University of Colorado
Department of Aerospace Engineering Sciences
Senior Projects – ASEN 4018

Geocentric Heliogyro Operation Solar-Sail Technology (GHOST)
Conceptual Design Document

September 30th, 2013

1.0 Information

1.1 Project Customer

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3.0 Project Description

3.1 Purpose

The GHOST project encompasses the design and integration of a heliogyro solar sail that will control the release of the solar sails during deployment, control the solar sail blade pitching capabilities, and coordinate blade pitching movements for orbit maneuvers. The goal of the design will be to improve current solar designs with the restriction on power, size, and mass to allow more affordable designs in the aerospace industry.

3.2 Objectives

The objective of the solar sail will be to design, build, and test a prototype CubeSat heliogyro solar sail in a 1G environment meant for a space environment. The two main functions of the solar sail are controlled solar sail blade release and controlled blade pitch capabilities. The solar sail blade must have a minimum blade aspect ratio of 100:1 yet gives the solar sail thrust/moment control capabilities with a minimum acceleration of 0.1 mm/sec^2. The mechanical systems for solar sail blade release and blade pitching will be designed to be in a packaged CubeSat no greater than 12U during a launch state, and un-package itself for operation given a command through a communications system. While in operation, the performance of the solar sail is restricted by a power source of 10W.

The customer is also interested in the strength of the design, therefore it needs to survive the vibrations simulating launch. In addition, the solar sail must have capabilities to transfer orbits with a minimum altitude of 1000 km to avoid drag effects.

3.3 Functional Block Diagram (FBD)

Figure 1 portrays the deployment and blade pitch control subsystems of GHOST and how they interact. Note that the team is designing only the Solar Sail Deployment Mechanism (SSDM) and the Blade

Pitch Control System (BPCS) and associated power subsystem (EPS), communication subsystem (COMM), and controller to fit onto an existing CubeSat.

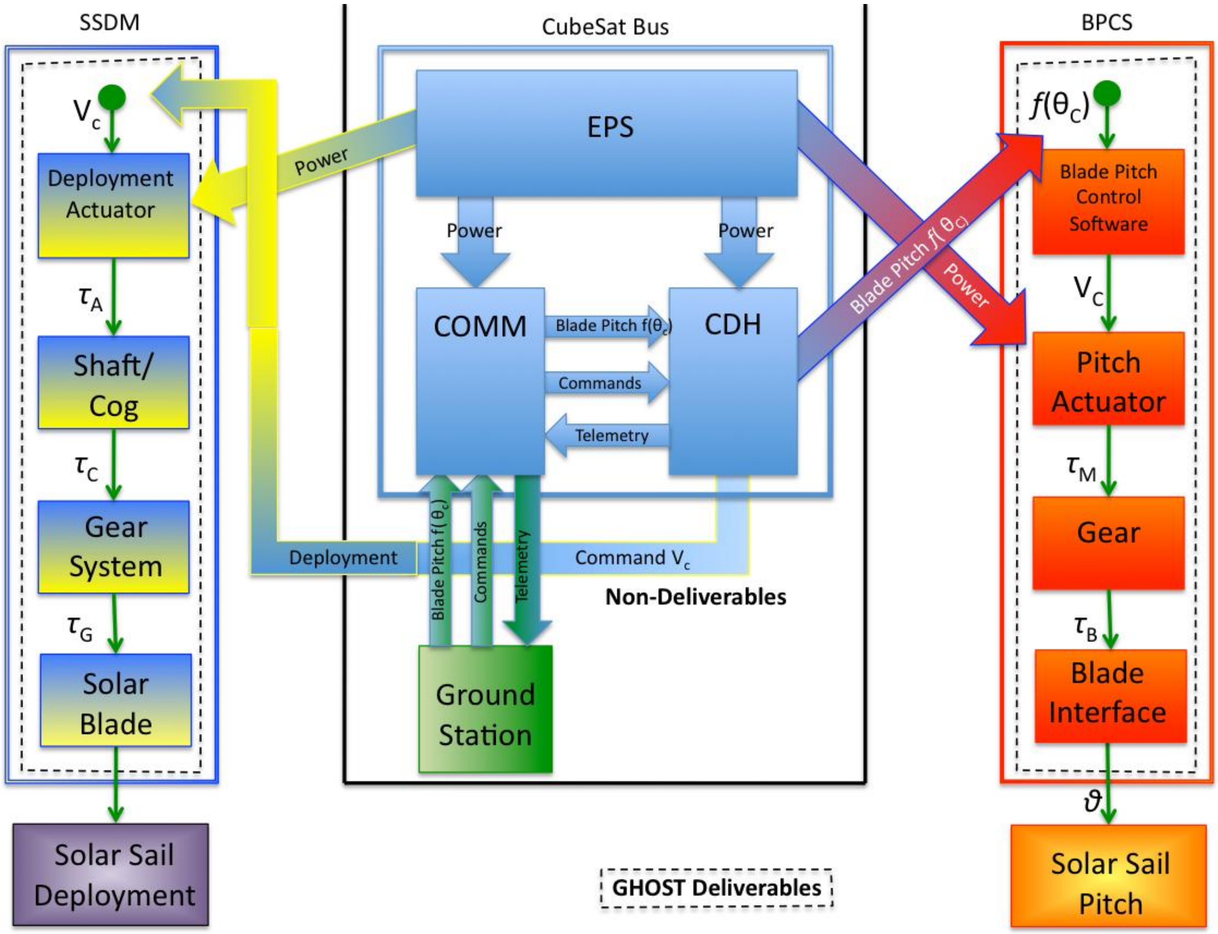


Figure 1. GHOST Functional Block Diagram

The GHOST team will design a Solar Sail Deployment Mechanism (SSDM) and Blade Pitch Control System (BPSC) to fit on a CubeSat. The CubeSat bus may be a purchased COTS CubeSat of less than 12U size or a simulated CubeSat reflecting the desired size specifications. Due to 1-G limitations, both the SSDM and the BPCS will be tested separately. The BPSC test will not control a full-sized sail due to aerodynamic forces and will instead be tested by an added mass equal to the equivalent blade mass. The SSDM, tested independent of the CubeSat and BPSC, may be tested in a 1-G environment on CU campus or a NASA Langley 20 meter vacuum chamber if funds allow. The 1-G environment on earth is used to simulate the acceleration on the sails due to the spacecraft's rotation needed in order to maintain the solar sail's structural stiffness. If one blade can be deployed the same system should work for as many blades as needed.

In its final production state, information of the deployment and pitch commands will come from personnel on the ground. The mechanical GHOST solar sail deployment mechanism will initiate once the deployment command is made. In the case of a pitch command (i.e. a specific blade pitch angle or pitch algorithm), the blade pitch control software will govern the actions of the blade pitch control system and actuate the blades to the desired pitch angle. Pitch control of undeployed solar sails in a 1-G environment will be used to simulate deployed solar sail through the assumption that there will be no drag enacted on the solar sail in space.

