Final Design Package

EML 4551C – Senior Design – Fall 2011 Deliverable 5

Team # 6

Panel Interlocking Mechanism for Solid Reflector

Patten, Thomas **Saunders, Ashley** **Slingsby, Cory**

Department of Mechanical Engineering, Florida State University, Tallahassee, FL

Project Sponsor

Mr. Gustavo Toledo

with

Harris Corporation

Project Advisor

Dr. Chiang Shih, PhD

Department of Mechanical Engineering

Reviewed by:

Contents

II. Acknowledgements

- Mr. Gustavo Toledo, Harris Co. – Project Sponsor
- Dr. Hovsapian, Dr. Kosaraju, Dr. Shih – Faculty Advising
- Bill Starch, Shop – Fabrication Research

III. Preface

This Final Design Report prepared by senior design team 6 represents all work performed by the team from August – December 2011. The work was carried out in accordance with the guidelines set forth by the FAMU-FSU College of Engineering Senior Design course requirements and the Statement of Work issued by Harris Corporation. The report includes four sections.

Section 1 - Introduction

An overview of the project is presented. The client needs and project scope are defined. A method to meet all requirements is developed and a timeline of milestones is prepared. Additional background information is also provided in this section.

Section 2 – Concept Generation & Selection

The team's concept generation methods are discussed. Concept selection criteria are developed. The team's top concepts are presented. The concept selection criteria are applied and the concepts winnowed. A discussion of how to interpret and utilize this information is presented.

Section 3 – Results

The final design is presented and discussed in detail. Fabrication and assembly methods are discussed and a proposal is made. Raw material requirements are defined and material sourcing is discussed.

Section 4 – Testing & Conclusions

Testing plans are discussed and a recommendation of how best to utilize the assembled model is offered. The team's final comments and conclusions are offered.

Section 1 – Introduction

1.1 Project Overview
1.2 Project Scope & Client Needs Assessment
1.3 Methodology
1.4 Project Background

1.1 Project Overview

1.1.1 Project Proposal & Introduction

This document details the scope of the contract between Mr. Gustavo Toledo ("the sponsor") and FAMU-FSU Senior Design Team 6 (Solid Panel Interlocking Mechanism, "Panel Team") for the production of a prototype high surface accuracy tangential deployable reflector dish for interstellar antennae applications. Devices of this nature are used to send and receive K_u band EMF transmissions, and require an aperture (Diameter of dish) of 4-10m. Special considerations must be further made for a space based application to accommodate restrictions on weight and volume, and to ensure function with zero maintenance.

Figures 1 and 2 below show a concept generation provided by the sponsor to help explain the aim of the project. The second figure illustrates the technology currently in use, generally known as a radial rib reflector. This technology consists of an elastic fabric type material that is stretched across a rigid frame. Such an approach offers excellent stowed volume, minimal weight, and reliable operation which explain why the method is the current standard. However, as one can imagine, the fabric skin "kinks" as it passes over each rib such that the reflector surface does not perfectly follow the ideal parabolic shape. This deviation, known as the Surface Accuracy, is expressed as a tolerance with units of length. Low surface accuracy results in lower efficiency and increased signal degradation as compared with reflectors of the same aperture that possess higher surface accuracy. High surface accuracy is achieved more easily with a solid reflector.

Solid reflectors have some rigid material that is cast, molded, rolled or otherwise shaped to match the chosen ideal parabolic shape. The use of this solid material makes extremely high surface accuracies possible, but they generally require a rigid framework to support the mass of the dish. In space applications however, mass is an issue for different reasons than for ground based applications, and adequate structural support can be achieved with minimal bracing. Figure 1 shows the general aim of the project; to produce a tangentially deployable solid reflector. The concept consists of multiple panels which are initially stacked. These panels rotate about a central point, translating in plane, thus achieving tangential deployment.

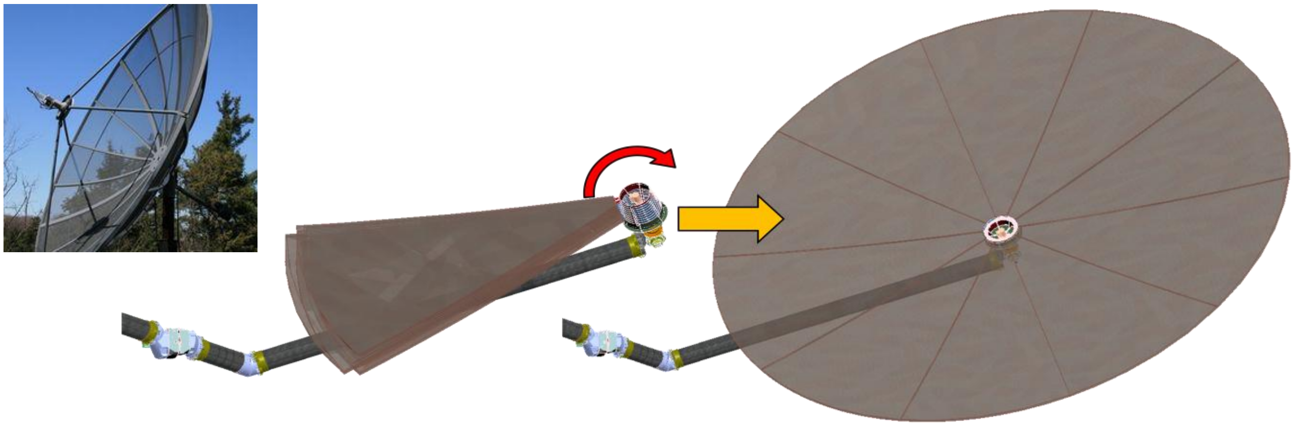


FIGURE 1: CONCEPT ILLUSTRATION FOR A SOLID, PANELED, TANGENTIALLY DEPLOYABLE REFLECTOR, COURTESY OF HARRIS CORP

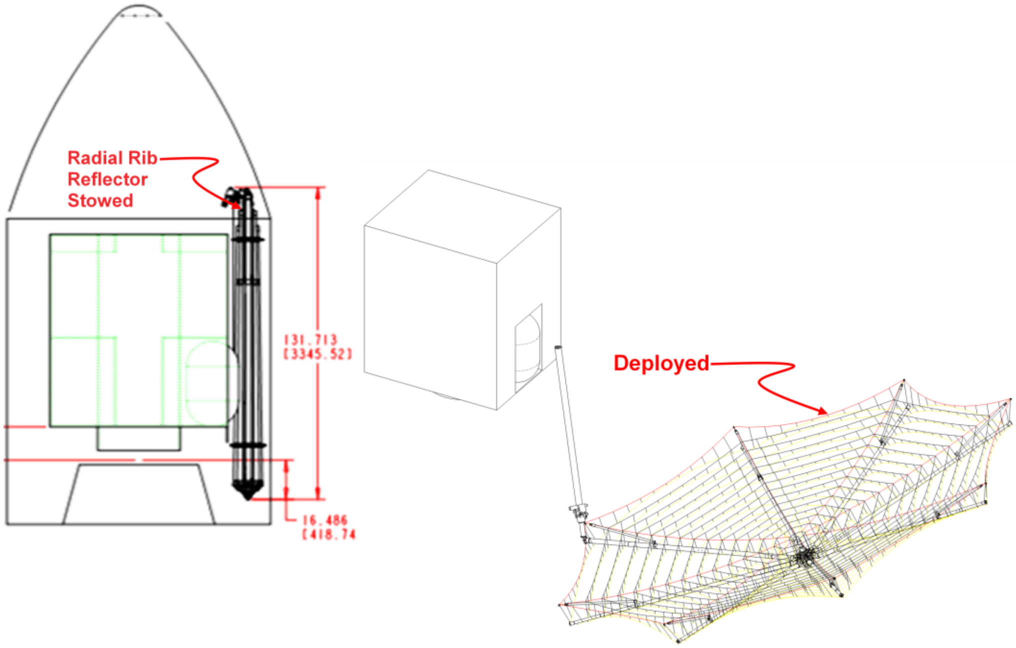


FIGURE 2: SCHEMATIC ILLUSTRATION OF A RADIAL RIB REFLECTOR IN STOWED AND DEPLOYED STATE, COURTESY OF HARRIS CORP.

The tangentially deployable solid reflector concept consists of two sub systems:

1. ***Hub Mechanism:*** This system drives and synchronizes the deployment of the panels. *See Team 5 for more detail.*
2. ***Panel Interlocking Mechanism:*** This system controls the manner in which each panel connects to its adjacent panels. **This is the focus of this and all subsequent documents prepared by Team 6 (Panel Interlocking Mechanism).**

The resulting function of these subsystems will be that the paneled reflector can be stored in a volume comparable to that of reflectors of a radial rib design. The reflector must then be cable of autonomously deploying. This deployment must include alignment and locking of the individual panels; interstellar applications will not allow for post deployment positioning of the panels, such that a misaligned panel would render the dish inoperable. The final deployed reflector must be capable of exhibiting higher surface accuracy and performance than comparable radial rib designs.

