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Deployable and Retractable Solar Array Mechanism for Satellite Applications

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ABSTRACT

The following report presents the initial design, simulation, and construction of a deployable and retractable solar array mechanism for satellite applications. Most small satellites such as CubeSats, do not incorporate the use of deployable and retractable solar arrays, but these could add increased versatility while on mission. This report also discusses multiple other projects that are like the one that the team is going to design. These reports helped the team understand what is needed to have a successful project and where they went wrong in their designs and executions. First, the initial concepts are shown, and the final selection is discussed. Analyses of the two main subsystems, a compound gear train, and a scissor linkage mechanism are given. A prototype was constructed, and testing was attempted, however issues with the gear train were uncovered and attempted to mend with no success. The project resulted in a design that shows potential for success by calculation and simulation but was not implemented well ending in a nonfunctional prototype.

Table of Contents

List of Figures

List of Tables

Deployable and Retractable Solar Array Mechanism for Satellite Applications

1. Introduction

Deployable solar arrays are used widely by popular space exploration agencies and companies such as NASA and SpaceX. These types of solar arrays have been made popular since they can be stored in a small space, and when desired, will be deployed into a large surface area. These mechanisms are so sought after that CubeSat creators are wanting to implement this into their designs. This also comes with some problems; designers of deployable solar array mechanisms make the design too complicated and most of these designs are strictly deployable. This project looks to design and build a solar array mechanism that can be deployable and retractable while also keeping the design simple.

1.1. Objective

The Objective for this project is:

To design and build a compact, deployable, and retractable mechanism capable of being fitted with solar arrays for satellite applications.

The motivation for this project comes from the fact that there are very few deployable and retractable solar arrays on satellites that could cater to the instances that a satellite mission team would wish to have these arrays pulled back and stored while on mission.

1.2. Deliverables

The deliverables for this project are:

- *A set of user instructions for the operation of the prototype mechanism*
- *A deployable and retractable solar array mechanism prototype*

Due to the complexity of the device, the team does not intend the device to be fitted with functional solar cells at the end of the build. However, the team intended to fit the mechanism with a replacement for the solar arrays. This was to prove that the solar arrays will not be damaged while being deployed or retracted; however, it will be discussed why the team was unable to complete this experiment. The prototype will also not be fitted to a CubeSat and will only be used as proof of concept, that the mechanism can deploy and retract without any issues. The prototype will not include any electrical components due to time restraints and is to be driven by a drill to prove that the mechanism is deployable and retractable.

This report supplies an in-depth look into the project of a deployable and retractable solar array mechanism. It begins with a background explaining why solar arrays with deploying and retracting capabilities is a problem that needs to be solved and the cost of not finding a simple solution to this issue. It looks specifically into three devices that can be used to solve the problem and the issues with each design. Additionally, this report follows the design of the deployable and retractable solar array mechanism for satellite applications including a set of requirements, a system hierarchy, a mechanical block diagram, a concept of operations, and a budget. Lastly, this report discusses the testing of the prototype and work this design could help with in the future.

2. Background

2.1. The Problem

CubeSats and other small satellites have massively grown in popularity within the last twenty years with only one launch in 2002 and over one hundred in 2014 and 2015 **[1]**. These satellites have also seen a large spike in academia, offering an educational paradigm for undergraduate and graduate engineering students alike. CubeSats and small satellites supply an inexpensive (and so, financially minimal risk) opportunity for these students to test elevated risk technologies on something that is low cost and significant to the students that work on the project. This presents a problem with small satellites such as CubeSats. Teams want to pack as much technology into a satellite as possible to get the most out of a small satellite's (CubeSat's) mission, however, this drives up the power requirements from their small solar arrays that are usually only pasted to the outside faces of the satellite. Small satellites have a comparably small surface area to gather energy from the sun, providing only enough power for limited technology inside. One of the risky technologies that are commonly sought after for their potential for high power output is deployable solar array systems. High power output on satellites can only be achieved through a large surface area available for solar panels. If this surface area can be folded up, stowed away, and deployed when ready, then satellite size will not be sacrificed when compactness is needed. One notable nanosat and one of the few small satellites that first featured deployable solar arrays was the QuakeSat launched in 2003 **[2]**. This satellite offered an extendable boom that then deployed solar panels.

Rarely seen, deployable and retractable systems are the next step in offering what no other satellite can achieve. Applying deployable and retractable capabilities to solar arrays would allow for further versatility to the already incredibly adaptable CubeSat. As mentioned, deployable solar arrays are desirable because of the promise of a high solar array surface area that can be stowed into a small package necessary for small satellite missions. If this system is also retractable, it could be useful for instance when a team would like to reduce drag on the satellite or protect the panels for any reason.

2.2. Similar Projects

2.2.1. University of Michigan eXtendable Solar Array (XSAS) Mechanism

With the growing popularity of small satellites, a common solution to the high-power requirements of the onboard systems is to have a solar array that is capable of being deployed once in orbit.

One design that was developed by the University of Michigan does an excellent job at achieving high stowage with a compact folding mechanism for large deployed solar array surface area. This design is also modular, capable of being integrated into any standard CubeSat configuration, making it incredibly convenient for design teams that may want a preconfigured deployable solar array system that is sure to work the first time. This extremely compact modular system is as large as a 1.5 U CubeSat giving it the dimensions 10x10x15 cm when collapsed **[3]**. In the open configuration, this system reaches 2 meters in length supplying an average power output of 23 watts **[3]**. The mechanism is actuated by a series of loaded springs at each joint. When in the closed configuration, all the springs are loaded, held in place by a burn wire keeping the system from opening. When it is decided to open the array, power is supplied to a Ni-Chrome burn wire. Once the burn wire is severed there is nothing holding the pre-loaded springs in place, so the entire system springs out within a half-second **[3]**. An image showing the deployment of this system can be seen in Figure 1.

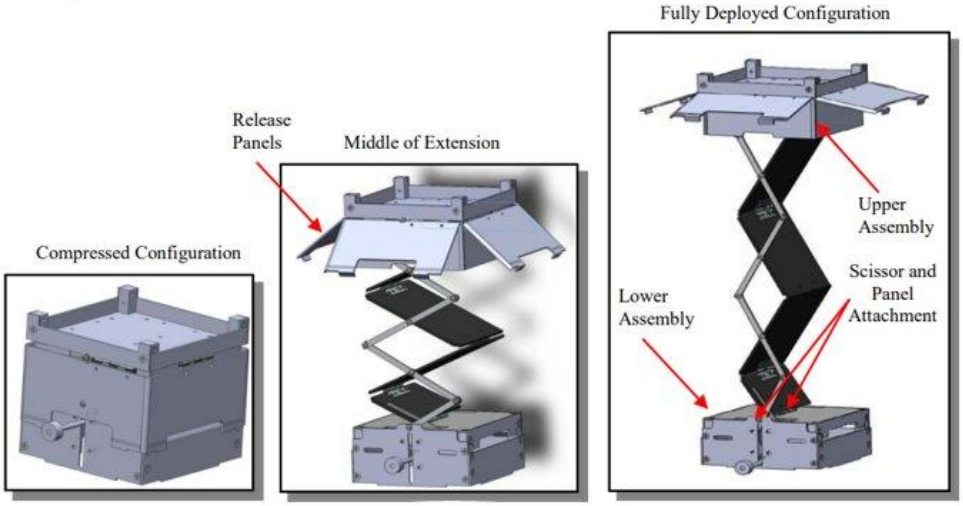

Figure 1. XSAS Deployment Sequence [3].

Here it can be seen how this system springs into action. The linkage within is spring loaded and held in the compressed configuration by release panels. The release panels are also spring loaded and have insertion points into the lower assembly holding the linkage back from extending. A burn wire is wrapped around the release panels to hold them in place and once this wire is severed, the release panels spring out of their insertion points, and the entire system can then unfold. A closer look at the burn wire can be seen below in Figure 2.

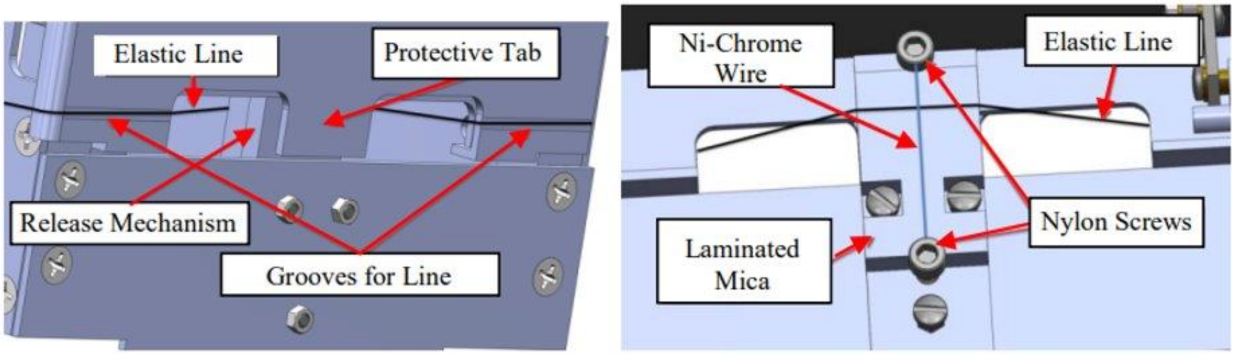

Figure 2. Release Panel Securing Process, Left: Outside of XSAS, Right: Inside of XSAS [3].

This system was tested in low gravity and had issues with the time of deployment. The team at University of Michigan calculated a deployment time of 4.3 seconds, however, the actual deployment time in low gravity ended up being 0.4 seconds. This sounds like a good thing until the team saw deformation in their scissor linkage and cracks in their circuit boards. This was from the linkage snapping into position and locking out too quickly, causing massive stresses while opening [3].