3.4 Concept of Operations (ConOps)

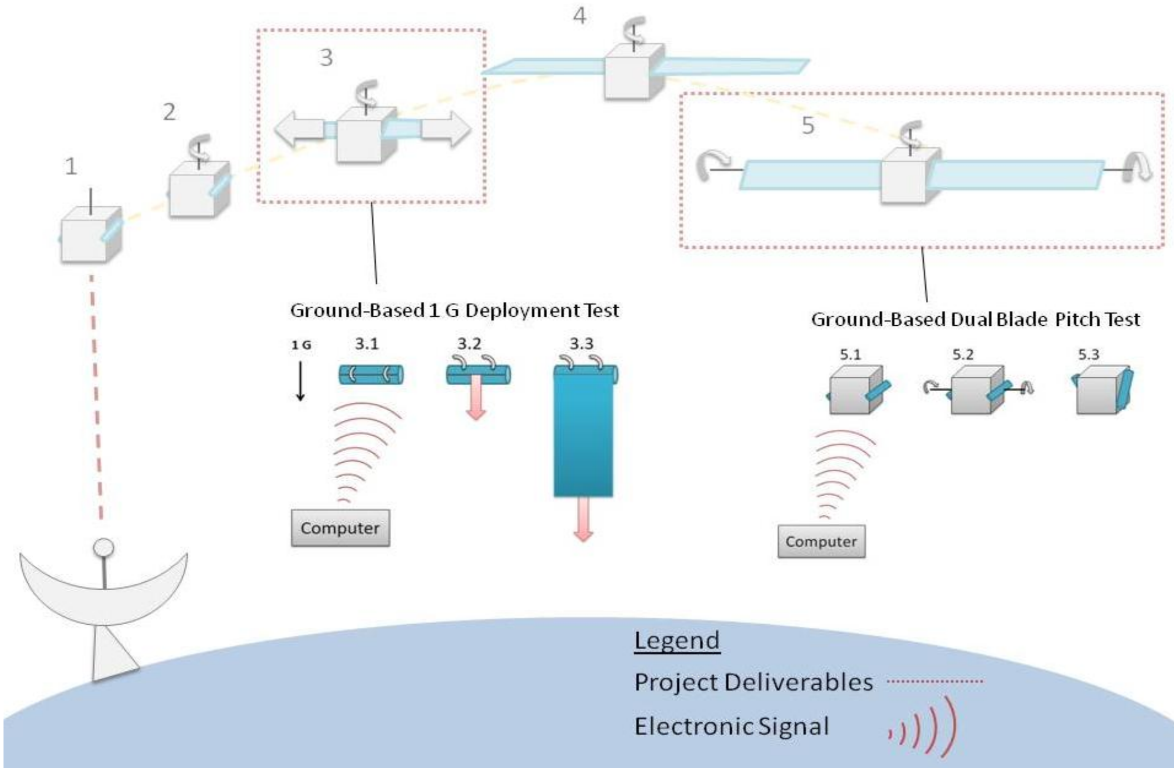


Figure 2. Blade Deployment Pitch Control Concept and Testing

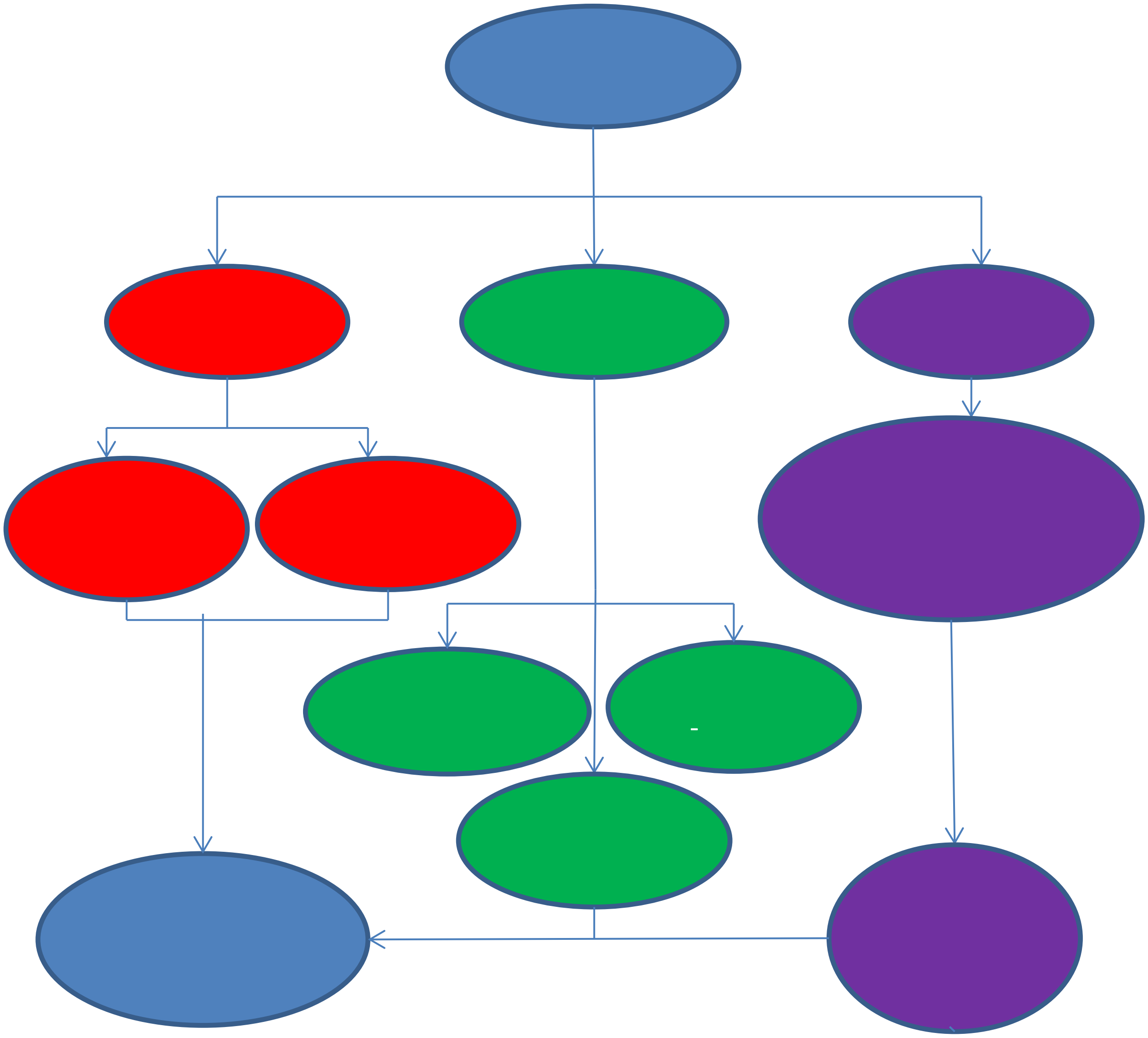
1.0 Establish connection with spacecraft
2.0 Initialize spin when satellite at appropriate altitude
3.0 Controlled deployment sails via motors (SSDM)*
3.1 Suspend undeployed blade in 1G
3.1.1 Establish electronic connection with locking mechanism
3.2 Initiate deployment mechanism
3.3 Sail deployment using motors
4.0 Spacecraft at full deployment
5.0 Pitch solar sail roots (BPCS)*
5.1 Establish remote connection with pitching mechanism
5.2 Send appropriate pitch command
5.3 Measure resulting torque from pitching using an outside accelerometer.
5.4 Measure resulting pitch angle
5.3.1 Record actual pitch angle and compare to expected pitch angle
5.3.2 Ensure both actuators are capable of generating synchronized- collective, ½ P, and 1P cyclic root pitch deflections.

***The bold sections of the ConOps indicate the two, independent operations tests that will be performed.**

3.5 Functional Requirements

The solar sail is comprised of three main design aspects: an electronic system, a deployment system, and a blade pitching system. The functional requirements for the electronics system are a maximum power available of 10W and there must be a wireless communications system. For the deployment system, the blade must have a minimum aspect ratio of 100:1 and have a controlled deployment rate at 1-10 cm/s. For the pitching system, there must be two blades that can rotate 180 degrees. And finally, all these systems must fit in a CubeSat that is no larger than 12U.

4.0 Design Requirements



1.0 Deployment system must release sail in a 1G environment that simulates controlled deployment at a sail release rate between 1-10 cm/s.

- 1.1 Deployment system initiates with wired electronic signal.
  - 1.1.1 Deployment system initiates with radio signal.
  - 1.1.2 This is a team GHOST requirement
- 1.2 Deployment system is compatible with 15-20 meter long solar sails.
  - 1.2.1 Deployment system is compatible with solar sails with 100:1 aspect ratio.
  - 1.2.2 15-20 meter solar sail is a team GHOST requirement
  - 1.2.3 100:1 aspect ratio is a customer requirement
- 1.3 Deployment system performs in vacuum chamber or similar environment.
  - 1.3.1 This is a team GHOST requirement

2.0 Blade control system performs controlled pitching given user input.
- 2.1 Blade control system demonstrates 180° pitching range from -90° to +90°.
  - 2.1.1 Blade control system performs controlled pitching given wireless or radio signals.
  - 2.1.2 Blade pitch control system displays the ability to employ all three pitch control algorithms: collective, ½P, and 1P
  - 2.1.3 Controlled pitching is a customer requirement
  - 2.1.4 The degree of pitching and the type of pitching are a team GHOST requirement.
- 2.2 Blade control system performs controlled, coordinate pitching without adding significant torque.
  - 2.2.1 Pitch with added mass, simulating the solar sail. This can be done because there are no aerodynamic forces in space.
  - 2.2.2 This is a team GHOST requirement
- 2.3 Change the surface area in order to simulate change in orbits by changing solar photon reflection.
  - 2.3.1 This will be validated using equations on orbits and solar photon energy
  - 2.3.2 Orbit changes is a customer requirement

3.0 Deployment and pitching system are both able to fit in a cube satellite or simulated bus satellite no greater than 120^3 cm^3.
- 3.1 Systems can withstand expected radiation
  - 3.1.1 This can be validated by researching the material and using computer simulations.
- 3.2 Systems can survive vibration test
  - 3.2.1 This can be validated by putting the final integrated design on a vibration stand
- 3.3 This is a customer requirement

4.0 Testing and validation of all systems
- 4.1 Validate in a 15-20 meter tall room that the solar sail can deploy at a rate of 1 to 10 cm/s.
  - 4.1.1 This will be used to validate team GHOSTs deployment mechanism
- 4.2 Verify and validate specified pitch angles within a 5% error of the command given with an ADIS16xxxIMU sensor (obtained through Trudy)
  - 4.2.1 This will be used to validate team GHOSTS pitching mechanism.

5.0. Materials, testing, and travel do not exceed budget of $5000
- 5.1 Obtain as many free materials from customer as possible
- 5.2 This is an ASEN department requirement

5.0 Key Design Options Considered

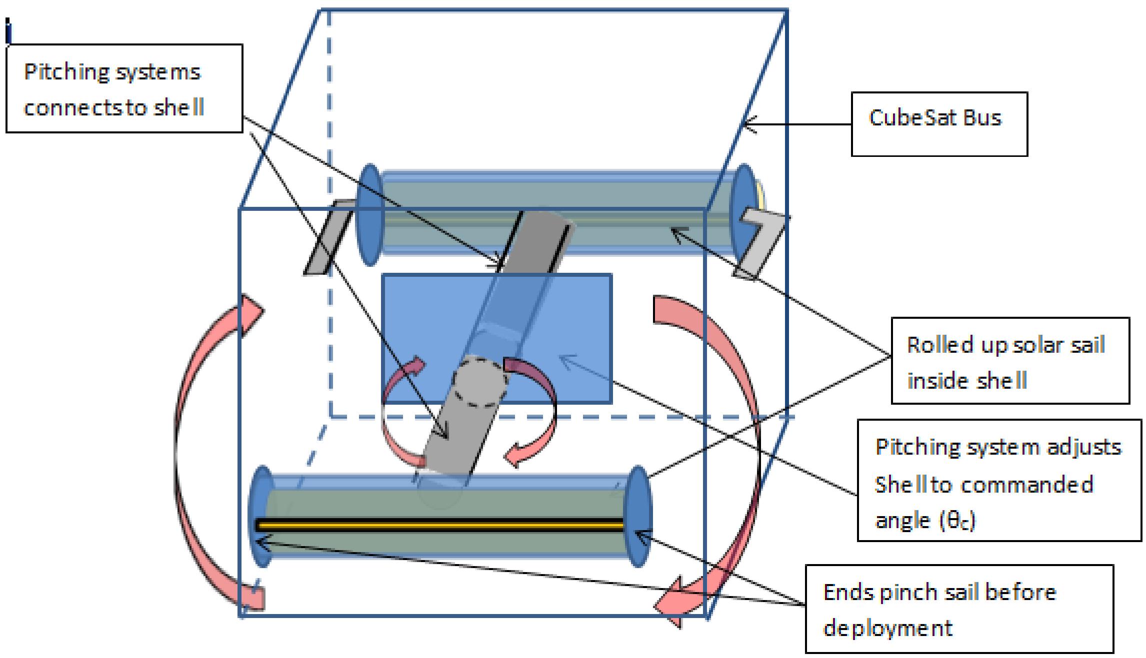
5.1 Interface:

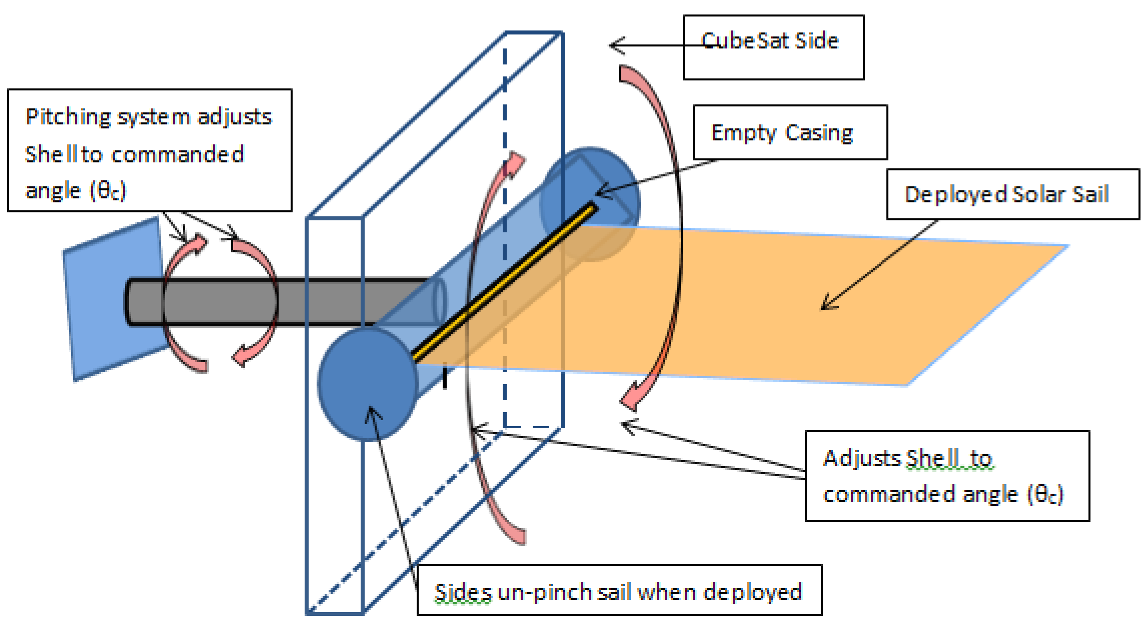
The GHOST team will be designing two separate systems: a solar sail deployment mechanism and blade pitch control system. Although both systems will not be tested together due to 1G limitation, creating a valuable and synchronized system for future use on the future HELIOS missions is vital to project success. In order to integrate the two systems together geometrically and validate their functional harmony, the GHOST team developed designs for an interface system to connect the deployment and pitching systems. The interface system is purely mechanical with no electronics or moving parts, but is a bridge between the pitching and deployment systems.

5.1.1 Shell Casing Assembly

The concept design of the casing roller is to integrate a gear mechanism in the inside of hollow tubing that will allow the blade to be unrolled and, if mission requirements dictate, rolled up. The design utilizes a motor attached to the end of metal tubing that will control the roller. Parallel to the length of the hollow tube, there is a slit where rollers may be attached at both ends to help glide the blades into and out of deployment. For initial packaging, the blade will stick out of the slit with weights attached to prevent the blade from being rolled entirely inside the casing, as well as aiding the blade to unravel when released. The rollers on either end of the slit will be designed to pinch the blade during packaging and will un-pinch the blade at the beginning of the blade deployment. The advantage of the casing will be to protect the sheet during launch, as well as protect the roller inside from direct solar radiation in addition to the ability to control when the blade is to be released.

Since the metal casing will extend from the bus, a mechanical deployment system must be designed to extend the roller out of the bus. Due to the weight of the casing, it must be stabilized by both ends, although it can be supported on one end if the arm is built stronger. The wiring for the system must also run along the length of the arm, so the design must be able to integrate the wiring during the extension of the arm so the wires do not interfere.