1.2 Project Scope &Client Needs Assessment

1.2.1 Intro and discussion of Methods

- First we define the project scope
    - Based on project proposal
    - Based on S.O.W
    - Based on sponsor feedback
- Next, we combine the project proposal and scope to derive a concise problem statement
- Finally, we worked with client to develop succinct, itemized needs
    - These itemized needs play a major role. They are one tool used to preserve the client's voice through the next section
    - The needs will be used to create one axis of the trade matrix

1.2.2 Project Scope

To illustrate the scope of the contract between Team 6 (Panel Interlocking Mechanism) and Harris Corp., we first consider the overall project scope, and then detail the role of Team 6 within that project. A high level project process for the development of a flight ready, deployable solid reflector is:

1. <u>Needs Assessment</u> Harris Corporation has identified the need for a solid reflector alternative to radial rib reflectors that exhibits improved surface accuracy.
2. <u>Concept Generation</u> Harris will employ several approaches to develop high level possible options that satisfy the needs assessment.
3. <u>Concept Analysis</u> Here the individual high level concepts are investigated to determine feasibility. **The entire scope of the contract with Team 6 lies within this set.**
4. <u>Idea Selection</u> After reviewing the conclusions formed in the previous step, a single approach will be selected for further development.
5. <u>Final Design</u> The final design including manufacturing processes and material suppliers are specified.
6. <u>Prototype Construction and Concept Verification</u> Full scale model is produced and tested to verify design and production processes.
7. <u>Manufacture and Installation</u> The final product is constructed and installed.
8. <u>Quality Assurance</u> The unit is checked to ensure successful implementation before being launched into space.

As introduced by the process map above, the scope of the FSU-Harris contract is for several students to assist with analysis of a particular concept; a tangentially deployable solid reflector. The general aim of such a concept analysis is to equip the project lead (Harris Corp.) with the information necessary to make an informed selection between designs. Together, the FAMU-FSU students are to produce a physical model that demonstrates the kinematics of a particular concept, the tangentially deployable reflector.

The focus of this team is the interlocking design for the rigid panels of the reflector system. The panels of the final working model must possess the ability to interlock with each adjacent panel and maintain a final side by side alignment. Although the final prototype does not have to demonstrate autonomous storage of the panels, it should be designed with the capability of going from its final deployed position back to its initial configuration. Thus, the latching design must also allow for disconnect and repetition.

The overall focus is to have a final working prototype for a collapsible, solid reflector. This prototype will use rotational and then translational motion to autonomously achieve its deployed position. The final model for the system will possess the ability to work while exhibiting 1g forces, and will be designed with the anticipation of experiencing and maintaining functionality in a 0g environment as well. We will maintain the efficiency of the system as well as follow appropriate safety measures for design.

1.2.3 Problem Statement

Our center of attention is on the latching mechanism used to engage and hold the panels in their final, flush positions. The panels are initially in a stowed position stacked on top of each other as can be seen below in figure 3.

FIGURE 3: SHOWS THE STOWED POSITIONING OF THE PANELS IN WHICH THEY REST ON TOP OF ONE ANOTHER

The hub mechanism will first use rotational motion to move the panels from their stacked position to their desired radial positions as can be seen below in figure 4.

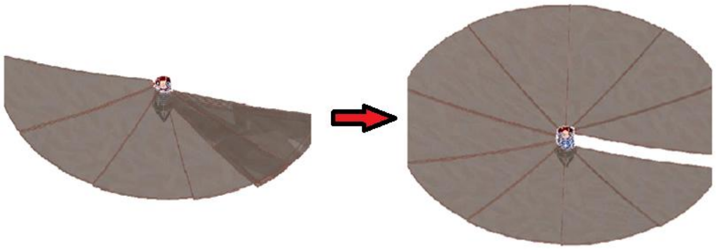


FIGURE 4: LEFT) THE HUB INITIALLY USES ROTATIONAL MOTION TO MOVE THE PANELS FROM THEIR STACKED POSITIONS. RIGHT) THE GEOMETRY OF THE PANELS ONCE THEY HAVE FINISHED THE ROTATIONAL MOTION PHASE.

Once the rotational phase of motion has completed, each panel will then be in its desired radial position. However, due to the initially stacked geometry of the panels, there is a vertical offset between panels which makes a second phase of motion necessary. In this phase, linear motion will be used to bring the panels to their fully deployed, flush positions (figure 5 below).

FIGURE 5: SHOWS THE PANELS IN THEIR FULLY DEPLOYED CONFIGURATION IN WHICH THE PANELS ARE BOTH VERTICALLY AND HORIZONTALLY FLUSH WITH ONE ANOTHER

The latching mechanism will be designed to engage in the linear motion phase of deployment. Ideally, it will be a passive design. It must securely hold each panel flush with their two adjacent panels and must be a reliable design.

By the project’s end, our latching design in conjunction with the hub mechanism design will be used to create a working prototype for a reflector system. Said prototype should be scalable to the desired dimensions for the actual system. It must meet the size, shape and movement requirements that were set forth prior to the commencement of the project.

1.2.4 Client Needs

- Tangential Deployment
    - The deployment path taken by the panels must consist of a primary rotational stage and secondary linear stage. Thus, the panels will first be aligned radially and then vertically. The client has requested a functional prototype that demonstrates this motion.
- Panels are flush when fully deployed
    - The seam between panels has a minimal gap in the plane of the panels, and all panels should be the same height relative to each other.
- Reliable Deployment
    - The panels must not catch on each other and the locking mechanism/s must successfully engage such that the prototype deploys autonomously and without adjustment with a reliability of 99.9% or higher.
- Panels Remain in Place
    - Once the panels are fully deployed in the final product, the reflector will need to remain in operation for 15-30 years with zero maintenance. The latching mechanism should keep the panels in alignment by remaining latched while undergoing the forces commonly experienced by such reflector antennae.
- Space Deployable
    - Space based applications require certain restrictions on usable materials and equipment. For instance, only certain motors have been demonstrated to operate in zero-G, and all materials may be exposed to high levels of radiation.
- Teamwork
    - All related assemblies must cooperate to produce a functioning kinematic model. For instance, the hub mechanism must provide sufficient positioning accuracy to enable the interlocking mechanism, and the interlocking mechanism must not inhibit deployment such as by snagging.

1.3 Methodology

1.3.1 Introduction & Description of Methodology

Once we have developed an understanding of the intended design, ideation can begin to turn into an actual working prototype. We will have to determine the best way to interlock the panels. This design must hold the panels together in a final, flush position, while also being capable of separating. Magnets along with a cup and cone design have been recommended, but we will have to do research for alternative methods to determine the best choice. The chosen latching design has to be carried out independently by the system and will be chosen with intentions for use in space.

Once the panels are fully designed we must choose the intended dimensions for the prototype, as it needs to be scalable to a larger solid reflector. It must be kept in mind that these panels must be able to initially hold a stowed, stacked position and then maintain a final deployed configuration in which they are side by side. Panels must be mountable to the hub, and the connection of the two components must be designed to ensure that the panels have enough support in a 1g environment. Although we are focusing on the latching mechanism while there are others focusing on the hub mechanism, communication between everyone throughout the entire design process is vital as the two components will come together to form a final working model and must be designed accordingly so.

Testing these designs of both the individual parts as well as the system as a whole is vital to this project. Once the panels have been designed and materialized, their interlocking capabilities can be tested. The design behind their connection must ensure each panel is keeping both adjacent panels in their defined final positions. Once the hub is ready, we will test the system as a whole. A successful design is dependent on both parts of the system working together to formulate a working model of a solid reflector system possessing an initial stowed position and having autonomous capabilities to achieve its final deployed position. Throughout testing if and as problems are encountered, the proper design alterations will have to take place. Devising a schedule that ensures enough time for testing to achieve a successful design is imperative.

1.3.2 Project Plan

Spring 2012 Schedule:

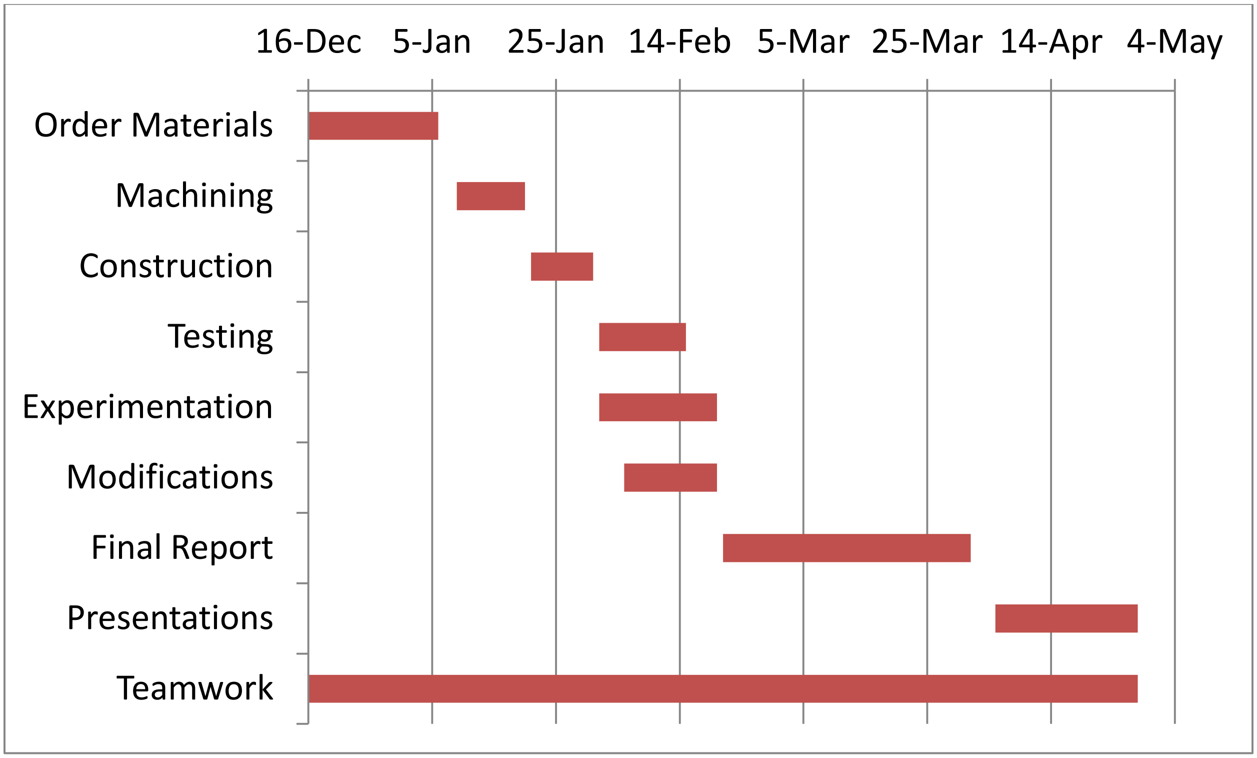


FIGURE 6: GANTT CHART FOR THE SPRING 2012 SEMESTER

Figure 6 above shows our Gantt chart for the upcoming semester. We will have our materials ordered by the beginning of January so that we can complete machining and begin assembly before January's end. Testing will commence towards January's end and extend through the middle of February to allow for experimentation and modifications of the original design.

