Prop IE: JPL University Projects

CDR Report

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ABSTRACT

This critical design review presents the development and proposed design of a deployable Solar Array Drive Assembly that could be flown on space-bound CubeSat missions. Our project addresses the need for reliable sources of power in spacecraft and other missions beyond the Earth's atmosphere. Our goal is to create a two degree of freedom SADA, including the passive retainment, deployment, and axial rotation of a solar array to track the sun during the CubeSat's orbit. It will have the ability to be easily adapted and integrated into other CubeSat builds but does not include other subsystems necessary for full satellite. The scope includes three main areas: the design and manufacture of a 90-degree locking hinge that allows multiple solar arrays to deploy from the stored launch state, the controlled axial rotation of the deployed panels, and the electronics necessary to manage these features with the potential for sun tracking algorithms. This report details the design decisions made in the development process, with the goal demonstrating its viability and receiving feedback for further improvement.

1 Introduction

We are a team of five mechanical engineering students at California Polytechnic University, Cal Poly SLO, who chose to partake in the JPL University Crowdsourcing Initiative (JUCI) program, a program which connects correspondents from JPL with university students such as us to work on real-world space science challenges. We all chose this project because we have deep interests in the aerospace field and believe that the program will be an enriching experience that offers ample opportunity for us to grow as collaborative engineers, prepare us for future career and personal endeavors, and embody Cal Poly's motto: learn by doing.

The goal of our project is to further CubeSat technologies and provide a reliable and efficient system that can orient itself to capture the maximum amount of solar power as possible, affected by its position relative to the sun, and assist these small satellites in their various and unique missions that focus on the exploration of space and the understanding of our universe.

Our objective is to design a working prototype of a two-degree of freedom solar array drive assembly, SADA, that can accurately track the sun and change the position of the solar panels to ensure maximum energy capture.

The following section will provide an overview of our system design, details about the different subsystems, and an explanation of the function of each subsystem using a system flow diagram, schematics, and CAD models. An initial cost estimation is presented along with our project budget as well as an up-to-date spending total.

Justification of our design follows, where we explain our reasoning for choosing this design and use our engineering judgement to highlight why we are confident that the design will meet all specifications. Preliminary calculations of the force required to keep the solar panels passively retained via fishing line and the spring stiffness needed from the torsion spring hinge mechanism are discussed. This section will also address the potential hazards of the design and any concerns regarding the design not meeting customer satisfaction.

The next section will be our manufacturing plan where we state how we plan on gathering materials and how we want our verification prototype to be manufactured and assembled. Specific steps on how to manufacture the key components are listed with corresponding CAD models for a better understanding in the hopes that these steps could be followed easily by those trained in the engineering discipline.

Our design verification plan follows, where we describe the tests that we intend to perform on our verification prototype to ensure that the product meets all our criteria. This prototype will be sufficiently tested and analyzed to guarantee that it will meet all necessary requirements for launch, space travel, and space operation. To assure customer satisfaction, this product should meet all the engineering specifications that we came up with, these will be explained further in subsequent sections.

This project hopes to accomplish our objectives in a cost-effective and safe manner.

2 System Design

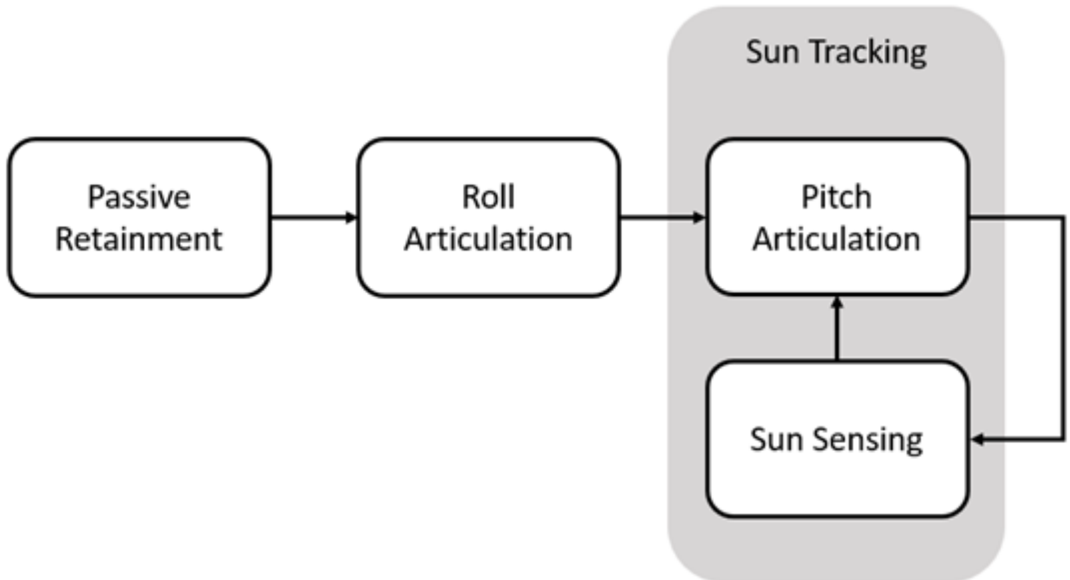


Figure 1 – System flow diagram

2.1 Design Description & Function

The first subsystem in the system flow diagram is passive retainment. In a small-sat mission, the satellites are stowed in a deployer with no connection to an outside power source. With the time spent in the deployer before launch being difficult to predict, CubeSat systems must not use any power during launch, both for the safety of the rocket and the main payload, and for the longevity of the CubeSat mission. When paired with a satellite that has a deployable, this requirement becomes more difficult to achieve. The reason for this difficulty lies in the fact that a deployable is something that is initially stowed, then deployed without physical human intervention. The first idea to solve this problem is often that of electrical background, however, electronics cannot be powered on during launch and thus whatever solution is thought up must be able to withstand the vibrations of launch without deploying, deploy consistently and repeatably, and must not require electricity to retain the deployable, hence, passive retainment.

A burn wire deployment mechanism was chosen and requires four components: a spring, fishing line, Nichrome wire, and a power supply. In traditional settings, the fishing line is tensioned against a strand of uninsulated Nichrome wire, and once the fishing line burns, a compressed spring launches the deployable into its final configuration. For a more in depth view of each subsystem along with functions, reference our FMEA in Appendix D.

The first step to designing a burn wire system is selecting the proper fishing line. The fishing line test – strength of the line – is determined by the deployable force it is trying to restrain. As an example, if the fishing line is wrapped around a block that sits atop a spring with a spring constant of 1 N/m, compressed 0.01 m from equilibrium, then the fishing line must be able to withstand 0.01 N of force. With this, hand calculations were performed to determine the force needed to withstand as around 5N with an appropriate factor of safety. Now that the correct strength of the fishing line is selected, the line must be pretensioned before use. Pre-tensioning is an important step as the fishing line has some elasticity and will lengthen when pulled on. With the main goal of preventing deployment during launch, this line must be held very tightly against whatever it is trying to retain. To accomplish this, the line must have weight held on to it under gravity for a period to pretension the line to the point where the expected deployable force will not cause any elastic elongation of the fishing line. The exact weight to be used for this pre-tensioning will be 5lbf which will sufficiently tension it past the required deployable force of 5N.

With the fishing line selected, the Nichrome wire system is determined. Nichrome wire is wound around and tensioned against fishing line, then attached to two opposite poles of the power supply. Nichrome wire itself is simply a piece of Nickel-Chromium alloy that has a higher electrical resistance than normal copper wire. When current passes through this electrical resistance, heat is generated and expelled into the environment. To select the proper Nichrome wire and power supply, the equations below can be used to parameterize the system.

$$R_N = \frac{Wire\ Length\ [in]}{12} \times RPF \qquad \text{(Eq 1.1)}$$

Where R_N is the total resistance and *RPF* is defined as the Nichrome wire's resistance per foot and can be found from a gauge table where the gauge of Nichrome wire relates to a specific *RPF* value. Next, simply use Ohm's law below to determine the voltage required.

$$V = I \times R_N \qquad \text{(Eq 1.2)}$$

Where I is the required current through the wire. This value is determined by the temperature that needs to be reached by the Nichrome wire to burn through the selected fishing line. With the current 8lb monofilament fishing selected for our project, we would require the Nichrome wire to heat up to approximately 230C to begin to melt the line. With the known temperature and our selected Nichrome gauge of 28 known, a value can again be looked up in a table to get the corresponding current. All these values give us a total resistance of 0.05Ω for a 3 cm piece of Nichrome and a required current of 2.7A. These values call for a power supply that can output 0.135V at 2.7A which is very doable in our system. A labeled drawing of this subsystem is provided below.

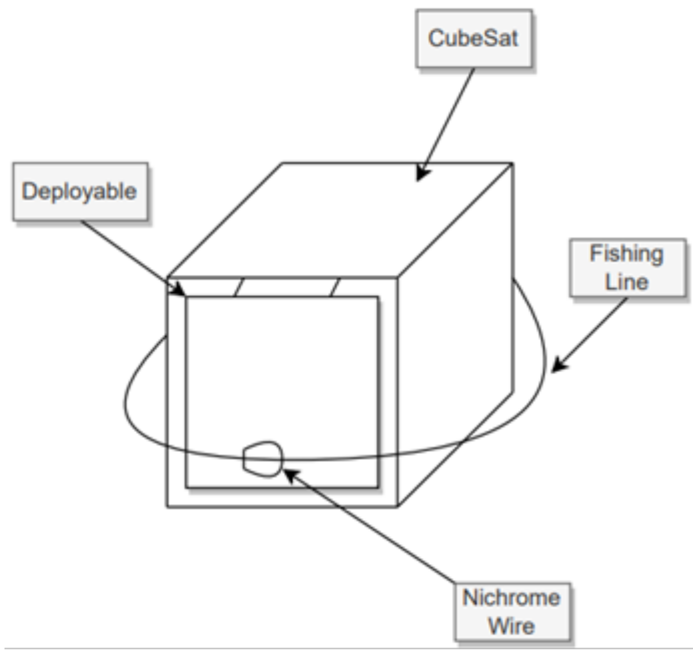


Figure 2 - Nichrome burn wire with fishing line retention for passive retainment.

Now that we have a way to retain our deployable during launch, we need a way to release it and get it into the correct position for sun tracking. This is by far the most complicated system as the solar panel must be able to change angle in the roll direction, then switch and provide continuous change in pitch angle throughout the mission lifetime (an image of roll, pitch, and yaw axes is provided in the appendices). Seeing as roll articulation is only needed when moving the solar arrays from the stowed to the active configuration, this system was designed to eliminate roll axis movement after proper mating with the pitch axis.

Due to external volume constraints placed on CubeSats forcing them to have nothing extend greater than one tenth of an inch on any side of the 10x10 cm cube, we are forced to deploy the solar arrays in this manner. This volume constraint also makes it so that external motors that may be attached directly to the solar array would be impossible to implement. With this in mind, we settled on a design that uses a spring-loaded hinge to deploy, then one motor to control solar array articulation.

Once the burn wire is severed, the deployable will be free. Each solar array will be mechanically attached to the bus through one spring loaded hinge that we have designed, along with a bracket to interface the solar array with the hinge. Before fishing line severance, the torsion spring hinge will be under the appropriate compression. This torsion spring is sized to have a spring constant of around 0.3 N/m for proper deployment force as seen in Appendix C. Once free, the potential energy stored in the torsion spring will be converted to rotational kinetic energy, along with some losses, and cause the solar array to flip up in a position close to perpendicular to the satellite bus. The hinge is designed so that the array will be locked in this position. This is accomplished with a spring-loaded plunger that follows a slot from zero to ninety degrees with a slight enlargement at the perpendicular position. The shaft follows the slot until this enlargement, where the plunger spring can release its stored potential energy and lock the hinge in place. Once the array is locked in this place via the hinge, it will not be able to unlock, unless acted upon by a separate input that compresses the spring back down. This feature was added for ease of testing, as it allows for quick repetition; however, it will not be used when this device is flown in space.

A few important notes about this design follow. Firstly, this hinge will be completely outsourced for manufacturing except for the plunger assembly. The hinge will be manufactured out of Aluminum 6061-T6 as it offers similar specific stiffness to steel, while maintaining low mass and lower melting point for burning up upon atmospheric reentry. Below you can find CAD images for all of the machined components in our design. Each of these images has a corresponding drawing in the bill of materials in Appendix A.

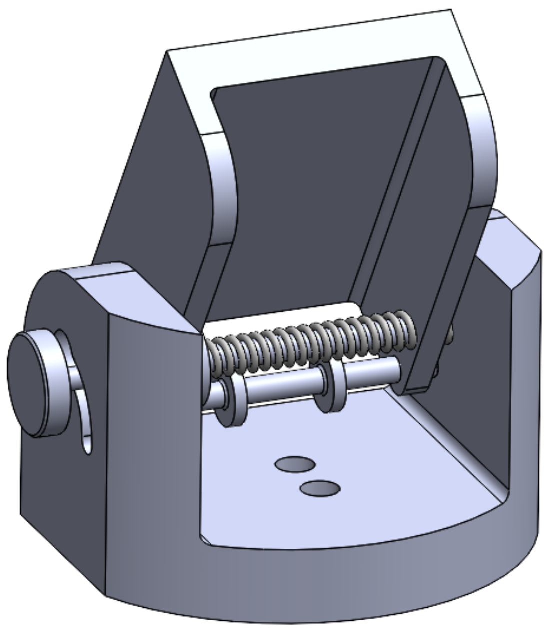


Figure 3 - Hinge design with slotted CAM to lock hinge perpendicular to base. The hinge is driven by a compressed torsion spring not pictured.

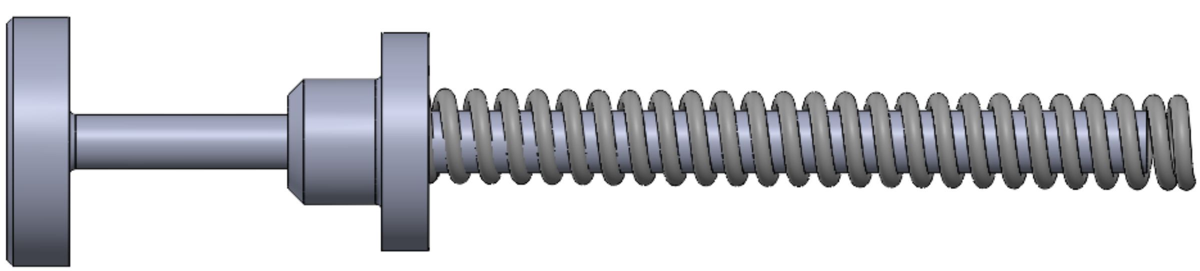


Figure 4 - Plunger design where the large surface area "button" provides a way to manually reset the lock by pushing down and recompressing the spring.

