

MECHANICAL ENGINEERING 102B

MECHATRONICS DESIGN

SPRING 2016 - Professor Liwei Lin

PROJECT APPA

Team SkyBison - Team 2
Final Report₃



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Executive Summary

The Problem

Currently the DJI Matrice 100 drone has up to a 40 minute flight time with a replaceable dual battery configuration. Each battery takes 100 minutes to recharge. Batteries are ineffective and inefficient for long flights. If drones were not limited to this short flight time, they could be used as temporary structures. For example, drones with unlimited flight can fly and supply data service acting as a temporary cell tower without having to build a structure. For these reasons, unlimited hover would allow drones to perform tasks that were previously impossible.

The Specification

DJI, the sponsoring team, has requested deliverables for the project:

1. Unlimited tethered hover operation of M100 quadcopter
2. Hover at least 100 feet
3. Automatic tether tension system
4. System has 50W buffer above peak drone power for future accessories
5. Stock M100 battery must be removed

Problem Analysis

To provide enough constant power for the unlimited drone flight, a powered wire (tether) must be attached to the drone. The tether must be long enough for the drone to fly 100 feet in the air. The tether must be managed so that it will not get caught in drone's blades and cause a crash. The stock vehicle battery is 22v DC and draws approximately 20 amps during hover. The powering system will need to supply 50W above max vehicle power. DJI suggested creating a high voltage power transfer system onboard the drone, allowing low current to be drawn through the tether, resulting in a small diameter wire that is easier to manage and reel.

The Plan

Initially, the team will need to learn how to fly the drone and become familiar with how the drone works. The power consumption of the drone will then need to be measured at both idle and max power. The capable drone payload will also need to be determined. After the power demands of the drone are known, the specification of the electrical system can be designed. The voltage step down and wire gauge will be designed and tested. Once the drone is capable of flying with a tether instead of batteries, the tether management system will be designed. The team attempted to learn to use the DJI SDK to access altitude and control input telemetry but was outside the programming capabilities of the team. Ideally this would have been used to control the tether management system. A reel and motor might be used to control the tether length. A mechanical reel with constant force spring and gearbox will now used instead because the SDK is too complicated for the amount of time available for the project. Testing will need to be done to ensure the drone's tether has enough slack to fly but is taut enough so that it does not get caught in the rotors. If time allows, accessories may be added to the drone to take advantage of the 50W power buffer.

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1. Introduction

DJI is an innovator in drone technology that constantly pushes for change and improved functionality. They focus on providing easy to maneuver and automatically stabilizing drones that are capable of high quality imagery. Their goal is to redefine the current drone industry and delve into previously unexplored fields. In order to add versatility and reliability to their drone, they want to provide unlimited hover power through a drone tether. Specifically, the goal of this project is to create a cable that will allow for the drone to hover at 100 feet for an unlimited amount of time. This tether cable will continuously transmit power to the drone and a reeling mechanism will maintain tension in the tether and prevent entanglement.



Figure 1: Project Visualization

If this project is successfully implemented, the tethered drone will have the capability to positively impact many different drone applications. One specific industry that this project will benefit is search and rescue. This project will allow the drone to be used as a temporary WiFi or cell tower, loudspeaker mount, light tower, or small weather station. The need for temporary, portable truss systems to reach altitudes can be eliminated with the use of a tether powered drone. The drone will now be able to survey areas over long periods of time since power is no longer limited to the time that a single battery can last. The tether will allow for media to record the entirety of games or performances without needing to change the drone's battery during them. **Figure 1** above shows a preliminary vision of a tethering apparatus that can transmit power to the drone.

2. Specifications

The most important customer specification for our drone project is unlimited tether hover operation at a high altitude. The tether should have a reeling mechanism that will ensure constant tension to prevent tangling. The drone should be able to fly without an onboard battery and have the capability to provide accessory power. All of these customer specifications and their translation into engineering requirements can be seen in the QFD below (**Figure 2**). Using our customer specifications, our team was able to create engineering requirements with specific, obtainable metrics which are outlined in the vertical columns in the QFD. We were able to rank the importance of these metrics in order to determine our design priorities and prioritize what quality characteristics that we will aim to meet first.

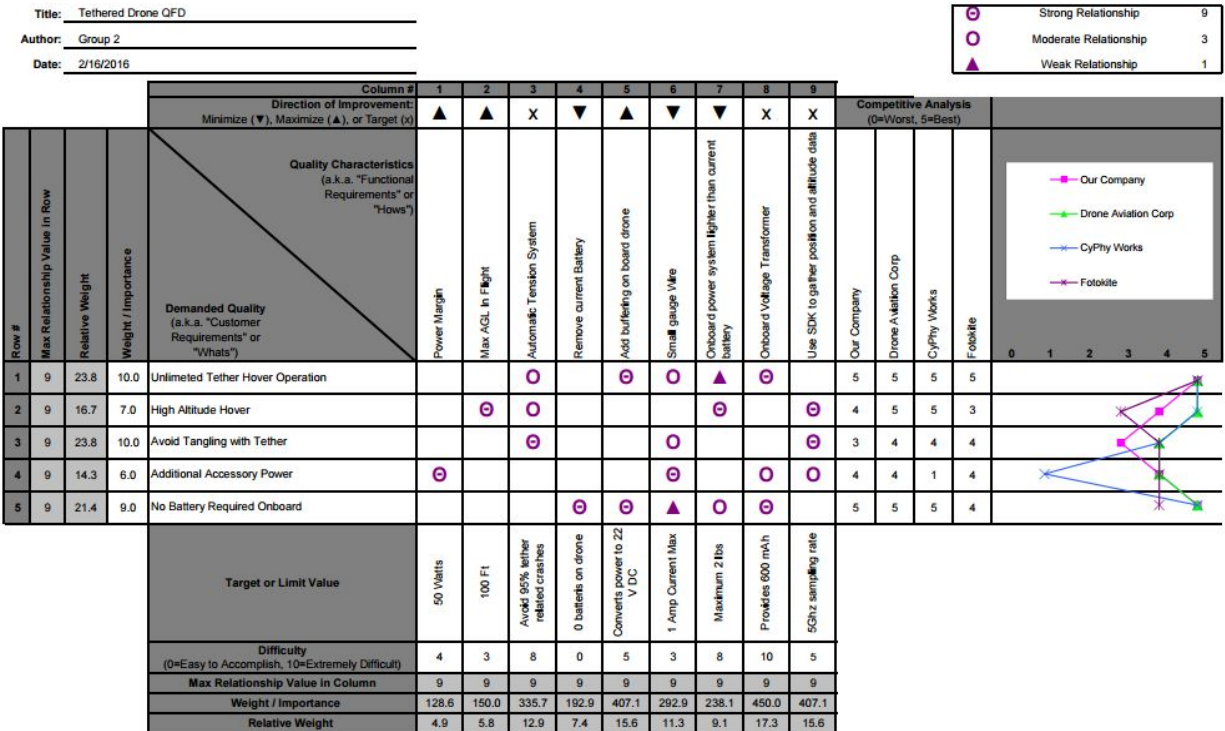


Figure 2: Quality Function Deployment

Many of the customer specifications such as hover time, altitude, power requirements were explicitly requested by the initial project deliverables. Additional metrics such as wire gauge and weight were factored in to create design goals. Although each of the various competitors were successful in meeting some of our customer specifications, none of them were a perfect combination of the features that we are hoping to exhibit with our drone. Since we only focused on companies which had tethered drones, many of them were completely successful in the unlimited hover operation requirement. However, some do not reach as high of an altitude or have a reeling mechanism that properly minimized tangling.

3. Concept Generation

Based upon the QFD chart, we determined that our top priorities are unlimited tether hover operation, avoiding tether entanglement, and no battery on board. After determining the main metrics for this project, we decided to look at existing solutions. Many drone companies have already implemented a power tether. However, we can improve upon it by increasing the amount of power transmitted to well above the maximum required power of the drone. Many of these tethers do not allow 100 foot or greater hover, something we look forward to achieving.

Some example concepts we came up with included a reeling mechanism with thin wire that uses constant tension to minimize slack on the cable without pulling on the drone and affecting its flight characteristics. A similar idea used the DJI SDK to control the reeling mechanism based on GPS and controller data. All of our concepts can be seen in the Appendix, specifically **Figure 16** and **Figure 17**, where they are drawn out.

4. Concept Selection

Concept 1	DC Power with Microcontroller Reeling					
Concept 2	AC Power with Microcontroller Reeling					
Concept 3	AC to DC Power Conversion Onboard with Mechanical Reeling					
Concept 4	DC Power with Mechanical Reeling					
Concept 5	AC Power with Mechanical Reeling					

Selection Criteria	Reference	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Power Efficiency	0	-	+	+	-	+
Size	0	+	0	-	0	-
Safety	0	-	+	0	-	+
Reliability	0	0	+	+	+	+
Meets customer needs	0	+	+	+	+	-
Unlimited hover	0	0	+	+	+	-
Cost	0	0	-	0	0	0
Feasibility	0	-	-	+	+	0
Weight	0	+	0	0	0	0
Total +	0	3	5	5	4	3
Total -	0	3	2	1	2	3
Total 0	9	3	2	3	3	3
Net Score	0	0	3	4	2	0
Rank	T-4	T-4	2	1	3	T-4
Continue?	No	No	No	Yes	No	No

Figure 3: Concept Selection Matrix

Based on our customer needs from DJI we came up with five preliminary concepts. The major decisions that we had to make were whether to use AC or DC power through the tether and how the reeling mechanism will work. If we were to use DC power, we would not need to convert the power onboard, a system that would add weight to the drone. However, sending 500+ Watts of DC power would require a heavy gauge wire and would be unsafe if the wire was disconnected. Thus, we decided to send high voltage AC power through the tether cable and then convert it onboard to DC.

The other major decision we made was whether or not to use the included SDK. After further research we decided it would be too difficult to use this given our programming experience and the difficulty of interfacing with a microcontroller on the ground. Given our resources and time constraints, making a constant tension mechanical reeling system is the better option for us.

Due to our decisions to use AC to DC power conversion onboard and mechanical reeling, Concept 3 was selected. This concept will satisfy customer needs while maintaining safety and reliability. The only weakness of this concept is the weight added onboard to the drone, but testing has proven that the drone is still capable of flying with a 5 lb payload, see **Figure 18** in appendix.

5. Concept Description

5.1 Power System

To power the drone, household 110VAC will first be stepped up to 240VAC using a voltage transformer. The transformer will connect to the powered tether cable via a NEMA 6-20 three blade plug. The tether will use three 22AWG wire that will be braided and heat shrunk every couple feet. At the drone, the tether will connect to the AC-DC converter power supply with ring terminals and the connection will be strain relieved. The power supply will mount with zip ties to the bottom of the drone for convective cooling from the propellers. The AC-DC converter will connect to the stock drone power input with a short cable and blade quick disconnect terminals. A flowchart is depicted below in **Figure 4**.



Figure 4: Power Solution Flow Chart (read left to right)

5.1.1 Power System Bill of Materials

Goldsource Step Up Voltage Transformer - AC 240 V

- Rated: 5000W at 240VAC

McMaster-Carr NEMA 6-20

- Rated: 20A at 250 VAC

McMaster-Carr Stranded Wire 22AWG

- Ampacity: 10A at 250VAC
- Operating Temperature -40° to 220° F
- Weight: 1.2 lbs for 3x 100 feet

McMaster-Carr Heat-Shrink Tubing 3/16" ID Before, 3/32" ID After, 25' Length

McMaster-Carr Standard Insulated Ring Terminal, 22-18 AWG, #6 Screw

TDK-Lambda PFE1000F-28 Power Supply

- Weight: 4.8 lbs (with heatsink)
- Input Range: 85-265 VAC
- Input Draw: 6.6A draw at 200VAC during full load.
- Operating Temperature: 0-100°C at 1000W
- Nominal Output: 36A at 28V Max
- Output Range: 22.4 - 33.6V

McMaster-Carr Battery Wire 10AWG

- Ampacity: 51A at 60VDC
- Operating Temperature -40° to 190° F

McMaster-Carr Flame-Retardant Quick-Disconnect Terminals, Straight (Female)

5.2 Tether Management

To manage the tether, a spooling mechanism is used. Tension is applied to the tether in order to prevent tangling with the drone's propellers. To apply the tension, constant force springs are used. There are three main subassemblies of the tether management system: the spool and gear subassembly, the spring subassembly, and the fixture subassembly. Each of these subassemblies and their interaction with one another is described below in detail. Drawings and exploded views for each subassembly, and the entire mechanism, may be found in the appendix with the Bill of Materials. Below is a rendered image of the entire tethering assembly. As shown in the image below, the spool is mounted on a shaft, which transfers through the gears and finally to the springs. The fixture subassembly holds it all in place.

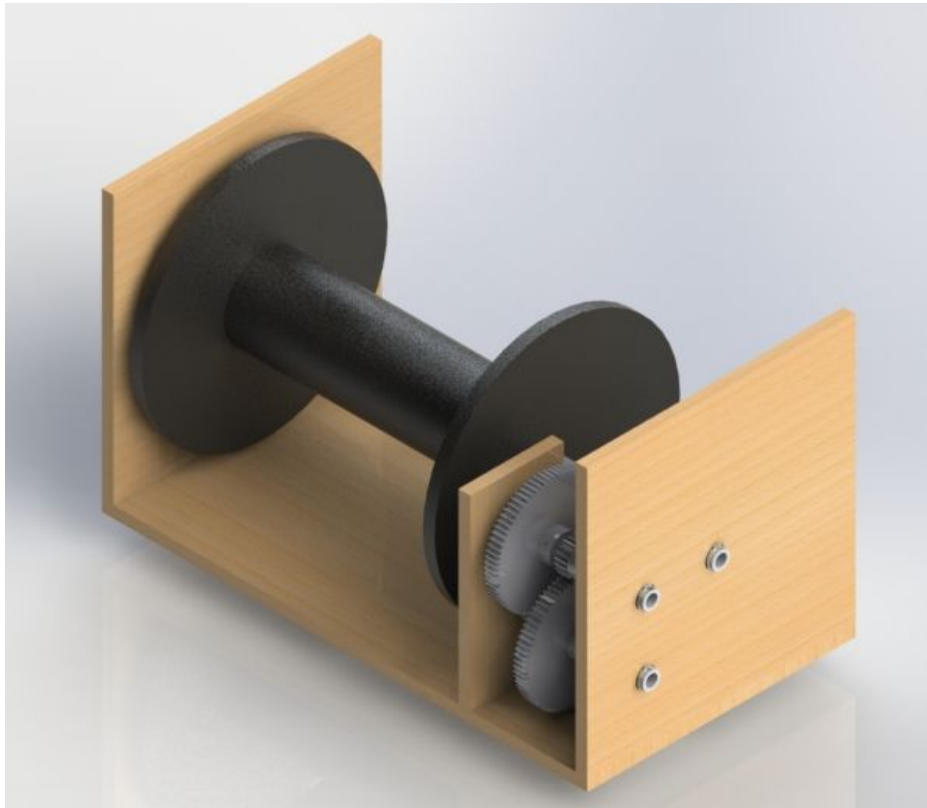


Figure 5: Tether Management Assembly

5.2.1 Gear Subassembly

Throughout the process of unreeling, the spool will rotate approximately 110 times, while the springs have a maximum capability to be unwound about 10 times. In order to solve this issue, the rotation of the spool will be geared down by a ratio of 14:1 to assure that the springs will not be overwound. The gear assembly will interface both with the spool and the springs to create a gear reduction between the spool and the springs.