1.3.3 Design Objectives

- Create a working prototype of solid reflector system
  - Should be scalable to desired dimensions for actual system
  - Should demonstrate systems performance
    - Move from stowed to fully deployed configuration using hub
    - Latching mechanism will keep adjacent panels in flush, defined position
  - Must meet size, shape and movement requirements previously set forth
- Method in which the system attains its fully deployed position will consist of 2 stages:
  - Rotation
  - Linear Translation
    - Design must facilitate both motions

        - Must recognize when rotational sequence is over and transition to linear motion
        - Must avoid snagging
- Method in which panels latch onto one another
    - It is during linear translation that interlocking mechanism must engage
    - Must maintain final position for prolonged period of time
    - Doesn’t need to be reversible, but ideally is resettable

1.3.4 Design Constraints

Function:

- Reflector for space based applications capable of autonomous deployment.
- Solid-skin rigid panels

Constraints:

- Total budget of $2,500.00
- Prototype will be a scale of the actual size
- Panels connect to form dish shape characteristic of parabolic reflector antennae
- Minimal compacted volume
- Panels must be mountable to hub mechanism
- Panels must be able to hold both a stowed (stacked) and deployed (spread out) configurations
- Panels will use rotational and then linear motion to achieve a final deployed configuration
- Panels must be flush and interlocked in fully deployed position
- Deployment operation must be reliably repeatable
- Minimize mass of panels
- Optimize stowable space
- Demonstrate a working prototype

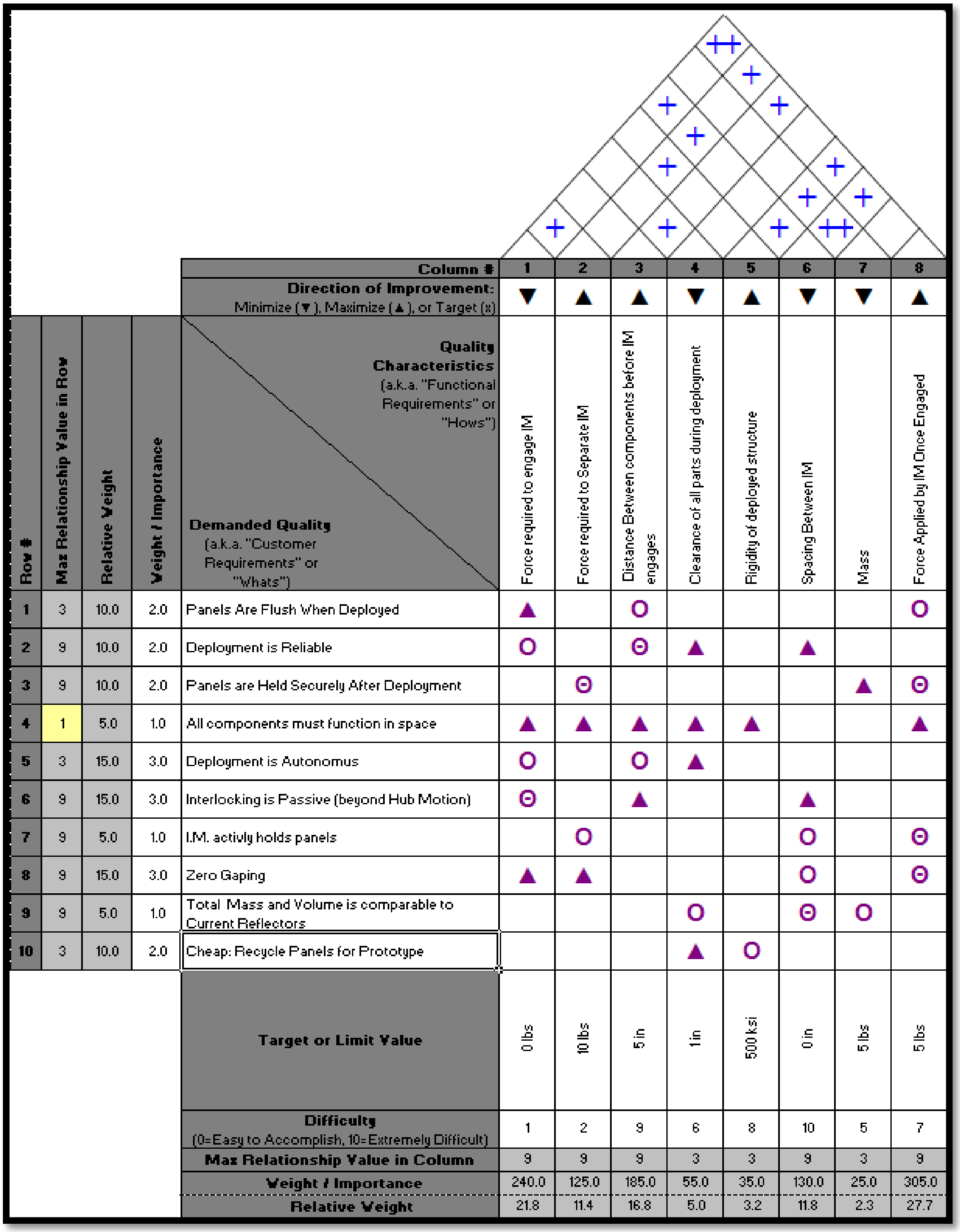
Free variables:

- Material of panels
- Interlocking mechanism (magnets recommended by Harris sponsor)

1.3.5 Engineering Specifications

- Engagement Proximity
    - This is the minimum distance the panels must travel before the interlocking mechanism can engage.
- Engagement Force
    - This is the force required to engage the interlocking mechanism once the panels are within the minimum *engagement proximity*. A negative force represents attraction, such as would be experienced with a magnetic based mechanism.
- Separation Failure
    - This defines the force required to separate the panel-panel seams once the interlocking mechanisms have engaged.
- Stability
    - Resistance to flexure after deployment, such as would be caused by acceleration of the assembly. Hypothetical sources include gravity for ground applications, and post deployment repositioning of a satellite for space applications. Stability also encompasses dynamic stability and vibration dampening.
- Mass
    - Mass of the total system should be optimized to weigh five pounds.
- Force applied by interlocking mechanism once engaged
    - Interlocking mechanism should have an applied active force while engaged to satisfy the no gapping criteria and allow the system to remain stable.
- Spacing between interlocking mechanisms
    - Depends on quantity of mechanisms required, available space, and force/weight requirements to maintain panel locking criteria.
- Clearance of all parts during deployment
    - During deployment of system, all parts should have at least a 1 inch clearance between all other moving parts.

1.3.6 Quality Function Chart (QFC)



				Column #	1	2	3	4	5	6	7	8
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	▲	▲	▼	▲	▼	▼	▲
Row #	**Max Relationship Value in Row**	**Relative Weight**	**Weight / Importance**	**Quality Characteristics** (a.k.a. "Functional Requirements" or "Hows") / **Demanded Quality** (a.k.a. "Customer Requirements" or "Whats")	Force required to engage IM	Force required to Separate IM	Distance Between components before IM engages	Clearance of all parts during deployment	Rigidity of deployed structure	Spacing Between IM	Mass	Force Applied by IM Once Engaged
1	3	10.0	2.0	Panels Are Flush When Deployed	▲		O					O
2	9	10.0	2.0	Deployment is Reliable	O		Θ	▲		▲		
3	9	10.0	2.0	Panels are Held Securely After Deployment		Θ					▲	Θ
4	1	5.0	1.0	All components must function in space	▲	▲	▲	▲	▲			▲
5	3	15.0	3.0	Deployment is Autonomus	O		O	▲				
6	9	15.0	3.0	Interlocking is Passive (beyond Hub Motion)	Θ		▲			▲		
7	9	5.0	1.0	I.M. activly holds panels		O				O		Θ
8	9	15.0	3.0	Zero Gaping	▲	▲				O		Θ
9	9	5.0	1.0	Total Mass and Volume is comparable to Current Reflectors				O		Θ	O	
10	3	10.0	2.0	Cheap: Recycle Panels for Prototype				▲	O			
				Target or Limit Value	0 lbs	10 lbs	5 in	1 in	500 ksi	0 in	5 lbs	5 lbs
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	1	2	9	6	8	10	5	7
				Max Relationship Value in Column	9	9	9	3	3	9	3	9
				Weight / Importance	240.0	125.0	185.0	55.0	35.0	130.0	25.0	305.0
				Relative Weight	21.8	11.4	16.8	5.0	3.2	11.8	2.3	27.7

FIGURE 7: QUALITY FUNCTION CHART

Figure 7 above shows our quality function chart (QFC). As you can see at the very top of the QFC, the force required to engage our latching mechanism and the force applied by the latching mechanism are the top two engineering specifications. These qualities are located in the first and last columns at the top under “Quality Characteristics”. It is important to notice that relative weight, located along the bottom of the QFC, establishes both of these forces. However, the largest impact on the engineering specifications is the requirement that all components work in space, as you can see in the fourth row down under “Demanded Qualities.”