2.2.2. L'Garde, inc. Inflatable Torus Solar Array Technology (ITSAT)

Developed by engineers at L'Garde, inc. and Caltech's Jet Propulsion Laboratory (JPL), the ITSAT is a new deployable solar array technology using inflatable channels to extend out the folded panels into place. The panels are to be folded onto each other like a hand fan, extended out by two slinky-like aluminum laminated helical channels that are inflated with compressed air. This method of extension allows for a rigid extended state since the channels are highly pressurized with a burst pressure over 620 MPa, more than enough to hold a solar panel straight. The prototypes constructed have been lab tested to resist extreme temperature fluctuations (-85 degrees C to 70 degrees C) as well as random vibrations in the stowed configuration to simulate shuttle launch **[4]**. This method of deploying a solar array lacks a way to retract. This design is a good, extremely compact array for those who only wish to deploy and leave it because the compressed air will be exhausted after an individual use. Retracting is not a necessity; however, the scope of this project highlights that ability as valuable. The ability to retract the solar array will offer protection when needed to the fragile solar arrays or to decrease drag if that is

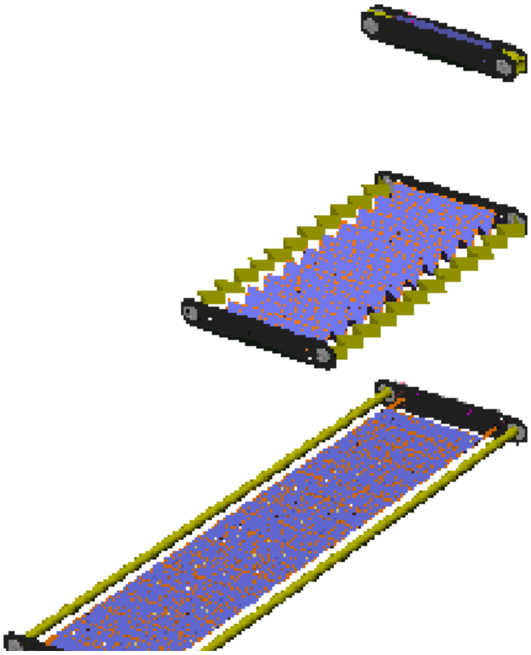

Figure 3. Inflatable Torus Solar Array Technology (ITSAT) Deployment Process [4].

desirable on a mission. In all, a system that is retractable will be far more versatile than one without this ability.

2.2.3. Composite Beam Roll-Up Array (COBRA)

Developed by SolAero Technologies, this high stow volume solar array is a novel design with the recent introduction of flexible solar panels. As stated in the name, this solar panel is attached to a composite blanket that can be rolled up before launch then released and rolled back out when solar power is needed during the mission. This composite blanket has curvature supplying stiffness when fully extended. What can be learned from that design is a flexible system can have stiffness with a slight change to unfolded geometry. This design is specifically for small scale satellites such as CubeSats and can supply power of up to 600 W at one astronomical unit (distance from Earth to the Sun) **[5].** This design is one of the best found being that it is compact, deployable, retractable, and has high stowage for largest solar array surface area. However, the design appears to be far too bulky with armatures used to shape the array as it extends that do not fold and a large canister to hold the arrays.

Figure 4. Composite Roll-Up Array (COBRA) [5].

2.3. Applicable Standards

CubeSat Satellites use a standardized sizing system of 10 cm^3, where this is also known as 1U; each CubeSat Unit (1U) should weigh approximately 1.33 kg **[6]**. The standard configurations for CubeSats larger than 1U are 1.5U, 2U, 3U, 6U, and 12U (10 x 10 x 10 cm, 10 x 10 x 15 cm, 10 x 10 x 20 cm, 10 x 10 x 30 cm, 10 x 20 x 30 cm, and 20 x 20 x 30 cm respectively) **[6]**. These common standards will apply to the team’s project and guide sizing of the components that are intended to be used on a 6U CubeSat configuration.

2.4. Factors That Impact Design

2.4.1. Public Health, Safety, and Welfare

This project does not directly impact the health safety and welfare in the typical way of people on the ground however it does have some impact. One of the greatest benefits of this project is the retractability of the solar array system, which can give a team better control of drag while in space allowing quicker missions and less time orbiting earth. This is important because with less time in orbit, there will be less time to fail and effectively become dangerous space debris for other important systems in space such as the ISS. Quicker mission times among small satellites will reduce traffic in orbit same as a freeway operating at speed versus in a traffic jam.

2.4.2. Global and Economic

This project is first and foremost a system that is meant to aid a small satellite in orbit. A satellite in orbit is of a global scale. Economically, if a satellite is capable of completing missions quickly due to drag control with deployable and retractable solar arrays, there will be less cost for extended operations and quicker results.

2.4.3. Ethical and Professional

The scope of this project and it’s intended use are effectively not impacted here.

2.5. Requirements

The following requirements were decided by the team to ensure the final goal is met. The prototype shall:

1. Demonstrate both deployable and retractable capabilities.
2. Supply solar panel available surface area greater than or equal to all four long faces of a 6U CubeSat.
3. Have dimensions that allow integration with a 6U CubeSat.
4. Demonstrate the ability to cycle without repairs for at least 100 iterations.

5. Deploy or retract within 4-6 minutes.

3. Concept Selection

When creating and selecting a conceptual design, the level of complexity, compactness, requirements made by the team, and reality on whether the team could complete a thoroughly engineered design and prototype within the allotted time were all factors considered. If a design was too complex or did not meet specified requirements, it was not considered as a final design any longer.

3.1. Design Concept 1:

This design is modeled after a hand fan using a folding method of stowage. The system would be equipped with a motor driven mechanism and a torsion spring as its main deployable and retractable drivers. The solar panels would all be attached on alternating sides, stacked in the closed configuration, and latched close with the torsion spring loaded, when the latch is released, the spring would snap the leading bars around and open the array fully for use. To close, the motor would drive the leading bars back to close simultaneously loading the spring for opening the array again.

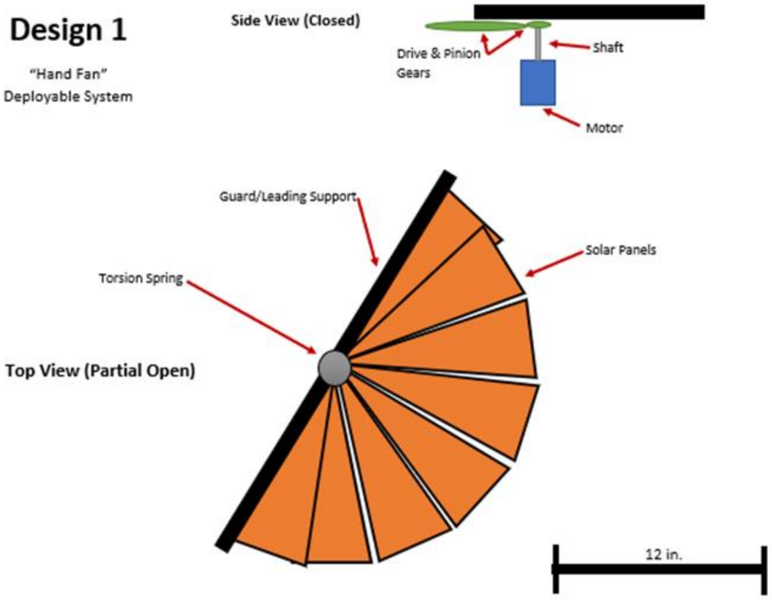

Figure 5. "Hand Fan" Deployable Solar Array System (Design 1).

This design has extremely high stowage volume with the stacking of panels without hinges and instead using a sliding motion to fan out. When fully extended, Concept 1 also offers a blanket of surface area that could be repeated on two sides of a satellite supplying maximum coverage, protecting the satellite from the extreme temperatures of the sun in space as well as using that energy to produce power. The largest downfall of this design is its complexity would result in an incomplete design by the end of this course.

3.2. Design Concept 2:

The second arrangement is simpler in its folded configuration. The large rectangular solar panels would lie flat on the CubeSat when stowed, and a scissor mechanism would drive them out into place when needed. This actuation would be powered by a gear train that reduces the input angular velocity offered by a cordless drill so that the motion of the scissor mechanism is slow and controlled. The crossmembers would consist of aluminum sheet metal links, and between them, a 3D printed support to hold the delicate solar panels.

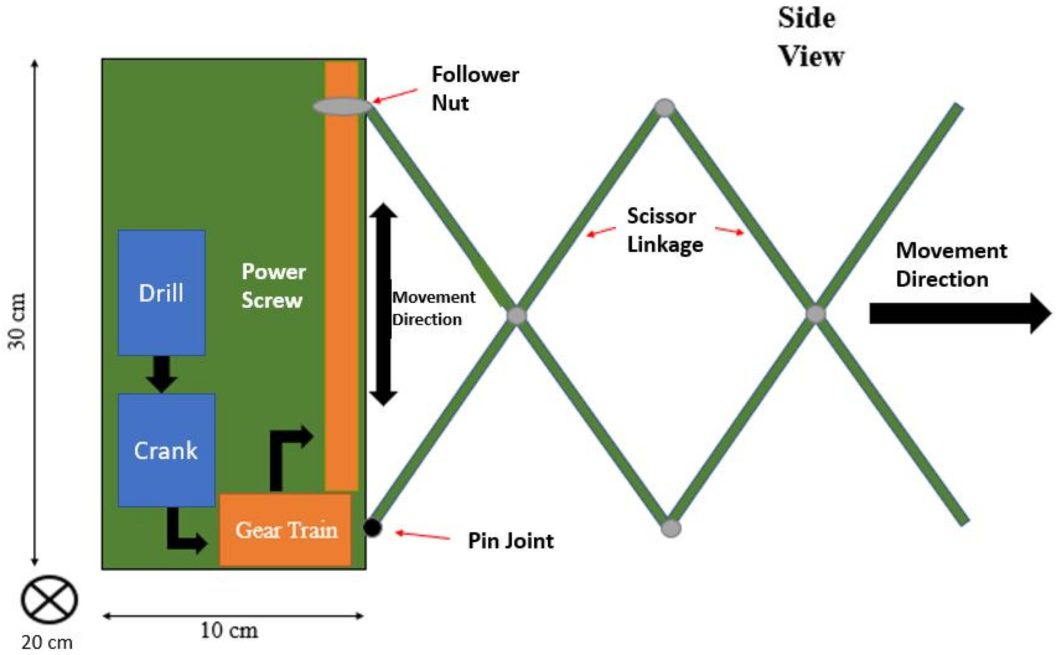

Figure 6. Scissor Mechanism Deployable Solar Array (Design 2).

This design is simple and will offer great stowage volume as well as surface area coverage when extended. If needed, this design could also be repeated on two sides of a rectangular satellite to make best use of the faces of the satellite for power production. The only drawback to this design is that all the gearing would be held inside of the satellite taking up space for other electrical instruments that could otherwise be included.

3.3. Design Concept 3:

Design concept 3 plays off USI's original CubeSat set-up by only having panels on all four faces of the CubeSat. In this design, however, the solar panels would have the ability to extend and retract to control its drag characteristics. The motor driver on this system would be attached to a rack and pinion gear train system to push and pull the solar panels out from inside the CubeSat. Additionally, this is the most reliable choice of the three designs due to the lack of complexity.