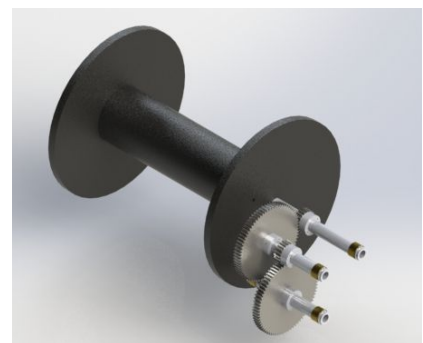


Figure 6: Gear Subassembly

5.2.2 Spring Subassembly

In order to maintain constant tension without creating too large of a force on the drone, the goal was initially to apply a pound of force to the tether. After reconsidering the total load on the drone, our team determined that two-thirds of a pound would be a large enough force. This force will prevent the tether from getting tangled in the rotors of the drone since the tether will be well maintained and taut. We used a constant force spring, since the force will not vary during the drone's flight. **Figure 7** shows a constant force spring which will be mechanically attached to the shaft where the gear system begins.

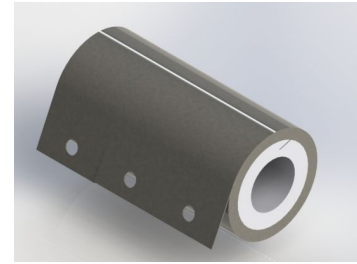


Figure 7: Constant Force Spring

5.2.3 Fixture Subassembly

The fixture subassembly provides support for the gear shafts and the springs. The fixture pieces are constructed from plywood, and holes are laser cut to support the shafts. Ball bearings will allow the shafts to spin with little resistance. All shafts will be supported on either side by a fixture so that none are cantilevered.



Figure 8: Fixture Subassembly

6. Parameter Analysis

6.1 Powering System

The power system is complete and integrates with the reeling system to spool in and out our 100 ft tether cable. Using a household 110V outlet the voltage is stepped up to 240V using a 5000W voltage transformer and then sent through 22 Gauge wire to the power supply onboard the drone. This voltage transformer was chosen because it is capable of supplying 5 times the max output of the onboard power supply. This buffer is needed during system startup where there will be a high inrush current. The onboard power supply draws 6A at 200VAC during full 1000W load. The wire selected can handle up to 10A at 300VAC which is comfortably above what the drone will require and has other desirable qualities such as its small diameter and flexibility. Lastly, the TDK-Lambda power supply has a 1000W output which leaves a large power buffer for additional components. All of the components work in unison to supply the drone with safe, reliable power through our 100ft cable.

Since design review II we have addressed the issues of heat and weight. The TDK-Lambda power supply weighs 3.2 lb, without the 1.5 lb heat sink. The weight of the power supply case and fan is 0.9 lb which saves 0.6 lb compared to the heat sink. While fully unwound, the tether will weigh 1.2 lb and have an additional 0.25 lb of tension. The drone can fly with a 6.2 lb payload without the stock battery which puts our onboard power system (5.3 lb) under the maximum payload. The power supply will be mounted to the bottom of the drone chassis. A top view of the drone and power supply can be seen in **Figure 9**. The power supply will also change the center of gravity of the drone but from our testing it has not changed the flight characteristics.

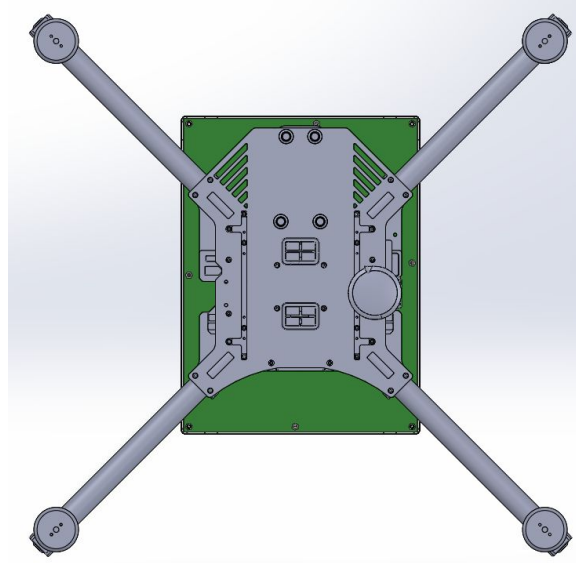


Figure 9: Drone with Power Supply

6.1.1 Power Supply Heat Generation Calculations

The heat generated by the components on the power supply is minimized by a heat sink. However, this heatsink weighs 1.5 lbs which is a large portion of the maximum payload. Removing this heatsink was accomplished by designing a case with a 120mm fan for convective airflow. Below are heat generation calculations to confirm that the heat sink is not necessary. For these calculations, the energy lost from converting from AC to DC power is assumed to be heat and we assumed airflow to be 2m/s over the plate.

$$Re_L = \frac{\rho u_{\infty} x}{\mu} = \frac{(1.225 \text{ kg/m}^3)(2 \text{ m/s})(0.16 \text{ m})}{1.846 \times 10^{-5} \text{ kg/m}\cdot\text{s}} = 21,235$$

$$Re_L < Re_{Cr} = 5 \times 10^5 \Rightarrow \text{Laminar Flow}$$

$$Nu_L = \frac{h_{air} L}{k} = 0.664 \sqrt{Re_L} * Pr^{\frac{1}{3}} = 0.664 \sqrt{21235} * (0.707)^{\frac{1}{3}} = 86.1987$$

$$h_{air} = \frac{Nu_L k}{L} = \frac{86.2 * 1.4}{0.16} = 754.24 \text{ W/m}^2\text{K}$$

$$\text{Power Supply Energy Generation: } AC_{in} = DC_{out} + \text{heat}$$

$$\text{Efficiency @ 100\% load} = 82.5\%$$

$$(1000 \text{ W}) * (1 - 0.825) = 175 \text{ W from heat generation}$$

$$q = hA(T_s - T_{\infty}) \Rightarrow 175 = 754.25 * (0.1 * 0.16)(T_s - 300)$$

$$T_s = 314.5 \text{ K}$$

The power supply components are rated at 412 K which means that the airflow over the power supply will cool the components enough that the 1.5 lb heatsink can be removed.

6.2 Tether Management

The tether management system is designed to apply tension to the tether to limit the possibility of tangling with the propellers. The tension that is applied to the tether drives all material selections, as any material we choose must be able to withstand the tensile forces applied by the springs. In addition, the material

selection is also driven by manufacturability. Some materials lend themselves to the manufacturing tools that are available to us, and hence would be more desirable to use.

6.2.1 Gear Reduction

A gear reduction is necessary to prevent the springs from being overwound. Since the spool must spin 110 times and the spring may only be unwound 10 times, we decide that a reduction ratio of 14:1 will be sufficient in keeping the spring safe. To achieve this, a shaft rotating with the spool will have a 20 tooth gear also mounted on it. This gear will interface with another gear of 75 teeth. This provides a gear ratio of 3.75:1. On that same shaft with the 75 tooth gear is another 20 tooth gear, which interfaces with an additional 75 tooth gear on a separate shaft, providing a gear ratio again of 3.75:1. The total gear ratio between these two step down is 14:1 reduction. As the drone takes off, for every 14 times that the spool is spun, the springs will rotate through just a single rotation, assuring that the springs will not be damaged or come loose in the process. The gears will have a diametral pitch of 16 teeth/inch such that the gears have coarse enough teeth to handle the load. For any larger diametral pitch, however, the gears become unreasonably large in diameter such that they do not fit well within the mechanism.

6.2.2 Spring Specification

Due to the gear reduction, the force applied at the reel from a single force spring will be reduced. Our goal is to apply one pound of tension to the wire tether. Therefore, we will need to place multiple force springs in series. We will use constant force springs to assure that the tension on the line doesn't vary with time. To calculate the force on the tether, we begin by calculating the torque applied by a single spring.

$$T = P * R$$

Torque is equal to the load, P, multiplied by half the diameter of the spring. For the spring specified for use, P = 10.6 lbs and R = 0.675 in., so we find that

$$T_{spring} = 10.6 * 0.675 \text{ in} = 0.5963 \text{ ft lbs}$$

In the scenario where there is no gear reduction between the spring and the spool, we can note that:

$$T_{spring} = T_{spool}$$

Thus, after the reduction, we can state that the torque is reduced proportionally to the gear reduction.

$$T_{spool, reduced} = \frac{T_{spool}}{Reduction} = \frac{0.5963}{14} = 0.043 \text{ ft lbs}$$

From the torque, the force is calculated simply by the following equation:

$$F_{spool, reduced} = \frac{T_{spool, reduced}}{R_{spool}} = \frac{0.043}{1.75 \text{ in.}} = 0.3 \text{ lbs}$$

Thus, if we want to maintain about a pound of tension on the tether, we will need three of these springs in parallel. These springs will be mounted on the same shaft as the 43 tooth gear, such that they will unwind once for every 13 rotations of the spool, providing a constant resistive force to the spool. A cylindrical plastic adapter will be used to attach the springs to the 3/4 inch shaft.

6.2.3 Delrin Laser Cut Gears

Because we chose to use gears that are not commonly available stock parts, we will need to prototype our own. The gear profiles are created using GibbsCAM gear dialogue which takes input of pressure angle, diametral pitch, pitch diameter, etc. Originally we thought the simplest way to prototype these gears was

to use 3D printing. After consulting the Etcheverry student machine shop staff, we will instead manufacture the gears by laser cutting delrin. The laser cutter will provide better resolution and allow for more accurately manufactured gears as well as save cost. Manufacturing will also be faster, only taking minutes to cut the delrin sheets instead of hours to print ABS. Delrin also has better wear properties and more than double the ultimate strength. To assure that the delrin is a sufficiently strong material to handle the load applied by the springs, it is necessary to calculate the force per unit area applied to the gears and compare that to the strength of delrin. The force applied by the springs is

$$P_{springs} = 10.6 * 3 = 31.8$$

Now calculating the stress applied to one of the teeth,

$$\sigma = \frac{F}{A} = \frac{31.8 \text{ lbs}}{0.07 \text{ in}^2} = 455 \text{ psi}$$

$$\sigma_{ultimate} = 11100 \text{ psi}$$

Since the ultimate strength is greater than the stress we will apply to the spring, we can be sure that the delrin material is sufficiently strong to handle the load applied to it.

Because we chose to laser cut the gears, they must have a 2-dimensional profile, so the gears will no longer have the collar for the set screw that was originally designed. Without a collar, the issue arises of how to fix the gears onto the shaft to transfer the torque. After discussing this with the technicians at the machine shop, we decided that laser cutting a collar that we could mechanically fix onto the gears would be best. The collar will be attached to the gears with two screws, and a set screw will attach the collar, and hence the gear to the shaft.

6.2.4 ABS Shaft Tubing

The shaft will be made from ABS tubing. Tubing is required because the tether will run through the shaft and out to the rotary device. Since the wires will be running through the shaft, it is preferable to have a material that is not conductive for safety purposes. Hence, a plastic material is ideal. The shaft itself will undergo relatively little stress since only a pound of force is to be applied at any time. The tubing is sufficiently strong to handle the pound of force with relatively little deflection.

6.2.5 Plywood Base Structure

Plywood was chosen for the base structure so that it can be easily and precisely manufactured using a laser cutter. Precision is important in manufacturing the base structure to assure proper meshing of the gears. The precision of the laser cutter will provide the precision we need. The wood is easily screwed together with wood fastening screws, providing the adhesive strength between the panels.

7. Final Design

The design has not altered largely from the initial concept description. The base of our tethered drone will contain a 220V outlet converter and our reeling device in a wooden box that can connect to a wall power outlet. Fastened under the base of our drone will be a 1000W AC-DC converter that is enclosed in a tight fitting plastic case to protect the components. This case will have cutouts to allow for airflow to help maintain a low temperature for the board. In order to fit the board more closely to the body of the drone, the case that initially contained the battery will be removed from the base of the drone. The final tether wire will be made from three 22 gauge stranded wires that carry up to 300V AC. The wires in the tether

will be braided together and wrapped in heat shrink every couple of feet in order to keep the wires together and attached to the drone. The overall weight of the tether should be 1lb. The mechanical reel will operate based on continual tension applied by a combination of constant force springs. The gear reduction of 13:1 will allow the spool to wrap 13 times for every turn of the force springs.

Line	Quantity	Product	Ships	Unit price	Total
1	1 each	7196K33 Straight-Blade, Three-Blade Male Plug, NEMA 6-20	today	\$12.45 each	12.45
2	1 each	8054T13 Stranded Wire, 300V AC, 22 Gauge, 200 Feet, Black	today	\$20.36 each	20.36
3	1 each	8054T13 Stranded Wire, 300V AC, 22 Gauge, 200 Feet, White	today	\$20.36 each	20.36
4	1 each	8054T13 Stranded Wire, 300V AC, 22 Gauge, 200 Feet, Green	today	\$20.36 each	20.36
5	1 each	6659T18 Vehicle Wire, 10 Gauge, 8 Feet Spool, Black	today	\$5.13 each	5.13
6	1 each	6659T18 Vehicle Wire, 10 Gauge, 8 Feet Spool, Red	today	\$5.13 each	5.13
7	1 each	7856K74 Heat-Shrink Tubing, 3/16" ID Before, 3/32" ID After, 25' Long, Black	today	\$15.56 each	15.56
8	1 pack	7130K32 Nylon Cable Tie, 8" Long, 2-1/8" Bundle Diameter, 10 lb. Break Strength, Black, packs of 100	today	\$5.62 pack	5.62
9	1 each	1839T421 Easy-to-Machine ABS Tube, 3/4" OD x 1/2" ID, 5' Length	today	\$18.30 each	18.30
10	4 each	9293K12 Stainless Steel Constant-Force Spring, 4000 Cycle Life, .016" Thick, 40.0" Long, 1" Wide	today (from our Chicago warehouse)	\$10.83 each	43.32
11	6 each	6391K256 Oil-Embedded Sleeve Bearing for 3/4" Shaft Diameter, 7/8" OD, 1/2" Length	today	\$1.47 each	8.82
12	1 pack	9763A250 Black-Finish Steel External Retaining Ring for 3/4" Shaft Diameter, packs of 100	today	\$12.30 pack	12.30

Figure 10: McMaster Carr Initial Purchase Order

A large quantity of the supplies for our project were ordered from McMaster Carr which can be seen above in **Figure 10**. The drawings for all parts that will be machined by Team SkyBison can be found in the appendix. These parts include the reel fixture base which will be made from wood and the gear shafts which will be manufactured from ABS tube stock.