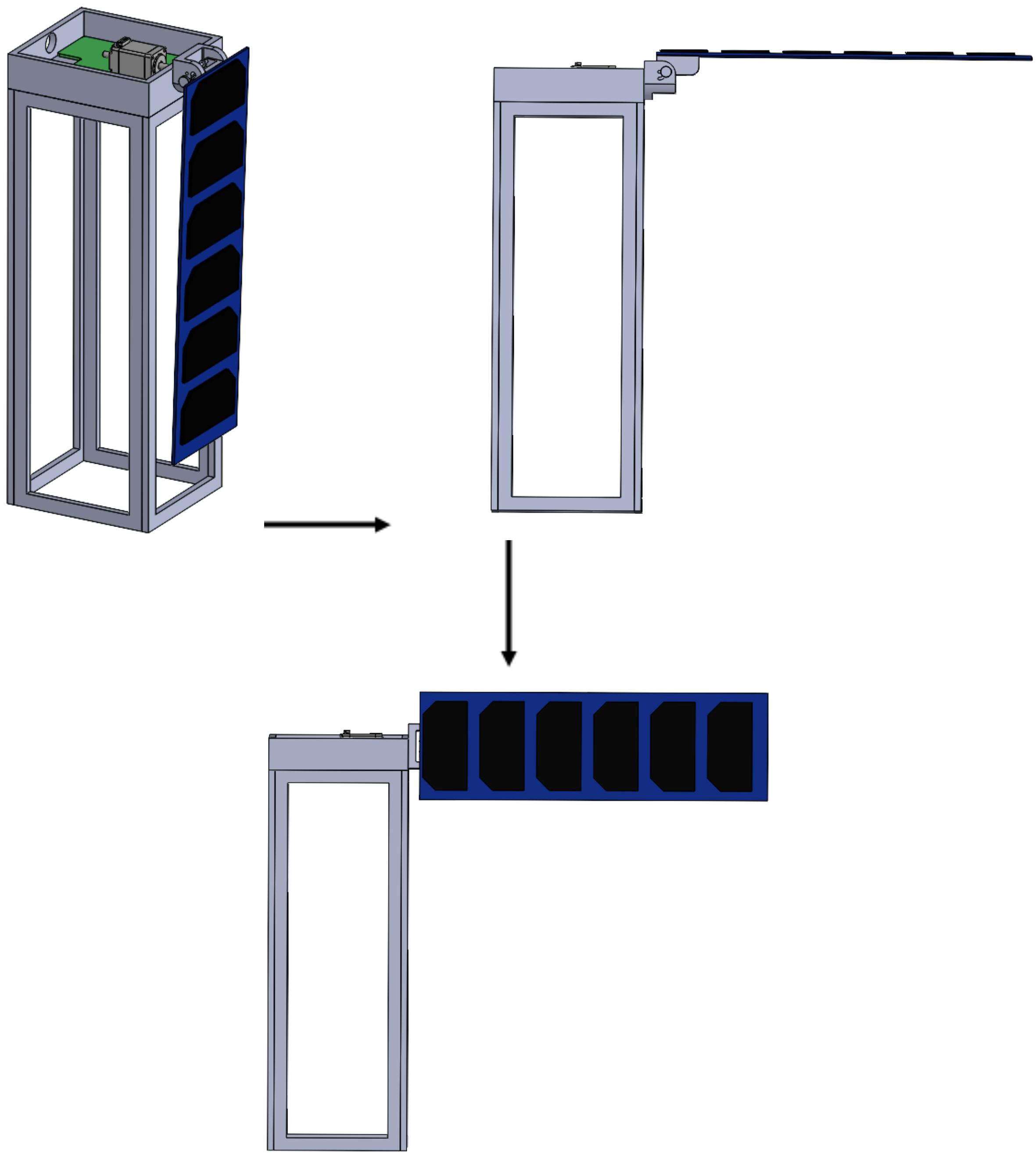


Figure 5 - CAD model of system flow from passive retainment to deployment, to sun tracking. Note: a 3U satellite is modelled, however, the size of the satellite does not influence our design.

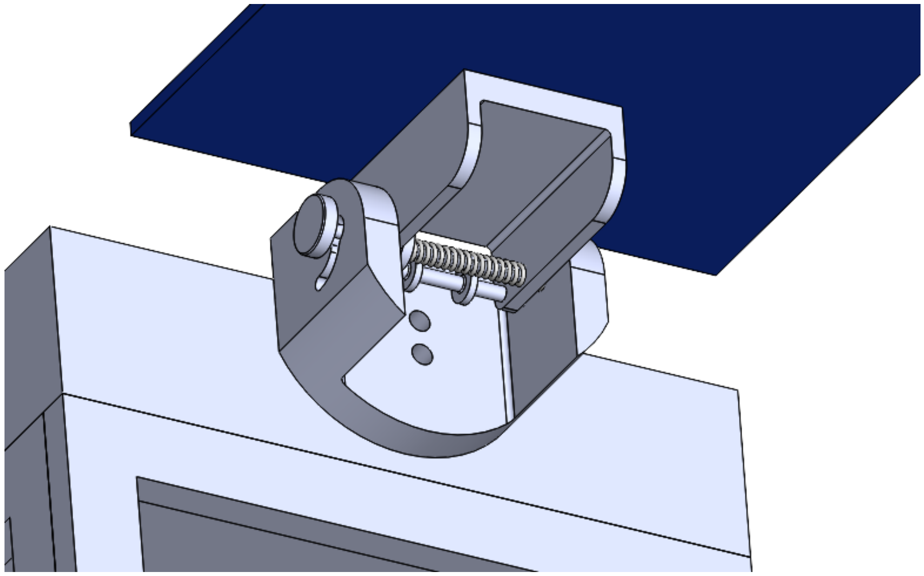


Figure 6 - Upon deployment, plunger locks into place and prevents the hinge from falling back down. Afterwards, the stepper motor can now freely rotate the solar array to track the sun.

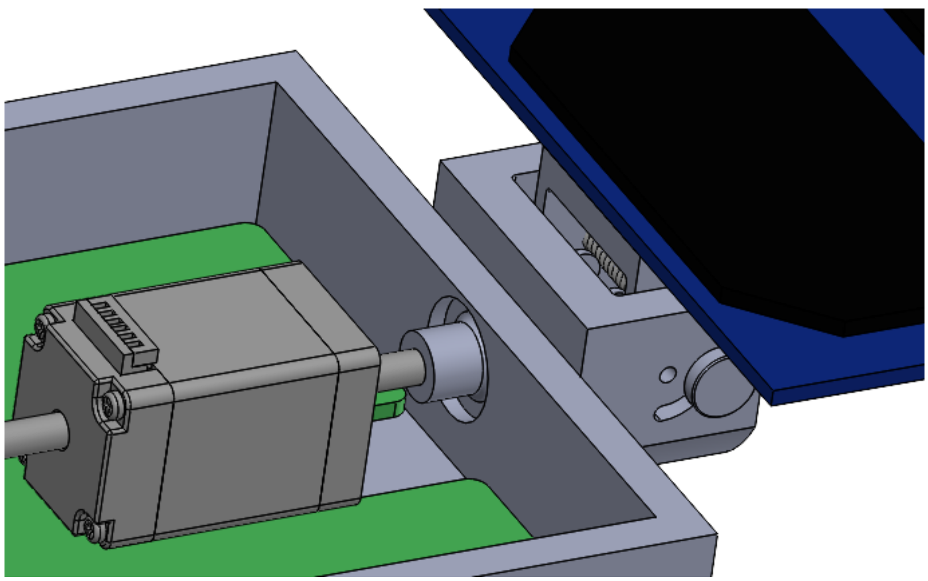


Figure 7 - After hinge locking, the stepper motor (model) can directly drive the turn table which then spins the hinge along with the solar array. See Appendix for PCB details

2.3 Cost Estimate

Based off the cost estimate from our Indented Bill of Materials (iBOM), attached in Appendix A, we expect the cost of constructing our final prototype to be about $450. The tables below show a summary cost breakdown for our verification prototype by subsystem.

Table 1 – Passive Retainment Subsystem Cost Breakdown

Passive Retainment

Item Description	***Quantity***	***Vendor***	***iBOM Part Number***	***Total Cost [$]***
Nichrome Wire	3 inches	Amazon	121000	2
Fishing Line	5 feet	Amazon	121200	1
Screws	5	Protolabs	121400	5
Subsystem Cost	8			

Table 2 – Deployment Subsystem Cost Breakdown

Deployment

Item Description	***Quantity***	***Vendor***	***iBOM Part Number***	***Total Cost [$]***
Torsion Spring	2	McMaster	111100	14
Compression Spring	2	McMaster	111200	10
Al Bar Stock 0.5'	1	GetMetals	111300	10
Al Bar Stock 0.25'	1	Grainger	111300	8
Hinge Base	2	Protolabs	111400	15
Screws	5	McMaster	111500	5
Subsystem Cost:	62			

Table 3 – Sun Tracking Subsystem Cost Breakdown

Sun Tracking

Item Description	***Quantity***	***Vendor***	***iBOM Part Number***	***Total Cost [$]***
Stepper Motor	2	Amazon	131100	20
9/16" Al Bar Stock	1	Grainger	131300	20
Turn Table Manufacturing	2	Protolabs	131300	6
Set Screws	2	Amazon	131400	6
Shaft Coupler	2	Protolabs	131500	10
Solar Array Bracket	2	Protolabs	131600	100
Solar Cells	6	Amazon	132100	72
Photodiodes	16	Amazon	132200	16
Photodiode Breakout Board	2	Oshpark	130000	40
SADA Shield	1	Oshpark	130000	50
Raspberry Pi Pico	14	Amazon	141000	14
USB Mini Cable	6	Amazon	142000	6
Screws	20	Amazon	143000	4
Subsystem Cost	364			

From our cost estimation breakdown for our verification prototype, we can now rank the subsystems from most expensive to least: Sun Tracking, Deployment, and Passive Retainment.

Since our design will require parts of extremely small components, we thought that it would be best to outsource the manufacturing of components such as the hinge base and the swing piece to Protolabs, a well-respected and reliable manufacturing companies that we are confident will provide us with quality parts at affordable prices. We plan to order multiple parts in the event of part malfunction during assembly since that will require meticulous handling and care on our part.

The sun tracking subsystem has the most parts out of all the different subsystems and will require several custom components to be outsourced for manufacturing such as the solar array bracket and shaft coupler. The rest of the components can be bought off the shelf on sites such as Amazon and Oshpark. The estimated total for the sun tracking subsystem is $364.

The deployment subsystem will require the hinge base to be outsourced for manufacturing and two different sizes of Aluminum stock to be purchased for the manufacturing of the plunger design. More details on the manufacturing process will be given in the Manufacturing Plan section of the report. Other components such as the springs and screws can be purchased off the shelf on McMaster. The estimated total for the deployment subsystem is $62.

The passive retainment subsystem has the fewest parts of all subsystems, a primary reason for it being the cheapest. The Nichrome wire and fishing line were bought on Amazon at very affordable prices. Custom screws are required which will be done by Protolabs. The estimated total for the passive retainment subsystem is $8.

It is important to note that this does not include the cost of materials used for building other prototypes or testing. There are still quite a bit of materials and equipment that we must still collect; we expect to spend a good portion of our budget during the building and testing phase of the project.

The total cost estimation for the processes leading to the construction of our final project is somewhere in the range of $2,000. This estimation was calculated by incorporating a safety factor of 1.5 to our total project cost estimation, which is shown as a table in Appendix B that summarizes key project details. The team is also considering allocating $300-$400 for a group trip down to the JPL facilities if possible. This is all still well within our total project budget of $3,500 with a reasonable cushion of extra funds in case of unforeseeable circumstances in the future.

As of February 16th, 2023, we have spent $90 in gathering the materials for our structural prototype which tested the functionality of our torsion spring design. The table in Appendix B summarizes our up-to-date expenditures as well as the status of the remaining balance of our project funds.

3 Design Justification

This section details how the three subsystem concepts will meet each of the design specifications. A table of engineering specifications is listed in Table 1 below.

Table 4 - Engineering Specifications Table

Spec. #	Specification Description	Requirement or Target	Tolerance	Risk*	Compliance**
1	Vibe Test Range	TBD	N/A	M	T
2	Thermal Cycling	-35 to 70 °C	N/A	M	T
3	Weight	0.60 kg	+- 0.06 kg	H	I
4	Passive Retainment	1 form	N/A	H	I
5	Cost	$1000	N/A	L	I
6	Power Used	100 mW	+- 10 mW	M	T
7	Number of Deployments	50	- 5	L	A
8	Volume	250 cm^3	+-25	H	I
9	Accuracy	0 degree variation	+- 5°	M	T
10	Deployment speed	10 minutes	+-2	L	T

* Risk of meeting specification: (H) High, (M) Medium, (L) Low
** Compliance Methods: (A) Analysis, (I) Inspection, (T) Test

Burn wire systems are the best method to passively retain the solar panels on the CubeSat because this method is frequently used in industry for various space applications such as CubeSat missions, is simple, and cost effective. Burn wire is made from the Nichrome alloy which is known for its high mechanical strength. A relatively high mechanical strength is needed for our passive retainment subsystem as the burn wire will need to counteract the force from the spring that is meant to rotate the panel about the roll axis; however, the spring will not exert a large force because the panels need a relatively low impulse to deploy in a low-gravity environment. A preliminary calculation of the force needed from the fishing line to keep the solar panels at rest is shown in the appendix. It was determined that a force of 0.62 Newtons is needed.

The spring and hinge concept for the deployment subsystem was chosen mainly due to its feasibility, compact size, and cost. The team is more familiar with working with spring hinge systems as compared to shape memory alloys, so this concept is most plausible in creating a reliable, robust, and cost-effective system design that will deploy the solar panel from its stowed. Spring hinge mechanisms are widely used in several industries for a wide variety of uses such as in self-closing doors in homes, controlling the closing and opening of cryogenic freezers in medical laboratories, and on doors and seats on aircraft. Hinges are both durable and strong and when combined with a torsion spring they offer a reliable and volume-efficient deployment mechanism. A preliminary calculation, shown in the appendix, was done to approximate the spring constant a torsional spring would need to deploy an average sized solar panel to its active position. Spring constants were estimated for a 1U and a 3U CubeSat, the results are summarized in Table 4 below.

Table 5 - Torsion Spring Constants to deploy a 1U and 3U SADA.

