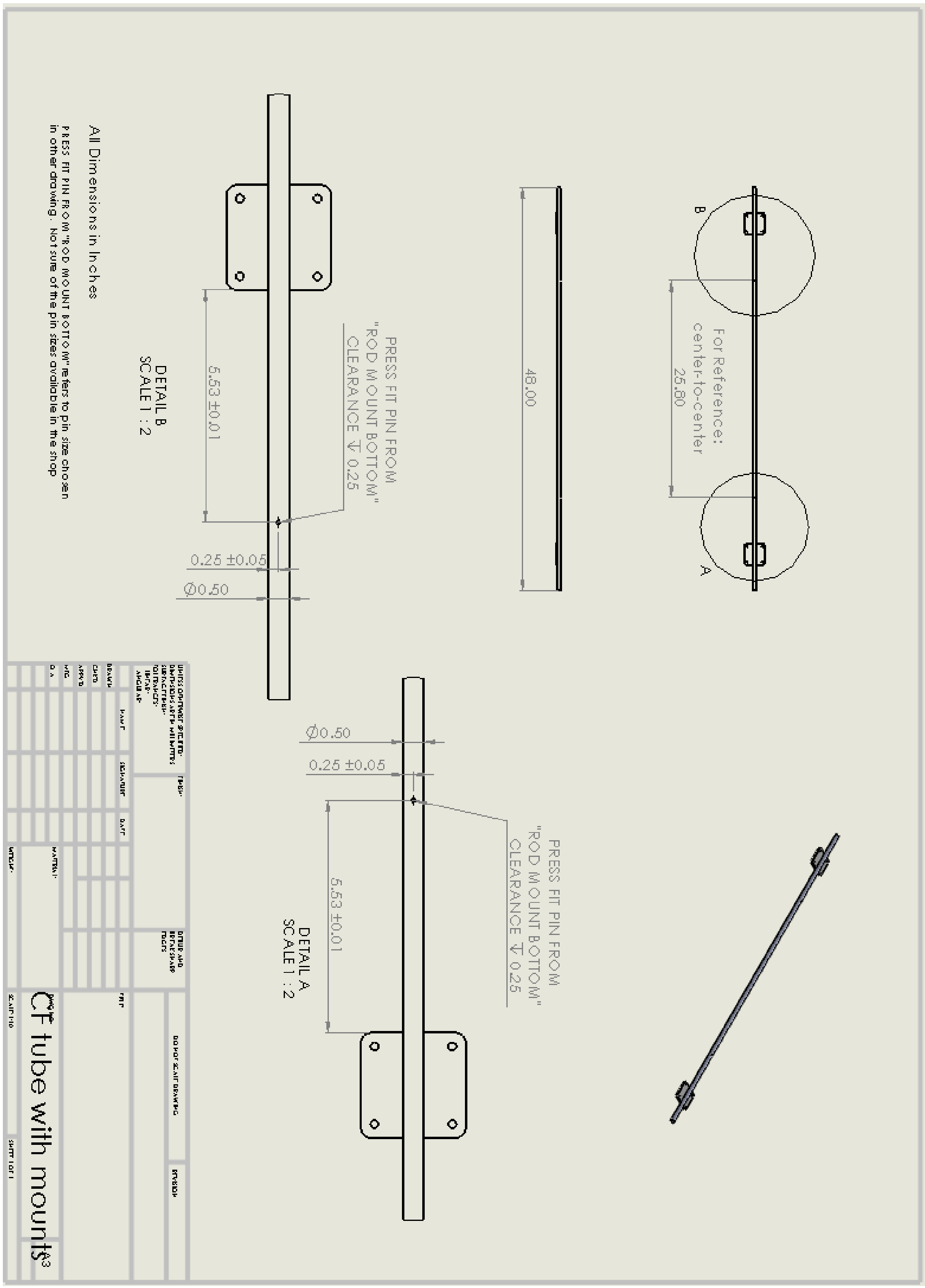
APPENDIX A
PART DRAWINGS

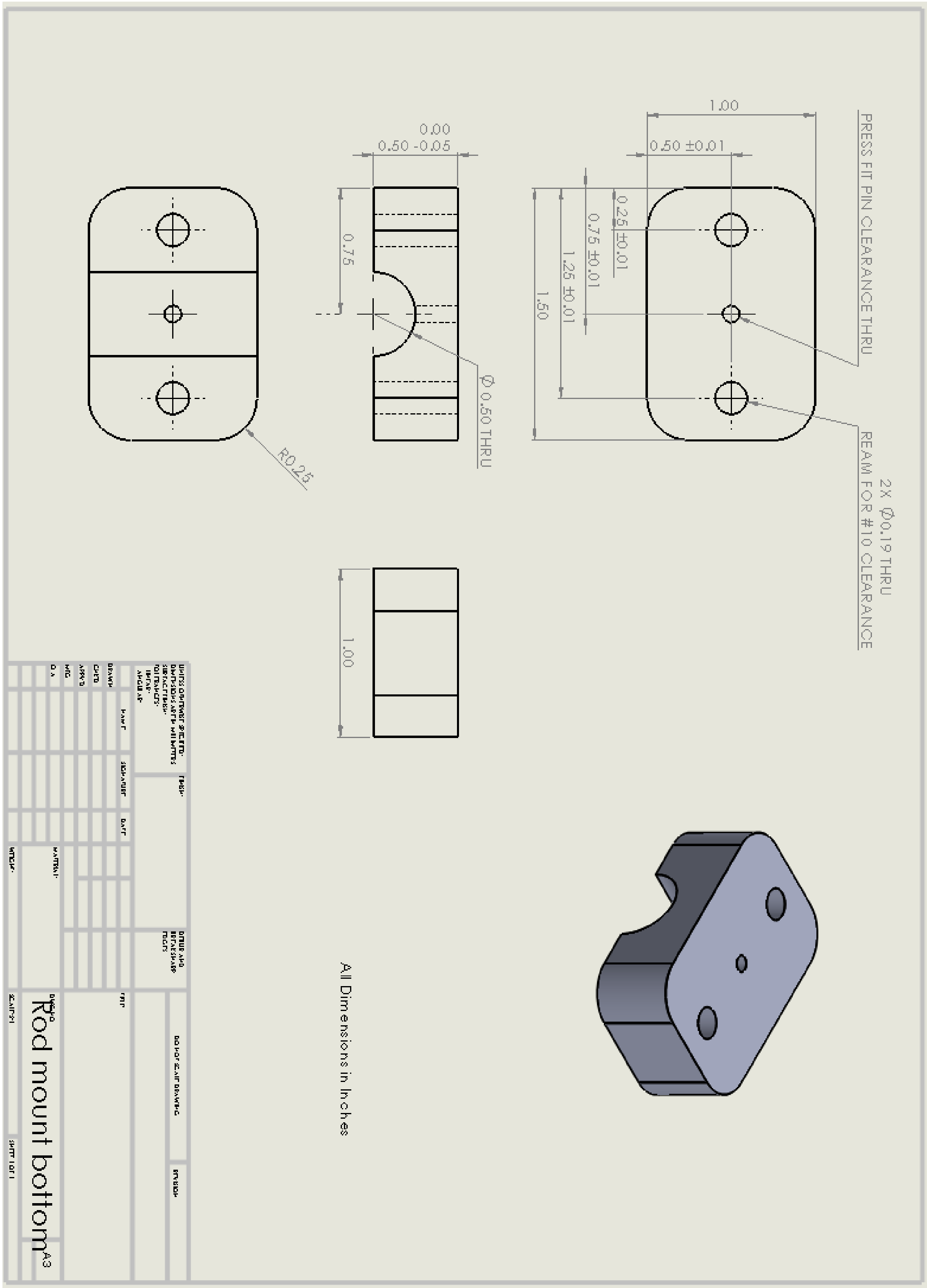


