Capstone 007: GeoShade

ME 493: Final Design Report

Sponsor:

Tim Sippel

Date:

6/5/2020

Group Members:

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Team Member Roles and Contributions

Team Member:	Role:	Primary Contribution:
Jake Chung	Mathematical Model	Derived a mathematical and body torque control model for the prototype. Designed a 3D toy model of the prototype sail
Johnathan Le	Sail Design Research	Made a 3D model of the unfolding mechanism and worked on research for the sail design.
Jonathan Valencia	Cost/Market Research. CAD modeling	Made CAD files and actuation performance/cost analysis.
Mohammed Afdup	Sail Animation	Animated the concept of how the solar sail orbits around earth before reaching its final destination at (L-1).
Vadim Naumchuk	Sail Design Research Sail animation	Blender CAD model of the 3 panel Prototype and an animation of the final orbital flight.
Vladi Ruchin	Mathematical Model	Created a simulation for system dynamics. Found a solar force model to describe the prototype's body torque.
Yahye Egal	Mathematical Model	Derived a torque model for the prototype so that it can be used for the sail's attitude control system.

EXECUTIVE SUMMARY

Project Objective Statement

By June 2020, provide ground-work research on system modeling, deployment procedures, and actuators to cost-effectively offset carbon emissions through the implementation of solar sail technology.

The final status of the design project

The members have researched and compiled their detailed analyses in the appendices. However, the GeoShade project is still considered to be in its infancy as the analyses are mostly preliminary.

The actuator team found a revolutionary method to provide radiation shielding at a significantly lower cost [1]. Radiation shielding was initially thought to be the greatest impediment to the project's development, for the sponsor did not account for its enormous cost at the initial conception of the idea.

The mathematical model proved that the sail panels can be controlled such that gyroscopic precession is prevented. This method can potentially be implemented in GeoShade's final design.

Our initial plan was to build a mock-up for the sail prototype during spring term. However, COVID-19 forced members to stay home and halt purchases. Fortunately, a member had access to a 3D printer at home, so we designed and printed a tabletop mock-up of the sail prototype. This item proved to be invaluable for visualizing sail dynamics, and it will serve greatly as a visual-aid for the sponsor.

Key performance Metrics

Since the GeoShade Capstone is primarily research-based, measurable performance values are hard to test or obtain. Research was conducted by suggesting goals and requirements, but it remained flexible for discoveries that changed its direction. As such, work was completed by referring to the sponsor's approval rather than comparing performance to a criteria.

CLIENT/MARKET REQUIREMENTS

GeoShade's goal is to determine design requirements so that it may be used to cost-effectively reduce large amounts of carbon emissions with existing technology. The sail deployment functions by using servo motors to pull rods and sails from their initial positions. In addition to deployment, the motors orientate five hundred twenty eight individual panels in and away from solar rays to create enough thrust as it sends the solar shade into orbit at Lagrange 1.

GeoShade's environmental impact is \$10 per ton of carbon dioxide while keeping the sail's density at 10 g/m²[2]. A lighter load would help achieve GeoShade's goal of staying in orbit for 20 years. The sunshade's deployment cost to sub-L1 depends on the reflective film and the launch. The launch cost relies on total mass and altitude destination, which can exponentially increase cost as altitude increases. To reduce cost, the sail will be launched to low Earth orbit and sailed to Lagrange 1.

Client/Market requirements for the GeoShade are as follows:

- Foundational work for the GeoShade project by exploring different configurations of the various subsystems
- Tangible results for the sponsor to show off at fundraising events or an elevator pitch
- Proof of concept for the trajectory maneuvering system using the sail panels
- Translating the sponsor's ideas to CAD files or models for visual-aid purposes
- Identify potential problems that might be overlooked by the sponsor

Key performances provide detailed descriptions of GeoShade in Appendix D. The Key performances, in conjunction with System-Level Requirements, facilitate the derivation that drives the GeoShade design. Performances and System level requirements are captured in a System-Level Matrix, which serves as a tracing tool for both requirements and test verification activities.

CONCEPTUAL DESIGN SUMMARY

The main objective of the GeoShade project is to reduce carbon emissions by deploying a large vehicle with highly reflective surfaces to Lagrange 1 (L1) where it will block out sunlight. The sail does not use traditional chemical fuel to travel in space. It uses solar radiation reflected off the surface to gain momentum. The solar pressure is weak compared to other kinds of pressure (9.12 micropascal [3]). If it is applied to a large surface in space, this pressure can build up high accelerations. The solar sail exploits this mechanism to travel in space. It has 528 sails panels to reflect light. Each panel is 50 meters by 100 meters, which gives it a total surface area of $2.64*10^6$ square meters. Assuming perfect reflection, this is approximately 24 newtons of force. This constant force is used to propel the vehicle in space.

The vehicle is packed in an efficient manner in a rocket booster to be delivered into low Earth orbit. When the vehicle is in Earth orbit, it will unfold and be deployed by a robotic arm. In order to escape Earth's gravitational pull, the sail vehicle has to stay in orbit for approximately 1.5 years before gaining enough terminal velocity to maneuver itself to L1.

The GeoShade is the final product envisioned by the sponsor. However, to attract investment, the sponsor plans to develop and launch a sail prototype vehicle to prove the flight concept. Solar sailing vehicles exist in space for a variety of research purposes. However, a solar sailing vehicle at this size and complexity has never been done. The prototype sail serves as an intermediate step to the full-size vehicle.

SUBSYSTEM HIGHLIGHTS

For the GeoShade Capstone, there are two primary subsystems that break off into smaller subsystems. The first primary subsystem is a package of mathematical models and the second primary subsystem is a combination of 3D models and animations that demonstrate the GeoShade design process.

Mathematical Model

When the vehicle is in orbit, it will need to adjust its trajectory and perform maneuvers. This can be accomplished by a control system. To design a control system, the general approach is to perform system analysis to accurately determine the transfer function of the system. In our case, this is still mostly theoretical work, so the transfer function needs to be determined analytically. Deriving a mathematical model for the dynamics of the sail vehicle is the first step in the process. The mathematical model can be refined over time to include more variables and validate the assumptions.

Appendix E, F, and G shows the detailed analysis and derivation of the mathematical models.

Model 1

The following model describes the magnitude and direction of solar forces acting on a sail panel’s center of mass. Once these forces are known, a torque equation is derived to describe the central hub’s body torque. To begin deriving the model for a sail panel, a few assumptions were made: the sail is perfectly flat and not a perfect reflector. These assumptions were used to determine that the total force exerted due to solar radiation pressure is the summation of reflection, absorption, and re-radiation. These forces are resolved into the following normal and transverse forces:

$$f_n = \{\mathbf{P}*\mathbf{A}*[\,(1+\tilde{\mathbf{r}}*s)*\ \cos^2\boldsymbol{\alpha} + \mathbf{B_f}*(1\text{-}s)*\ \tilde{\mathbf{r}}*\cos\boldsymbol{\alpha} + (1-\tilde{\mathbf{r}})*\frac{\epsilon_f*B_f - \epsilon_b*B_b}{\epsilon_f+\epsilon_b}*\cos\boldsymbol{\alpha}\,]\}\ \mathbf{n} \quad (1)$$

$$f_t = [\mathbf{P}*\mathbf{A}*(1\text{-}\tilde{\mathbf{r}}*s)*\cos\boldsymbol{\alpha}*\sin\boldsymbol{\alpha}]\ \mathbf{t} \quad (2)$$

The torque equation for the hub's center of mass is dependent on the transformation matrices, which are written for the sun, hub, and sail panels. The matrices contain the lever arms and directions for the normal and transverse force of each panel. Thus, the torque created due to each panel's center of mass can be calculated. The torques are added together to express the hub's torque at every point in time.

Model 2

The assumptions of this model are the following:

- The sail panels are rigid, i.e. neglecting billowing effects.
- The frames are rigid, so the sail panels' struts do not bend.
- We neglect the equal and opposite torque predicted by Newton's Third Law when a torque is applied to rotate a panel.
- The center of mass of the vehicle is static regardless of the sail panels' motion.

Under these assumptions, the mathematical model can be used to test different panel rotational configurations to produce a non-precessive pitch maneuver. The mathematical model is also a portal to provide a more in-depth understanding of the sail vehicle's dynamics. This model was derived for the prototype sail, but the method could be scaled to the full-size GeoShade. Figure A2 shows that the body torque vector can be controlled to produce a constant torque with an oscillatory amplitude at 4% of the torque magnitude. The equation for the body torque vector is the following:

$$\vec{\tau}_b = \begin{bmatrix} -P_s AQcos(\theta_1)\cos(\phi_1) - P_s AQcos(\theta_2)\cos(\phi_2) - P_s AQcos(\theta_3)\cos(\phi_3) \\ P_s AQcos(\theta_1)\sin(\phi_1) + P_s AQcos(\theta_2)\sin(\phi_2) + P_s AQcos(\theta_3)\sin(\phi_3) \\ 0 \end{bmatrix} \tag{3}$$

The pitch vector equation

$$\vec{\tau}_b = \vec{\gamma} \times I\vec{\Omega} \tag{4}$$

can be used to calculate the body torque required for controlling the attitude of the vehicle. However, due to the asymmetry of the sail when it rotates, the mass inertia tensor I cannot be derived analytically. This would require a numerical method to approximate each time step. Appendix F shows the analysis to obtain the mathematical model.

This model predicts that the maximum body torque that can be generated by the 3 panels is about 2.5 Nm (Figure A2, panel E). This maximum torque is a function of the amplitude of the sail's sinusoidal motion (Figure A2, panel A, B, and C). Knowing the sinusoidal angular position equation, we can derive the acceleration equation. We calculated that the maximum torque required to rotate a panel at this acceleration is about 1.9 Nm. This can be used as a torque requirement metric for the actuator selection.

Model 3

The torque model formulation assumes that the sail panels are rigid, and a constant solar pressure force is directed at a sail panel's center of mass.

Utilizing these assumptions, this model formulation helps identify all the torque components that are caused by the solar radiation pressure force. The theoretical torque model's "x", "y", and "z" components can be expressed as a function to control the sail prototype's orientation.

$$\therefore \boldsymbol{T} = \boldsymbol{f}(\boldsymbol{\theta_i}, \boldsymbol{\varphi}) = \begin{bmatrix} \sum_{i=1}^{3} \left([P_s \cdot L \cdot dcos(\theta_i)] \cdot \left[\frac{L}{2} + (\rho - L)\right] \cdot [1 - sin(\varphi) - sin(60^\circ - \varphi)] \right) \\ \sum_{i=1}^{3} \left([P_s \cdot L \cdot dcos(\theta_i)] \cdot \left[\frac{L}{2} + (\rho - L)\right] \cdot [cos(\varphi) - cos(60^\circ - \varphi)] \right) \\ I\alpha \end{bmatrix} \quad (5)$$

The “x” and “y” components are the summation of the torques acting on each of the three panels, while the z-component is the torque resulting from the rotation of the body frame and known pitch caused by the rotation of the sail panels. The angular acceleration in the model equation is denoted by “Alpha” and can be determined from the pitch and rotational velocity.

Design Aids

Unfolding Mechanism

In our meetings with the sponsor, we discussed the general design for the GeoShade and how the sails would deploy; these discussions slowed the progress of our results because we had to be able to interpret complex folding patterns, sketches, and drawn up prototypes. As such, it was decided that it would be best to do 3D modelling to create a simple model. The model provided us with the opportunity to make sure that the design performed the correct motions as it unfolded. Solidworks was chosen because it was user-friendly in terms of creating 3D models and small animations. Starting with the core unfolding mechanism from the sponsor's designs, we broke it down to two frame pieces and an assortment of other pieces for the latching mechanism. More details regarding the process towards the 3D model can be found in Appendix I.

Animation

Blender Animation

The animation team was tasked with creating a visual aid of the GeoShade 3-panel prototype in space. Packing and deployment process being the main focus up to this point, it was the goal to animate the deployment process provided by Tim Sippel. However, since we did not have CAD models of the deployment mechanism it was proposed we instead work on a deployed solar sail. From the available animation softwares Blender was chosen as it's free to use but, most importantly the popularity behind Blender provided much needed tutorials. The final animation illustrates the Prototype completing its final earth orbit as it sets its journey towards Lagrang-one. Important key factors that were shown in the animation clip, are the Panel orientation with respect to the sun. As can be seen in the beginning the panels are oriented parallel to the sun for maximum propulsion. Continued the panels slowly rotate 90 degrees about their local axis as they complete their last orbit, in which it will be important to have the least amount of projected surface area. For an in depth explanation of the animation process, refer to Appendix J.

