<u>The Sunflower: A Modular and Hexagonally Symmetric SEP Cargo Transport Spacecraft</u>

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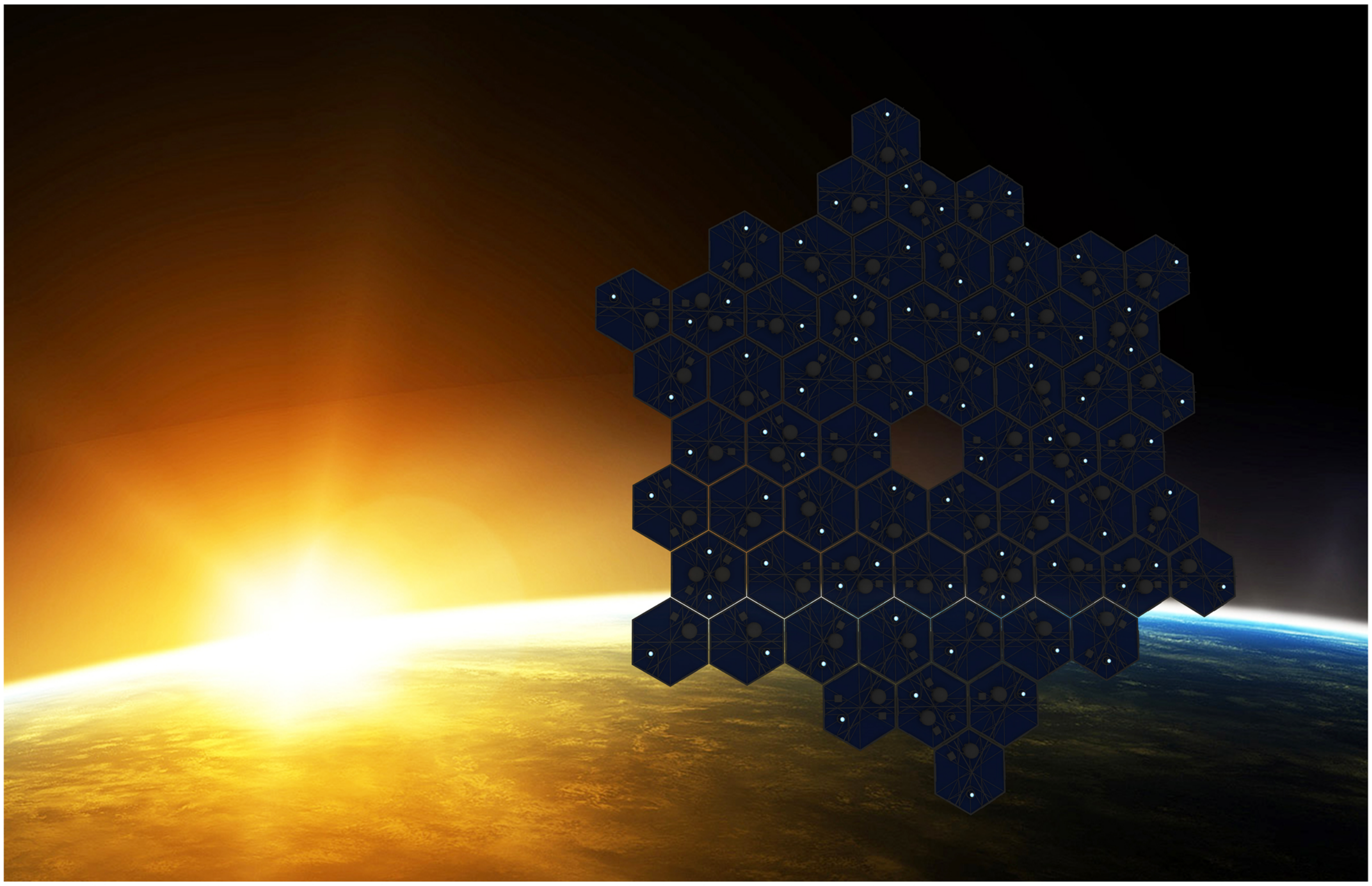

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1- System Overview

1.1 Introduction

As spaceflight missions travel farther with heavier payloads, new forms of propulsion are needed to provide delta-v to vehicles moving beyond earth's orbit. For long term missions to the Moon or Mars, alternative forms of propulsion are necessary. The concept of a reusable solar electric space (SEP) "tug" to ferry a payload spacecraft from low earth orbit (LEO) to a lunar distant retrograde orbit (LDRO) is an attractive solution to this problem. We propose the "Sunflower", a Modular, Hexagonally Symmetric, SEP Cargo Transport Spacecraft.

The Sunflower's structure, power, and navigation systems are distributed across a large surface composed of 12 identical and connected modules. Each module contains an independent set of solar panels, fuel, propulsion, and navigation systems. To form a 200 kW array, the required surface area of solar panels is approximately 800 m^2. The modules of the Sunflower are launched in two separate launch vehicles and aggregate in LEO within 60 days. During launch, up to six modules are folded and stacked inside the launch vehicle payload bay. The panels of the module are hexagonally symmetric, and fold efficiently into the payload bay while generating a spatially efficient deployment pattern. The front side of the Sunflower contains a 291 kW array of photovoltaics. The photovoltaics power an array of 72 Hall-effect thrusters, providing 19.44 N of thrust and consuming less fuel than traditional chemical propellant-based propulsion.

Modules are aggregated using technology adapted from the Restore-L mission. They are then connected via reversible electropermanent magnet joints, and a secondary mechanical locking mechanism. This docking technique eliminates the need for a secondary robotic assembly entirely. The power, mass, and thrust of the tug is proportional to the number of modules connected. Additional modules can be added to the Sunflower to achieve 727 kW of power or more. Unwanted modules can be jettisoned from the Sunflower and replaced by new modules, allowing for operational refurbishment. These qualities make the Sunflower a simple but versatile means of bringing post-launch delta-v to any spacecraft and for transport to LDRO.

1.2 Prior Art

1.2.1 Photovoltaics

The Sunflower modules use triple-junction XTJ Prime space grade solar cells, manufactured by Spectrolab. These cells were chosen due to their ability to achieve 30.7% efficiency at beginning of lifetime (BOL) under AM0 solar spectrum, and for their small thickness and weight.

1.2.2 Mechanical Hinge Patent

The rotating joint is based off of patent US5785280. This system is designed specifically for unfolding solar arrays and has operated in space many times. This hinge design unfolds and locks panels at 180 degrees.

1.2.3 Triangular Space Frames

To minimize the amount of welded connections and potential for failures from thermodynamic changes, patent US8820025 was referenced to provide an ideal base structure to develop a simple triangular space frame that minimized the number of welds. The tanks and engines are bolted to the frame to distribute weight and thrust force in a ground testable system. The frame uses Aluminum Lithium Alloy 8090 tubing.

1.2.4 Electropermanent Magnet Connections

NicaDrone OpenGrab EPM v3 Electropermanent magnets have been used for various tasks such as cargo lifting and robot workholding. The OpenGrab EPM v3 uses a winding coil inside AlNiCo material to align its magnetic domains in an orientation so that it forms a magnetic circuit with a ferrous target when ~100 mW of power is temporarily pulsed through a 5 V source.

1.2.5 Ion Engines

The Aerojet BPT-4000 Hall-effect thruster was chosen for its high thrust, a specific impulse greater than 1700 sec, and scalability for a large design. The thruster includes a compact power processing unit (PPU) by the same manufacturer.

1.2.6 Xenon Fuel Tanks

Large Xenon propellant tanks, manufactured by Cobham, are used as fuel tanks for the Hall-effect thrusters. These tanks are mission-proven, and the shape and size of the tanks sustain the pressure changes from terrestrial and space atmosphere.

