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The inability to land and take off from uneven terrains is a major constraint of current helicopters and aerial drones. The objective of this senior design project was to design and build an aerial drone with a landing gear system that would allow leveling and take off from a sloped terrain.

MEMS 411 Final Report

Self-Leveling Drone

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Table of Contents

List of Figures	5
List of Tables	6
1 Introduction	7
1.1 Project problem statement.....	7
1.2 List of team members	7
2 Background Information Study	7
2.1 A short design brief description that defines and describes the design problem	7
2.2 Summary of relevant background information	7
2.2.1 Patents:	7
2.2.2 Articles and URLs:.....	7
3 Concept Design and Specification.....	8
3.1 Performance Metrics and Measures.....	8
3.2 Concept drawing	8
3.3 Concept Selection and Feasibility	9
3.4 Design Constraints	9
3.4.1 Functional.....	9
3.4.2 Safety	9
3.4.3 Quality.....	9
3.4.4 Manufacturing.....	9
3.4.5 Timing.....	10
3.4.6 Economic.....	10
3.4.7 Ergonomic	10
3.4.8 Ecological	10
3.4.9 Aesthetic	10
3.4.10 Life cycle.....	10
3.4.11 Legal	10
4 Embodiment and fabrication plan	11
4.1 Embodiment drawing.....	11
4.2 Parts List.....	11
4.3 Draft detail drawings for each manufactured part.....	12
4.4 Description of the design rationale for the choice/size/shape of each part	15
4.4.1 Frame Configuration	15

4.4.2	Electronic Components	17
4.5	Gantt chart	19
5	Engineering analysis.....	20
5.1	Engineering analysis proposal.....	20
5.1.1	A form, signed by your section instructor.....	20
5.2	Engineering analysis results	20
5.2.1	Motivation. Describe why/how the before analysis is the most important thing to study at this time. How does it facilitate carrying the project forward?	20
5.2.2	Summary statement of analysis done. Summarize, with some type of readable graphic, the engineering analysis done and the relevant engineering equations.....	21
5.2.3	Methodology. How, exactly, did you get the analysis done? Was any experimentation required? Did you have to build any type of test rig? Was computation used? 21	
5.2.4	Results. What are the results of your analysis study? Do the results make sense? ...	22
5.2.5	Significance. How will the results influence the final prototype? What dimensions and material choices will be affected?	25
5.2.6	Summary of code and standards and their influence. Similarly, summarize the relevant codes and standards identified and how they influence revision of the design.	25
5.3	Risk Assessment	27
5.3.1	Risk Identification.....	27
5.3.2	Risk Analysis	27
5.3.3	Risk Prioritization	28
6	Working prototype.....	30
6.1	A preliminary demonstration of the working prototype (this section may be left blank). ..	30
6.2	A final demonstration of the working prototype (this section may be left blank).	30
6.3	At least two digital photographs showing the prototype	30
6.4	A short videoclip that shows the final prototype performing	31
6.5	At least four (4) additional digital photographs and their explanations	31
7	Design documentation.....	35
7.1	Final Drawings and Documentation.....	35
7.1.1	A set of engineering drawings that includes all CAD model files and all drawings derived from CAD models.....	35
7.1.2	Sourcing instructions.....	35
7.2	Final Presentation	35
7.2.1	A live presentation in front of the entire class and the instructors.....	35
7.2.2	A link to a video clip version of 1	35

7.3	Teardown	35
8	Discussion.....	36
8.1	Using the final prototype produced to obtain values for metrics, evaluate the quantified needs equations for the design. How well were the needs met?	36
8.2	Discuss any significant parts sourcing issues?	36
8.3	Discuss the overall experience:.....	36
8.3.1	Was the project more of less difficult than you had expected?	36
8.3.2	Does your final project result align with the project description?	36
8.3.3	Did your team function well as a group?	36
8.3.4	Were your team member’s skills complementary?	37
8.3.5	Did your team share the workload equally?	37
8.3.6	Was any needed skill missing from the group?	37
8.3.7	Did you have to consult with your customer during the process, or did you work to the original design brief?.....	37
8.3.8	Did the design brief (as provided by the customer) seem to change during the process? 37	
8.3.9	Has the project enhanced your design skills?	37
8.3.10	Would you now feel more comfortable accepting a design project assignment at a job? 37	
8.3.11	Are there projects that you would attempt now that you would not attempt before? 38	
9	Appendix A - Parts List	39
10	Appendix B - Bill of Materials.....	39
11	Appendix C - CAD Models	40
12	Annotated Bibliography	44

List of Figures

Figure 1: Concept Drawing: Linked Bar Leveling System.....	8
Figure 2: Embodiment Drawing	11
Figure 3: Base Plate	12
Figure 4: Controller Connector.....	13
Figure 6: T-Arm	14
Figure 7: Landing Gear.....	14
Figure 8: Lower Leg.....	15
Figure 9: Summary of engineering analysis done before building the prototype.....	21
Figure 10: Large and Small Servos	22
Figure 11: 2000 kV Brushless Motor and 7x4E Propeller.....	23
Figure 12: Final Circuit Schematic	23
Figure 13: Initial Prototype and Final Prototype.....	25
Figure 14: Initial Working Prototype.....	30
Figure 15: Final Working Prototype.....	31
Figure 16: Close up of the hinged landing gear joints.....	32
Figure 17: Accelerometer and Flight Controller.....	33
Figure 18: Quad-copter at an approximately 15 degree angle during testing.....	33
Figure 19: Close up of the full circuit.....	34
Figure 20: Teardown agreement.....	35

List of Tables

Table 1: Initial Parts List 11

Table 2: Gantt Chart..... 19

Table 3: Risk identification, corresponding events, and effects on project..... 26

Table 4: Potential effects specification for Table 3..... 27

1 Introduction

1.1 Project problem statement

1.2 The objective of this senior design project was to design and build an aerial drone with a landing gear system that would allow leveling and take off from a sloped terrain. The drone should be able to level on a slope with a maximum incline of 20 degrees and the leveling process should not exceed 30 seconds. In addition, the leveling system must be automatic and deployed using the flight controller.

1.3 List of team members

- Jillian Rose
- Sarah Schubert
- Anne Shellum
- Andreea Stoica

2 Background Information Study

2.1 A short design brief description that defines and describes the design problem

The goal of this project was driven by a major constraint on current helicopters and aerial drones - inability to land and take off from uneven terrains. Thus the team was tasked with designing and building an aerial drone with a landing gear system that would allow it to level and take off from a sloped surface.

2.2 Summary of relevant background information

2.2.1 Patents:

- US 3857533 A - Helicopter self-leveling landing gear
- US 9033276 B1 - Telescoping landing leg system
- US 20100012776 A1 - Method for Vertical Takeoff from and Landing on Inclined Surfaces
- S 9145207 B2 - Remotely controlled micro/nanoscale aerial vehicle comprising a system for traveling on the ground, vertical takeoff, and landing

2.2.2 Articles and URLs:

- [DARPA Leveling Landing Gear](#)
- [NASA Passive Self-Leveling Landing Gear](#)

3 Concept Design and Specification

3.1 Performance Metrics and Measures

- The drone must be able to fly in order to demonstrate leveling gear. Desired flight time is five minutes.
- The drone weight should not exceed 5 lbs.
- The drone must be able to level from a maximum incline of 20 degrees.
- The leveling gear must function repeatedly. Desired lifetime is 100 take-offs.
- The user must be able to deploy landing gear using the flight controller.
- The leveling process should not exceed 30 seconds.
- The drone should be able to level from any orientation.
- The leveling landing gear should stay folded during flight and refold upon takeoff.

3.2 Concept drawing

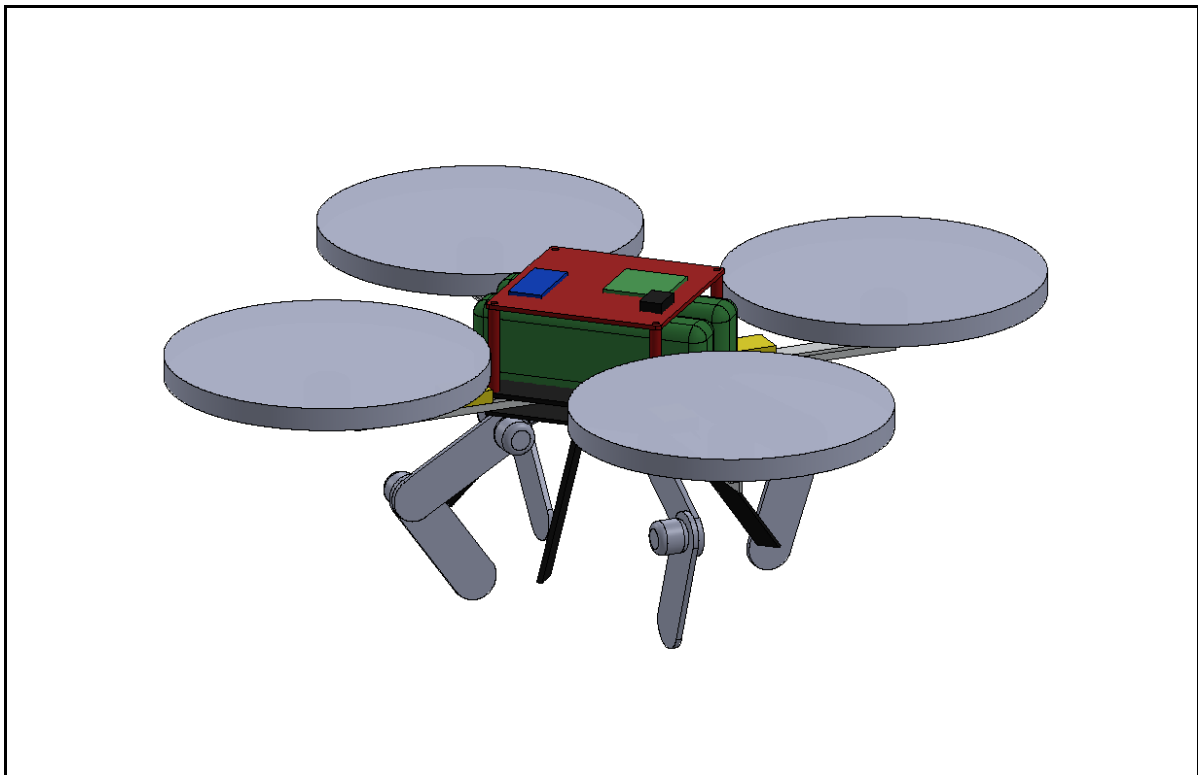


Figure 1: Concept Drawing – Linked Bar Leveling System

3.3 Concept Selection and Feasibility

The concept selections were broken down into two separate design components: flight system and leveling system. For the flight system both single-rotor configuration and quadcopter configurations were considered. The quadcopter configuration was selected as it allows for thrust distribution among the four motors, it provides better balancing capabilities in flight and it offers more freedom in placing the leveling system. In selecting a leveling system configuration multiple concepts were considered including telescoping legs, single bar actuated landing gear and the double linked bar leveling system. The double linked bar leveling system was selected due to the reduced load on each of the leveling system segments, the simplicity of the design and leveling algorithm, and the relatively lower weight and energy consumption of the actuators.

3.4 Design Constraints

3.4.1 Functional

The most challenging functional constraint in our design was energy. Batteries are by far the heaviest component on a quadcopter and we were therefore limited to at most two 3000 mAh lithium-ion polymer batteries (for a total of 6 Amp-hours of charge). Each of the four motors used for flight consume significant amounts of power (360 watts at their maximum), as did the eight servo motors controlling the self-leveling landing gear.

3.4.2 Safety

As with any engineering project, there were many safety constraints to consider. One of the biggest safety concerns in quad-copter design is the damage that can be done by the propellers when powering on the quad-copter. To protect against unwanted propeller damage a failsafe was added to the flight control configuration such that the propellers must be manually armed before they will spin each time the quadcopter is connected to power.

3.4.3 Quality

The quality of the electronic components, in particular the servos was a constant challenge in this project. Four of the eight servos needed to be replaced because their plastic internal gears could not consistently handle the torque needed to lift the quad-copter. The remaining four servos did not have the accuracy needed to achieve perfect leveling.

3.4.4 Manufacturing

The speed of manufacture of this design could be greatly improved by either injection molding most of the body components or by using laser cutting for the metal components. As it stands this design was made entirely with manual and CNC milling, which are time and labor intensive.

3.4.5 Timing

The largest timing constraint on this project was the roughly two month maximum time frame in which it needed to be completed. This very short time frame was made more challenging by the need to order most necessary components online. The combination of these two timing constraints led to many less than optimal materials and electrical components being used.

3.4.6 Economic

The overall budget for this project was \$400. While the initial design was able to fit within this budget, broken and malfunctioning equipment forced the project to go over.

3.4.7 Ergonomic

One of the most critical user needs constraints for any RC design is compatibility with standard RC controllers. In order to make our design compatible with most RC controllers as well as capable of controlling both the flight and leveling circuits on the quad-copter a standard Spektrum AR6210 6-channel DSMX Receiver was used.

3.4.8 Ecological

The most pressing ecological consideration of our project is the potential damage that the lithium-ion polymer batteries could have on the environment. Of particular concern is the possibility that, if damaged during flight or because of a crash landing, the batteries pose a potential fire hazard. The best method of preventing a fire caused by crash landing is housing the batteries such that they are protected from shock and all sharp objects.