Size of CubeSat	Spring Constant [Nm/rad]
1 U	0.04
3U	0.12

We were able to find several types of self-locking hinges, such as the one shown below in Figure 8, for worktables, garages, and such on online websites such as amazon that are very similar to the concept that we came up with, so this gave us some confidence in our designs ability to function. We have bought two of these hinges to understand how they work and implemented one into the structural prototype. They worked as intended, though we will be creating a bespoke solution for our CubeSat.

Figure 8 - Folding bracket self-locking spring hinge found on Amazon.

Due to the volume constraints, low friction requirement, and unique application, designing the hinge in-house is the optimal strategy. It will be small, on the order of 2 to 4 cm in length. In the purchased folding hinges that we tested friction was a large constraint on the efficacy of the hinge. This is another reason that designing our own system will be critical, because a lower friction hinge requires a smaller string and gives a larger function of safety to the passive attainment systems. Additionally, the stronger the spring needed to deploy the hinge, the larger the change in angular momentum the satellite will have when the panels are locked into place, leading to spin. While an implemented CubeSat would have magnetorquers or something similar, the less they need to correct for spin upon deployment, the lower energy used or chance of failure.

Photodiodes are chosen for sun tracking primarily for the cost and ease of implementation. Other solutions include sun tracking based on the solar panel voltages (inaccurate) and off-the-shelf APS sensor breakouts, which are far too expensive for our requirements. These are proven solutions for applications like this through hobbyist projects. Since the deployment subsystem is the most crucial part of our design and to create a reasonable scope, we are treating the sun tracking control system as a bonus of the project rather than a set requirement. We are confident that we can create a two degree of freedom system but due to our time constraint and the late notification of our design challenge, we have chosen to focus our efforts on creating a reliable hardware system and leaving the control algorithms as an added bonus that we will get to if time allows.

3.1 Meeting Design Specifications

The most critical design specifications for this actuation mechanism are weight, volume, and reliability. Weight and volume are easy to target in the design phase as we are making a bespoke actuation hinge that allows us to have complete control over the form factor. Since the CubeSat is very small and operates in a 0G environment, it will not need to withstand large forces other than the vibration of launch. In terms of reliability, the actuation components are unlikely to have significant wear over the 50-repetition test that we have planned for the deployment. Since in the actual deployment of this system in space it would only require 1 deployment, this is more than conservative. Testing the springs to ensure they do not deform or wear out is the most likely point of failure, though we do not foresee it being an issue. Power generation and accuracy of the sun tracking mechanism will also be easy to predict based on the quality and size of components we purchase. The stepper motors operate at 5V and due to the relatively slow actuation are very unlikely to use more than 100mW on average over the course of an orbit.

3.2 Structural Prototype

The structural prototype of our project was focused on developing a good model of our most complicated subsystem. The subsystem that was designed was the deployment subsystem with a focus on the spring-loaded and locking hinge. The prototype was constructed out of wood, a self-locking hinge from Amazon, fishing line, and Nichrome wire. An immediate issue we noticed with the hinge purchased from Amazon was that the spring-loaded plunger caused a significant amount of friction on the hinge which prevented it from smoothly opening. To overcome this, we sprayed the hinge with WD-40 and cut the spring of the plunger to decrease the amount of compression the spring underwent. This made the hinge significantly easier to rotate and allowed us to continue. Finally, we attached a compression spring between the panel and the base which allowed us to compress the spring, tie fishing line, then burn the line with Nichrome wire. Upon burning, the solar array popped out and locked into place in the ninety-degree position.

Figure 9 – Side View of Structural Prototype in Stowed State

[Click Here for Structural Prototype Deployment Video]

Video 1 – Video Demonstrating the Deployable and Compression Spring Features of the Design

There were multiple learnings from the structural prototype that will inform future design of the SADA. The first of these is the passive retainment lines: with multiple of a lower strength, there is a risk of them burning at different times due to the transient heating of the wire. In some tests, this caused the panels to partially open before the line was burnt enough for complete deployment, slowing the panels down enough that they couldn't fully deploy. To counteract this, we plan on using a single strand of thicker fishing line on the final design. Below are the currents needed to burn through the fishing line in preliminary tests that we attempted.

Table 6 – Results from test to determine necessary burn current

Nichrome Burn Wire Test			
Trial	Amps [A]	Volts [V]	Time [s]
1	0.5	0.2	N/A
2	1	0.4	N/A
3	1.2	0.5	20sec
4	1.4	0.6	Instant

Another learning regarded the friction of the locking hinge. The store-bought options we found had a lot of friction, and even after modification had significant remaining. The bespoke hinge assembly that we are designing must have very low friction to minimize the strength of the spring needed to deploy it, since the stronger the spring the more angular momentum a CubeSat's magnetorquers would have to counteract.

3.3 *Safety, Maintenance, & Repair*

The system will be interacting with people during the building and testing phase. Care should be taken through the use of proper Personal Protective Equipment when operating laboratory equipment during the manufacturing phase for processes such as lathing, drilling, and stick welding. For a full list of all the hazards present in this system, reference our design hazard checklist in Appendix E.

Another hazard arises during the testing phase when we are dealing with the burn wire mechanism which can burn those in near contact and potentially ignite a fire. To reduce the risk of injury we will have a safety warning when the burn wire is active so those around may maintain a safe distance. To reduce the risk of damage, we will always keep a fire extinguisher nearby during testing. This is detailed in the Design Hazard Checklist.

There is also a hazard during the testing of the deployment phase as the spring-hinge mechanism swings the solar panels upward from its stowed to active configuration. While our system is small and will not move with high accelerations, the risk of damage to those nearby is present. For a 1U SADA, the damage inflicted to a person from this movement is minimal, but for a 3U SADA that has a longer moment arm this motion can produce more damage. We plan to keep a safe distance during the deployment phase and to avoid the line of swing of the SADA.

The device must also be able to completely incinerate upon reentry of Earth's atmosphere. The damage from a CubeSat falling at great heights could be severe. Since most of the CubeSat will be made from Aluminum which has a sufficiently low melting point of about 1200 degrees, it would not survive reentry.

In terms of maintenance, the system will not be serviceable since it is not feasible to do any sort of repairs in space.

3.4 *Remaining Concerns*

One remaining concern is the accuracy of the photodiodes used for the sun sensing aspect of the SADA. While they were the only practical choice to use for this subsystem, they are known to be relatively inaccurate. Our design specification aims for a bilateral tolerance of 5 degrees which we foresee being achievable, though this is only a prediction until the system is fabricated and tested. The amount of solar energy harnessed is proportional to the cosine of the angle between the solar panel's normal vector and the angle of sunlight, so the difference between 0-degree variation and 10 degree variation is less than a 2 percent efficiency drop; therefore, it should not represent an impact to the usability of the system.

4 Manufacturing Plan

The following manufacturing plan goes into detail on the procurement of all materials needed as well as our plan to manufacture the design prototype. A list of the materials we will need to construct our final prototype is specified in the Indented Bill of Materials, iBOM, shown in Appendix A. We have divided up the plan for manufacturing into two of our major mechanisms: the hinge mechanism and the sun tracking device. We then delve into the steps needed to assemble the components into our final design prototype.

4.1 PROCUREMENT

Due to this project being used on future CubeSat missions, many of the parts must be extremely small. This, along with the stringent requirements of the space industry, has led to the need for custom parts instead of off the shelf. The main custom parts we will be machining are the hinge, the bracket to connect the solar panels, and the turn table to transfer the rotational motion of the motor to the hinge. All these parts will be manufactured out of 6061-T6 Aluminum for its high specific strength and low melting point. Along with these three manufactured components, we will be designing custom PCBs for use in sun tracking data collection. These PCBs will be outsourced to a 3rd party manufacturer, and everything else will be manufactured in-house on the lathe, manual mill, and CNC where applicable.

4.2 MANUFACTURING

Our design has 2 subsystems that we must manufacture: The solar array hinge and sun tracking devices. Each subsystem has 3 components that we must purchase, modify, manufacture, and assemble. Below is a breakdown of each subsystem and its components along with our manufacturing plan listed in Appendix F.

Hinge subsystem

Base of Hinge

The base of the hinge is what attaches to the outside of the CubeSat device. The other components of the hinge will be attached to the base of the hinge. The base will be made of Aluminum 6061-T6 and will be manufactured on a CNC mill by Protolabs.

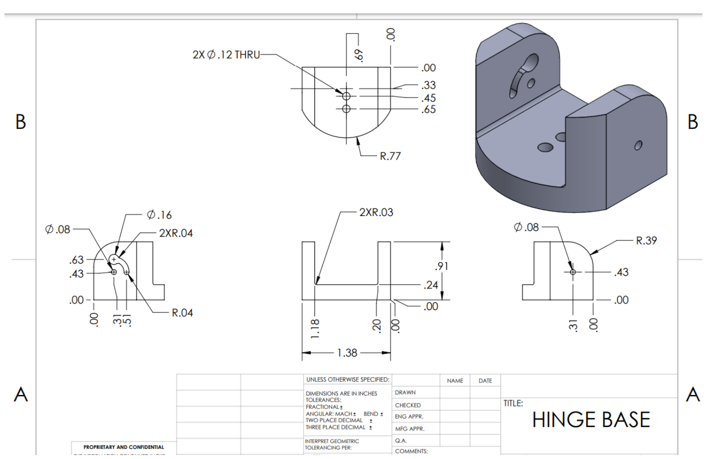


Figure 10 – Technical drawings base of hinge

Hinge Plunger

The plunger that is used on the hinge will all be manufactured on the lathe and made of Aluminum 6061-T6.

1. Acquire 3 separate bar stock.
    a. 0.25 inch diameter – Plunger shaft.
    b. 0.50 inch diameter – Plunger button.
    c. 0.50 inch diameter – Plunger button and shaft mate.
2. Starting with the plunger shaft stock, simply cut the stock to length 0.25 in, set aside.

    a. Use a deburring tool to clean up the edges of the cut.
3. Tap both sides of the shaft to 0.25 in with a #6 tap.
4. Now, take the plunger button stock and place in the chuck of the lathe.
5. Face down the stock, so that the overall length of the piece is 0.50 in.
6. Now, turn 0.40 in of the stock to a diameter of 0.20 in.
    a. Remove the piece and debur all edges.
7. Use an external tap tool to tap the length of the shaft with a #4 tap.
8. Now, take the stock for the plunger button and shaft mate and face the part down to 0.25 in.
9. Next, turn down the diameter of the shaft to 0.35 in for 0.1 in of the shaft.
    a. Now, remove the part and debur all edges.
10. Tap drill an #4 hole on the face with the smaller diameter.
11. Tap drill an #6 hole on the face with the larger diameter.

Top of Hinge

The top of the hinge is what the solar arrays are mounted on. The hinge plunger connects the base of the hinge to the top of the hinge. This part will also be made of Aluminum 6061-T6 and manufactured on a CNC mill by Protolabs.

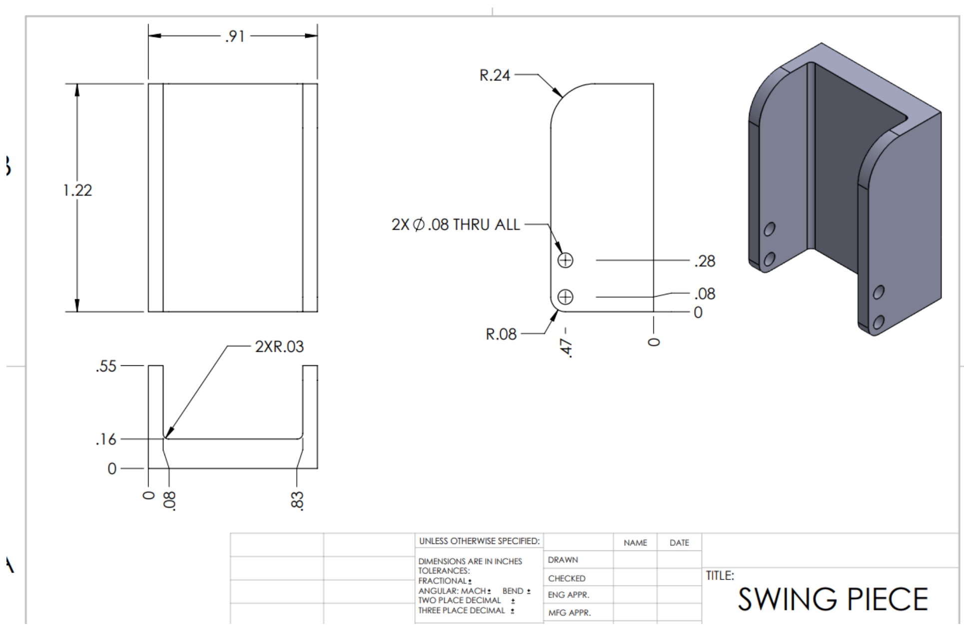


Figure 11 – Technical drawings top of hinge

Sun Tracking Subsystem

Motor

We will purchase our motors from Amazon.

Turn Table

The turn table will connect the hinge and motor, while still allowing axial rotation. It will be made of Aluminum 6061-T6 and manufactured on a lathe and drill press.

1. Acquire 0.5625” round Aluminum bar
2. Cut the length of the bar to 0.41”
3. Turn bar until a diameter of 0.55” is reached
4. Mark 0.12” from the end of the bar, turn the remaining 0.28” until it reaches a diameter of 0.31”
5. Drill press 2 holes of diameter 0.12”, each hole 0.1” away from the centerline

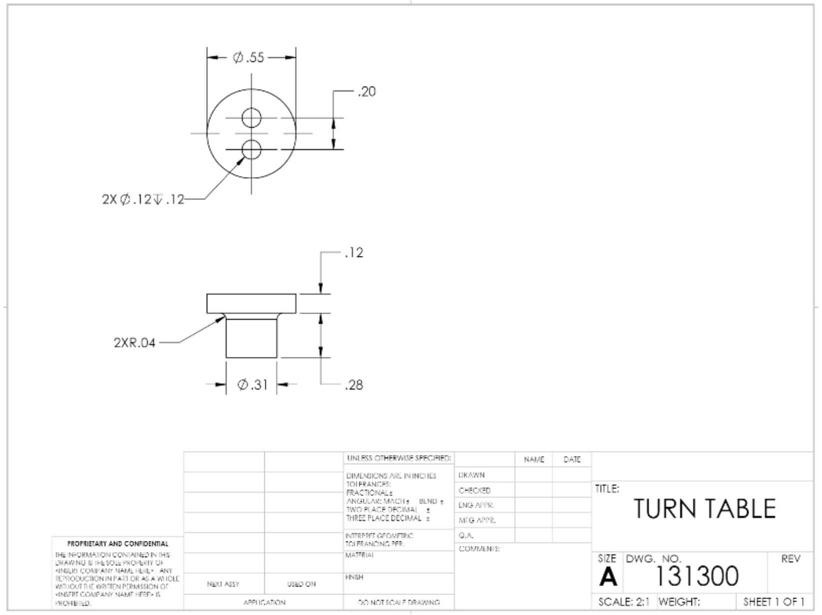


Figure 12 – Technical drawing of turn table

PCB

All custom PCBs will be outsourced to a PCB manufacturing company. Long lead times are expected, so early design and finalization of these parts is of the upmost importance. Each board will have multiples of it purchased to help alleviate any potential manufacturing or user error issues.