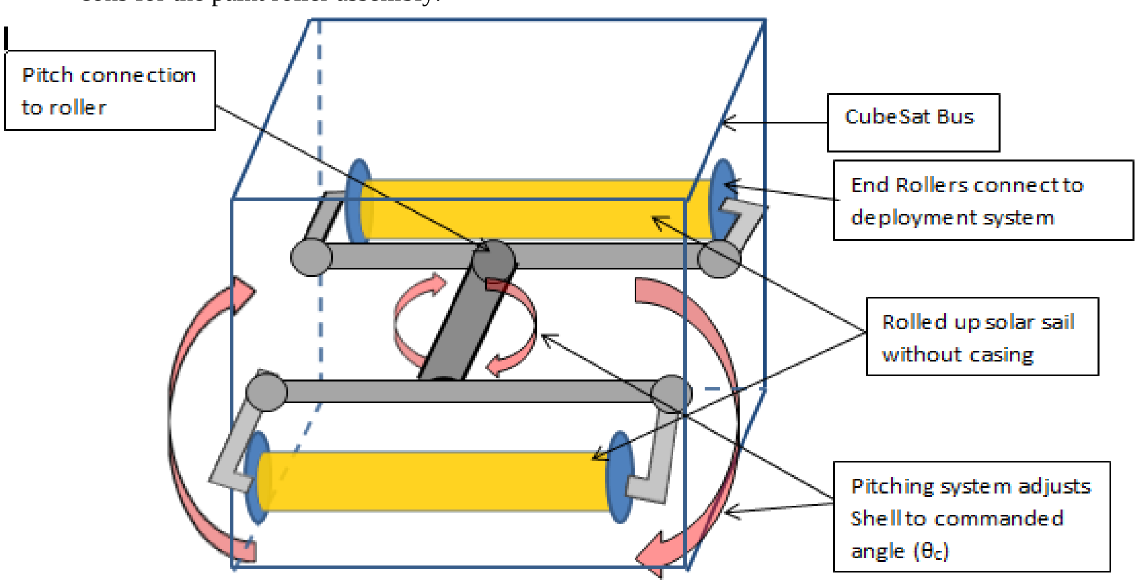
The shell would be designed to be made of aluminum, as aluminum is a lightweight material, and the shell does not undergo extreme stress conditions, so a stronger material, such as titanium, would not be needed. While the solar sail is being unraveled, the angular velocity should prevent the solar sail from bunching inside the shell, but less error-prone design would be to design the rollers with motors such that the rollers pull on the solar sail during deployment while the main reel motor pushes the solar sail out. The designed motors for the rollers would be roller screw actuators [1] which would allow the rollers to spin and give the solar sail sheets a linear velocity.

Table 1. Shell Casing Pros and Cons

Factor	Description	Pro/Con
Space Applicability	The casing will allow protection for the blade, as well as roller from debris and solar radiation.	Pro
Cost	The cost of the shell would be $15 and the cost of both rollers is $18. The total cost would be $33 not including integration materials. With a roller screw actuator to turn the rollers, (each $500) [4], total cost is $1033.	Con
Mass	The density of aluminized mylar is 1.00 g/cm^3 [1], density of aluminum is 2.70 g/cm^3 [2], and mass of rollers are 0.09 kg [3]. The total mass is about 0.5 kg [A1]. Addition of motors, mass would increase to 0.7 kg. [4]	Con
Volume	The volume of the casing with the rollers is about 440 cm^3 [3], since the additional motors would slide inside the rollers.	Pro
Simplicity of Mechanics	Multiple moving parts, two extra motors attached, and then the functionality would still be questionable.	Con
Testability	Motor allows the blade to be reeled in, multiple tests can be performed.	Pro
Integration	Would need an extra motor that is external to the bus, thus the complication of running power externally would make it harder to function with the bus. In addition, the angular velocity of the reels and rollers must give the same velocity based on their radius.	Con
Launch-Survivability	The stability of the casing will protect the blade from entanglement and tearing.	Pro

5.1.2 Paint Roller Assembly

Another idea to deploy the heliogyro solar sail blade stems from the structure was taken from the idea of a paint roller. Each blade is rolled up on a large axle, which has two rollers attached to each side. The rollers will be connected to a gear depending on the deployment method chosen. The motors of the deployment mechanism are secured on the holding structure by brackets to make sure they do not pivot or become misaligned with the gears. The structure forms a boxy 'U' shape around the entire mechanism for maximum stability. The axle that holds the rolled up blade and the motors all are secured by their attachment with the holding structure. Finally, the motor cables and wiring can be fed through the holding structure if needed (assuming it is hollow) and travel down to the bulk of the CubeSat bus where the necessary wattage is provided to the motors. Table 2 summarizes the pros and cons for the paint roller assembly.



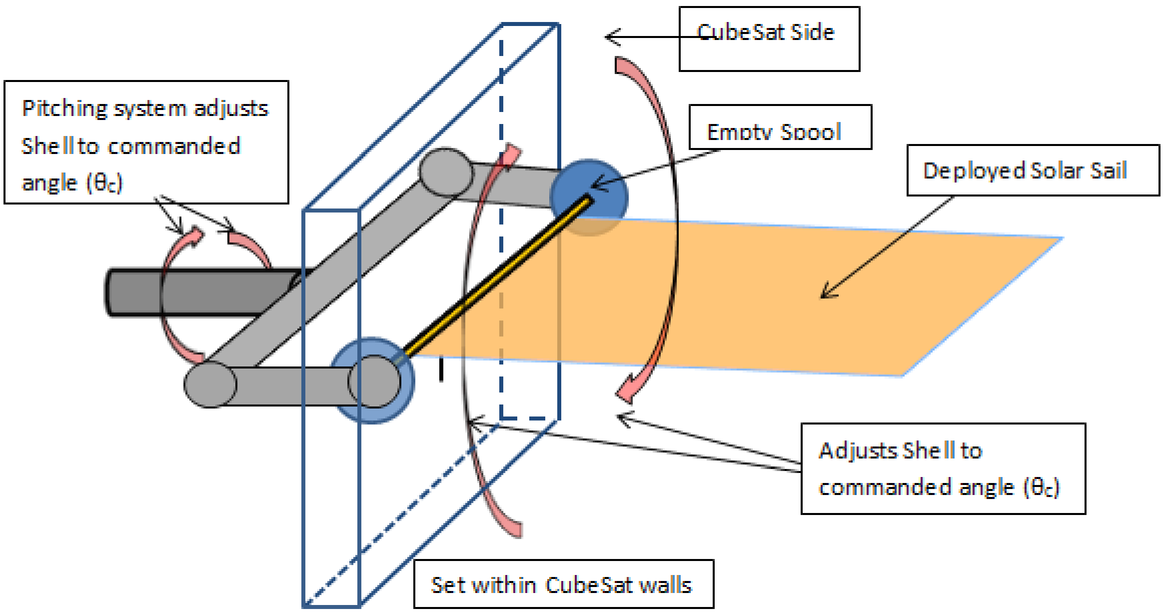
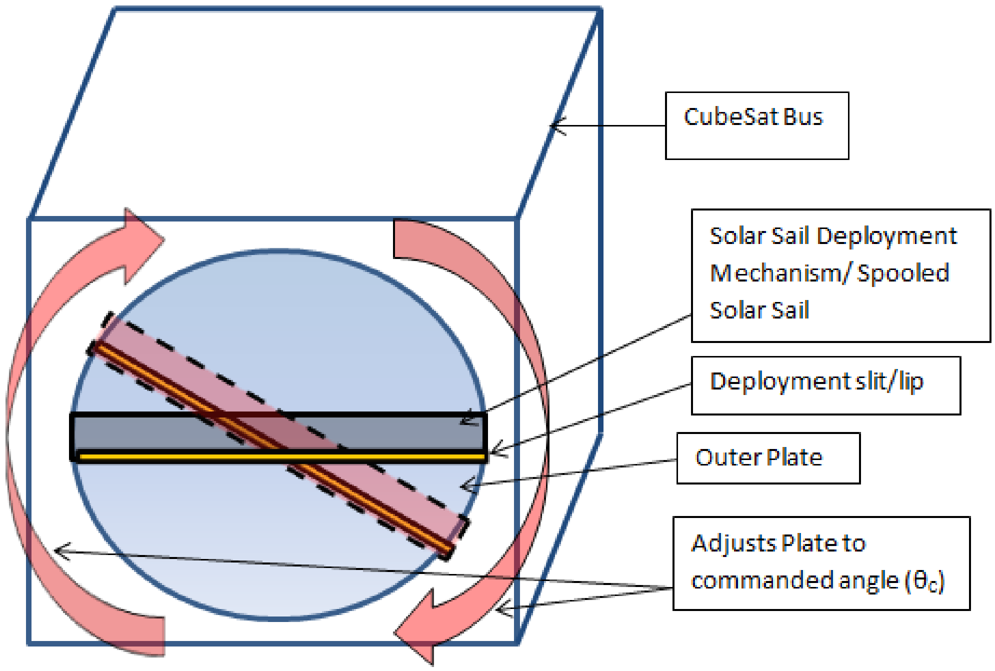


Table 2. Paint Roller Pros and Cons

Factor	Description	Pro/Con
Space Application	Slight modifications to structure will improve launch survivability allowing an acceptable space relevance.	Pro
Cost	Low mass per U and volume of structure per blade, parts needed to build mechanism are relatively simple (machining costs low, common parts can be ordered). Majority of structure is aluminum, which is $0.40/kg [5]. For entire structure, with gears and motor, total cost is $620. [A2]	Pro
Mass	Density of aluminized mylar is 1.00 g/cm^3 [1] giving a blade mass of 0.01 kg. Density of aluminum is 2.70 g/cm^3 [2], giving a structure mass of 0.21 kg. With the added gears, axles, and motors, the total mass comes to about 0.45 kg.	Pro
Volume	Total volume of structure with gears, axles, and motor is about 140 cm^3. With necessary empty space between gears and structure, total volume should not exceed 200 cm^3.	Pro
Simplicity of Mechanics	Many parts (although small and light) will be needed to fully construct the assembly for one blade, number of needed parts will greatly increase with each added blade.	Con
Testing	Motor used to control blade deployment allows for an easy return to initial state, repeatable tests practicable.	Pro
Integration	All cables and wiring can be led through base of structure to communicate and work with other subsystems (control, power, communication, electronics).	Pro
Launch Survivability	Delicate structure with precise part association may be shifted or damaged during launch, vibration analyses would have to be performed to reduce this risk.	Con

5.1.3 Circular Plate Assembly

The circular plate interface design utilizes a plate embedded within the CubeSat to turn as a dial. As the plate turns the commanded amount, the solar sail and deployment mechanism, which is embedded within the plate, turn as well. The plate fits onto a CubeSat side and is controlled from the the pitching mechanism inside. The dimensions of the plate are sized to the CubeSat structure and the solar sail width. The plate could be made up of material dependent on mass, volume, or inertia constraints.. Below in Table 3 describe the pros and cons of this interface design.