MATLAB SimScape Multibody Simulation

Since Team GeoShade is unable to test prototypes in a zero-gravity environment, it was decided that it would be appropriate to use simulation software to determine whether our mathematical models accounted for all system dynamics. Many suggestions were made as to what programs we would use. The first two were *Blender* and *Kerbal Space Program*. In the end, we decided to use *Simscape Multibody* because companies such as Lockheed Martin Space Systems used it “to translate mechanical models of the spacecraft developed in CAD software into an accurate mechanical dynamics model using a repeatable, reliable, and automated process” [4].

Simscape Multibody is a MATLAB add-on that provides a 3D environment for simulating multibody mechanical systems. These systems are modeled using blocks that are represented by bodies, joints, constraints, force elements, and sensors. The program numerically solves the equations of motion for a complete mechanical system so that a 3D animation can be generated. This animation helps users visualize system dynamics. For inexperienced users who are not familiar with the addon's block diagram system, the program allows individuals to import CAD assemblies into Simscape Multibody so that the model can be generated for them. This model considers the mass, inertia, joints, and constraints for each CAD assembly.

PERFORMANCE SUMMARY

1. Mathematical model performance

The mathematical model aims to provide information about the dynamics of the prototype vehicle. We showed a method to control the sail panels of the vehicle to prevent gyroscopic precession (Figure A2). We would like to attribute this concept to the sponsor; we only applied numerical methods on the model to show how it would work.

The system is generalized such that it can be scaled to the GeoShade vehicle. However, the mathematical model carried significant assumptions that have yet to be validated. Such assumptions might prove to be the achilles' heel of the system.

In the Matlab simulation of the mathematical model, the body torque vector shows small oscillations about the desired direction of torque. We do not know the source causing this oscillation. However, the magnitude of the oscillation is small compared to the magnitude of torque (~4%).

Using the angular position pattern that the sail panels need to generate, we were able to derive a torque requirement for the actuators controlling the panels to be 1.9 Nm.

2. Actuators Performance

In order for the sail to rotate and orbit around the earth with maximum efficient velocity, we examined several actuator performances, characteristics, and requirements. The actuators desired for the project must have during and after shock operations, high torque-to-weight ratio, high torque-to-inertia, high stiffness, and continuous operation in a vacuum. A reliability of (80 – 95) % is necessary for a 10-15 year lifetime operation due to lack of maintenance and continuous applications in a wide range of temperatures ranging between hot and cold. According to NASA researchers', brushless motors are the most appropriate and best equipped to survive the extreme and harsh environmental conditions of space [13].

The sail panels of the GeoShade design can be oriented independent of each other. Thus, it is vital that the selected actuator performs its functions as the sails rotate and orbit around the earth. Ionized radiation is an outstanding issue to all electronic devices used in space. To provide protection to devices, they get shielded through a process known as radiation hardening, which is quite expensive. From our research, we found a new technique developed by researchers at North Carolina State University, which requires devices to be coated with rust [1]. This technique improves shielding and has a minor effect on the device's weight.

To determine the torque required to rotate the sail panel, the equation in Model 1 was used: The mass of inertia for a panel is multiplied with angular acceleration to get the maximum torque required. Since the primary function of the motor is to spin the sail panel, it needs to be spinning at a fast rate due to the spinning rotation of the sail panel. It was determined using Model 1that the maximum torque required for the motor is 1.91 Nm. This is explained thoroughly in Model 1 found in Appendix F.

FINAL STATUS

1. High level summary

The GeoShade project is still very much in its infancy. The sponsor performed some calculations on the design of the project, but most of them are preliminary calculations. We understand that we significantly lack the knowledge required for designing a complete space sail vehicle. As such, we wanted to focus our project on the ground level research aspect so that next-generation designers can continue working on the project. Since we are not experts in solar sail or aerospace dynamics, we could only verify models by using engineering intuition, which is inadequate. However, we were able to produce tangible results and spearhead the design process. The sponsor can use our work to gain traction for the GeoShade project because GeoShade does not have any funding sources . The next step in the project is to validate our work and its feasibility (in terms of folding design).

2. Subsystem status

a. Mathematical Models

The solar force model is incomplete. To use it, three things must be accomplished. First, the optical coefficients for the CP1-polyimide must be determined experimentally. Second, the pitch angle for each sail panel must be determined by tracking the angular position of the actuators. Third, the transformation matrices must be defined for the sun, hub, and sail panels.

If the optical coefficients and the pitch angle for each sail panel are known, the normal and transverse forces can be easily modeled using Simscape Multibody. In the MATLAB add-on, the center of mass for each panel can be defined. These centers of masses contain frames that have x,y, and z components; the normal and transverse forces can be modeled by applying them to the appropriate x,y, or z-component.

For the two torque dynamic models, model validation has yet to be completed. As we lack the knowledge and expertise in aerospace design and testing, the models can only be numerically evaluated to an extent. Sensitivity studies need to be done for the models to determine their applicability.

b. Actuators

As the actuator team, our role consisted of distinguishing different types of actuators. The research was based on identifying actuators that were capable of unfolding sails and rotating sail panels. During our research, we examined various motors and created a table of our findings for the sponsor and adviser. Thereafter, we scaled down our goals and workload that were expected to be our deliverables.

For the actuator mechanics, we recommend that GeoShade uses motors that meet the majority of design requirements. The actuators could be used in conducting experiments to prove a concept. For example, the wave propagation experiment, which was carried out in the design process. We found it beneficial to demonstrate that slow rotation prevents the ends of large sails from experiencing extreme stress.

With more time, we would have created a business report to cost analyze the actuators and attitude control devices. Analyses could be simplified by organizing actuator performances within excel where the torque required to rotate a panel can be calculated based on the mathematical model. Another area worth researching is how adjusting actuator speeds can help reduce resonant frequencies.

c. Design Aid

At the end of the project, we successfully converted a sketch into a simple 3D model for the unfolding mechanism. The model currently consists of seven separate model files (Appendix B, Capstone-007-GeoShade\SolidworksFiles\UnlatchMechanism). In the current state, the models are intended only to demonstrate the unfolding mechanism's movements, for they don't exactly match intended dimensions, so this would inhibit demonstration purposes.If the 3D model for the unfolding mechanism was redone, we would suggest quickly creating a rough draft so that less time would be spent on a model that had inherent issues; this allows issues to be identified earlier so that they could be addressed sooner rather than later. With the simple mechanism model completed, the next step is modeling to scale and correcting dimensions so that the model is complete and manufacturable.

In addition to dimensional accuracy, we would like to optimize materials and parts for the model with FEA and other software so that it is prepared for space. The simplistic model was a useful visual demonstration piece because it explained the mechanics of the complex motions, and with time, it will serve as a building block on the steps towards a complete and manufacturable design.

For orbital mechanics, a simulation of the prototype orbiting around the earth was demonstrated. However, the animation is lacking several other steps to show a complete demonstration of the entire concept from beginning to the end. Since the project starts from packaging to launching and finally unfurling in space as it launches itself to L-1, it would be pertinent and satisfying to see this animated. Step one would be to launch the packaged GeoShade prototype in a long narrowed object that gets ejected from a spaceship; thereafter, the prototype ejects from the package into earth's orbit as it unfurls its panels. Afterwards, an illustration shows the panels rotate about motor axes. Ultimately, the animation will show the GeoShade prototype acquiring and reaching terminal velocity before it launches itself to L-1 where it will reside to omit and offset carbon emissions.

The Simscape Multibody simulation successfully modeled the external normal forces that are being applied to the solar sail prototype in a zero-gravity environment.

However, in order for the model to be complete, the model must take the transverse force that is acting on each panel into consideration. The transverse force can be determined by referring to the solar force model that is presented in this report. Unfortunately, the transverse force component cannot be determined until CP1-polyimide’s optical coefficients are known.

Once an accurate model of the sail dynamics is determined, the control system can be designed for the GeoShade or sail prototype. The controller design can be automated in Simscape Multibody so that the process is repeatable and reliable as design changes are being made to the sails. As a result of testing controllers in MATLAB, GeoShade can eliminate the need for prototypes.

Model verification for the simulations consisted of observing inputs and outputs. For a specific input, we knew with complete certainty that a specific output must occur. Inputs were external forces applied to different parts of the solar sail. The outputs were the motions generated as a result of those forces. For every input, the expected output did occur. However, there were other motions that were not accounted for. These discrepancies have led us to the conclusion that our simulated model may be incomplete. An expert in the field of sail dynamics would need to be consulted to determine whether these discrepancies represent the sail’s dynamics or software errors. Regardless of whether the results of the simulation model are infallible, the model is useful. The sponsor can use it for future analyses and visual aid purposes.

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Appendix A: Supplemental Images

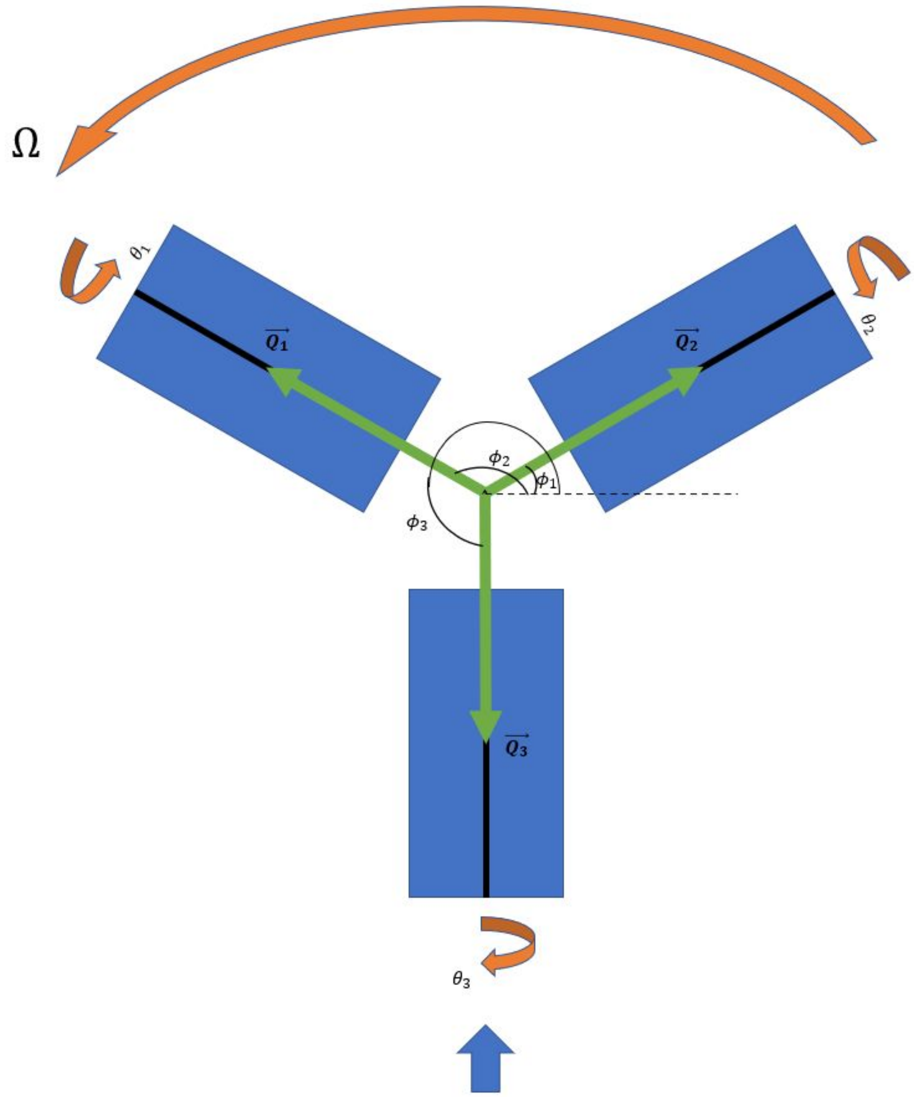
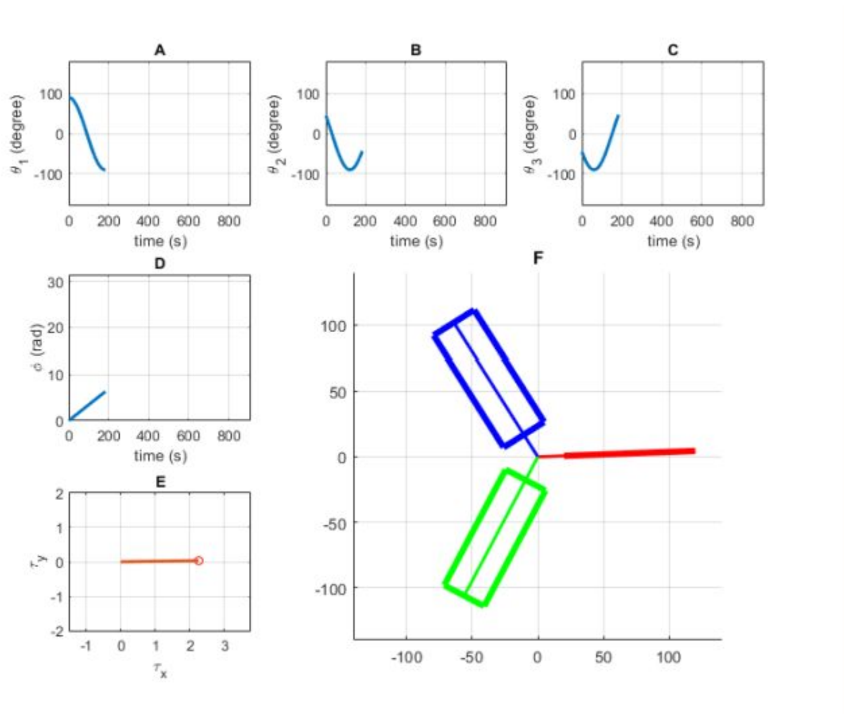


Figure A1: The free body diagram of the prototype sail. The variable list is presented in Table Model 2.