4.3 ASSEMBLY

Our assembly will include putting together our hinge mechanism and attaching the hinge and turn table to our sun tracking electronics. Below is a drawing of our hinge assembly. In addition to assembling the hinge components, there will be a torsional spring that will be stick welded to part number (3) in Figure 12. The hinge will attach to the CubeSat device through the base (1). The solar array panels will be attached on the top of the hinge (4). Once the hinge is assembled, we will attach the turn table in between the motor and the hinge to connect each of those parts. The motor will be attached to our sun tracking electronics.

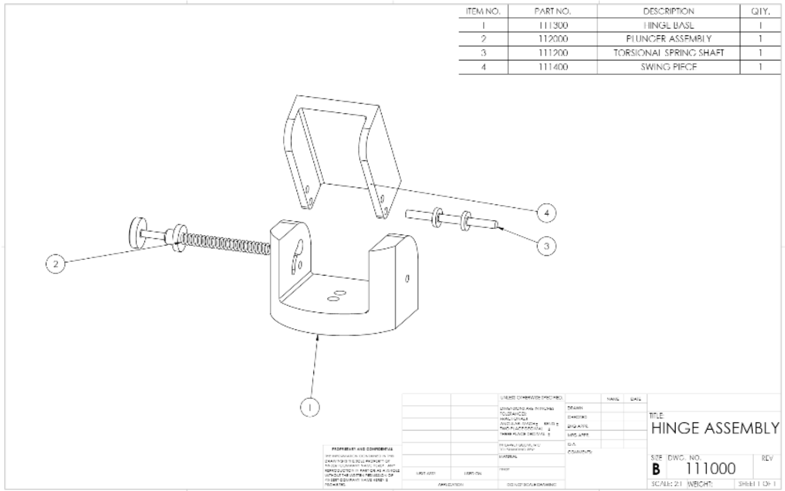


Figure 13 – Assembly of hinge

5 Design Verification Plan

Our first and second specifications for vibe testing and thermal cycling are based on the need for the system to survive in the vacuum of space. While these requirements are very important for a space worthy system, given the nature of our prototype and the focus on testing the other features, we have yet to determine whether we will get to vibe and thermal tests. While these things might not get tested, each subsystem has been designed to satisfy these requirements and tests would be conducted in the Cal Poly Aero lab that contains a TVAC chamber.

Our third specification is a maximum mass of 0.60 kg. This specification is very straightforward when confirming whether it is passed simply by placing the SADA system on a scale and measuring the weight of the system. The result of this test will simply either be a pass or a fail, based upon the mass of the system. This test will not require any special facility and the only equipment required is a scale with precise measurement, which will be determined later. This should take no longer than 15 minutes to conduct.

Our next specification requires the system to be passively retained during its time on the launch vehicle. This means that the solar arrays will not deploy during the deployment state where there is no power. This will be tested with two separate tests. The first test will require the fishing line to be wrapped around the solar arrays, ensuring whether the fishing line will be able to keep the arrays in stowed position even while the spring tries to open the arrays. There is no measurement taken with this test, it is purely based on visual assessment. The next way in which the passive retainment system is tested is with the heating up of the nichrome wire to burn the fishing line. This will also require the fishing line to be wrapped around the arrays and then the nichrome will have current run through it by a power supply to test the current and voltage needed to burn different gauges of fishing line. No special facility will be required but it will require a power supply and a fire extinguisher for safety. We have already conducted both tests on the structural prototype and each test took under 20 minutes to conduct; however, for the verification prototype, we plan to take longer for each test, ensuring accuracy. Furthermore, we will be testing having the fishing line hold the system in its closed position for a long period of time, simulating what would happen after the CubeSat has been handed off to the launch provider.

Our sixth specification states that the system will use a max of 100 milliwatts. This will be done by attaching the entire system to a DAQ and measuring the power usage of each of the subsystems under max power draw. The test will not require any special facility but will require a DAQ. The test is being allocated two hours to conduct to test the system under various conditions, testing for strange power occurrences.

Even though the system will only need to deploy once in space, we want to ensure the reliability of the system, so our seventh specification states that the system will be able to cycle 50 times without breaking. Most focus will be placed on the hinge durability within the deployment subsystem. Since this is a completely new design it is the most likely to fail within our system. The test will require not special facility but will require a power supply. The system will need to cycle 50 times without failing and after each of these tests, visual inspection will be done to check for cracks or other noticeable damage. We are allocating 3 hours to test these 50 cycles.

The eighth specification limits the volume of the system to 250 cm^3. This is based upon the constraints of overall CubeSat volume. James will oversee this requirement. Any volume of 250 cm^3 or less will pass this requirement. No special equipment or facilities will be required for this test, simply an engineering scale. The test should take only 30 minutes to conduct.

A table explaining all the tests, who oversees each test, and the planned dates for them can be found in Appendix G.

6 Conclusion

Our critical design review has thoroughly examined the various aspects of the design, including the materials, manufacturing, and the mechanical and electrical systems. Through the application of our best engineering practices, and the use of precision-made components, we are confident in the ability of our deployable solar array drive assembly to meet or exceed the project requirements.

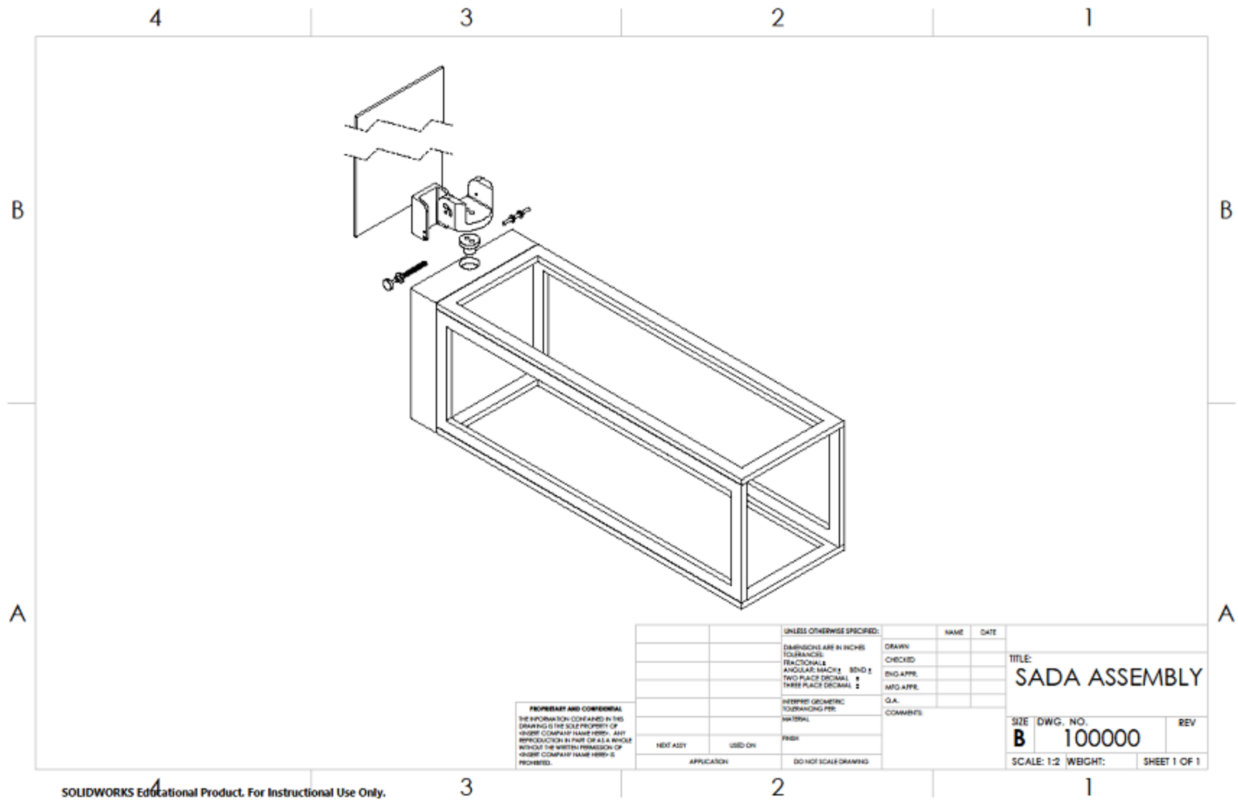
Furthermore, the feedback we received from our peers in our senior design project class after our first couple of project presentations has been valuable in guiding further development and improvement of our design. The team will continue to work diligently to ensure that the final design is robust, reliable, and able to meet the demanding requirements of outer space travel. We are excited to continue to progress towards the completion of this project and to see the positive impact that it will have on the future of small-sat space missions.

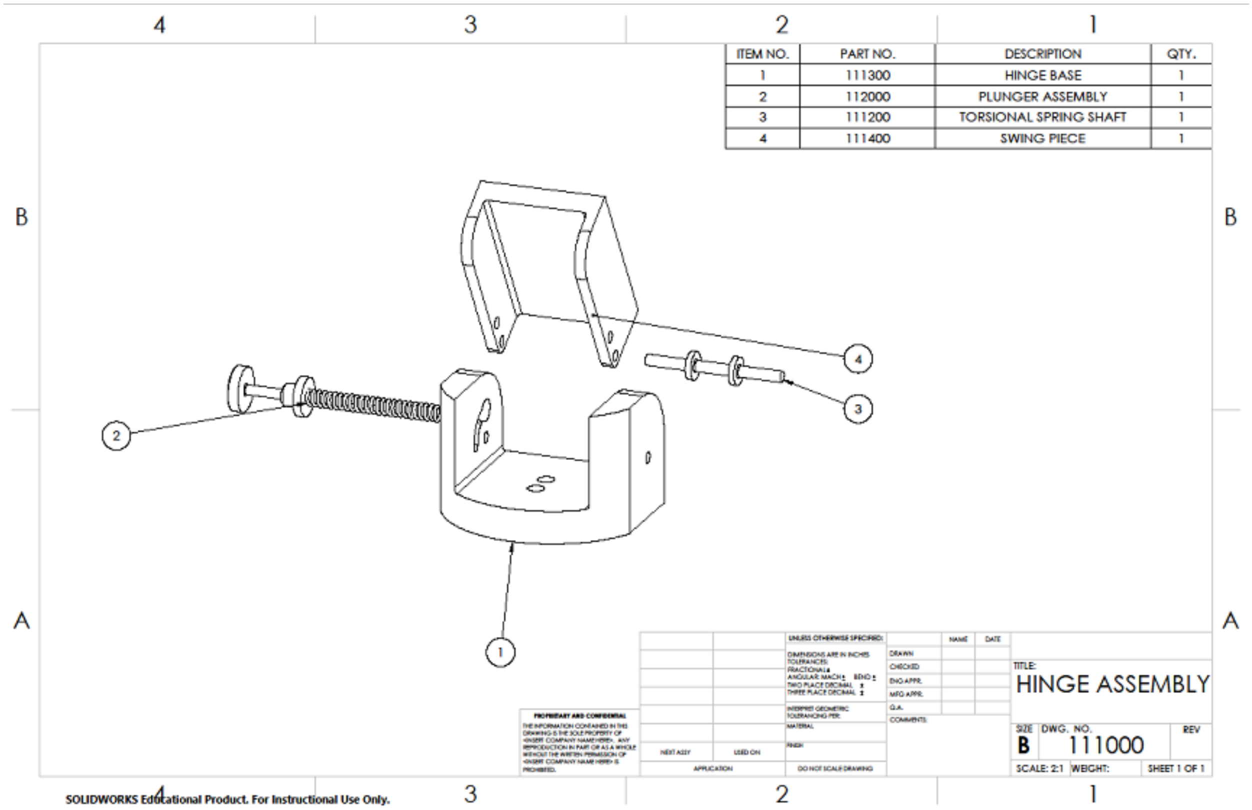
The next key steps are summarized in our Gantt chart, located in Appendix H, which are to continue with the purchasing of the materials and equipment needed for the building and testing of design prototypes. This will be done in the next couple of weeks. Risk assessment and the actual manufacturing of the protypes will occur in the coming weeks and then the testing procedures will be written following that. We hope to gain some insight or feedback from the reader that they feel will help us navigate effectively in the final half of this design project. Thank you for your time.