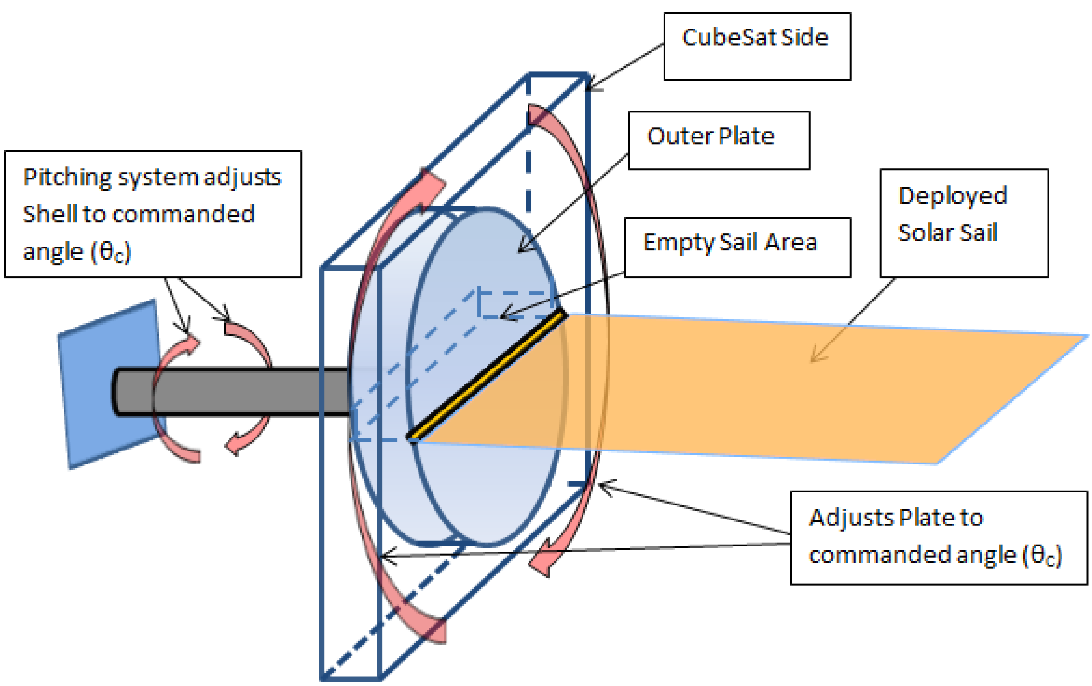


Table 3. Circular Plate Pros and Cons

Factor	Description	Pro/Con
Space Applicability	Of each interface design, this is the simplest and most likely to perform in space.	Pro
Cost	Higher cost depending on material. Approximate is $720. [A3]	Con
Mass	Less than a solid wall on the side of the spacecraft.	Pro
Volume	Essentially one of the walls of the satellite, takes up no extra volume.	Pro
Simplicity of Mechanics	Simple design with one part.	Pro
Testability	Easy to test strength with load analysis and test.	Pro
Integration	Easy to integrate with any chosen deployment system and any chosen pitching system.	Pro
Launch Survivability	A single part should survive launch, but this is not proven.	Con

5.2 Deployment:

5.2.1 Motor and Gear Deployment Method

The motor and gear deployment uses an electronic deployment signal sent to the CubeSat to initiate the deployment command. A decoder will receive this command and begin the deployment process by starting the motor. The motor is connected to a rotor, which is connected to a main gear which rotates with the motor. A smaller, central gear, which is welded to the solar sail rod, moves with the bigger gear so that the motor can use less power. The motor uses less power because the smaller gear moves faster than the bigger gear. The solar sail will be held by a deployment lip that will release with the deployment command to assist with deployment. A weight will be placed at the solar sail (as seen in diagram) end to keep the sail taught during deployment and prevent bunching of the spool. The motor should be a brushless motor because it needs to simulate space travel. "Glues, insulation's, varnishes, greases and other materials selected for lowest cost, typically evaporate or outgas very quickly in a vacuum. In addition special attention needs to be given to open connections to prevent arcing when the insulation effects of air are removed. Finally, without the cooling medium of air, the motors run hotter than normal, the higher temperatures lead to rapid failure." [6] Brushless servo motors are vacuum rated and can be used in space. The Table 4 below shows the pros and cons of this deployment design.

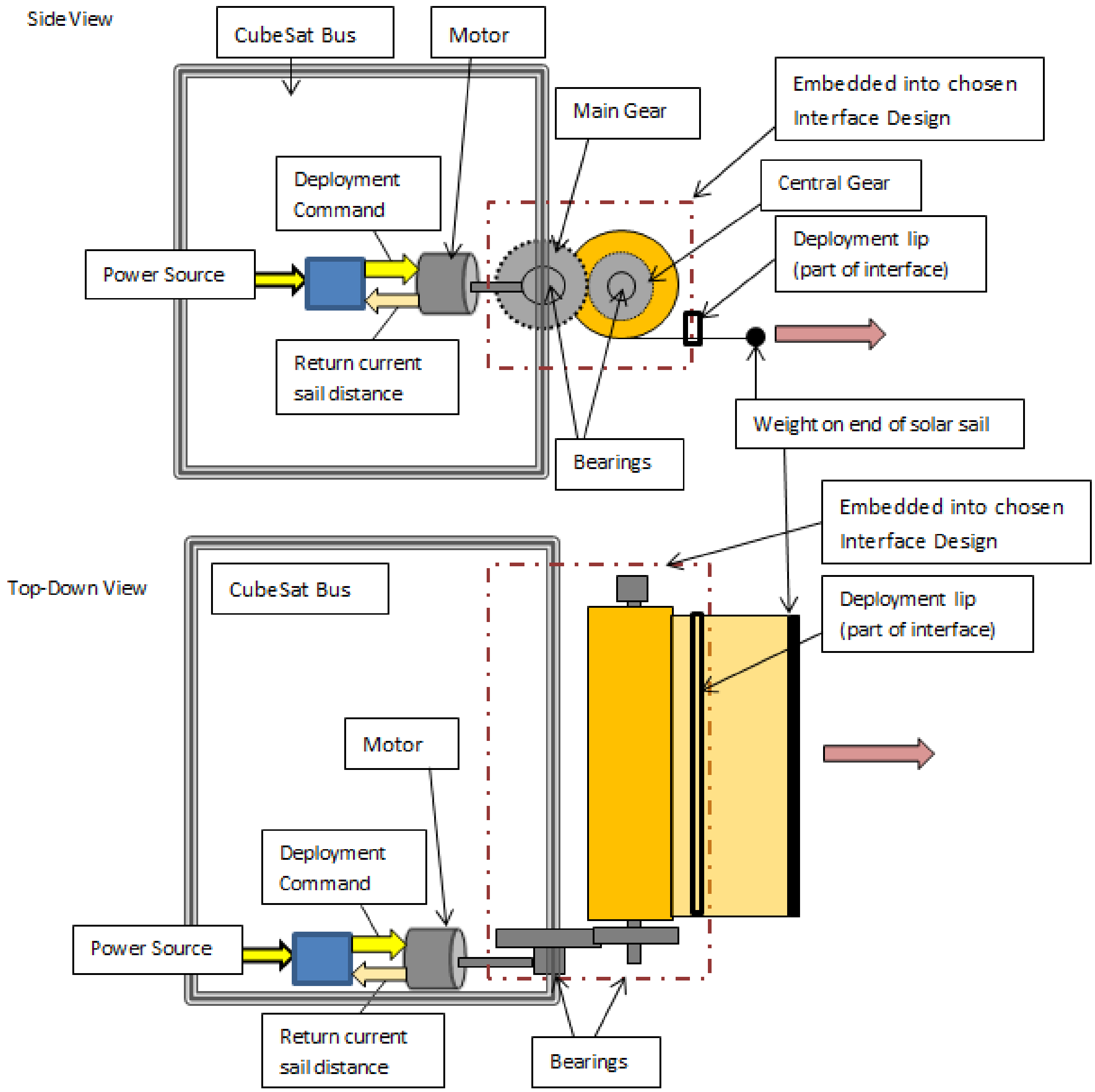


Table 4. Motor and Gear Deployment Pros and Cons

Factor	Description	Pro/Con
Space Applicability	Motors and Gears are space-applicable. The deployment rate is controllable, and it is possible to roll it back in.	Pro
Cost	Medium cost of motors and gears.	Neither
Power	Power needed to run the motor will not require a large percent of provided power.	Pro
Mass	Medium. Need to consider the weight of the motors and gears.	Neither
Volume	Motor and gears would take up a lot of room because of all the parts.	Con
Simplicity of Mechanics	Multiple parts. Not as simple as it could be.	Con

Controllability	Can control very easily how fast the motor deploys the solar sail.	Pro
Testability	Very easy to test and repeatable.	Pro
Integration	Very easy to integrate with pitching, any interface could work with it.	Pro
Launch-Survivability	Gears and motors are very sturdy (locking mechanisms help secure structure).	Pro

5.2.2 Spring Deployment Method

In the following figure, the rolled-up solar sail (yellow) is deployed via a locked spring mechanism. Initially, the latches (black) are in place and keep the springs compressed. A deployment command is then sent to the two latches and the spring suppressors are removed. This allows the springs to reach their full extent which, in turn, removes the locking mechanism from the undeployed solar sail and begins to spin the central spool of the solar blade. (Note that, in the locked position, the motor would be unable to pitch. As an advantage, it would be stable during launch, but as a drawback, it could only be pitched after the blades are deployed.) A deployment lip is located on one end of the solar blade role in order to help guide the unfolding sail and to keep the sail flat during deployment. The solar sail tip will be held by a deployment lip with an attached weight to keep the sail deployment uniform. Table 5 summarizes the pros and cons of the spring deployment method.

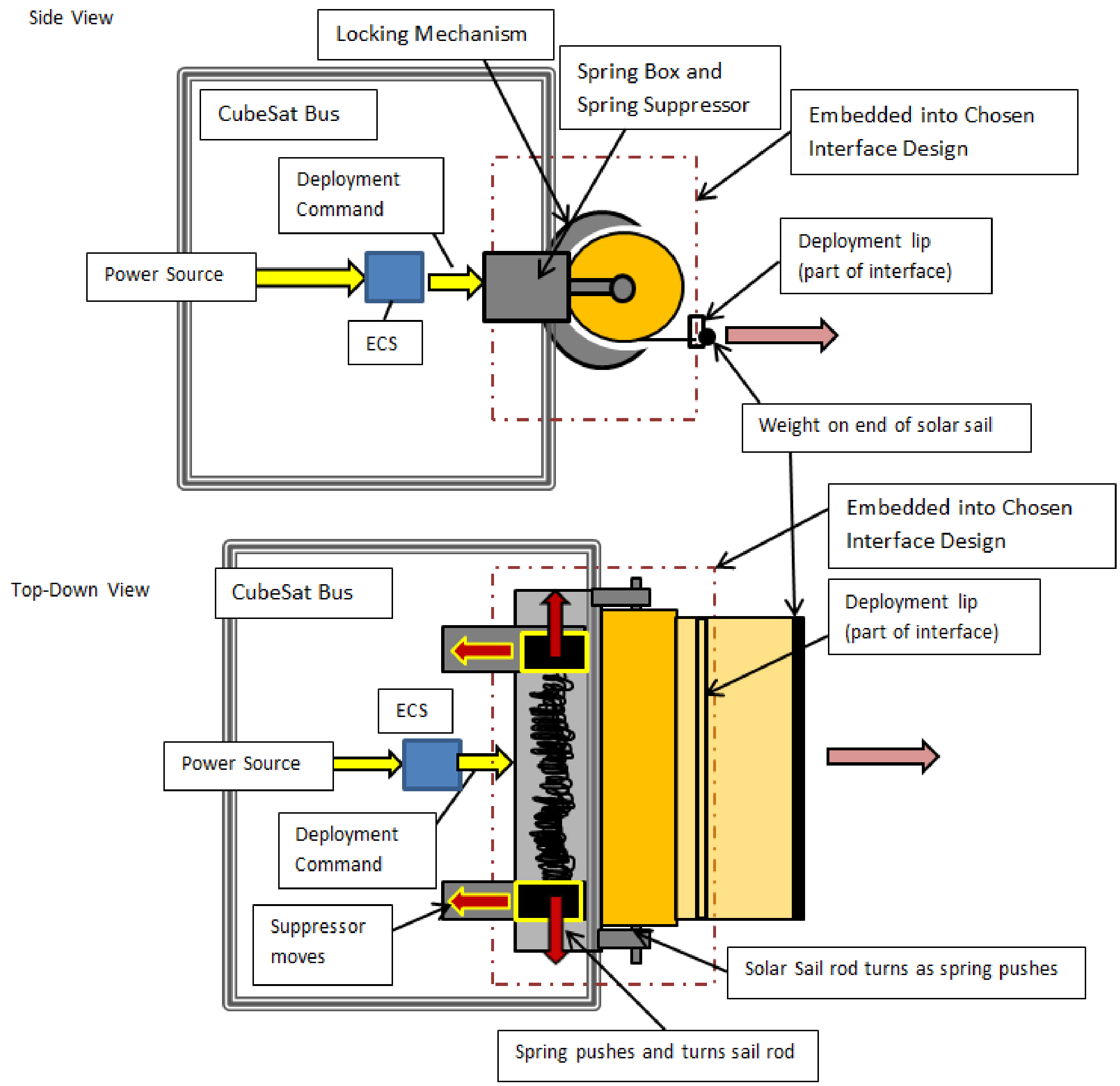


Table 5. Spring Deployment Pros and Cons

Factor	Description	Pro/Con
Space Applicability	It has been proven on previous space missions, but is not particularly applicable to the HELIOS mission as the point of the HELIOS mission is to deploy without additional structural support.	Con
Cost	Cheap (two springs and a strips of passive, measuring-tape-like material).	Pro
Power	None; fully mechanical deployment.	Pro
Mass	Low. Would not need a shell or motors/actuators Weight of one 1" spring = 0.02 lbs = 9 grams [7].	Pro
Volume	Springs would take up less room as there are less moving parts Volume of one 1" spring with a diameter of .25" = 0.05 in^3.	Pro
Simplicity of Mechanics	Very simple, completely mechanical.	Pro
Controllability	It would deploy all at once and the rate would not be controlled. (Spring stiffness constant = 9.58 lb/in).	Con
Testability	Very easy to test, but not as easily repeatable.	Con
Integration	No electronic parts, so integration would be simple. Also easy to integrate with all three interface options.	Pro
Launch-Survivability	It is less sturdy as the mechanical system would have more parts incorporated into the structure.	Con