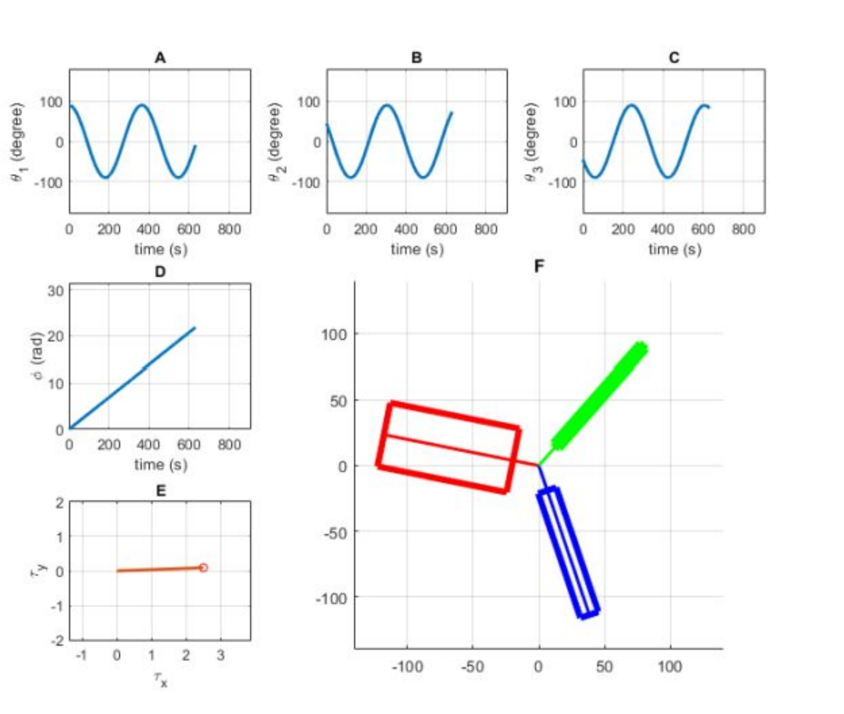


Figure A2: Two frames out of the animation created to visualize the control method for the sail panels such that the torque vector (panel E) is stable.

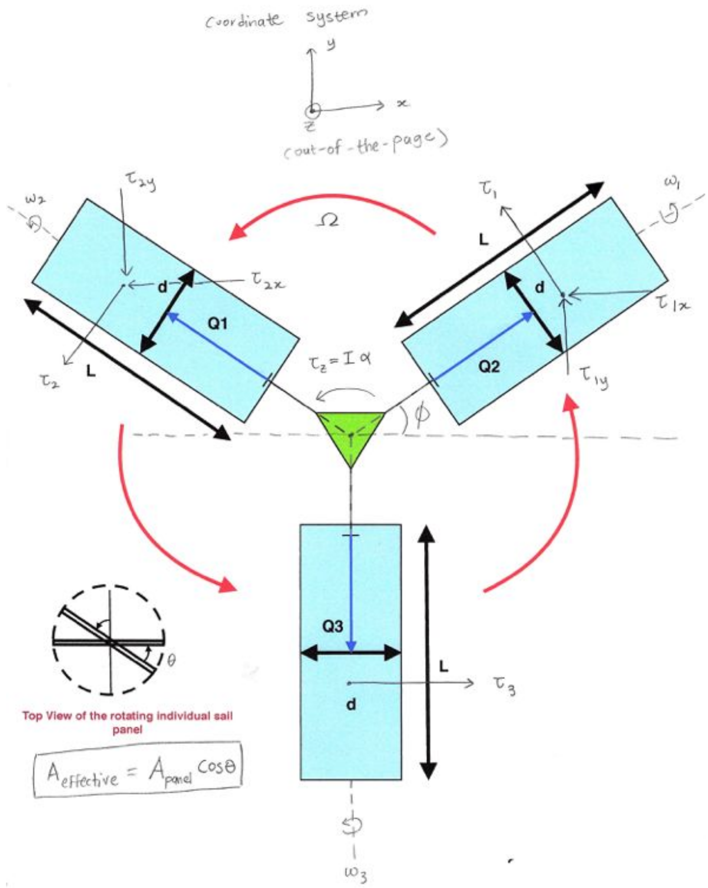


Figure A3: The free body diagram of the prototype sail design showcases the torque vectors that result from the solar pressure force acting on the sail body frame to spin it in different orientations.

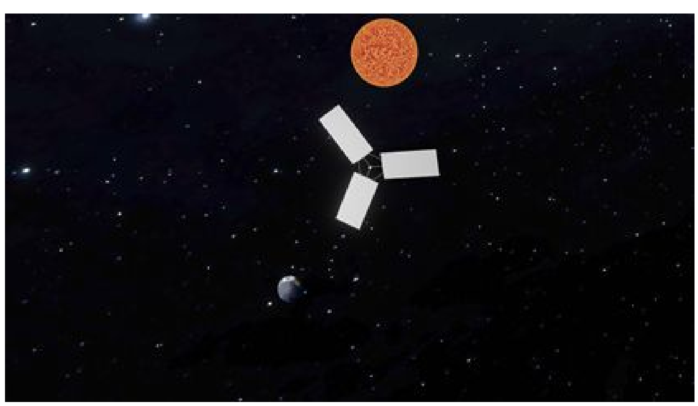


Figure A4: Prototype facing the sun.

Appendix B: Catalog of Design Artifacts

The following Github repository contains all design artifacts of this Capstone project.

https://github.com/jakechung42/Capstone-007-GeoShade

1. AnimationFiles
    a. Simscape Multibody: Simscape Multibody simulation
    b. Blender
        i. VN - Vadim Naumchuck's blender
        ii. MA - Mohammed Afdup's blender files
2. Experiments
    a. Experiment A: containing all raw data and Matlab, Arduino files to control and analyze the data from the Wave propagation experiment.
    b. Experiment B: containing all raw data and Matlab files for the carbon fiber natural frequency vibration experiment.
3. Paper Assignments: all paper assignments related to capstone (project proposal, progress report, and final report)
4. Solidworks Files
    a. tabletopToyModel: Solidworks files for the 3D printed toy model
    b. UnlatchMechanism: Solidworks files for the Unlatch Mechanism
5. VirtualPresentation: containing the Youtube link to the virtual presentation. The file is too big to upload to Github

MasterMeetingNotes.dox: a cumulated document of all the meeting notes between team members, the sponsor, and the project advisor.

Appendix C: Concept Analysis

Our team started by familiarizing ourselves and researching the concept of GeoShade with the main goal being the design of a prototype that could be used for demonstration purposes and proof of concepts. Thereafter, the team dived deep into literature review and concluded several components that were worth developing. For example, FEA models, animations, folding patterns, mathematical models, fabrications, deployment mechanisms, computer/electrical components, and actuators.

Due to the scale of the project, it was broken down to three parts as suggested by Andrew Greenberg from the Portland State Aerospace Society. We focused on the mathematical model to study the dynamics of the sail vehicle. The model also enables us to help the other two branches in either completing or moving forward to the next step. The second component we examined is the deployment mechanism, which entails how the sail will deploy its sail panels and initiate its deployment. The last part is actuator selection and a business report that evaluates the actuator’s cost benefits.

As we progressed to the final design concept part, we did not deviate as much as we had imagined during the second phase of the capstone project. At the end, we were able to deliver a physical component that the sponsor could use for demonstration purposes. Some particular components from the design components had to be eliminated in the third phase of the capstone project because the social distancing order did not allow physical labs to be accessed. As a result, we made simulations and animations for the project. The main factors that we have not achieved in our project were fabrication, business report, and computer/electrical components.

Appendix D: System-Level Requirements Matrix

Key Performance Measures	**Description**
Actuated Sail Panels	528 panels rotate independently and at different velocities and accelerations.
Solar Sail Deployment	Incorporate centrifugal forces and actuated motors to assist the unfolding mechanism located at the center of the structure.
Trajectory maneuvering systems	Adjust GeoShade trajectory to rotate 90 degrees for every 10 minutes by performing system analysis to accurately determine the transfer function of the system.
Solar force model	Mathematical model which describes magnitude and direction of solar forces acting on sail and the central hub's body torque
Actuation performance/cost analysis	Analysis of actuators that have high torque-to-weight ratio, high torque-to-inertia, high stiffness, and continuous vacuum operation.
System Dynamics	Use simulation software to determine system dynamics by incorporating mathematical models. Simscape turns CAD assemblies into MATLAB models.

Appendix E: Model 1

A few assumptions were made to derive the solar force model for a single sail panel: the sail is perfectly flat and not a perfect reflector.The sail must be flat for two reasons: concentrated forces and lever arms. Force distributions along a sail are not constant if a panel's shape changes with time. Tensor calculus is required to describe the non-constant force distribution. If lever arms, the distance between the hub and a panel's center of mass, changes, differentials must be written to describe these changes. The differentials must describe the deflections occurring on a panel due to solar forces, actuator torques, etc. Tensor calculus is needed to express differential force distributions, deflections, and lever arms. Unfortunately, no member of the modeling team is familiar with such math.

The total force exerted on the solar sail due to solar radiation pressure may be written as

$$\mathbf{f}=\mathbf{f}_r+\mathbf{f}_a+\mathbf{f}_e \tag{6}$$

where f_r is the force due to reflection, f_a is the force due to absorption, and f_e is the force due to emission by re-radiation [3].

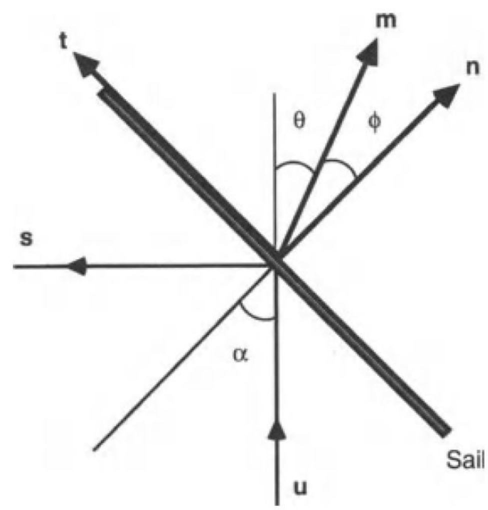


Figure 5: The free body diagram for one sail panel. The variables are described in table 2.

Table 2: Variable list for model 1.

Variable	Description
a	The absorption coefficient, where **a** = 1- $\tilde{\mathbf{r}}$.
α	The pitch angle of the solar sail relative to the Sun-line.
A	The area of the sail panel.
$\mathbf{B_b}$	The non-Lambertian coefficient for the back of the sail. The coefficient describes the non-uniform brightness of the material.
$\mathbf{B_f}$	The non-Lambertian coefficient for the front of the sail.
c	The speed of light.
ϵ_b	The back emissivity of the sail.
ϵ_f	The front emissivity of the sail.
n	The normal unit vector.
P	The solar pressure, where **P** = $9.12*10^{-6}\frac{N}{m^2}$ for a perfect reflecting sail.
$\tilde{\mathbf{r}}$	The reflection coefficient.
s	The direction of reflected photons, where **s** = - (cos **α**) **n**+ (sin **α**) **t**.
$\tilde{\sigma}$	The Stefan-Boltzmann constant, where $\tilde{\sigma} = 5.670373*10^{-8}\frac{W}{m^2*K^4}$.
t	The transverse unit vector.
T	The temperature of the sail, where **T**=$[\frac{(1-\tilde{r})*c*P*\cos\alpha}{\tilde{\sigma}*(\epsilon_f+\epsilon_b)}]^{1/4}$.
u	The direction of incidence for photons, where **u**= (cos **α**) **n**+ (sin **α**) **t**.