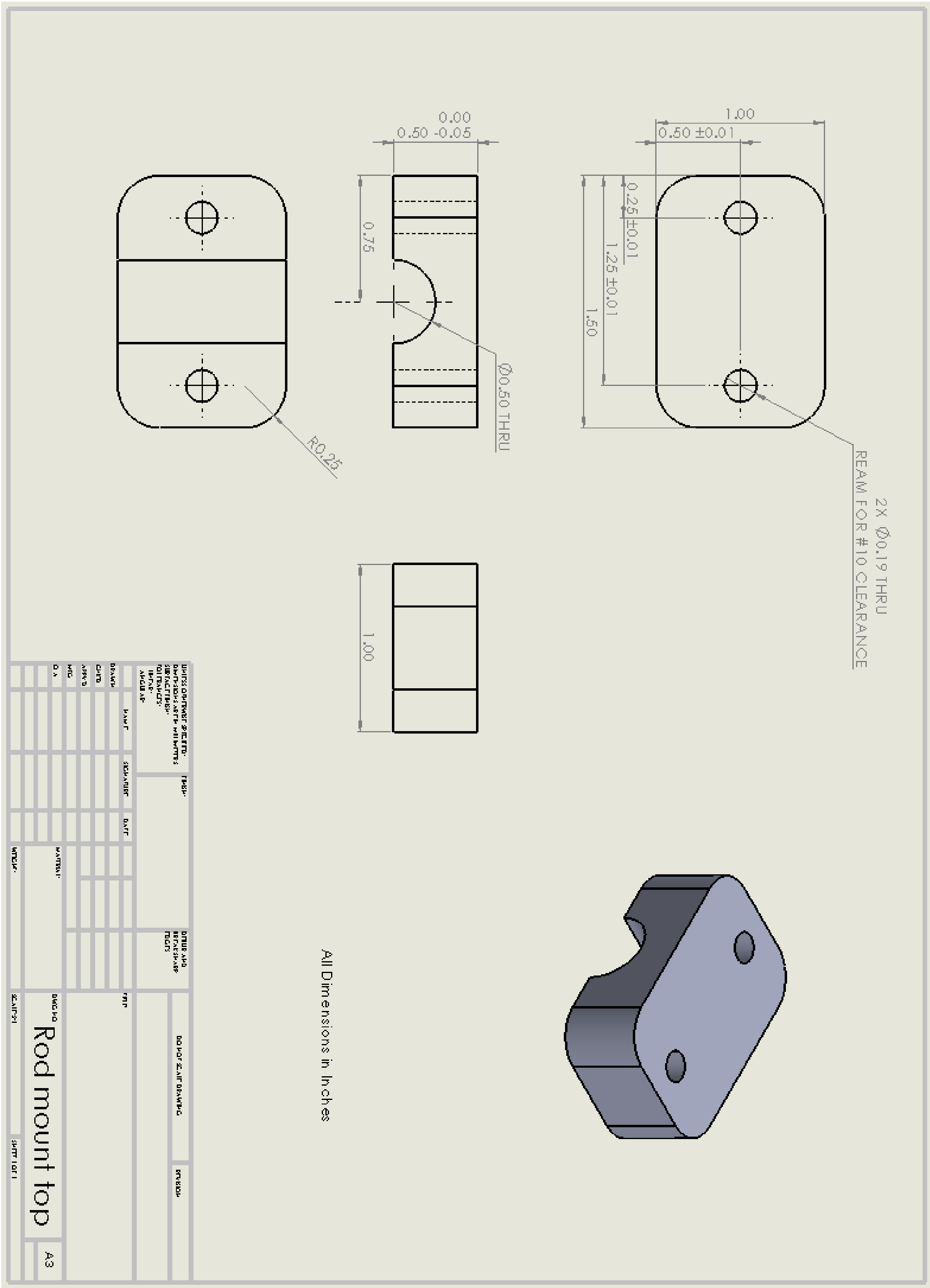


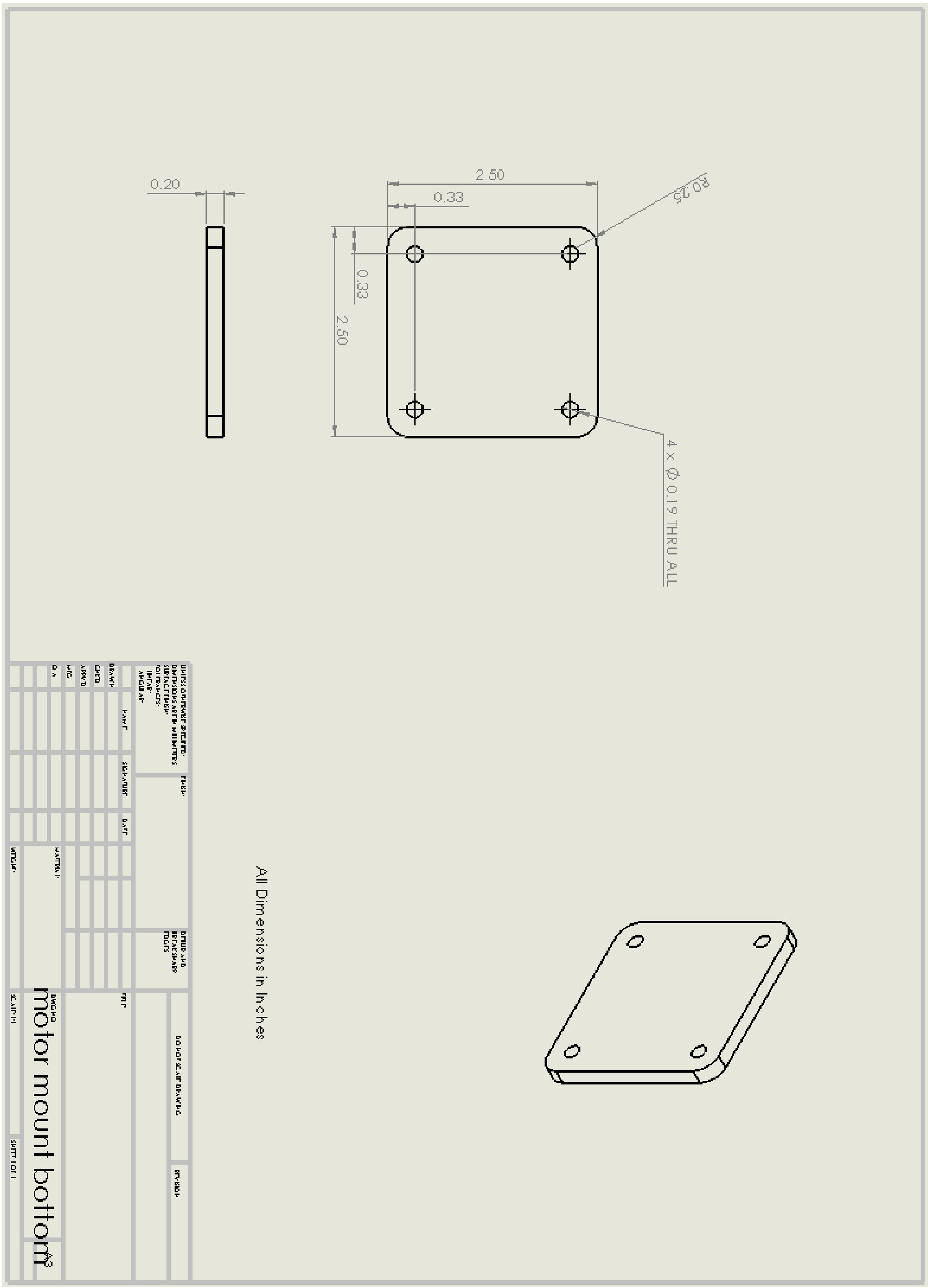
DETAIL C
SCALE 1 : 1
DETAIL A
SCALE 1 : 1
2 x Ø0.20 THRU
3x Ø0.27 THRU ALL
3x Ø0.50 ↧0.25
All Dimensions in Inches
0.50
1.00
1.97
19.15
21.65
24.15
41.34
43.31
1.47
2.47