1.2.7 Mechanical Locking System

The Mechanical Lock System (MLS), designed by Eurockot, is used for hard locking between modules. This locking device was originally designed to deploy several satellites during a single launch.

2- Module Design

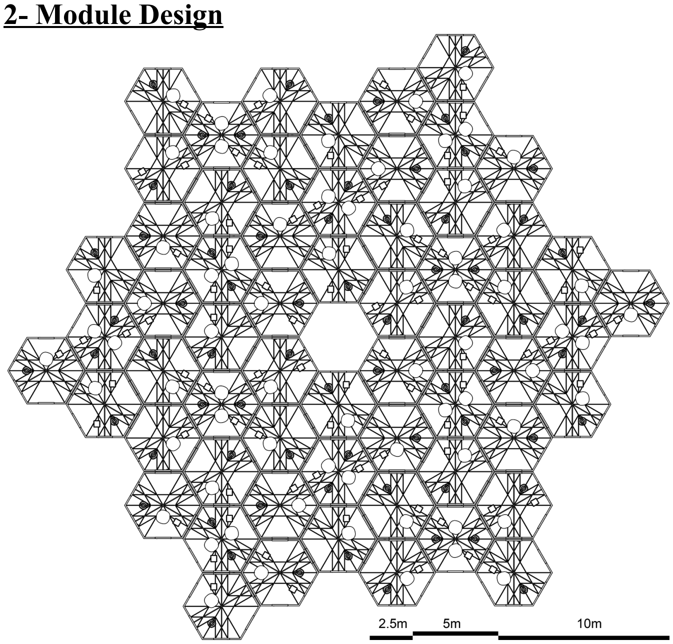


Figure 2.0.1: Full 291 kW Sunflower

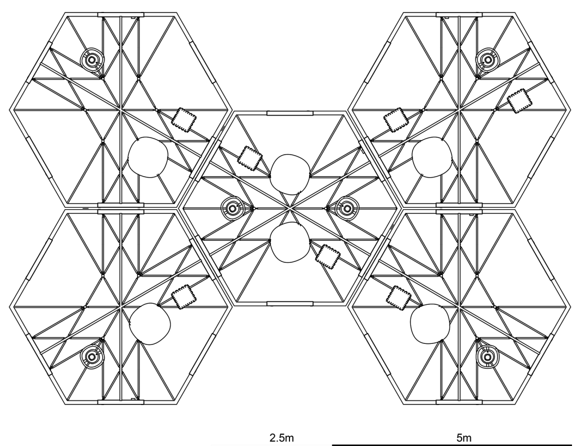


Figure 2.0.2: Individual module

The Sunflower design, seen in figure 2.0.1, is composed of 12 interconnected modules. It achieves structural modularity by distributing propulsion systems and tanks uniformly across the large surface of the solar array. This allows for a linear increase in propulsion and power when more modules are added. Each module contains five hexagonal panels connected by mechanical hinges and hard locks. A set of six ion engines, xenon fuel tanks, power supplies, and communications are distributed uniformly across each module. A lithium-aluminum alloy truss provides structural support to the module, and defines the perimeter of the five hexagonal solar panels. Each module weighs 890 kg without fuel, and is outlined in figure 2.0.2. Figure 2.0.3 and 2.0.4 show the location of the components on each module and hexagon.

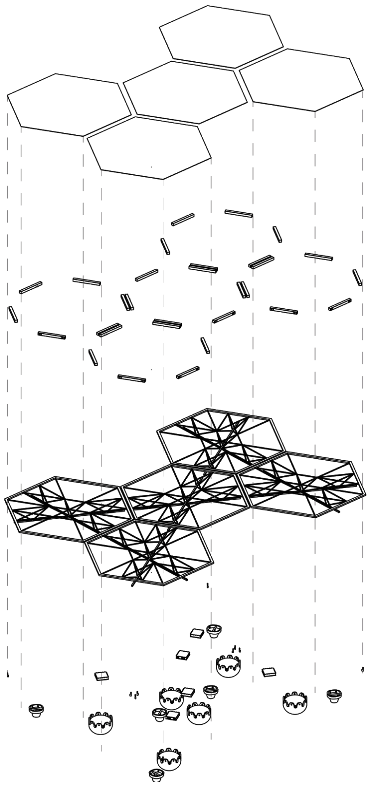


Figure 2.0.3: Exploded module isometric

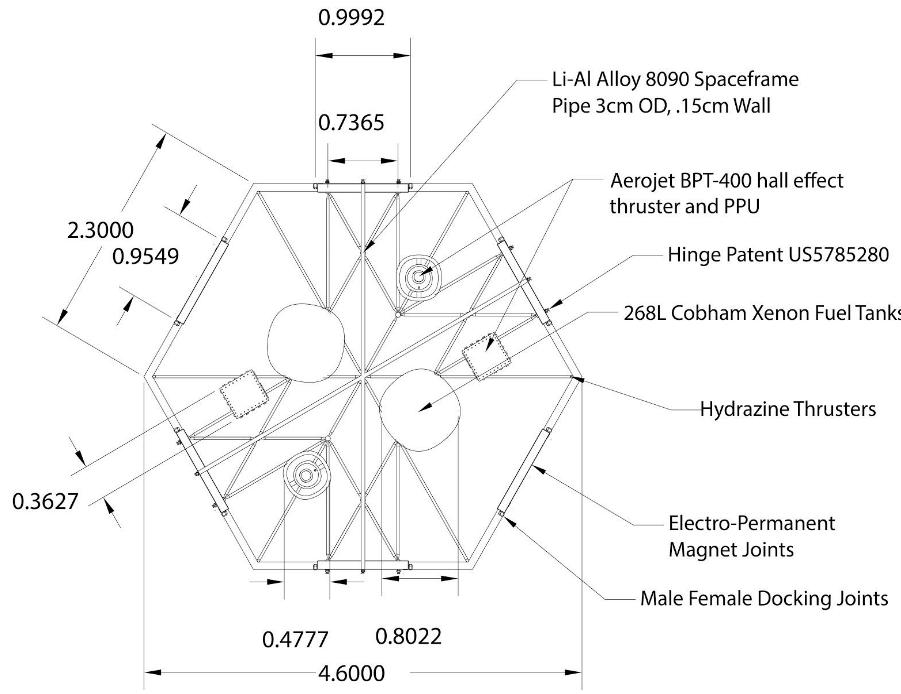


Figure 2.0.4: Schematic of central panel

3-Mission Plan

3.1 Launch Configuration

A single hexagon's diameter measures 4.5m, allowing it to be stored inside the 5.0m diameter cylindrical payload bay of commercial launch vehicles such as the Falcon 9 FT. To stow for launch, modules are folded as shown in figure 3.1.1. Each module, when folded, measures 2m tall. A Falcon 9 FT payload bay is 13.1m tall and delivers a payload of 22800 kg to LEO. At a mass of 3414 kg per module (fully fueled), six modules weigh 20,484kg. Each launch is able to carry up to 6 modules, delivering the full 12-module Sunflower with two Falcon 9 FT launches into orbit.