The initial testing for the power system has been completed and the drone successfully powered on, the system can be seen in **Figure 11**. Household 110VAC was transformed to 240VAC and then converted to 24VDC to power the drone. Once the battery board circuit is received from DJI, we can further test power supply heat and drone payload.

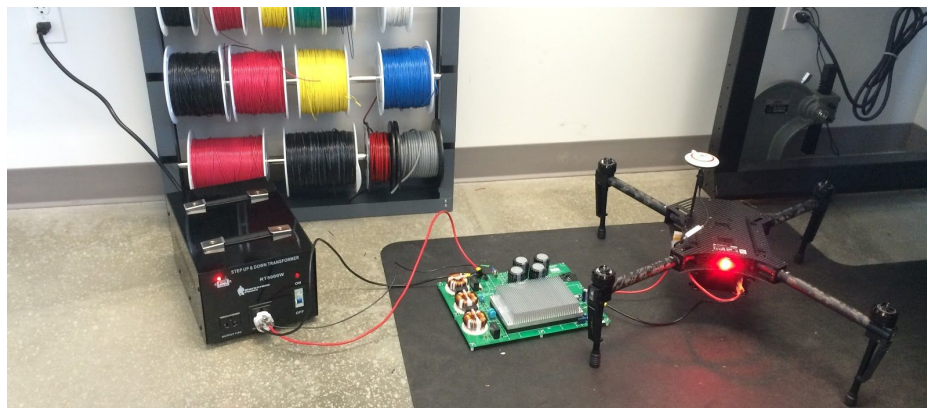


Figure 11: Powering System Initial Test

Another design decision is how to protect the power supply on the drone. We have been designing a case that would have a fan to help circulate air and slots on the sides to permit airflow. This case would protect the power supply while providing enough airflow to remove the heavy heatsink which would reduce the

overall weight. We plan to print the case with a 3D printer so that it will be light weight. An initial design for our case can be seen below in **Figure 12**.

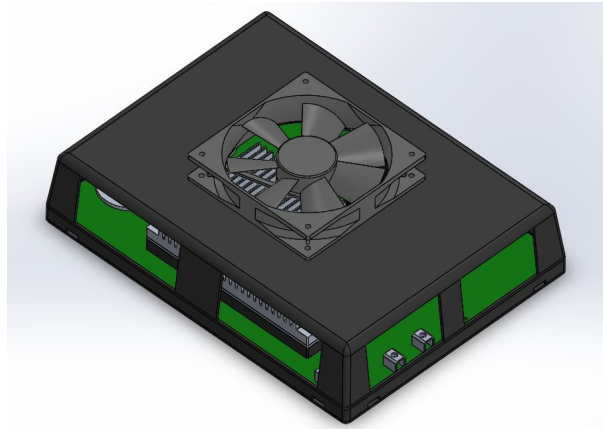


Figure 12: Power Supply Case

After running numerous tests to verify our thermal calculations, we determined that we were able to remove the heat sink as long as our box had a fan to add additional cooling.

8. Plan

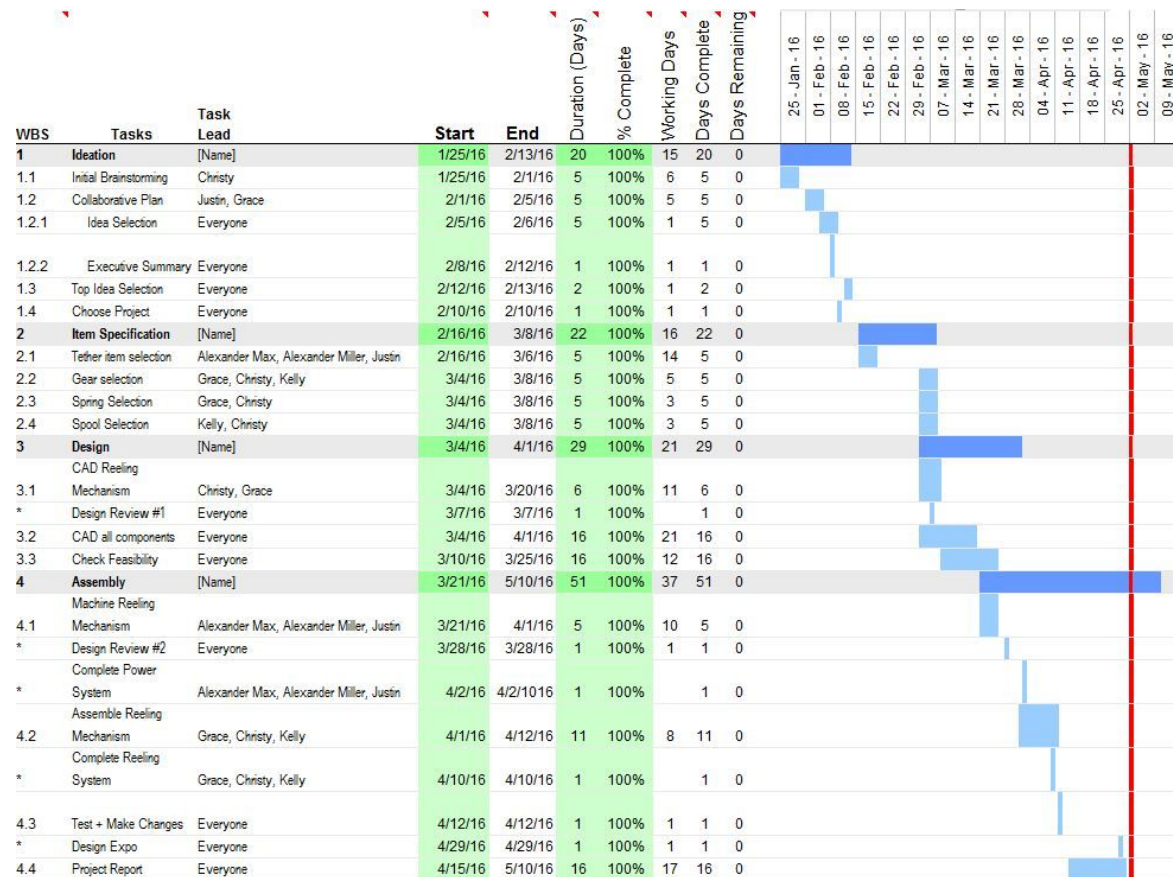


Figure 13: Gantt Chart (*denotes milestone)

This final report is the final milestone for our project. Throughout the past weeks, we have been able to finish the ideation, design, and assembly phases as they were planned in our Gantt chart shown above. The first phase of the project was done collectively with our entire team, but in order to maximize efficiency for the design phase, we broke up into subgroups. Alex, Justin, and Xander focused on determining how the power will work, while Christy, Grace and Kelly developed a design for the reel. Grace and Justin took the lead for the manufacturing phase while Xander and Christy focused on designing the website.

9. Manufacturing and Test Results

9.1 Tether Cable

Manufacturing the tether cable was the first major component of the power system that was built. Using the 120 foot lengths of green (ground), white (neutral), and black (live) wire was decided to be bound with heat-shrink tubing. Initially the design was to braid the wire to keep the wires in the tether from separating but braiding 120 continuous feet of wire by hand was too difficult. After experimenting, it was decided that $\frac{1}{4}$ inch sections of heat-shrink tubing needed to be placed every 6 inches was suitable to maintain the tether. Once completed, a multimeter was used to test the resistance of each wire in the cable to verify it was not broken internally. Each wire had a resistance of 1.8Ω at room temperature.



Figure 14: Completed Tether Cable on Spool (Weight = $5845 - 39 = 545$ grams = 1.2 lb)

9.2 Power Supply Case Manufacturing

After doing some rough heat transfer equations, the decision was made to remove the heatsink on the power supply and add a fan to remove heat from the onboard power supply. We designed a case that would protect the bottom of the power supply while keeping the same design as the rest of the drone. A negative mold of the case was 3D printed using a Stratasys Dimension 1200es printer. The case was

printed in halves because the 9.5x11" size of the case did not fit in the print bed. The halves were joined together with duct tape. To create the final case, a vacuum former was used to form 1/8" ABS sheet over the 3D printed mold. This final case was one piece, lighter, and stronger than the original ABS mold.

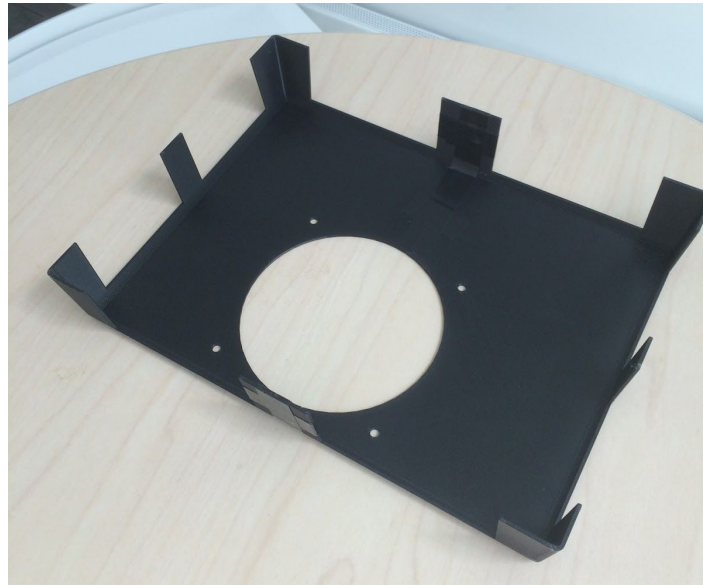


Figure 15: 3D printed case mold

The vacuum formed shelled had holes drilled into the side walls for fan ventilation. The original design of slots was changed to holes to increase rigidity of the case and for aesthetics. The 24 VDC was bolted to the bottom of the case such that air was blowing downward. This orientation was chosen to prevent dust from the ground being sucked into the case. With no heat sink, the power supply reached temperatures of 120°F after a minute of flight. With the case and fan, the power supply never exceeded temperatures of 90°F even after prolonged 10 minute flights.

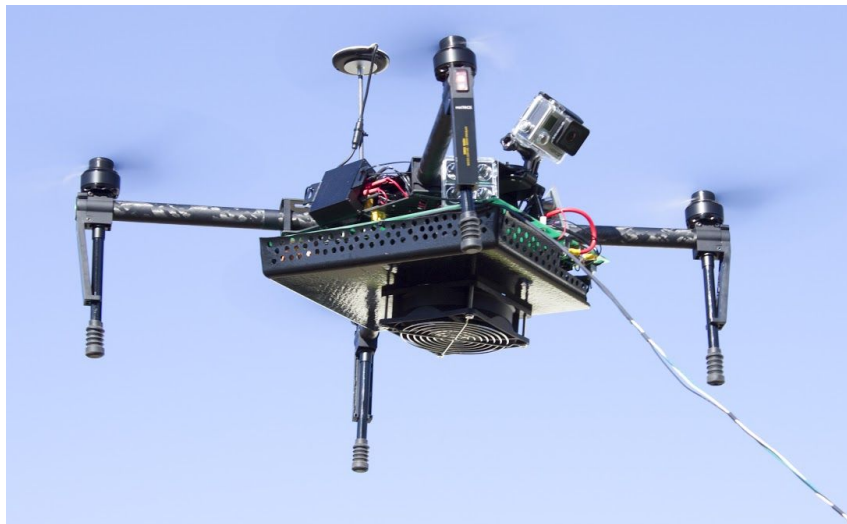


Figure 16: Final case and fan mounted on drone



Figure 17: Final Weight of Onboard Power Supply Case (Weight = 0.9 lb)

After weighing the case it was over 0.6 pounds lighter than the stock heatsink, provides protection, and increases cooling while improving the design aesthetic.

9.3 Reel Manufacturing

The majority of the reel components were created using a Universal Laser Systems ILS12.75 laser cutter. Delays in the manufacturing timeline occurred during the project because of unforeseen equipment repairs and material choice issues. The timeline was delayed two weeks due to the lens being burned out twice. The laser cutter in Jacob's hall is an equipment shared and used by many students and is prone to misuse and breakdowns. The gears in the reel assembly were originally chosen to be made of Delrin as suggested by the Mechanical Engineering Student Shop staff due to its good wear properties. But when the first gear was being made, flaming occurred and the gear teeth were heated to a high temperature. The heat affected zone in the teeth caused distortion and was unsuitable to be used in the gear train assembly. The material choice was changed to acrylic due to its laser cut manufacturability, strength, and aesthetics. Although these gears will wear away over time, the material choice is suitable for the prototype. For a final product, delrin would be a good choice for gear material.

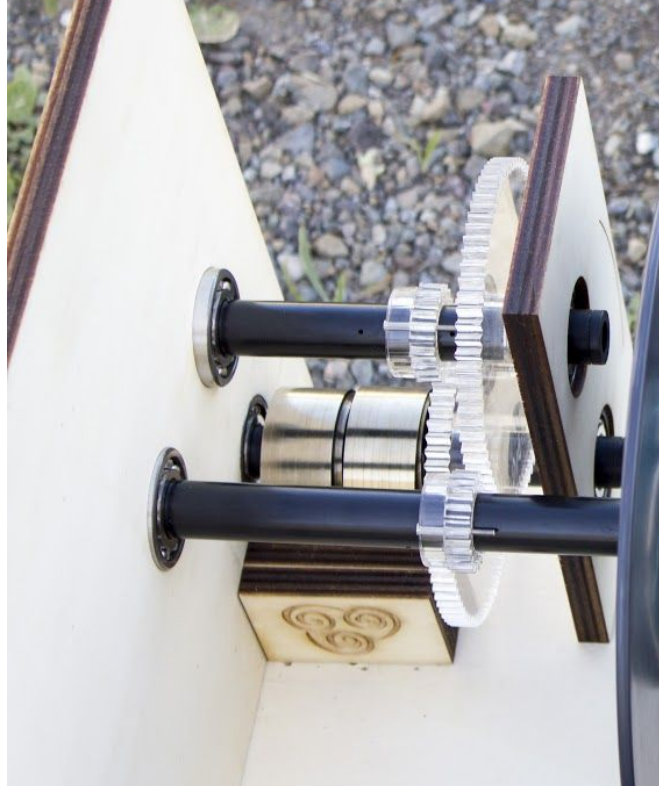


Figure x: Final acrylic gear train assembly

The wood for the frame and supports of our reeling system was also cut using a Universal Laser Systems ILS12.75 laser cutter. The pieces were then attached with wood fastening screws for a tight fit which allowed us to ensure the the gears meshed together properly. The plywood for the frame was $\frac{1}{2}$ " thick which was thin enough to be lasercut but give the support and rigidity needed for the reeling mechanism. The ball bearings were pressed into the wood walls of the structure. At first the fit was tight and retained the ball bearings but after some wear from repeated assembly and disassembly, the bearings started to slip. For a final product a plastic or aluminum frame would be the ideal material choice for rigidity and weight.