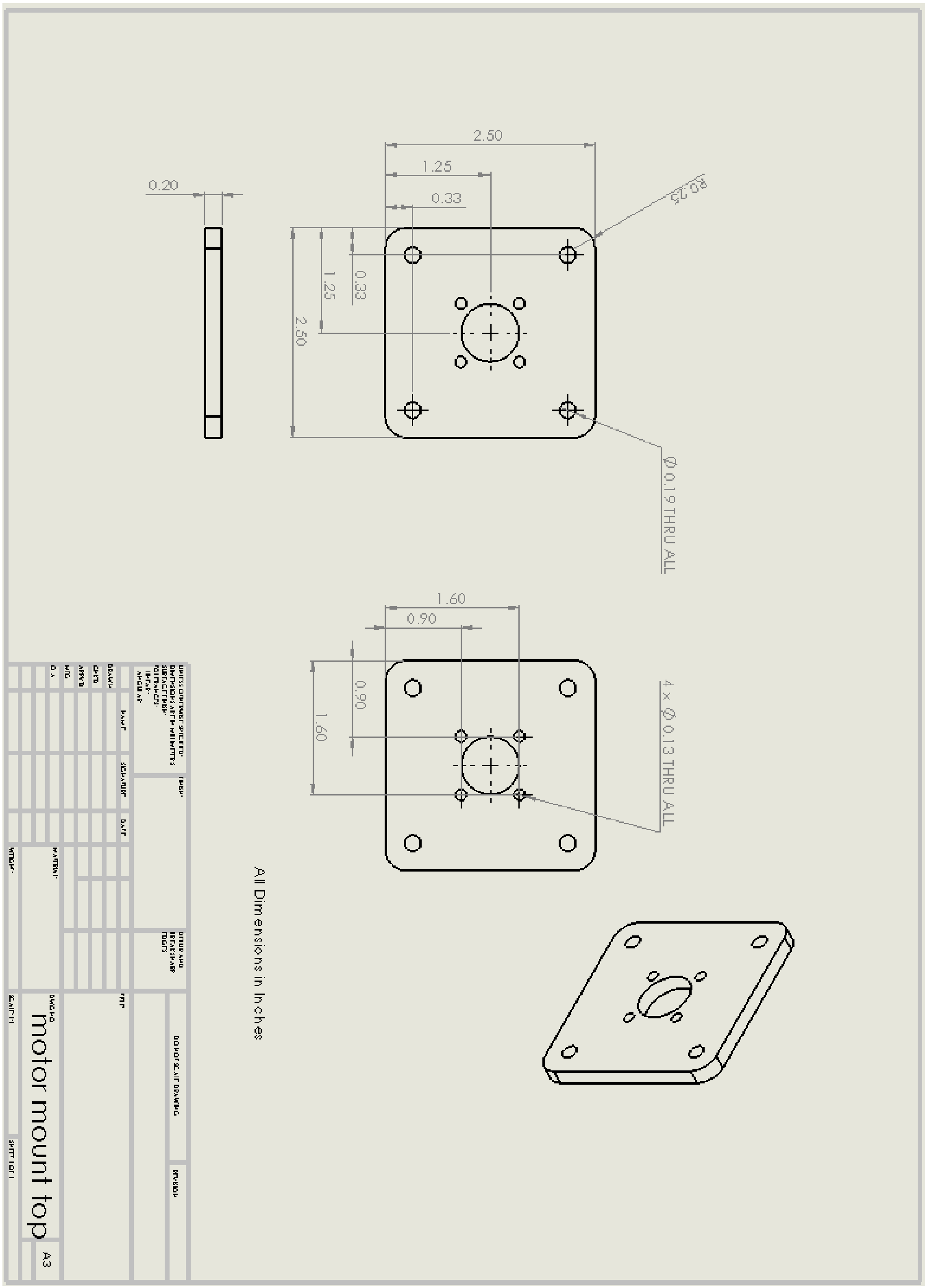


CF tube with mounts
All Dimensions in Inches
PRESS FIT PIN FROM "ROD MOUNT BOTTOM" refers to pin size chosen in other drawing. Not sure of the pin sizes available in the shop
For Reference:
center-to-center
25.80
48.00
PRESS FIT PIN FROM
"ROD MOUNT BOTTOM"
CLEARANCE ↧ 0.25
5.53 ±0.01
0.25 ±0.05
Ø0.50
DETAIL B
SCALE 1 : 2
DETAIL A
SCALE 1 : 2
A
B


PRESS FIT PIN CLEARANCE THRU
2X Ø0.19 THRU
REAM FOR #10 CLEARANCE
1.00
0.50 ±0.01
0.25 ±0.01
0.75 ±0.01
1.25 ±0.01
1.50
0.00
0.50 -0.05
0.75
Ø 0.50 THRU
R0.25
1.00
All Dimensions in Inches
Rod mount bottom
A3