An important aspect that the QFC helped us to notice is that most of the engineering specifications are inversely related. For example, we can’t make our panels more lightweight without making them weaker and, similarly, we can’t make them more lightweight without reducing their stiffness. While our objectives are to minimize the mass of the panels while increasing the strength and stiffness of them, we will constantly have to reassess our limiting values in order to best satisfy all areas.

1.3.6 Expected Results

The expected result of the FSU-Harris partnership is the completion of a scaled prototype that demonstrates autonomous deployment of a rigid panel deflector dish utilizing the patented bi-directional motion. Our contribution to the prototype will be to:

1. **Ensure the panels reach the correct deployed position**. *The panels must not catch or snag during deployment. Once hub motion completes, the panels should be correctly aligned with each other and the hub; the seams between panels should be flush. The panels should reach this position with a high degree of reliability.*
2. **Ensure the panels are securely held in the deployed position.** *Once deployed, the panels should be capable of retaining their alignment while exposed to the operational conditions of a satellite; the seams should not unintentionally separate, the individual panels should maintain their initial geometry, and the panels should not separate from the hub.*

The emphasis of this project is to provide a proof of concept for the patent being applied for by Harris Corporation. We expect to have a fully working prototype of a deployable solid reflector by the end of this project. The prototype will be a scaled model of an actual solid reflector, but it will fully demonstrate the mechanics and the design of the deployment. The working prototype will be able to redeploy whenever necessary.

1.4 Project Background

1.4.1 Reflector Technology

All satellite communications systems consist of two basic elements: the satellite itself and a ground station. Applications of satellite communication systems today include:

- ***Traditional Telecommunications*** Providing a link between transoceanic communications systems, or to geographically remote regions and countries with less developed communications infrastructure.
- ***Cellular*** Providing additional bandwidth for ground based cellular networks.
- ***Marine Communications*** Providing links to ships at sea.
- ***Airborne Communications*** Providing passengers of commercial airlines access to land based telecommunications networks.
- ***Global Positioning*** Services enabling navigational equipment for broad field of applications.
- ***Television Signals*** Since the 1960's satellites have connected broadcast television company's network hubs and their subsidiaries. The ability to receive the same satellite signal at home arose in the 1970's, marking the beginning of the Direct To Home (DTH) industry.

Of the applications, perhaps the simplest example illustrating the background for this Interlocking Panel Mechanism project is satellite systems for television signals. Currently, two technologies are commonly employed, one utilizing the lower frequency C-band and the other utilizing the higher frequency Ku-band range of microwaves.

The lower frequency range of C-band transmissions (approx 4-8GHz) provides increased signal stability, offering improved signal resolution even in heavy rain (rain fade) or snow (snow fade) conditions over Ku-band. However, a C-band receiver dish must be approximately 3m (~10 ft) in diameter, affectionately earning C-band systems the nickname "BUD" or Big Ugly Dish systems. While some broadcast television subscribers do install at-home BUD receiving systems, the more common application of C-band based communication is to have local broadcast-cable stations, which receive the C-band signal from the television company and disseminate the broadcast via cable to subscribers at their homes. This broadcast-cable system approach has proven to be an affective competitor in the Direct to Home (DTH) television market. However, reducing the receiving dish size would make home receivers more practical than running kilometers of cable to location where the raw signal is already being sent.

Ku-band systems (frequencies of approx 12-18 GHz) use receiving dishes as small as 0.45m (18 in) making them suitable for DTH applications. Cable systems do have some advantages; a Ku-band system requires slightly higher power for transmission, and additional error correction measures are required to compensate for signal degradation due to rain or snow fade. However, both C and Ku-band systems are common, and many Hybrid satellites are in orbit today carrying receiver/transmitter systems for both frequency ranges. Our team is part of the process for constructing a new type of dish for space applications. Now that we are familiar with C-Band and Ku-Band systems that we are designing for, we can derive some general criteria for the design.

For both C and Ku band systems, the satellite requires a dish reflector with an aperture of approx 3.5m (11.5 ft). The reflector must also have low mean surface deviation (>0.001”) and good performance/efficiency (percent of EMF incident on the reflector that does not reach the receiver). There are two types of reflectors commonly used: mesh and solid. Mesh reflectors consist of compliant material stretched over radial symmetric rigid ribs. These reflectors have the advantage of being collapsible, but minute adjustments are required to achieve a suitable mean surface deviation and performance is generally lower. Solid reflectors typically require rigid frameworks that support a dish consisting of one solid piece or multiple solid panels. The use of solid pieces for the reflecting surface allow for excellent mean surface deviation and efficiency, but without being collapsible, typical solid reflectors are not suitable for space applications.

Section 2 – Concept Generation & Selection

2.1 Concept Generation

2.1.1 Introduction & Methods

The method in formulating various design concepts for our latching mechanism was dependent on the assortment of requirements and constraints of the device as a whole. As the device transitions from its fully stowed to its fully deployed state, the requirements and limitations of each panel transition from state to state as well. In order to best design a means of fully satisfying the needs of our design, all states of our mechanism and their corresponding expectations and restraints must be considered.

2.1.2 Design Tools

State Function Analysis

In figure 8 below, we have a visual representation of the 8 different states the system passes through.

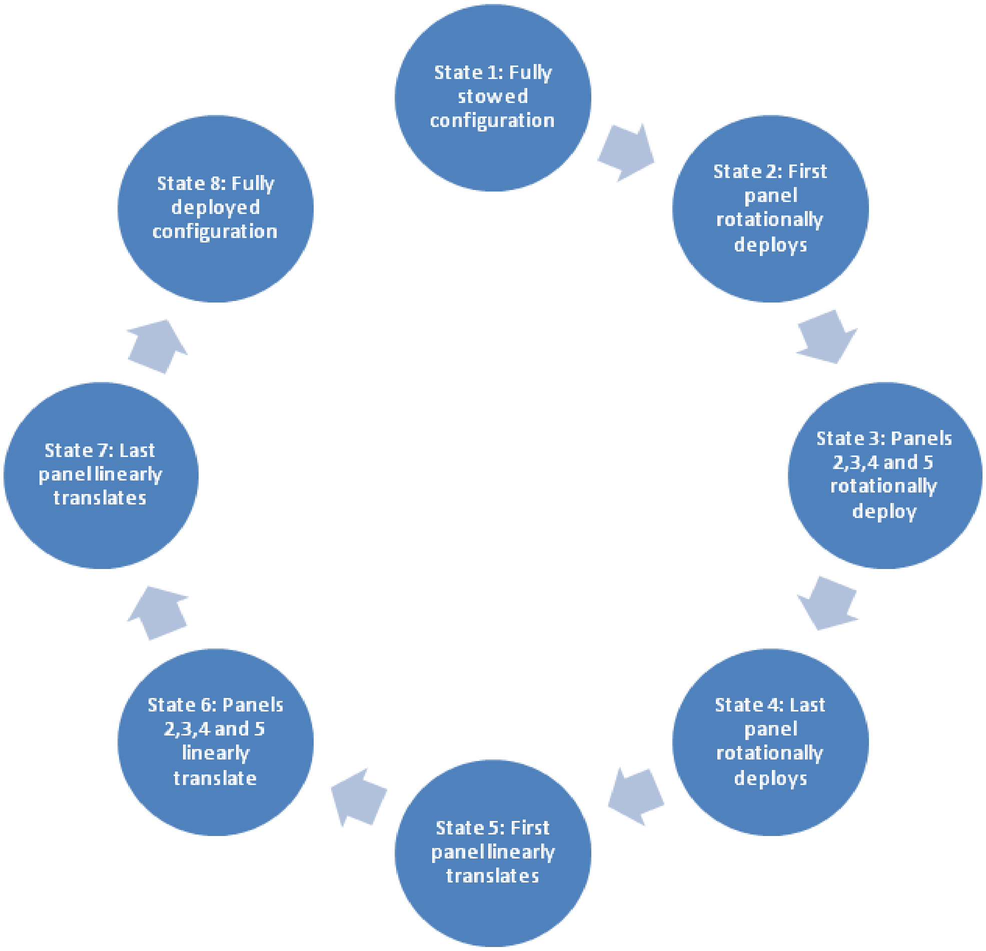


FIGURE 8: SHOWS THE 8 STATES OF DEPLOYMENT THAT OUR DESIGN MUST SATISFY

As the requirements of a panel change based on their status in deployment, the state changes as well. Panels that undergo the same requirements at that point in deployment are categorized into the same state. The breakdown and conditions of each state is as follows:

- State 1:
    - All components must remain stowed during launch and into orbit
- State 2:
    - The first panel deploys
        - This panel will not be preceded by any other panels
        - Latching mechanism (LM) must not catch leading edge
        - LM must not catch during deployment
        - LM must not catch on trailing edge
        - Panel will be followed by second panel
- State 3:
    - Panels 2, 3, 4, and 5 deploy one after the other
        - These panels will be preceded by the another panel
        - LM must not catch leading edge
        - LM must not catch during deployment
        - LM must not catch on trailing edge
        - These panels will be followed by another panel
- State 4:
    - The last panel deploys
        - This panel will be preceded by panel 5
        - LM must not catch leading edge
        - LM must not catch during deployment
        - LM must not catch on trailing edge
        - This panel will not be followed by any other panels
        - Once state 4 is over, all 6 panels are in their intended radial positions
- State 5:
    - The first panel linearly translates
        - First panel to reach its fully deployed configuration
        - This panel comes down with no panels on either side initially
- State 6:
    - Panels 2,3,4 and 5 linearly translate
        - Each of these panels comes down adjacent to the preceding panel
            - As panels come down, LM should engage with preceding panel
        - Each of these panels, once in their final linear position, will have a panel coming down on the edge opposite the preceding panel
            - As following panels come down, LM should engage with the following panel

- State 7:
    - The last panel linearly translates
        - This panel will be coming down with two fully deployed panels on either side
        - This panel will not be followed by any other panels
- State 8:
    - Fully deployed configuration
        - All components remain flush and secure with their two adjacent panels

In being conscious of the 8 states the system goes through and their correspondingly changing requirements, we know all that is expected of each individual panel and at what point in sequence it is expected. In doing so, we can now formulate the best design to transition the system from state 1 successfully through all 8 states and ultimately devise the best design to achieve the overall goal in autonomously taking these panels from a fully stowed to a fully deployed configuration.