3.4.9 Aesthetic

Of greatest aesthetic concern in our design is the exposed circuitry. While exposed wiring is ideal for prototyping because it allows for easy modification, for a final commercial design all circuitry components should be housed such that they are not visible.

3.4.10 Life cycle

As for most quadcopter designs, this product would require some maintenance throughout its functional life. In addition to consistently charging and replacing batteries when needed, it is very common to need to replace broken propellers. All other components would be difficult to repair or replace

3.4.11 Legal

The legal implications of flying drones as a hobbyist continue to evolve and grow more rigorous. The Federal Aviation Administration is responsible for ensuring safe and responsible use of all unmanned aircraft, including quad-copters. The FAA regulations for hobby and recreational use of model aircraft are given in section 5.2.6.

4 Embodiment and fabrication plan

4.1 Embodiment drawing

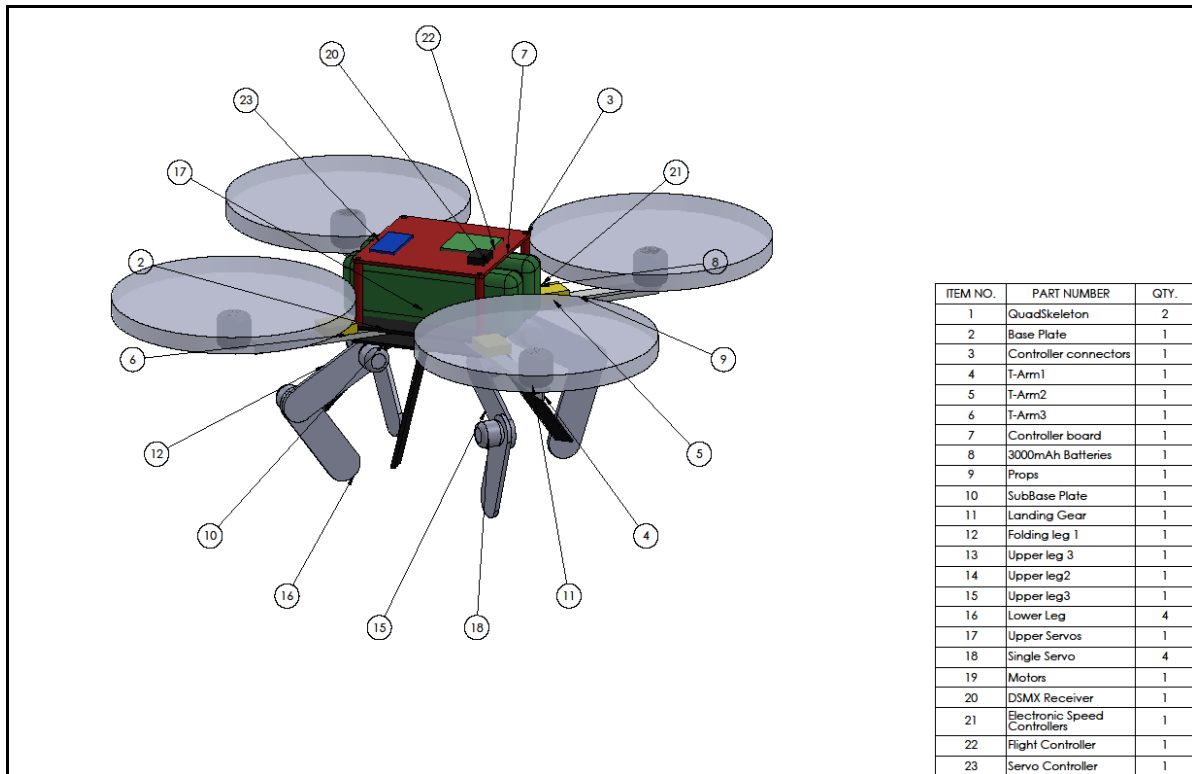


Figure 2: Embodiment Drawing

4.2 Parts List

Table 1: Initial Parts List

ITEM NO.	PART DESCRIPTION	QTY.
1	QuadSkeleton	2
2	Base Plate	1
3	Controller connectors	1
4	T-Arm1	1
5	T-Arm2	1
6	T-Arm3	1
7	Controller board	1
8	3000mAh Batteries	1
9	Props	1

10	SubBase Plate	1
11	Landing Gear	1
12	Folding leg 1	1
13	Upper leg 3	1
14	Upper leg2	1
15	Upper leg3	1
16	Lower Leg	4
17	Upper Servos	1
18	Single Servo	4
19	Motors	1
20	DSMX Receiver	1
21	Electronic Speed Controllers	1
22	Flight Controller	1
23	Servo Controller	1