9.4 Test Results

The powering and tethering system were tested separately in several stages to ensure that manufacturing and component choice was suitable before proceeding.

The powering system required minimal manufacturing other than wiring. After all the components were received, the voltages were checked in every component, the wall outlet, the voltage transformer, and onboard power supply. The corrected voltages ensured that none of the components would be damaged in future tests. The most difficult challenge in the powering system was integrating the battery board (**Figure 17**). DJI did not have any documentation about how the board worked. The boards were also easily damaged with any overvoltage and were very limited in quantity and availability. Discussions with DJI employee Arjun Menon and experimentation with multiple boards ultimately led to successful

integration of the battery board in the powering system. Initially the battery board and drone, without attached propellers, were hooked up to a bench power supply. This test was to ensure that the drone would start and the motors would spin without the stock battery. Then the drone was powered by the powering system (**Figure 11**) first without the 100 foot tether to ensure the system components were suitable for the drone. After all of the components worked with a short ground cable, the full length of 100 ft wire was tested. Integrating components one at a time allowed for variables to be eliminated in case the system didn't work. Fortunately all the powering components were suitable in powering the drone. After all the components were verified to power the drone, the propellers were attached and a short, low altitude test flight was conducted indoors to test the payload of the system. After the short flight, the power supply had a higher temperature than expected so the addition of a fan was needed to cool the system.

Manufacturing for the reel was done in phases to allow for testing along the way. The first step of manufacturing was laser cutting the gears so that it could be verified that they would mesh properly. The first set of manufactured gears were laser cut from wood. The initial gear profiles created from SolidWorks Toolbox had too much lash. As suggested by Jesse, Senior Student Shop Technician, the gear profiles were made in GibbsCAM instead. These profiles again were cut from wood and verified to be sufficient.

Originally the shafts of the reel assembly were fit in oil impregnated bronze bushings. These bushings did not sufficiently reduce the friction of the rotating shafts so more expensive ball bearings were used instead.

Once all the parts were manufactured and the reel was assembled, the tether tension was tested. Initially with one constant force spring, the tether had no tension and would not reel back into the spool. Ultimately this was decided to be caused by the friction in the rotary connector, friction losses in the spring, lash in the gears, and compliance in the assembly. Another constant force spring was added to double the tension resulting in tether reeling into the spool. The constant force springs did not ultimately extend as long as expected but still managed to reel at least 50' of tether.

After the powering and reeling system were verified to work independently, the two were combined for a full system test. Initially the propellers were not attached to verify electrical connections in the powering system. Then the propellers were added and low altitude flights were performed and the temperature of the power supply was checked to ensure the cooling fan was suitable. After initial tests, all systems seemed successful and higher altitudes and longer flight times were tested to ensure the deliverables were met.



Figure x: Full system altitude test (40 feet AGL)

10. Discussions

Since the project was sponsored by DJI, an initial goal was set to ensure that all of the specifications listed by DJI would be met. In order to be positive that our design would work, simplicity in design was chosen. This route involved an onboard AC-DC conversion with a known power source to ensure that there would be no electrical danger and a simple mechanical reel that does not rely on the functionality of motors and more electrical components. With more time and resources the project would have integrated higher risk items in the design to enhance the final prototype.

The strengths of our project are its simplicity and minimal points of failure. Components such as the 5000W power transformer and TDK Lambda power supply have already been validated and tested. Our group can be confident these components will not be the point of failure in our power system. Other components such as the wire and slip ring are also unlikely to fail because they are only carrying a current to the drone. The most likely scenario for a loss of power to the drone would be blowing a fuse on the circuit breaker where the system is plugged into the wall. Other strong points to our project are the simple and effective design of our reel. Using constant tension force springs to control tension in the reel worked well at reeling in the wire.

Areas of improvement for our project would not change its functionality drastically. However, they would make the reeling smoother and the system would be lighter, thus draw less power from the wall. From our Concept Generation in Section 3 we decided not to use an electronic reel due to time and knowledge restrictions. However, updating the mechanical reel with one that would be controlled electronically based on the position and control inputs to the drone would be a significant update. This would be accomplished by using the DJI SDK to pull live information off the drone. This includes the drone's GPS location, altitude, as well as control input from the pilot. To successfully use the DJI SDK along with an Arduino would require a vast amount of coding work since the SDK is coded entirely in C++ and an Arduino is programmed in Java. Although our team is not comfortable with C++, if given additional time to learn the

language and become comfortable with coding, interfacing this information with an electronic reel to spool in or out the tether cable would then be possible. An electronic reel would stop the jerking motion of the drone when the cable has some slack and the drone moves away from it. This was a bit difficult to account for as beginner pilots. Also, another area that could be improved upon is the spooling of the cable onto the reel. Oftentimes it does not wind evenly and having a guide controlled by a servo would make the spooling more reliable and completely eliminate the possibility of a tangle.

Other improvements that could have been made regarding the power system are lowering the weight on the drone. The power supply from TDK Lambda had a lot of extra components on the board that were not utilized by our group. Taking these components off the board could have lowered the weight added to the drone, thus improving performance. With all of these changes our project would still meet the deliverables set by DJI while being a more refined tether power system.

11. Information Sources

During the initial stages of the project, we looked at other companies that produce tethered drones such as Drone Aviation Corp, CyPhy Works, and Fotokite to see possible solutions.

We picked the power supply that matched the power demands of the drone and the deliverable requirements. Most of the information was gathered from the specification sheets provided by the manufacturers of the power supplies. The power supply has detailed input and output information supplied by TDK-Lambda. The specification sheet helped choose which power supply would be suitable for the drone. The input current of the power supply helped determine which gauge wire would be suitable for the tether. The ampacity and weight specifications of the wire were gathered from the distributor McMaster Carr. Although nominal and max power information was on the specification sheets, we will still need to measure and check the actual current draw in the wires when the drone is powered. This information will allow us to downsize the wire if possible to save weight.

The tension of the tether is currently designed to be 1 lb. This was based off of the force needed to extend tape measures. Although not very much force is expected to manage the tether, testing will need to be done to see if this is sufficient to keep the tether from being caught in the rotors and low enough to not strain the drone flight controller.

12. Problem Analysis

The demands of the drone are roughly estimated with the battery capacity and flight time.

TB47D (stock)	4500 mAh	22.2V	
	Hovering Time (min)	Avg I (A)	Power (W)
No Payload	22	12.27	272.45
1.1lb/500g	17	15.88	352.59
2.2lb/1kg	13	20.77	461.08

Figure 16: Power Estimate Table

Figure 16 shows estimates for hover power draw but actual power demands for a loaded drone thrusting up will be greater. This is why a power supply with double the hovering power wattage is chosen. Although removing the battery and replacing it with a power supply seems simple, there were some underlying challenges. The battery acts as a large capacitor and with the ground replaced by an AC power supply, ground reference difference may be an issue for the drone electrical system. This will need to be checked with testing. The drone also has a 4-pin connector for the battery that reads information about the battery such as battery health and life. Without this connector, the drone will not fly. DJI responded to our concern about this issue and provided a solution that involves using a battery board circuit to mimic the signals from a stock battery. This solution has been successfully tested by Team SkyBison and can be seen in **Figure 17**. The critical parts in the power system are the tether wire gauge and the power supply. Power supply heat and weight and tether wire diameter have all been validated during testing.

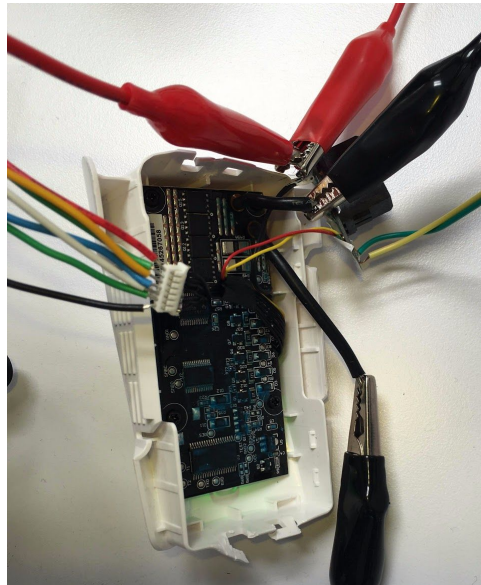


Figure 18: Battery Board Circuit

After receiving the necessary parts for our power solution, we ran into a couple potential issues. The AC to DC converter that we purchased to attach in the drone and allow us to pass an AC current up the wire is large and heavy. As discussed in Section 7, our group was able to create a solution for a way to attach and protect this device. We were able to successfully design a case that has the capability to create enough ventilation that we can remove the heatsink on the board since that is the greatest contributor to the board weight.

The two main challenges with the reel were spooling and tension. We had to ensure that the tether will reel in and out without any complications, such as tangling or falling off the spool. We were able to make sure that the cable wrapped properly by following the model of a fishing reel. We also had to calibrate the tension mechanism to provide appropriate force for any flight height up to 100 feet. This required a thorough understanding of the tension springs used. The critical parts in the tether management system were the gears and constant force springs. The tension of the tether will was verified through testing.

13. Conclusion

Project APPA successfully met the deliverables requested from DJI. The stock battery was removed and the additional 50W above peak vehicle power was demonstrated with the onboard high powered LED floodlights. The tether was 120 feet long which was automatically managed with the reeling system. The drone flew for two hours during the design expo without any issues and would be able to fly indefinitely.

The project description was fulfilled and customer specifications were met by implementing a mechanical reeling mechanism for the thin-gauge tether cable. The power source is a common 3-prong household AC outlet, stepped up with a voltage transformer and converted to the drone's DC power onboard. The mechanical reeling system applied an ample amount of tension to keep little slack on the the tether cable but not too much so that it will affect the drones flight characteristics.

The final prototype met the expectations of DJI and can eventually be made into a consumer product. Possible issues and product features discovered from Project APPA will be useful for DJI and their future high-end drones.

14. Reference List

Consultants

Darren Liccardo - *Project Supervisor*, DJI
Gary Gin - *Electronics Design Specialist*, Jacobs Institute for Design Innovation
David Wang - *Chief Technical Officer*, NetSapiens
Dr. Allen Yang - *Principal Investigator*, Department of EECS, UC Berkeley
Arjun Menon - *Simulation Software Engineer*, DJI
Jesse Lopez - *Etcheverry Senior Lab Mechanician*
Mick Franssen - *Etcheverry Senior Lab Mechanician*
Dennis Lee - *Etcheverry Principal Lab Mechanician*

Web Resources

TDK-Lambda - PFE1000F-28 Power Supply
http://www.tdk-lambda.com/products/sps/ps_pm/pfe_f/pdf/pfe1000f_spc.pdf
TDK-Lambda - PFE1000F-28 Evaluation Board
https://www.us.tdk-lambda.com/ftp/manuals/pfe1000f_eb_manual.pdf
Mercotac - Model 330 Rotary Electrical Connector
<http://www.mercotac.com/html/330.html>
Cosel - GHA500F-24 Power Supply
<https://www.trcelectronics.com/ecomm/pdf/gha500f.pdf>
Excelsys - XS500-24N-000 Power Supply
<http://www.excelsys.com/wp-content/uploads/2014/05/XSMay2014.pdf>
Excelsys - XS1000-24N-000 Power Supply
<http://www.excelsys.com/wp-content/uploads/2014/05/XSMay2014.pdf>
Bel Power Solutions - ABC600-1024G Power supply

http://belpowersolutions.com/sites/belpowersolutions.com/files/documents/power/datasheet/bcd.00336_ac_abc600_series.pdf