5.3 Pitching:

5.3.1 Bike Chain: Dual Motor Dual Belt Pitch Actuation Design

The basis of the design is using a single motor attached to a single belt in order to actuate a single solar blade to the desired pitch angle. The total system is comprised of two setups that are either parallel or opposite of one another. For simplicity, the details of an individual symmetric pitch actuation setup are explained. The brushless motor will connect to a horizontal (adverse) gear that will then control the movement of a belt interfaced with this gear. The motor gear connection will be in the middle of the spacecraft at one end of the belt. The end of the belt will interface with another horizontal (adverse) gear that is also attached to a vertical gear just below it. This vertical (central) gear will then connect to the blade pitch interface and thus, the solar blade. When the motor is given a command from the blade pitch control software, it will rotate the primary horizontal gear and move the belt a certain direction and distance corresponding to the desired pitch. The belt will then rotate the end horizontal gear and therefore, the vertical gear. As a result, the solar blade will achieve a pitch of the desired amount. Both setups are individual systems, and together, make up a symmetric solar blade pair where each blade can be pitched independently of one another.

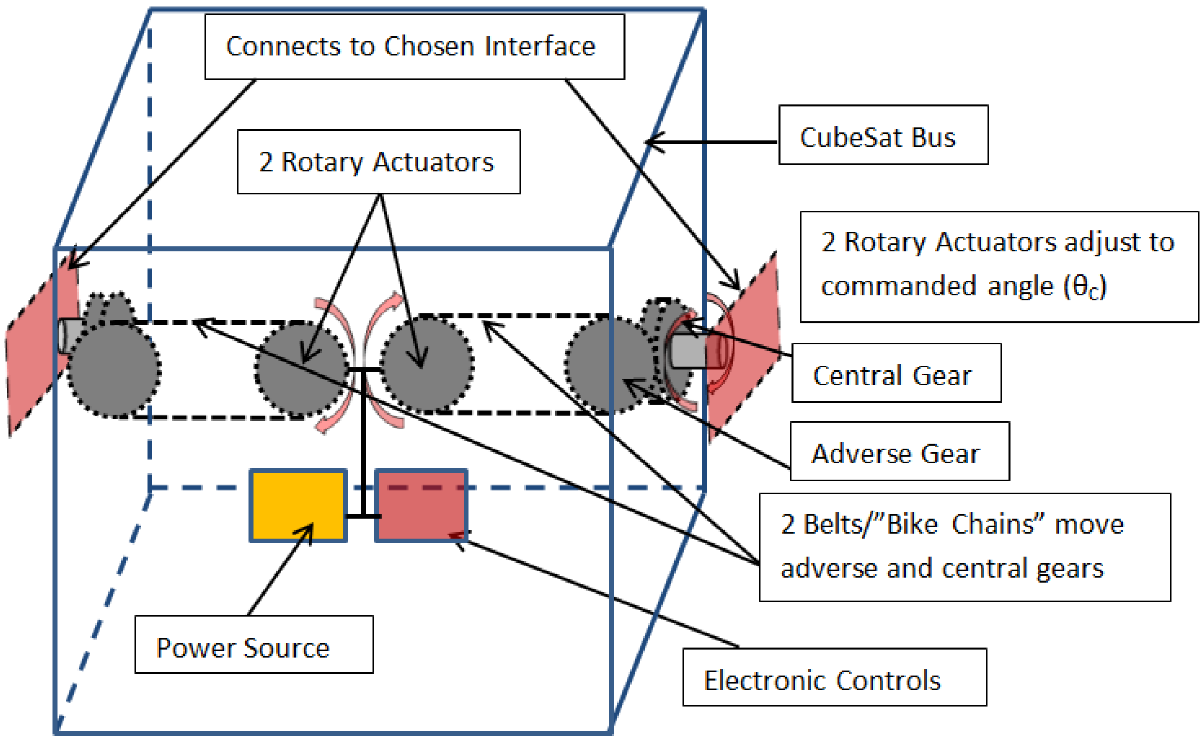


Table 6. Bike Chain Pros and Cons

Factor	Description	Pro/Con
Space Applicability	Not very space applicable; belt (carbon fiber reinforced polyurethane [9]) will likely snap in a cold environment, and any kind of lubrication for belt – gear system will freeze as well. Would need further thermal protection systems to translate to a space environment.	Con
Cost	Very cheap (two belts, two motors, and 4-6 gears) Estimate: ~$600 to $800.	Pro
Power	Nominal: 2 Motors ~5W each = ~10W [8].	Neither
Mass	Total mass ~1 kg.	Neither
Volume	Belt configuration will take up a lot of space inside of s/c: >1000 cm^3 for total volume [9].	Con
Simplicity of Mechanics	Fairly simple, completely mechanical.	Pro
Accuracy	With a gear-belt assembly, it will be very difficult to achieve the accuracy necessary for a space-ready system.	Con
Testability	Very straight-forward to test and repeatable.	Pro
Integration	Software & Electrical: Easily integrated into system Mechanical: Very difficult to keep belt in position from deployment from spacecraft to active use.	Neither
Launch-Survivability	Not very good; very possible that belt will come out of position amidst launch vibrations.	Con

5.3.2 Gear and Spring Pitching Design

This system uses an actuator hooked up to two gears. The size of the gears is determined so that the gear ratio is large enough to prevent back-driving, but low enough to provide a rapid response to changing commands. The gear ratio must also be large enough to provide an acceptable level of accuracy. Between the blade and the second gear is a spring that provides a damping coefficient to minimize twisting and torsional effects of the solar blade as the blade root is pitched. This design is based slightly on Mr. Richard S. Blomquist's Two Actuator Design proposed in "Heliogyro Control." [12] Blomquist's original design incorporated two actuators: a main actuator providing the pitching control and a second actuator to dampen the resulting twisting. His overall idea to provide a method of control and damping to keep the solar sail blade from twisting was used in this simplified design shown below.

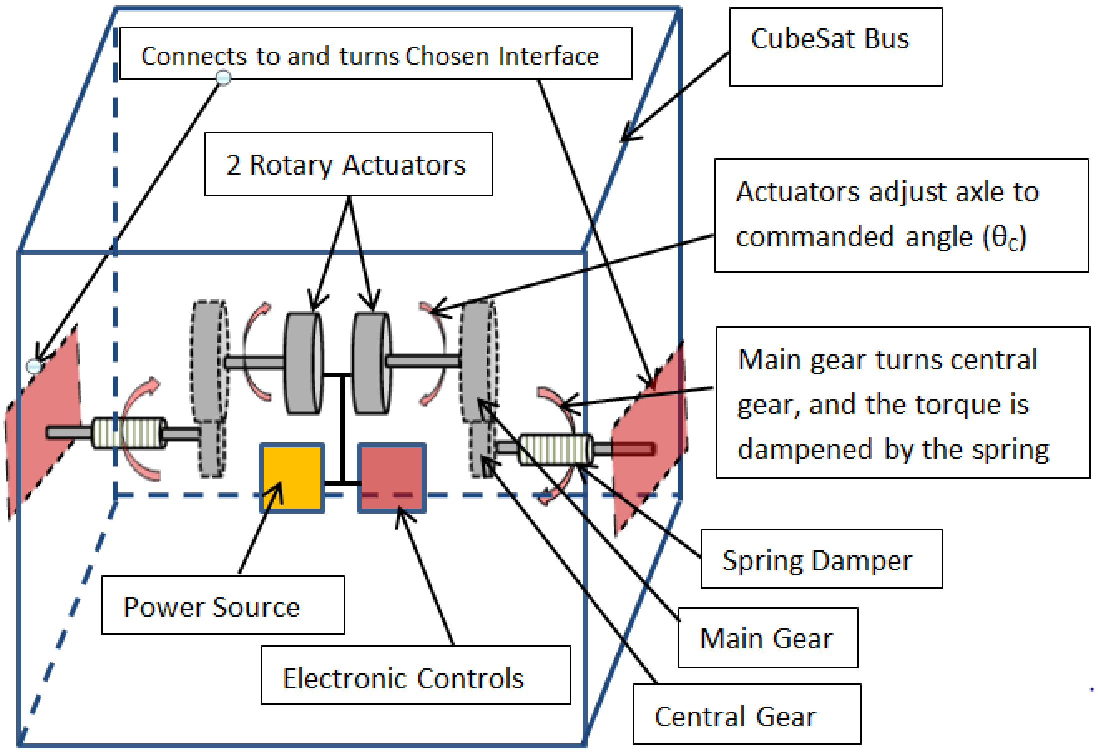


Table 7. Gear and Spring Pros and Cons

Factor	Description	Pro/Con
Space Application	Using space grade materials and slight modification to ensure launch survivability will make this design high space relevant.	Pro
Cost	Using one actuator and a spring with a specific stiffness coefficient per blade will make this design more costly.	Con
Power	This design will only require one actuator per blade and will not run while the deployment mechanism is drawing power.	Pro
Mass	One actuator, two gears and one spring per blade.	Con
Volume	Minimal structural design and small parts.	Pro
Simplicity of Mechanics	Many parts (although small and light) will be needed to fully construct the assembly for one blade.	Con
Accuracy	Higher accuracy can be obtained by changing the gear ratio.	Pro
Testing	Actuator, gears and spring are all unaffected with each test, allowing for numerous testing without resetting the system.	Pro
Integration	The design may attach to any type of solar sail interface and will not interfere with the deployment system.	Pro
Launch Survivability	A sturdy structure with few delicate parts leads to a high level of launch survivability.	Pro

5.3.3 Bi-Axle Pitching Design

The bi-axle pitching design utilizes two identical axles within the CubeSat to turn to a commanded degree at the same time. The actuators or gears are controlled and powered by a central control box. The system may be designed to send two commands that would be interpreted by both sides independently or uniformly. As the axles turn the commanded amount, the solar sail and interface mechanism turn as well. The central control box fits into the bus center and can be sized according to the CubeSat and solar sail size. This design would also limit the volume as all of the hardware and software would fit into the designed central control box. Below is a table to analyze the pros and cons of this pitching design.