4.3 Draft detail drawings for each manufactured part

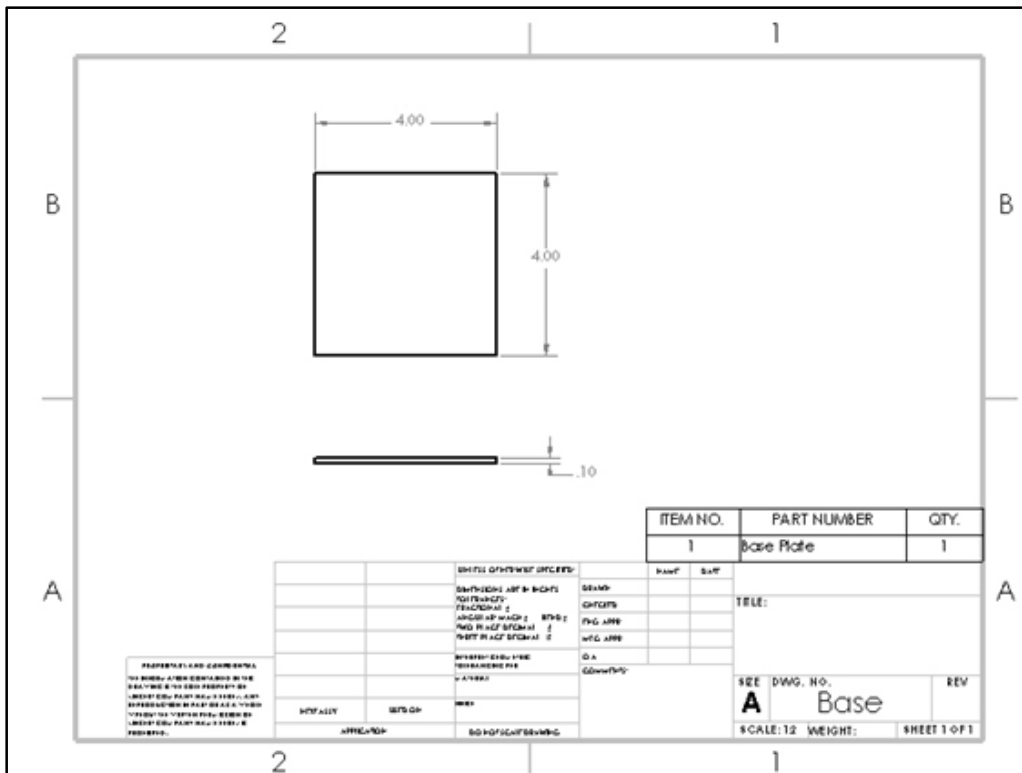


Figure 3: Base Plate

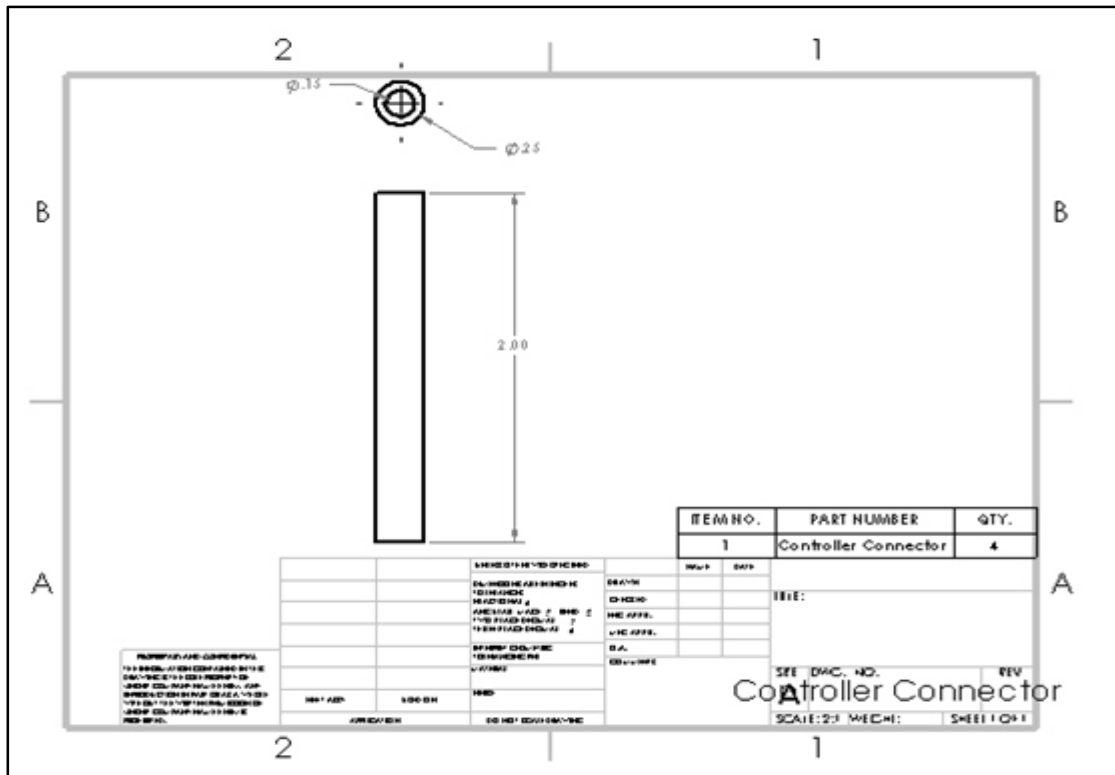


Figure 4: Controller Connector

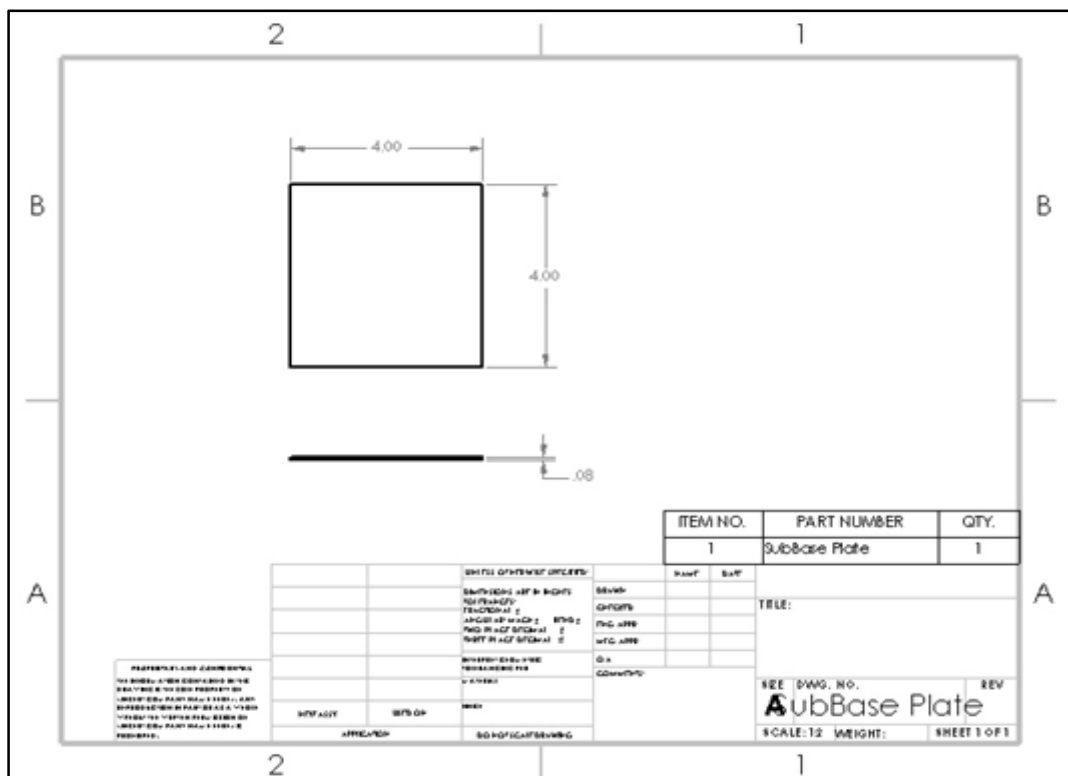


Figure 5: Sub-Base Plate

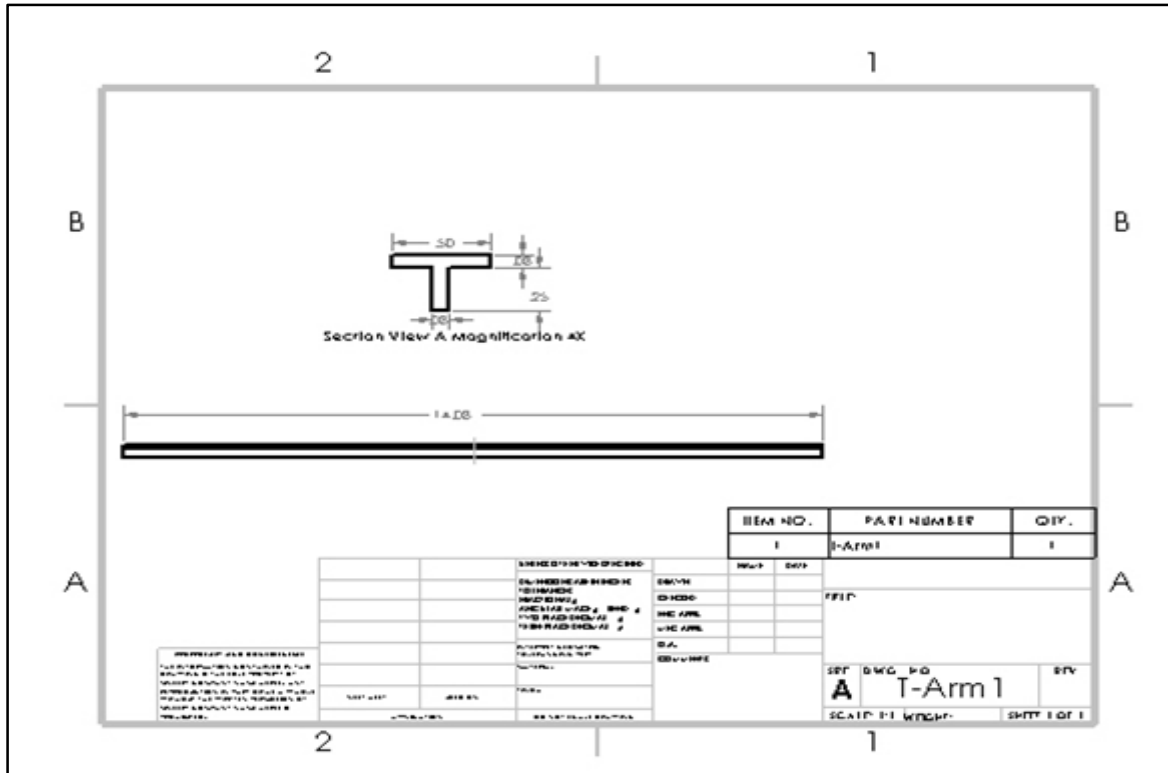


Figure 6: T-Arm

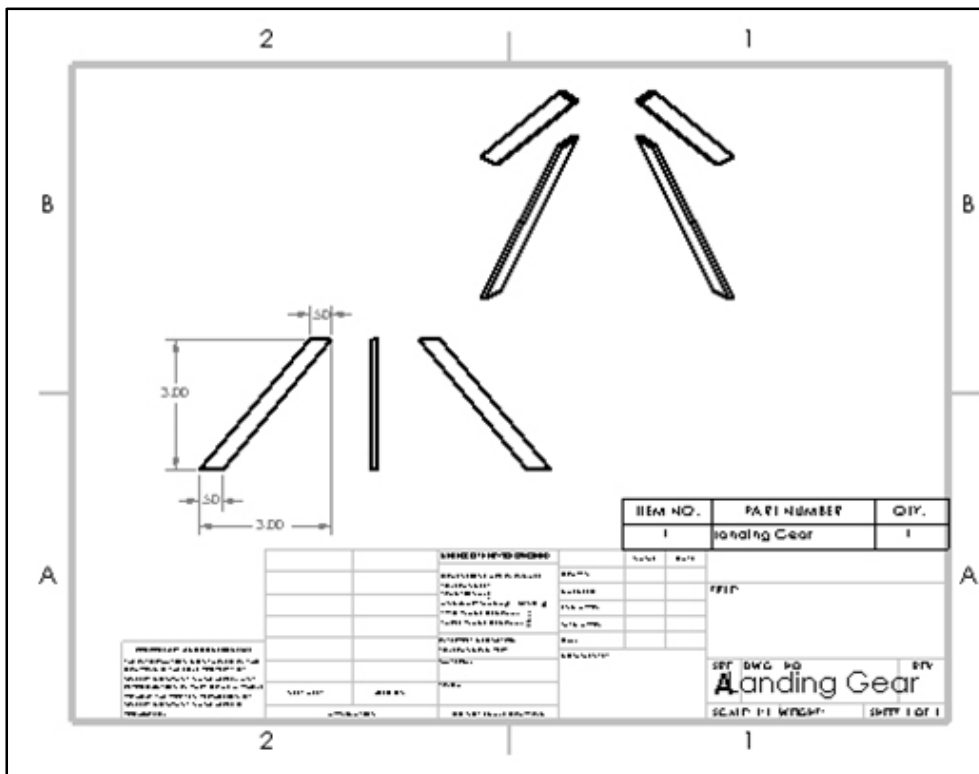


Figure 7: Landing gear

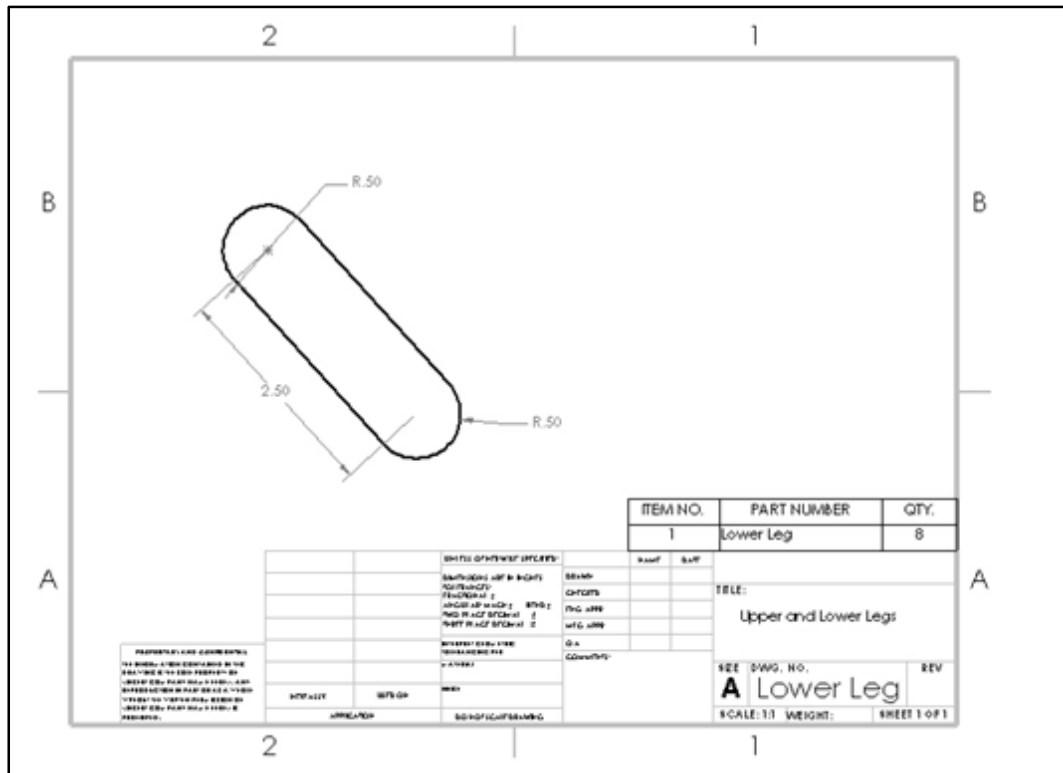


Figure 8: Lower Leg

4.4 Description of the design rationale for the choice/size/shape of each part

4.4.1 Frame Configuration

4.4.1.1 Overall Considerations

A quadcopter configuration was chosen for the frame design due to its symmetrical configuration and ease of control, as movement in any direction can be achieved by controlling the thrust of each motor. In order to incorporate the stabilizing landing gear, spacing between the quadcopter arms was maximized by choosing a plus type configuration (arms perpendicular to each other). As the frame represents the structural element of the quadcopter, it needs to be able to support the weight of the electronic components and withstand the bending moments caused by the rotating propellers, while being as lightweight as possible. Thus the shape and material of each frame element were chosen with the goal of obtaining the best compromise between weight and strength, while also taking machinability and price into consideration.

4.4.1.2 Arms

The main failure mechanism of the quadcopter arms is bending failure due to the bending moments created by the propellers thrust. Aluminum, fiber reinforced plastics (both carbon and glass fiber), acrylic, PVC, and ABS were considered as candidate materials. Although arms made from fiber

reinforced plastics would represent the best option from a weight-strength perspective, their significantly higher cost and difficulty in machining eliminated them as an option. Acrylic, PVC, and ABS tubes are comparable in price to aluminum, however their larger flexibility (lower Young's modulus) would result in higher beam deflections while the propellers are running. In addition, the shape and size of acrylic, PVC, and ABS tubes/beams is limited by what can be found on the market. Thus the selected material for the quadcopter arms was 0.08" thick aluminum 5052-H32 sheet due to its increased strength and ease of machinability. A T-beam design was chosen as it provides an increase in material strength and a decrease in weight in comparison to other geometries such as solid rectangular rods or hollow rectangular beams. The T-beam geometry will be constructed by connecting two 0.08 in thick and 0.5 in wide aluminum sheets. The two arms will be connected under the base plate. In order to prevent the arms from crossing each other under the base plate, one arm will be cut into two shorter pieces.

4.4.1.3 Center Plates

The center plates act as the connection point for the quadcopter arms and provide support for all the electronic components. Both acrylic and aluminum sheets were considered as material candidates. In order to reduce the weight of the frame, a 0.08 in thick acrylic sheet was chosen as the material.

4.4.1.4 Landing Gear

The landing legs will have the role of providing the initial landing support for the quadcopter. Thus they will have to be able to support the quadcopter weight, as well as be able to withstand any bending moments created as the quadcopter will stabilize itself before taking off. The maximum bending moments on the landing legs will be dependent on the load distribution over the four landing legs and four stabilizing legs. Given the strength of aluminum and the fact that aluminum sheets are used for hexapod legs, 0.08" in thick 5052-H32 aluminum sheets were chosen as the leg material. However, further analysis of the maximum bending moments on the landing legs is required in order to determine the appropriate leg material and thickness and given the complexity of the problem, consultation with a MEMS faculty member is required.

4.4.1.5 Stabilizing Legs

The stabilizing leg design was broken down by length, form, and material with the goal of being capable of supporting the weight of the quadcopter and taking the quadcopter from a 20 degree maximum tilt to perpendicular to the gravitational pull. The necessary length for achieving this maximum leveling angle was calculated to be $4\frac{1}{3}$ inches. As the first failure point of the stabilizing legs would be caused by bending, an accurate estimate of the bending moments acting on each stabilizing leg is needed. We have completed preliminary computations, however as this represents a complex problem we plan to contact a MEMS faculty member to review our computations. Our original leg

design required two leg segments, each comprised of two parallel bars joined by a servo motor (four total pieces). It was later decided that the added weight of putting two bars in parallel for each leg segment was not justified given the strength of aluminum. Our calculations for torque and lift requirements were based on a no slip condition at the point where the leg contacts the ground. A rubber treaded foot was designed to meet this requirement.

4.4.2 Electronic Components

4.4.2.1 Overall Considerations

There are multiple ways to execute almost any circuit, so the focus throughout the circuit design was simplification. The easiest way to accomplish this goal was to use one power source for the drone flight control, sensors, Arduino, and servo motors. Although this resulted in the need for a Battery Eliminator Circuit (BEC), the condensed geometry of a single battery pack allowed for significant design improvements to the structure.

4.4.2.2 Accelerometer

To determine the angle required to stabilize the drone, both a gyroscope and an accelerometer were considered. An accelerometer was chosen because it calculates required stabilization angle on a fixed reference point, whereas gyroscopes only measure angular changes. Accelerometers options ranged from fine-grained measurement of +/- 2g (accuracy of $2 / 1024 = 0.002g$), to +/-16g (accuracy of $16 / 1024 = 0.0156$.) The selected mode has a digitally outputs the x, y, and z position, compatible with our selected microprocessor.

4.4.2.3 Microcontroller

Servo motors are controlled by Pulse Width Modulation (PWM). As such, our microcontroller should contain at least 8 PWM pins. Models that include the number of required pins were found to be overly complex and heavy for our design requirements. Instead, a PWM shield was selected to supplement the standard Arduino Uno processor.

4.4.2.4 Servos

The maximum torque on the servo motors must be calculated before making a selection. In order to simplify initial calculations, the following assumptions were made:

- At most, the entire weight of the drone could be placed on one lifting leg (this is very conservative, and will prevent overloading of the servo).
- The maximum torque occurs in the leg elbow at the moment when the leg touches the ground, when the moment arm will be the longest.
- The total force was modeled by a point force acting at the point of the top pin.

These broad simplifications do not provide a sufficiently accurate torque for final design. The complexity of the torque force is such that expert consultation will be sought. Given the essential function of the motors, it is important that this calculation be done correctly before sourcing specific motors.

The angle turned by each positive pulse to the servo and the speed at which the pulses would be emitted will also be into account to ensure that quick rotation will not throw the drone off-balance. A model will that is capable of communicating with our chosen microcontroller will be selected.

A typical small-sized servo draws about 150 mAmp running with no load. This draw increases with torque on the motor. Online literature suggests that the maximum draw for a servo motor of this size is 1.5 amps, a relatively low load on the battery compared to the propeller motors.

4.4.2.5 BEC

The battery eliminating circuit was selected based on its ability to handle up to 8 servos at 5-V. It is recommended for high torque applications and will not create radio interference if located more than 2" inches from the receiver. This configuration is possible given current geometry restrictions.