APPENDICES

APPENDIX A – INDENTED BILL OF MATERIALS (IBOM)

Assy Level	Part Number	Name					Qty	Part Cost	Source	URL	More Info
		Lvl0	*Lvl1*	*Lvl2*	*Lvl3*	*Lvl4*					
0	100000	SADA							------		
1	110000		Deployment Subsystem						------		
2	111000			Hinge assembly			1		Custom	https://www.	Purchased for initial
3	111100				Torsion spring		2	$ 7.00	McMaster	https://www.	
3	111200				Compression spring		2	$ 5.00	McMaster		
3	111300				Shaft		2	$ 5.00	Custom		
3	111400				Hinge Base		2	$ 15.00	Custom		
3	111500				Screws		5	$ 5.00	McMaster		
1	120000		Passive retainment assembly				1		------		
2	121000			Burn wire assembly			1		------		
3	121100				Nichrome		6in	$ 8.00	Amazon	https://www.	
3	121200				Fishing line		1ft	$ 10.00	Amazon	https://www.	
3	121300				Burn wire dev board		1	$ 50.00	Amazon		
3	121400				Screws		5	$ 5.00	Custom		
1	130000		Sun Tracking Assembly				2		------		
2	131000			Articulation Assembly			1		------		
3	131100				Stepper motor		1	$ 10.00	Amazon	https://www.	
3	131200				Stepper driver board		1	$ 5.00	Amazon	https://www.	
3	131300				Turn table		1	$ 6.00	Custom		
3	131400				Set screws		2	$ 6.00	Amazon		
3	131500				Shaft coupler		1	$ 10.00	Custom		
3	131600				Solar array bracket		1	$50.00	Custom		
2	132000			Sun Sensing Assembly			2		------		
3	132100				Solar cells		1		Amazon		
3	132200				Photodiodes		4	$10.00	Amazon		
1	140000		Electrical				1		------		
2	141000			Raspberry Pi Pico			1	$ 14.00	Amazon	https://www.	
2	142000			Usb mini cable			1	$ 6.00	Amazon	https://www.	
2	143000			Screws			5	$ 2.00	Amazon		
	Total Parts						**47**	**$229.00**			





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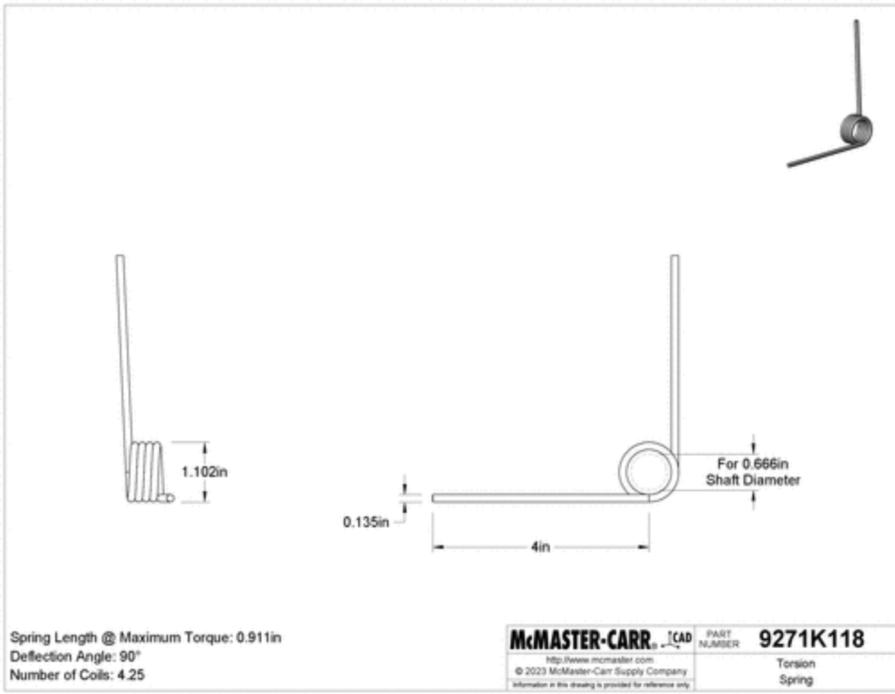
3	111200	TORSIONAL SPRING SHAFT	1
4	111400	SWING PIECE	1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For 0.666in
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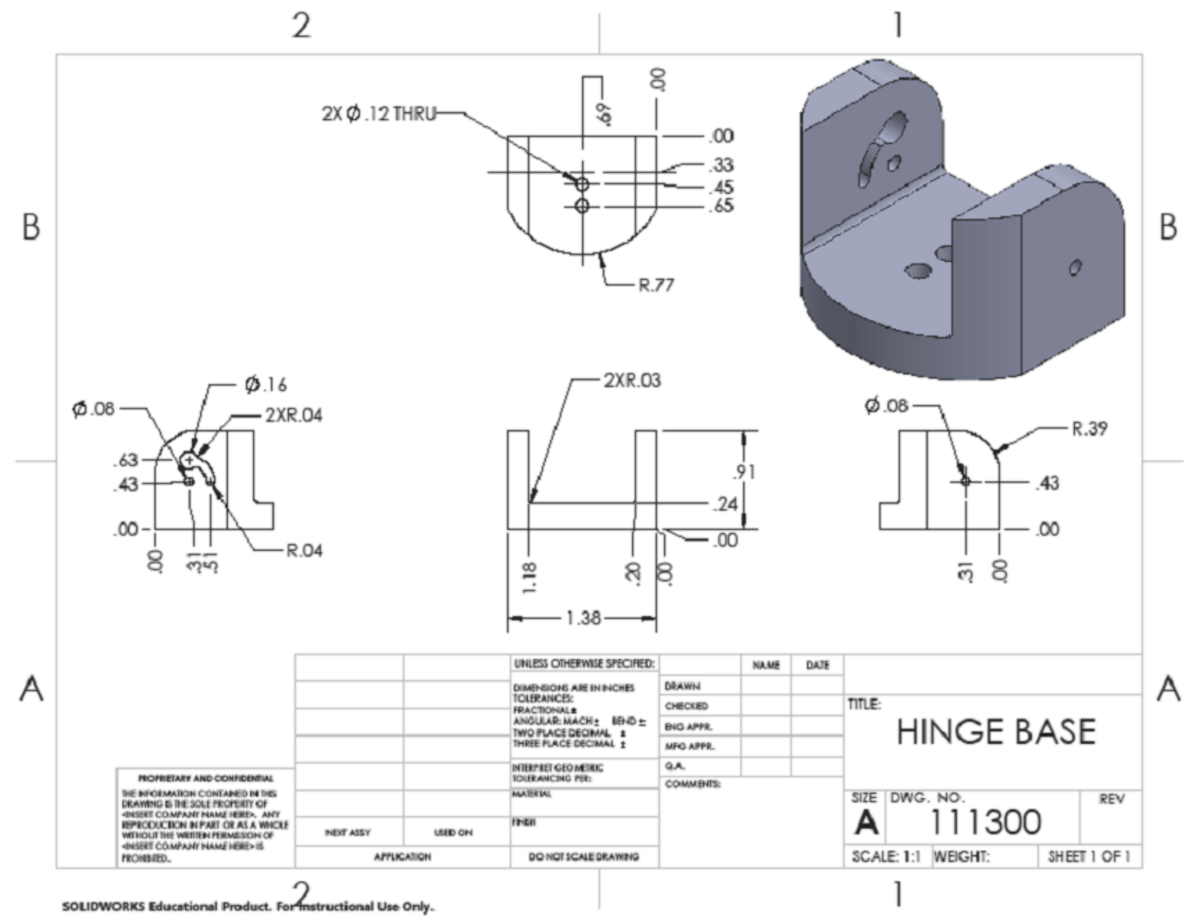
Spring Length @ Maximum Torque: 0.911in
Deflection Angle: 90°
Number of Coils: 4.25
McMASTER-CARR
PART NUMBER
9271K118
http://www.mcmaster.com
© 2023 McMaster-Carr Supply Company
Torsion
Spring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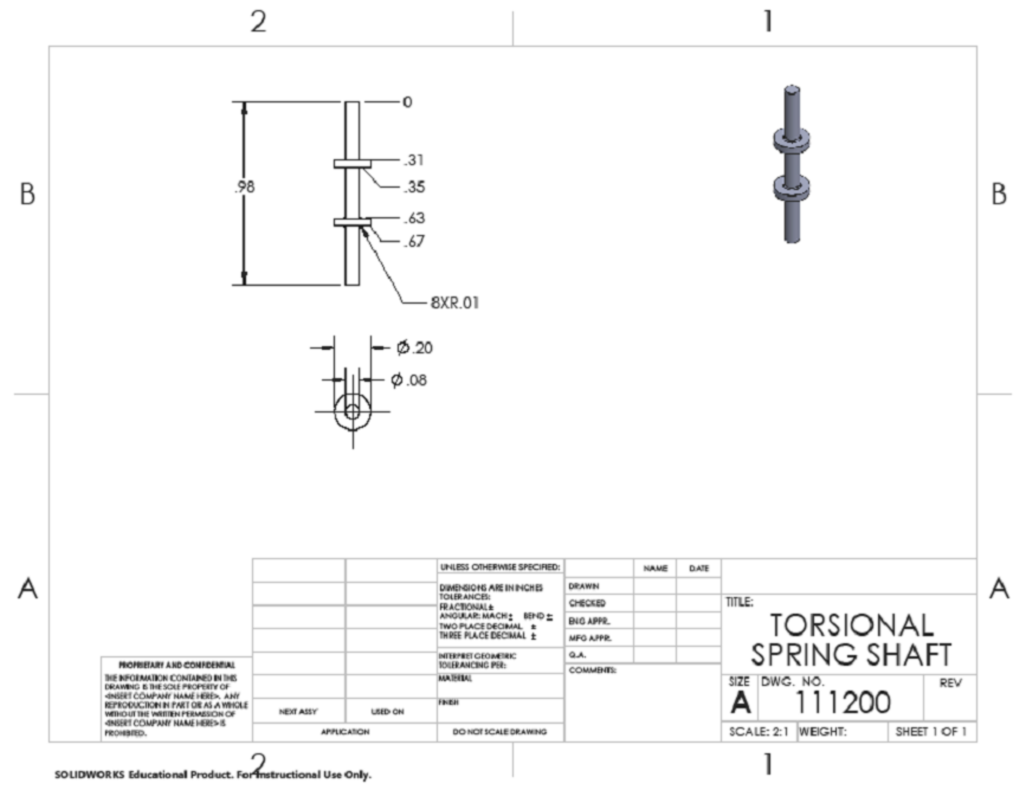
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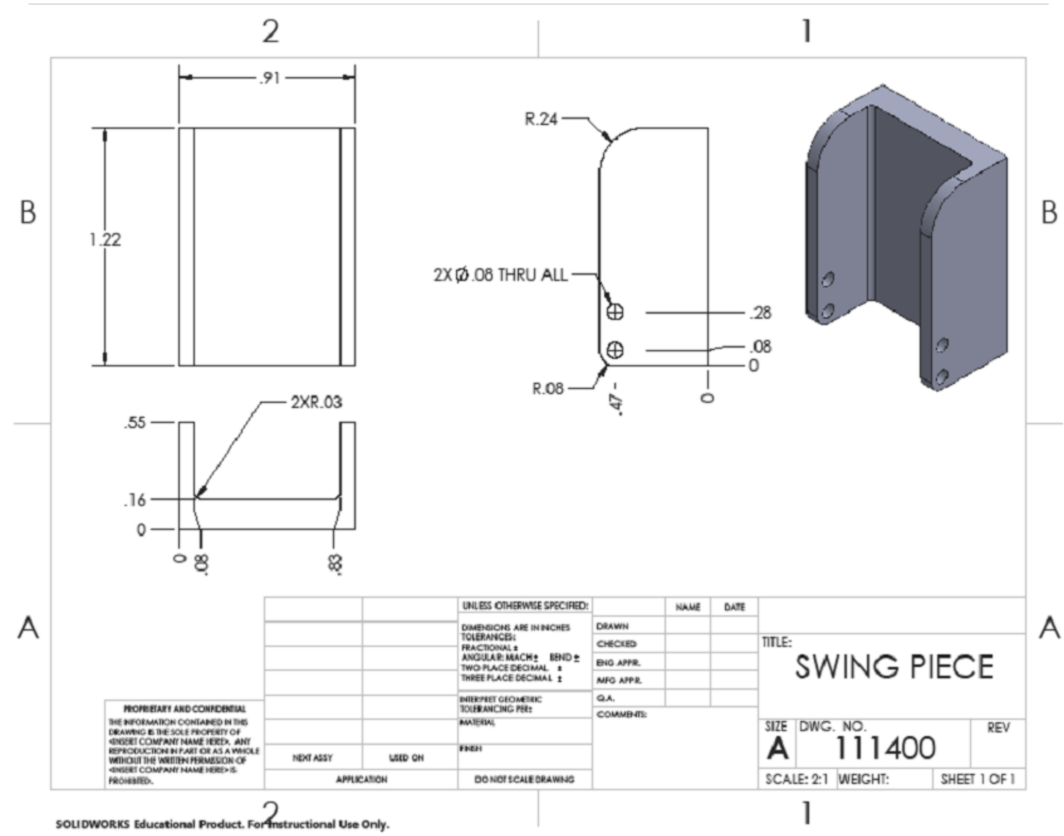
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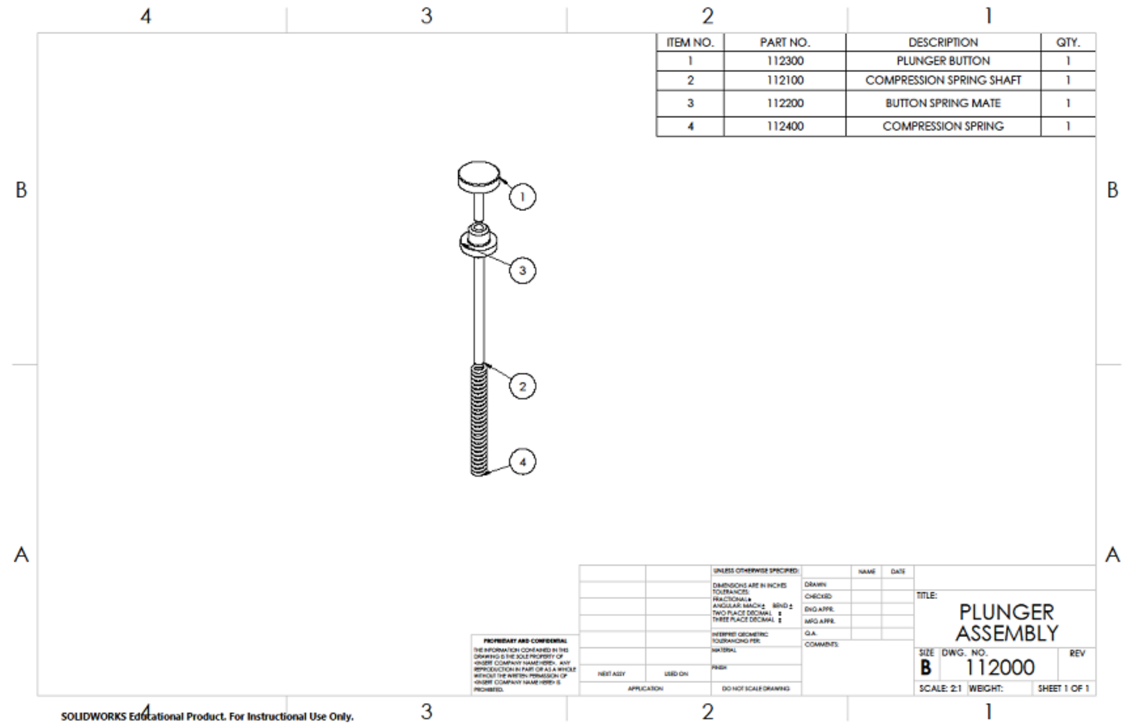
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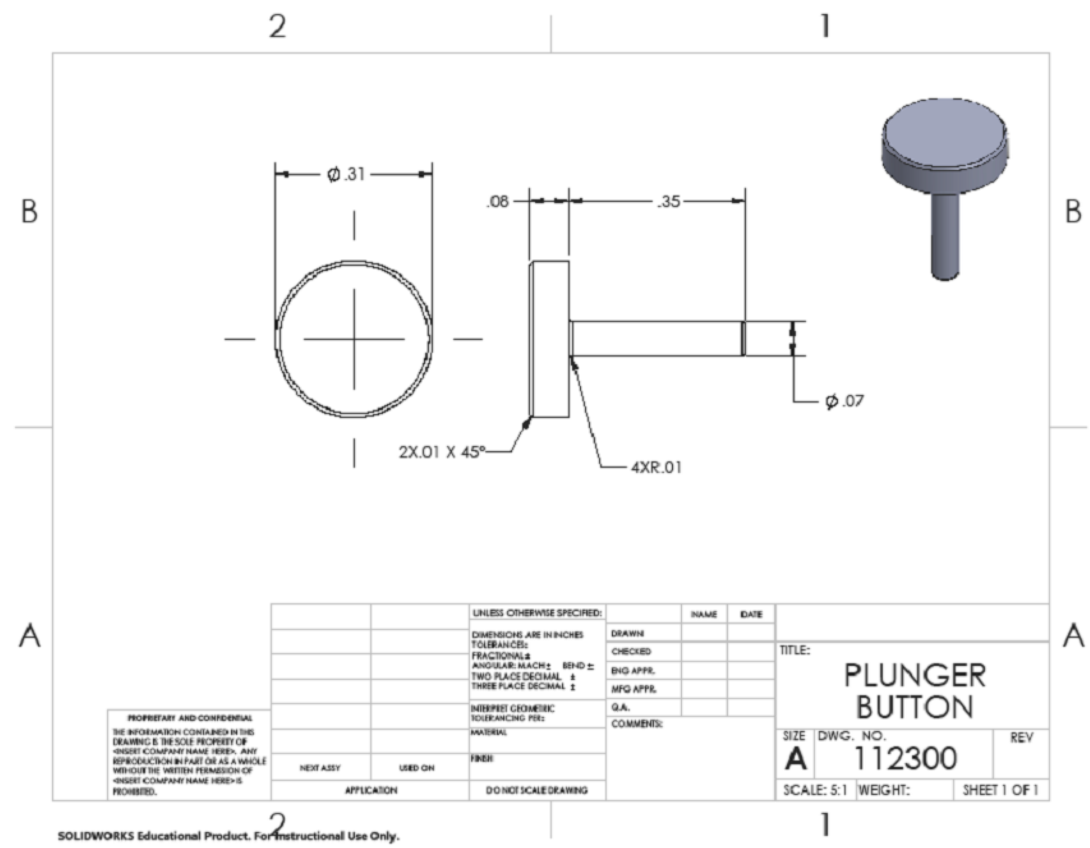
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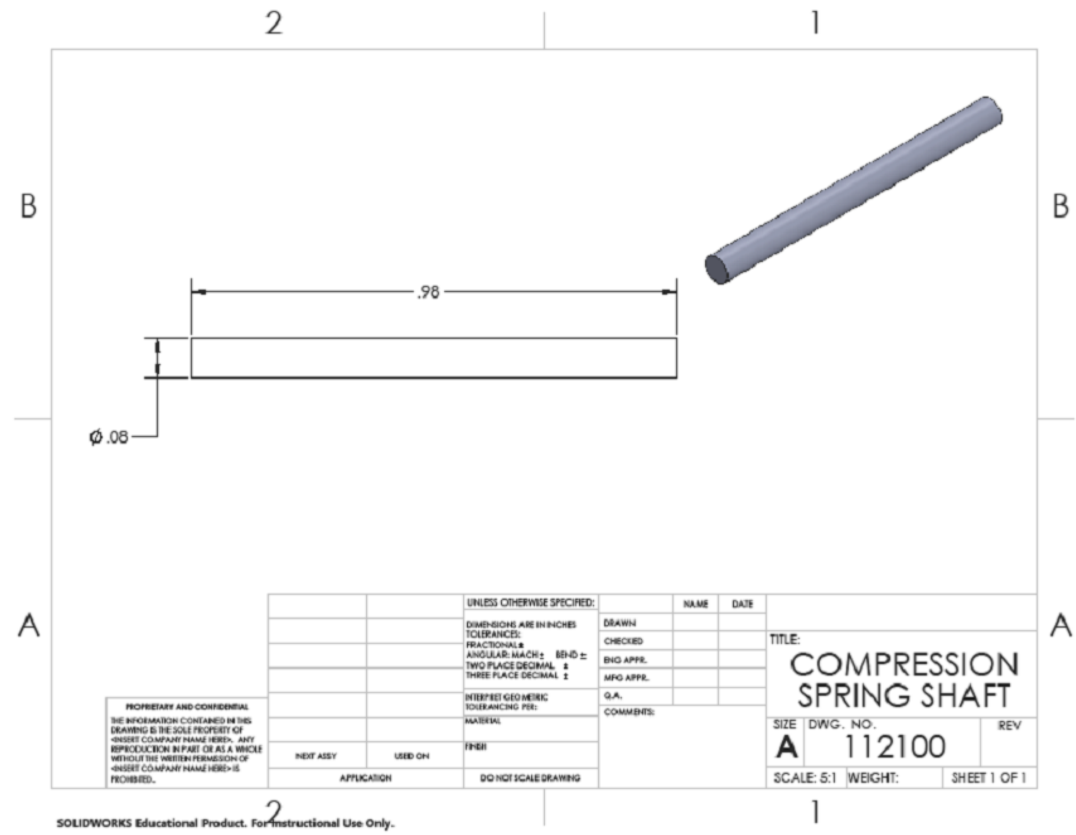
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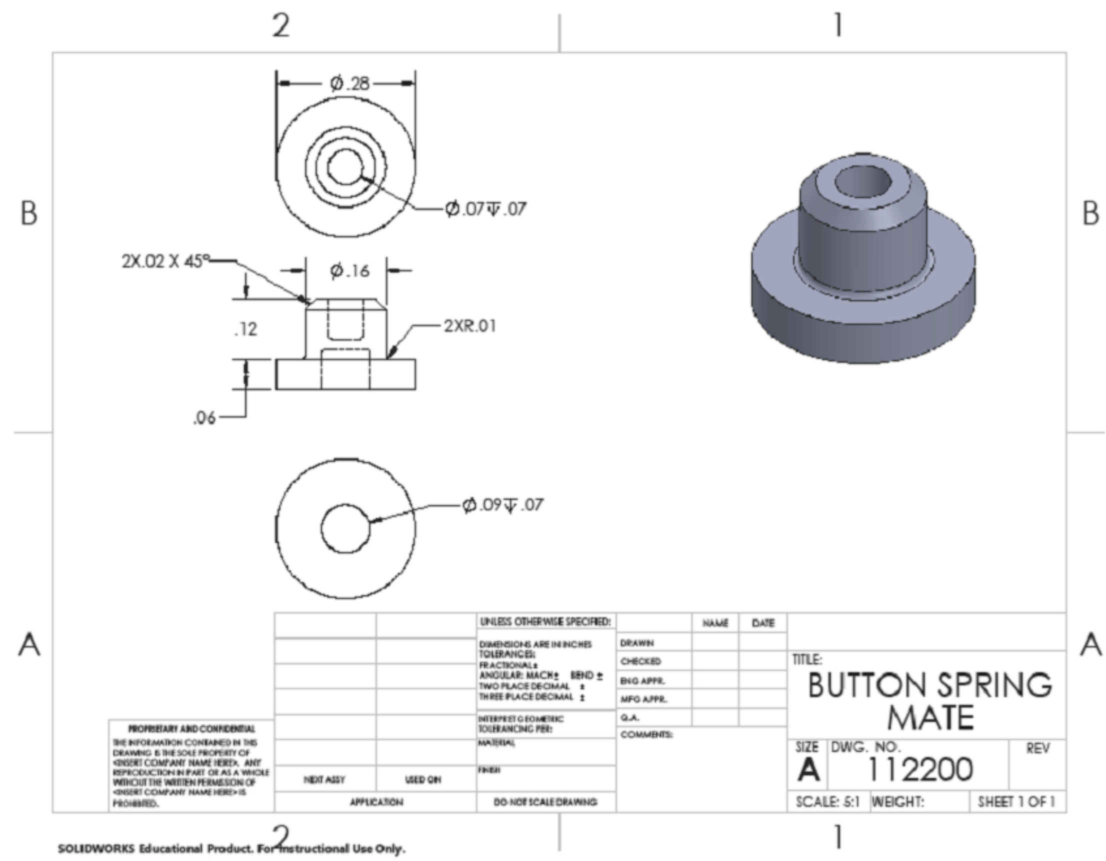
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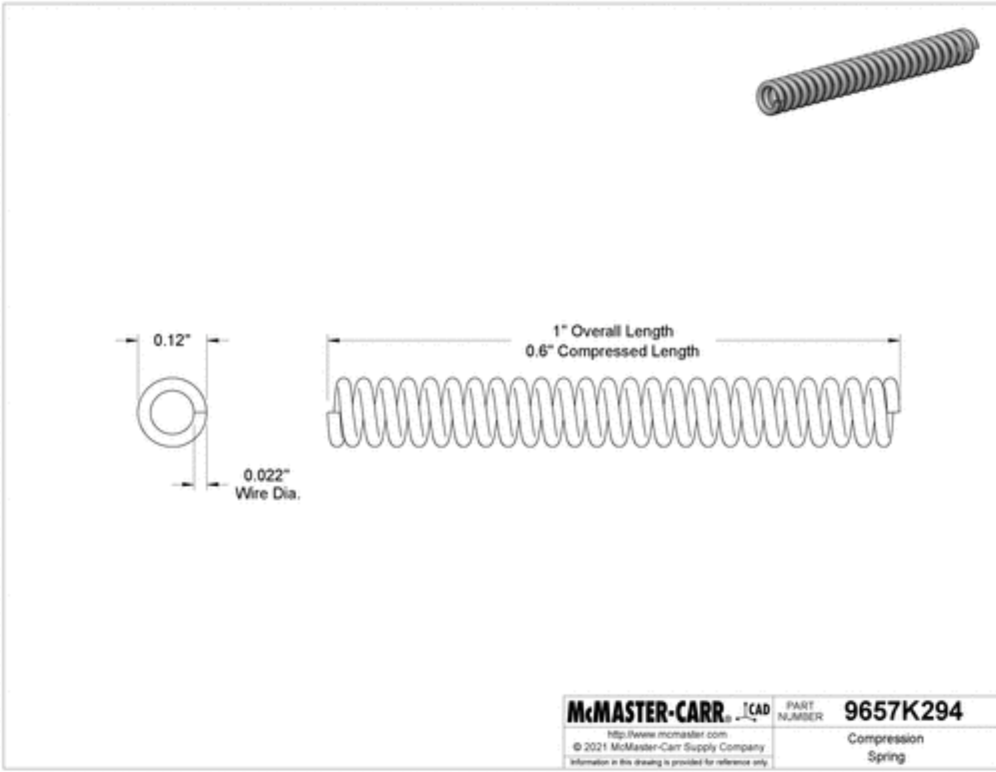