2.2 Concept Descriptions

2.2.1 Mechanical Concepts

The goal of the mechanical concepts is to use rigid mechanical components to very securely hold the panels in place. The mechanical latch is an extremely mature technology. However, the design challenges facing this method are many. Space is limited everywhere: at the site of engagement, in and around the hub, and on either side of the panels. The no-gapping criteria all but necessitates an active retaining force be applied post engagement. Finally, the ability of a panel to push back a latch strike is likely very limited at best. The following concepts represent the team's consensus of potential designs that may be able to accommodate these challenges.

Mechanical Concept 1: Plate Design

This concept is very simple and easy to install. A stiff plate is installed beneath each panel and the adjacent panel will rest on the plate once the panels are collapsed. The simplicity of this design is important because it can be applied with other designs if needed. The design on its own will not be secure enough.

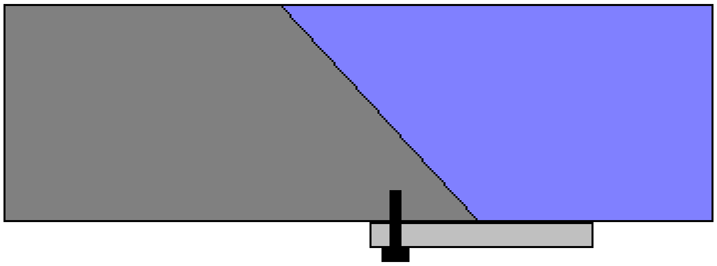


FIGURE 9: CROSS SECTION, SIDE VIEW OF TWO PANELS

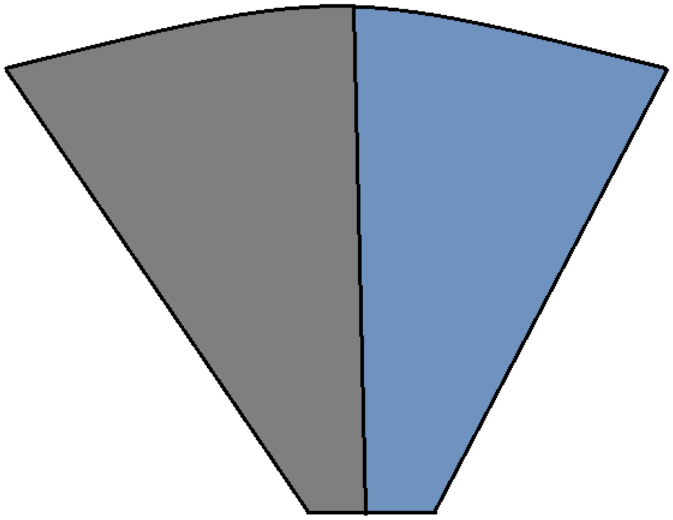


FIGURE 10: TOP VIEW OF TWO PANELS

Mechanical Concept 2: Cup and Cone Design:

This design concept is a simple cup and cone. Each panel will have a cup on one side and a cone on the other. When the panels come together, the cups and cones will mesh together just like a jigsaw puzzle. This will help lock the panels together and keep them from shifting around after the panels collapse. This design concept will be able to be utilized with other designs as well.

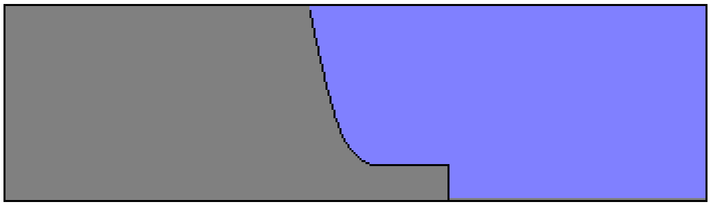


FIGURE 11: CROSS SECTION, SIDE VIEW OF TWO PANELS USING THE CUP AND CONE DESIGN

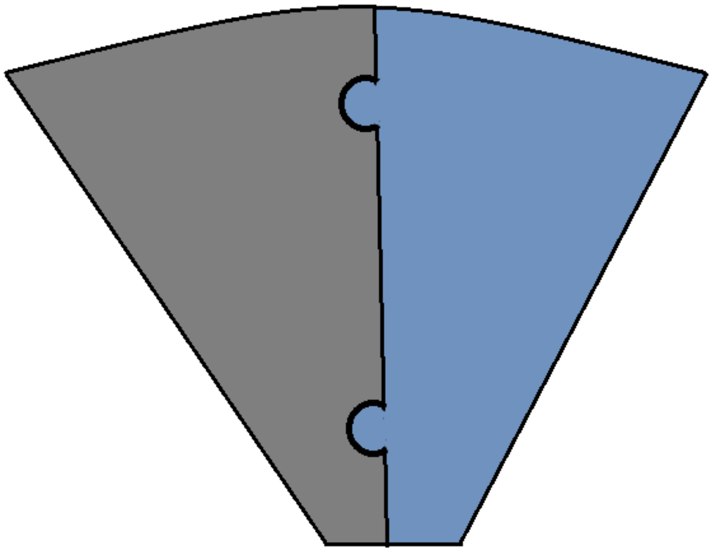


FIGURE 12: TOP VIEW OF TWO PANELS USING CUP AND CONE DESIGN

Mechanical Concept 3: Double Spring Design

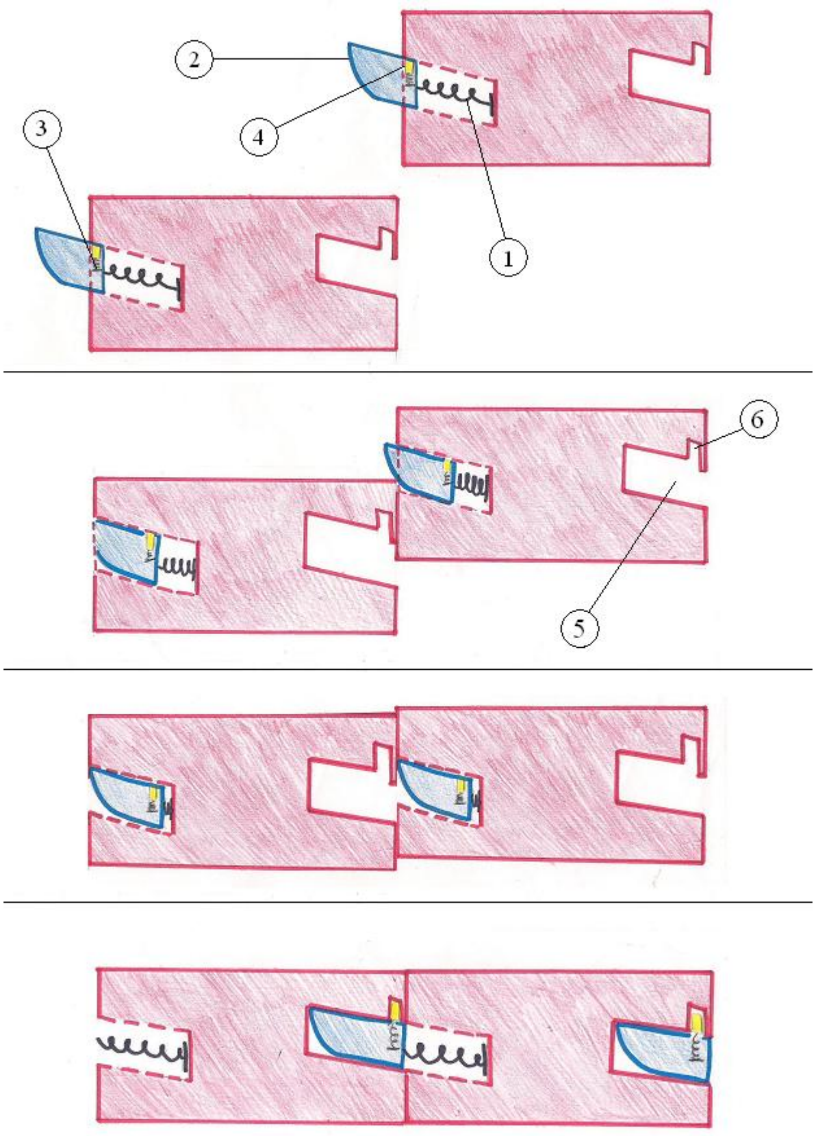


FIGURE 13 SHOWS A VISUAL REPRESENTATION OF THE STAGES DURING LATCHING FOR THE DOUBLE SPRING DESIGN

This design (shown in figure 13 to the right) implements the use of two springs as the means to the latching between panels. There is one large spring (1) contained within the cross section of each panel. This spring is connected to a piece of material (2) that is designed with a curved bottom and a flat top. Within this material is a smaller spring (3) connected to a smaller piece of material (4) that is rectangular in shape. The smaller spring (3) is initially fully compressed while the larger (1) remains uncompressed in its stowed position. Once the panels have completed their path of rotational motion, they will move downward to find a final, level position. As two panels come together at a time, one side of the lower stationary panel will essentially be pushing along the curved bottom of the piece of material (2) which is exposed on the opposing side of the moving panel. This will force the larger spring (1) to compress and the exposed material (2) to submerge within the panel's cross section. The material (2) will continue to be pushed until the larger spring (1) reaches its fully compressed state. This mechanism is designed so that once the surfaces of the two panels are flush, the large compressed spring (1) and material (2)will meet an opening (5) and no longer have a force to maintain its compressed state. It must then be released, and the material (2) will be moved into the opening of the opposite panel beside it (5). As it is inserted, the smaller spring (3) is designed with the same intentions as the larger, only releasing in an upward direction. There is a small slot (6) within the larger opening (5) on the side of the panel that will hold the smaller piece of material

(4) once the smaller spring (3) is released. The larger spring assembly is used to restrict vertical motion, while the smaller spring assembly restricts horizontal motion, thus providing a final, flush position between panels.