4.4.2.6 Propellers and Motors

The propellers and motor were selected based on the static thrust requirements. The static thrust that the quad-copter can produce is a function of the Kv rating of the motors, the type, diameter and pitch of the propellers, the voltage drop over the motors, and a number of other variables. Using the equations below the static thrust for several combinations of propellers and motors was calculated. In order to balance the thrust with the size and weight of the quad-copter, 7x4E APC propellers (Thin-electric propellers with a 7 inches diameter and 4 inch pitch) were paired with 2000 Kv motors. Assuming an applied voltage of 11V, the calculated thrust is approximately **3.35 lbs/motor** (or 1.51 Kg/motor).

Thrust equations used [1]:

Thrust created by one propeller:

$$T = \frac{\pi}{4} D^2 \rho v \Delta v = \frac{\pi}{8} D^2 \rho (\Delta v)^2$$

T = thrust [N]

D = propeller diameter [m]

v = velocity of air at the propeller [m/s]

Δv = velocity of air accelerated by propeller [m/s]

ρ = density of air [1.225 kg/m³]

The velocity of air accelerated by the motor can be found using the power that is absorbed by the propeller from the motor:

$$P = \frac{T\Delta v}{2} \rightarrow \Delta v = \frac{2P}{T}$$

Substituting for Δv , one can calculate the thrust by using the following equation:

$$T = \left[\frac{\pi}{2} D^2 \rho P^2 \right]^{1/3}$$

This can be expressed in terms of mass using the following equation:

$$m = \frac{\left[\frac{\pi}{2} D^2 \rho P^2 \right]^{1/3}}{g}$$

Where $g = 9.81 \text{ m/s}^2$.

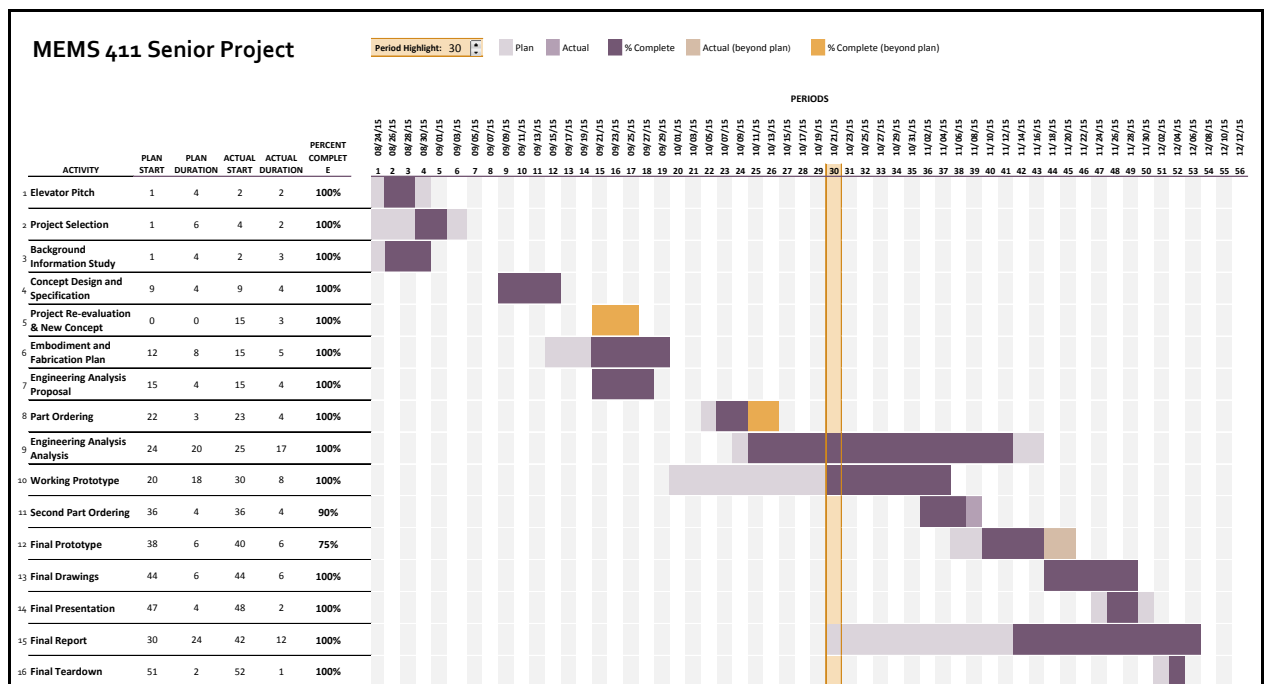
We confirmed our calculations using online thrust calculators as well. [2, 3]

4.4.2.7 Transmitter

The controller we will be using to fly the drone is a Spektrum DX5E borrowed from ASME. The only requirement for a transmitter was that it be compatible with this controller and have at least 5 channels.

4.5 Gantt chart

Table 2: Gantt Chart



5 Engineering analysis

5.1 Engineering analysis proposal

5.1.1 A form, signed by your section instructor

<p>ANALYSIS TASKS AGREEMENT</p> <p>PROJECT: Self-Stabilizing Drone: INSTRUCTOR: Jakiela, Malast</p> <p>Anne Shellum</p> <p>Sarah Schubert</p> <p>Andreea Stoica</p> <p>Jillian Rose</p> <p>The following engineering analysis tasks will be performed:</p> <ol style="list-style-type: none">1. Torque analysis: material and servo motor considerations corresponding to torque on landing gear.2. Thrust calculation: firm up weight calculations and calculate required thrust. Analyze resulting power and part requirements and their effects.3. Circuit design and coding: flight control, landing gear control, interface between the two circuits.4. Landing gear and flight testing mechanisms: develop reliable and safe experiments to test flight control, landing gear functionality, reliability. <p>The work will be divided among the group members in the following way:</p> <ol style="list-style-type: none">1. Anne2. Andreea3. Sarah4. Jillian <p>Instructor signature: _____; Print instructor name: _____</p> <p>(Group members should initial near their name above.)</p>
--

5.2 Engineering analysis results

5.2.1 Motivation. Describe why/how the before analysis is the most important thing to study at this time. How does it facilitate carrying the project forward?

5.2.2 Summary statement of analysis done. Summarize, with some type of readable graphic, the engineering analysis done and the relevant engineering equations

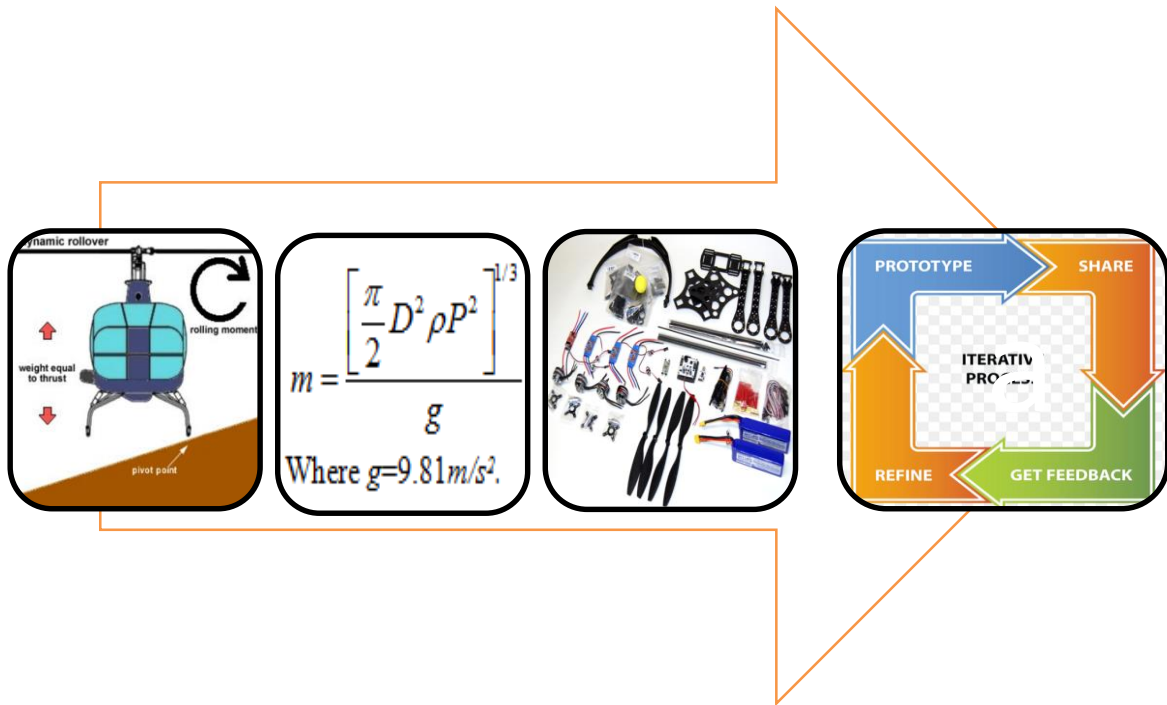


Figure 9: Summary of engineering analysis done before building the prototype

Photo 1: Our team set out to find a solution to the problems faced by rotorcraft when taking off on a slope. A four-legged automatic leveling mechanism was designed for a quadcopter to enable takeoff from an incline.

Photo 2: Engineering calculations were performed and the circuitry designed to define the mechanisms of the prototype, as outlined in Section 4.4.

Photo 3: Parts were researched and ordered. The initial prototype was built.

Photo 4: The initial prototype was tested, critiqued by our team and professors, refined, and tested again until the final prototype was presented.

5.2.3 Methodology. How, exactly, did you get the analysis done? Was any experimentation required? Did you have to build any type of test rig? Was computation used?

Our single most useful tool in performing the initial analysis was SolidWorks Computer Aided Design software. We modeled various geometries and mechanical components of our leveling mechanism to visualize the motion. The software helped us to understand geometric constraints on our quad copter and create drawings used to prototype that were precise and properly scaled. Once the geometries had been established, calculations and analysis were performed as described in section 4.4. The most involved analysis included the thrust and torque calculations, material selection, and circuitry

requirements. These analyses were performed manually based on the team's understanding of engineering principles learned in class. Some methodologies, such as thrust calculation and corresponding part selection, had to be researched and backed up using online calculators.

5.2.4 Results. What are the results of your analysis study? Do the results make sense?

5.2.4.1 Materials

The goal in selecting materials was having the highest strength to mass ratio. The optimal material for the drone frame and landing gear would have been carbon fiber, however it was not a viable option due to economic constraints. Based on our weight and the torque analysis in section 4.4, the selected materials were 0.08" thick garolite sheet for the base plates, 0.08" thick aluminum sheet for the lower leg segments and landing gear, 0.08" thick acrylic sheet for the upper leg segments and aluminum T-beams for the quadcopter arms.

5.2.4.2 Servos

Four large servos were selected for the middle joints of the landing gear and four small servos were selected for shoulders. The voltage and amperage requirements were checked to ensure compliance with the circuit design. These small servos were changed for a model with a higher torque after the failure of our initial servos, described in section 5.2.4.5. The following models were selected:



Figure 10: Large Servo [left] and Small Servo [right]

Model: FS5106B
 Torque: 83.7 oz-in
 Rotation: 180 Degrees
 Dimensions: 40.8 x 20.1 x 38 mm
 Mass: 40 g

Model: Model HS-82MG
 Torque: 47.2 oz-in
 Rotation: 180 Degrees
 Dimensions: 29.8 x 12 x 29.6 mm
 Mass: 19 g

5.2.4.3 Propeller and Motors

Propeller and motor selection was based on the thrust analysis detailed in section 4.4, with a per motor thrust of 3.35lbs and a total thrust of 13.4 lbs. A 2000KV Brushless motor and 7x4E Propeller combination are capable of producing this thrust.



Figure 11: 2000 kV Brushless Motor [left] and 7x4E Propeller [right]

5.2.4.4 Circuitry Design

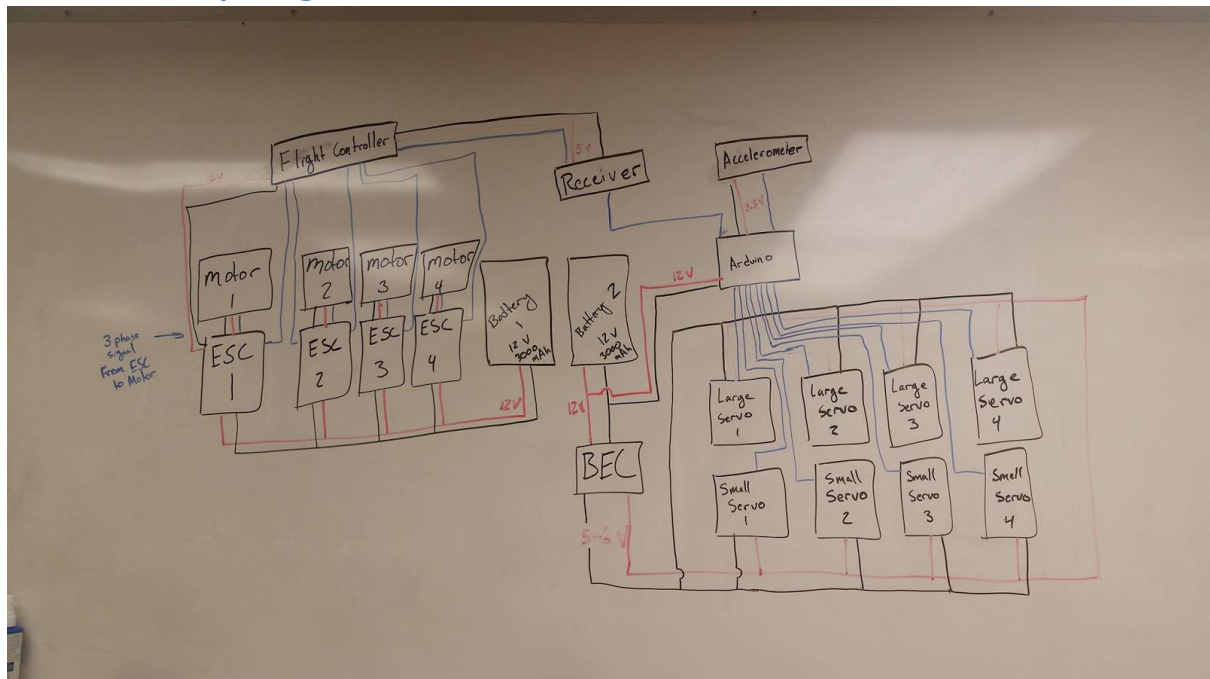


Figure 12: Final Circuit Schematic

The quadcopter had two primary circuits, the servo circuit and the flight circuit, each of which was connected to its own battery. The only connection between the two circuits is through the receiver which is powered through the flight controller and primarily used to control flight. Channel 6 on the receiver, however, connects to the arduino and is used to initialize the leveling code and to retract the legs upon command. While it was deemed unnecessary during prototyping, to improve the durability

of the design a common ground should be established by connecting the ground of each separate circuit. A common ground would ensure that the signal transmitted by the receiver to the arduino is high enough to be picked up by the arduino.