Engineering Tool Box - Wire Gauge Equation

http://www.engineeringtoolbox.com/electric-wire-calculation-d_1880.html

Homebuilt ROVs - Slip Ring

<http://www.homebuiltrovs.com/slipringreel.html>

RayHigh Tower - Manage that Tether

<http://rayhightower.com/blog/2014/09/10/manage-that-openrov-tether/>

Drone Aviation Corp

<http://www.droneaviationcorp.com/>

CyPhy Works

<http://cyphyworks.com/>

Fotokite

<http://fotokite.com/>

NIST - High Voltage Regulations

http://www.nist.gov/el/isd/mmc/upload/high_voltage_rules_revised.pdf

15. Appendix

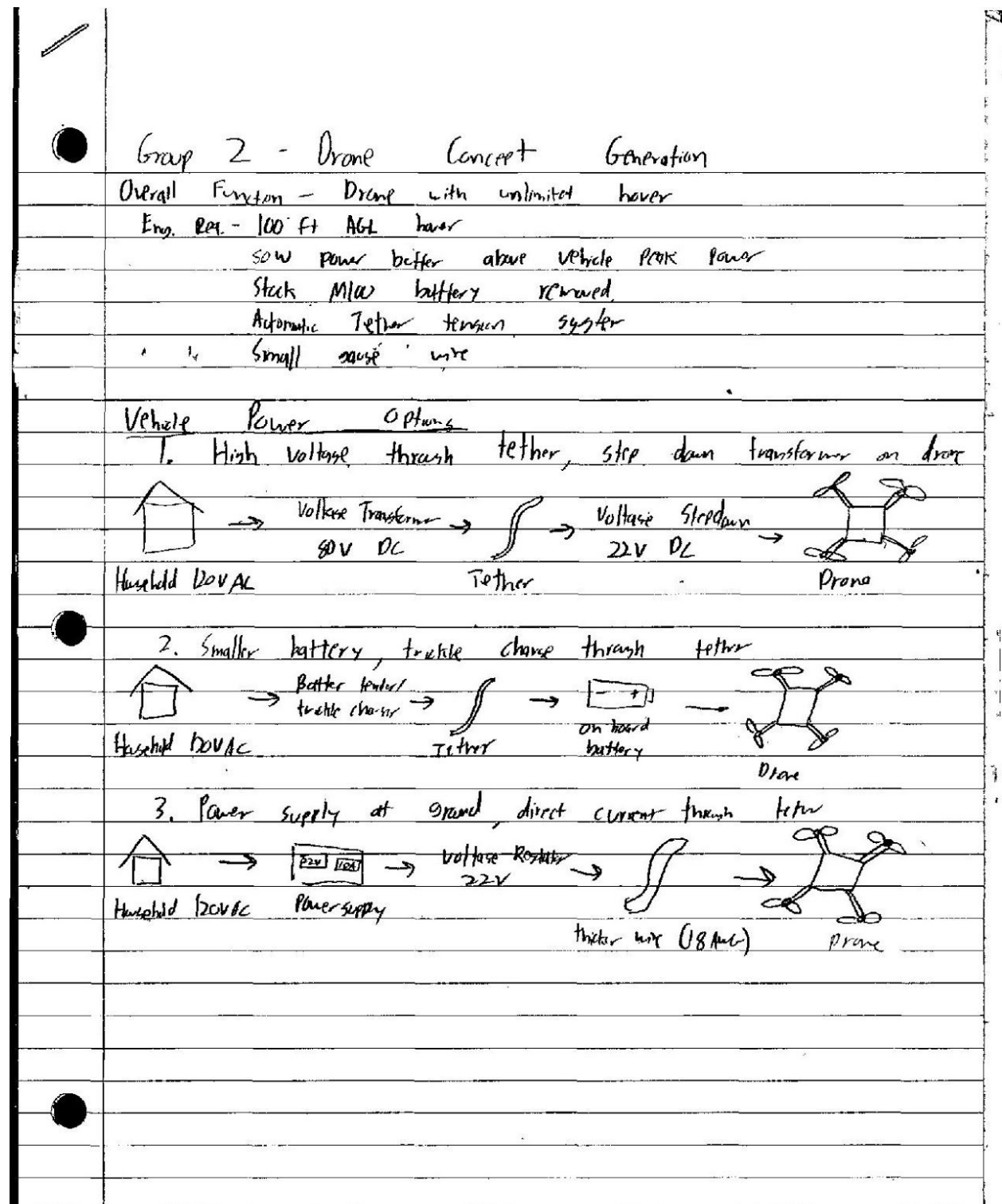
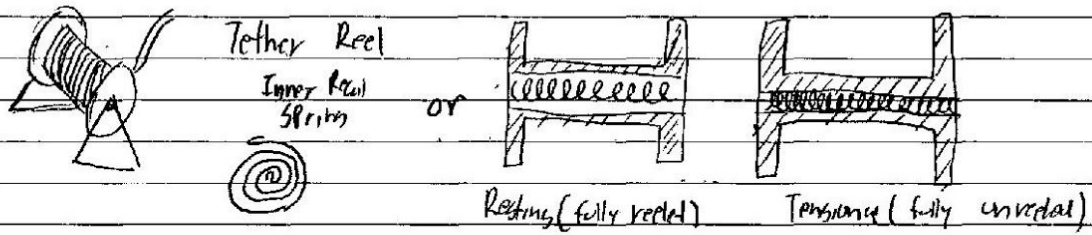


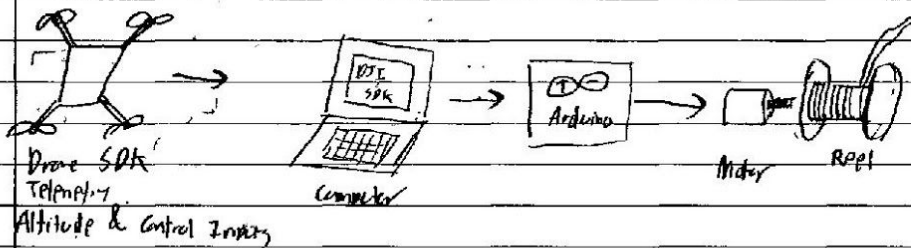
Figure 19: Concept Selection Page 1

Tether Management

1. Mechanical Tether management via tension spring



2. Motor driven Reel via Drone SDK Telemetry



3. Hinged Tether deployment

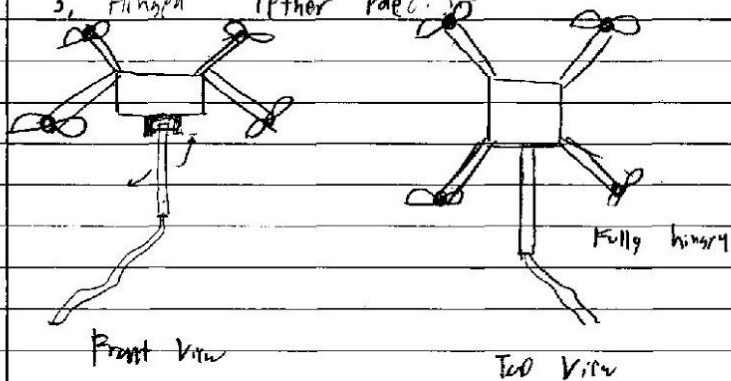
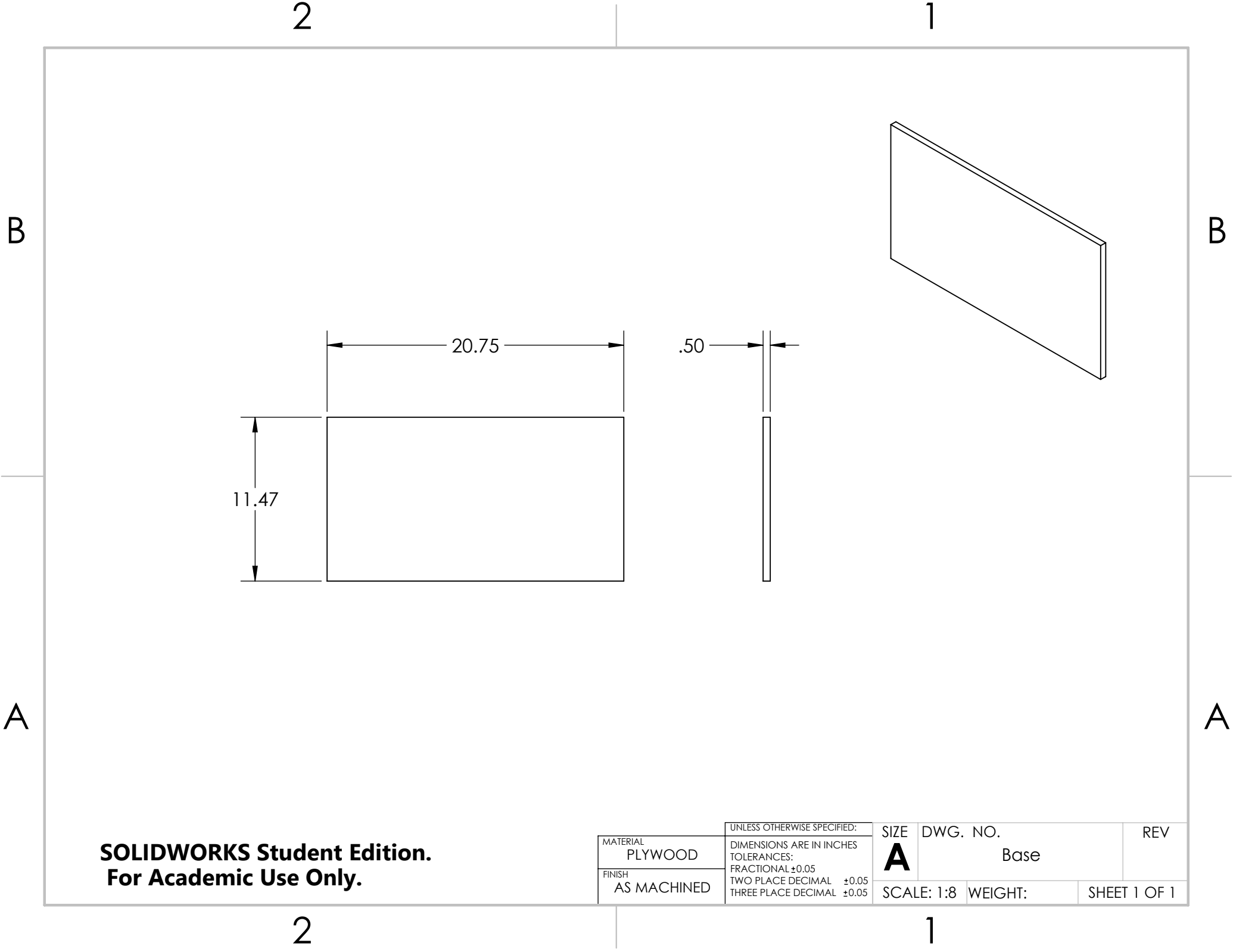


Figure 20: Concept Selection Page 2



Figure 21: Payload Test - Drone carrying 5 lbs

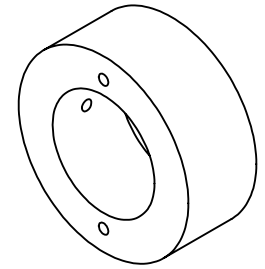
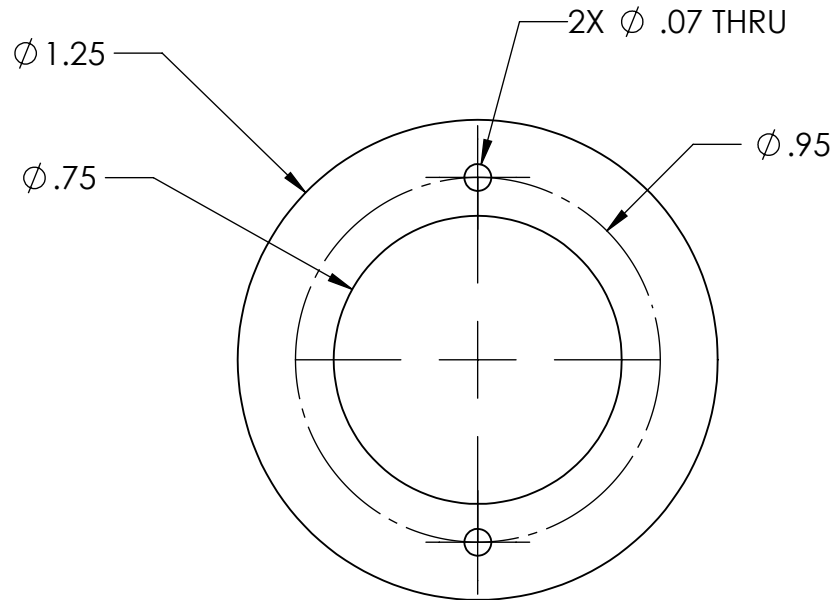
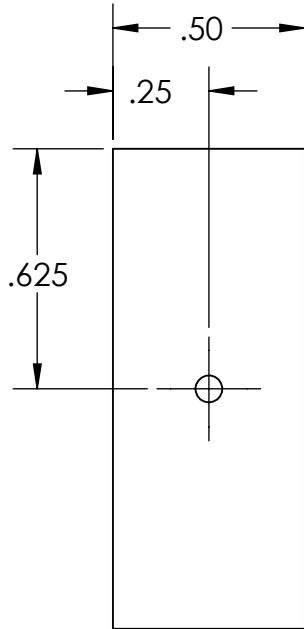