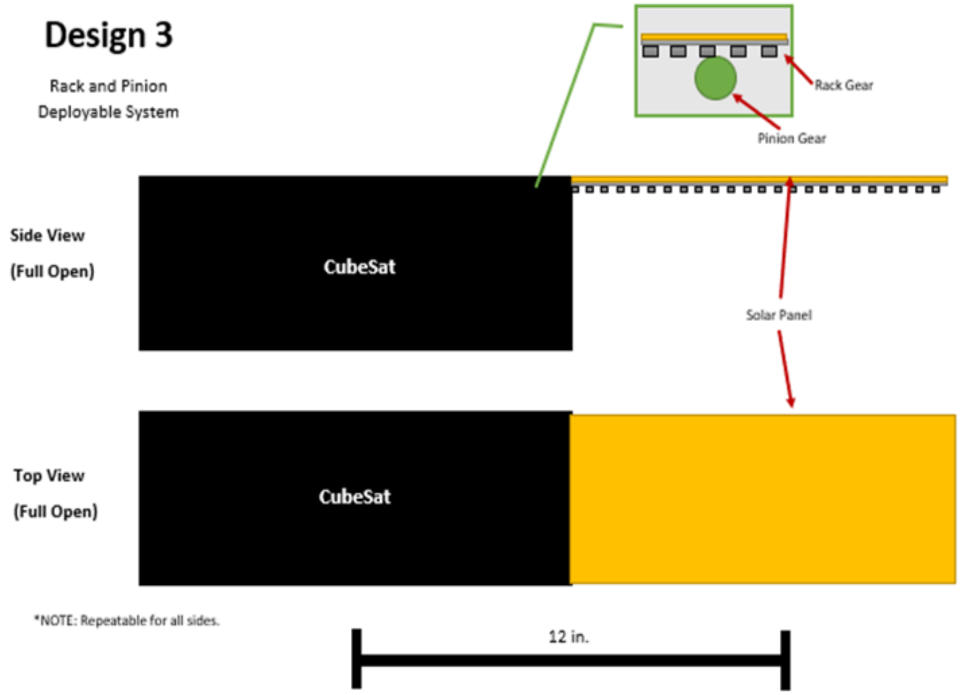

Figure 7. Rack and Pinion Deployable Solar Array System (Design 3).

This design is remarkably simple and reliable, making use of a rack and pinion gear set. The panels would be retracted back inside the satellite so this design would offer great protection from space debris when needed. The downfall of this design is that it gives no added solar array surface area than could be obtained by placing panels on all four faces of a rectangular satellite.

3.4. Design Chosen Justification

The design chosen for detailed analysis and construction was design concept number two. This concept offers a simple yet effective solution to all the requirements. Design one was not chosen because it was far too complex for construction and would be difficult to find a way to house all the components such as the gears, motor, and fan mechanism within the satellite on launch. This would leave a lot of room for the configuration to break on launch if it cannot be protected within the satellite. Design three had no potential to offer more surface area than could be more simply obtained by keeping the solar arrays on the outside faces as seen in USI’s last CubeSat mission **[7]**. Thus, design two was chosen because it meets all the set requirements, it has potential for higher power output than the earlier mission, it is simple yet well within the standards for a senior project, and it has a small stowage volume.

4. Final Design and Analysis

4.1. Overview of Operations

The steps for operation of the deployable and retractable solar array mechanism are the following:

1. Place system on a secure platform with the scissor link facing up. Ensure there is at least 1 meter of open vertical space from the platform surface.
2. Grab the power drill and attach the chuck to the center pinion gear shaft.
3. To deploy the mechanism, turn the power drill to the clockwise setting and pull the trigger.
4. To close the mechanism, turn the power drill to the counterclockwise setting and pull the trigger.
5. Detach the drill chuck when finished.

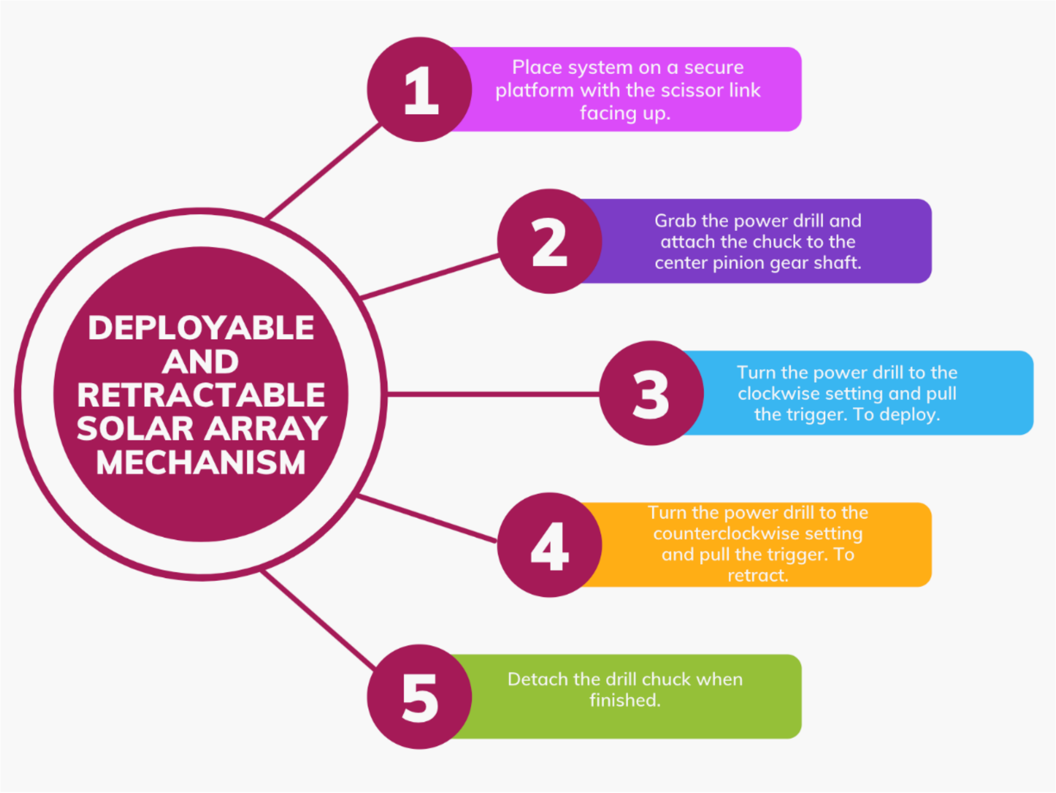

Figure 8. Deployable and Retractable Solar Array Mechanism - Concept of Operations.

4.2.Systems Overview

The entire system is composed of one subsystem that is divided into 4 subsystem blocks according to their operation in the mechanism. The system hierarchy is displayed below in Figure 9 and shown larger in Appendix C.

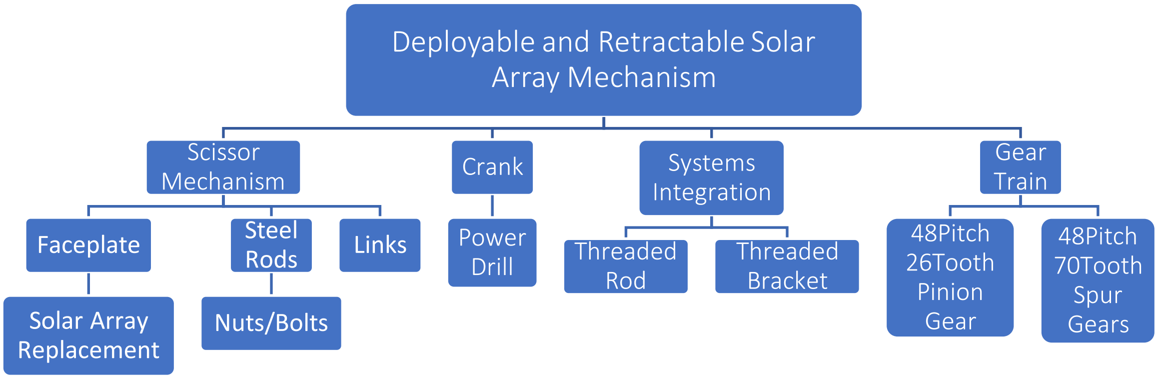

Figure 9. Deployable and Retractable Solar Array Mechanism – System Hierarchy.

4.3.SolidWorks Modeling

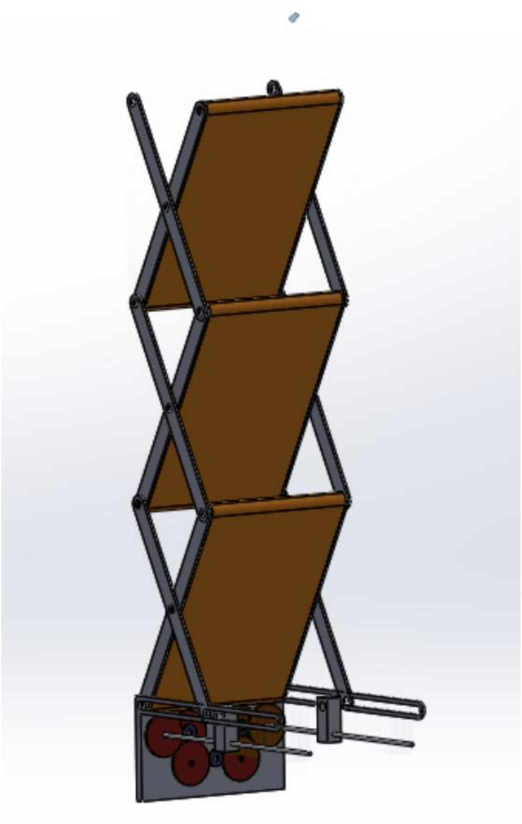

Figure 10. Completed Solidworks Model.

4.3.1. Scissor Linkages

The design of the scissor linkage mechanism was chosen due to its simplicity to integrate and its ability to offer great stowage volume as well as surface area coverage when extended. When we compared the scissor linkage concept to the origami-based concept, this seemed like something that the team could implement with the given time restraints. The first and third concepts had caused concern that they would end up being too complex to implement in the design of a deployable and retractable solar array. Additionally, the first and third concepts had a limited amount of surface area to apply solar panels to. This did not work for the team because surface area was something that the team wanted to maximize. The scissor linkage design has been used before in the University of Michigan's XSAS; however, their scissor linkage design was flawed. The University of Michigan used thin links that were susceptible to deflection. The team wanted to ensure that we had designed links that would be able to minimize this deflection. The team used SolidWorks to design a scissor linkage mechanism that will be able to fit to a 6U CubeSat. Figures 11 and 12 show the scissor linkage mechanism in the deployed and retracted positions.

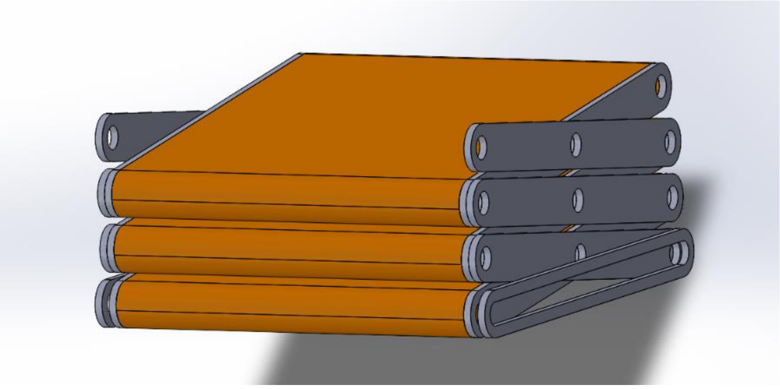

Figure 11. Scissor Linkage Retracted.