Servo Circuit:

Eight Servos were used to control the leveling gear, one small servo connected to the arms of the quad-copter and one larger servo at the elbow joint of each leg. An Arduino Uno was used to filter and analyze the data coming in from the accelerometer and control the servos accordingly. The accelerometer, a triple axis MMA8452 accelerometer breakout board from Sparkfun, was used to determine how far from level the quad-copter was. Unfortunately, the data received from the accelerometer contained too much noise to be useful so a moving filter was placed on the incoming data with a filter size of 15 data points.

MMA8452 Accelerometer Breakout Board:

The filtered accelerometer data was then used to move each pair of servos. Upon initialization of the servo code each large servo moves 90 degrees and then each pair of servos continues to move according to the data received by the accelerometer. The servos retract to their zeroed position when the operator switches off channel 5 on the transmitter.

Early in our design it was assumed that the servos could only be controlled by the PWM (pulse width modulation) pins on the arduino board, which, because an arduino uno only has 6 PWM pins, necessitated a PWM shield. While servos are controlled by PWM signals, it was later discovered that they need not be controlled through PWM pins because the servo libraries native to arduino produce the exact PWM signal needed to communicate with the servos. This greatly simplified the circuit.

Flight control circuit:

The foundation of the flight control circuit is our Naze32 flight controller. This flight controller was chosen for a number of reasons including its compatibility with Baseflight, the software we used to program the flight controller. Our Naze32 included an accelerometer, a gyroscope and a barometer, each used to sense and control the flight dynamics of our copter. The FC controlled each of the four electronic speed controllers and received commands via the receiver.

5.2.4.5 Continued Analysis through Prototyping

5.2.5 Significance. How will the results influence the final prototype? What dimensions and material choices will be affected?

The influence of the results of our analysis are demonstrated through the prototyping process detailed in section 5.2.4.5. Although we performed careful calculations before beginning construction, prototyping proved to be the only way to uncover inaccurate assumptions and truly understand the influence of each mechanism on the overall prototype. As a result, the analysis did not stop once the prototyping began. Each glitch in our design required a new analysis to determine the best path forward, and we became more informed in our analysis with each iteration.

The most important design changes are summarized by the contrast in the initial and final drawings shown below:

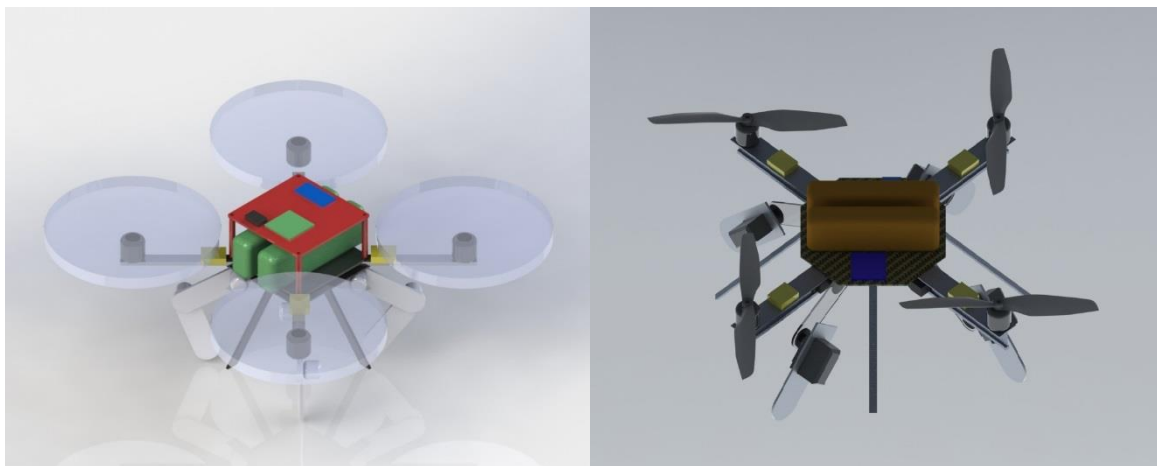


Figure 13: Initial Prototype [left] and Final Prototype [right]

5.2.6 Summary of code and standards and their influence. Similarly, summarize the relevant codes and standards identified and how they influence revision of the design.

A quadcopter falls under the very broad category of unmanned aircraft systems (UAS). The associated codes and standards for UAS are constantly changing because drones are relatively new to the engineering world. Applications for drones are extremely broad, and standards must be developed for each new application.

Primary oversight bodies include the Federal Aviation Administration (FAA), ISO (International Organization for Standardization), American Society for Testing and Materials (ASTM), and Association for Unmanned Vehicle Systems International (AUVSI) for public and civil use only.

The Federal Aviation Administration's policy is separated into three categories: Public, Civil, and Model Unmanned Aircraft, for which code and standards vary considerably. Our prototype is designed for recreational and hobby use only, and is considered a model aircraft by FAA standards.

Statutory parameters of model aircraft operation put forth by the Federal Aviation Administration are outlined in Section 336 of Public Law 112-95 (the FAA Modernization and Reform Act of 2012).

- 1) Aircraft flown strictly for hobby or recreational use;
- 2) The aircraft is operated in accordance with a community-based set of safety guidelines and within the programming of a nationwide community-based organization;
- 3) The aircraft is limited to not more than 55 unless otherwise certified through a design, construction, inspection, flight test, and operational safety program administered by a community-based organization;
- 4) the aircraft is operated in a manner that does not interfere with and gives way to any manned aircraft; and
- 5) when flown within 5 miles of an airport, the operator of the aircraft provides the airport operator and the airport air traffic control tower (when an air traffic facility is located at the airport) with prior notice of the operation (model aircraft operators flying from a permanent location within 5 miles of an airport should establish a mutually-agreed upon operating procedure with the airport operator and the airport air traffic control tower (when an air traffic facility is located at the airport)).

Where Model Aircraft is defined:

- 1) Capable of sustained flight in the atmosphere;
- 2) Flown within visual line of sight of the person operating the aircraft; and
- 3) Flown for hobby or recreational purposes.

These guidelines are detailed in advisory circular AC 91-57A- Model Aircraft Operating Standards.

Additional applicable guidelines include,

- ASTM F3005 Standard Specification for Batteries for Use in Small Unmanned Aircraft Systems
- ASTM F3003-14 Standard Specification for Quality Assurance of Small Unmanned Aircraft System
- ISO/TC 20/SC 16 – Unmanned Aircraft Systems (Still in development)
- Academy of Model Aeronautics National Model Aircraft Safety Code

Given that our parts were purchased from well-established model aircraft suppliers, we did not purchase specific standards related to things such as batteries and motors, assuming that the distributor had ensured compliance. We did confirm, however, that our prototype falls within the weight, size, and flight specifications of Unmanned Model Aircraft. The codes and standards outlined above will most heavily impact our quad copter during flight. FAA regulations state simply that UAS may not be flown in prohibited areas as determined by the private regulations in that location. Washington University property permits model aircraft and will serve as our testing site.

5.3 Risk Assessment

5.3.1 Risk Identification

There is risk associated with the budget, schedule, operation, construction, and testing of our quad copter. Risks associated with industry engineering projects such as market share or manufacturing considerations are not applicable for the scope of this project.

Table 3 in section 5.3.2 identifies conditions under which the project will take place and associated risks.

5.3.2 Risk Analysis

The risks identified in section 5.3.1 were discussed during the initial engineering analysis stage of our project and efforts were made to mitigate them. Calculations were repeatedly checked in attempt minimize errors, the CAD model was refined in order to streamline the machining process, and value engineering was performed to ease budget concerns. Throughout the prototyping process, extensive research was done before testing the electronics in order to avoid a malfunction. Potential events resulting from these risks are listed in the third column and numbers for the resulting effects on the project are listed in the fourth. Table 4 specifies these effects.

Table 3: Risk identification, corresponding events, and effects on project

Condition	Associated Risk	Potential Event	Potential Project Impact	Probability	Impact (1-5)
Final prototype must be completed by semester end	1) Parts unavailable	a) Parts do not come in on time b) Part malfunctions	1	high	4
	2) Scheduling conflicts limit time that engineers can dedicate to prototyping	a) Engineers cannot meet often enough to complete required prototyping b) Engineers rush through prototyping	1,2	medium	3
Prototype must be completed under budget	1) Cost of parts miscalculated	a) Part malfunctions b) Incorrect part selected	3	high	2
	2) Allotted budget inadequate for design requirements	a) Corners cut in design and part selection b) Design halted when budget reached	2	low	2
Prototype must be operable by user	1) User not trained in UAV flight	a) User cannot utilize leveling gear as intended b) User crashes drone	2,3,4	low	5
	2) Heavy wind conditions	a) Drone cannot be maneuvered properly b) Battery life shortened	2,4	low	1
	3) Circuit jarred during flight	a) Leveling gear cannot deploy resulting in crash b) Flight mechanism failure	2,3,4	medium	5
	4) Drone lands in rough terrain	a) Leveling gear cannot deploy b) Leveling gear or landing gear breaks	1,2,3	medium	3
Prototype must meet design specifications	1) Design requirements too ambitious	a) Additional research and practice by engineers needed	1	low	2
	2) Gap in engineering knowledge of part functionality results in incorrect part selection	a) New part must be ordered b) New part must be machined	1,2,3,4	high	3
	3) Miscalculation in initial engineering analysis	a) Prototype is not properly machined b) New part must be ordered	1,2,3	high	3
Prototype must be tested	1) Leveling gear breaks during flight testing	a) Leveling gear must be remade, parts reordered b) Prototype cannot be fully demonstrated	1,2,3	low	5
	2) Flight mechanism breaks during testing	a) Prototype cannot be fully demonstrated b) Parts must be reordered	1,2,3	low	4

Table 4: Potential effects specification for Table 3

Potential Effects Specification
1 Unable to complete the prototype as designed by the deadline
2 Prototype does not function as desired
3 Unforeseen cost increase potentially resulting in prototype being over budget
4 Injury may occur to user/designer

5.3.3 Risk Prioritization

Our team recognized that our budget was adequate for the purpose of our design, and understood that additional funds could be allocated in the event that we slightly surpassed the budget

requirements. Therefore, risks associated only with cost considerations were determined to be less critical than those associated with scheduling and prototype performance. The most concerning risks were those that could push back the schedule. Even if no setbacks occurred, our team would have been hard pressed to produce a prototype that met our design specifications by the deadline. Some of our electronic parts were specialized and required over a week to arrive, rendering the biggest risk to our project.

Had our team reached the flight testing stages, the sensitive nature of the electronics associated with the leveling gear would have posed the highest risk to our project. This risk was given particular attention and a testing plan put in place to minimize it (as described in section 5.2.4.5).

The probability of the events associated with each risk is in column 5 of Table 3. Column 6 shows our predicted income on the overall project success. A combination of these two metrics was used to prioritize our risk mitigation efforts.