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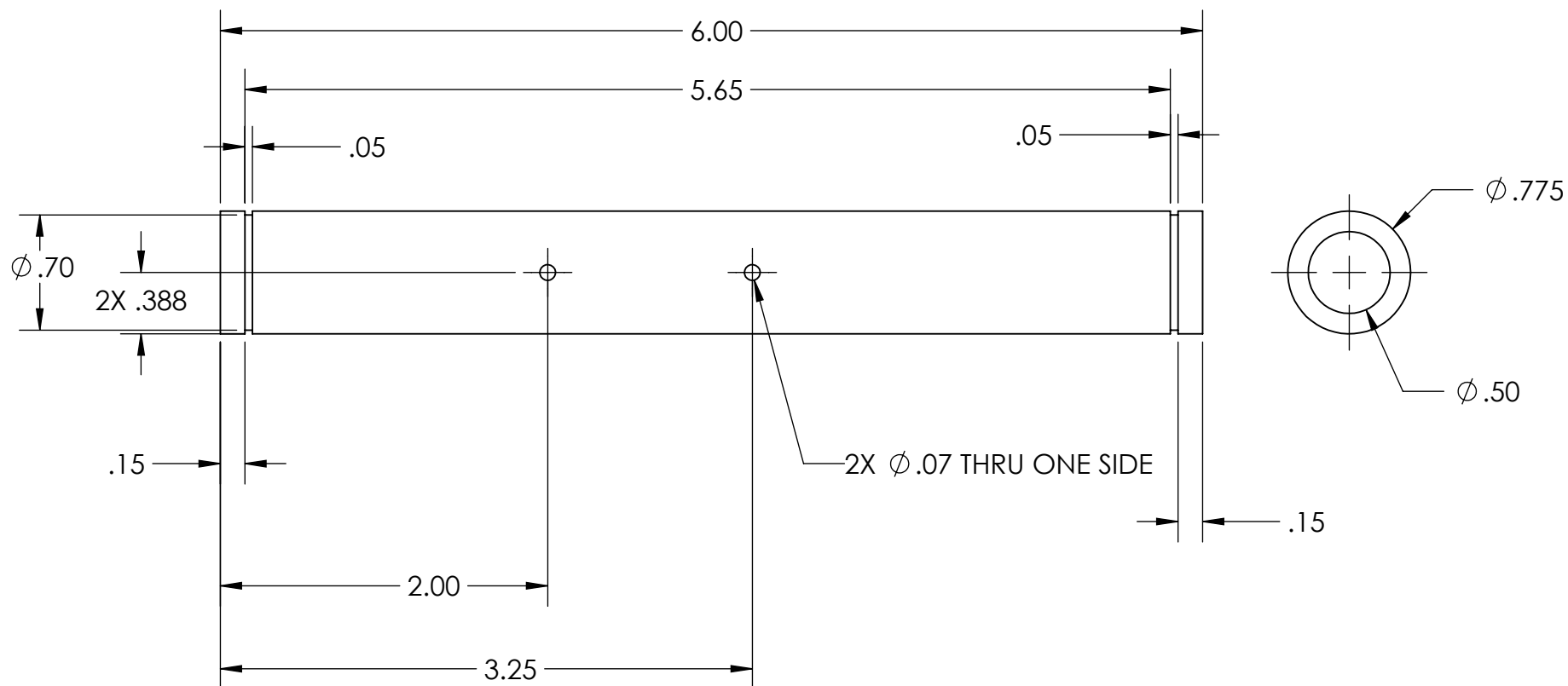
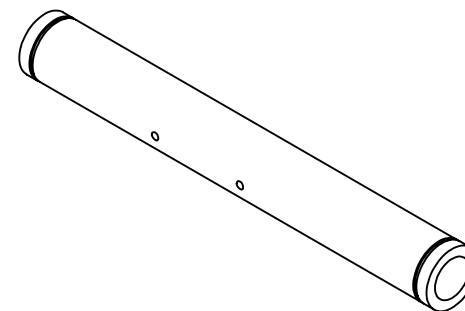
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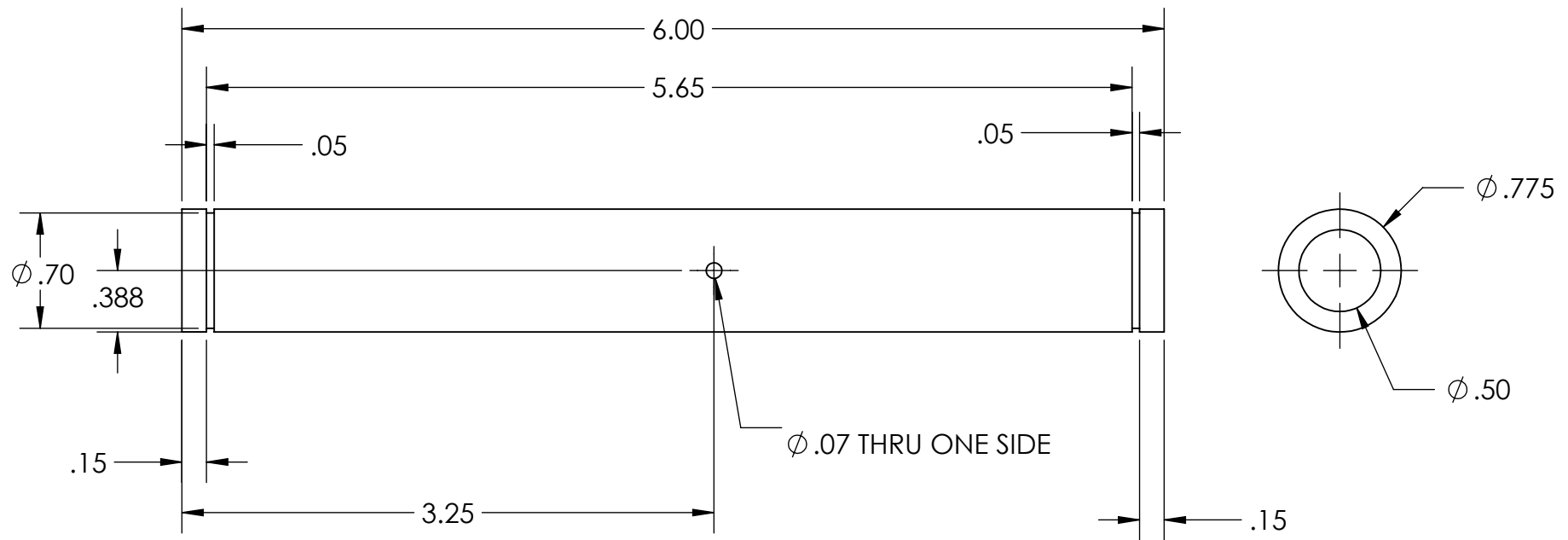
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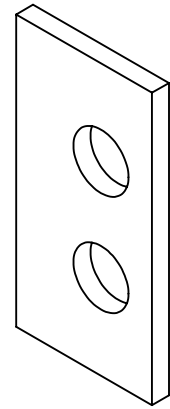
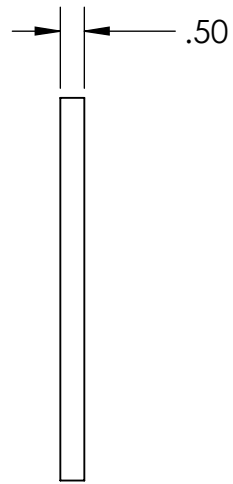
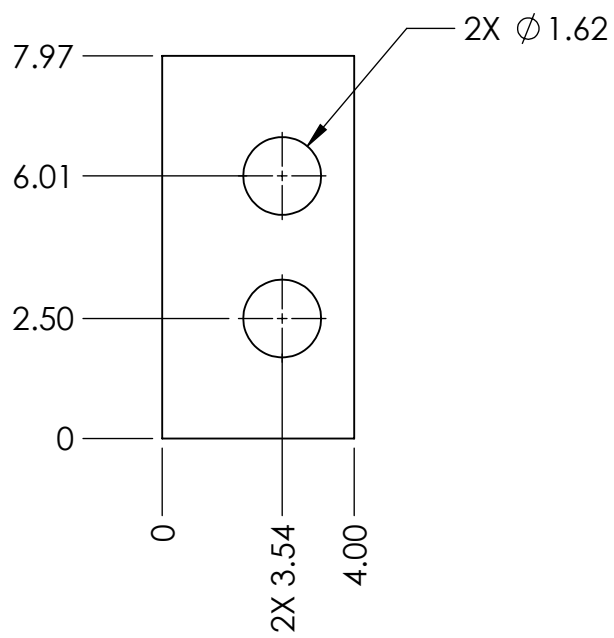
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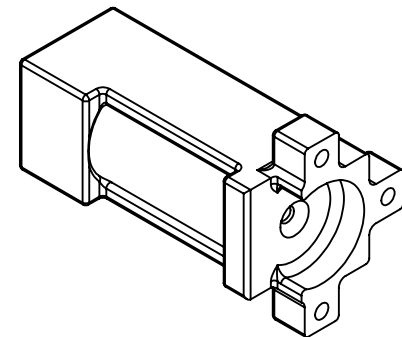
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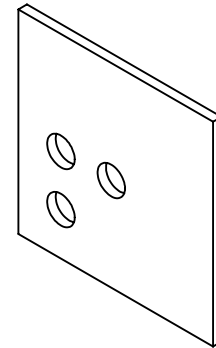
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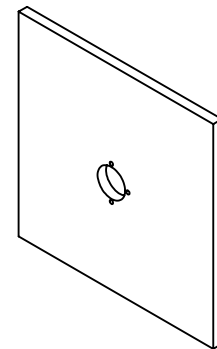
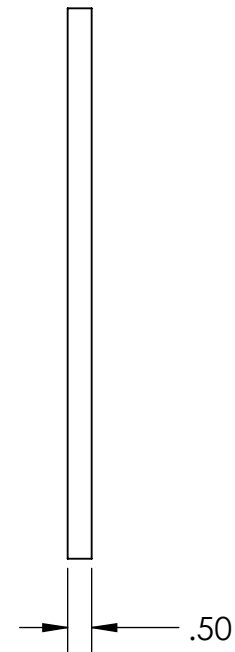
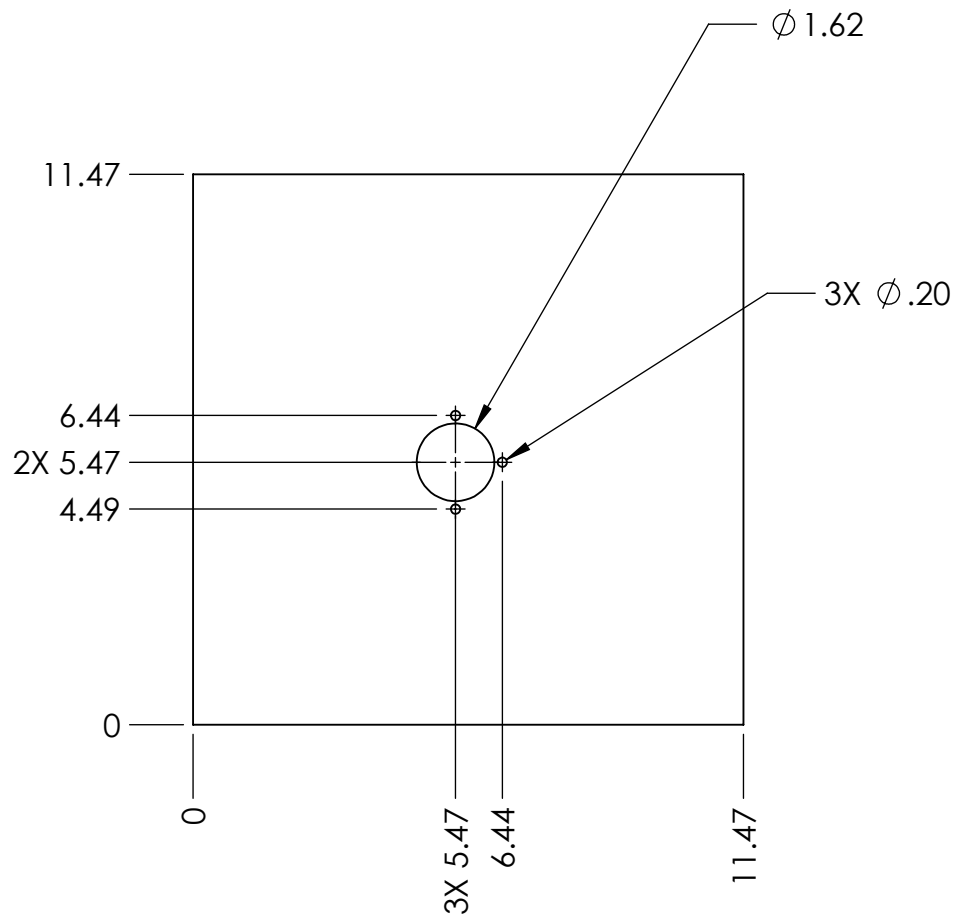
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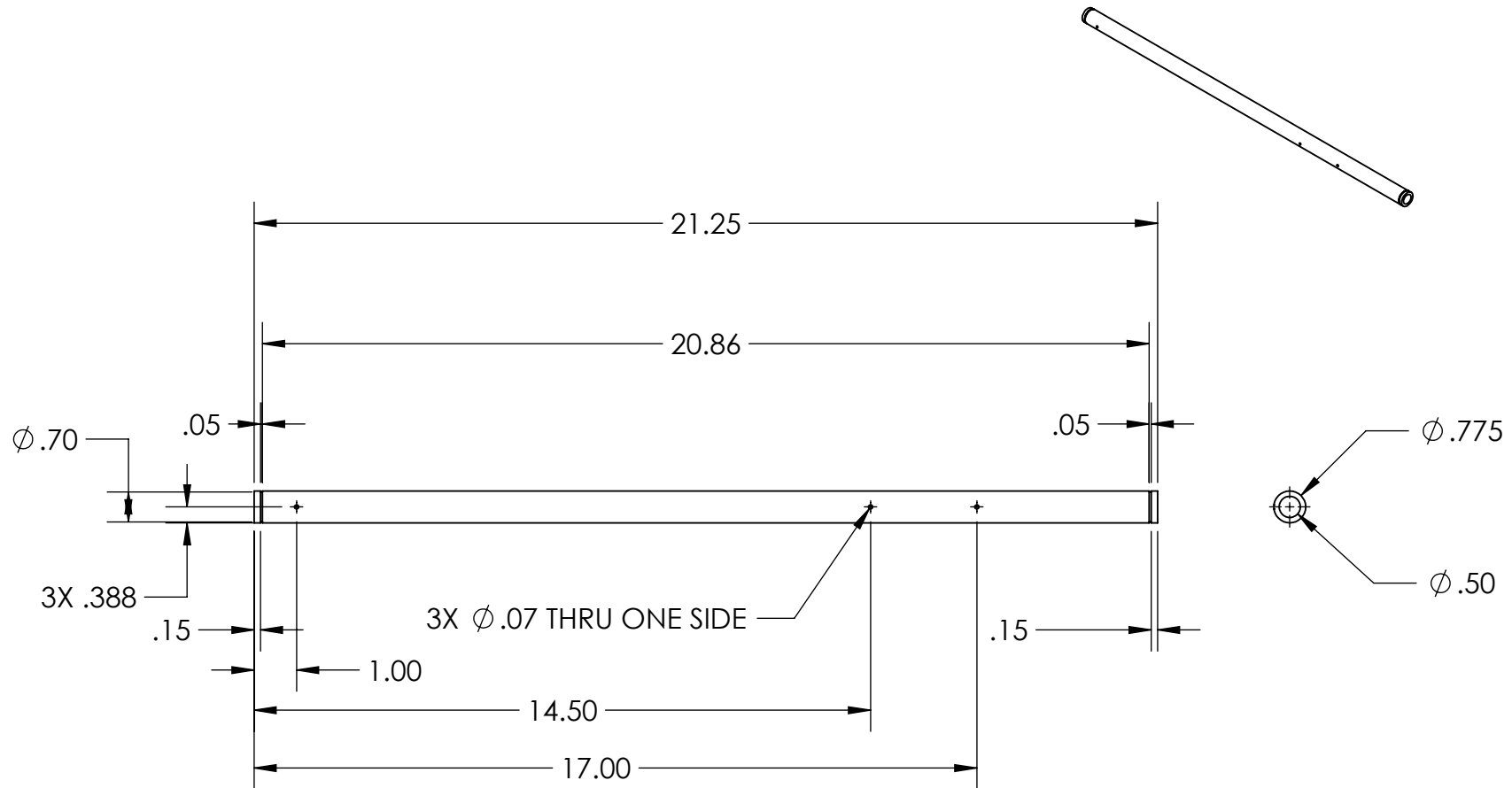
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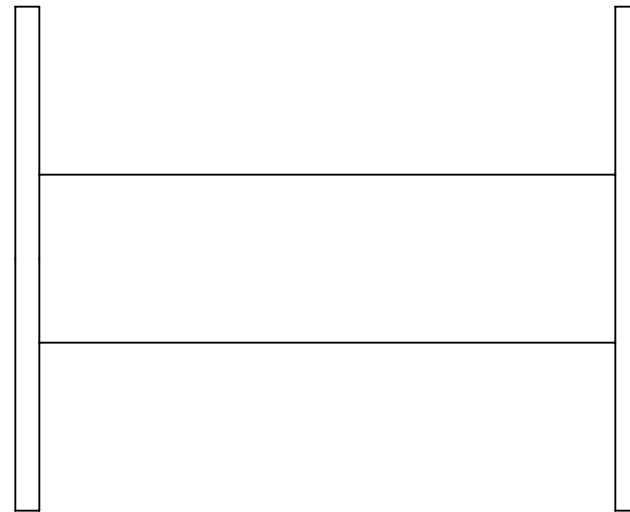
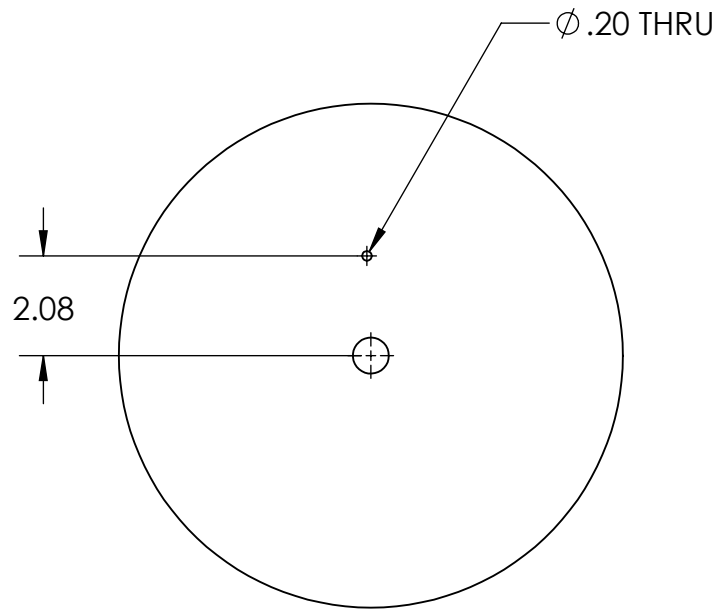
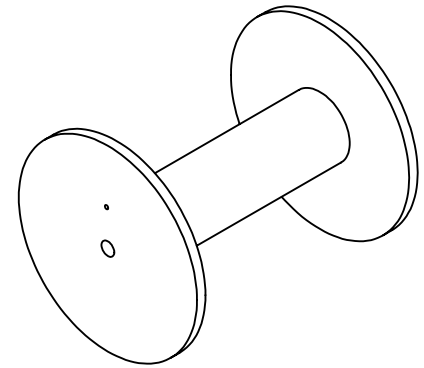
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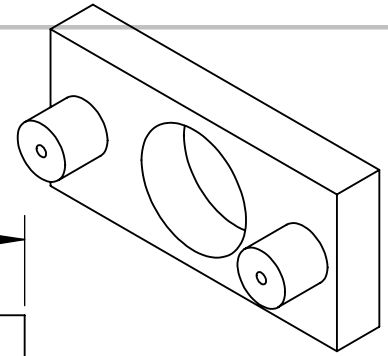
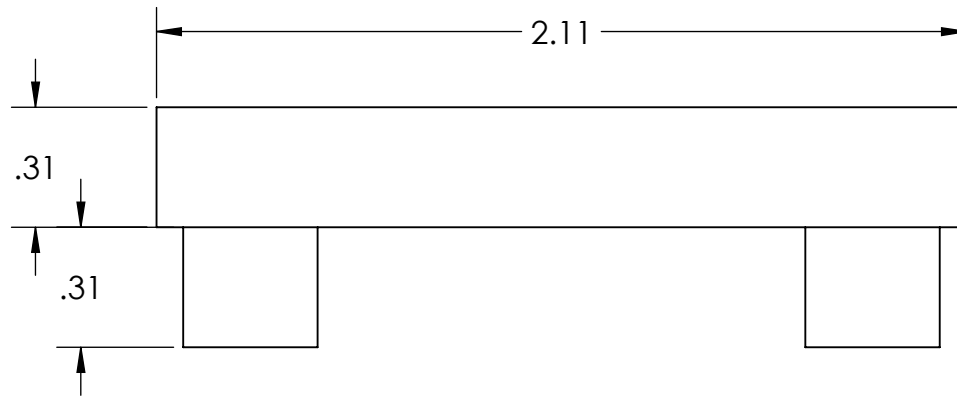
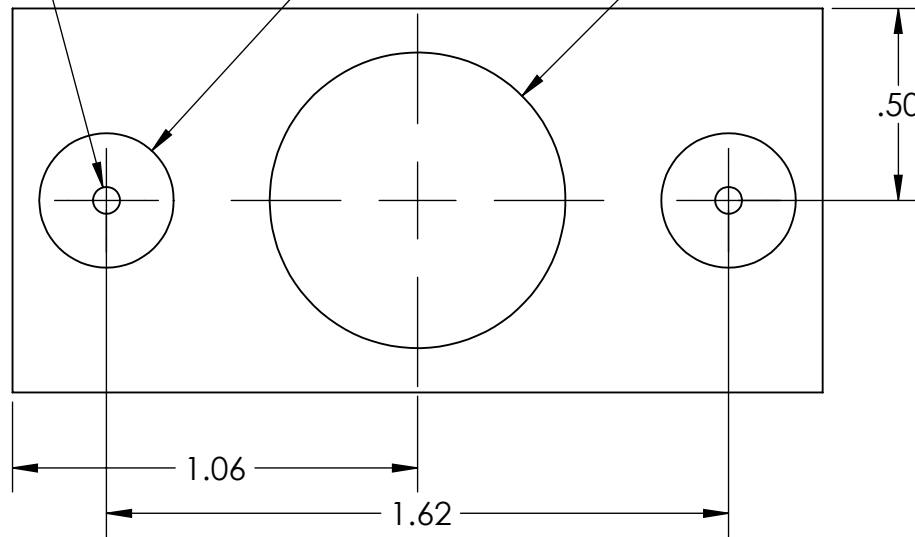
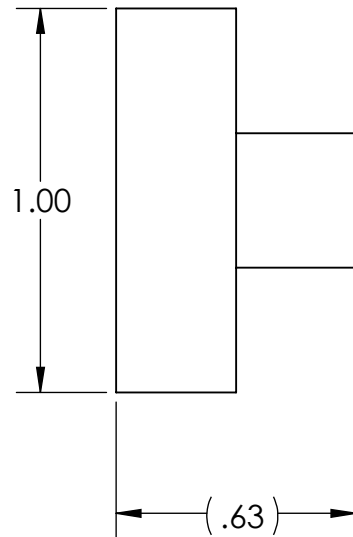
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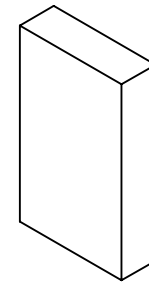
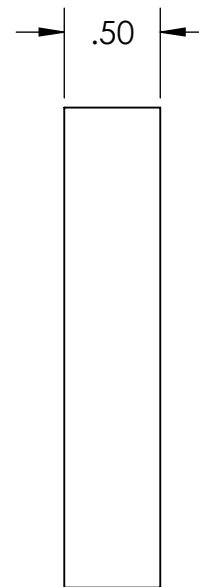
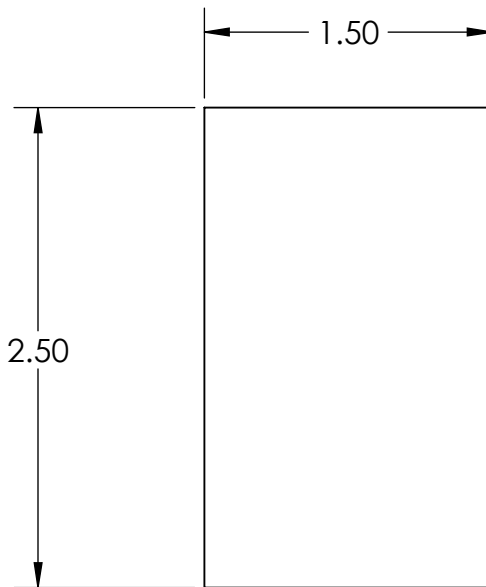
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MATERIAL PLYWOOD	UNLESS OTHERWISE SPECIFIED:		SIZE	DWG. NO.		REV
	FINISH AS MACHINED	DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 0.05 TWO PLACE DECIMAL ± 0.05 THREE PLACE DECIMAL ± 0.05	A	Spring Support		
			SCALE: 1:1		WEIGHT:	SHEET 1 OF 1