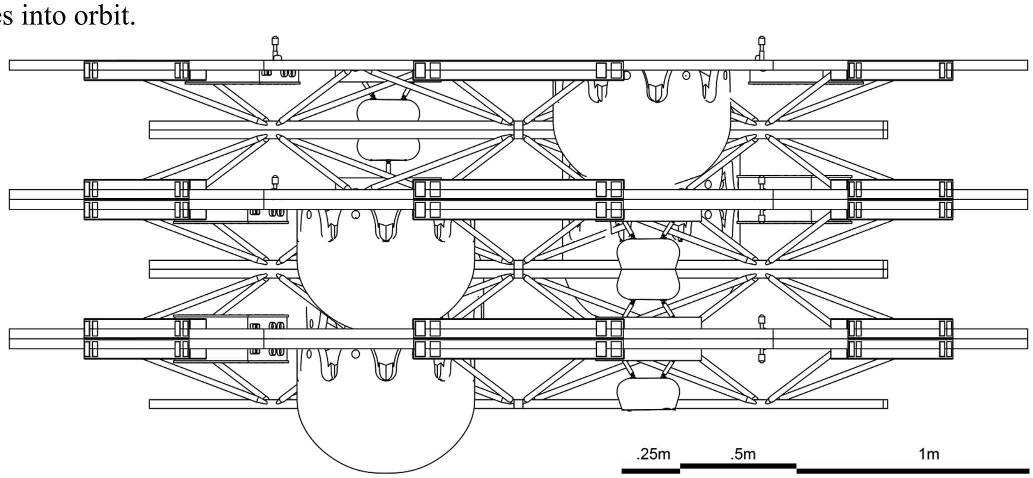


Figure 3.1.1: Single module launch configuration

3.2 Deployment

Once a 6 module stack is released in space, it unfolds via special hinges to form a half of the Sunflower. A locking mechanism engages after modules unfold, forming a rigid structure (see figure 3.2.1). A loaded spring unfolds the panel, which is met by a friction force to maintain a constant angular velocity. A stack of 6 modules are connected via hinge joints. They unfold one module at a time along continuous chain. During the unfolding stage of deployment, the first and last hexagons of each module remain in parallel planes, minimizing torque between the array and the stack. Once deployed, the two half-Sunflowers are fully operational SEP spacecrafts that can use their ion engines to rendezvous and dock, forming the full Sunflower.

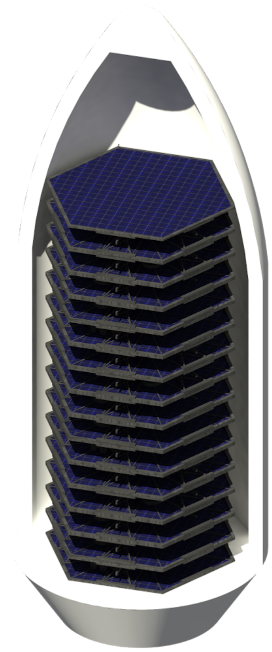


Figure 3.1.2: Payload launch configuration

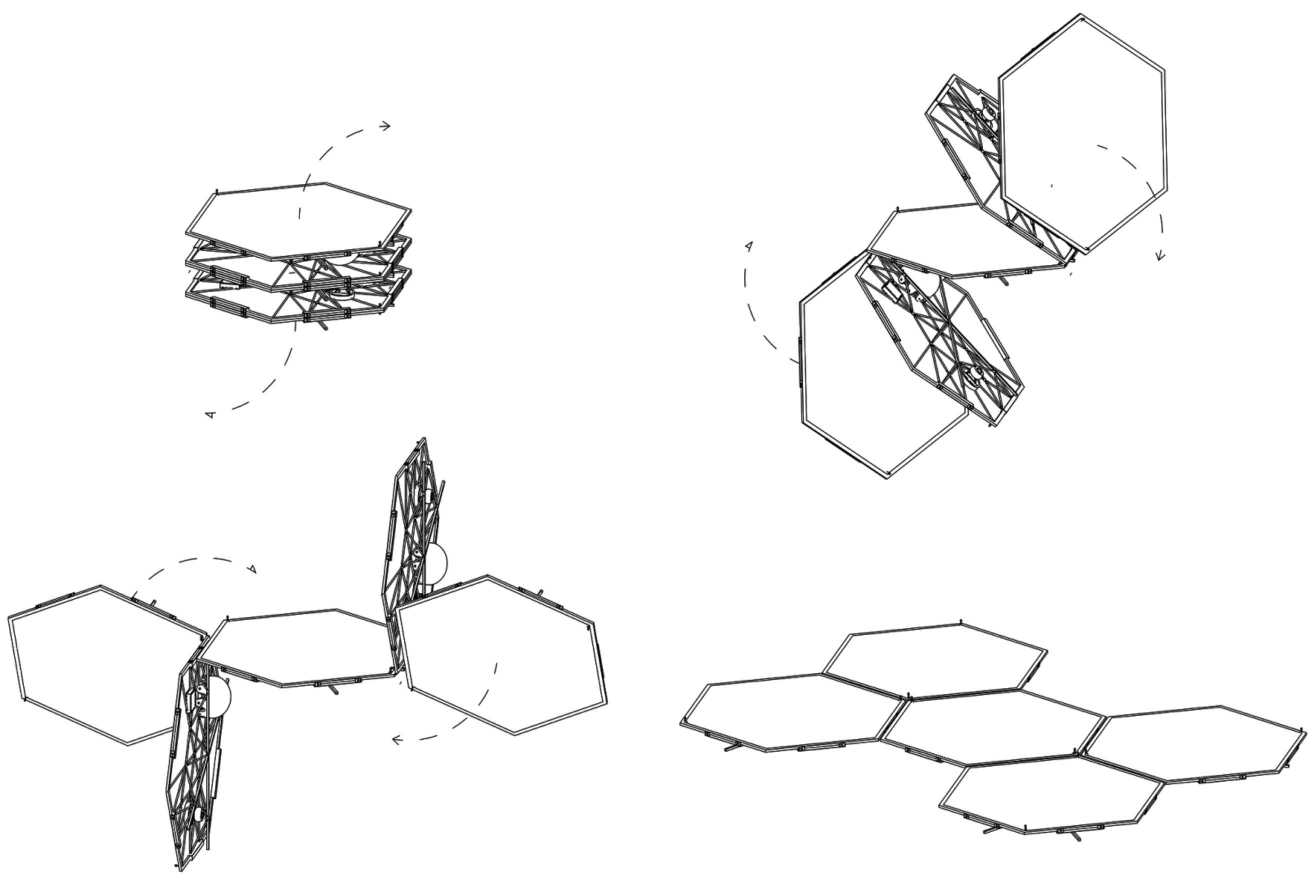


Figure 3.2.1: Single Module Folding Sequence

3.3 Movement to Orbit

Once assembled, the Sunflower will ferry a payload from LEO to LDRO. Payloads aggregate in the center of the Sunflower and dock via magnetic joints facing the center of the ring. During the propulsion phase, the 72 Hall-effect thrusters will simultaneously thrust the Sunflower with a force of ~19.4 N. Continuous thrusting brings the Sunflower and payload from LEO to an elliptical transfer orbit, followed by insertion into LDRO. `The solar panel array remains perpendicular to the Sun, while the ion engines swivel to provide thrust tangential to orbital motion. Relative to the surface of the solar panels, the engine's thrust vector rotates within a range of 100 degrees. The orbital model below simulates the transition from LEO to LDRO, with the results summarized in Table 3.3.1. A fully fueled Sunflower weighs 40,968 kg, while an unfueled Sunflower weighs 10,738 kg, allowing for a large range of payload weights. Depending on the weight of the payload and onboard fuel, the Sunflower will take between 138 and 335 days to thrust to its LDRO injection orbit, an orbital distance of ~200,000 mi from the Earth. The maximum fuel capacity of the 12-module Sunflower is 32,400 kg of Xenon fuel, meaning the Sunflower can make up to three round trips to LDRO without refueling. This continuous operation spans approximately three years. Additional trips require either refueling, facilitated by the cargo spacecraft, or module replacement. Calculations were performed using a custom orbit simulation c-code assuming first-principles Newtonian orbital models.