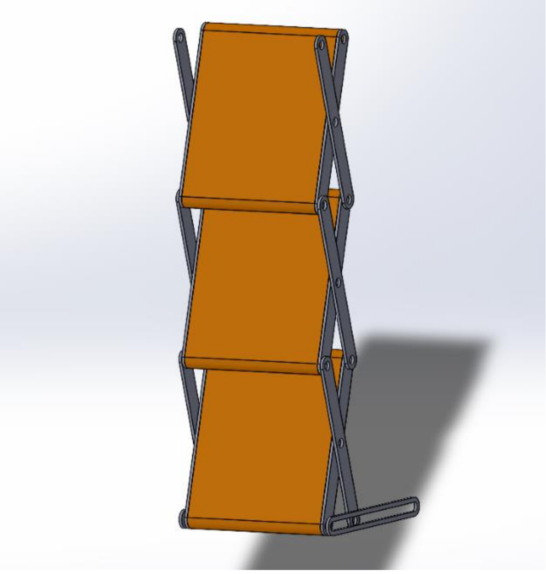

Figure 12. Scissor Linkage Deployed.

4.3.2. Compound Gear Train

To actuate the scissor linkage, a compound gear train configuration was chosen because of its ability to reduce the high speeds of an electric motor to the desired angular velocity. Michigan's XSAS for example, presented one major problem, it extended much too quickly causing failures in their mechanisms. By using a compound gear train, the team aims to not repeat this issue. A slow angular velocity could be achieved through turning a hand crank slowly, however, it must be kept in mind, that if this system were to fly in space, an electric motor would need to take the hand cranks position. The need for a gearing subsystem is the result of knowing there will be an eventual requirement for a design that must transfer the high angular velocities of an electric motor to slow and controlled motion of the scissor linkage shown above. In the final construction, a cordless drill will be used operating at 1300 rpm to turn the input gear.

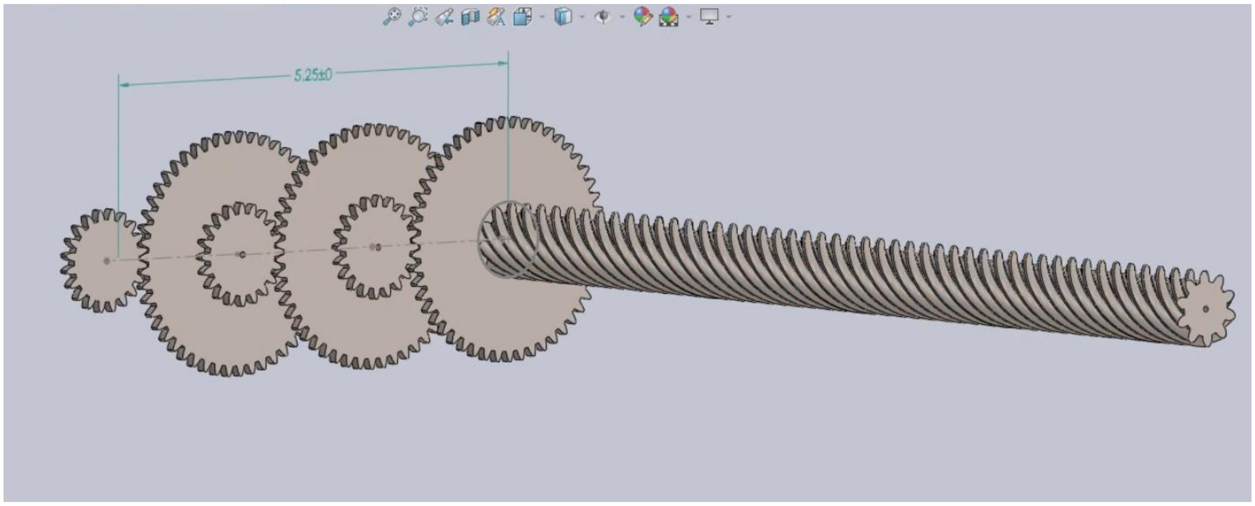

Figure 13. Oblique View of the Initial Compound Gear Train Design.

The first design was a compound gear train with all the gears in a line side by side one another. This design offered a high gear ratio, however, with the gears in line with the system, was seven inches long for half of the gear train. There are only eight inches at the end face of a 6U CubeSat so this design would almost double the acceptable length.

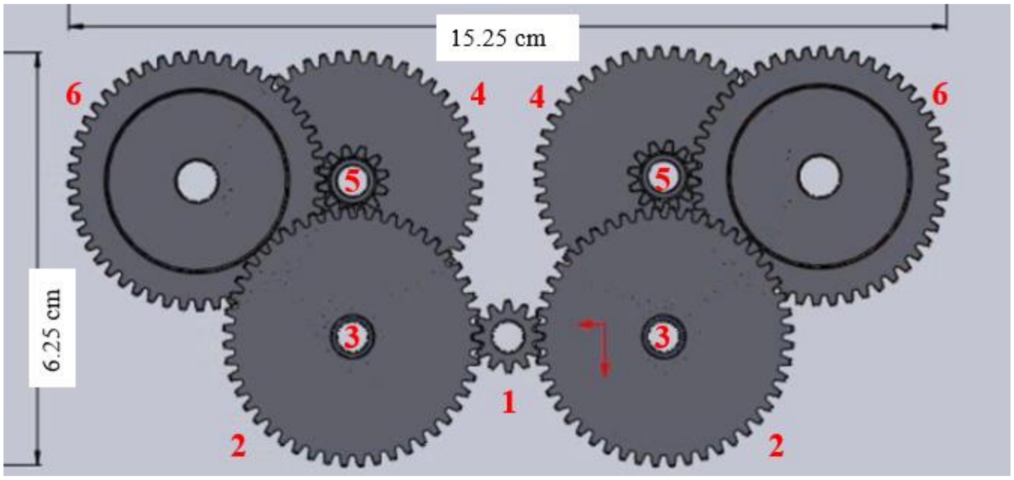

Figure 14. Final Compound Gear Train Design.

The final design shown above is a reconfiguration of the previous design. By making better use of the vertical space, the overall length of the gear system was reduced to six inches. Different gears were also selected with a higher pitch so that more teeth can fit on a smaller gear and offer a higher ratio from one gear set to another. The final gears selected have a pitch of 48 and alternate between 26 and 70 teeth. With three sets of gears on each side, the total ratio from gear one to six is 19.5:1. Table 1 shows how the angular velocity is slowed from the input to the output. The gear set shows which gear numbers in the system are rotating together on the same shaft. Pd is the pitch of the gears which is how many teeth per inch are on the gear. N is the number of teeth around the perimeter of the gear. Dp is the diametral pitch and tells the team the diameter of the pitch circle of the gear (very closely related to gear diameter). ω shows the direction and speed that particular gear is rotating at.

Table 1: Compound Gear Train Information.

Gear Train Design (Single Side)

Gear set	Gear #	Pd (teeth/in)	N (#of teeth)	Dp (in)	ω (rpm)
1	1	48	26	.5416	1300
	2	48	70	1.4583	-482.86
2	3	48	26	.5416	-482.86
	4	48	70	1.4583	179.35
3	5	48	26	.5416	179.35
	6	48	70	1.4583	-66.62

The breakdown of one side of the gear train shown above shows how the input velocity of 1300 rpm is reduced through each of the three gear sets to 66.62 rpm at gear six. Appendix D will give more detailed information on how these numbers were found.

4.4. Components

4.4.1. Links/ Connecting Rods

The links and connecting rods are what make up the scissor linkage mechanism. The links were set to be made from 6061 aluminum sheet metal. This metal was chosen due to it being certified to use on CubeSats. The connecting rods were initially going to be made of a double threaded steel rod. The team decided to go with an aluminum rod that we could thread ourselves to decrease the cost of the project. The links and connecting rods can be seen below in Figures 15 and 16.

Figure 15. Links.

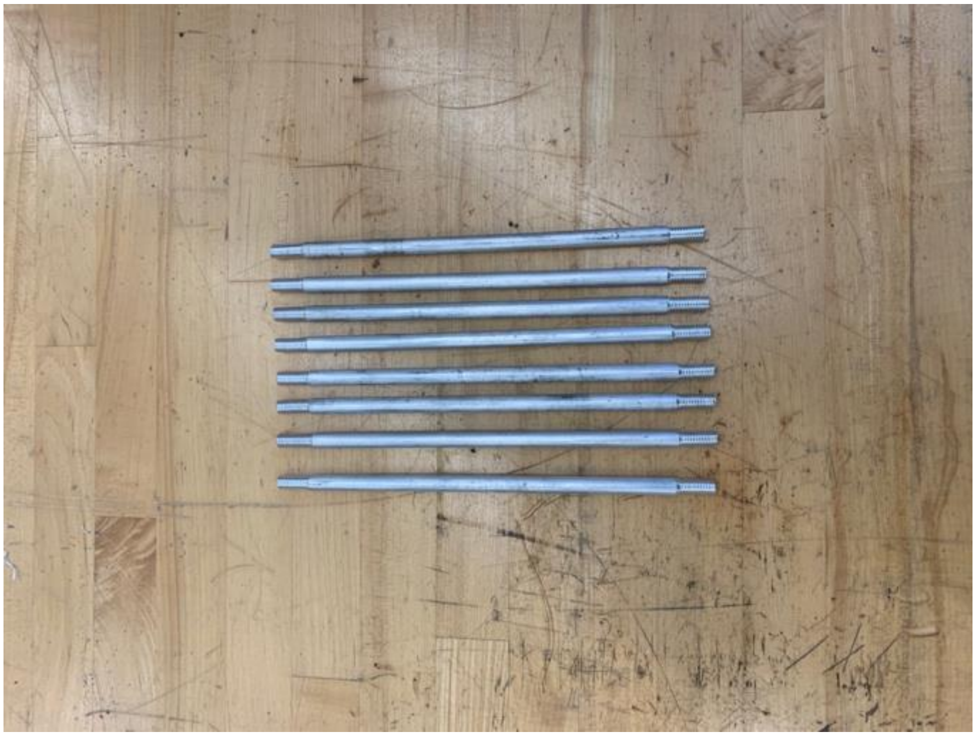

Figure 16. Connecting Rods.