The following three equations represent the forces acting on a panel's center of mass; these are the forces due to reflection, absorption, and re-radiation:

$$f_r = \mathbf{P}*\mathbf{A}*[\ (\tilde{\mathbf{r}} * s * cos^2\,\boldsymbol{\alpha} + \mathbf{B_f}\,(1\text{-}\mathbf{s})* \tilde{\mathbf{r}}*\cos\,\boldsymbol{\alpha})\ \mathbf{n} - (\tilde{\mathbf{r}} * s * cos\,\boldsymbol{\alpha}*\sin\,\boldsymbol{\alpha})\ \mathbf{t}] \tag{7}$$

$$f_a = \mathbf{P}*\mathbf{A}*[\ (cos^2\,\boldsymbol{\alpha})\ \mathbf{n} + (\cos\,\boldsymbol{\alpha}*\sin\,\boldsymbol{\alpha})\ \mathbf{t}] \tag{8}$$

$$f_e = [\mathbf{P}*\mathbf{A}*(1 - \tilde{\mathbf{r}})*\frac{\epsilon_f * B_f - \epsilon_b * B_b}{\epsilon_f + \epsilon_b}*\cos\,\boldsymbol{\alpha}]\ \mathbf{n} \tag{9}$$

The solar forces were resolved into normal and transverse unit components in order to describe the normal and transverse force acting on each sail panel's center of mass:

$$f_n = \{\mathbf{P}*\mathbf{A}*[\ (1+\tilde{\mathbf{r}} * s) * \ cos^2\,\boldsymbol{\alpha} + \mathbf{B_f} *(1\text{-s})* \tilde{\mathbf{r}}*\cos\,\boldsymbol{\alpha} + (1 - \tilde{\mathbf{r}})*\frac{\epsilon_f * B_f - \epsilon_b * B_b}{\epsilon_f + \epsilon_b}*\cos\,\boldsymbol{\alpha}\ ]\}\ \mathbf{n} \tag{10}$$

$$f_t = [\mathbf{P}*\mathbf{A}*(1\text{-}\tilde{\mathbf{r}} * s)* \cos\,\boldsymbol{\alpha}*\sin\,\boldsymbol{\alpha}]\ \mathbf{t} \tag{11}$$

The optical coefficients for each sail will be approximately equivalent. However, the normal unit vector, the transverse unit vector, and the pitch angle are unique for each sail. The unit vectors for each sail panel can be solved by defining a transformation matrix for the sun, the central hub, and the sail panel x. By multiplying the transformation matrices in the following order

$$\mathbf{T_{sun}}*\mathbf{T_{hub}}*\mathbf{T_{panel\ x}} \tag{12}$$

the direction of incidence for photons (**u**) can be solved for panel x. The transformation matrices contain the orientation of each component (Sun, hub, and panel) in the x, y, and z directions. It also describes the distance between each component in the x, y, and z-direction. Note, to define transformation matrices, an origin must be established. The appropriate origin to define in this case is the sun. Every transformation matrix contains a rotation matrix. The hub's rotation matrix must describe the angle it makes with respect to one of the origin's (the Sun's) arbitrary axes. Panel x's rotation matrix must describe the angle it makes with respect to one of the hub's arbitrary axes. By knowing the transformation matrix of each object at any point in time, the transverse and normal unit vector can be solved for each panel. If the unit vectors of each panel are known, the panel x's pitch angle can be solved for.

The torque equation for the hub's center of mass is dependent on the transformation matrices for each panel. The transformation matrix contains the lever arms for the normal and transverse force of each panel. It is also used to describe the direction of the normal and transverse force. Thus, the torque created due to each panel's center of mass can be calculated. The torques are then summed together to express the hub's torque at every point in time.

Appendix F: Model 2

In Figure A1, the free body diagram is presented. The variable list is in Table 2.

Table 2: Variable list for Model 2.

P_s	Sun pressure $(9.12 * 10^{-6}\ Nm^{-2})$[1]
A	Area of the sail panel (m^2)
θ_i	Angles made with the vehicle's plane (figure X) (rad)
ϕ_i	Angle of each panel made with the positive x-axis (rad)
τ_b	Body torque of the vehicle (Nm)
I	Moment of inertia tensor of the vehicle
γ	Pitch velocity (rad/s)
Ω	Angular velocity vector of the stabilizing spin of the vehicle.

The solar force applied on a sail panel is a function of the angle a panel makes respect to the plane that contains the sail vehicle. We define effective area as

$$A_{eff} = Acos(\theta_i) \tag{13}$$

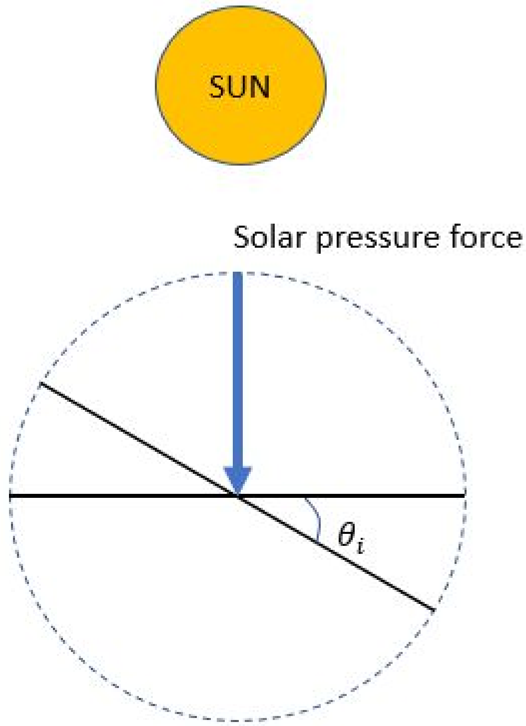


Figure 6: Cross-section view of a panel facing the sun.

The effective area is an indirect way to adjust the amount of force being applied to a sail panel. We can then define the solar pressure force applied on a panel as

$$F_i = P_s * A_{eff} = P_s * A * \cos(\theta_i) \tag{14}$$

Each solar pressure force is acting at the center of a sail panel. The cross product of the solar force and the moment arm $\mathbf{Q_i}$ (figure X, the free body diagram fig) describes the torques created by each sail panel. Due to the symmetry of the sail panels, the torque vectors cancel each other. However, as one panel rotates, it will create an imbalance in the summation of torques.

The moment arms $\mathbf{Q_i}$ is a function of the rotation Ω, which is defined as the primary rotational velocity. In our assumptions, we set Ω to be constant. The moment arm $\mathbf{Q_i}$ can be written in terms of the primary angular position as

$$\overrightarrow{Q_1} = Q\begin{bmatrix}\cos(\phi) \\ \sin(\phi]) \\ 0\end{bmatrix}$$
$$\overrightarrow{Q_2} = Q\begin{bmatrix}\cos\left(\phi + \frac{2\pi}{3}\right) \\ \sin\left(\phi + \frac{2\pi}{3}\right) \\ 0\end{bmatrix}$$
$$\overrightarrow{Q_3} = Q\begin{bmatrix}\cos\left(\phi + \frac{4\pi}{3}\right) \\ \sin\left(\phi + \frac{4\pi}{3}\right) \\ 0\end{bmatrix} \tag{15}$$

where Q = 70 meters as approximated from the sail geometry. Since each sail panel is 120° apart, we only need one variable to keep track of the position of each sail panel. As the torque vectors are summed up, they contain the information of the pressure force on the sail and the position of each sail panel. The torque equation is the following:

$$\vec{\tau}_b = \begin{bmatrix}-P_sAQcos(\theta_1)\cos(\phi_1) - P_sAQcos(\theta_2)\cos(\phi_2) - P_sAQcos(\theta_3)\cos(\phi_3) \\ P_sAQcos(\theta_1)\sin(\phi_1) + P_sAQcos(\theta_2)\sin(\phi_2) + P_sAQcos(\theta_3)\sin(\phi_3) \\ 0\end{bmatrix} \tag{16}$$

Since we only focus on the steady state response of the vehicle, the body torque vector only has x and y components. We showed that the torque vector can be controlled by adjusting the motion of the three panels such that gyroscopic precession is prevented.

The parameters to control the body torque vector are the panel's sinusoidal amplitude and phase shift. The amplitude controls the magnitude of the torque vector and the phase shift controls the direction of the torque vector (figure A2, panel A, B, and

C). An analytical relationship has not been established, but numerical estimations can be determined using the Matlab simulation.

The current panel size is 50 meters by 100 meters. With the given solar pressure, the maximum body torque is 2.5 Nm. Given that this prototype sail only has 3 sail panels, the GeoShade final design can generate significantly more torque with 528 panels. However, the GeoShade also has high mass inertia so the rate of pitch is still undetermined.

The body torque is used to control the pitch of the sail vehicle following the equation

$$\vec{\tau}_b = \vec{\gamma} \times I\overrightarrow{\Omega} \tag{17}$$

where γ is the pitch vector, and I is the inertia tensor of the vehicle. The inertia tensor of the sail is constantly changing due to the rotation of the sail.

Appendix G: Model 3

As the solar sail vehicle is launched from earth's orbit, the orientation of the vehicle's body frame would require torque control to ensure that the solar sail does not fall from its course to Lagrange 1. For this purpose, a mathematical model that represents the solar sail's body torque as a function of angle (θ_i) and body frame angle (ϕ) is derived. The input angle is determined from each sail panel. The body frame angle is the angle of the solar sail body frame as it rotates from its equilibrium position.

The sail prototype design consists of a central vehicle that connects three sail panels that can each rotate with an angular velocity (ω_i). The body frame of the solar sail rotates at an angular velocity Ω. The x, y, and z torque components of the solar sail are denoted by τ_x, τ_y, and τ_z.

The torque with respect to the central hub (vehicle) due to the solar pressure (P_s) applied is given by,

$$\tau_i = \sum_{i=1}^{3}\left(F_i \cdot \left(\frac{L}{2} + (\rho - L)\right)\right)$$

$$\tau_i = \sum_{i=1}^{3}\left([P_s \cdot A\cos(\theta_i)] \cdot \left[\frac{L}{2} + (\rho - L)\right]\right)$$

$$\therefore \tau_i = \sum_{i=1}^{3}\left([P_s \cdot L \cdot d\cos(\theta_i)] \cdot \left[\frac{L}{2} + (\rho - L)\right]\right) \tag{18}$$

The combined torque for each component is derived from the free body diagram based on the sail prototype design where the "x" and "y" component of the torque vector is the following:

$$\tau_x = \sum_{j=1}^{3} \tau_{x_j} = \tau_{x_1} + \tau_{x_2} + \tau_{x_3}$$
$$\tau_x(\varphi_j) = [-\tau_i \cdot sin(\varphi_1)] + [-\tau_i \cdot sin(180° - \varphi_2)] + \tau_i$$
$$\therefore \tau_x(\varphi_j) = \tau_i - \tau_i \cdot sin(\varphi_1) - \tau_i \cdot sin(180° - \varphi_2) \quad (19)$$

$$\tau_y = \sum_{k=1}^{3} \tau_{y_k} = \tau_{y_1} + \tau_{y_2} + \tau_{y_3}$$
$$\tau_y(\varphi_k) = \tau_i \cdot cos(\varphi_1) + [-\tau_i \cdot \cos(180° - \varphi_2)] + 0$$
$$\therefore \tau_y(\varphi_k) = \tau_i \cdot cos(\varphi_1) - \tau_i \cdot cos(180° - \varphi_2) \quad (20)$$

The body frame angle of the second panel can be expressed as a function of the first panel's angle. The body frame angle between the first two sails is:

$$\varphi_2 = \varphi_1 + 120° \quad (21)$$

The body frame angle of the first panel (ϕ_1) is equal to a particular value that can be specified as "ϕ". The body frame angle of the third panel is not included since the torque vector acting on that panel cannot be expressed in terms of ϕ_3. The "z" component of the torque vector is obtained from the Inertia of the body frame and the angular acceleration given by:

$$\therefore \tau_z = I\alpha = \mathrm{I}\left(\frac{\Omega}{t}\right) \quad (22)$$