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Wire Dia.
McMASTER-CARR
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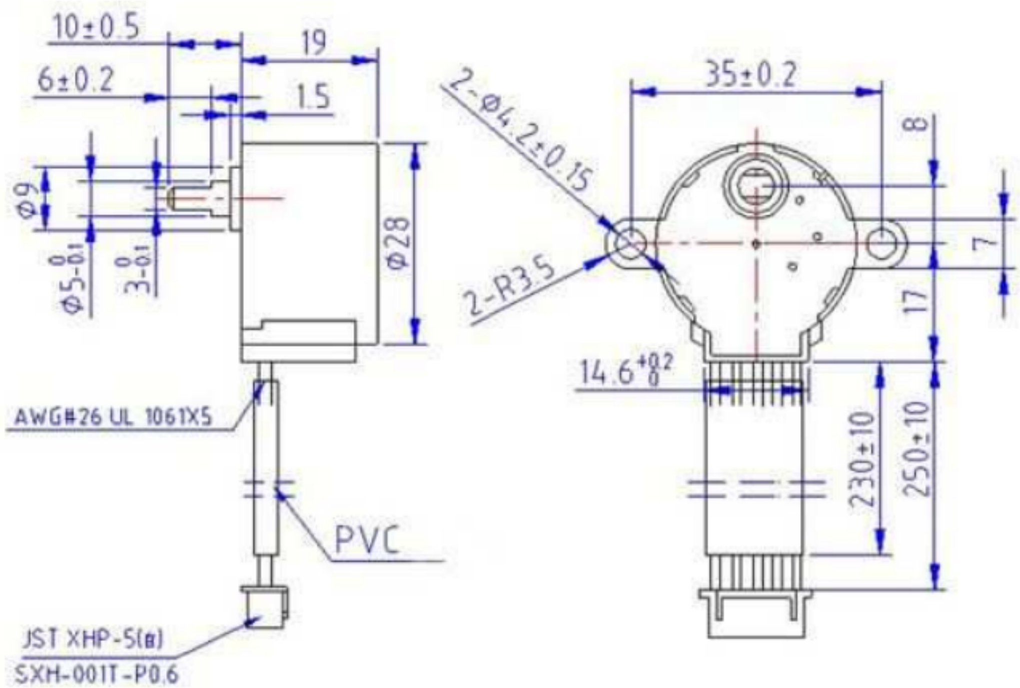
http://www.mcmaster.com
© 2021 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Compression
Spring