4.4.2. Gears

The gears transfer the high velocity angular motion of the cordless drill to the slow and controlled translational motion of the scissor linkage. Initially, the team chose high grade steel gears to eliminate any potential of stripping gear teeth. After creating a budget, this selection in gears was quickly changed to nylon gears to reduce the cost to almost a tenth of what the steel gears would have been. The size of the gears was also greatly reduced by choosing a gear with a higher pitch (teeth/in) so that for every inch the gear increased in diameter, there would be a larger change in gear ratio. This allowed for a higher total gear ratio using a compound configuration to fit in the small available area on the end face of a 6U CubeSat.

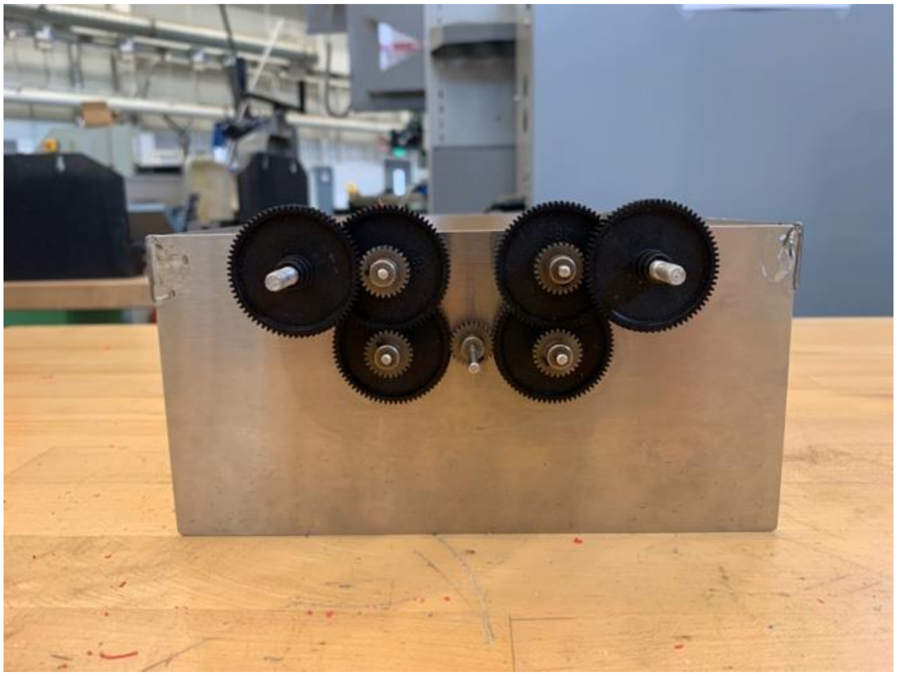

Figure 17. Gears.

4.4.3. Frame/Guiding Rails

To allow the scissor linkage mechanism to move or slide slowly in a linear motion, the team needed to design guiding rails to allow that type of movement. The first option for these guiding rails was to cut them out of the same material as the linkages. This caused concern for the team because the aluminum that was used for the links was much thicker. The team wanted to minimize any friction that the guiding rails would add to the system, so the team decided to cut the two rails out of a thin piece of stainless steel. This allowed the guiding rails to become a part of the frame for the mechanism. The guiding rails/frame can be seen below in Figure 18.

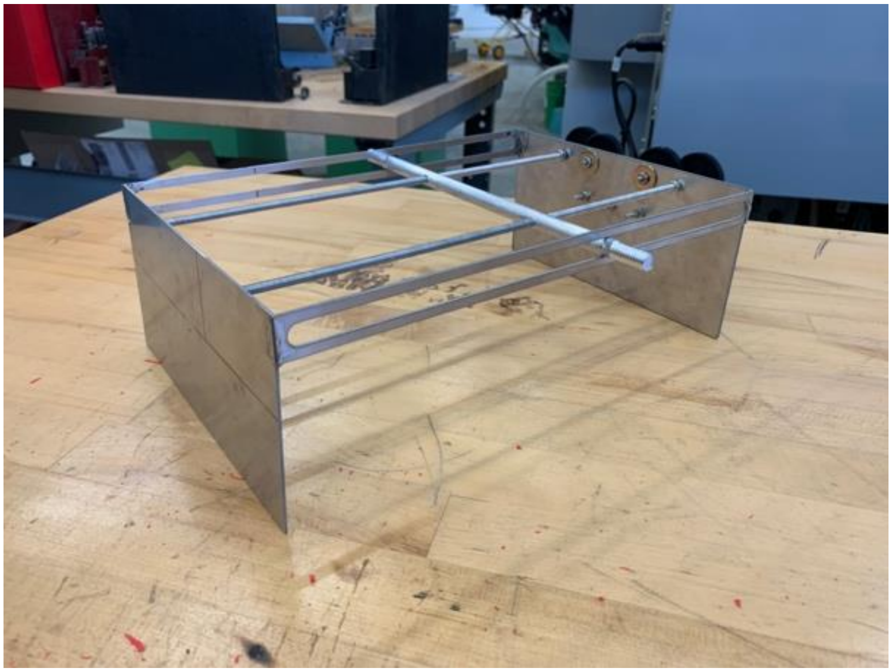

Figure 18. Frame with Guiding Rails.

4.4.4. Faceplates

The faceplates are what hold the solar panels to the mechanism. The first option that the team explored for these faceplates was a piece of sheet metal that would be supported by the connecting rods. This option presented some complications for the team. The team thought that this would be too heavy for the scissor mechanism to support so the team opted to 3-D print the faceplates. 3-D printing the faceplates allowed the connecting rods to go through the faceplates. This allowed them to rotate on the connecting rods while the scissor linkage mechanism was being deployed or retracted. The final design for the faceplates can be seen below in Figure 19.

Figure 19. Faceplates.

4.4.5. Power Screws

Chosen to act as the system integration between the gears and the scissor linkage mechanism, two fully threaded rods would rotate along with gears 6 and pass through a drilled and tapped connecting rod that connects the two ends of the scissor linkage. As these power screws rotate, they can either pull or push the scissor mechanism closed or open depending on the direction of rotation.

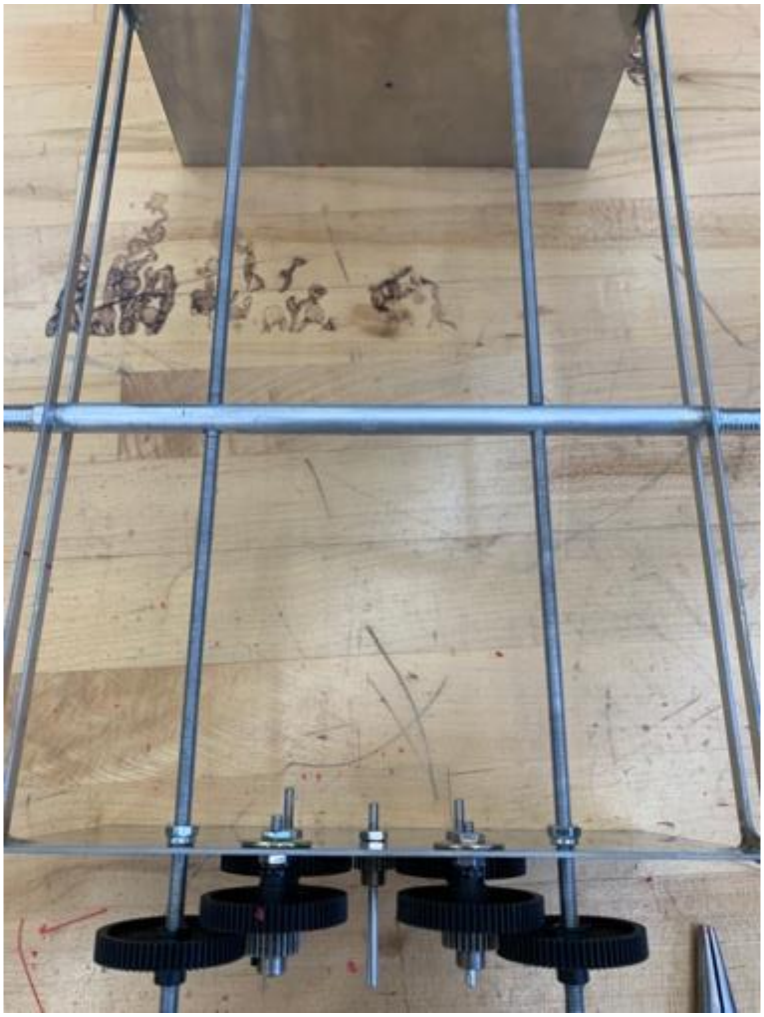

Figure 20. Power Screws Connected to Gears and Frame.

4.5. Construction

The construction of the deployable and retractable solar array mechanism began with the links and frame. 6061 aluminum was chosen for the links due to its great strength to weight ratio. The dimensions for the links were obtained from the Solidworks model. To cut the links, the team used the waterjet located at the Applied Engineering Center (AEC) at the University of Southern Indiana. Figure 21 shows the links being cut by the waterjet.

Figure 21. Links Being Cut in the Waterjet.

In addition to the links, the frame was also cut using the waterjet. The frame was cut out of a thin sheet of stainless steel. This worked well for the team because we wanted the guiding rails to be as thin as possible to reduce and friction that would be caused by the connecting rods and the guiding rails touching. Figure 22 shows the frame being cut using the waterjet.

Figure 22. Frame Being Cut by the Waterjet.

The next step was to 3-D print the faceplates. To do this the team had to save the SolidWorks part as a .STL file so that we could add the part into PrusaSlicer. Once the part was in PrusaSlicer we could orient the baseplate to fit on the printing bed of the 3-D printer and export the G-code. After the G-code is exported we were then able to load it on the 3-D printer to print. Figure 23 shows one of the 3 faceplates being printed with the 3-D printer.

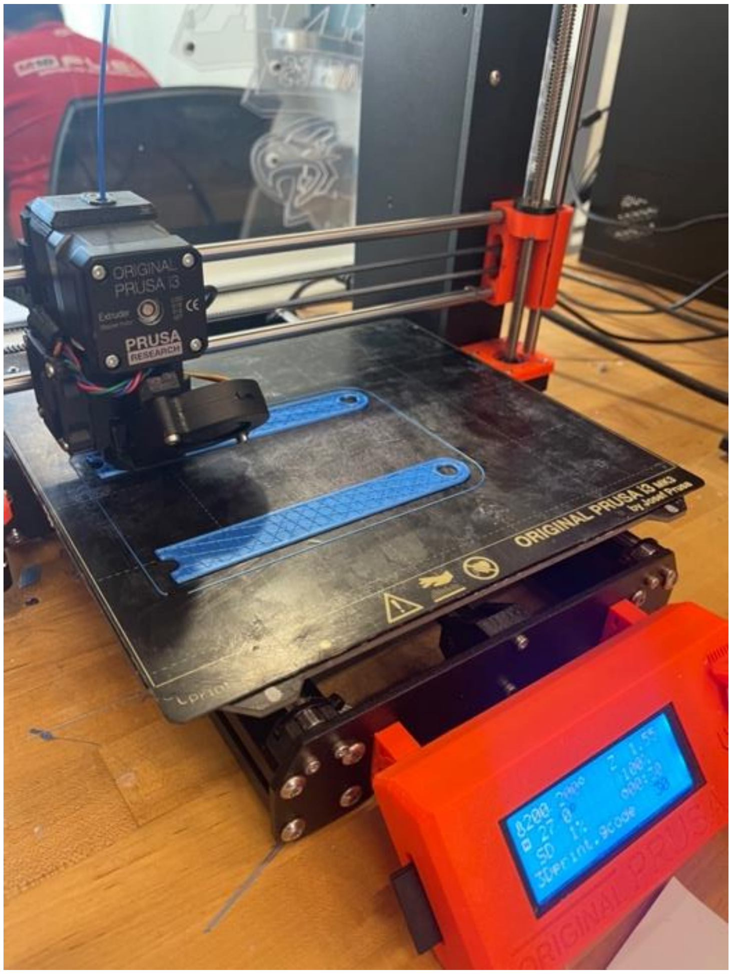

Figure 23. Baseplate Being Printed on 3-D Printer.