The torque model of the prototype solar sail design is expressed as:

$$T = f(\theta_i, \varphi) = \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} = \begin{bmatrix} \tau_x(\varphi_j) \\ \tau_y(\varphi_k) \\ \tau_z \end{bmatrix} = \begin{bmatrix} \tau_x(\theta_i, \varphi_1, \varphi_2) \\ \tau_y(\theta_i, \varphi_1, \varphi_2) \\ \tau_z \end{bmatrix}$$

$$T = f(\theta_i, \varphi) = \begin{bmatrix} \tau_i - \tau_i \cdot sin(\varphi_1) - \tau_i \cdot sin(180° - \varphi_2) \\ \tau_i \cdot cos(\varphi_1) - \tau_i \cdot cos(180° - \varphi_2) \\ I\Omega \end{bmatrix}$$

$$\therefore T = f(\theta_i, \varphi) = \begin{bmatrix} \tau_i \cdot [1 - sin(\varphi_1) - sin(180° - \varphi_2)] \\ \tau_i \cdot [cos(\varphi_1) - cos(180° - \varphi_2)] \\ I\Omega \end{bmatrix} \quad (23)$$

The model for the torque with respect to the central hub (vehicle) of the sail body frame is denoted by the following function:

$$\therefore \boldsymbol{T = f(\theta_i, \varphi_1, \varphi_2)} = \begin{bmatrix} \sum_{i=1}^{3} \left([P_s \cdot L \cdot dcos(\theta_i)] \cdot \left[\frac{L}{2} + (\rho - L)\right] \cdot [1 - sin(\varphi_1) - sin(180° - \varphi_2)] \right) \\ \sum_{i=1}^{3} \left([P_s \cdot L \cdot dcos(\theta_i)] \cdot \left[\frac{L}{2} + (\rho - L)\right] \cdot [cos(\varphi_1) - cos(180° - \varphi_2)] \right) \\ I\Omega \end{bmatrix} \quad (24)$$

However, as mentioned before that "ϕ_1" is specified as a particular fixed value signified by "ϕ". Since $\phi_2 = \phi + 120\,°$, the body frame angle of the first panel and second panel can be written in terms of that particularly fixed value.

The mathematical model that describes the central hub's torque is the following:

$$\therefore \boldsymbol{T = f(\theta_i, \varphi)} = \begin{bmatrix} \sum_{i=1}^{3} \left([P_s \cdot L \cdot dcos(\theta_i)] \cdot \left[\frac{L}{2} + (\rho - L)\right] \cdot [1 - sin(\varphi) - sin(60° - \varphi)] \right) \\ \sum_{i=1}^{3} \left([P_s \cdot L \cdot dcos(\theta_i)] \cdot \left[\frac{L}{2} + (\rho - L)\right] \cdot [cos(\varphi) - cos(60° - \varphi)] \right) \\ I\alpha \end{bmatrix} \quad (25)$$

The parameters for the torque model derivation is listed below.

L = The length of the individual sail panel.

d = The width of the individual sail panel.

ϱ = The distance from the center of the hub to the free end of the individual sail panel.

Ps = The solar pressure force from the sun.

ϕ = The angle of the solar sail body frame as it rotates from its initial position.

θ_i = The input angle for individual sail panels.

I = Inertia of the solar sail body frame.

Ω = Angular velocity of the solar sail body frame.

ω_i = Angular velocity of the individual sail panels.

Appendix H: Folding Research

The purpose of this section is to evaluate previous packaging and deployment methods used for solar sails to provide a plausible folding pattern for GeoShade's solar sail. For GeoShade to successfully complete its mission *in space*, it is important to look into the major factors of packaging a large membrane structure to fit inside a rocket and deploy it in lower earth orbit. The membrane structure will have a central hub frame,a sail deployment mechanism, and reflective foldable sail material. To have a better understanding of the solar sail types and different deployment processes, research was conducted and will be presented in the following subsection, which examines three types of solar sails. These sails have different deployment methods and unique folding patterns.

The fundamental goals for each solar sail is to increase *reflective* surface area and reduce mass. These sails use different methods to remain flat. To reduce mass, disc and helio-gyro sails using spinning motion to be rigid. The other methods use lightweight rigid beams as supports.

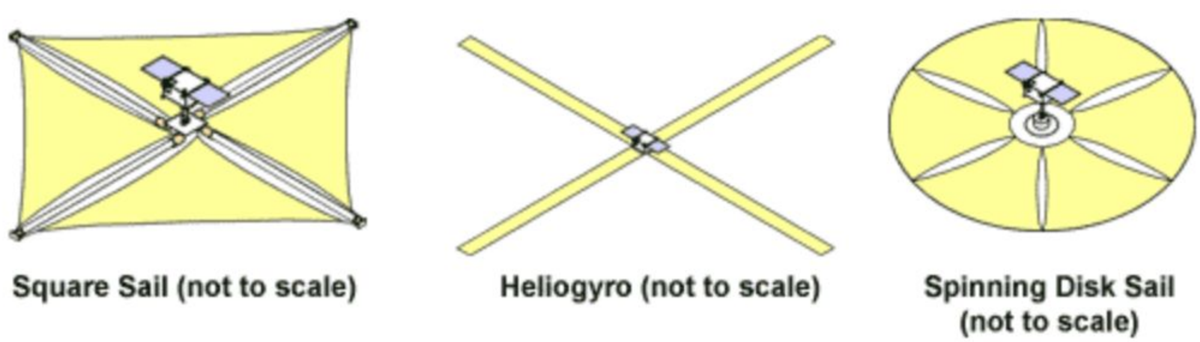


Figure 7: The square sail is to the left, the Heliogyro sail is in the middle, and Spinning sail is to the right [10].

Square Sails

One sail is in the shape of a square as it is the most efficient design in terms of mass-to-area ratio [5]. A general example of a square solar sail would be the light sail 2, which consists of a central hub with four deployable spars called booms attached to the sail material. Normally, booms are cantilevered from the central hub with a rolling mechanism that unfurls the booms and tensions so that the sail film can provide structural support. This design has become the most common form of solar sailing due to its simplicity and high level of controllability. Also, another benefit to having a beam enforced solar sail would be removing the need of having an outside force to maintain rigidity. However, in terms of creating the most efficient solar sail, the other two types of solar sails designs remove rigid beams outside the central hub and use centripetal force to maintain rigidity.

Spinning Sails

Spinning sails use centrifugal force to deploy sail membranes and provide gyroscopic rigidity. Spinning sails do not require any supporting structure; therefore, they are preferable in terms of reducing system weight. However, spinning sails have one major concern as they could easily defrom in space, so this largely affects the attitude motion. Currently, there is one spinning solar sail named IKAROS having a square 14 x 14m sail membrane. IKAROS used tip masses at its end to provide additional rigidity [6]. The next challenge in using a spinning sail would be the attitude control device. One method that has been proven to work for IKAROS would be to electrically control the optical properties of the surface [6]. However, reflectivity control devices have a problem with environmental space effects and sail deformities. Therefore, knowledge of membrane deformation is vital to solar sailing and achieving spin for spinning membrane space structures.

Heliogyro sails

Helio-gyro sails are helicopter-like, spinning solar sails. They were first introduced by MacNeal in 1967 [7]. Fundamental heliogyro solar sails use simple unrolling motion to extend a finite width of sail film for kilometers.This allows many difficulties associated with stowage and large membrane deployment to be avoided. Similar to spinning sails, helio-gyros use centripetal force to slowly unroll a series of sails and provide rigidity to the film material. Attitude control is accomplished by pitching the blades at the central hub by changing their orientation with respect to the sun. Together, the blades generate torque about the spinning axis, They also spin the helio-gyro up, down, cyclically, in a pre-revolution fashion, and generate thrust in components that are in the plane of rotation [8]. Currently, there aren't any helio-gyro sails in space; however, NASA is actively working on prototypes to send one out in the near future.

GeoShade (how it compares to the other three)

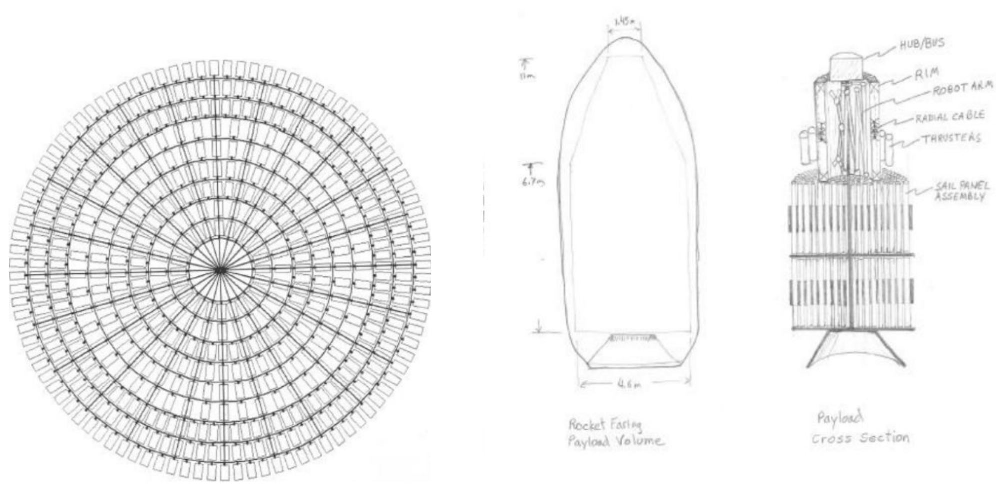


Figure 8: The left image is a representation of a fully deployed GeoShade sail, and to the right is GeoShade packaged inside a rocket capsule [9].

GeoShade is currently in the initial stages of what will become the largest man made space vehicle designed to reduce CO2 emissions from the sun. This solar sail will effectively incorporate existing sail technology to reduce total cost [9]. As the sail is projected to be 1.1 km in radius, using beams to provide rigidity will be impractical due to increased costs and the inability to package large beams. Therefore, this solar sail will use spinning motion to sustain rigidity. From ground up, the GeoShade sail will have *"528 sail panel assemblies that can be packed with its hub, collapsible rim, and robot arm and potentially small thrusters to provide initial rotational speed. The rim has a 15 meter radius, and is used as the base for releasing the cable structure and sail panel assemblies. The robot arm can reach throughout this rim area. The hub position within the rim is adjustable with cables to give the opportunity to adjust the center of mass relative to the center of solar pressure. The robot arm un-stows and attaches each sail panel assembly to the cable structure starting from the outermost ring. After each ring of sail panels is readied, radial cables are extended to allow that ring to extend away from the rim. The process is repeated for each ring. Once the cable mesh has been fully extended from the rim, with sail panel assemblies attached, each sail panel is unfurled using simple rotational motions by its actuator. So the in-space assembly and deployment only relies on robot operation around the central hub and rim area. If needed the robotic operations can be performed through manual remote control and feedback from cameras on the robot arm."* [9]

The GeoShade prototype will also use spinning to assist in the deployment process, and it will have the final product's deployment mechanism and folding pattern; however, it will use actuators to control pitch and have a light weight central hub. This will provide proof of concept and additional data to improve on the final product. Throughout the deployment research, the team emphasized the importance of determining how to reduce costs and failures in the deployment process.

The deployment process considered three factors: sail panel packaging, deployments mechanisms, and folding patterns. From a design perspective, the driving force will be the folding pattern, which is followed by the other two; therefore, the research was focused on folding. Although GeoShade is unlike other sails in space, the studies conducted on other sails provided ground work. From there, we came up with a plausible deployment method. Also, another method was introduced by the sponsor.

Z-Fold & Rolling Fold

The advantages of having a parallel Z-fold is that there are no crease line convergences and it's simple to package. Similar to the Z-fold, the rolling fold is simple to package. One advantage to rolling is that it avoids crease lines all together; however, one major disadvantage is that the sail's width is limited to the rocket's storage height. Therefore, Z-Fold and Rolling fold won't work for Geoshade unless they are combined or a double Z-fold is used.

Z-Fold followed by a Rolling Fold

The deployment process consists of an unwrapping stage followed by an unfolding stage.