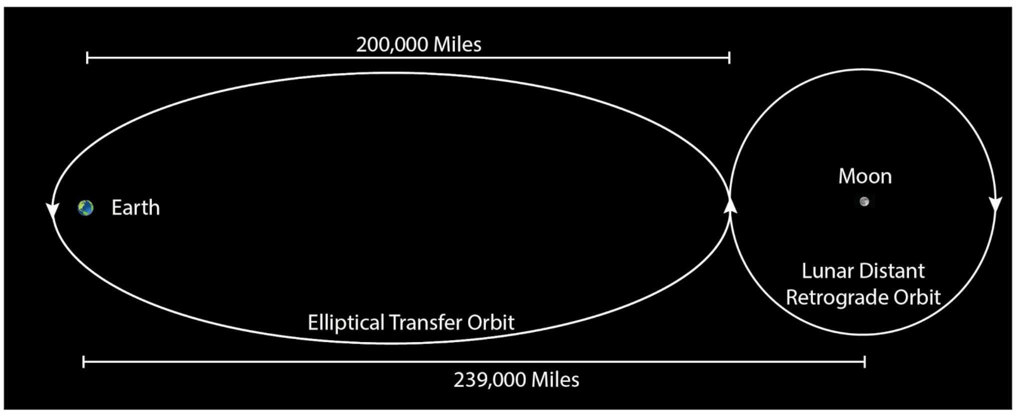


Figure 3.3.1: Orbital Summary

Initial Mass (Payload + Sunflower) (kg)	Days to reach LDRO	Fuel Consumed (kg)
70,000	335	17608
60,000	289	15045
50,000	231	12238
40,000	196	10185
30,000	138	7401

Table 3.3.1: Fuel consumption and days to reach LDRO relative to mass of payload (maximum fuel capacity of 32400 kg)

4- Propulsion Components Details

4.1 Photovoltaics

Thin-film photovoltaic cells cover one side of each hexagon, yielding an effective photovoltaic area of 60 square meters per module. The photovoltaics are 100 microns thick, with a cell mass of 84 mg per sq centimeter. They have a the beginning of lifetime (BOL) efficiency of 30.7% and an end of lifetime (EOL) efficiency of 26.7% The photovoltaic cells are 36 kg per module. At BOL, each module produces 24.2 kW of power, assuming AM0; EOL power production is 21 kW per module. The solar cells are connected to a C channel structure about the perimeter of each hexagon. These Spectrolab photovoltaics have been mission-proven and have a Technology Readiness Level (TRL) of 9.

4.2 Hinge Joints

Each module contains four hinges connecting the five hexagonal panels to unfold the modules during deployment. The patented hinge design was modified to fit on the perimeter support structure on the Sunflower, as shown in figure 4.2.1. A spring pushes the locking bar towards the center of the joint while it slides around a curved edge. When the joint has completely unfolded, the bar falls into a groove, locking the hinge in place. The hinge joint will also be used between separate modules when unfolding the 6-module chain during the assembly process. This joint has been deployed in space for decades, and has a TRL of 9.

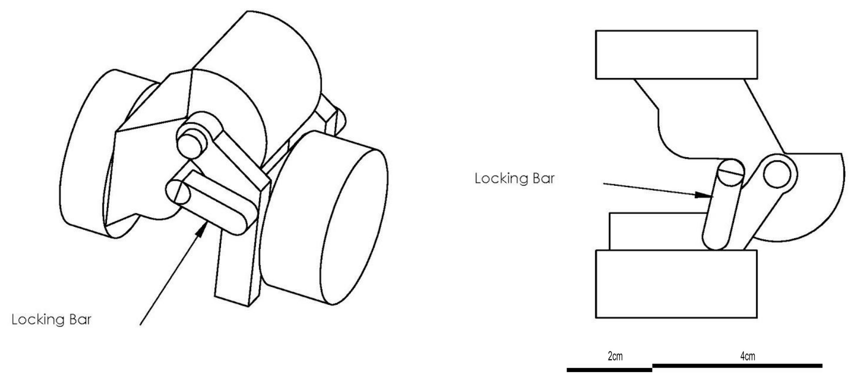
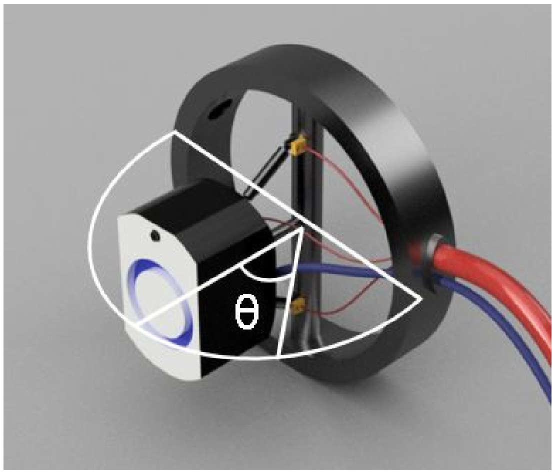


Figure 4.2.1: Hinge joint connecting hexagons and allowing modules to unfold

4.3 Hall-Effect Thrusters

Each Aerojet BPT-4000 thruster produces 270 mN of thrust while consuming 4.5 kW of power. The full Sunflower will have six engines on each module, yielding 1.62 N of thrust per module and a total of 19.44 N for the complete Sunflower. The engines are oriented symmetrically along the back face of the modules to distribute the acceleration load on the Sunflower. The engines are aligned in the same direction, rotating along two degrees of freedom. During manufacturing, each engine block, visualized in figures 4.3.1 and 4.3.2, is identical; they are only rotated when put in place on the module to ensure that all engines are aligned relative to an external reference point. Figure 4.3.1 shows the lateral swivel of the engine, controlled by motors at the end of the main support rod. Vertical degrees of freedom can be achieved with two separate motors, shown in yellow, that control the gimbal joints. This design allows for a lateral swivel of ±50° and vertical gimbal of ±25°. This swivel capability allows the thrust vector to point tangent to the orbital velocity, while maintaining the orientation of the photovoltaics towards the sun. The Aerojet BPT-4000 engines have a TRL of 9. The support and swivel system is a new mechanical design and must undergo ground testing before mission implementation.



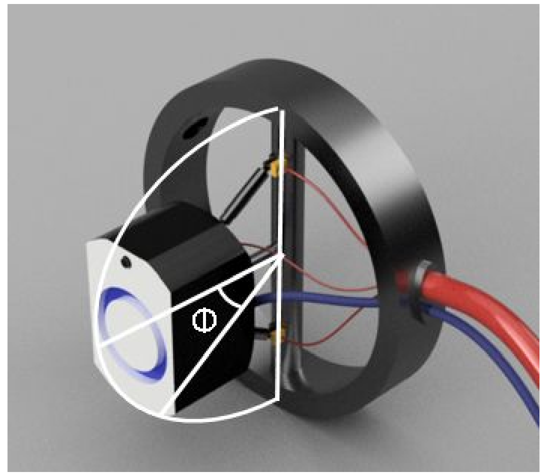


Figure 4.3.1: Engine lateral swivel *Figure 4.3.2: Engine vertical gimbal*

4.4 Fuel Tanks

Six Cobham Xenon propellant tanks are located symmetrically on the module, allowing for fuel delivery to each corresponding Hall-effect thruster. Each Cobham fuel tank weighs 22.2 kg and can store 450 kg of Xenon propellant pressurized to 1250 psig. These mission-proven tanks are assigned a TRL of 9. The tanks are currently a main constraint for stacking efficiency and weight. Future designs for custom shaped tanks can streamline the efficiency of our design.