The benefit to this design is its security. Once the panels have reached their fully deployed positions, the interlocking provided by the spring assemblies will lock and hold them together. However, this design is non reversible. Additionally, with numerous moving parts the chances of failure are increased due to the complexity of design. The material selection would also be limited to those stiff enough to support the force of the large spring against the thin panel wall without failing.

Mechanical Concept 4: Ring and Latch Design

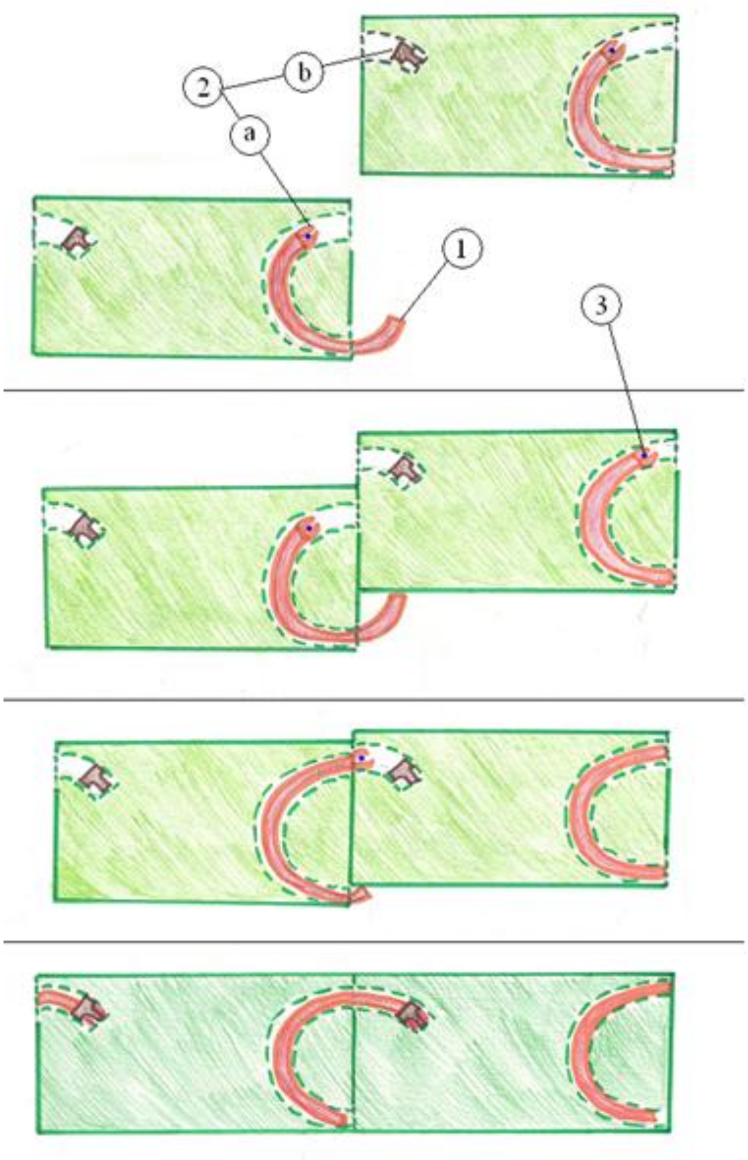


FIGURE 14 SHOWS THE RING AND LATCH DESIGN IN DIFFERENT STAGES DURING THE LATCHING OF THE MECHANISM

This design (shown in figure 14 to the right) incorporates a ring (1) and a latch assembly (2ab) to hold the panels together. Within the cross section of each panel is a ring (1) that is partially exposed on one side. After panels are rotationally flush, they begin to move downwards. Due to their offset vertical position relative to one another, the process of aligning panels happens as the panels meet and latch together one at a time, with a brief period of time in between connections. In focusing on two panels at a time, it can be modeled as one panel moving downwards towards a lower, stationary panel. At this point the panels are rotationally flush, and as they come together the moving panel will come in contact with the semi-exposed ring (1) contained within the other panel. The downward force of the moving panel will, in turn, cause the ring (1) to rotate within the other panel. As rotation continues, the ring will circle back around to an opening in the first moving panel. The moving panel is essentially pushing the ring (1) through the other panel and back into itself. This panel must exert enough force to both move the ring (1) and then engage the latching mechanism (2ab). The latching mechanism consists of two parts. The first half (2a) is located on the upper end of the ring (1). It consists of two pieces of material that are held together using an uncompressed spring (3). The second half of the latching mechanism (2b) rests inside the opposite end of the panel. It is designed with intentions of the first half of the mechanism (2a) to fit, but only when the spring (3) is under compression. Thus, the panels must be exerting enough force on the ring (1) to rotate it and, in turn, produce enough force so when both ends of the latching mechanism (2ab) come together, the spring (3) on the first half (2a) will compress and slide through the second half (2b). The second half (2b) is also designed so that when the first half (2a) reaches a certain point, there is no longer any compression on the spring (3) and it can return to its uncompressed state, remaining locked in place.

The benefit to this design is its security. Once the two pieces of the latching mechanism (2ab) have interlocked, there are no forces acting inside of the panels to recompress the spring (3) and release it from its fastened state. However, this design is not reversible and the dependency on the force of the panels to rotate the ring (1) increases the chance of failure. Also, the force that is being exerted on the ring (1) is dependent on the angle of contact between the panel and the ring (1). This angle is constantly changing due to the rotation of the ring and is, in turn, changing the force the panel is exerting. This fluctuation increases the chance of snag which increases the chance of failure.

2.2.2 Magnetic Concepts

Permanent, rare earth magnets offer the unique capacity to engage and apply an active retaining force with no moving parts. While they have not been proven for use in interstellar applications, the technology seems strikingly well suited for the application.

Magnet Concept: Magnet Design

This design uses magnets to lock the panels together. The magnets are a cheap way to unite the panels once deployed without having any worries of mechanical failure. When reversing the operation to bring the panels back to a stowed position, the force of the magnets will have to be overcome by the hub. As a result, the magnets cannot be too powerful for the reversible prototype.

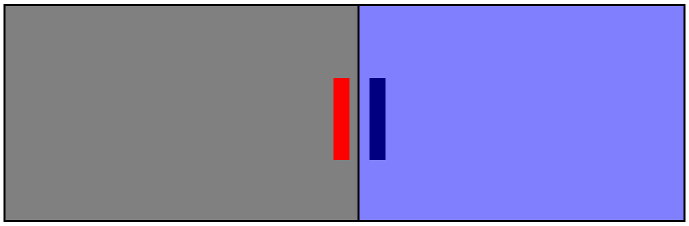


FIGURE 15: CROSS SECTION, SIDE VIEW OF TWO PANELS USING MAGNETS

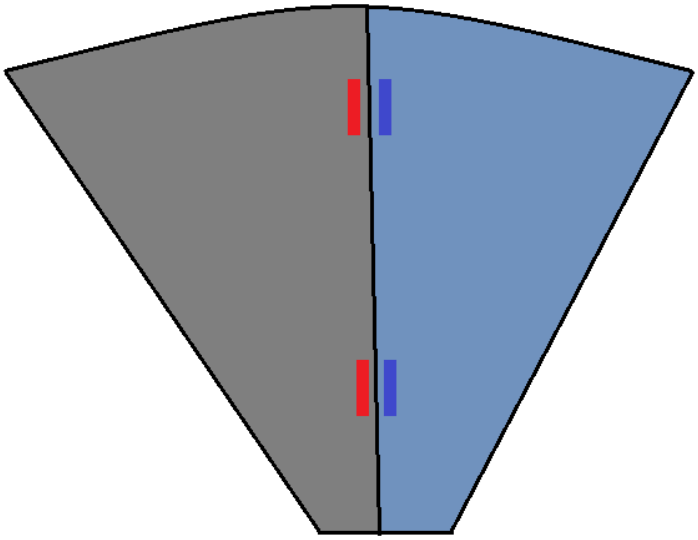


FIGURE 16: TOP VIEW OF TWO PANELS USING MAGNETS

2.2.3 Cable Concepts

An obvious concern of employing cables for support, electrical current, or any other reason, is that the cables are likely to get caught, snag, or otherwise impede deployment. Tension must be carefully controlled by a motor and spool or other mechanism, as over or under tensioning would likely result in failure. Never the less, the potential for a single spooling unit to apply tension across a many areas of the reflector is a feat not closely matched by any other method. The following concepts are a selection of characteristic cable implementations.

Cable concept 1: Guyline

Tensioned guylines are used to restrict movement of a structure beyond a certain point. They are commonly employed to increase the effective base of a collapsible or portable structure while only nominally increasing the stowed footprint.