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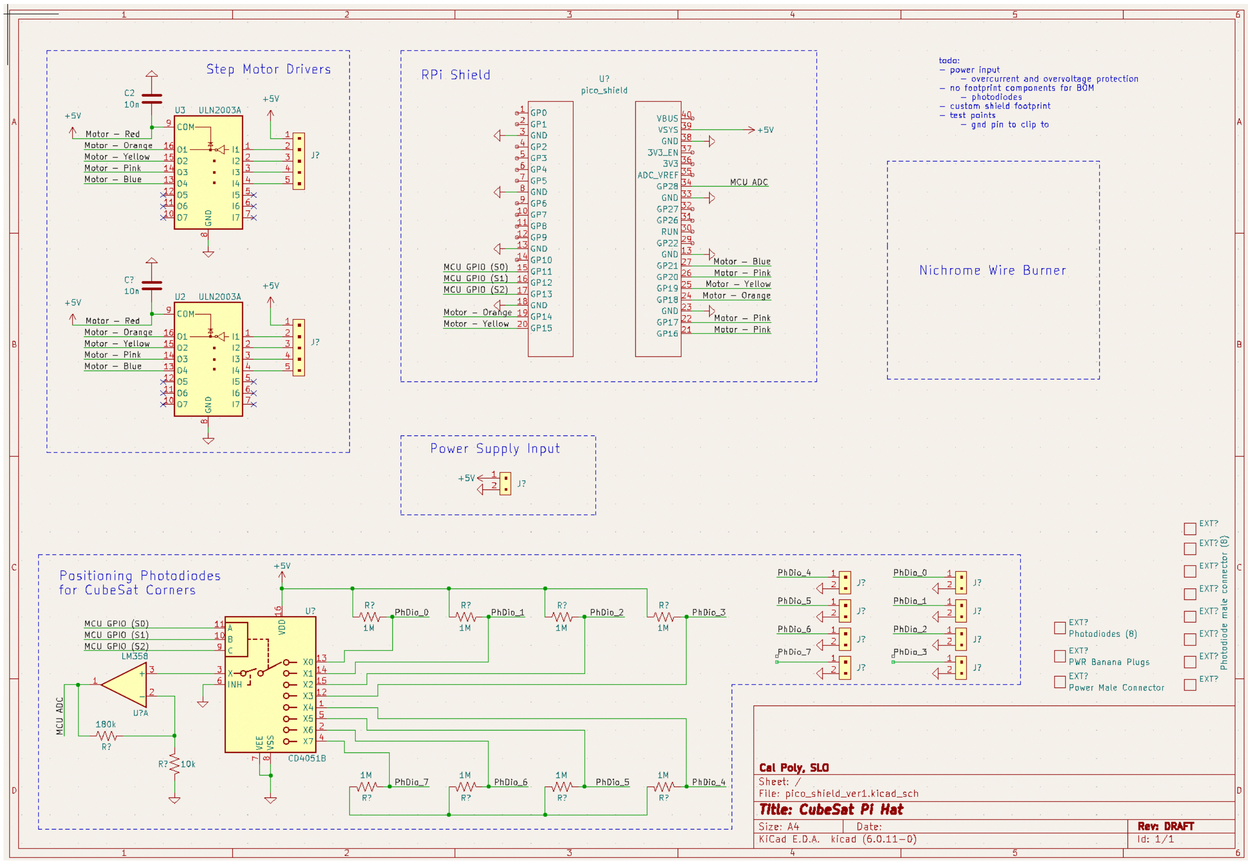

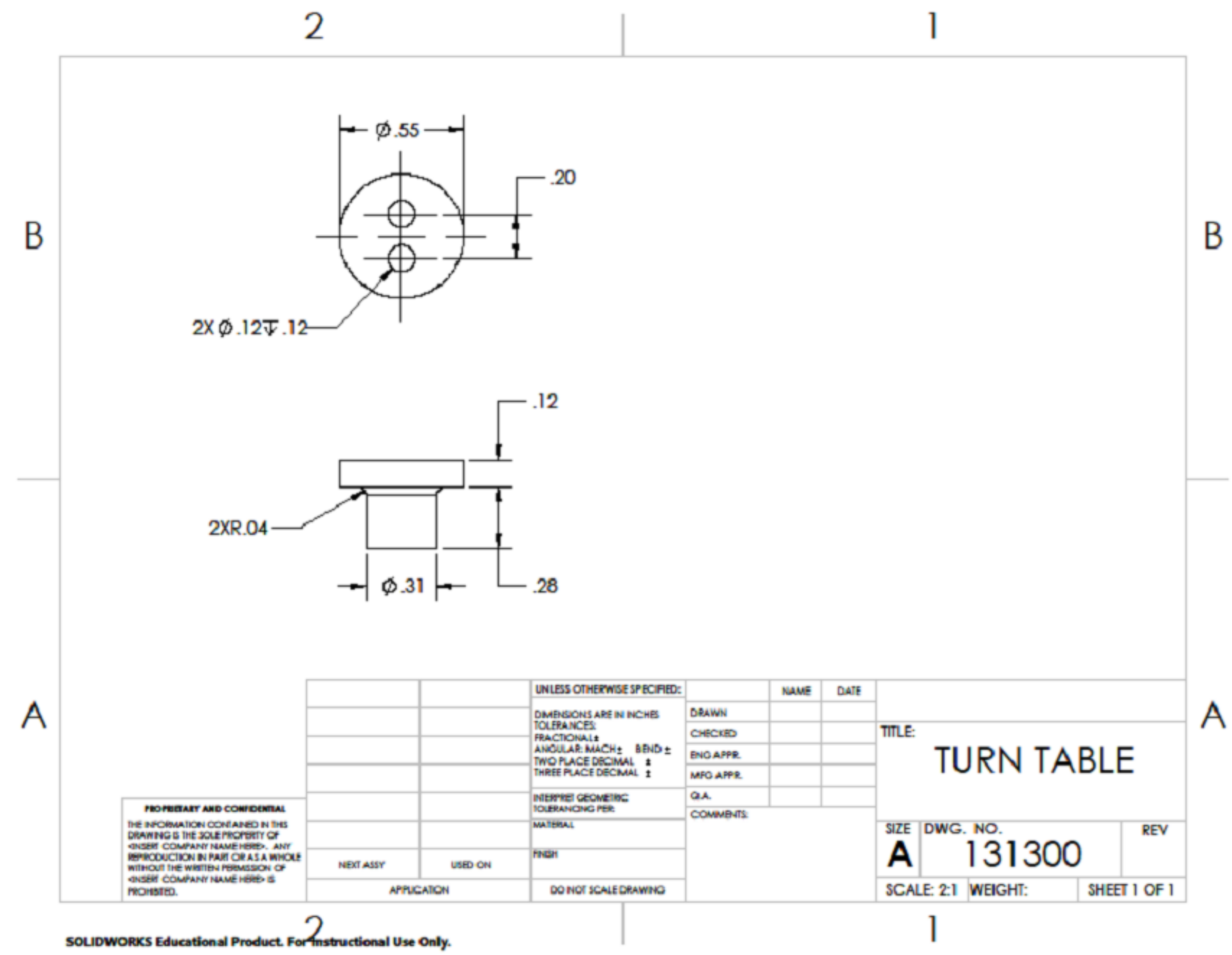

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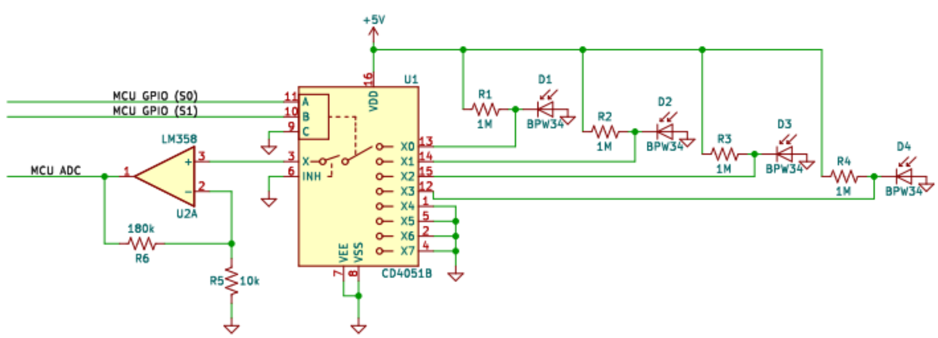

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MCU ADC
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U2A
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R6
R5
10k
VDD
VEE
VSS
INH
X0
X1
X2
X3
X4
X5
X6
X7
CD4051B
R1
1M
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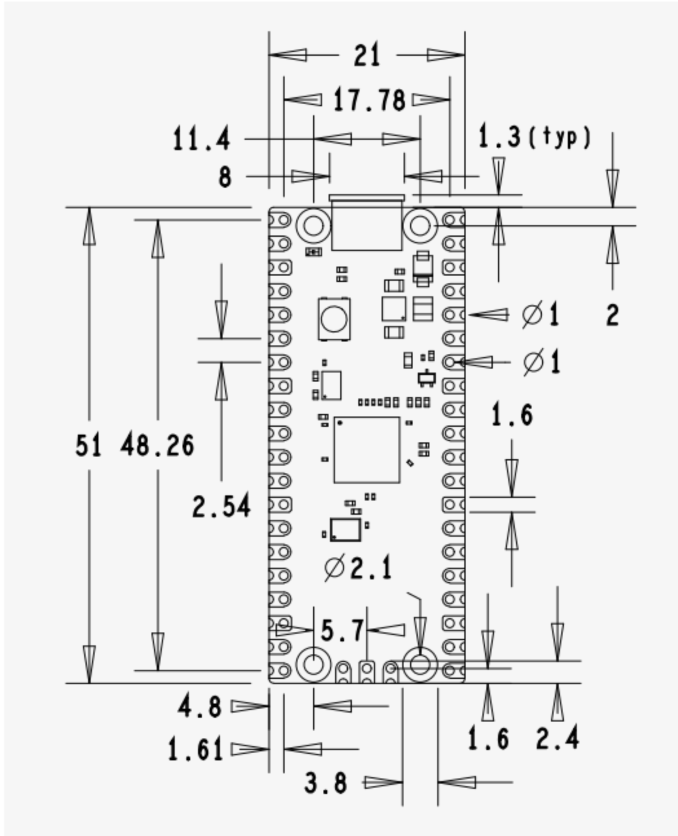
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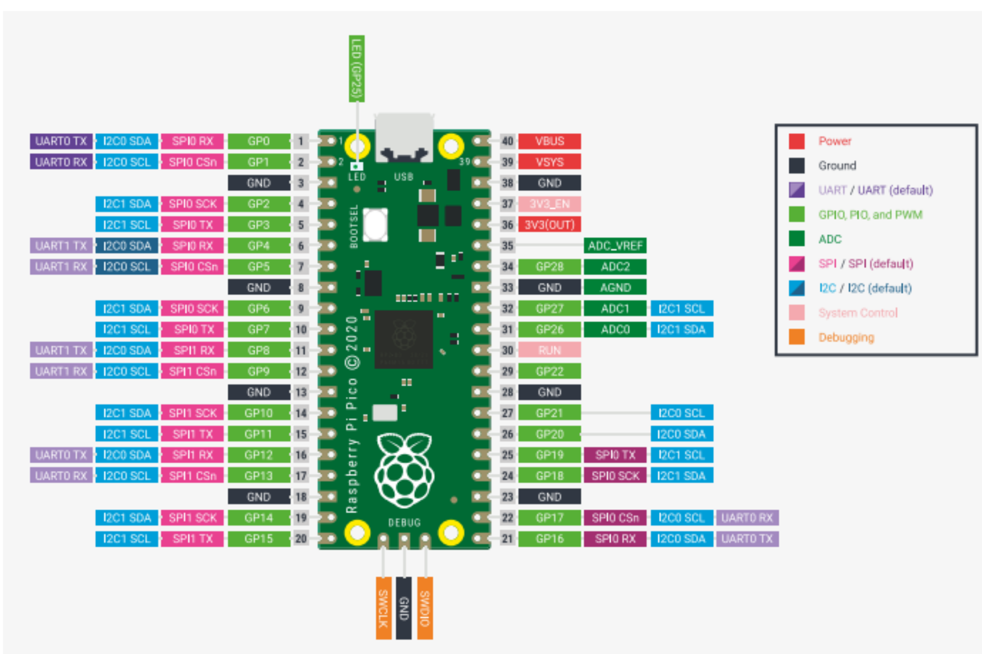
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USB
BOOTSEL
Raspberry Pi Pico ©2020
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GND 3
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I2C1 SCL SPI0 TX GP3 5
UART1 TX I2C0 SDA SPI0 RX GP4 6
UART1 RX I2C0 SCL SPI0 CSn GP5 7
GND 8
I2C1 SDA SPI0 SCK GP6 9
I2C1 SCL SPI0 TX GP7 10
UART1 TX I2C0 SDA SPI1 RX GP8 11
UART1 RX I2C0 SCL SPI1 CSn GP9 12
GND 13
I2C1 SDA SPI1 SCK GP10 14
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I2C1 SCL SPI1 TX GP15 20
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39 VSYS
38 GND
37 3V3_EN
36 3V3(OUT)
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34 GP28 ADC2
33 GND AGND
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29 GP22
28 GND
27 GP21 I2C0 SCL
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25 GP19 SPI0 TX I2C1 SCL
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GND
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Ground
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GPIO, PIO, and PWM
ADC
SPI / SPI (default)
I2C / I2C (default)
System Control
Debugging

APPENDIX B – PURCHASED PARTS & BUDGET

Purchased Parts

Date Purchased	Vendor	Part Number	Description of Items Purchased	Item Cost	Shipping and Tax	Transaction amount
01/26/23	Amazon	-	Folding self-locking door bracket	14	3	$ 17.00
01/26/23	McMaster	111100	Torsion Springs	7	3	$10.00
01/26/23	Amazon	121200	Fishing Line	10	3	$13.00
01/26/23	Amazon	121000	Nichrome Burn Wire	8	3	$ 11.00
01/26/23	Amazon	141000	Raspberry Pi Pico	14	3	$ 17.00
01/26/23	Amazon	142000	USB micro-Cable	6	3	$9.00
01/26/23	Amazon	131100	Stepper Motor	10	3	$13.00

Project Budget Details

Total Estimated Cost	$1,284
Budget	$3,500
Current Expenses	$88
Remaining Balance	$3,412

Planned and Already Purchased Parts

Item Description	Quantity	Vendor	iBOM Part Number	Total Cost [$]	How puchased	Date Purchased
Torsion Spring	4	McMaster	111100	7	Team Reimbursement	1/26/2023
Nichrome	6"	Amazon	121100	8	Team Reimbursement	1/26/2023
Fishing Line	1'	Amazon	121200	10	Team Reimbursement	1/26/2023
Stepper Motor	1	Amazon	131100	10	Team Reimbursement	1/26/2023
Photodiodes	4	Amazon	132200	10	Team Reimbursement	1/26/2023
Raspberry Pi Pico	1	Amazon	141000	17	Team Reimbursement	1/26/2023
USB Mini Cable	1	Amazon	142000	9	Team Reimbursement	1/26/2023
Self-Locking Door Bracket	2	Amazon	-	17	Team Reimbursement	1/26/2023
Screws (Custom)	5	Protolabs	121400	5	Team Reimbursement	Planned
Stepper Driver Board	5	Amazon	131200	5	Team Reimbursement	Planned
Al 6061-T6 9/16" Stock	2	Grainger	131300	40	Team Reimbursement	Planned
Al 6061-T6 1/4" Stock	2	Grainger	111300	40	Team Reimbursement	Planned
Al 6061-T6 1/2" Stock	4	GetMetals	111300	40	Team Reimbursement	Planned
Compression Spring	4	McMaster	111200	5	Team Reimbursement	Planned
Set Screws	2	Amazon	131400	6	Team Reimbursement	Planned
Shaft Coupler (Custom)	1	Protolabs	131500	10	Team Reimbursement	Planned
Solar Array Bracket (Custom)	1	Protolabs	131600	50	Team Reimbursement	Planned
Shaft (Custom Part)	2	Protolabs	111300	5	Team Reimbursement	Planned
Hinge Base (Custom Part)	2	Protolabs	111400	15	Team Reimbursement	Planned
Screws (Deployment)	10	McMaster	111500	5	Team Reimbursement	Planned
Solar Cells	1	Amazon	132100	50	Team Reimbursement	Planned
Photodiode Breakout Board	2	Oshpark	130000	40	Team Reimbursement	Planned
SADA Shield	1	Oshpark	130000	50	Team Reimbursement	Planned
3D Printer	1	Undecided	-	800	Team Reimbursement	Planned
PLA Filament	1 Spool	Amazon	-	30	Team Reimbursement	Planned

W23	JUCI TEAM	ME 429 - 04	PRELIMINARY CALC.: TORSION SPRING	1

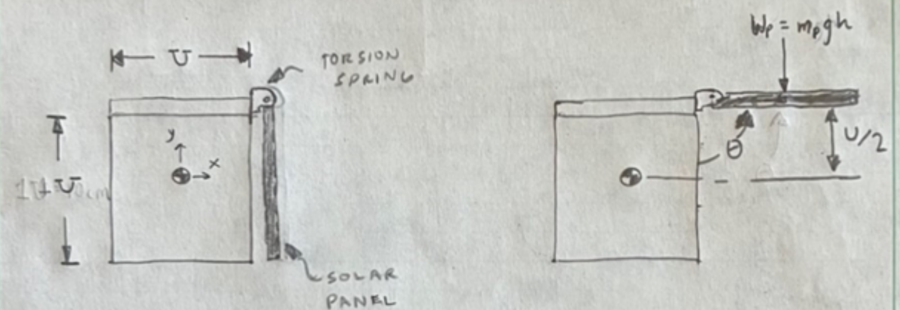
OBJECTIVE: APPROXIMATE THE SPRING CONSTANT FOR THE TORSIONAL SPRING TO BE USED IN OUR SPRING-HINGE DEPLOYMENT SUBSYSTEM.