2

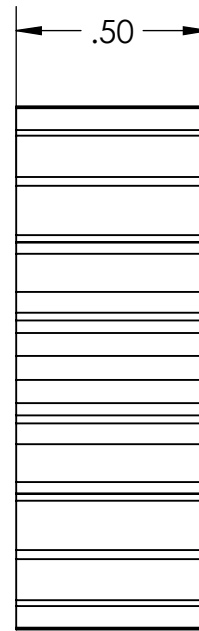
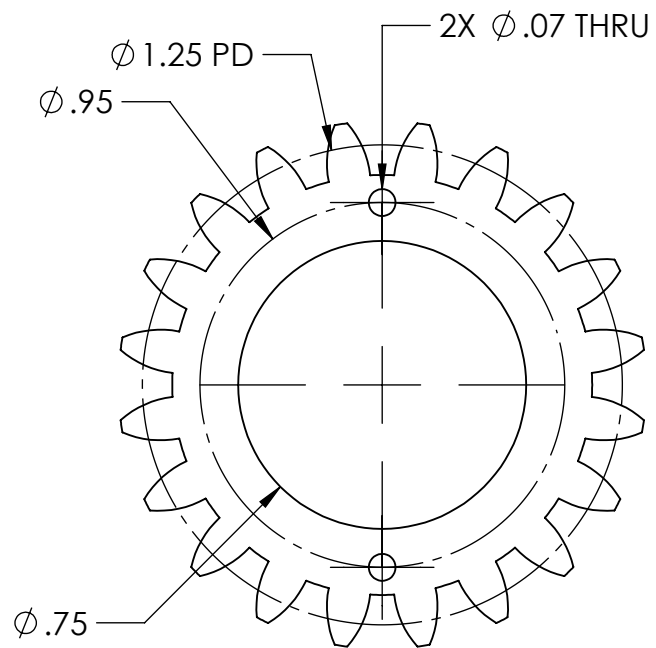
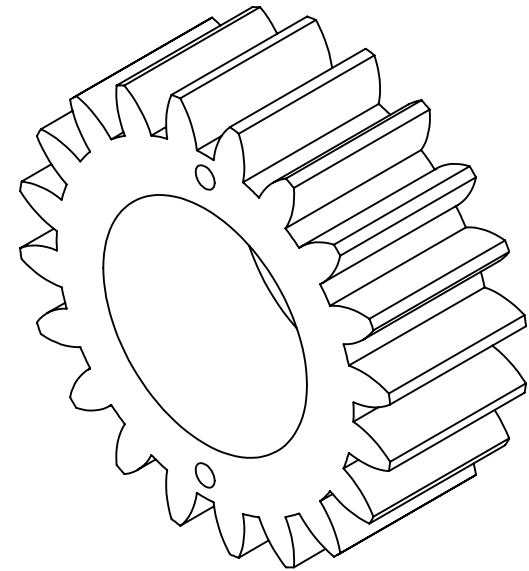
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2

1

NOTES

1. Diametral Pitch of 16
2. 20 Teeth



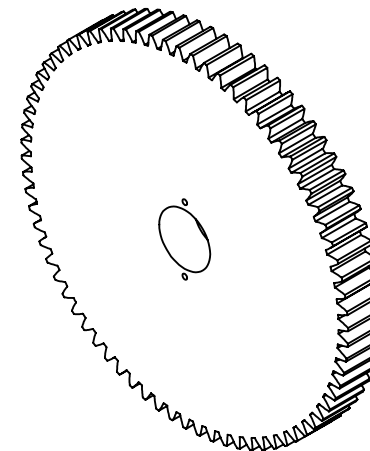
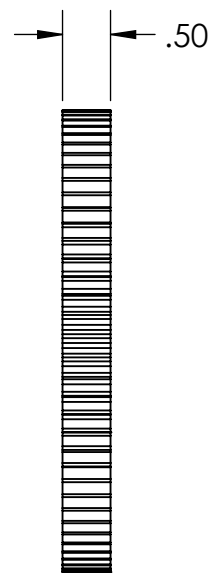
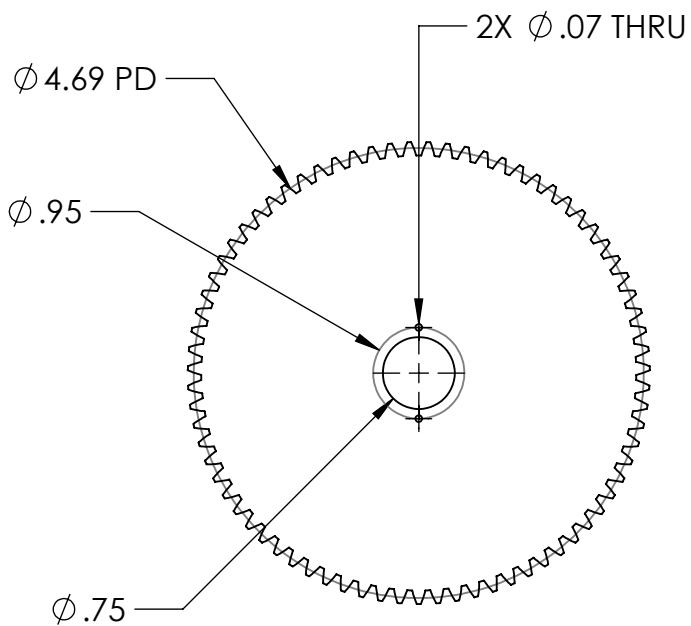
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UNLESS OTHERWISE STATED		SIZE	DWG. NO.	REV
MATERIAL	DELIN	A	20 Tooth Gear	2
FINISH	AS LASERCUT	SCALE: 2:1	WEIGHT:	SHEET 1 OF 2
DIMENSIONS ARE IN INCHES				
TOLERANCES:				
FRACTIONAL ± 0.05				
TWO FRACTIONAL DECIMAL ± 0.05				
THREE PLACE DECIMAL ± 0.05				

1

NOTES

1. Diametral Pitch of 16
2. 75 Teeth



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2

MATERIAL	DELRIN
FINISH	AS LASERCUT

UNLESS OTHERWISE STATED

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
TWO FRACTIONAL DECIMAL ± 0.05
THREE PLACE DECIMAL ± 0.05

SIZE

A

DWG. NO.