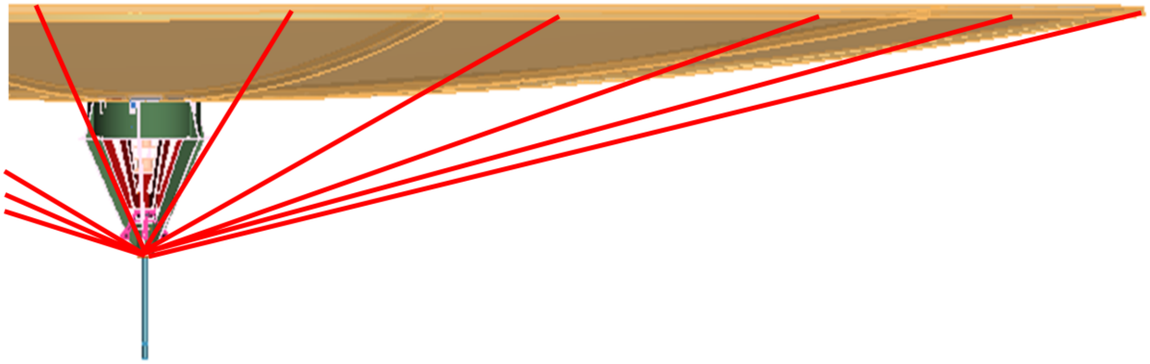


FIGURE 17: GUYLINE CABLE CONCEPT

The figure illustrates a side view of a potential guyline implementation. The guyline cables (red) run between the hub assembly and the outer edges of each panel. This concept will require slack cable to accommodate the stowed position of the reflector, necessitating some means of tensioning the cables either during or after deployment. A tensioner of some kind will be necessary for all cable implementations. The tensioner may feasibly be incorporated into the hub assembly, which would increase the functionality of the hub motor.

Compared to alternate cable implementations, this guyline concept requires less cable, meaning less potential for cable snag. Guylines may be particularly well suited for applications where the reflector is expected to experience high forces, such as would result from a wind gust.

Cable Concept 2: Shoelace

The shoelace concept consists of slots along the edges of each panel (dark red). A cable (red) passes through a slot on one panel and then through a corresponding slot on the mating edge of the adjacent panel. The cable continues in this fashion, passing back and forth from panel to panel through mating slots along the length of a panel-panel seam. The concept could be implemented with a single cable that skips to the next seam after running the length of the panels, or multiple cables could be employed, one per seam.

The image shows two stages of deployment with a shoelace interlocking cable. The right-most panel-panel seam is in the deployed configuration, while the zigzag of cable to the left illustrates the path of the cable during deployment.

The unique quality of such an interlocking mechanism is that in addition to securing the panels in their deployed configuration, the shoelace cable can be tensioned during deployment to assist with deployment and ensure appropriate positioning. As the cable is tensioned, the mating slots on adjacent panels will be pulled together. This differs from a buckle mechanism for instance, where the hub assembly alone must bring the panels into alignment such that the mating features of the buckle meet precisely. The buckle clasp were to miss, they mechanism would not engage and the reflector would not be considered to have successfully deployed. Such a cable implementation could be advantageous for implementations where alignment is complicated by the panels sagging out of place as by gravity.

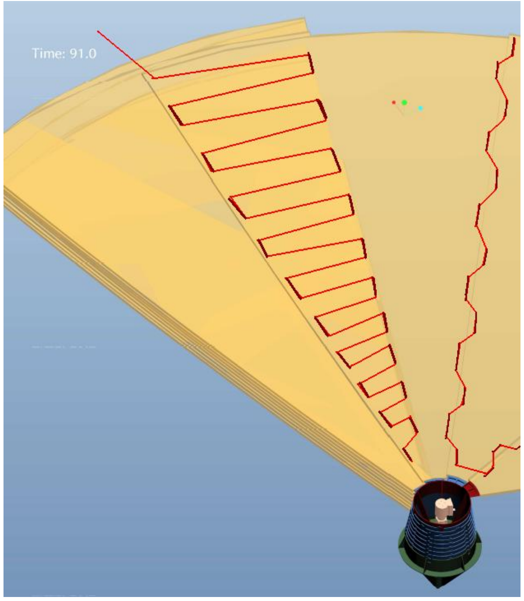


FIGURE 18: SHOELACE CABLE CONCEPT

Cable Concept 3: Ring Tensioner

The final cable concept is an adaptation of the shoelace. Here, a cable makes a single pass around the deployed reflector. Much of the benefits of the shoelace are achieved while drastically reducing the total length of cable required to achieve a stowed position.

The top right of the image shows a 90% deployed panel-panel seam. Mating rings from adjacent panels are nearly aligned, awaiting only the horizontal hub motion that will bring the panels into a single contiguous plane. Along the left edge of the image are the radial edges of two panels with the ring tensioner cable in the "zigzagged" or stowed position; notice that the cable must run approximately 2x the length of the radial edge to correctly pass through the rings.

A variation of this concept would be to mount the rings along the back surface of the panels. Doing so could mitigate risk of the cable catching on the corners of the panels, as well as reducing the total length of required cable.

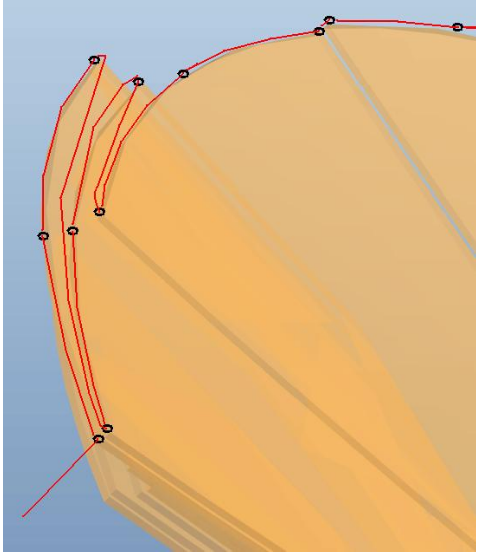


FIGURE 19: RING TENSIONER CABLE CONCEPT

2.2.4 Other Concepts

This section contains concepts not directly applicable to the categories previously established.

Other Concept 1: Solenoid Design

This concept utilizes the common plunger solenoid. By sending an electrical current into a solenoid, the plunger deploys into the adjacent panel where a hole is located. The plunger will secure the two panels together. Using solenoids will require that the mechanism has a source of power, which can be a drawback compared to other designs that do not require power. However, the strength of the connection may be more important than the inconvenience of needing power.

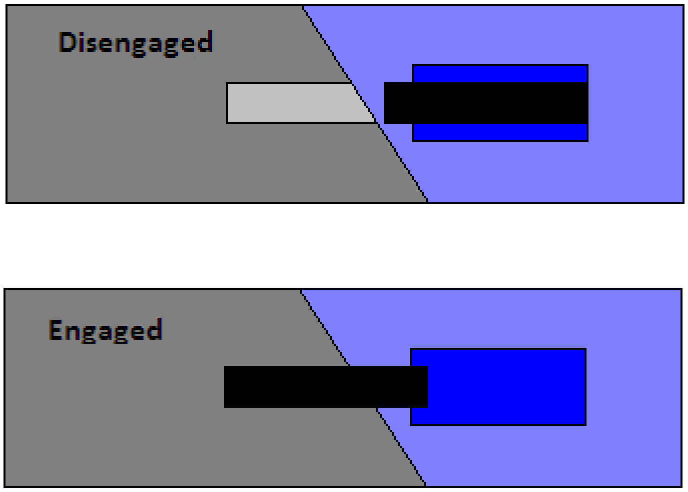


FIGURE 20: CROSS SECTION, SIDE VIEW OF TWO PANELS USING SOLENOID DESIGN

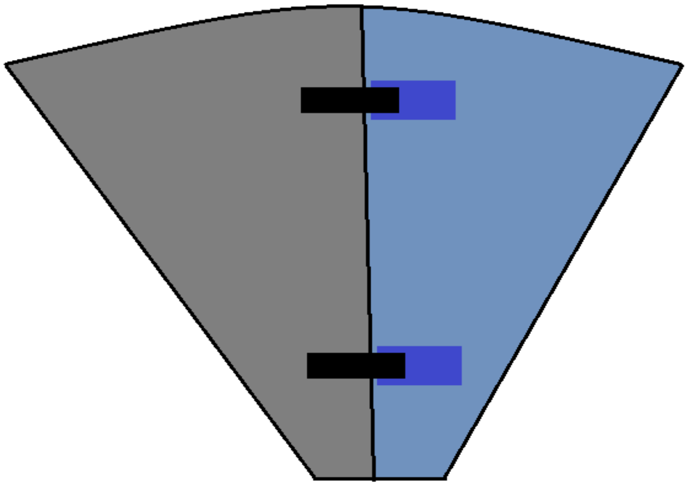


FIGURE 21: TOP VIEW OF TWO PANELS USING SOLENOID DESIGN

Other Concept 2: Magnet and Pin Design

This design utilizes a pin (1) and three magnets. One magnet (2) is located within the neck of the pin (1) while two others (3) act as a latch. This magnetic latch (3) is connected onto the base of the panels by hinges (4), essentially acting as a door. For each panel, the pin (1) rests at the base of one side of the panel, while the magnetic latch (3) is located at the base on the opposite side of the adjacent panel. As one panel moves downwards, its pin (1) and the latch (3) on the stationary panel beside it are designed to come into contact with one another. The pin (1) will use the force exerted by the moving panel to overcome the restriction of the latch (3). As the panel continues to move down, the latch (3) will continue to open until it surpasses a maximum point and the latch doors (3) are no longer in contact with the pin (1). At this point, the latch (3) will return to its initial position, only now all three magnets (2 and 3) are aligned and the pin (1) of one panel is contained within the magnetic latch (3) on the opposite adjacent panel.

This design is beneficial in that it is reversible. However, the design also uses the panel's downward movement as a latching force, as opposed to solely using the motor to connect the panels. This adds extra stress to the panels and increases risk of failure.