Rod mount top
All Dimensions in Inches
2X Ø0.19 THRU
REAM FOR #10 CLEARANCE
Ø0.50 THRU
R0.25
1.00
0.50 ±0.01
0.25 ±0.01
1.25 ±0.01
1.50
0.00
0.50 -0.05
0.75
1.00
A3


0.20
2.50
0.33
R0.25
0.33
2.50
4 x Ø0.19 THRU ALL
All Dimensions in Inches
motor mount bottom
A3


2.50
1.25
0.33
0.20
R0.25
1.25
0.33
2.50
Ø0.19THRU ALL
1.60
0.90
0.90
1.60
4 × Ø0.13 THRU ALL
All Dimensions in Inches
motor mount top
A3

Appendix B
FMEA

Component	Function	Failure Mode	Failure Effect	Severity	Potential Failure Causes	Occurrence	Preventative Action	Detection Action	Detection	RPN	Recommended Actions	Who's Responsible?	Action Taken
1. DC Motors	Provided rotational motion of propellers	DC Motor burned out	Unable to fly	7	Surpass maximum current rating	2	Watch power load on motors	Monitor active load on motors	2	28			
					Extended time above 80% power	2	Watch power load on motors	Monitor time and load on motors	2	28			
2. G10 Motor mounts	Attactment of motors to carbon fiber rods	Epoxy fails	Damage motors, props, or plane	9	Large shears stress	3	Ensure vertical mount	Visual	4	108	Ensure Machine shop drills holes correctly into CF rods	Chris	Ensured by Machine shop holes could be drilled and kept vertical
					Crash landing	1	Attach to testing aparatus	Manually attach	2	18			
					Extended use of epoxy	3	Bolt motor mounts around CF tube	Manually attach	2	54			
3. CF tubes	Attactment of motors to base	CF tubes fracture	Damage motors, props, or plane	9	Fatigue of tubes	1	Material selection	Visual	4	36			
					Crash landing	1	Attach to testing aparatus	Manually attach	2	18			
					Large shear stresses created	2	Vertically allign motors	Visual and manually attach	4	72			
					Bending Stresses	2	FEA analysis and Material selection	Visual	4	72			
4. Aluminum Rods	Attachment of CF tubes to base	Aluminun rods fracture	Damage motors, props, or plane	9	Fatigue of AL rods	1	Material selection	Visual	4	36			
					Tear out failure of bolts	2	Washers and material Selection	Visual	4	72			
					Bending Stresses	2	FEA analysis and Material selection	Visual	4	72			
					Crash landing	1	Attach to testing aparatus	Manually attach	2	18			
5. Wood Base	Attacment of aluminum rods to base	Wood Base Fracture	Damage motors, props, or plane	9	Vibrations	5	Insert foam pad to dampen vibrations	Visual	4	180	Use Mission planner to track vibration	Gavarni and Jermaine	Observe while testing
					Large moments from AL rods	3	Vertical alignment of motor	Visual	4	108	During testing observe twisting in frame	John	Observe while testing
					Tear out failure of bolts	1	Using Washers to distrubute forces	Visual	4	36			
6. APM	Microcontroller to control all aspect of plane	Loss of connection to controller	Damage motors, props, or plane	9	Battery dies/Loss of power	5	Charge Battery/ESC fail safe	Monitor battery life	1	45			
					Damaged GPS	3	GPS Fail Safe	Monitor mission planner	2	48			
		Loss of GPS Signal	Plane Runaway	8	Poor GPS Mount	1	Mount GPS away from other electrical components	Visual	2	16			
7. ESC's	Speed controllers for DC motors	Speed controls loose power	Damage motors, props, or plane	9	Loss of power	2	Monitor battery life	Flight Planner software	2	36			
					ESC burns out	3	Set throttle maximum to reduce AMPS	Flight Planner software	2	54			
					Loose connection to power supply	2	Visuallly inspect wires	Visual	4	72			
8. Plane flaps	Used to control plane	Flaps fail to operate	Damage motors, props, or plane	9	Servo motors do not operate properly	3	Ensure all aspect of plane are function before take off	Pilots operations	3	81	Only have liscened pilots fly plane	David	Have a contact for a liscens pilot to fly the plane when need be