KNOWNS:
- WEIGHT OF SOLAR PANELS
- DIMENSIONS OF CUBESAT BUS
- MOTION FROM STOWED CONFIGURATION TO FULLY DEPLOYED CONFIGURATION

SCHEMATIC

STATE 1: STOWED CONFIGURATION

STATE 2: ACTIVE CONFIGURATION



VALUES:

$m_p \approx 100g$

$1U = 10cm$

$\theta = 90^\circ$

ANALYSIS:

EMPLOYING THE PRINCIPAL OF CONSERVATION OF ENERGY BETWEEN STATES ① AND ②

$$\underbrace{\cancel{T_1}}_{\text{AT REST}} + \underbrace{\cancel{V_{g_1}}}_{\text{AT DATUM}} + V_{e_1} + \underbrace{\cancel{U_{1\to2}^{NC}}}_{\text{NO FRICTION, DRAG, NORMAL FORCES}} = \underbrace{\cancel{T_2}}_{\text{AT REST}} + V_{g_2} + \underbrace{\cancel{V_{e_2}}}_{\text{SPRING IS DEPLOYED}} \quad [1]$$

ANALYSIS CONT'D

SIMPLIFYING EQN [1] WE GET,

$$\frac{1}{2} K \theta^2 = mg\frac{U}{2}$$

$$K = \frac{mgU}{\theta^2}$$

WHERE $\theta = 90°$ OR $\frac{\pi}{2}$ rad

SO, $$K = \frac{mgu}{(\pi/2\,\text{rad})^2}$$

$$\boxed{K = \frac{4mgu}{\pi^2}}$$ [N·m/rad]

EXPRESSION FOR SPRING CONSTANT LEFT IN SYMBOLIC FORM.

PLUGGING IN KNOWN VALUES:

$$K = \frac{4(100g)(9.8\,m/s^2)(10\,cm)}{(\pi^2)}\left(\frac{1kg}{10^3 g}\right)\left(\frac{1\,m}{100cm}\right)$$

$$K = 0.0397\ kg\frac{m}{s^2}\cdot m\left(\frac{1\,N}{1\,kg\,m/s^2}\right)$$

$$\boxed{K = 3.97\,E\text{-}2\ \frac{N\cdot m}{rad}}$$

SPRING CONSTANT FOR DEPLOYING A 1U SADA.

FOR A 3U SADA

$$K = 3\left(\frac{4mgu}{\pi^2}\right)$$

$$= 3(3.97E\text{-}2\ N\cdot m/rad)$$

$$\boxed{K = 0.119\ \frac{N\cdot m}{rad}}$$

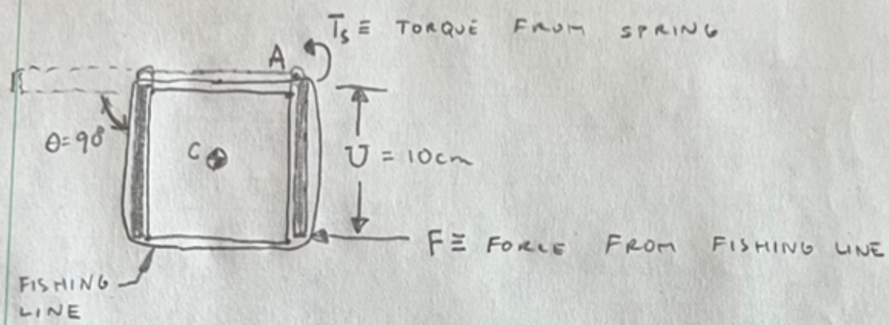
SPRING CONSTANT FOR DEPLOYING A 3U SADA

W23	JUCI TEAM	ME 429-04	PRELIMINARY CALC.: FORCE FROM FISHING LINE	1/1

OBJECTIVE: CALCULATE THE REQUIRE FORCE NEEDED BY THE FISHING LINE TO KEEP THE SYSTEM IN PLACE DURING PASSIVE RETAINMENT.

KNOWNS:
- TORQUE IN TORSIONAL SPRINGS
- DIMENSIONS OF CUBESAT BUS.

SCHEMATIC / FBD:



ANALYSIS:

$$\circlearrowleft + \sum M_A = 0$$

$$T_s - FU = 0$$

$$F = \frac{T_s}{U}$$

WHERE $T_s = K\theta$; $\theta = \pi/2$ rad

NOTE: SPRING STIFFNESS VALUES WERE CALCULATED SEPERATELY IN "PRELIMINARY CALC: TORSION SPRING".

THUS, $F = \frac{K\theta}{U}$

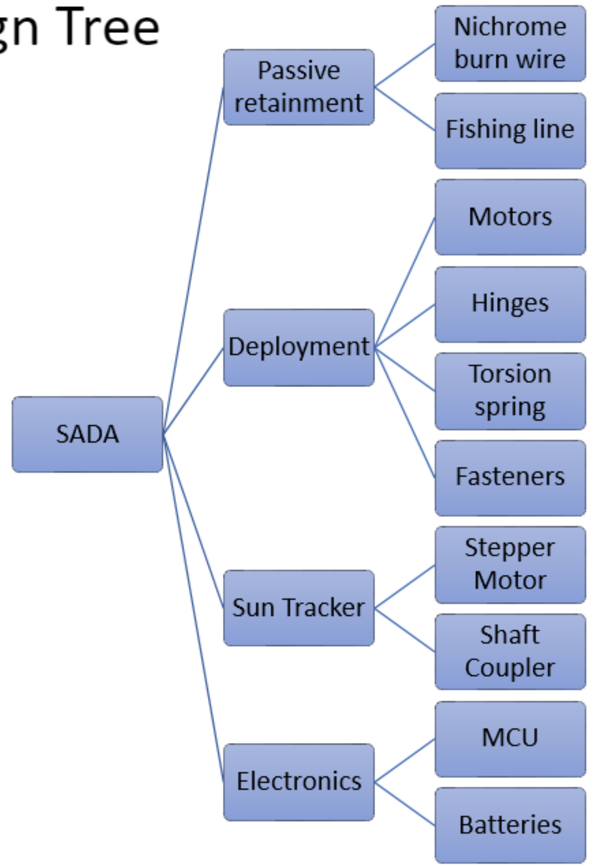
FOR A 1 U CUBESAT, W/ $K = 3.97E-2$ N·m/rad

$$F = \frac{(3.97E-2\ N \cdot m/rad)(\pi/2\ rad)}{(10\ cm)} \cdot \frac{1}{\left(\frac{1\ m}{100\ cm}\right)}$$

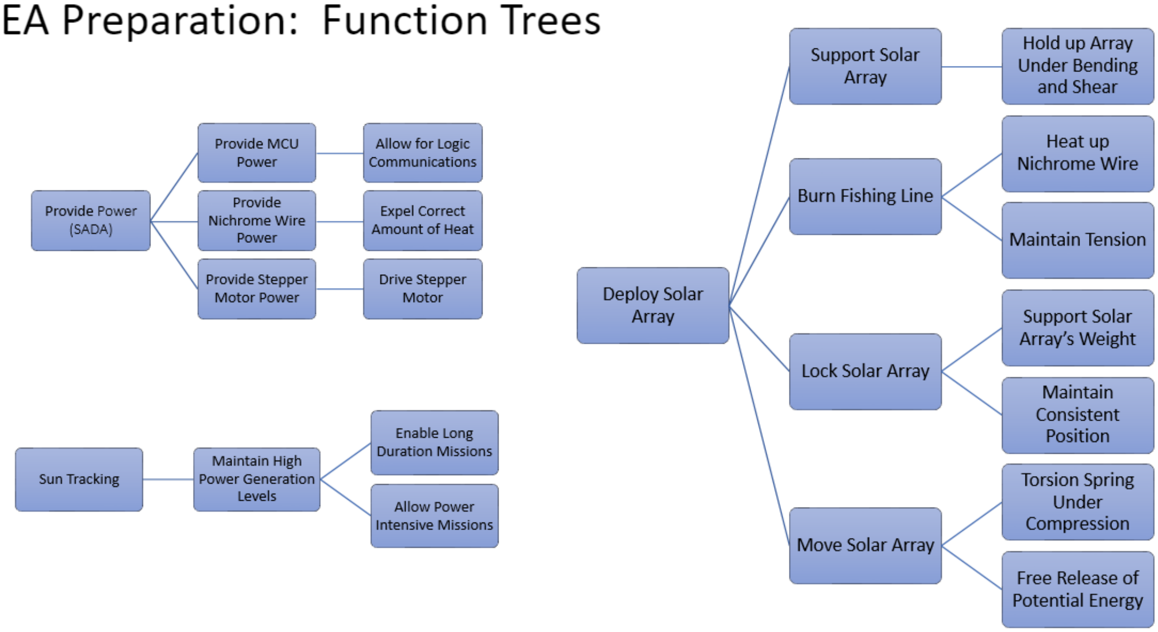
$\boxed{F = 0.62\ N}$ ← FORCE NEEDED BY FISHING WIRE

Appendix D – Failure Modes & Effects Analysis (FMEA)

FMEA Preparation: Design Tree



FMEA Preparation: Function Trees



APPENDIX E – DESIGN HAZARD CHECKLIST

Y	N	
	N	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	N	2. Can any part of the design undergo high accelerations/decelerations?
	N	3. Will the system have any large moving masses or large forces?
	N	4. Will the system produce a projectile?
	N	5. Would it be possible for the system to fall under gravity creating injury?
	N	6. Will a user be exposed to overhanging weights as part of the design?
	N	7. Will the system have any sharp edges?
	N	8. Will any part of the electrical systems not be grounded?
	N	9. Will there be any large batteries or electrical voltage in the system above 40 V?
	N	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	N	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	N	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
Y		13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	N	14. Can the system generate high levels of noise?
Y		15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
Y		16. Is it possible for the system to be used in an unsafe manner?
Y		17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, on the reverse side add:
(1) a complete description of the hazard,
(2) the corrective action(s) you plan to take to protect the user, and
(3) a date by which the planned actions will be completed.

Description of Hazard	Planned Corrective Action	Planne d Date	Actua l Date
Burn Wire could burn humans	Have a safety warning up when burn wire is active to maintain distance. Keep a fire extinguisher nearby	2/16	
Hazardous conditions in space such as cold temperatures and higher levels of radiation from the sun.	Don’t go into space with the system		

APPENDIX F – MANUFACTURING PLAN

Subsystem	Component	Purchase (P) Modify (M) Build (B)	Raw Materials Needed to make/modify the part	Where/how procured?	Equipment and Operations anticipate using to make the component	Key limitations of this operation places on any parts made from it
Solar Array Hinge	Torsion spring	P	N/A	Purchase from Amazon	Stick welder to mate the ends of torsion spring to hinge	Material of torsion spring and hinge should be the same for weldability
	Hinge	B	Sheet metal or 3D printing	Purchase from local sheet metal store or Amazon	Mill for cutting hinge from sheet metal, drill press for drilling holes for pin	Need very small toolheads and lots of precision since the part is
	Fishing Wire	P	N/A	Part already provided by James	Drill press to create mounting holes	Need line-of-sight access to mounting hole
Sun Tracking	Motor	P	N/A	Purchased from Amazon	N/A	Torque and step size limitations
	Turn Table	B	MIC6/6061 AL	Purchased from McMaster	Manual lathe and drill press	Motor shaft mounting could have slop, flatness needs to be exact
	PCB	P	Digikey	Outsourced to 3rd party	Solder using hot plate and heat flux pa	N/A

APPENDIX G – DESIGN VERIFICATION PLAN (DVP)

DVP&R - Design Verification Plan (& Report)

Project: JUCI CubeSat 2-DOF SADA | Sponsor: JPL

TEST PLAN

Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING Start date	TIMING Finish date
1	3	Place system on a scale and record weight readings for late conversion to mass	Mass	0.60 kg	Scale	Entire system	Gavin	4/20/2023	
2	4	Wrap fishing line around solar array and test whether pannels stay closed without power	N/A	Not springing open	N/A	Solar array, Nichrome wire, fishing line, modelled bus	Kory	4/20/2023	
3	4	Burn the fishing line with nichrome to test passive retainment system	Current and Voltage	Fishing line burns and subsystem springs open	N/A	Solar array, Nichrome wire, fishing line, modelled bus, deployment PCB, power supply	Gavin/Miles/James	4/20/2023	
4	6	Use DAQ to measure power usage by all subsystems	Current and Voltage	100 mW	DAQ	Entire System	Miles	4/13/2023	
5	7	Test spring deploying the system multiple times	Number of Cycles	50	N/A	Entire System	James	4/13/2023	
6	9	Test sun tracking accuracy	Angular Accuracy	+- 5 deg	Outdoor space with sunlight	Sun tracking subsystem	Gavin/Miles	4/13/2023	
7	8	Test overall volume of system	Volume	250 cm^3	Ruler	Entire system	James	4/20/2023	

Appendix H – Gantt Chart