6 Working prototype

6.1 A preliminary demonstration of the working prototype (this section may be left blank).

6.2 A final demonstration of the working prototype (this section may be left blank).

6.3 At least two digital photographs showing the prototype

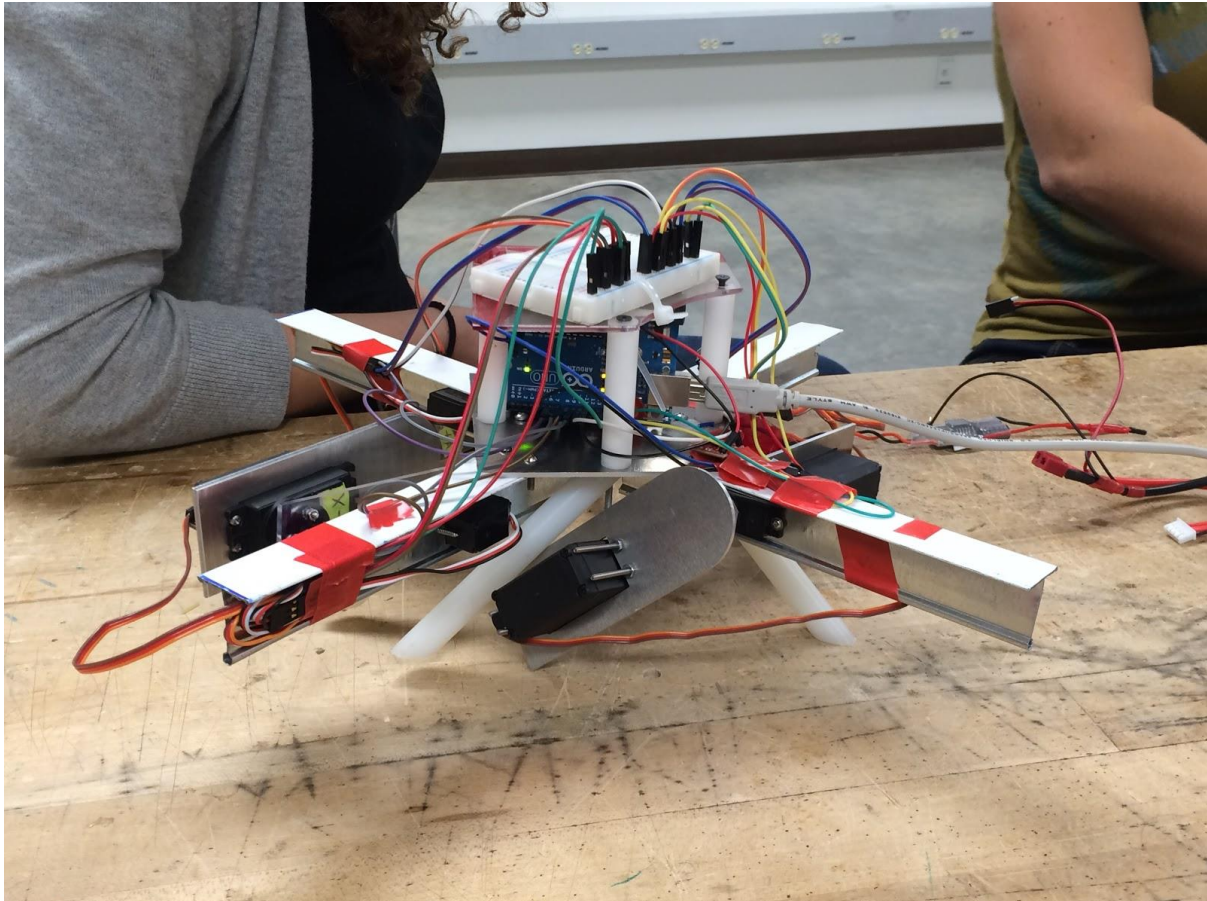


Figure 14: Initial Working Prototype

Figure 14 shows the initial working prototype. For the initial prototype we focused on the leveling aspect of the drone. At this point in the process both of the joints on each leg rotate the same amount to create a scissor like effect. After this initial prototype we opted to change this functionally to rotate the bottom joint to 90 degrees then begin rotating the top joint. This was to reduce the amount of drag that the “foot” would create on the ground. To accommodate this new motion we had to lengthen the rigid landing gear legs and at this point we chose to modify the materials as well. We also decided to modify the body shape from a square plate to a hexagonal plate in order to create more room for the electronic components and to prevent the need for a second layer.

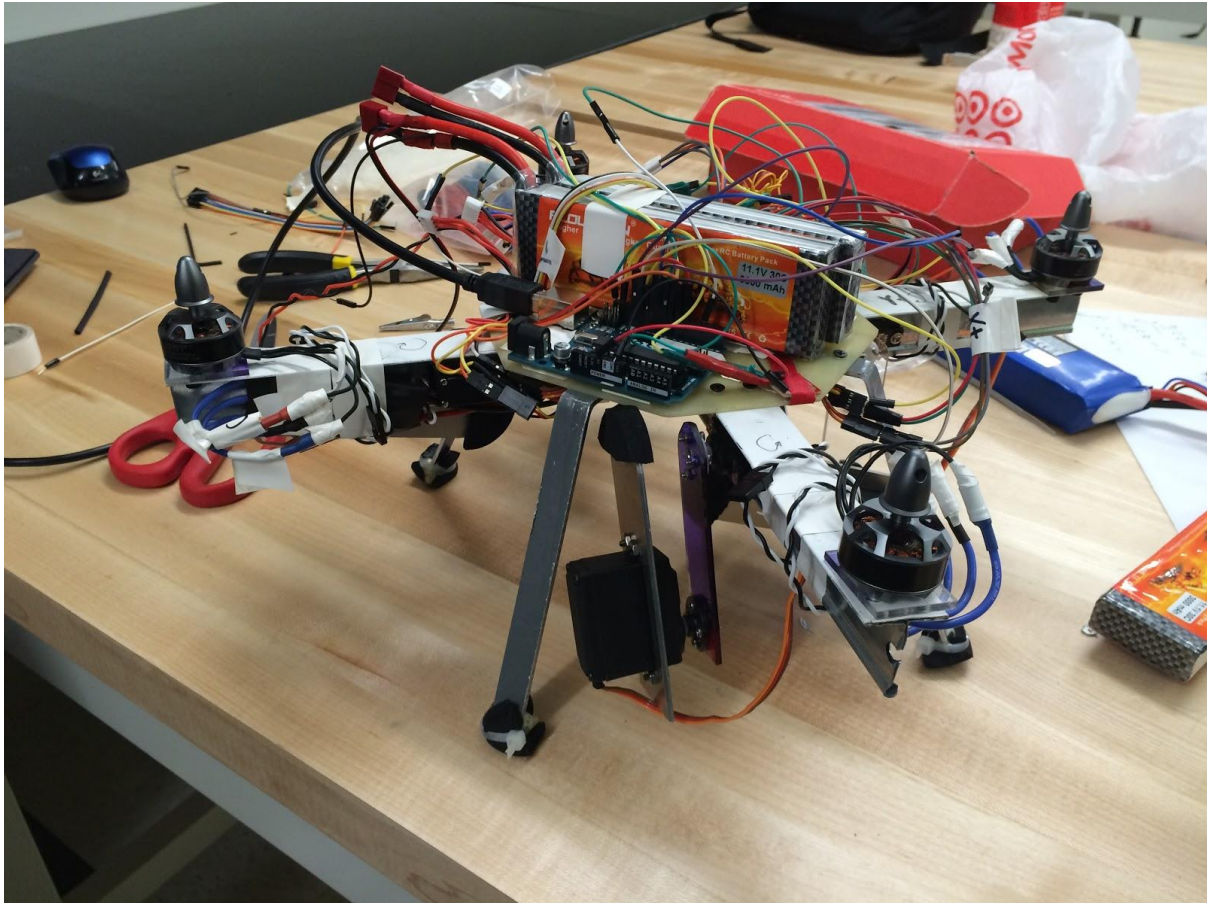


Figure 15: Final Working Prototype

This final working prototype shown in Figure 15 shows the completed quadcopter with a functioning leveling gear as well as a completed flight system. Also pictured here is the new rigid landing gear, made of aluminum rather than plastic rods, and the new hexagonal base plate, which is able to hold all of the necessary electronics for both flight and leveling.

6.4 A short video clip that shows the final prototype performing

These video clips demonstrate the drone's ability to zero and level automatically based on remote user input. This partial leveling video depicts the drone leveling with use of a single leg on a slope of approximately 15 degrees.

[Zeroing Demo](https://www.youtube.com/watch?v=xkND9DpJPRA&feature=youtu.be) (https://www.youtube.com/watch?v=xkND9DpJPRA&feature=youtu.be)

[Leveling Demo](https://www.youtube.com/watch?v=guKJlOmqtg&feature=youtu.be) (https://www.youtube.com/watch?v=guKJlOmqtg&feature=youtu.be)

6.5 At least four (4) additional digital photographs and their explanations



Figure 16: Close up of the hinged landing gear joints

Figure 16 depicts the two leg joints used to level the drone. The joints are moved by servos which are controlled by the arduino. The arduino takes input from the accelerometer and determines the orientation of the drone. The arduino uses the information from the accelerometer to determine which leg or legs to move to achieve a level orientation.

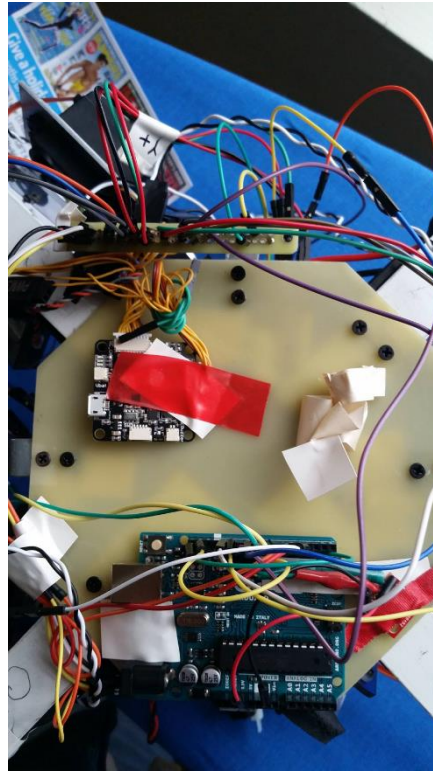


Figure 17: Accelerometer and Flight Controller

Figure 17 depicts the orientation of the accelerometer and the flight controller in relation to the body of the drone. Note that the corners of the flight controller point in the axial directions, while the sides of the accelerometer are oriented towards the axes.

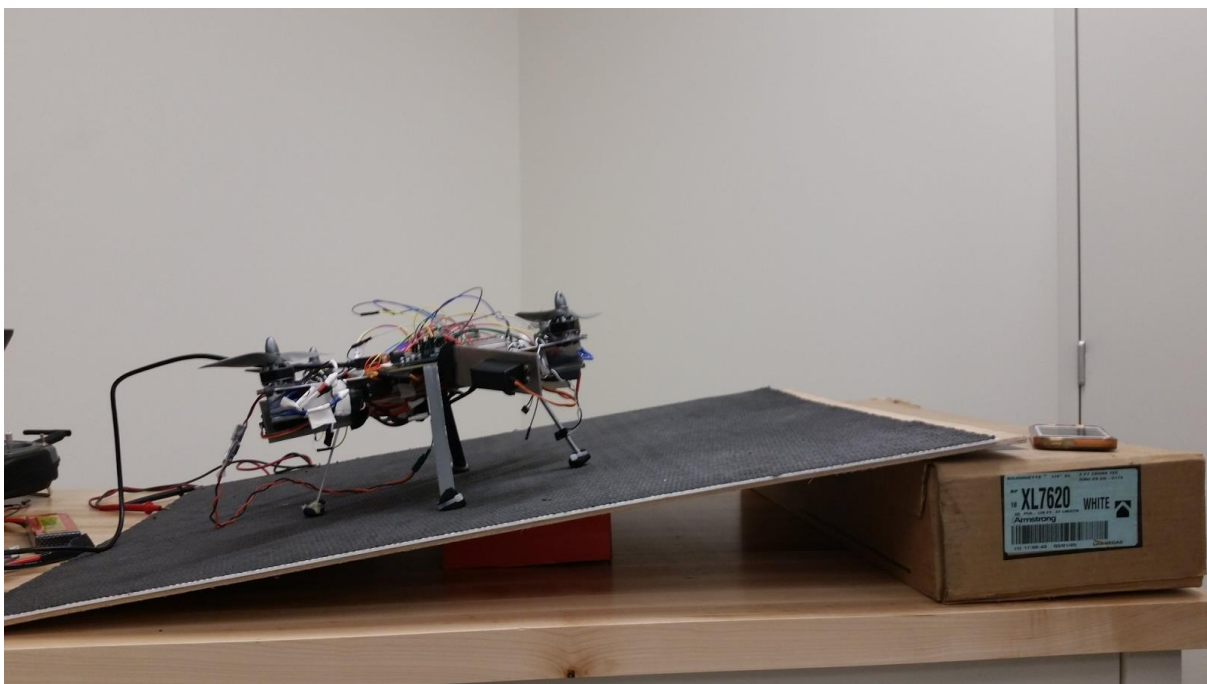


Figure 18: Quad-copter at an approximately 15 degree angle during testing

Figure 18 shows the quad-copter during leveling testing. In figure 18 the landing gear has not yet deployed and is awaiting a signal from the transceiver. Both the flight and leveling circuit are attached to the drone for the purpose of testing the leveling gear at maximum load.