5- Module Aggregation in Orbit

Each launch of modules deployed in LEO forms a six-module string, or half Sunflower. Locked and unfolded Sunflower halves begin the rendezvous process, illustrated in figure 5.0.1, using Hall-effect thrusters to bring the two halves into the same orbit. They continue thrusting into the same plane, with hydrazine thrusters providing assistance for precise maneuvering. As the modules approach each other, the ion engines are disengaged and the hydrazine thrusters become the primary thrust mechanism. The autonomous navigation is controlled by STORMM, which guides the half-Sunflowers to within 5m of each other. Once within 5m, the modules then align their electropermanent magnets and engage them to provide further attraction force between the two half-Sunflowers. The magnetic field can be quickly pulsed to provide small and controlled attraction forces. Once together, they form a rigid joint; the electropermanent magnet joints allow for the aggregation and assembly of Sunflower modules without requiring external robotic assistance. Hard mechanical joints will also engage to provide further support and locking redundancy. The Sunflower is now fully operational producing 291 kW (BOL). The assembly process will take 12-20 days to complete, allowing for controlled and precise navigation. Cargo is placed in a 4.5m hole in the center of the Sunflower, which also is equipped with magnetic joints for docking.

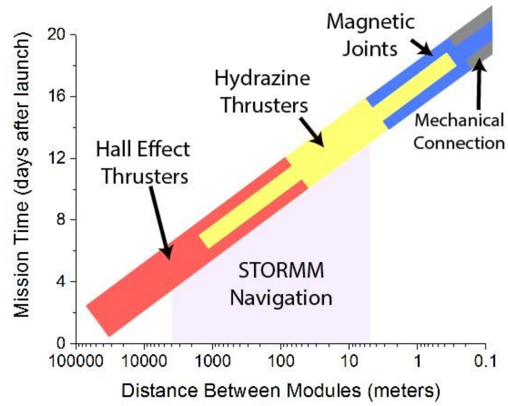


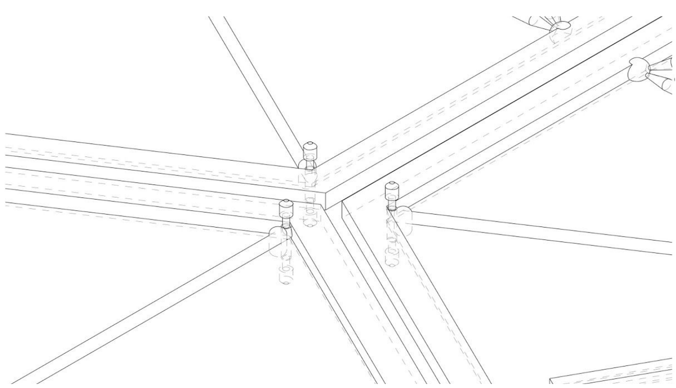
Figure 5.0.1: Module aggregation timeline, starting at the release of modules from launch vehicle cargo fairing in LEO, and ending with magnetic and mechanical docking connection engagement.

5.1 Autonomous Vehicle Navigation

The Sunflower adapts and implements the existing rendezvous and docking technology from the Restore-L project and recent Orion missions. Each module is equipped with its own Vision Navigation Sensor (VNS), an autonomous rendezvous and docking system. The VNS relies on a time of flight LIDAR (Flash Light Detection and Ranging) technology. LIDAR measures both intensity of light, and a range of information at each pixel. The current prototype, STORRM (Sensor Test for Orion Relative Navigation and Risk Mitigation), generates a flight path for the aggregating halves of the Sunflower, accurate for distances between 4.8 km and 5m. These systems function together to program a rendezvous flight path for aggregating modules. STORRM is in development for other missions, and will be adapted for use in the Sunflower.

5.2 Hydrazine Thrusters

Hydrazine thrusters aid the ion engines for more precise maneuverability. The 1N chemical monopropellant hydrazine thrusters are controlled via VNS to follow the STORRM flight path. Each module contains 6 total hydrazine thrusters, 2 paired for each direction of motion. The perpendicular thrusters in figure 5.2.1 control the roll and pitch, aligning the Sunflower halves in the same plane. The planar thrusters in figure 5.2.2 control the yaw of the craft, orienting the modules to dock appropriately.



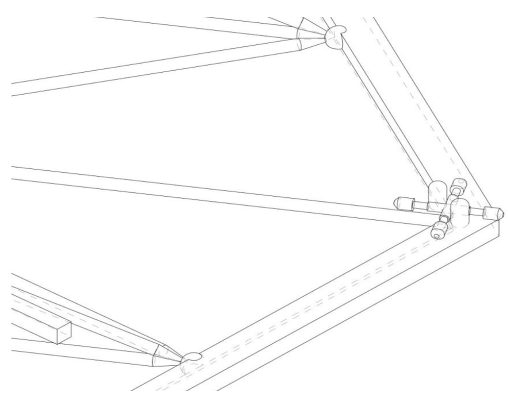


Figure 5.2.1: Perpendicular (pitch/roll) hydrazine thrusters *Figure 5.2.2: Planar (yaw) hydrazine thrusters*

5.3 Magnetic Joints

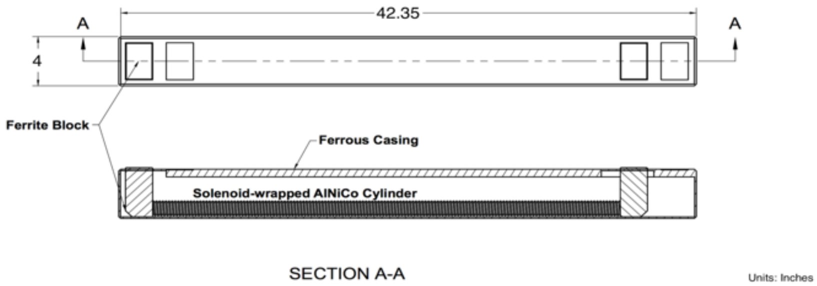


Figure 5.3.1: Schematic drawings of Magnet Joint

When the modules are brought within 5m of each other, the magnetic joints engage. Fine maneuvering and docking between modules is controlled by the hydrazine thrusters, while the magnetic joints gently pull the modules toward each other. These magnetic joints use electropermanent magnets, a uniquely reversible permanent magnet. These magnets require an estimated power of 350 W to switch polarity to engage or disengage, but require no active power once engaged. The magnets are packaged into a joint structure, as shown in figure 5.3.2, and placed on all edges of the perimeter of each module. Once joined, both electropermanent joints are fully magnetized and provide an estimated holding force of 8900 N. The magnet is composed of N52 Neodymium metal, a high coercive material, and AlNiCo, a low coercive material that can switch polarity. These materials are joined by an iron alloy block, labeled "ferrite block" in Figure 5.3.1. In the "on" state, magnetic joints on opposite Sunflower halves are attracted towards each other. Figure 5.3.2 demonstrates the flow of the magnetic field as it pulses between the "on" and "off" states. It should be noted that the magnetic field remains confined within the magnetic joints when two joints are joined together, preventing the magnetic field from interfering with other components on the spacecraft. In order to adjust the docking approach velocity, the polarity can be alternated rapidly by a pulsing current. This allows for a variable effective attractive force. When a module needs to be jettisoned for replacement, magnet joints can be deactivated.