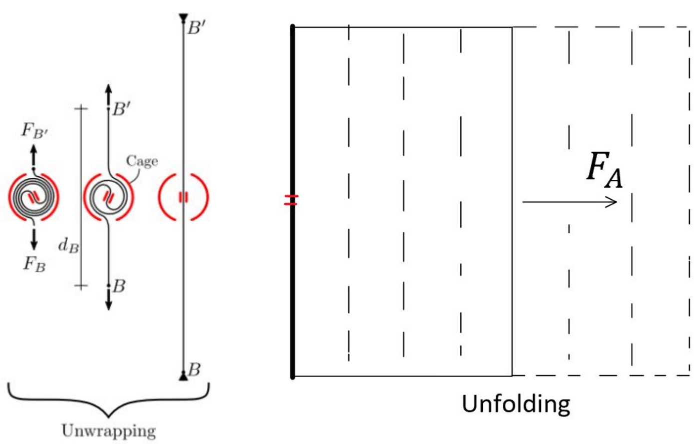


Figure 9: The unwrapping and unfolding stage occur to the left and right, respectively [11].

In the unwrapping stage, two ends B & B' will be hinged to a boom that will extend in both directions through the use of pre-tension springs or through a low friction gear system. A pre-tension system would be recommended on its own as it will not require an actuator; however, GeoShade will use actuators to control flight in space. Thus, a multi use actuator would be beneficial to reduce weight and provide controllability during the unwrapping stage. Once the booms fully unwrap, they will be hinged in place to provide rigidity. For the second stage to start, an outside force will be needed to provide initial spinning motion that will assist in the Z-Fold's unfolding process. Since the concepts of using an actuator to control the first stage of deployment and centripetal force to complete the second stage have not been tested, we are uncertain if a boom can extend from the actuator to the sail tip due to control-ability and unexpected wrinkles that will create stress concentrations. To answer these uncertainties and others that may come up, a physical prototype will need to be created and analyzed.

Double Z-Fold

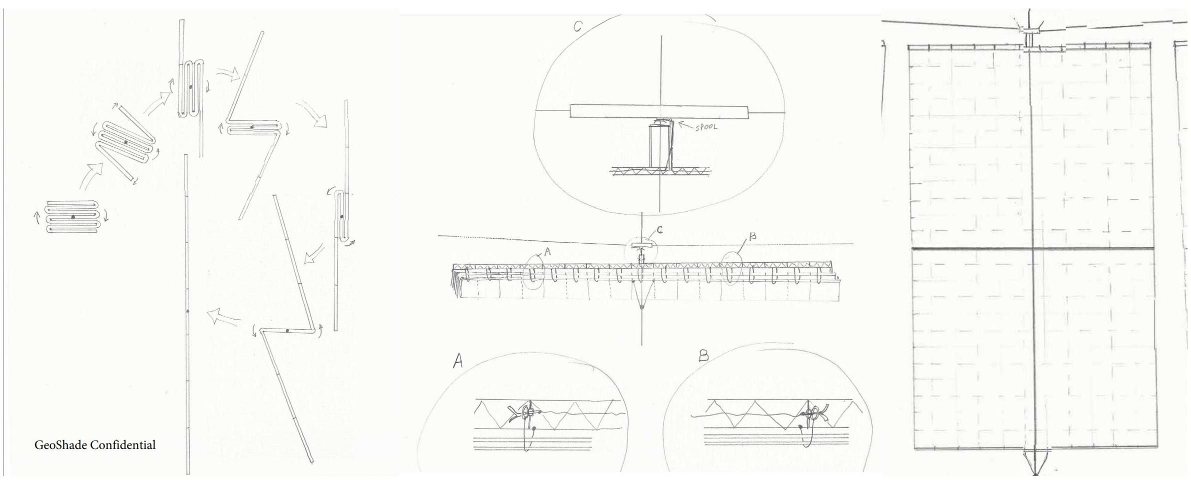


Figure 10: The left photo shows the deployment mechanism performing the first Z-Fold. The middle photo shows the second stage, and the right photo shows the final stage [9].

The double Z-Fold deployment was provided by Tim Sippel, the sponsor. When referring to a double Z-Fold, it means a two stage process of a single Z-Fold. The first stage as shown in Figure 10 shows the sail unfolding from its central local axis and locking in place to form a rigid beam. Once that step is complete, two latch mechanisms release as shown in the middle Figure 10 to allow the second stage to begin. The second stage consists of a Z-Fold unfolding along the radial direction, which is guided along a light weight cable. At its final state as shown in the right Figure 10, the sail will be locked in at both ends for rigidity. To further improve the sail design, two additional beams are proposed as shown in the right figure [Vadim.D]; this will allow for modifications in the sail film to distribute the stress points by having more attachment points.

From our research, there are currently two proposed folding methods that will require testing. Unfortunately, due to COVID-19 safety concerns, the capstone team was unable to use school resources and have in person meetings. However, for progress not to end there, the team was split into groups that focused on CAD modeling, deployment mechanisms, and animations that showed the prototype orbiting the earth. Regardless of COVID-19, there still would have been a CAD modeling team that designed a prototype. Other team members would have been working on a test setup to analyze the deployment. The end goal would be creating a functioning small scale model for a single sail that performs deployment.

Appendix I: Unfolding Mechanism

In this section, we'll be walking through the process that was taken to convert a sketch of the unfolding mechanism into a 3D model. Following that, we'll deliver a brief step by step understanding of how to operate the model for demonstrations.

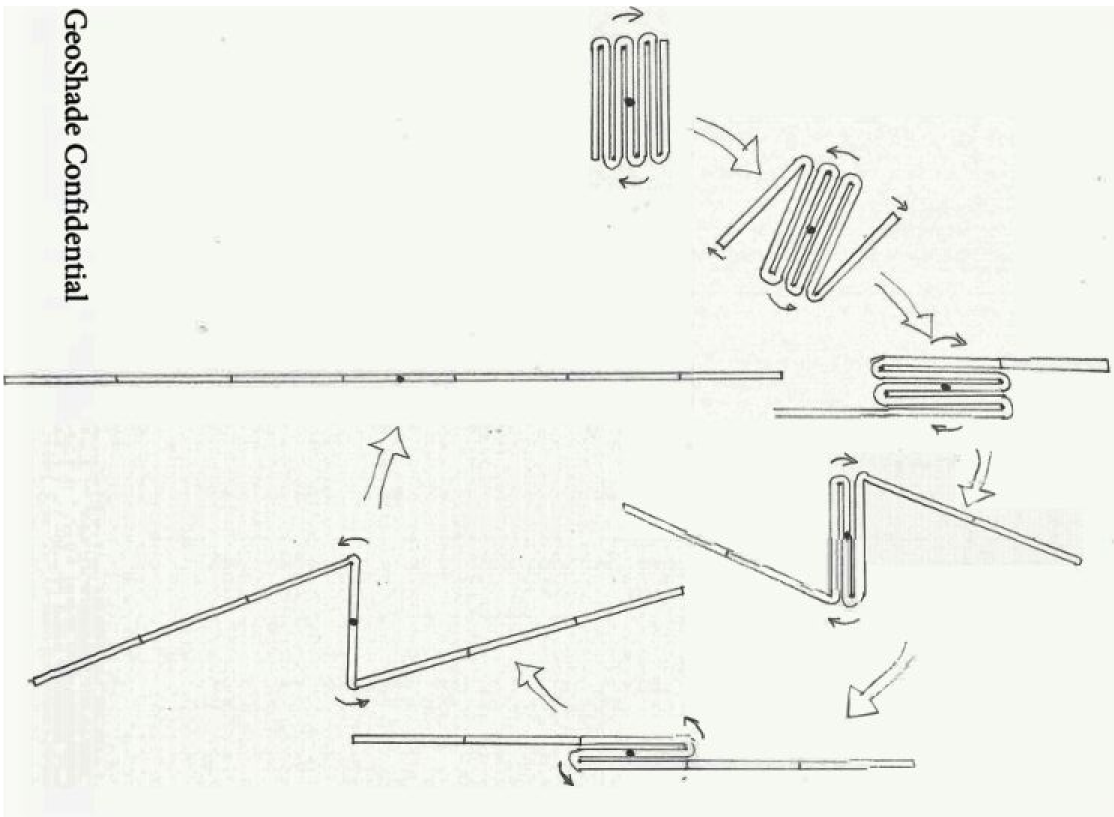


Figure 11: Figure shows the general unfolding motion from a top-down view. (From sponsor's original drafts)

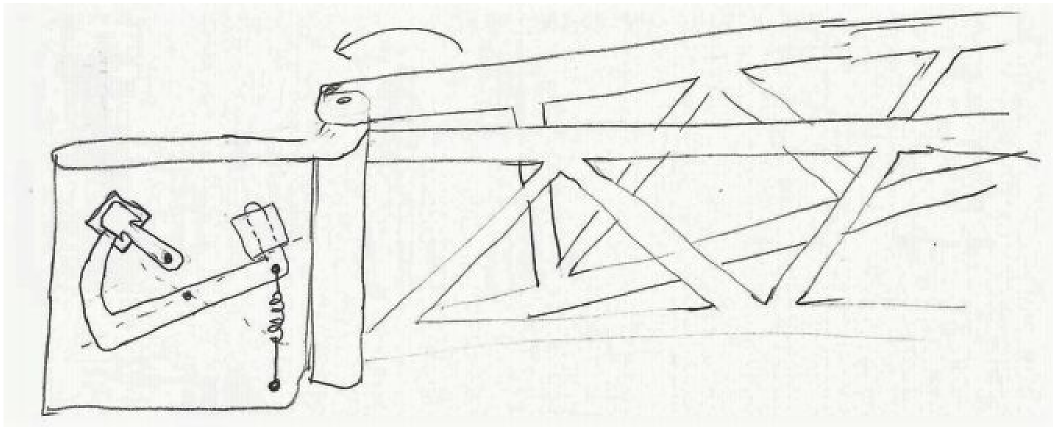


Figure 12: Figure shows the latching mechanism before the unfolding motion.(From sponsor's original drafts)

To start, we first look at the two main sketches provided by the sponsor shown in Figures 11 and 12. From figure 10, we see that the intent for the unfolding mechanism is to move from a point where the frames are folded up in a condensed z-fold to the unfolded rigid structure that makes up the horizontal length of the sail. In Figure 12, we see a close-up side view of the hinge where the frames meet and the general look of the latching mechanism. Based on explanations from the sponsor, the unfolding mechanism works by rotating the frame at the center, which is indicated by the dark circular spot in Figure 11. The back and forth motions let the outermost frames swing along their hinge until they line up with the next outermost frame. At that point, a protrusion on the first frame will connect with the latching mechanism on the second frame. This locks it in place while simultaneously unlocking the second frame from the third frame. This process repeats on both sides of the center frame until all frames are collinear. Regarding the latching mechanism, initially, a loop holding onto frame three is caught onto the rotating latch. The latch will maintain its position due to a spring forcing it to rotate clockwise into a pin or another latch. At that point in time, when frame one rotates and its protrusion knocks the pin out, the lock will continue its rotation by freeing itself from the loop of frame three, which allows frame two to move freely. At the same time, the rotating lock will connect with the protrusion locking frame one to frame two.