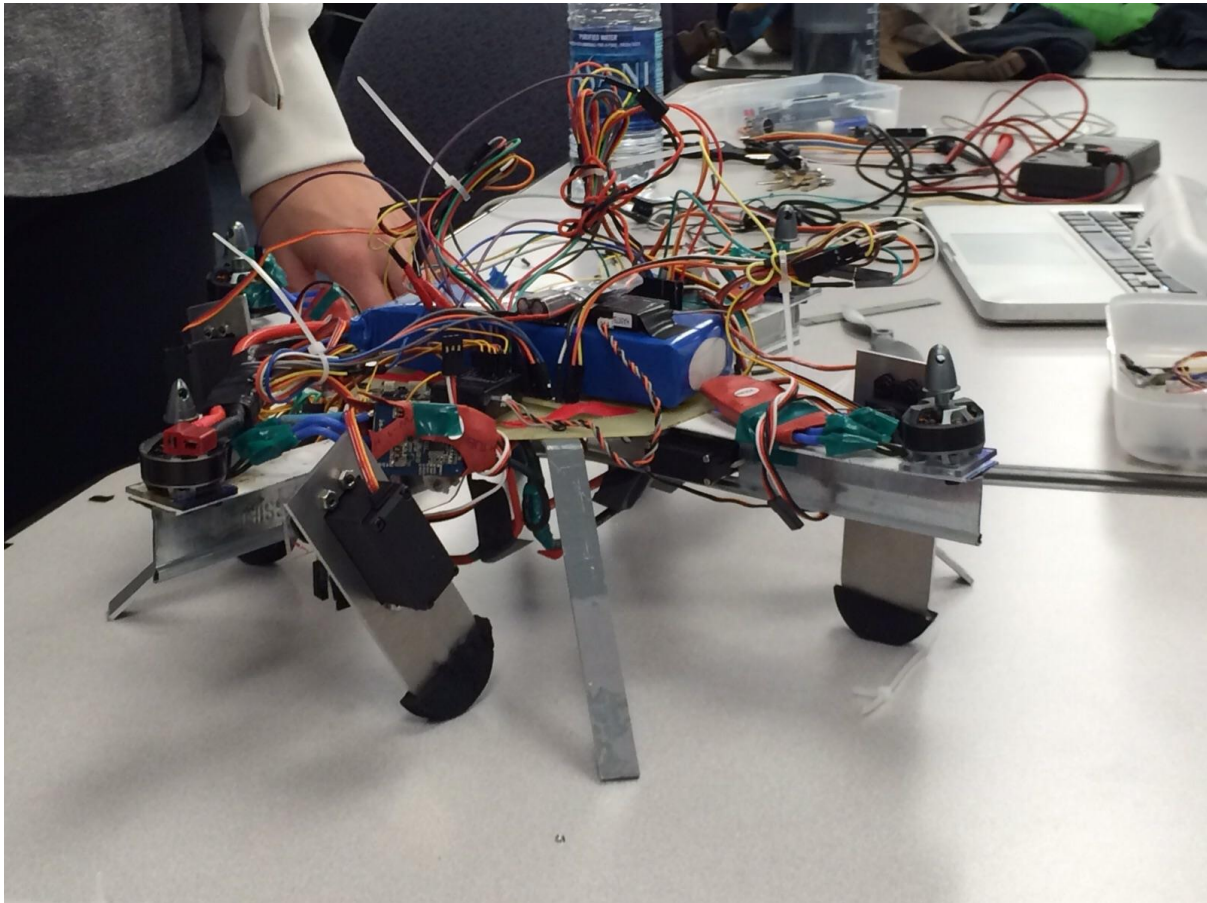


Figure 19: Close up of the full circuit

Figure 19 shows the drone with all circuit components added prior to circuit cleanup. Although the drone was not able to fly due to part malfunction, both the flight controller configuration the flight circuitry were completed.

7 Design documentation

7.1 Final Drawings and Documentation

7.1.1 A set of engineering drawings that includes all CAD model files and all drawings derived from CAD models.

Engineering drawings can be found under Appendix C. All CAD model files can be found under the following link.

7.1.2 Sourcing instructions

The Bill of Materials can be found under Appendix B.

7.2 Final Presentation

7.3 Teardown

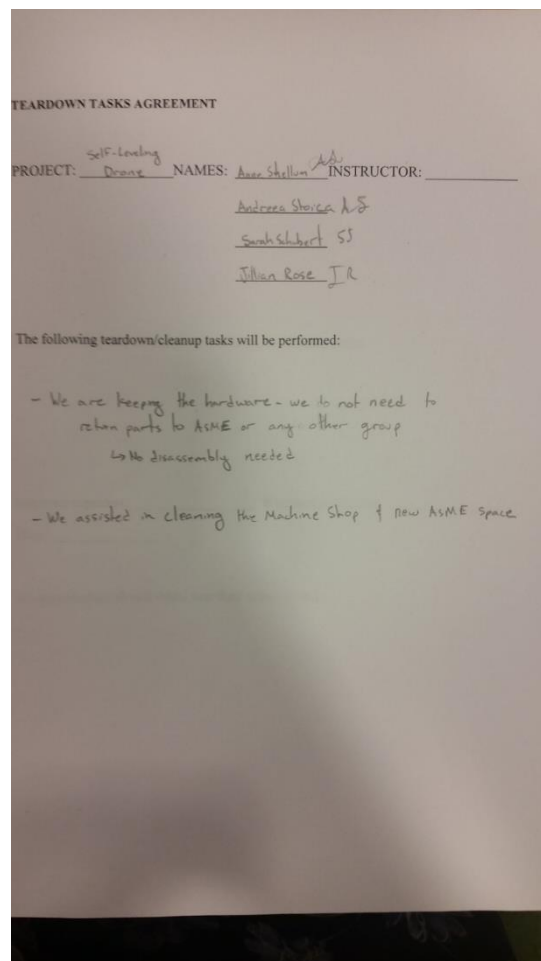


Figure 20: Teardown agreement

8 Discussion

8.1 Using the final prototype produced to obtain values for metrics, evaluate the quantified needs equations for the design. How well were the needs met?

Unfortunately, due to a number of part malfunctions, flight was never achieved. Therefore, the drone's ability to fly for five minutes remains untested. However, the completed drone weighed a mere 3.4 lbs, well under the 5 lbs goal. Additionally, the landing gear was able to achieve accurate leveling for up to a 20 degree angle and it did this consistently, through the transmitter and is capable of leveling in approximately 5 seconds. The drone was proven to be able to level from any orientation and the leveling gear can refold at any point via a command from the transmitter.

8.2 Discuss any significant parts sourcing issues?

For our parts we relied heavily on Sparkfun and Amazon. For the most part there were no unreasonably long part delivery times, with the exception of a set of electronic speed controllers that had to be reordered when they were lost in transit. Many of our parts were borrowed from ASME and from friends, primarily things used for testing such as servo testers and battery chargers. It is highly recommended for future projects that students be very aware of the connectors they will need for electronic components. It is likewise beneficial to note that no high quality batteries can be ordered online as it is technically illegal to ship them. Students needing LiPo batteries should start in electronic stores nearby, such as MicroCenter.

8.3 Discuss the overall experience:

8.3.1 Was the project more or less difficult than you had expected?

As is always the case with any project, especially those with electronics, it is always harder than you expect.

8.3.2 Does your final project result align with the project description?

Our final project aligns very well with the project description. We were able to fulfill the vast majority of our quantified needs and created a product very similar to that which we imagined from the outset.

8.3.3 Did your team function well as a group?

Our team worked well together, even under pressure. We were able to communicate well and did a fairly good job of splitting up tasks.

8.3.4 Were your team member's skills complementary?

Most of the skills we used in this project we picked up over the course of the project. However, because we specialized from the outset, we did end with complementary skills.

8.3.5 Did your team share the workload equally?

With some exceptions, our team did an excellent job of sharing the workload equally.

8.3.6 Was any needed skill missing from the group?

Because we started with very limited machining and programming skills and functionally no electronic prototyping skills, many skills were missing from the group. However, these skills were developed over the course of the project.

8.3.7 Did you have to consult with your customer during the process, or did you work to the original design brief?

We did not consult with our customer during the process. We worked to the original design brief.

8.3.8 Did the design brief (as provided by the customer) seem to change during the process?

There was little or no change to the design brief during the design process.

8.3.9 Has the project enhanced your design skills?

Many skills were developed that had never before been used, including CNC milling, much of the programming, electronic prototyping, etc.

8.3.10 Would you now feel more comfortable accepting a design project assignment at a job?

Having gone through this process, accepting a design project assignment at a job would be much easier.

8.3.11 Are there projects that you would attempt now that you would not attempt before?

There are a few projects that have been inspired by this one that we look forward to working on, however, there are no projects we would not otherwise have attempted had we not gone through this process.

9 Appendix A - Parts List

ITEM NO.	PART DESCRIPTION	QTY.
1	Base Plate	1
2	Landing Gear	4
4	Micro Servo	4
5	Micro Servo Horn	4
6	Quadcopter T-Arm	1
8	Upper Leg	4
9	Lower Leg	4
10	Standard Servo	4
11	Standard Servo Horn	4
12	Motors	1
13	Propeller	4
14	3000mAh Batteries	1
15	Electronic Speed Controllers	1
16	DSMX Receiver	1
17	Servo Controller	1

10 Appendix B - Bill of Materials

PART	USE	VENDOR	MODEL NUMBER	QUANTITY	UNIT PRICE	TOTAL PRICE
Aluminum T-Beam	Arms	Home Depot	N/A	4	\$2.00	\$8.00
Acrylic Sheet	Base Plate and Legs	Home Depot	N/A	2	\$3.50	\$7.00
Aluminum Sheet	Landing Gear and Legs	Amazon	B003JKJET6	1	\$19.10	\$19.10
Rubber thread	Leg Traction	MEMS Machine Shop	N/A	4 sq. inches	\$0	\$0.00
Arduino Uno Rev 3	Flight/Servo Control	Sparkfun	LC-066	1	\$24.95	\$24.95
PWM Shield	Servo Control	Sparkfun	BOB-10616 ROHS	1	\$19.95	\$19.95
BEC	Power Distribution/Reduction	Dimension Engineering	SportBEC	2	\$29.95	\$59.90
Servo High Torque	Leg Stabilization	SparkFun	ROB-11965 RoHS	4	\$12.95	\$51.80
Servo Sub Micro	Leg Stabilization	Sparkfun	ROB-09065 RoHS	4	\$8.95	\$35.80

Buffered 3D Accelerometer	Leveling	Sparkfun	SEN-12756 RoHS	1	\$9.95	\$9.95
ESC	Motors/Flight	Amazon	B013G4XR92	4	18	\$72.00
3000 mAh Lithium Polymer Battery	Energy	Amazon	B00HWQ4OLG	2	\$19.99	\$39.98
2000 kV Brushless Motor	Motors/Flight	Amazon	B00ZP84OA4	4	\$13.25	\$53.00
Emax Skyline32 Flight Controller	Flight Controller	Amazon	B014WCFEN4	1	\$37.99	\$37.99
Receiver	Flight/Servo Control	Amazon	B004M166WE	1	\$70	\$70.00
Additional Circuitry	Leg Stabilization	Micro Center	N/A	1	\$27	\$27
Servo Micro	Leg Stabilization	Amazon	B0012YXRJE	4	\$20	\$80
Propellers	Flight	APC	7x4E	12	\$2.45	\$29.40
Total						\$645.82