The next step was to cut and thread the connecting rods. This was done by taking a 6-foot-long aluminum rod and cutting them into 10-inch segments. The team cut these segments of aluminum with a handsaw to ensure we were getting the correct lengths. Once the rods were cut to length, the team proceeded to thread both sides of the rod. Figure 24 shows team member Joey threading the connecting rods.

Figure 24. Joey Threading Connecting Rods.

After the frame had been cut by the water jet, the gears, rotary shafts, and power screws could be assembled. One of the main issues the team dealt with when assembling the gears was that the bore of the two gear types were much different. This was a problem because the two differently bored gears had to fit together on the same rotary shaft. The sizes of the gear bores were known to the team but it was not realized that this would cause issues down the road in construction. The chosen solution to this was to use electrical tape to wrap around the rotary shaft until it fit the bore of the larger gear. Next, the gear was secured in place with J.B. SuperWeld so it would not spin freely on the shaft. After this, each shaft was threaded so that they could be lightly secured to the frame and vertically spaced correctly with nuts. After all the gears were meshing correctly, the nuts were secured on the shaft to prevent unwarranted loosening or tightening from the rotating gears with super glue.

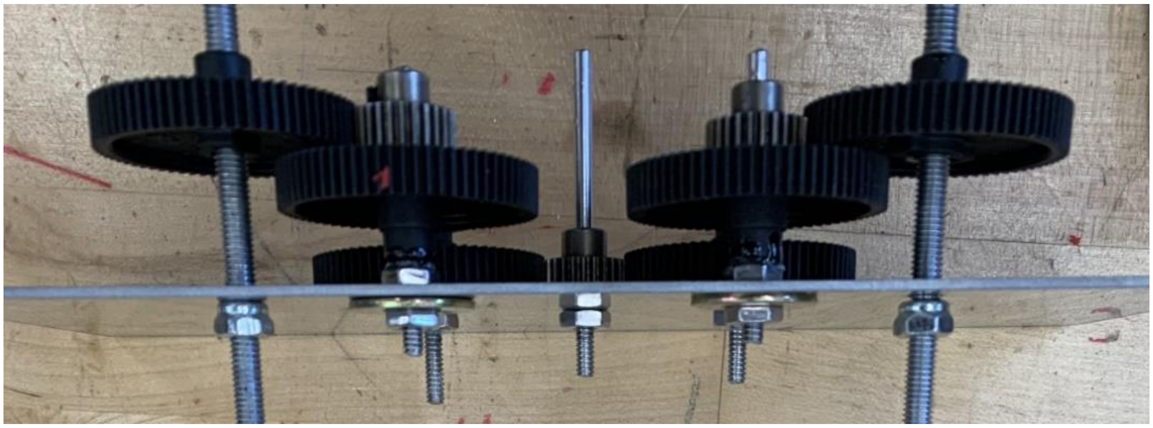

Figure 25. Secured Gears to Frame of Prototype.

5. Final Prototype Testing Results

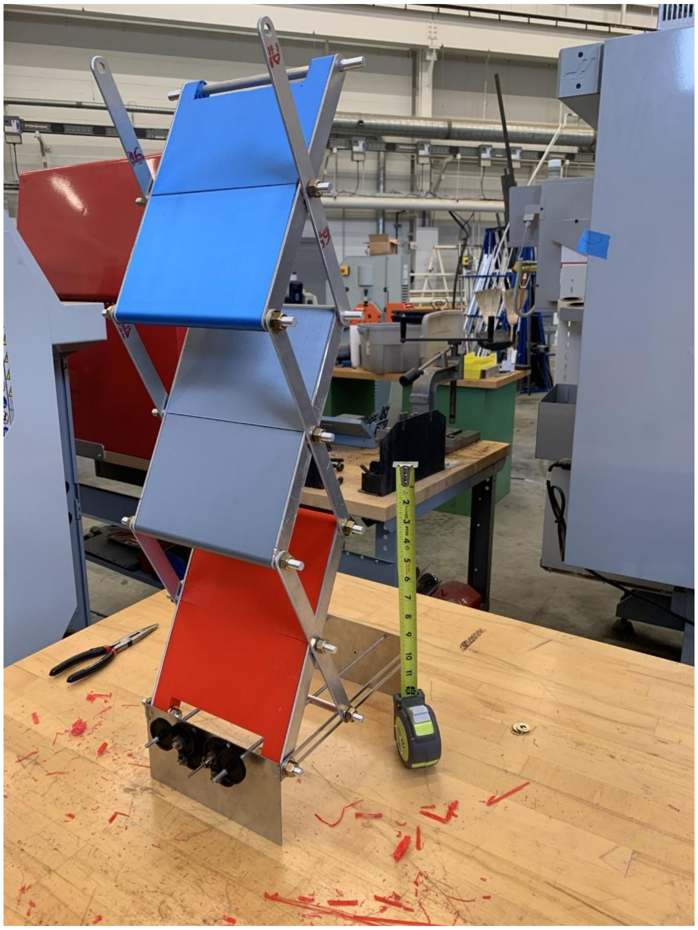

Figure 26. Final Prototype Design.

Once the prototype was constructed, shown in Figure 26, the team attempted to test the system. The drill was attached to the input at gear one in the center and the speed was slowly increased until the drill was operating at its maximum speed of 1300 rpm. This was maintained for almost two minutes before the gears began to show signs of play, and within 15 seconds, the gears were moving enough to stop meshing. Testing was temporarily halted, and a team member attempted to hold the gears together while testing continued. Once again, the drill was brought to speed but this time the bolts securing the gears to the frame tightened enough to seize the system. To prevent breaking the gears, the team quit testing immediately to think of viable solutions to these problems.

In the following weeks, attempts were made to secure the gears by adding a second plate for the gear rotary shafts to go through and eliminate the wobbling. This did not work because of threads on these shafts grabbing the second plate and again seizing the system. It was then suggested that a thicker plate be used to secure the gears instead of two. This solution would have required a deconstruction of the entire gear train system. During early construction however, in order to keep the gears in place, J.B. SuperWeld was used to make sure nothing could rotate freely on the shaft which worked phenomenally. The only problem with how well this glue worked was that now it was impossible the team had to deconstruct the gear train without destruction of almost all materials involved. With time to test the prototype running out and documentation due dates approaching in days to come, the team made the difficult decision to report the prototype as not functional.

The team believes this design is a viable solution to achieve deployable and retractable solar array capabilities on small satellites, as proven by calculation and simulation, but these results could not be verified by testing a physical prototype.

6. Disposal Plan

Due to the simplicity of the parts and the low part count for the prototype, the disposal plan, seen in Table 2, could be defined as parts that can be reused or recycled.

Table 2. Disposal Plan for Deployable and Retractable Solar Array Mechanism.

Part/ Material	If in good condition		If in fair condition		If in bad condition		If obsolete	
	Sale or Reuse	For $	Sale or Reuse	For $	Reuse or Recycle	At a Local Recycling Depot	Recycle	At a Local Recycling Depot
Links	Reuse		Reuse		Reuse or Recycle		Recycle or Dispose	As "Metal"
Faceplates	Reuse		Reuse		Recycle		Recycle	As "Plastic"
Gears	Sale	For $14.00	Sale	For $14.00	Reuse or Recycle		Recycle or Dispose	As "Metal" or "Plastic"
Frame	Reuse		Reuse		Recycle or Dispose		Recycle or Dispose	As "Metal"
Connecting rods	Reuse		Reuse		Recycle or Dispose		Recycle or Dispose	As "Metal"
Power Screws	Reuse		Reuse		Recycle		Recycle	As "Metal"
Rotary Shaft	Reuse		Reuse		Recycle		Recycle	As "Metal"

7. Budget

The team set a budget of $500 as a limit for the cost of the prototype, this budget was not exceeded since the approximate expenses for the prototype was $217.75. This number does not include the student and faculty labor but only the materials needed. The budget in Table 3 shows the approximate price of each component, including student and faculty labor. Note that there were materials and machines that USI had in its possession to be used at the Applied Engineering Center.

Table 3. Budget.

Items	Cost
Sheet Metal	$40.58
Gears	$45.00
Defective Solar Cells	$55.40
Rotary Shaft	$32.16
Steel Rods	$33.90
Fully- Threaded Rod	$7.71
Total Cost of Materials	**$217.75**
Student Labor (100 Hours-$15 per hour)	$1,500
Faculty Labor (18 Hours-$100 per hour)	$1,800
Total Cost Including Labor	**$3517.75**

Table 4. AEC Provided Materials & Equipment

Tape Measure
Nuts
Washers
Belt Sander
Cordless Drill
Water Jet
3-D Printer
Drill Press
Tap and Die Set
Wrenches
Grinder

8. Lessons Learned

Collaboration and Communication are important in the Engineering Design Process

One of the more important skills to have as an engineer is the ability to work effectively as a team with one or more people. To be able to effectively work as a team each member must have practice with their collaboration and communication skills. Through the duration of this project the team got experience in both collaboration and communication skills. It was crucial that our team communicated to each other properly so that we would stay on the same page. This required the team to have meetings outside of the weekly meetings with the project advisor. During the weekly meetings with the project advisor, it was important that we effectively communicate with the project advisor so that we could get helpful feedback.

During the duration of this project, the team knew that we would have only 16 weeks to implement a design. Knowing this, the ability to manage time was important. The team had a tentative schedule to follow throughout the semester. By setting due dates for various tasks, like finishing SolidWorks modeling and beginning construction, the team did its best not to fall behind. A factor that wasn’t accounted for in the schedule was unforeseen issues. Looking back at the project we should have given ourselves more room to work with problems that we didn’t see coming. An example of one of these problems was parts coming in late, so the construction had to be rushed to stay on schedule.