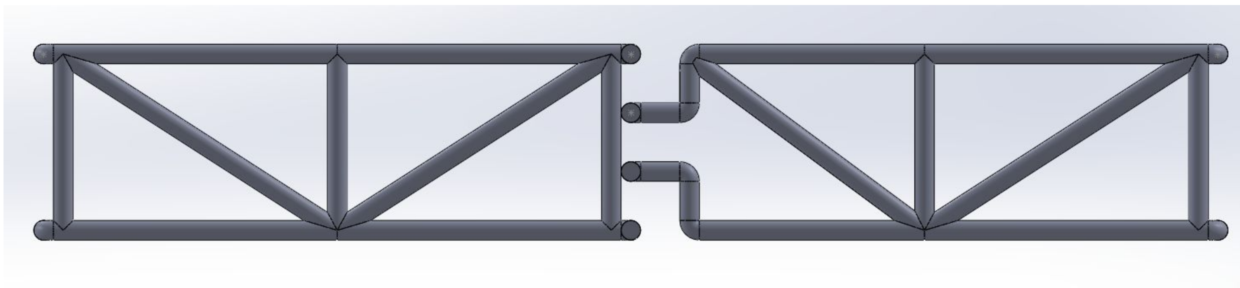


*Figure 13**:** Frame on the left is the central frame. The frame on the right is the asymmetric chain frame.*

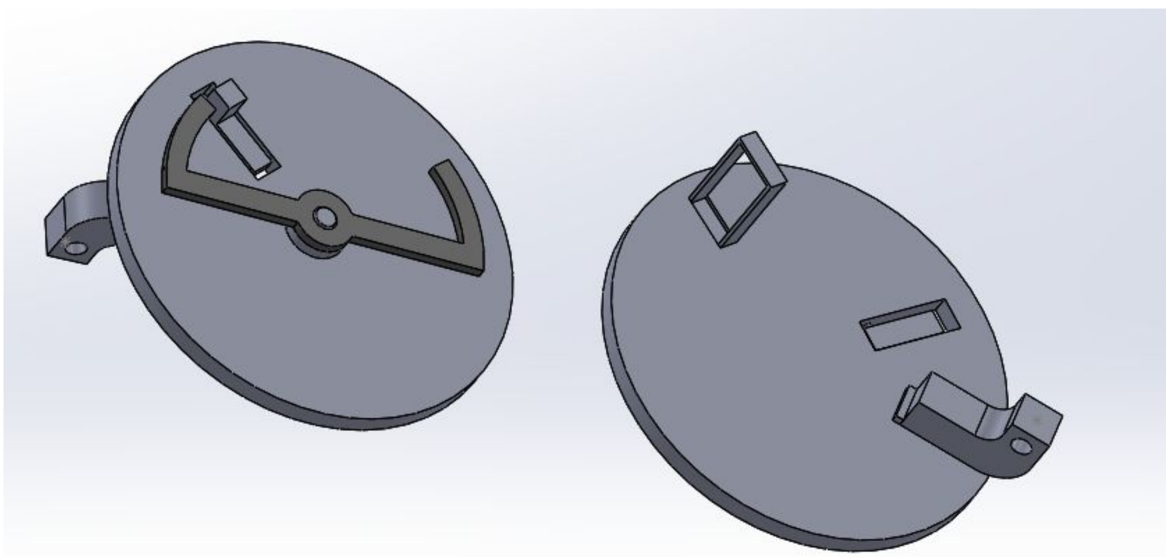


Figure 14: On the left is the front side of the latch mechanism, and the right is the back side.

With the general concept of the mechanism out of the way, we can start talking about the modeling process. The process was quite simple once we properly understood the mechanism. To start, we knew we were going to need a central frame and an asymmetric frame that would chain together. After making a few cardboard mockups, we simply drew a 3D sketch of the frame and extruded a circular shape across the frame, which made it appear like a frame made of pipes. We intentionally chose to shorten the actual length of the frame as the lengths that were chosen for the design would be long and small; this would inhibit our ability to use it as a demonstration piece. The results of the frames can be seen in Figure 13. For the latching mechanism, it was decided that for the purposes of demonstration that it wasn't necessary to include a spring, for it would be difficult to animate in the long run and it would impede the demonstrational motions. Instead, the focus for the latching mechanism was displaying the rotational motions of locking and unlocking, the impedance that prevents the frames from moving out of order, and the loop that locks the frame into place. The final product for the latching mechanism can be seen in Figure 14**.** Figures 15, 16, and 17 show different points of view for the assembled unfolding mechanism.

Figure 15: Top-down view of the unfolding mechanism.

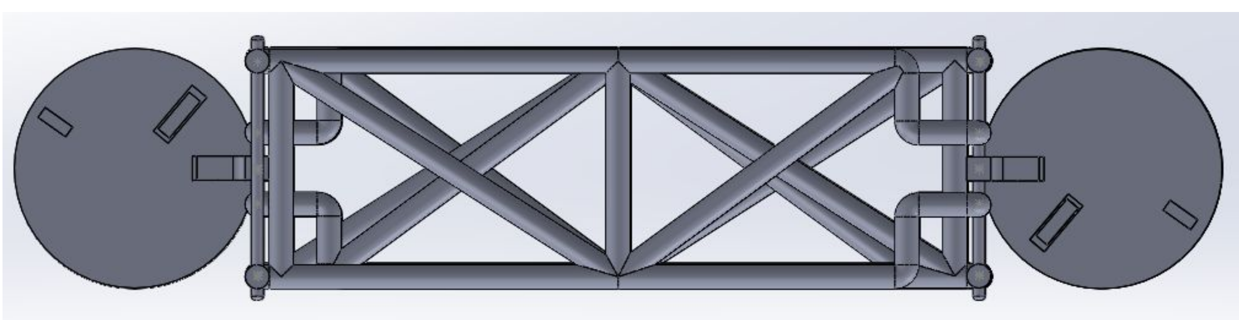


Figure 16: Front view of the unfolding mechanism.

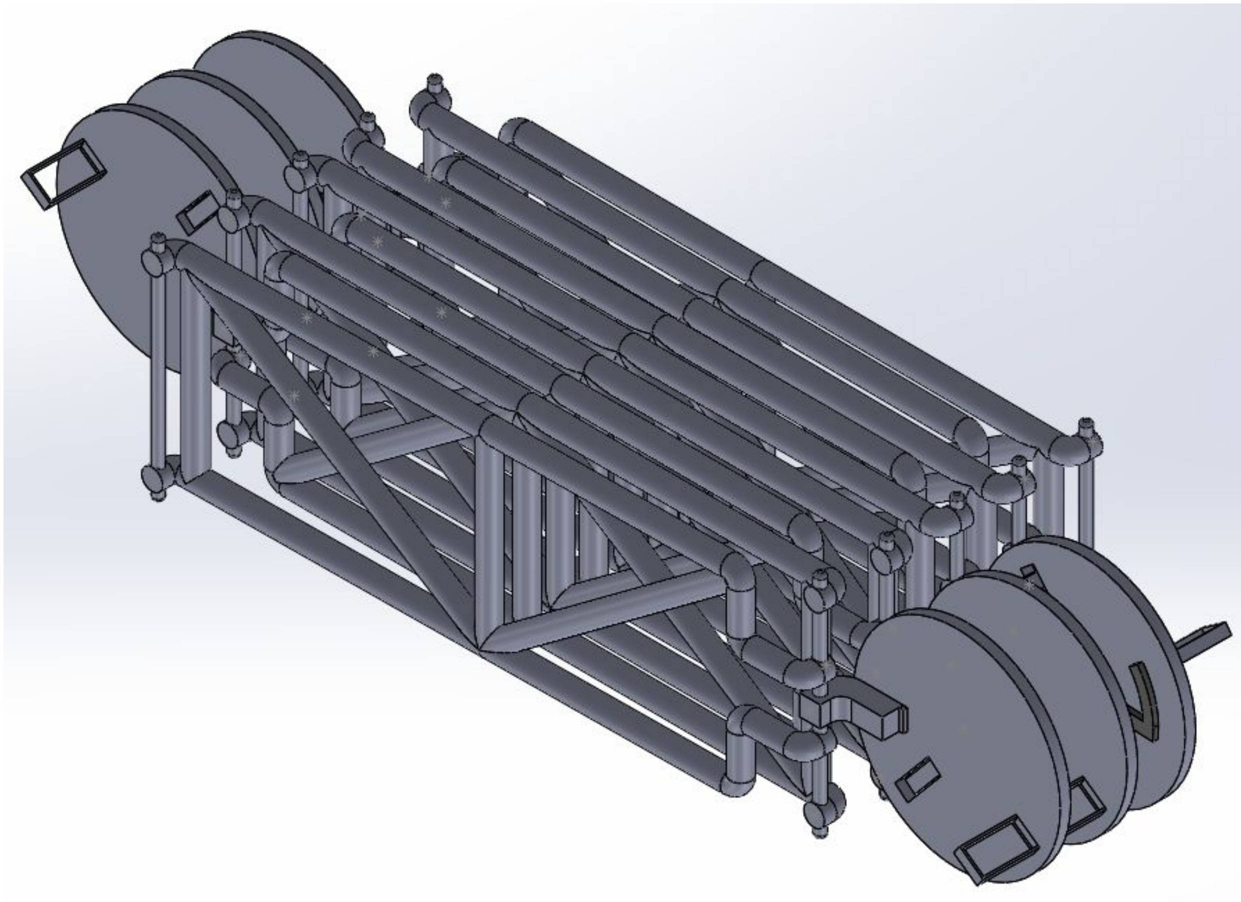


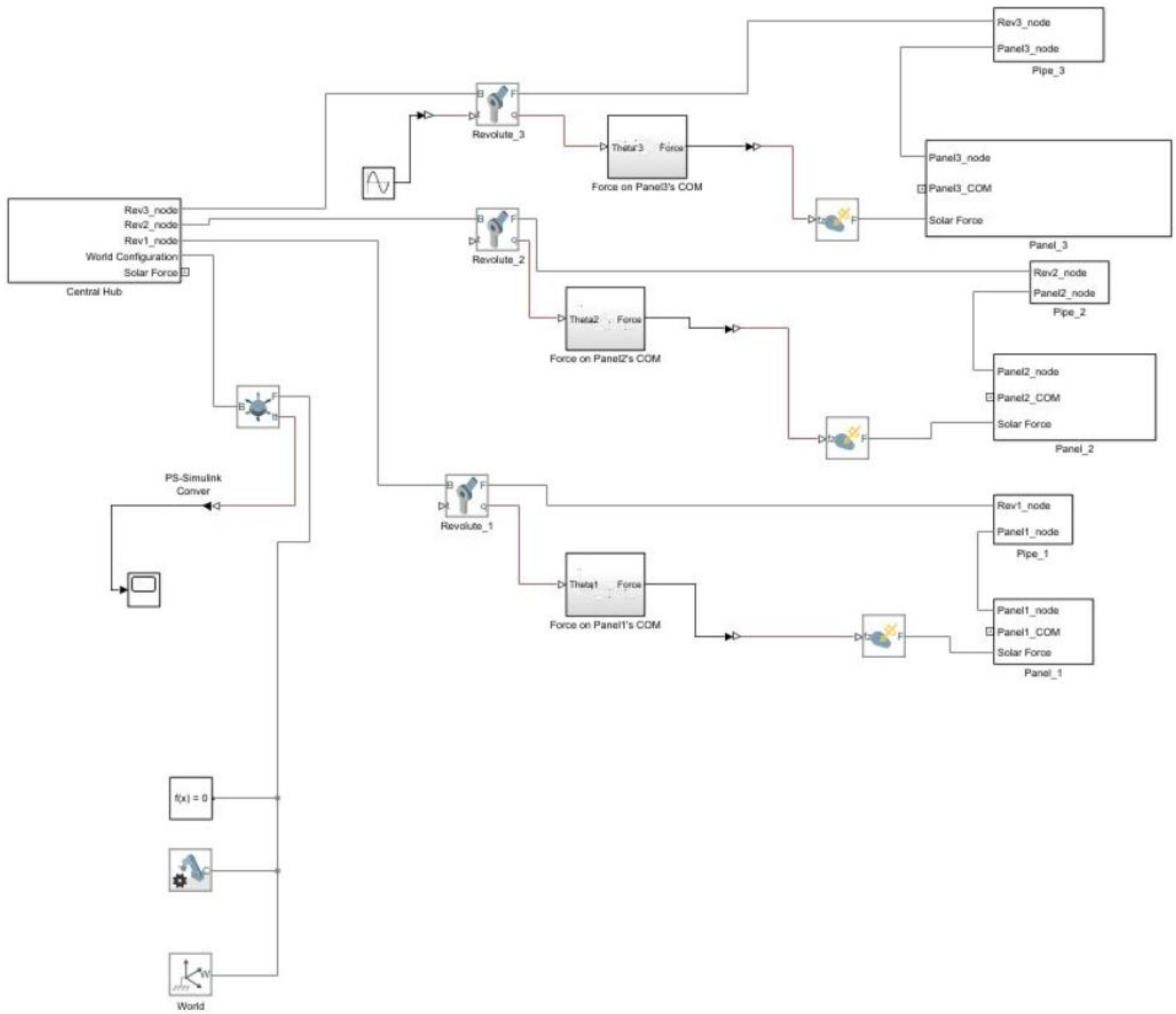
Figure 17: Angled view of the unfolding mechanism.

Appendix J: Animation

Simscape Multibody

To begin using *Simscape Multibody,* the team referred to MATLAB's Help center, which contains a section called “Install the Simscape Multibody Link”. The section described how users must install and download a file that allows CAD software to export files that Simscape Multibody is compatible with. Once the Simscape Multibody Link for SolidWorks Plug-In was enabled, the pipes, panels, and central hub for GeoShade's solar sail prototype were created on SolidWorks. The sail prototype had to be assembled in SolidWorks in a manner such that the exported file would create an accurate model in Simscape Multibody. To ensure that this was the case, we referred to chapter five of a book called *Design of Mechanisms with SolidWorks Motion Analysis and MATLAB/SIMSCAPE* to determine what mating patterns needed to be used in our SolidWorks Assembly. Once the assembly was complete, the file was exported from SolidWorks and imported into MATLAB.