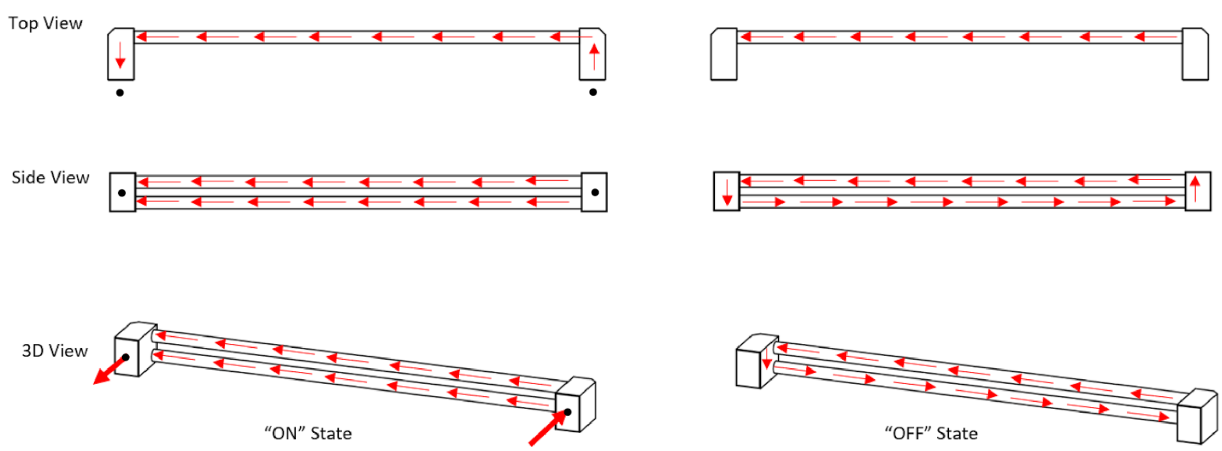


Figure 5.3.2: Conceptual representation of magnetic joint states

Electropermanent magnets have been used for various terrestrial applications, but their use in spaceflight has yet to be demonstrated. An extensive research and prototyping phase is crucial to adapting this existing technology for the Sunflower. The TRL of this joint is 4, making it a primary mission-enabling technology.

5.4 Locking Mechanism

The secondary locking mechanism chosen for our design is based off of the currently used Mechanical Lock System (MLS) designed by Eurockot, as shown in figure 5.4.1. This lock has been mission tested and has a TRL of 9. The locks engage between all adjacent hexagons of the modules and of the Sunflower, and share a housing within the structural frame around the magnetic joints. The main function of these locks is to lessen the shear forces on the electropermanent magnets. Male and female components secure the connection of two modules. By activating an electric motor, the female component releases the male, allowing for the modules to separate. The locks are also attached to the hinge joints between separate modules to allow module strings to separate if operational refurbishment is needed.

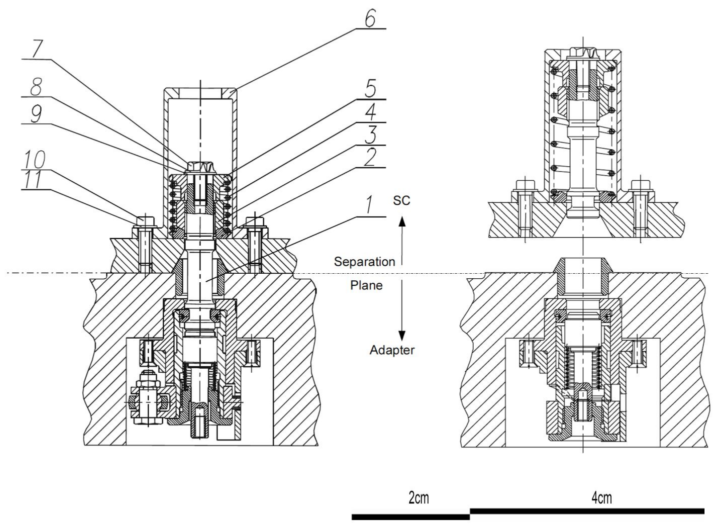


Figure 5.4.1: MLS from Eurockot

5.5 Operational Refurbishment

If needed, modules can be removed and replaced from the Sunflower by deactivating the electropermanent magnet joints and the mechanical lock systems. The module is thrusted out of the ring via its ion engines and hydrazine thrusters. New modules can be launched into LEO, deployed, and brought to the Sunflower. The new module can be inserted into the vacant spot in the Sunflower using an established method of VNS rendezvous assisted by Hall-effect thrusters, hydrazine thrusters, and magnetic joints. This process is performed when the Sunflower is in LEO to aggregate replacement modules.

5.6 Refueling

The Sunflower design references Restore-L, VNS, LIDAR, and STORRM as contemporary prototypes for rendezvous servicing and refueling missions. The existing Xenon propellant tanks hold a small volume relative to the scale of the Sunflower, and fuel is spread across 72 tanks. The broad arrangement of these tanks is beneficial to the structural performance of the craft. In future missions, as a modification to accommodate easier in-orbit refueling, the Sunflower could combine these tanks through carbon fiber tubing to a centralized refueling station for each module. This would result in 12 refueling ports, which can then be accessed by a refueling spacecraft. As larger and custom shaped Xenon fuel tanks are developed, the Sunflower can be modified to house more efficient tank arrangements.

5.7 Expansion above 291 kW

To expand above 291 kW, individual modules can be connected onto the outer edge of the Sunflower. A 727 kW (BOL) option can be made using 30 modules, capable of producing 48.5 N of thrust (Figure 5.7.1).

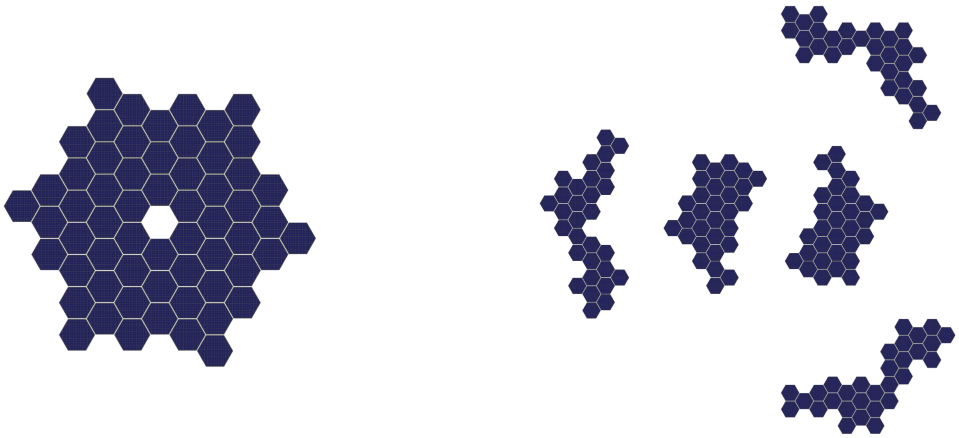


Figure 5.7.1: Standard Sunflower configuration options, 12-module 291 kW configuration (left) and 30-module 727 kW (Right).

Sunflower Configuration (# Modules)	BOL Power (kW)	EOL Power (kW)	Mass (fully fueled) (kg)	Thrust (N)	Number of Launches (Falcon 9 FT)
12	291	252	40978	19.4	2
30	727	630	102446	48.5	5

Table 5.7.1: Summary of Sunflower size and power configurations

6- Sunflower Performance

6.1 Vibrational Analysis

Preliminary vibration analysis carried out using Autodesk Fusion 360's vibrational analysis package revealed the smallest fundamental vibration frequency to be 7.5 Hz, above the 0.05 Hz requirement for this spacecraft. The scale for the simulation results is a normalized displacement. This shows which areas of the craft structure will deflect the most and least under load, without specifying absolute displacement. Testing was carried out on the individual modules, assuming that the vibration modes of the assembled 12-module Sunflower aggregate will scale linearly, and that the circumference of the aggregate is an oscillating member approximately 12 times the length of an individual module. Due to this, it is assumed that a reasonable approximation of the aggregate vibrational mode is 7.5 Hz / 12, which is 0.625 Hz. Since this value is still an order of magnitude larger than the specification (0.05Hz), it was determined that the design has fulfilled this requirement.