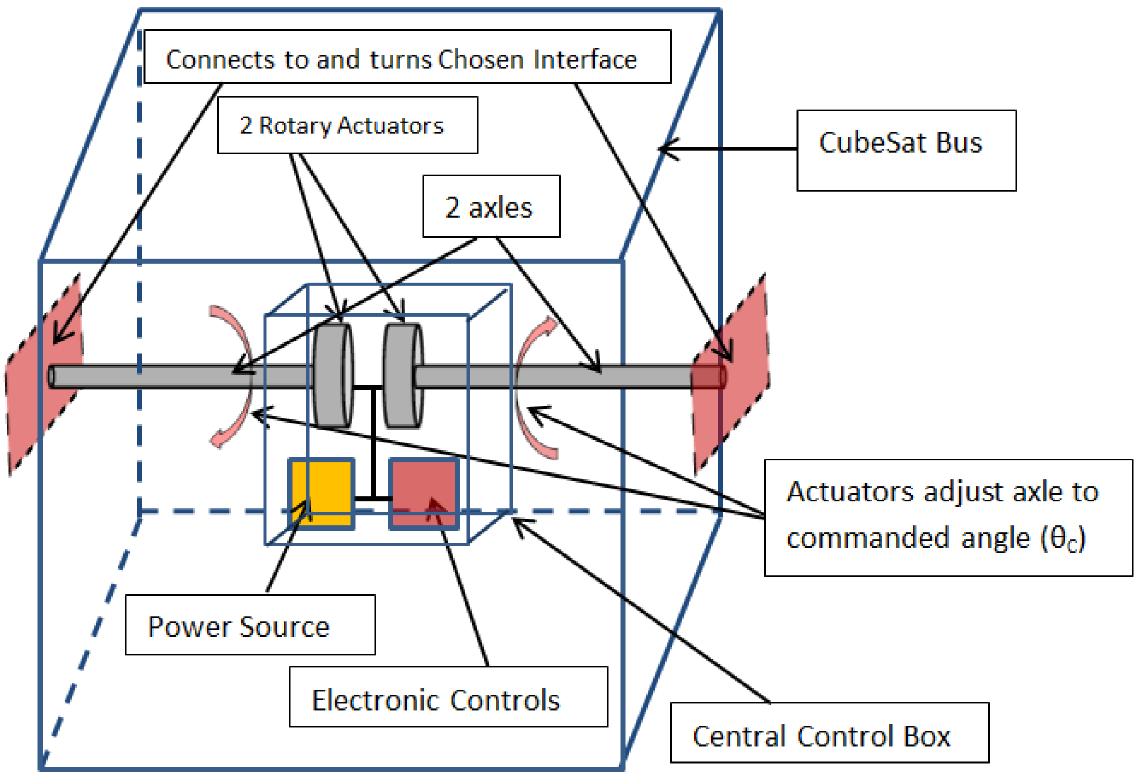


Table 8. Bi-Axle Pros and Cons

Factor	Description	Pro/Con
Space Application	Using space grade actuators and axles will make this design space relevant.	Pro
Cost	Space Grade actuators and gears are expensive; however, the customer may be able to provide them free of cost.	Con
Power	This design will utilize some of the power allowed to our system, but not a substantial amount.	Neither
Mass	Two actuators, a central control box, and 2 axles will most likely be heavier than its counterparts.	Con
Volume	The central control box minimizes the design volume of the pitching system.	Pro
Simplicity of Mechanics	The axle/actuator design is relatively simple and examples can be found in many engineering applications.	Pro
Accuracy	Space grade actuators are highly accurate.	Pro
Testing	Actuator and axle should all be unaffected by testing. Testing this design will be very straightforward.	Pro
Integration	The design may attach to any type of solar sail interface and will not interfere with the deployment system.	Pro

6.0 Trade Study Process and Results

The various proposed ideas for the structure and integration of the solar sail deployment and blade pitch control were divided into three sections for comparison in the trade studies presented below: structural interface, blade deployment, and blade pitching. This was because the different designs for each section were compatible with each other, and if each design was looked at independently, it would have been much more complicated and tedious to perform a single trade study with the numerous influences to consider. A trade study was performed for each idea within its designated section: shell, roller, and plate for structural interface, motors with gears and springs for blade deployment, and bicycle chain, axles, and gears with springs for blade pitching. Each trade study looks at a number of possible elements to consider and with specific weighting factors, a conclusion baseline model was determined.

6.1 Reason for grading:

Table 9. Defined Scores of Each Factor in Performed Trade Studies

		Score			
Factor	**Abbr.**	**1**	**2**	**3**	**4**
Space Application	**SA**	Only works in Earth environment	Works in space but not practical	Minor changes needed to work in space	Space ready
Cost	**$**	> 40% of budget	25-40% of budget	10-25% of budget	< 10% of budget
Power (W)	**P**	P > 10	10 > P > 8	8 > P > 5	5 > P
Mass (kg/U)	**M**	M > 0.4	0.4 > M > 0.3	0.3 > M > 0.25	0.25 > M
Volume (U)	**V**	V > 1.5	1.5 > V > 1	1 > V > 0.5	0.5 > V
Simplicity of Mechanics (# of parts per blade)	**SoM**	parts > 15	15 > parts > 10	10 > parts > 6	3 > parts
Accuracy (°)	**A**	° > 10	10 > ° > 5	5 > ° > 0.5	0.5 > °
Testability	**T**	Can't be tested	Can be tested, but no measure	Can be tested, and measured once	Can be tested, measured multiple times
Integration	**I**	System itself doesn't work	Works with > 1 system	Works with > 2 systems	Works with > 3 systems
Launch Survivability	**LS**	Does not survive	Survives, but is not operational	Some parts don't survive, still operational	No damage
Controllability	**C**	Speed of deployment performed within error greater than 20%	Speed of deployment performed within error of 10-20%	Speed of deployment performed within error of 5-10%	Speed of deployment performed within error of less than 5%

6.2 Interface:

The three proposed designs for the interface of the solar sail are as follows: shell, paint roller, and plate. These ideas were compared and contrasted in a trade study in order to determine the optimal design choice. Each of the weighted factors were decided by the overall significance to the design requirements. The reasoning behind each weighted factor is summarized in Table 10.

Table 10. Trade Space Weighting Factors and Reasoning for Interface Designs

Weight (%)	Category	Reasoning
20	**Space Application**	The interface system integrates the deployment and pitching systems. While purely mechanical, its performance in a space environment is critical for mission success.
15	**Cost**	There is a very limited budget for the project. As a connective interface between two complex systems, the importance of low cost is high.
7.5	**Mass**	Mass is not a major concern for the interface as it greatly depends on the materials chosen.
10	**Volume**	Volume is not a major concern for the interface as it essentially replaces some of the CubeSat wall.
5	**Simplicity of Mechanics**	Less man hours spent on interface design allows more time to be spent on other systems; however, all interface designs are purely mechanical, simple systems.
15	**Testability**	We must be able to test and verify the interface to validate applicability.
15	**Integration**	It is critical that the interface design works in conjunction with other aspects of the system
12.5	**Launch Survivability**	Consideration for the launch of the design is important and the interface is a bridge between the functional systems.

After thorough research on the necessary parts each interface would use, an approximate total value for mass, volume, and cost was determined for each design. The cost of the motors needed varies greatly on performance and quality, and are therefore is not included in the total price. These comparisons are displayed below in Table 11.

Table 11. Total Approximated Values for Interface Designs

	Shell [A1]	Paint Roller [A2]	Plate [A3]
Mass (kg)	0.7	0.45	0.65
Volume (cm^3)	440	140	191
Cost ($)	933.00 + 2 motors	520.00 + 2 motors	720.00 + 2 motors

The advantages of the shell casing interface are the space application and testability, which both received a rating of 4 in the trade study. Due to the strong structural build, the motorized roller would stay protected from space debris and direct solar radiation. Also, the motorized reel would enable the solar sail to be deployed at different speeds, and the procedure would be easily repeatable as the reel could bring in the blade back in as well. Minor changes for this interface would be its integration ability at a low score of 1 and its launch survivability, which earned a rating of 3 in the trade study. Although the shell casing is strong, it would be a heavier configuration that may not withstand the vibrations during launch. Yet the shell design would still be able to protect the sail from unwrapping; it would just have to be built onto a heavier structural arm. In addition, since the shell has a motor for the reel, the fashion in which the motor draws power and interacts with the rest of the solar sail would be more difficult. Also, the amount of moving parts on the shell, including the reel and the rollers, would complicate the design, and more parts would have to be made. Most of the trade study rated the shell idea as impractical, which included the cost, mass, volume, and the simplicity of mechanics. Since there are multiple parts to the shell concept, this would increase the simplicity of the mechanics due to the precise measurements and cuts to the cylinder that would be made. With the external motor to the CubeSat, this would increase the mass, and the cost of the parts, where each blade could cost more than $1000. Due to the bulk of the design, and the motor, the design would be spacious in volume, and take up necessary volume in the CubeSat during packaging. Thus, a final score of 2.8 was given to the shell concept, thereby disqualifying the design from further processing.

For the paint roller idea, both the simplicity of mechanics and launch survivability, which are directly related, were scored at a low 2. This is because the design aspect consists of many parts that would have to be machined with a small tolerance. The wiring of the cable would have to be fed through the base of the structure, which necessitates a hollow interior or some kind of protection over the cables, making it difficult to construct. Going hand-in-hand with mechanical difficulty is the launch survivability. With more parts to consider and mount together comes a greatly likelihood of the structure becoming damaged during the conditions of launch. The space application and integration were both scored with a 3, as the use of the paint roller structure to deploy the solar sail blades could be well applied to a real space mission. The main risk of this idea is the ability to survive launch, but after certain tests and experiments, minor changes could be made to successfully endure the launch, and the mechanism would be appropriate for a space operation. The volume of the interface was additionally rated at a 3. The paint roller idea will not take up space within the CubeSat, allowing more room for the necessary subsystems and electronics. At the highest ratings were the cost and mass. The cost and mass relate to the volume of the interface. A smaller needed volume (smaller CubeSat size) to hold the blade deployment mechanism leads to a smaller mass and a lower structural cost. Finally, the testing capability was scored highly, as the motors controlling the blade deployment allow for an ease of repeatability in testing. By use of the motors, which spin the gears connected to the axle holding the rolled up blade, not only is the deployment regulated at a desired speed, but the direction of spin can be reversed, and the blades can be mechanically rolled back up. This would allow for simplicity of replicating tests, because the structure would not have to be taken apart or disassembled to be hand-rolled after each deployment test. Conclusively, the paint roller tallied a 3.2 cumulative score, marginally too low to be considered for further processing and use as a legitimate interface design option.

The strengths of the plate interface design come from its simplicity and easy integration, which scored a 3 and 4 out of 4, respectively. As it is essentially one of the walls of the spacecraft bus, it takes up minimal extra volume (scoring another 4). Built with the same or similar materials to the frame itself, it would easily survive launch (graded a 3) and the space environment (given another 4) and only add a small additional mass (score of 3) for the casing of the solar sail itself. Compatible with the same deployment methods as the paint roller, it has a high testability and repeatability for the same reasons, and was given a score of 4 for testing as thus. The lowest score the plate interface design received was in the cost area, where it received a 2. As the largest design, the material costs for the interface would be higher as it would require the most material; however as a significant portion of the interface also serves as the bus wall, the cost is really being redistributed from structural bus costs. Thus, the end additional cost of this design is not as high as it may seem. In totality, and as a result of the interface scoring structure, the plate concept received a score of 3.45 and was therefore deemed the most legitimate interface design for use in this project.

The following table summarizes the trade study performed for the interface designs.

Table 12. Interface Trade Study

	SA	$	M	V	SoM	T	I	LS	Total
Shell	4	2	1	4	2	4	1	3	2.8
Paint Roller	3	4	4	3	2	4	3	2	3.2
Plate	4	2	3	4	3	4	4	3	**3.45**
Weight	0.2	0.15	0.08	0.1	0.05	0.15	0.15	0.13	

6.3 Pitching:

Similar to the interface design, the following three methods for blade pitching were compared in a trade study: bike chain, axle, and gears/spring. The reasoning for the weights are portrayed in Table 13.