The file imported into MATLAB simulated the system dynamics for the sail prototype. However, the model was incomplete. The hub did not move as intended. The center of mass for each sail panel could not be edited within the program as well. The team was forced to reconstruct the SolidWorks assembly so that the center of mass would be displayed for the hub and panels. The exporting and importing process was then repeated. The sail prototype model in MATLAB was edited such that the hub's center of mass contained six degrees of freedom and the sail panels' center of mass experienced forces due to solar pressure. As a result of our efforts, we were able to create the following Simscape Multibody model for the sail prototype in a zero-gravity environment:



The model is able to simulate external normal forces, actuator torques, and show how the forces acting on the panels affect the orientations of the central hub and each other.

Blender

The purpose of an animation was to illustrate the prototype's capabilities. The prototype was chosen to be animated over GeoShade for two reasons. The first reason being that the modeling team and deployment team was working on a prototype. The second being the complexity of designing GeoShade in a software that no team member was familiar with. The first task was determining which animation software we would use after looking at different recommendations for softwares. Blender looked like the most promising. To lighten the workload, the team was broken into two separate animations. One team displayed the prototype in a zero-gravity environment as actuators were applied. The other not-to-scale animation showed the prototype orbiting the earth. Blender has the capability of accepting .STL files. This was convenient because it allowed us to read files that were designed from Solidworks, a program we were more familiar with. The results of the model are shown in figure 18.

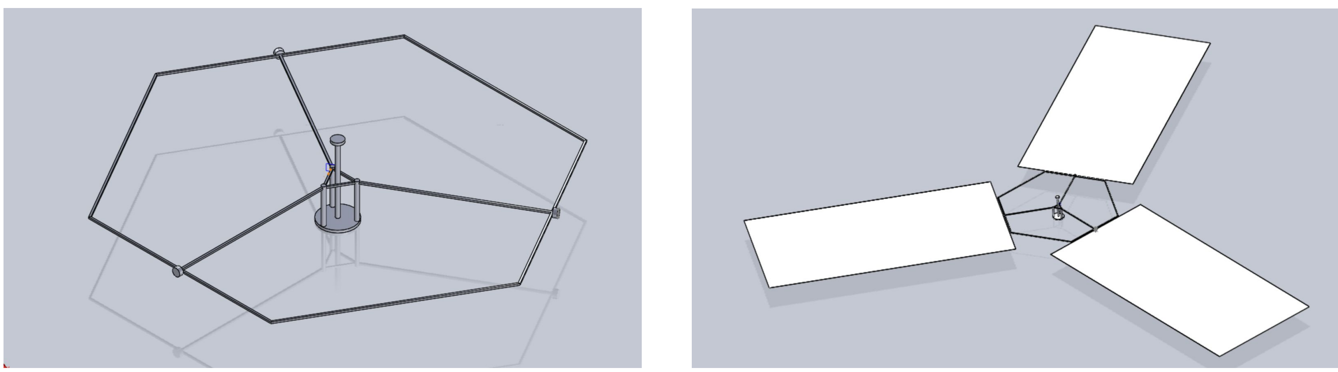


Figure 18: On the left is the central hub, and to the right is the prototype.

The animation itself requires 3 parts to complete the physical model and its subsystems. The surrounding environment contained the earth, sun, and space. Lastly, the projected path the system will follow and the camera angles.

The goal of the first stage was to create a central body that affects the sub-bodies and have the sub-bodies independently move without affecting the central body. For this to work, the imported .stl files of the prototype were modified to only include the central hub, and the panels were then independently created in Blender. This process was then completed by parenting the independent sub-bodies with the central body. Although Blender was capable of animating each panel moving independently, it had a difficult time wrapping images' textures onto the model. This was caused due to Blender using quadrilateral meshes, whereas Solidwork uses Tetrahedral meshes. To solve this, the tet faces were deleted and replaced with quad faces. Also, during this process, the central hub was updated as shown in Figure 19 [Vadim.2].

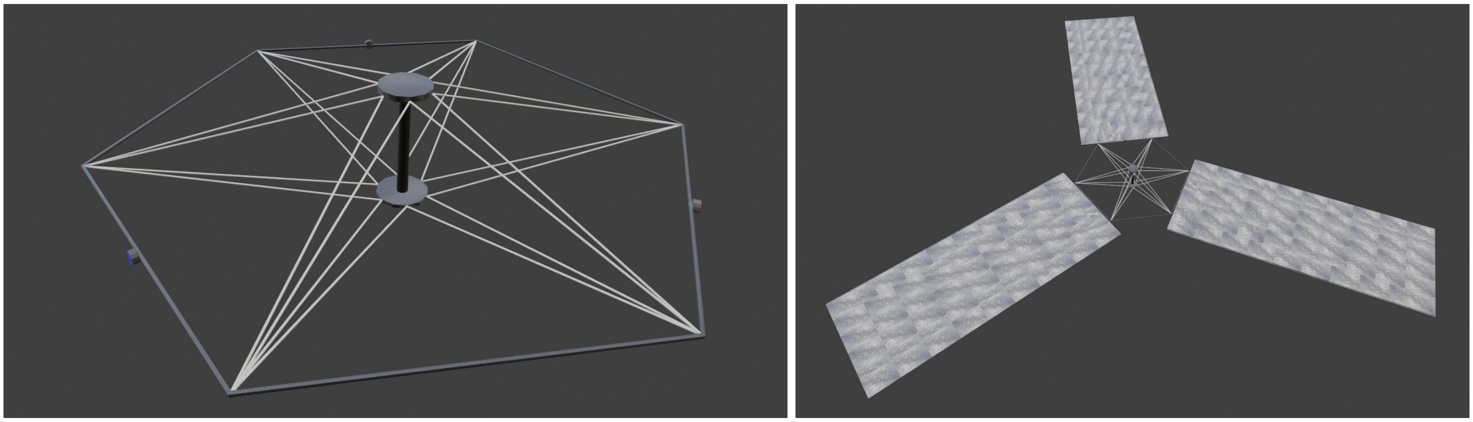


Figure 19: The second iteration of the prototype with material properties applied[vadim].

For the second stage, a YouTube tutorial was used to determine how to animate the surrounding environment [12]. The only modifications that were used to fit the earth and the prototype together were scaling and global placements. Lastly, after a few iterations, it was determined to be plausible to animate a final orbit around earth. To see the final animation clip, go to (Appendix B, \Capstone-007-GeoShade\AnimationFiles\Blender\VN\testrun_050001-0585.mp4)

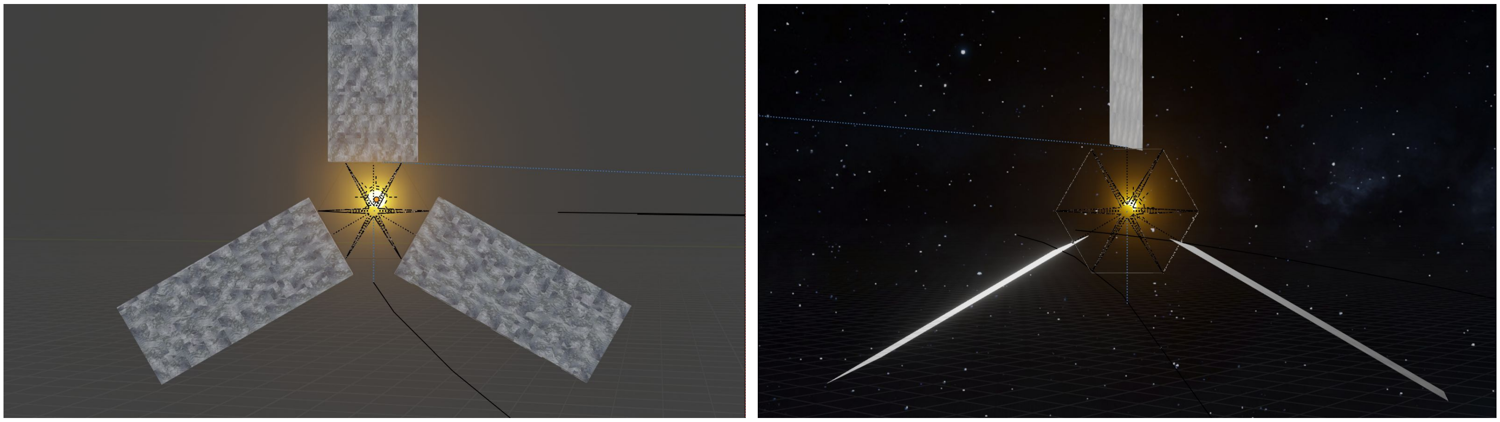


Figure 20: The panel orientations at the start of the orbit, and the panel's path to lagrange one.

The animation that was first tasked with illustrating the actuator movement of separate panels was able to later incorporate orbital movement. The second not-to-scale animation was discarded as it would be repetitive to include two animations performing the same task. Aside from the current final animation, future animation projects would include animating the deployment process in space. Also, for the current final animation, future improvements would be to include solar panels, electrical components, actuators, and other small components.

Appendix K: ABET Objectives

ABET Learning Outcome - 1

Mathematical models:

Our mathematical model is the prime example for this learning outcome. Even though it is incomplete and not validated, we were able to present the dynamics of the sail vehicle by applying physics and vector calculus to decompose the different forces applied on the prototype sail. We showed the model in action in the Matlab animation. The animation can be view by running the Matlab program sailPlots.m in the directory Capstone-007-GeoShade\AnimationFiles\Matlab\Model 2

Experiment A:

In this experiment, we wanted to calculate the speed at which a wave propagates on a thin sheet of material. We applied the two dimensional wave equation to derive a formula that works for our model.

$$v_{theoretical} = \sqrt{g(L-y)} \tag{27}$$

The velocity of the wave at length y on a thin sheet is a function of the total length of the sheet (L) and the gravitational constant (g) (reference the experiment writeup). To derive this equation, we applied the knowledge of wave physics and differential calculus.

Experiment B:

In this experiment, we were interested in the dominant damped natural frequency of various lengths of carbon fiber rods. To calculate the angular frequency numerically, we used Finite Element Analysis on the rods to calculate its natural frequency (reference the Experiment B paper). The accuracy of those values were validated by obtaining a data set of values from IMUs that were attached to those rods.

ABET Learning Outcome - 6

The experiment was done to validate the wave propagation model that we derived from the two dimensional wave equation. The experiment consists of hanging a thin sheet of material vertically and generating a wave pattern on one end to measure the wave motion propagated on the sheet. The sinusoidal wave was generated by a Dynamixel motor mounted on a test frame. The wave motion is captured by 2 Inertial Measurement Units (IMU) attached to the thin film material.

We filtered the data using Fast Fourier Transform and measured the period of the wave to calculate the experimental wave speed. Unfortunately, due to the weights of the IMUs and wiring, along with missing phase shift data, we were not able to make a concrete validation of the wave propagation model. The complete experiment set up and data analysis can be found in the final report in the Github repository of the Appendix B (Capstone-007-GeoShade\Experiments\Experiment A\Torque Propagation Experiment_ME411_J.Chung_Y.Egal_T.McKay_V.Ruchin.pdf).

ABET Learning Outcome - 7

Team GeoShade was unable to test prototypes in a zero-gravity environment, so we decided to use simulation software to determine whether our mathematical models accounted for all system dynamics. After some discussion, we chose *Simscape Multibody*, which is a MATLAB add-on, because companies such as Lockheed Martin Space Systems used it to simulate similar mechanical systems.

Simscape Multibody provides a 3D environment for simulating multibody mechanical systems. Systems are modeled with blocks that represent bodies, joints, constraints, force elements, and sensors. The program numerically solves the equations of motion for a complete mechanical system so that a 3D animation, which shows the system dynamics, can be generated.

Since we are inexperienced users who are not familiar with the add-on's block diagram system and had to deal with time constraints, we were forced to refer to outside resources to understand the software. We did some research on the MATLAB website to determine that Simscape Multibody allows individuals to import CAD assemblies into the program so that a block diagram model can be generated for them. The website describes in detail how to download and install Multibody Link and CAD Plug-In so that they may communicate with one another.However, it did not describe the manner in which mates must be defined in SolidWorks such that models would be correctly defined in MATLAB. To overcome this issue, we referred to a book called *Design of Mechanisms with Solidworks Motion Analysis and MATLAB/Simscape* to properly define mates. As a result of our efforts, we were able to create a Simscape Multibody model for the sail prototype in a zero-gravity environment.