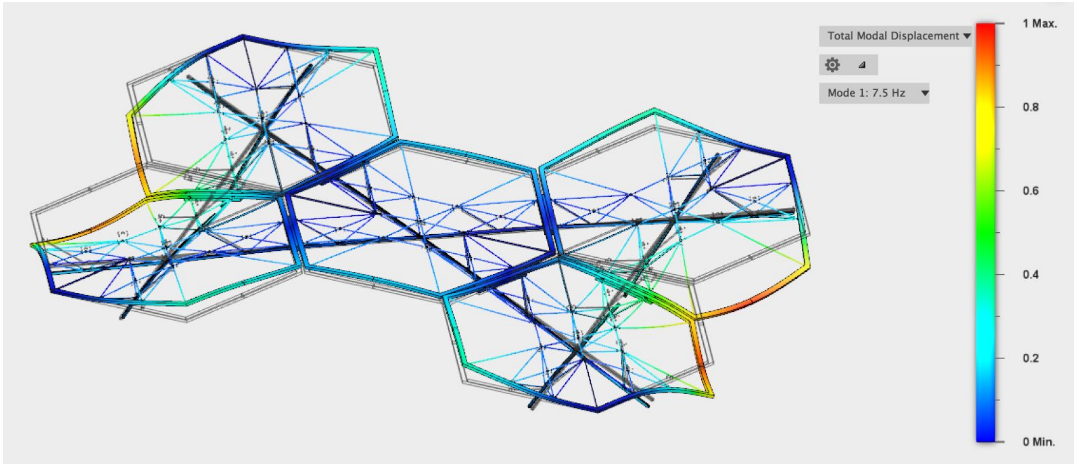


Figure 6.1.1: Vibrational analysis of module truss system

6.2 Force Analysis

The electropermanent magnet joints were tested using static stress analysis and Von Mises Stress simulations. The strongest forces and torques on the spacecraft is experienced by the magnetic joints. Deformation of the joint is shown in figure 6.2.1. The analysis, showing an 8,900N force on the magnetic joints, indicates that the main failure points would be the ferrite blocks, which is the main contact point between magnetic joint assemblies, particularly in areas close to openings in the module casing. This is reasonable, as the openings are areas of anisotropy, which allow stresses to concentrate.

The normal maximum holding force of each joint is approximately 8,900 N when two joints are locked together. This value was obtained through extrapolation of data created using the magnetic force calculator on the KJ Magnetics website. These joints, in combination with the mechanical locking system, are expected to withstand accelerations beyond 0.4 g's. This assumption is aided by the distribution of the Hall-effect thrusters throughout the array, which reduce the moment arm experienced by each connection. The secondary consideration for deformation comes from the thrust force of the ion engines. For an acceleration of .4 g's, the deflection is plotted in figure 6.2.2. These analyses were done on both the joints and the individual modules, which operate independently and therefore are assumed to be valid for the entire Sunflower.

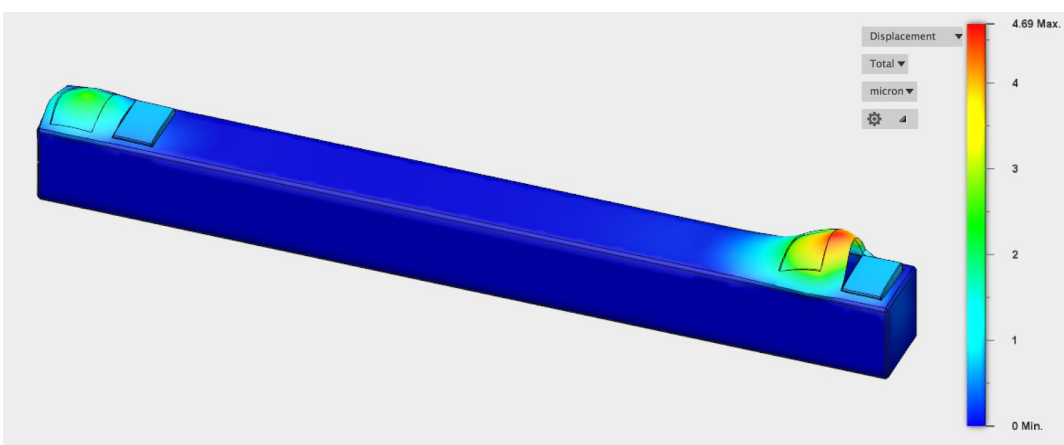


Figure 6.2.1: Magnet Joint Displacement Under 8900N Load

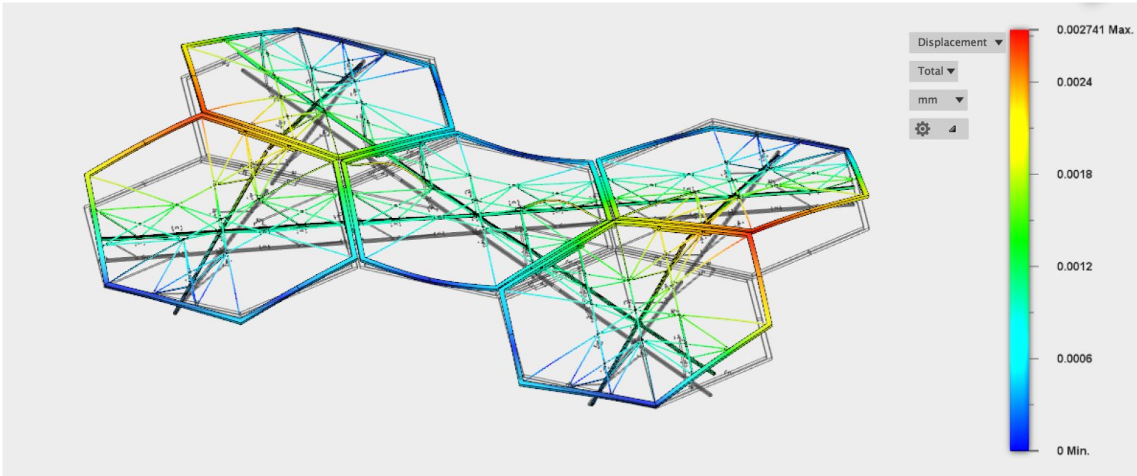


Figure 6.2.2: Deflection analysis under 0.4 g acceleration of support frame from the thrusters

6.3 Thermal Analysis

Thermal analysis of the Sunflower was carried out using the COMSOL Multiphysics finite element analysis software package. Simulations were conducted using the solar constant of 1362 W/m^2 (AM0) and with 13.15 m^2 of area per hexagon. The Sunflower is exposed to 17.910 kW per hexagon, for a total of 1.075 MW for the full Sunflower. The conservative assumption that all power not absorbed by the solar panels (30.7% BOL) or reflected by the solar panels (12%) is converted into heat states that panels absorb 0.616 MW of heat from solar radiation. They reach a maximum temperature of 523 K without any cooling system, shown in Figure 6.3.1. At approximately 350 K the degradation of the solar cells will severely reduce performance, and thus a cooling system will likely be needed. This could be accomplished using a passive cooling system (conductive heat fins), or an active cooling system consisting of liquid ammonia that is pumped behind the solar panels through radiator plates. The radiators on the International Space Station have been shown to dissipate 330 W/m^2. Radiators such as these can be attached to the rear side of the panels and implemented onto the truss backbone.