20 Tooth Gear

REV

2

SCALE: 1:2

WEIGHT:

SHEET 2 OF 2

B

B

A

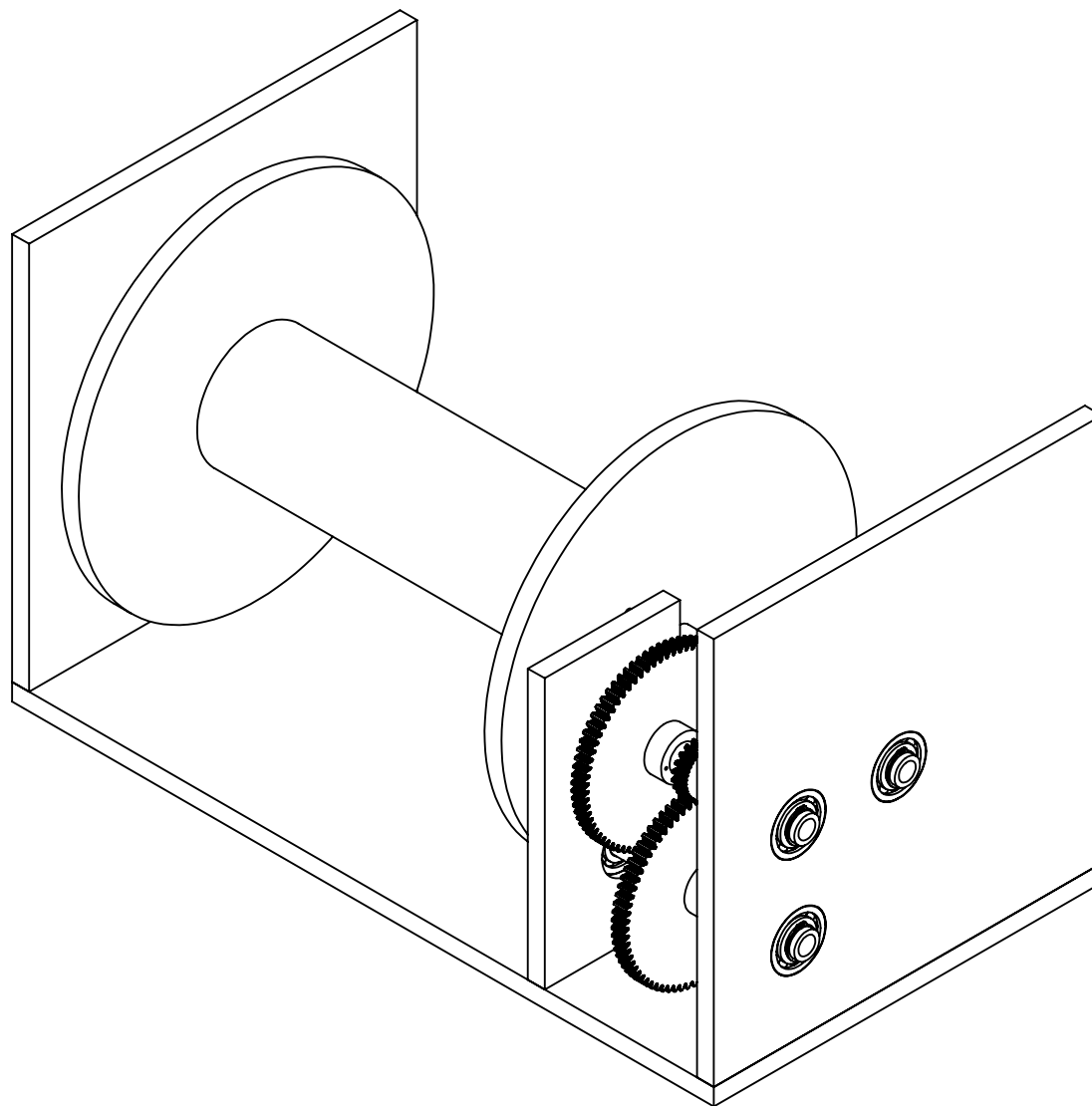
A

2

1

2

1

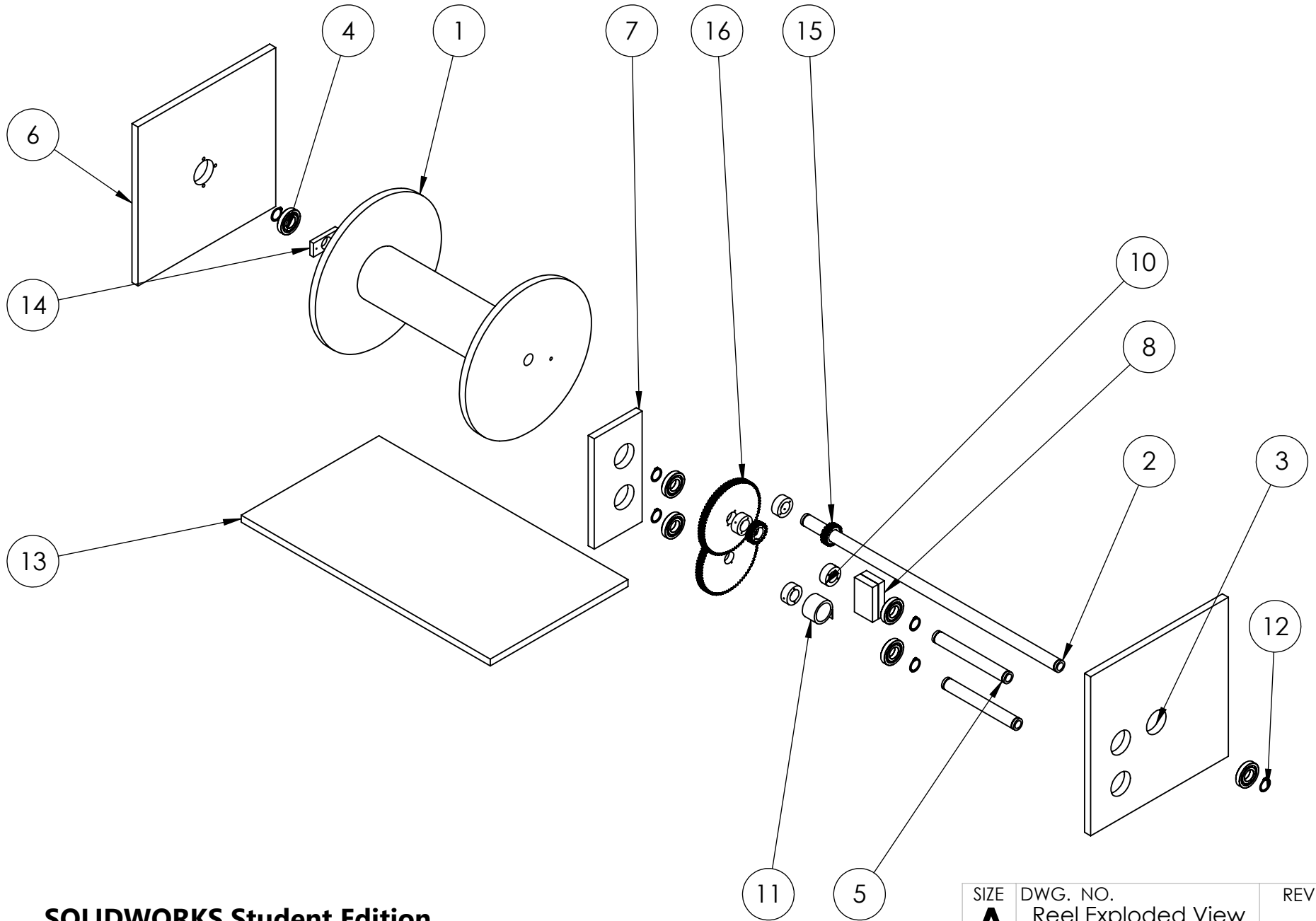


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SIZE	DWG. NO.	REV
A	Isometric Reel Assembly	
SCALE: 1:4	WEIGHT:	SHEET 1 OF 5

B

B



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SIZE	DWG. NO.	REV
A	Reel Exploded View	
SCALE: 1:8	WEIGHT:	SHEET 2 OF 5

2

1

A

A

2

1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Spool	Polystyrene Spool	1
2	Spool Shaft	ABS Tubing	1
3	Side Support 1	Plywood Shaft Support	1
4	Ball Bearing	Ball Bearing	6
5	Gear Shaft	ABS Tubing	1
6	Side Support 2	Pywood Shaft Support	1
7	Intermediate Support	Pywood Shaft Support	1
8	Spring Support	Plywood Spring Support	2
9	Rotary Connector	Mercotac 330 & Housing	1
10	Collar	Gear Collar	4
11	Constant Force Spring	Stainless Steel	1
12	Snap Ring	Steel	6
13	Base	Plywood Base	1
14	Spool Collar	Spool Collar	1
15	20 Tooth Gear		2
16	75 Tooth Gear		2

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SIZE A	DWG. NO. BOM	REV
SCALE: 1:1	WEIGHT:	SHEET 3 OF 5

2

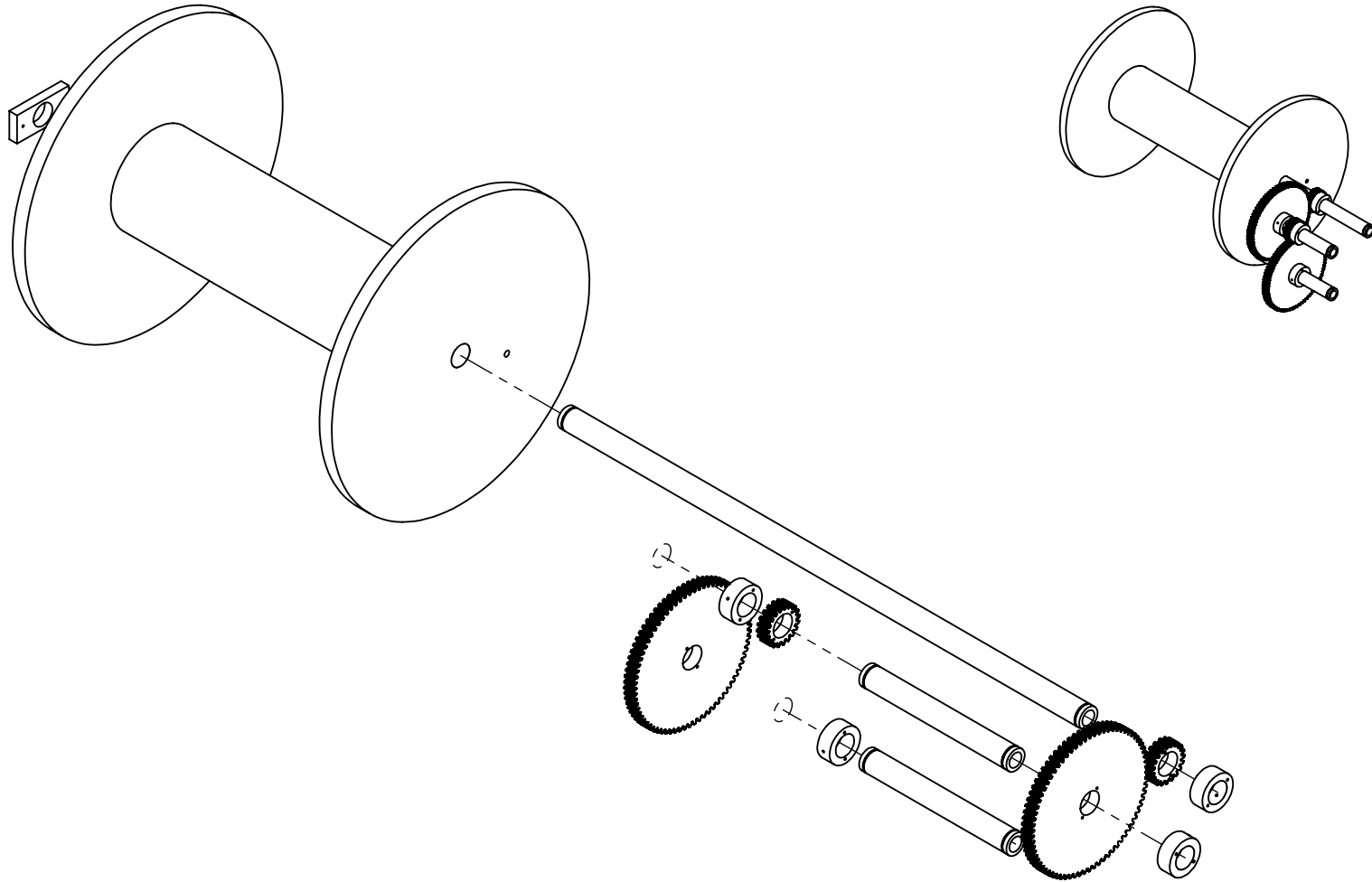
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B

B

A

A



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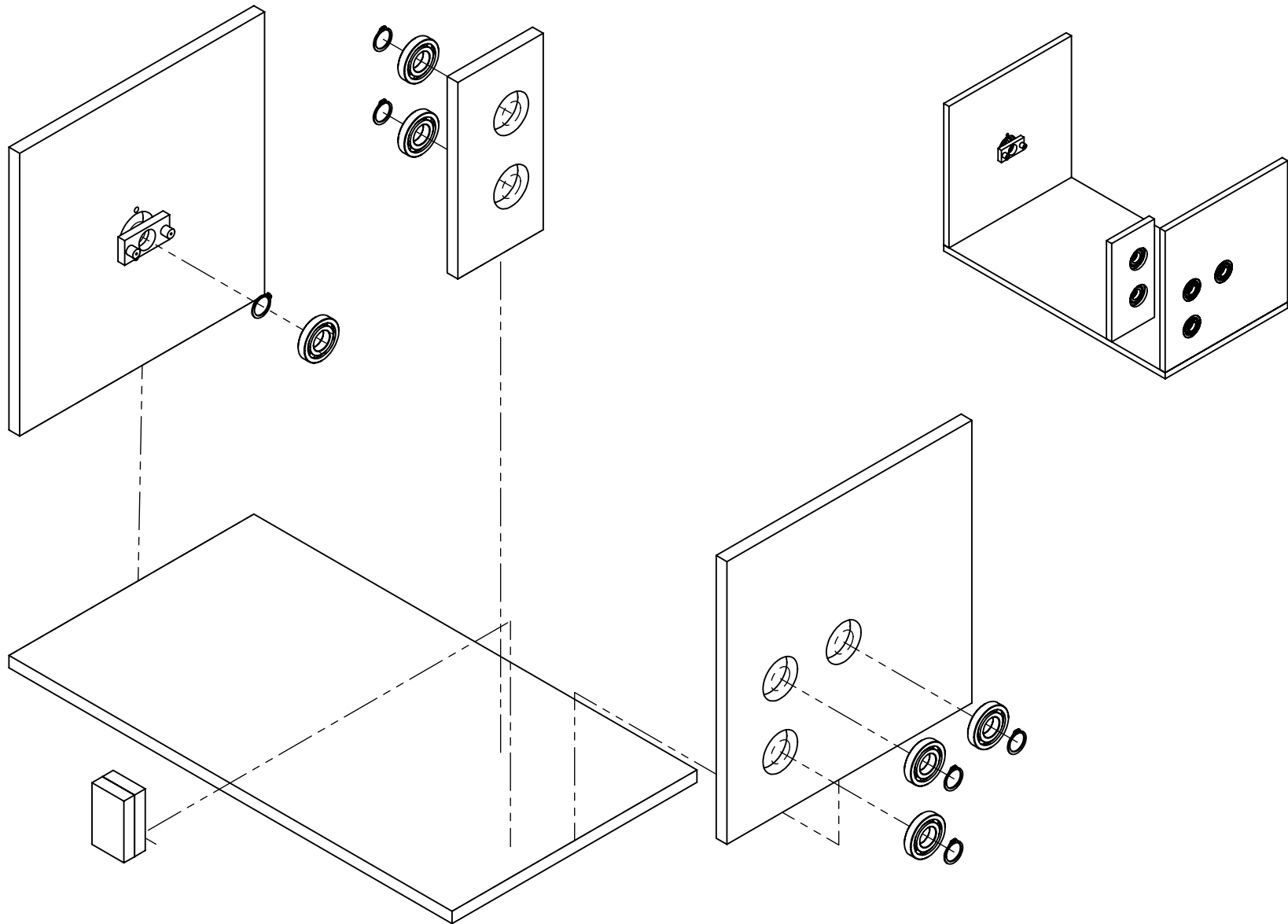
SIZE	DWG. NO.	REV
A	Gear Subassembly	
SCALE: 1:5	WEIGHT:	SHEET 4 OF 5

2

1

B

A



B

A

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SIZE	DWG. NO.	REV
A	Fixture Subassembly	
SCALE: 1:5	WEIGHT:	SHEET 5 OF 5