When designing a project, it is easier to break down the design process into three stages: Initial design, Simulation, and Construction. Breaking the process down into these three stages allows the process to be simplified. During the initial design, we were able to look at multiple concepts and discard of the ones that didn’t manage to meet our requirements. During the simulation phase it gave the team a good look into how the project was going to come together and be implemented. During the construction stage it was immediately clear that the prototype was going to have to be implemented differently than what the simulation suggested. This process helped the team get first-hand experience with how the engineering design process works.

9. Future Work

The team came across many ways in which the design in simulation was not easily replicable in implementation. Below are some recommendations for any future work carried out on this project.

9.1. Gears' Frame

Account for thickness when running a rod through material for stability. When attempting to supply power through the gear train, the gears had wiggle room to move around and stop meshing with one another. Some solutions to this problem that delayed prototype construction immensely is to ensure that the rotary shafts attaching the gears to the frame, has a thick piece of material to go through or have two intersection points with the frame. Although the holes in the frame were the same dimensions of the rotary shafts, they could still move around because the sheet metal had little thickness.

9.2. Material Alternatives

The team chose to construct most of the prototype out of aluminum or steel. In the future this should be wooden or polycarbonate to allow for easy machining. Metal is extremely difficult to work with and allows for little to no error when fitting pieces together. This made for a construction that does not move smoothly.

10. Conclusion

The objective of this project was to design and build a compact, deployable, and retractable mechanism capable of being fitted with solar arrays for satellite applications. The team managed to build a prototype that was capable of minor deployment and retractability. When the team tested the prototype, they uncovered many issues with the gear train. This system worked well in simulation but had some discrepancies when implementing in the prototype. Although all the requirements were met with calculation and/or simulation, they have yet to be verified through experimentation leaving much room for improvement. Overall, the project was not successful in constructing a working prototype but showed a great proof of concept that this design could work if implemented correctly.

11. References

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12. APPENDIX

12.1. Appendix A. Gear Ratio Calculations

To calculate the total gear ratio, the number of teeth for the gears must be known. The gear train uses two types of gears, a 48 pitch, 26 tooth gear, and a 48 pitch 70 tooth gear. Meshing these gears creates one gear set of which there are three. The calculations are shown below.

$$GR = (total\ gear\ ratio)$$

$$gr = \frac{26}{70}(Gear\ ratio\ between\ each\ gear\ set)$$

$$GR = (gr)^3 \tag{1}$$

$$GR = \frac{1}{19.5} = \frac{\theta_{out}}{\theta_{in}}$$

Gear ratios are important to understand how the gear train will operate. A gear ratio of 19.5:1 means that the first gear (input gear) will need to rotate 19.5 times for the final gear (gear 6) to make one rotation. Other than slowing down the rotations, a gear ratio like this will also provide an increased torque. An analogy to understand this relationship can a wrench or breaker-bar for example. If a bolt is hard to loosen, a wrench with a longer handle is required to complete the task. In this case, the stubborn nut is the output gear that does not want to move easily, the end of the wrench handle is the input gear, and the length of the handle is the gearing ratio. The longer the handle (higher the ratio) the easier it will be for the user (motor) to turn the nut (gear 6).

12.2. Appendix B. Open/Close Time Calculations

With the use of a power screw, the threads per inch must be accounted for when calculating the time to close or open.

$$\omega = 66.62\, rpm (output\ angular\ velocity)$$

$$\delta = 32 \frac{threads}{inch} (\#of\ turns\ per\ inch\ of\ motion\ along\ power\ screw)$$

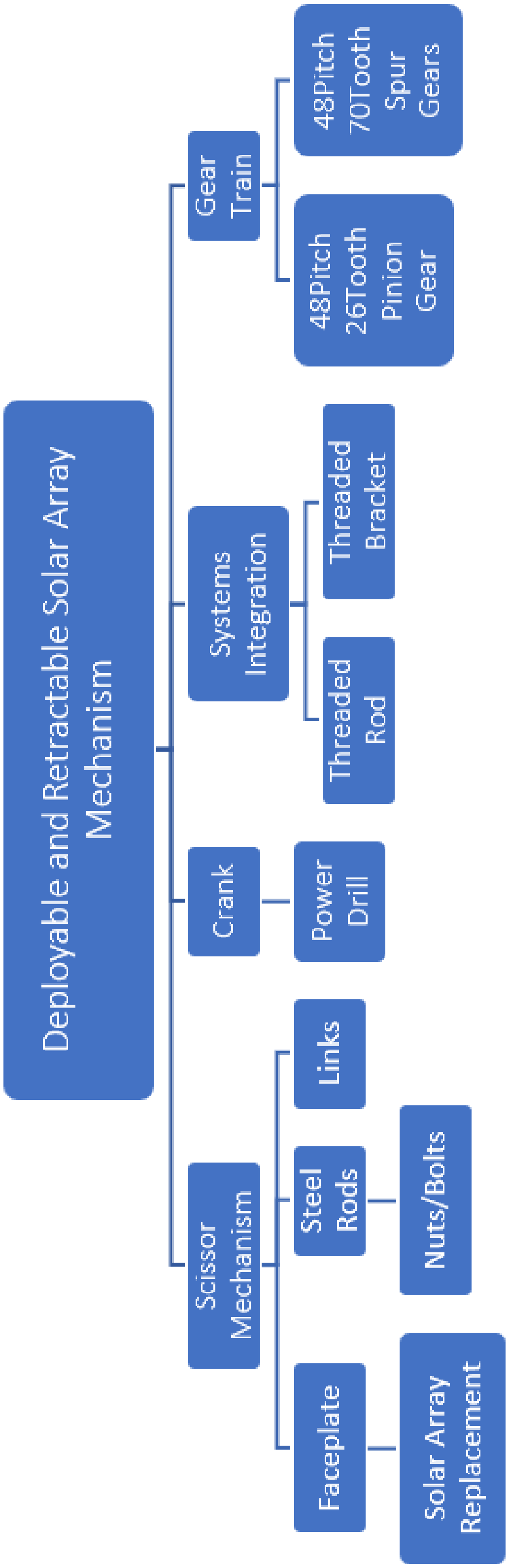
$$t = \frac{\delta * L}{\omega} \qquad (2)$$

$$t = 5.67\, min$$

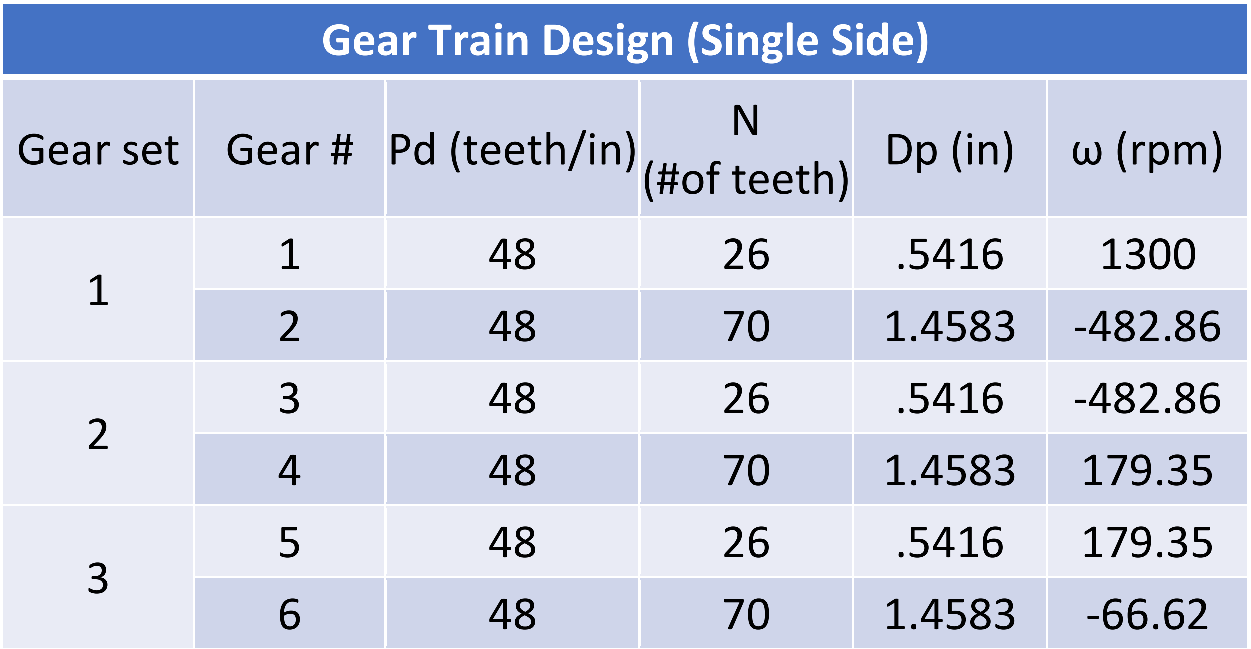
$$5\ min\ 40\ sec$$

Knowing the length of the power screws, the threads per inch, and the angular velocity, the time to close or open can be calculated. This is because the power screws turn at the same rotational speed of gear 6 (66.62 rpm), and the power screw has 32 threads per inch. This means that the power screw will need to turn 32 times per inch of linear motion along the screw. If the screw is turning at 66.62 revolutions per minute and is 11.8 inches long, it will take 5 minutes and 40 seconds to traverse the length of the screw.