11 Appendix C - CAD Models

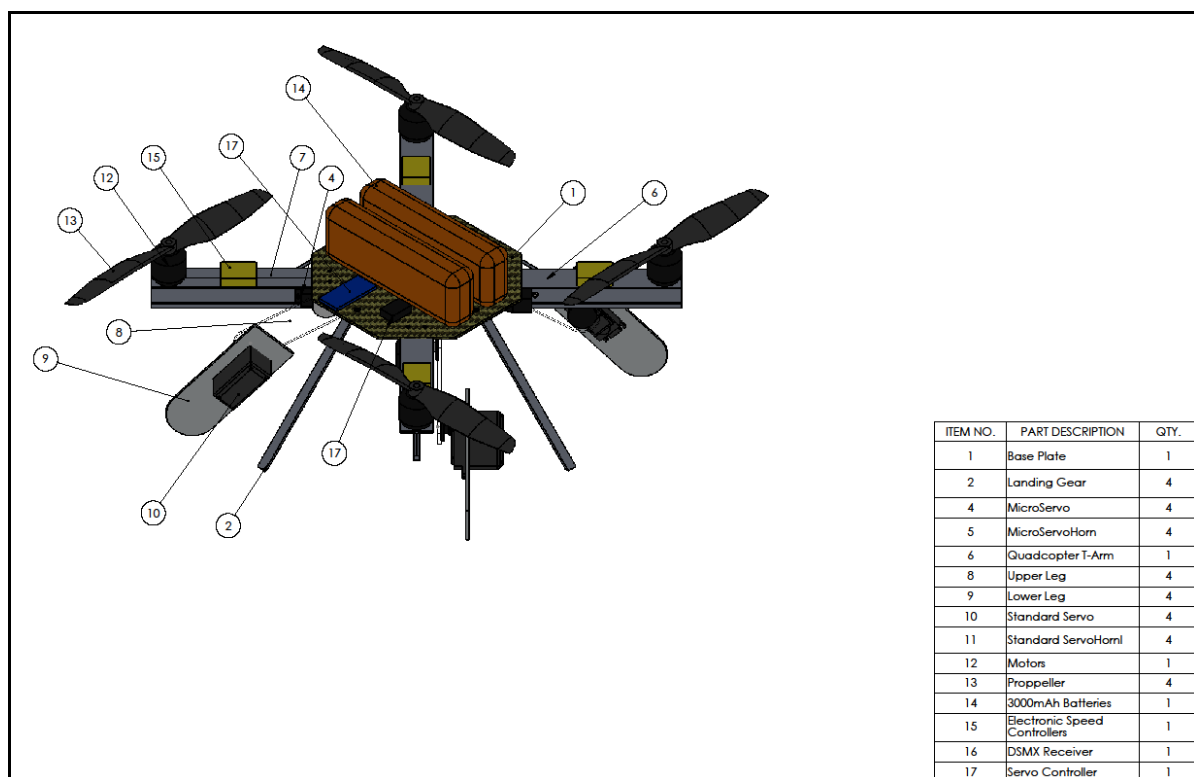


Figure 21: Drone Assembly

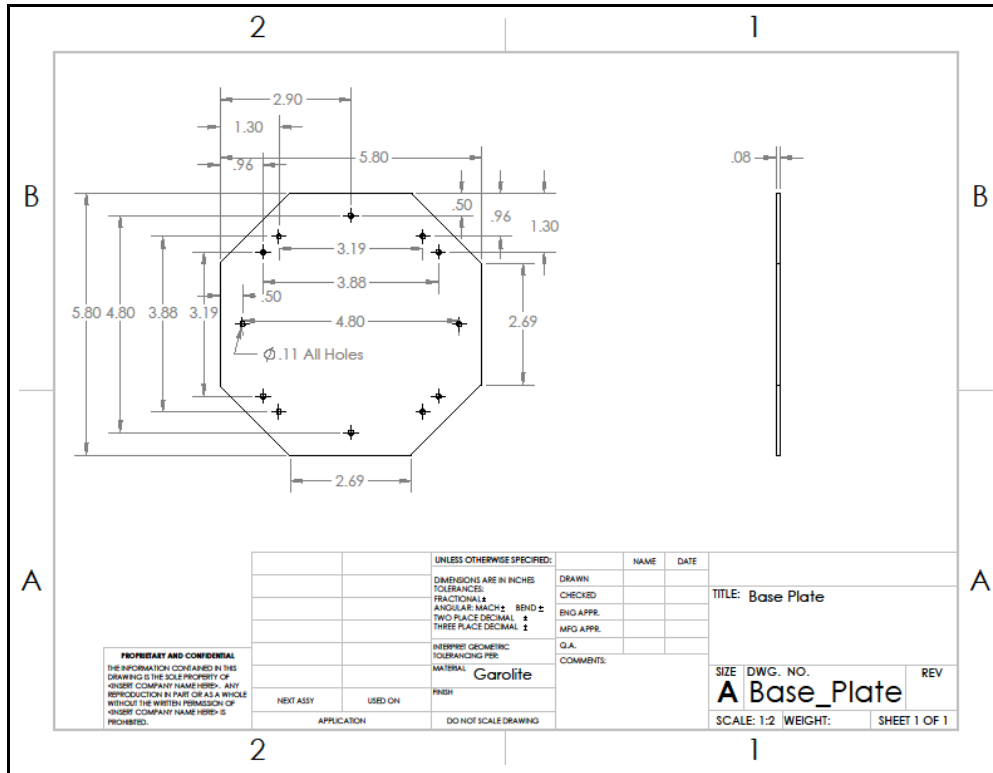


Figure 22: Base Plate

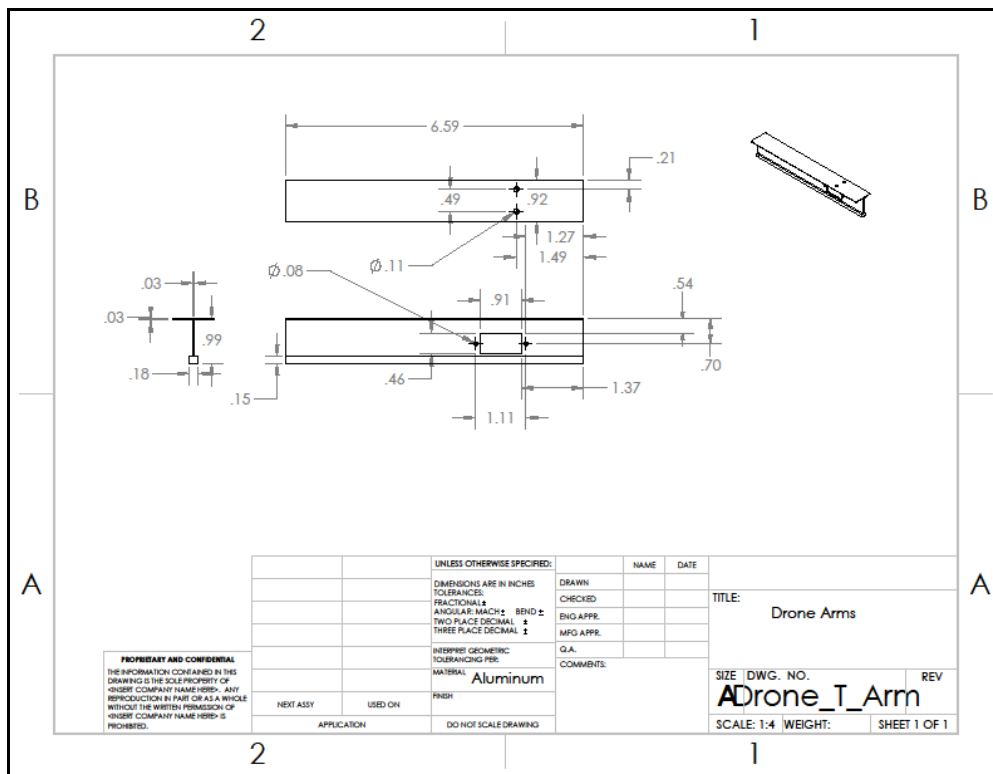


Figure 23: T-Arm

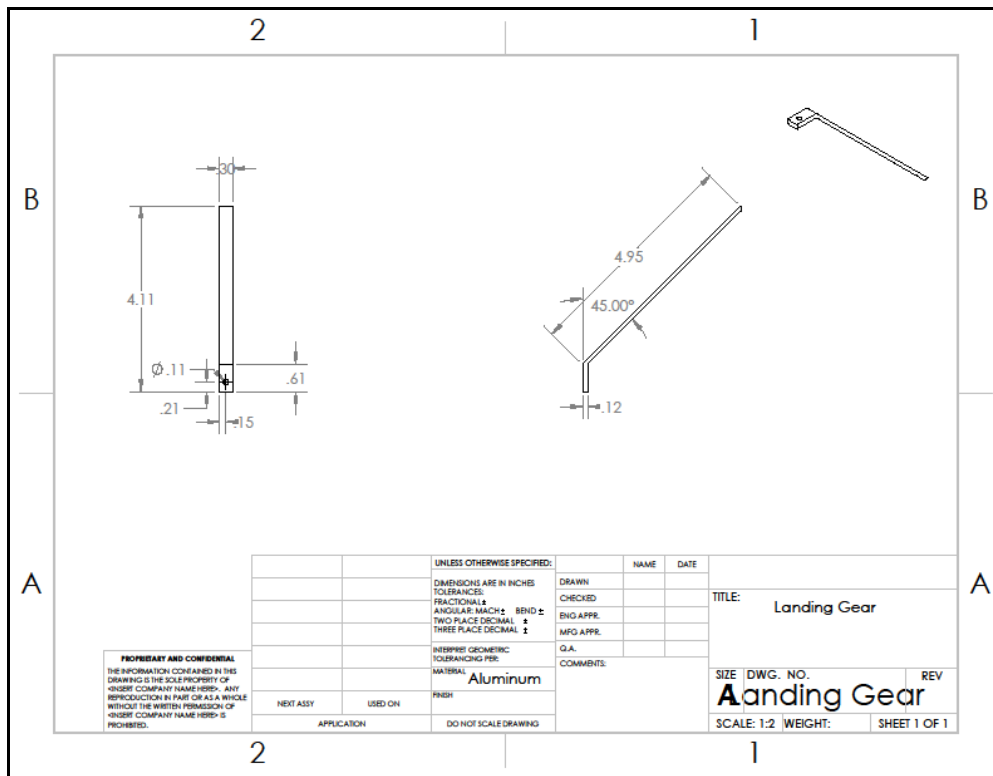


Figure 24: Landing Gear

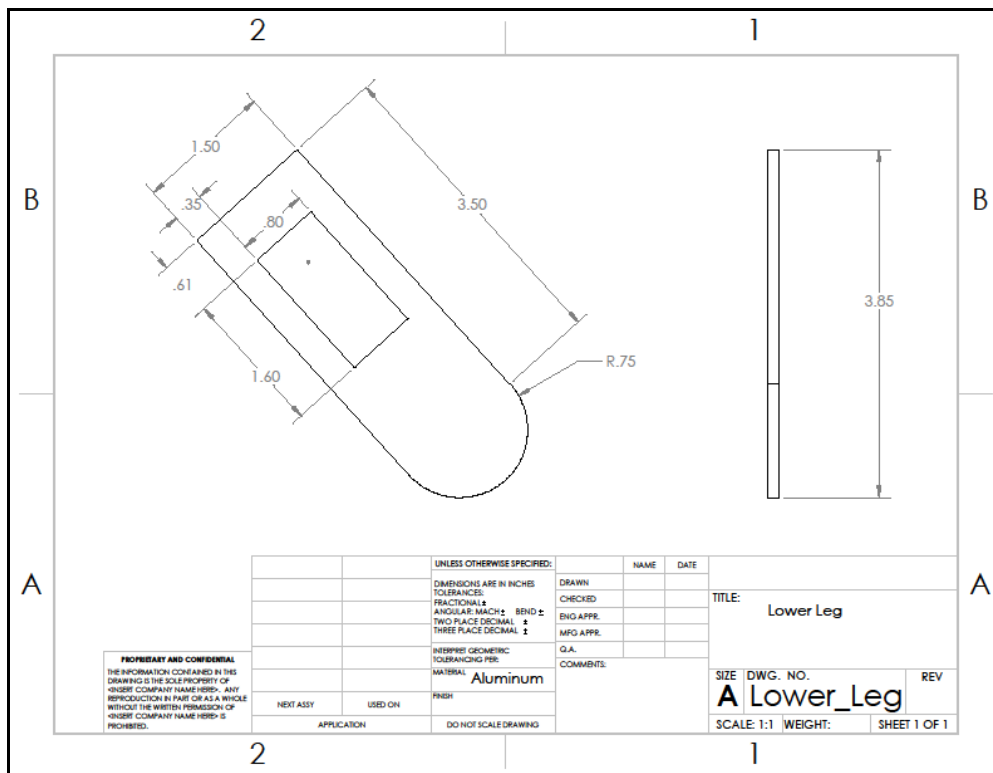


Figure 25: Lower Leg

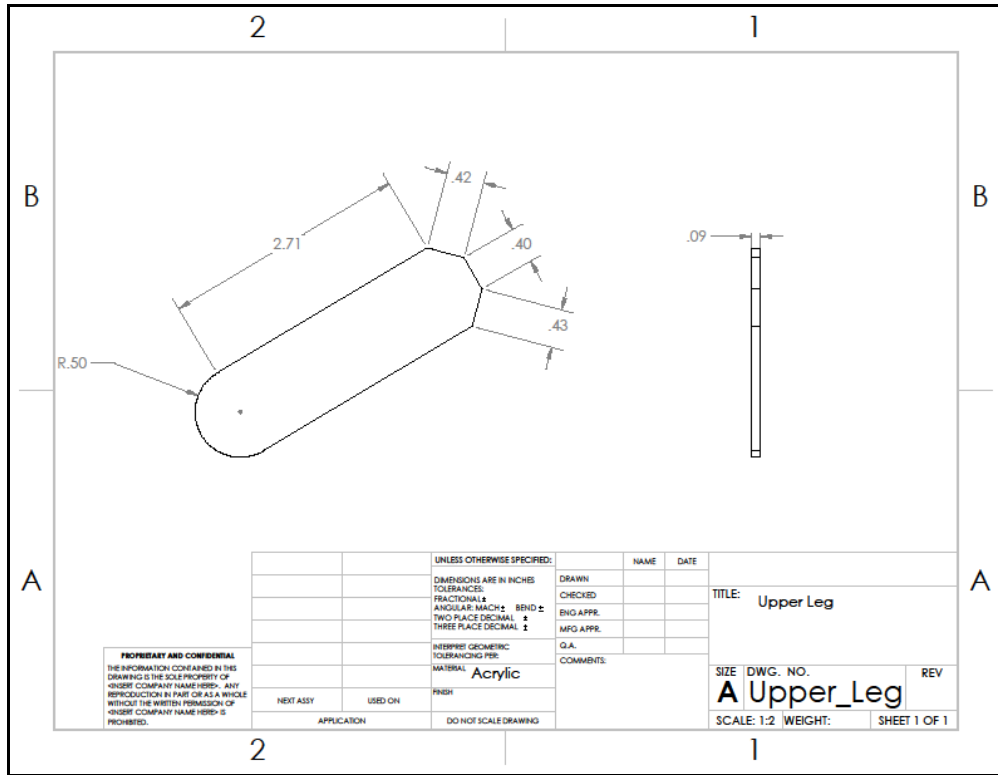


Figure 26: Upper Leg

12 Annotated Bibliography

[1] U.S. Department of Defense. "Robotic Landing Gear Could Enable Future Helicopters to Take Off and Land Almost Anywhere." *DARPA RSS*. Defense Advanced Research Projects Agency, 9 Oct. 2015. Web. 07 Dec. 2015.

A detailed description of DARPA's ongoing attempts to design self-leveling landing gear for helicopters.

[2] Rippere, Tony. "An Approach to Designing Passive Self-leveling Landing Gear with Application to the Lunar Lander." *NASA Archive* (n.d.): n. pag. NASA.

This article details the creation of NASA's self-leveling landing gear for their Lunar Rover. Though relatively different in application, the qualified needs for NASA's design closely mirror those developed for our project.

[3]"Static Thrust Calculation." *AirWolf 2*. Quadcopterproject, 12 Sept. 2011. 06 Dec. 2015.

An online static thrust calculator used to verify our thrust calculations.

[4]Dickey, J. "Static Thrust Calculation." *Quadcopterproject*. Aircraft World, 12 Sept. 2011. Web. 07 Dec. 2015.

Used to determine static thrust calculations.

[5] Federal Aviation Administration. "Model Aircraft Operations." *Model Aircraft Operations*. US Department of Transportation, n.d. Web. 07 Dec. 2015.

A description of federal regulations regarding the use of unmanned aerial vehicles for recreational purposes.