Table 13. Trade Space Weighting Factors and Reasoning for Blade Pitching

Weight (%)	Category	Reasoning
15	Space Application	A space applicable pitching system is critical as control of the deployed blades depends on it. All parts and systems should have legacy to minimize risk of functional failure.
10	Cost	There is a limited budget for the entire design. Each pitching option will require design specific parts, the most expensive of which will be provided by the customer (i.e. rotary actuators)
5	Power	As at this stage in design, it is assumed that all methods would use the same rotary actuators and the power used relatively similar. Low priority.
5	Mass	The mass of the pitching system will mostly consist of the rotary actuators and interface connections. The team has little control over the actuator mass.
5	Volume	Maximum volume is 12000 cm^3. The volume of any pitching system chosen should be easy to fit into this.
12.5	Simplicity of Mechanics	System mechanics should be straightforward so more time can be put into control and testing of the system.
12.5	Accuracy	The more accurate the pitching system is, the more viable our design will be for the customer. High priority.
10	Testability	In order to validate our design for the customer, we must be able to test the pitching system for accuracy and functionality.
15	Integration	It is critically important for the functional requirements that the design works in conjunction with the interface.
10	Launch Survivability	Consideration for the eventual launch of the design is important. The pitching system should be durable and viable for use.

Each method of design was then scored on a scale of 1 to 4 according to the definitions set in Table 9. For uniformity and simplicity, redundant parts such as rotary actuators and gears are assumed the same in each design. Table 14 below illustrates a simplified parts listing and basic research for the specifications of each part. This table assists in a fair scoring of each method on the scale described in Table 13 above.

Table 14. Specifications of Necessary Parts for Blade Pitching

					Total (two blades)		
Mechanical Part	Mass (g)	Power Used (W)	Volume (cm^3)	Cost ($)	"Bike Chain"	Bi-Axle	Gears/ Spring
Gear	62-87 [13]	0	~89 [15]	60.00 [15]	6	2	4
Spring	9 [7]	0	0.82 [7]	6.00 [7]	0	0	4
Rotary Actuator	300 [8]	5 (Nominal) [8]	151 [8]	Varies	2	2	2
Belt/chain	~90 [9]	0	~750 [9]	60.00 -70.00 [9]	2	0	0
Axle (Megan)	~6 [10]	0	.79 [10]	2.86 [10]	0	2	2

An approximate total value for mass, volume, and cost was added up and determined for each design from Table 14. The cost of the motors needed varies greatly on performance and quality, and are therefore not included in the total price. These comparisons can be seen in Table 15.

Table 15. Total Approximated Values for Blade Pitching Designs

	Bike Chain	Bi-Axle	Gears/Springs
Mass (kg)	1.14	0.786	0.996
Power Used (W)	10	10	10
Volume (cm^3)	2200	481.58	662.58
Cost ($)	500.00 + 2 motors	126.00 + 2 motors	270.00+ 2 motors

First of all, the bike chain idea was graded a 1 out of 4 for space applicability, due to the fact that any sort of belt or belt lubrication would likely fail due to freezing and/or breaking at very cold temperatures. As far as cost, this idea scored a 4 due to the relatively inexpensive parts (belt, gears, and motor) needed for this system. Power received a 3 because, like all other comparable pitching conceptual designs, it requires only a power source for the motors/actuators. The mass of the design was given a 3 due to the large distribution of mass (the belts) away from the center of mass of the CubeSat. Similar to the mass, the volume constraints of the bike chain idea was given a 2 out of 4 score because the belt inside of the bus pre-deployment would take up a considerable amount of room. Furthermore, the simplicity of mechanics was scored a 3 due to the fact that the intact deployment of the belt and functional use thereafter would be a somewhat difficult task. Next, the accuracy of the idea was rated a 2, because the transfer of command of the motor through the belt and finally the gears would surely result in a large loss of precision. The testing of the system was deemed to be relatively simple and repeatable and as thus scored 4 out of 4. As far as integration is concerned, software and electrical components would be easily integrated. However, mechanically, especially fitting the design into a 12U CubeSat or smaller and it being able to successfully deploy lead to the score of 2 for this category. Finally, as previously mentioned, the difficulty of maintaining structural integrity of the belt through deployment lead the group members to believe that the launch survivability of the concept was low and thus a score of 2 resulted. Due to the combination of the aforementioned factors, the bike chain received a weighted cumulative score of 2.475 out of 4 and was therefore disqualified as a reasonable candidate for legitimate pitch actuation design.

The gear and spring model received a score of 4 for the level of space application because this design is already space ready, provided space safe materials are used. It received a score of 2 for cost because it would require the cost of one actuator, one spring and several gears per blade, however the spring would need to have a specific stiffness coefficient (to be determined), making it more expensive. It received a score of 3 for power because it only uses one actuator per blade, meaning it will require some power, but not much. It received a mass score of 2 because the actuator can be small, and there is not a lot of hardware required for this design, but additionally pieces could add up. It received a high score of 4 for volume because the design is small and will not take up much space. Simplicity of mechanics was rated 2 because there are a fair number of parts in this design and it is possible that the gears and spring will have to be specially machined. Accuracy received a score of 4 because the gear configuration will allow the design to be highly accurate. Testability received a high score of 4 because there is no reason why the design cannot be tested easily again and again. Integration received a high score of 3 since this design would work with any of the deployment and interface designs. Finally, it received a 4 for launch survivability because there is no part of the design that is inherently fragile. As a result, the gear and spring concept scored a cumulative total of 3.25, marginally too low to be considered as a legitimate design concept.

The axle was graded a 4 out of 4 for space applicability because similar mechanisms are used on various satellite solar panels in the commercial market. This fact also leads to a rating of 2 out of 4 for cost, because all of the materials needed are commercially available and would not require design or special order, but the number of pieces could add up. Each competitor scored 3 out of 4 for power usage, as each requires an equivalent power source for the motors or actuators. The mass of the axle system scored 2 out of 4 because the system requires actuators, axles, and a powering electronic system. The volume of the axle ranked a high 3, because it essentially takes up some space across the entire CubeSat, but this total volume is minimal. The simplicity of mechanics scored 3 out of 4, as the bi-axle system is a fairly simple model that has been replicated over a wide array of fields. The accuracy of the axle system ranked the highest, 4 out of 4, as most space grade actuators are accurate to about 5 arc-seconds. The testability of the bi-axle system would be very straightforward and repeatable. The integration of the axle design scored a 4 of 4 because the bi-axle and central control box would be relatively easy to implement on a CubeSat smaller than 12U. Finally, the launch survivability scored 4 out of 4 because similar actuator/axle systems have survived launch for various research and commercial missions. Adding in each category with the assigned weight of importance, the bi-axle system scored a 3.475, the highest of the pitching design category.

The following Table 16 summarizes the trade study performed for the blade pitching designs.

Table 16. Blade Pitching Trade Study

	SA	$	P	M	V	SoM	A	T	I	LS	Total
Bike Chain	1	4	3	3	2	3	2	4	2	2	2.475
Gears/Spring	4	2	3	2	4	2	4	4	3	4	3.25
Axle	4	2	3	2	3	3	4	4	4	4	**3.475**
Weight	0.15	0.1	0.05	0.05	0.05	0.13	0.13	0.1	0.15	0.1	

6.4 Deployment:

The two methods for deployment: motor/gears and springs were also compared in a trade study, similar to the interface and pitching. The reasonings for the weighted factors are evinced in Table 17.

Table 17. Trade Space Weighting Factors and Reasoning for Blade Deployment

%	Category	Reasoning
15	Space Application	A space applicable deployment system is critical to functional requirements. The system should have legacy and a working simulation to minimize risk of functional failure.
10	Cost	Each deployment design option requires specific parts. The most expensive will be provided by the customer (brushless motor)
10	Power	As at this stage, it is assumed that all designs use the same amount of power per motor. The deployment and pitching systems will not be powered at the same time, so there is not a strict power requirement.
5	Mass	The mass of each deployment system option will be relatively similar. The mission has no strict mass requirement.
5	Volume	Each deployment method must fit the rolled sail inside while fitting the chosen interface. Therefore, designs should be fairly large.
10	Simplicity of Mechanics	Simple mechanics would allow more time to be focused on sail deployment control and testing.
15	Control	To satisfy functional requirements, the blade must release at a controlled rate.
10	Testability	In order to validate our design for the customer, we must be able to test sail release rate and functionality.
10	Integration	It is critical for the design fits and works with the interface system.
10	Launch Survivability	Consideration for the eventual launch of the design is important. The deployment system should be durable and viable for use.

A similar evaluation of the necessary parts for each design was performed and can be seen in Table 18.

Table 18. Specifications of Necessary Parts for Blade Deployment

Mechanical Part	Mass (g)	Power Used (W)	Volume (cm^3)	Cost ($)	Total (one blade) Motor/ Gears	Total (one blade) Spring
Gear	62-87 [13]	0	5 [13]	60.00 [13]	2	0
Spring	9 [7]	0	0.82 [7]	6.00 [7]	0	2
Rotary Actuator	300 [8]	5 (Nominal) [8]	151 [8]	Varies	2	0
Motor (Megan)	300 [11]	4.8 [11]	100 [11]	Varies	1	0

An approximate total value for mass, volume, and cost was developed for each design from Table 18. These comparisons can be seen in Table 19.

Table 19. Total Approximated Values for Deployment Designs

	Motor/Gears	Spring
Mass (kg)	1.074	0.018
Power Used (W)	14.8	0
Volume (cm^3)	412	1.64
Cost ($)	120.00 + motor and actuator	12.00

Motors and gears have been used in space before, “In the aerospace industry, gearboxes are used in space and air travel, i.e. airplanes, missiles, space vehicles, space shuttles and engines.” [14] This means that motors and gears have been used in many space missions, and therefore are very space applicable and can survive launch, and are both rated a 4 as such. Motors and gears can easily control what speed the solar sail will deploy by having the right amount of gears that can either increase or decrease the speed of deployment, deeming a controllability rating of 4. Testing also scored a 4 due to the fact that the solar sail deployment can be tested multiple times, because the motor can run in reverse. This allows the solar sail to have to capability to be retracted in order to repeat the test. This idea can be easily integrated with any of the pitching and interface systems (integration score of 4). This contributes to the high ratings for space applicability, launch survivability, integration, testability, and controllability for the motor and gears, which all received a 4 out of 4. Motors cost a decent amount of money, require high power, have a large mass, and take up a lot of space, resulting in scores of 3, 3, 3, and 2, respectively. Also, the whole motor gear system has a lot of parts in order to work properly, leading to a simplicity of mechanics rating of 3. This contributes to the low ratings for cost, power, volume, mass, and simplicity, as mentioned above. However, the overall score for the motor/gears concept received a cumulative total of 3.55, leading one to believe it is the strongest design concept for further application in the project.

A score of 2 for space applicability was given to the spring-based deployment system because this method of deployment has been proven to work on space missions in the past. However, it was not given the highest possible score, as the purpose of the HELIOS mission is to deploy solar sails without the need of supporting structure to the sails. A spring-based deployment and structure undermines the point of the Langley mission. The cost is given the highest score of 4 because the system would be purely mechanical, and thus would not require actuators or motors. Because of this, power also receives a 4. Again, mass, volume, and simplicity also score a 4, because the system would take up less weight and room by not having electronic constituents. It only receives a 2 in controllability, however, as the system can only be deployed at one speed, and would not be able to be reeled back in without the addition of more springs. It receives a 2 in testability because a spring-based deployment system would be easily tested, but not as easily reset for multiple trials. Integration would be simple with each of the various proposed interface options, so this category also receives a 4. Launch survivability is given a score of 2, however, as a spring-based deployment would have more mechanical parts than a motor or actuator based deployment system. Conclusively, the spring design scored an overall resultant 3 out of 4, leading to the decision to not move forward with the concept.

The following table summarizes the trade study performed for the blade deployment designs.

Table 20. Deployment Trade Study

	SA	$	P	M	V	SoM	C	T	I	LS	Total
Motor/Gears	4	3	3	3	2	3	4	4	4	4	**3.55**
Spring	2	4	4	4	4	4	2	2	4	2	3
Weight	0.15	0.1	0.1	0.05	0.05	0.1	0.15	0.1	0.1	0.1	

7.0 Selection of Baseline Design

The trade studies were used to help the design team chose an optimal design for each of the three research areas: deployment mechanism, pitching mechanism and the interface connecting each. As demonstrated above, there were ten criteria initially examined, although not all criteria were applicable to the interfacing mechanism. Each criterion was given a weight to reflect the importance of that particular criterion in the final design selection. For example, space applicability was weighted more important than volume, since the volume limit is large for this project. In the case of the interface and the deployment mechanism, the trade study yielded one result that scored much higher than the others. Therefore, it was easily determined that the circular plate interface design and the motor and gears deployment design were most optimal for the system. However, the results of the pitching mechanism trade study were not as conclusive, leaving two options that scored very close together. Therefore, it was necessary to determine an additional criterion to be used to determine the optimal design.