12.3. Appendix C. System Hierarchy



12.4. Appendix D. Gear Train Table Explained

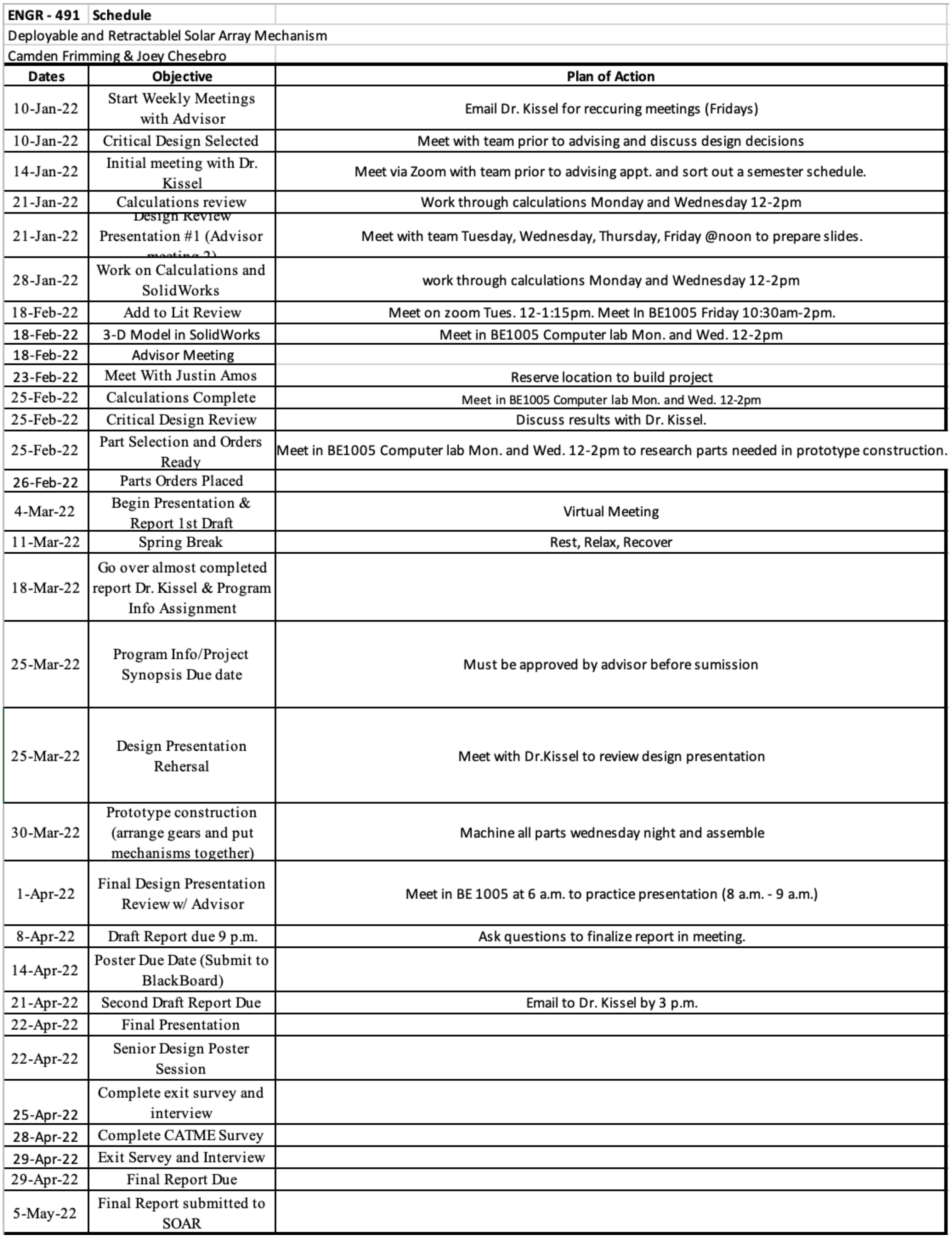


Gear Train Design (Single Side)

Gear set	Gear #	Pd (teeth/in)	N (#of teeth)	Dp (in)	ω (rpm)
1	1	48	26	.5416	1300
	2	48	70	1.4583	-482.86
2	3	48	26	.5416	-482.86
	4	48	70	1.4583	179.35
3	5	48	26	.5416	179.35
	6	48	70	1.4583	-66.62

The two gear types used in this train are 48 pitch with 70 teeth or 26 teeth. The pitch of the gear gives how many teeth per inch there are around the gear and can be described as the spacing of the teeth or how compact the teeth are on a gear. The other numbers, 70 and 26, give how many teeth are on the gear. A rule that must be followed when designing a gear train is that the pitch of meshing gears must match, that is why the gears were chosen to have a pitch of 48. The value Dp is the diametral pitch, this number lets the team know the diameter of the gear. The ratio of each gear set can be found by dividing the first gear in the set by the second, in this case it is always 26/70. Omega (ω) is angular velocity which is how many rotations that gear makes per minute (rpm). This value is calculated by multiplying the ratio of the gear set by the angular velocity. Repeat this process until the end of the gear train is reached. Appendix A shows how quick this calculation can be by making use of exponents that are related to the number of gear sets.

12.5. Appendix E. Schedule



ENGR - 491	Schedule	
Deployable and Retractablel Solar Array Mechanism		
Camden Frimming & Joey Chesebro		
Dates	**Objective**	**Plan of Action**
10-Jan-22	Start Weekly Meetings with Advisor	Email Dr. Kissel for reccuring meetings (Fridays)
10-Jan-22	Critical Design Selected	Meet with team prior to advising and discuss design decisions
14-Jan-22	Initial meeting with Dr. Kissel	Meet via Zoom with team prior to advising appt. and sort out a semester schedule.
21-Jan-22	Calculations review	Work through calculations Monday and Wednesday 12-2pm
21-Jan-22	Design Review Presentation #1 (Advisor	Meet with team Tuesday, Wednesday, Thursday, Friday @noon to prepare slides.
28-Jan-22	Work on Calculations and SolidWorks	work through calculations Monday and Wednesday 12-2pm
18-Feb-22	Add to Lit Review	Meet on zoom Tues. 12-1:15pm. Meet In BE1005 Friday 10:30am-2pm.
18-Feb-22	3-D Model in SolidWorks	Meet in BE1005 Computer lab Mon. and Wed. 12-2pm
18-Feb-22	Advisor Meeting	
23-Feb-22	Meet With Justin Amos	Reserve location to build project
25-Feb-22	Calculations Complete	Meet in BE1005 Computer lab Mon. and Wed. 12-2pm
25-Feb-22	Critical Design Review	Discuss results with Dr. Kissel.
25-Feb-22	Part Selection and Orders Ready	Meet in BE1005 Computer lab Mon. and Wed. 12-2pm to research parts needed in prototype construction.
26-Feb-22	Parts Orders Placed	
4-Mar-22	Begin Presentation & Report 1st Draft	Virtual Meeting
11-Mar-22	Spring Break	Rest, Relax, Recover
18-Mar-22	Go over almost completed report Dr. Kissel & Program Info Assignment	
25-Mar-22	Program Info/Project Synopsis Due date	Must be approved by advisor before sumission
25-Mar-22	Design Presentation Rehersal	Meet with Dr.Kissel to review design presentation
30-Mar-22	Prototype construction (arrange gears and put mechanisms together)	Machine all parts wednesday night and assemble
1-Apr-22	Final Design Presentation Review w/ Advisor	Meet in BE 1005 at 6 a.m. to practice presentation (8 a.m. - 9 a.m.)
8-Apr-22	Draft Report due 9 p.m.	Ask questions to finalize report in meeting.
14-Apr-22	Poster Due Date (Submit to BlackBoard)	
21-Apr-22	Second Draft Report Due	Email to Dr. Kissel by 3 p.m.
22-Apr-22	Final Presentation	
22-Apr-22	Senior Design Poster Session	
25-Apr-22	Complete exit survey and interview	
28-Apr-22	Complete CATME Survey	
29-Apr-22	Exit Servey and Interview	
29-Apr-22	Final Report Due	
5-May-22	Final Report submitted to SOAR	

12.6. Appenix F. Failure Modes and Effects Analysis

Item	Failure Mode(s)	Cause of Failure	Possible Effects	Probability	Possible Action to Reduce Failure Rate or Effects
Project Design Schedule	Get Behind	- Poor Scheduling - Lack of Effort - Time Management	Unfinished SD Project	Extreme	Plan, generate schedules, and set milestones to meet deadlines. Communicate with team to delegate responsibilities clearly.
Parts	Delayed Delivery	-Incorrect part selection. - Not company's highest priority.	Delayed prototype construction	High	Factor delays into schedule allowing for shipping mistakes or backordering.
Prototype	Ill-fitting construction	-Incorrect Calculations leading to subsystem discrepancies in sizes.	No prototype construction/ restart prototype construction.	High	Double and Triple check sizing and subsystem fittings before cutting/bending/attaching materials. Model Design before construction.

12.7. Appendix G. Bill of Materials

Item	Website	SKU/UNSPSC/Model#	Unit Cost	Quantity	Total Cost (+shipping & Tax)
Stainless Steel Round Bar 316\316L 0.375" (A)	Store.buymetal.com	SSR316.00.3750	$6.78	6	$59.70
Fully Threaded Rod, Aluminum, 10-32, 3 ft Length	Grainger.com	31161618	$7.71	1	$18.69
26-T Pinion	Traxxas.com	2426	$3.00	5	$18.67
Spur Gear, 70 Tooth	Traxxas.com	8357	$3.00	10	$34.83
Rotary Shaft, 316 Stainless Steel, 3 mm Diameter, 200 mm long	Mcmaster.com	1265K31	$16.08	2	$34.66
Aluminum Sheet 6061-O 0.125” (t) x 24” x 12”	Store.buymetal.com	S61.1250	$40.58	1	$59.23
SunPower C60 Solar Cell 3.55W	Fullbattery.com	Not Found	$55.40	1 (20 Cells)	$59.90

12.8. Appendix G: Scissor Linkage Calculations

To find the length of each link we will use the drawing seen in Figure 27.

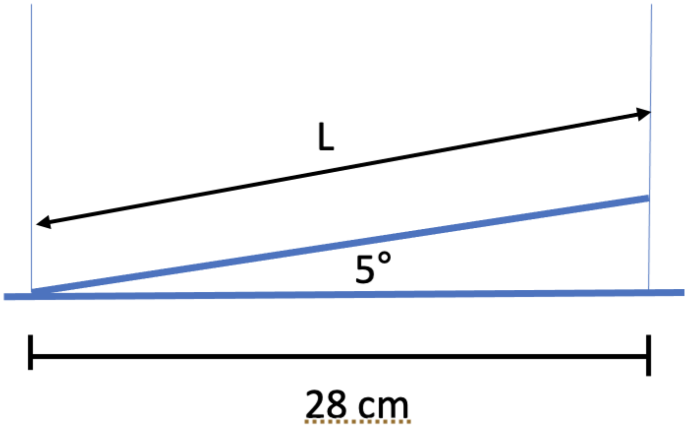


Figure 27. Finding Length of the Links

To find the lengths of the links we start by using the equation below.

$$cos(5^{\circ})=\frac{28}{L}$$

We have all the given information to determine the length L of each link so doing algebra and solving we get.

$$L=\frac{28}{\cos\,(5^{\circ})}$$

L=28.1cm

Now that we have found the length of the links, we can now figure out the maximum and minimum height of the scissor linkage mechanism. Below is the equation for the maximum height of the scissor mechanism.

$$H_{max,tot}=h_1+(2)(N)(Sin(\alpha_{max}))$$

h_1 is the thickness of the platform, N is the number of crossing links, and α_{max} is the maximum angle of the links in the open/deployed position. So, filling out the information below we get.

$$H_{max,tot}=0.079375+(2)(3)(Sin(45°))$$

$$H_{max,tot}=11.45\text{cm}$$

We can then use the equation below to figure out the total height of the scissor linkage in the closed position.

$$H_{min,tot}=h_1+(2)(N)(Sin(\alpha_{min}))$$

h_1 and N will be the same as before and α_{min} is the smallest angle the links will have in the closed/retracted position.

$$H_{min,tot}=0.079375+(2)(3)(Sin(5°))$$

$$H_{min,tot}=1.48\text{cm}$$