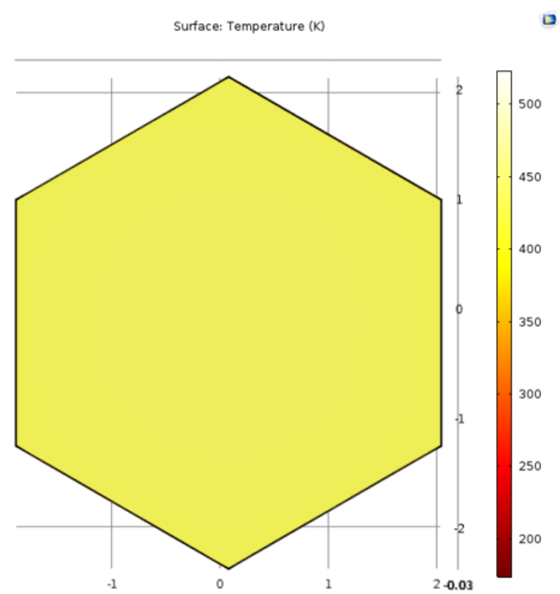


Figure 6.3.1: Temperature of front side of solar panel

6.4 Magnetic Analysis

The magnetic flux density of the electropermanent magnet joints was modeled in COMSOL Multiphysics using finite element analysis to determine the performance and confirm the function of the magnetic joints. Figure 6.4.1 shows a normalized vector field as the two modules approach during the docking process. The COMSOL model used several assumptions. The material N52 Neodymium was chosen due to its high coercive force value of 11.2 kilo-Oersteds (kOe). The material Alnico 8HC (Anisotropic, Sintered) Hard Magnetic Alloy was chosen for its coercive force value of 1797 Oe. The magnetic property values of Neodymium were used to calculate the magnetic holding force. The resulting magnetic field lines demonstrate the magnetic attraction orientation between the joints and also indicate the magnetic interference that is experienced by adjacent joints during aggregation. Figure 6.4.2 shows the magnetic attraction between two magnetic joints as a function of spacing distance. This analysis is a key factor in the modules coming together. It also demonstrates that the magnetic attraction between two joints is only large when the joints are within ~10cm of each other. Therefore, the amount magnetic interference between adjacent joints is minimized.

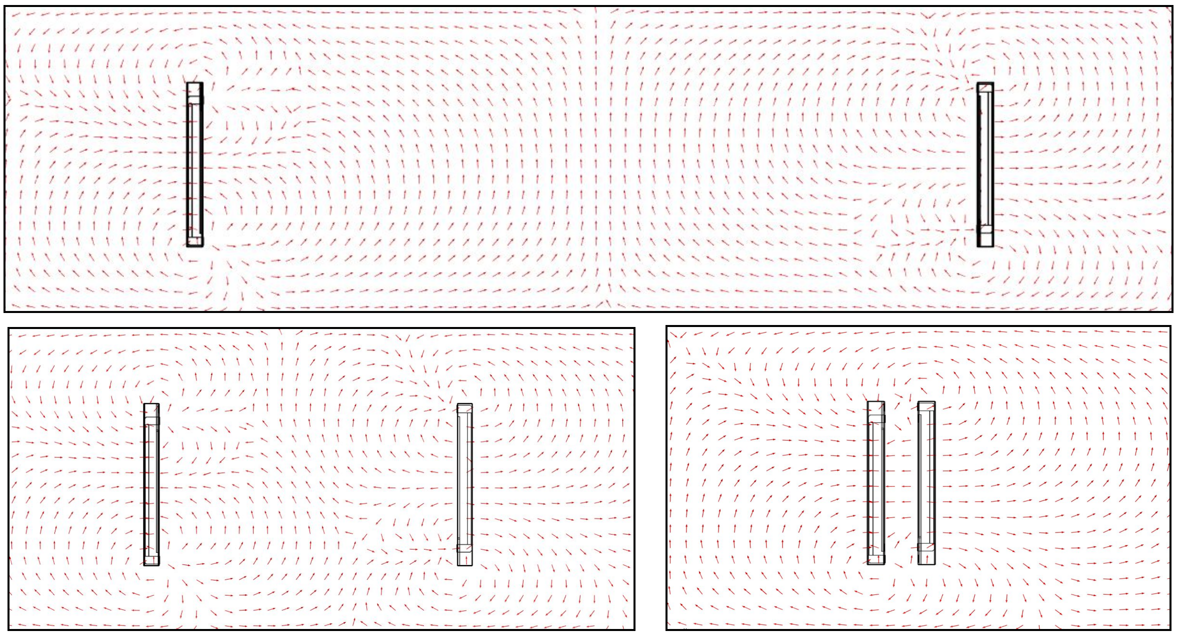


Figure 6.4.1: Normalized magnetic field lines in two-joint system, with joints spaced 5 m (top), 2 m (bottom left), and 0.2 m (bottom right) apart.

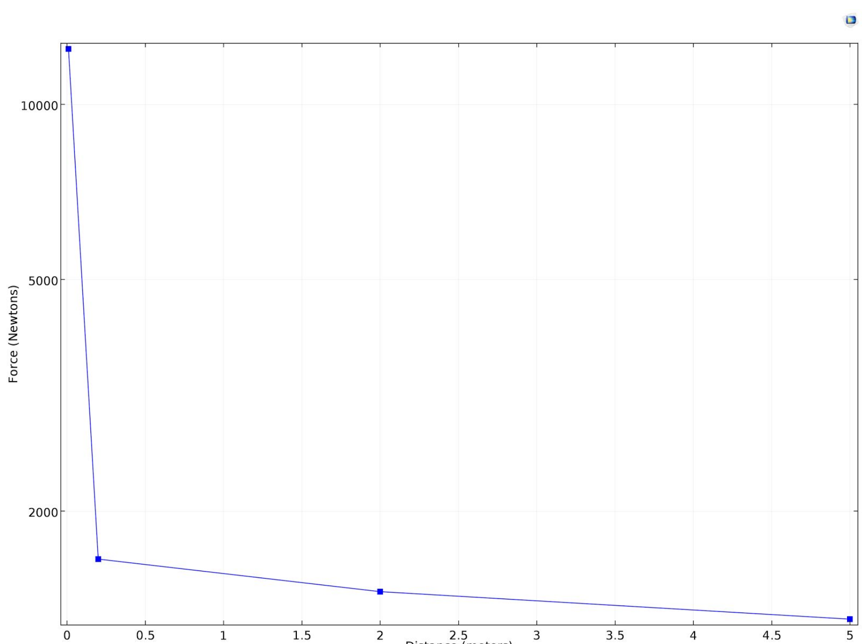


Figure 6.4.2: Magnetic force between two electropermanent joints as a function of spacing between joints.

7- Implementation

The Sunflower relies on many existing technologies, emphasizing a high level of technological readiness and potential for ground testing. The primary technology that must be developed is the electropermanent magnet joint system. The large size and unique design of the Sunflower joints requires substantial ground testing followed by in-flight qualification. Prototype electropermanent magnets have been procured for a scaled demonstration of this design. A second technology for development is the swivel-gimbal system of the Hall-effect thrusters. This component must also be built, tested, and qualified. Furthermore, structural models for the Sunflower were prototyped at 1=1/100 and 1=1/20 scales. Testing and detailing for this system will continue throughout the design process. Further analysis of refueling concepts, rendezvous maneuvers, heat dissipation, and structural soundness will also be carried out in future analyses.

8- Conclusions

The Sunflower SEP tug concept is a completely modular solution to transfer cargo from LEO to LDRO. A 12-module Sunflower can be sent to orbit using two commercial launches and can bring payloads to LDRO in as few as 138 days. The option for operational refurbishment can expand the lifetime of the Sunflower indefinitely, and the hexagonal symmetry of the spacecraft allows for continuous expansion to larger array options. The Sunflower drew from several existing technologies while innovating in key areas. The design process was carried out completely by students, and was approached from a range of perspectives. The Sunflower is a comprehensive and unique concept for delivering cargo and crew to distant orbits.

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