While both the axle design and the gears and spring design scored within about .2 of each other, it is important to note that the axle scored slightly higher. In order to approach the designs from a different angle, both designs were then evaluated solely on how many man-hours would be required to design, fabricate and test each mechanism. Though this related to the simplicity of mechanics, instead of simply accounting for how many parts are in the design, the new trade study would take into account whether each part could be bought or would have to be specially machined, and how long it would take to integrate the design as a whole. It was found that the spring in the gears and spring design might have to be specially machined, and the system would have to be tested multiple times in order to find the optimal stiffness coefficient for the spring and optimal gear ratio. Furthermore, the leading difference between the two designs was the presence of a spring dampening system in the gears and spring design, which was nonexistent in the axle design. Though the dampening system would help to stabilize any perturbations in the solar blade should it be disturbed, it was concluded that such a system would be too complicated to design and - ultimately - outside the scope of this project. Given the complexity of this system, it was determined that the gears and spring development would take more effort than the axle design and would require a more complex analysis. Seeing as how the timeline for GHOST is extremely strict and unmalleable, the gears and spring design was discarded in favor of the axle design.

The final baseline design of the project consists of the following: the rolled, undeployed solar blades will be embedded in a plate-like structure flush with the bus of the CubeSat. The plate will be pitched using an axle interface, which is turned via an internal rotary actuator. The solar blades will be deployed by a motor and gear based system within the plate interface to control the speed of deployment. A mass will be connected to the sail end while the unfurling sail is fed through a lip in order to deploy the blade in a controlled, uniform manner. The pitching subsystem will be verified through the synchronized pitching and control of two undeployed solar blades or equivalent mass. The deployment subsystem will be verified in a 1-G environment in order to approximate acceleration due to the angular velocity that would be acting on the heliogyro craft in space. Though it is recognized that 1-G of acceleration is much higher than the angular acceleration produced by the rotation rate of the craft in a space environment, it will be the closest approximation the GHOST team will be able to achieve in an Earth-based environment. Kinematic models will be produced to simulate the mechanics behind the pitching and deployment systems and will be used to verify the feasibility of such systems in a space environment.

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9.0 Appendices

9.1 Appendix 1 [A1]

```
% ASEN 4018 - Trade Study for Metal Casing
% Purpose: This program is used to calculate important properties of a
%   metal casing, including the diameter, mass, and spacial volume.
% Instructions: Alter the thickness of the gear inside tube, the length of
%   sheet, or density of material (currently only titanium is considered).
% Author: Nicholas Busbey

clc,clear,close all
```

```
%% Define parameters
% Define diameter of gear
d_gear = 4;             % [cm]
% Define length and width of sheet
L_sheet = 20*100;       % [cm]
w_sheet = L_sheet/100;  % [cm] AR 100:1
% Define thickness of sheet
t_sheet = 2.5*10^-6*100;% [cm]
% Define density of aluminized mylar and calculate mass
rho_mylar = 1.00*10^-3; % [kg/cm^3]
m_sheet = rho_mylar*t_sheet*L_sheet*w_sheet;    % [kg]

%% Calculate radius of shell
C_gear = d_gear*pi; % [cm]
C_0 = C_gear;       % Define inital circumfrence
% Initiate while loop for determining length of sheet
L_used = 0;         % Length of sheet used
n = 0;              % Number of wraps
d_wrap_0 = d_gear;  % Define diameter of wrap
while L_used <= L_sheet
    d_wrap = d_wrap_0 + 2*t_sheet*n;% Calculate diameter at nth wrap
    L_used = L_used + d_wrap*pi;    % Calculate length used
    n = n+1;                        % Iterate number of wraps
end

%% Calculate volume and mass of titanium shell
% Define properties of casing
rho_titanium = 4.506*10^(-3);   % Density of titanium [kg/cm^3]
rho_aluminum = 2.7*10^-3;       % Density of aluminum [kg/cm^3]
t_casing = 0.5;                 % Thickness of casing [cm]
% Calculate volume of casing and mass of metal for casing
r_i = d_wrap/2;                     % Inside radius [cm]
r_o = r_i + t_casing;               % Outside radius [cm]
V_casing = w_sheet*pi*r_o^2;        % Volume of casing [cm^3]
V_metal = (pi*r_o^2 - pi*r_i^2)*w_sheet;    % Volume of metal [cm^3]
m_casing = V_metal*rho_aluminum;    % Mass of casing [kg]
% Calculate mass of rollers
d_roller = 1;                           % Diameter of roller [cm]
V_roller = (pi*(d_roller/2)^2-((d_roller-2*t_casing)/2)^2)*w_sheet;   % Volume of
casing [cm^3]
m_roller = V_roller*rho_aluminum;       % Mass of roller [kg]
% Calculate total mass and total volume
m_total = m_casing + m_sheet + 2*m_roller;  % Total mass [kg]
V_total = 2*V_roller + V_casing;            % Total volume [cm^3]
```

9.2 Appendix 2 [A2]

```
% ASEN 4018 - Trade Study for Paint Roller
% Purpose: This program is used to calculate important properties of a
%   paint roller interface, including the diameter, mass, and spacial volume.
% Instructions: Alter the thickness of the gear inside tube, the length of
%   sheet, or density of material (currently only titanium is considered).
% Author: Nicholas Busbey (edited by Karynna Tuan)

clc
clear all
close all

%% Define parameters
% Define diameter of gear
d_gear = 4;             % [cm]
% Define mass of motor
m_motor = 0.1; % [kg]
% Define length and width of sheet
L_sheet = 20*100;       % [cm]
w_sheet = L_sheet/100;  % [cm] AR 100:1
% Define thickness of sheet
t_sheet = 2.5*10^-6*100;% [cm]
% Define density of aluminized mylar and calculate mass
rho_mylar = 1.00*10^-3; % [kg/cm^3]
m_sheet = rho_mylar*t_sheet*L_sheet*w_sheet; % [kg]
```

```
V_sheet = m_sheet/rho_mylar; % [cm^3]

%% Calculate radius of shell
C_gear = d_gear*pi; % [cm]
C_0 = C_gear;        % Define inital circumfrence
% Initiate while loop for determining length of sheet
L_used = 0;          % Length of sheet used
n = 0;               % Number of wraps
d_wrap_0 = d_gear;   % Define diameter of wrap
while L_used <= L_sheet
    d_wrap = d_wrap_0 + 2*t_sheet*n;% Calculate diameter at nth wrap
    L_used = L_used + d_wrap*pi;    % Calculate length used
    n = n+1;                        % Iterate number of wraps
end

%% Calculate volume and mass
% Define properties
rho_titanium = 4.506*10^(-3);   % Density of titanium [kg/cm^3]
rho_aluminum = 2.7*10^-3;       % Density of aluminum [kg/cm^3]
w_gear = 0.5; % [cm] (approx)
w_structure = 0.5; % [cm] (approx)
d_motor = 1; % [cm] (approx)
t_structure = 1; % [cm] (approx)
d_axle = 0.5; % [cm] (approx)
m_weight = 0.01;
V_weight = 1;
% Calculate volume and mass of holding structure
rec_out = (w_sheet + 2*w_gear + 2*w_structure)*(d_motor + 2*d_gear);
rec_in = (w_sheet + 2*w_gear + 0.5)*(d_wrap + d_axle + 1);
V_structure = (rec_out-rec_in)*t_structure;    % [cm^3]
m_structure = V_structure*rho_aluminum;    % [kg]
% Calculate volume and mass of gears
V_gear = d_gear*pi*w_gear;
m_gear = V_gear*rho_aluminum;
% Calculate volume and mass of axle
V_axle = d_axle*pi*(w_sheet + 2*w_gear + 2*w_structure);
m_axle = V_axle*rho_aluminum;
% Calculate volume of motor
V_motor = d_motor*pi;
% Calculate total volume and mass
m_total = m_sheet + m_structure + 2*m_gear + m_axle + m_motor + 2*m_weight % Total mass
[kg]
V_total = V_sheet + V_structure + 2*V_gear + V_axle + V_motor + 2*V_weight % Total
volume [cm^3]

%% Total Cost
c_sheet = 0; % Can get free from NASA
c_structure = 0.4; % [$/kg]
c_gear = 60;
c_axle = 0.4;
c_motor = 500;
c_total = c_sheet + c_structure*m_structure + 2*c_gear + c_axle*m_axle + c_motor % [$]
```

9.3 Appendix 3 [A3]

```
% ASEN 4018 - Trade Study for Plate
% Purpose: This program is used to calculate important properties of a
%   plate interface, including the diameter, mass, and spacial volume.
% Instructions: Alter the thickness of the gear inside tube, the length of
%   sheet, or density of material (currently only titanium is considered).
% Author: Nicholas Busbey (edited by Karynna Tuan)

clc
clear all
close all

%% Define parameters
% Define diameter of gear
d_gear = 4;             % [cm]
% Define mass of motor
m_motor = 0.1; % [kg]
```

```
% Define length and width of sheet
L_sheet = 20*100;       % [cm]
w_sheet = L_sheet/100;  % [cm] AR 100:1
% Define thickness of sheet
t_sheet = 2.5*10^-6*100;% [cm]
% Define density of aluminized mylar and calculate mass
rho_mylar = 1.00*10^-3; % [kg/cm^3]
m_sheet = rho_mylar*t_sheet*L_sheet*w_sheet; % [kg]
V_sheet = m_sheet/rho_mylar; % [cm^3]

%% Calculate radius of shell
C_gear = d_gear*pi; % [cm]
C_0 = C_gear;       % Define inital circumfrence
% Initiate while loop for determining length of sheet
L_used = 0;         % Length of sheet used
n = 0;              % Number of wraps
d_wrap_0 = d_gear;  % Define diameter of wrap
while L_used <= L_sheet
    d_wrap = d_wrap_0 + 2*t_sheet*n;% Calculate diameter at nth wrap
    L_used = L_used + d_wrap*pi;    % Calculate length used
    n = n+1;                        % Iterate number of wraps
end

%% Calculate volume and mass
% Define properties
rho_titanium = 4.506*10^(-3);   % Density of titanium [kg/cm^3]
rho_aluminum = 2.7*10^-3;       % Density of aluminum [kg/cm^3]
w_gear = 0.5; % [cm] (approx)
w_structure = 0.5; % [cm] (approx)
d_motor = 1; % [cm] (approx)
t_structure = 1; % [cm] (approx)
d_axle = 0.5; % [cm] (approx)
m_weight = 0.01;
V_weight = 1;
% Calculate volume and mass of plate
cir_out = pi*((w_sheet + 2*w_gear + w_structure)/2)^2;
rec_in = (2*w_sheet + 2*w_gear + 1)*(d_wrap + d_axle + 1);
V_structure = (cir_out-rec_in)*t_structure;    % [cm^3]
m_structure = V_structure*rho_aluminum;    % [kg]
% Calculate volume and mass of gears
V_gear = d_gear*pi*w_gear;
m_gear = V_gear*rho_aluminum;
% Calculate volume and mass of axle
V_axle = d_axle*pi*(w_sheet + 2*w_gear + 2*w_structure);
m_axle = V_axle*rho_aluminum;
% Calculate volume of motor
V_motor = d_motor*pi;
% Calculate total volume and mass
m_total = m_sheet + m_structure + 2*m_gear + m_axle + m_motor + 2*m_weight % Total mass
[kg]
V_total = V_sheet + V_structure + 2*V_gear + V_axle + V_motor + 2*V_weight % Total
volume [cm^3]

%% Total Cost
c_sheet = 0; % Can get free from NASA
c_structure = 0.4; % [$/kg]
c_gear = 60;
c_axle = 0.4;
c_motor = 500;
c_total = c_sheet + c_structure*m_structure + 2*c_gear + c_axle*m_axle + c_motor % [$]
```