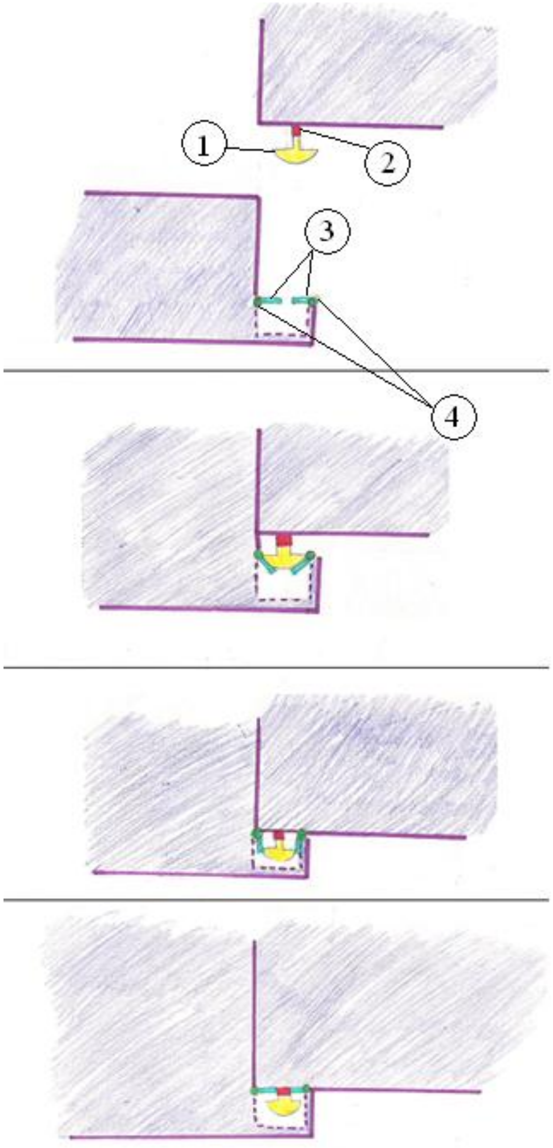


FIGURE 22 (ABOVE): MAGNET AND PIN DESIGN AT DIFFERENT STAGES DURING LATCHING

FIGURE 23 (BELOW): ALTERNATIVE DESIGN OF A NON MAGNETIC MINI TOUCH LATCH

This particular design can be altered in both the contour of the panels as well as the latching mechanism. For example, instead of using magnets a non magnetic mini touch latch (seen in figure 12 on the right) could be used to replace the pin (1) and magnets (2 and 3).

2.2.5 Comments – Omitted Concepts

Of all the concepts generated, some novel ideas were simply deemed unfeasible for this stage of development. In future efforts, these concepts may be worth reconsidering.

Actively Engaging Mechanical Latch

The security and strength of connection is unparalleled by mechanical latches. With this design approach, the force required to engage such a latch is supplied by an external source. This source might take the form of individual motors at each latching site, or a gearing system that couples multiple latches. Development of this concept was discontinued due to the volume/space requirements, and the intricacy which resulted in a drastic increase in failure modes.

Spring/Roller Assisted Cam Latch

This concept incorporated a standard spring/roller with a "C" shaped cam unit. A deploying panel would push the bottom of the C-cam down as the panel collapsed vertically. Once the spring/roller past a particular contour on the cam, the spring force would be applied in such a way as to force the top of the C-cam over on to the deploying panel. In this manner, an interlocking device is achieved that is passively engaging, actively retaining, and mechanically latching, all without requiring external power to augment the force supplied by the panel motion. It was decided that the force a panel would be able to apply to engage the cam would likely be insufficient, and that the space required for the cam's rotation could not be accommodated by the panel spacing.

2.3 Concept Selection

2.3.1 Concept Selection Introduction & Methods

In order to evaluate concepts, a selection criterion is necessary. Since one of the main needs of this system is to autonomously deploy in space, reliability is very important. System failure is a waste of money and resources. Another important factor to consider is the security of the panel to panel connection. The panels are meant to be for a solid reflector, any gapping or separation of the panels is a design failure. Other important attributes the concepts will screen include: reversibility, complexity, and price. Detailed descriptions of each selection criterion are found in section 2.3.2.

The best method of evaluating each concept is to develop a trade matrix based on the selection criteria. A weighted ranking system is used to determine the importance of the criteria and a score is given to the concept based on its ability to satisfy that criteria. The total score for each concept is summed up to give a total that can be used to compare designs against each other. A trade matrix for each design can be found in section 2.3.3.

2.3.2 Selection Criteria

- Alignment Criteria
  - **(1) Engagement Proximity**
    - This is the minimum distance the panels must travel before the interlocking mechanism can engage.
  - **(2) Engagement Force**
    - This is the force required to engage the interlocking mechanism once the panels are within the minimum *engagement proximity*. A negative force represents attraction, such as would be experienced with a magnetic based mechanism.
- Structural Criteria
  - **(3) Separation Failure**
    - This defines the force required to separate the panel-panel seams once the interlocking mechanisms have engaged.
  - **(4) Stability**
    - Resistance to flexure after deployment, such as would be caused by acceleration of the assembly. Hypothetical sources include gravity for ground applications, and post deployment repositioning of a satellite for space applications. Stability also encompasses dynamic stability and vibration dampening.
- Implementation Criteria
  - **(5) Reversibility**
    - The ability of the reflector to collapse into the stowed position after deployment. An autonomously reversible reflector would be ideal for many ground applications, but is outside of the project scope where the primary consideration is for spaced based applications. Demonstration of the prototype, however, will require assisted separation of the panels, and the final design must take this into consideration.
  - **(6) Complexity**
    - Intricate designs will incur increased costs for production, and increase potential sources of failure. The simplest possible solution that satisfies the all criteria should be favored.

2.3.3 Trade Matrix

		Double Spring		Ring and Latch		Magnet & Pin		Solenoid		Flat Plate	
Specifications	Weight Factor	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Reliability											
Engagement Proximity	0.15	3	0.45	3	0.45	3	0.45	4	0.6	4	0.6
Engagement Force	0.15	2	0.3	2	0.3	3	0.45	4	0.6	3	0.45
Secure											
Separation Failure	0.1	5	0.5	5	0.5	4	0.4	5	0.5	3	0.3
Stability	0.1	4	0.4	4	0.4	3	0.3	4	0.4	3	0.3
Gapping	0.1	3	0.3	4	0.4	4	0.4	4	0.4	2	0.2
Reversibility	0.2	0	0	0	0	4	0.8	5	1	5	1
Complexity	0.1	2	0.2	3	0.3	4	0.4	4	0.4	5	0.5
Price	0.1	4	0.4	4	0.4	4	0.4	4	0.4	5	0.5
		Total:	**2.55**	**Total:**	**2.75**	**Total:**	**3.6**	**Total:**	**4.3**	**Total:**	**3.85**

		Cup and Cone		Magnet		Guyline		Shoelace		Ring Tensioner	
Specifications	Weight Factor	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Reliability											
Engagement Proximity	0.15	4	0.6	5	0.75	4	0.6	4	0.6	4	0.6
Engagement Force	0.15	4	0.6	5	0.75	4	0.6	4	0.6	4	0.6
Secure											
Separation Failure	0.1	4	0.4	5	0.5	3	0.3	4	0.4	3	0.3
Stability	0.1	4	0.4	4	0.4	3	0.3	4	0.4	4	0.4
Gapping	0.1	5	0.5	4	0.4	3	0.3	4	0.4	3	0.3
Reversibility	0.2	5	1	5	1	3	0.6	2	0.4	2	0.4
Complexity	0.1	5	0.5	5	0.5	3	0.3	2	0.2	2	0.2
Price	0.1	5	0.5	4	0.4	4	0.4	3	0.3	4	0.4
		Total:	**4.5**	**Total:**	**4.7**	**Total:**	**3.4**	**Total:**	**3.3**	**Total:**	**3.2**

FIGURE 24: SHOWS THE DECISION MATRIX AND SPECIFICATIONS USED TO RANK THE 10 PROPOSED DESIGNS IN ORDER TO QUANTITATIVELY COMPARE THEM AGAINST ONE ANOTHER

2.3.4 Concept Selection Conclusion

By using a trade matrix, it is apparent that the top three design concepts are solenoids, cup and cone, and magnets. In order to optimize the strengths of the designs, it was decided to combine a coupling mechanism (cup and cone) with magnets for increased security. Solenoids were not chosen for a final design due to the requirement of power which would complicate the design of the panels and lead to a risk of failure during deployment.

A cup and cone coupling mechanism allows the panels to deploy in the correct position. The addition of magnets will secure the panels in their positions once deployed and maximize security of the panel to panel connection. The combination of these two concepts has a very low chance of failing since all parts are passive and can be used for indefinite cycles of operation.

As a team, our task is to develop a working prototype to meet our sponsor's needs. The use of our coupling mechanism with magnets will allow us to test with many different magnets and give our sponsor feedback about the feasibility of possible use of magnets in space. In addition, the prototype will be highly modifiable, so any changes or additions to the design will be possible.

Section 3 – Results

3.1 Final Design

3.2 Fabrication and Assembly

3.1 Final Design

3.1.1 System Description

The chosen latching mechanism incorporates the use of a kinematic coupling component (cup and cone) along with magnets. The cup and cone design was chosen because it provides a means of helping guide the panels to their final, intended locations. Once the panels have finished their rotational course of motion they will then transition to a linear phase of motion. Even the most minimal radial misalignment before this linear phase of motion drastically increases the chance of failure of the latching mechanism to engage. By using cups and cones, the design accounts for a small range of potential misalignment. In the case that the panels are not in their intended positions after the first phase of motion, incorporating the kinematic coupling component into the second phase of motion will then guide the panels to their precise location.

The cup and cone design was implemented to further ensure each panel reaches its intended fully deployed location. Magnets were incorporated into the cup and cone design so that once the panels have reached this location, they are kept there. The magnets and cone, which is made of ferrous material, will create an attraction and hold the panels in a compressive state. Thus, by incorporating the cup and cone as well as the magnets into our design, we are ensuring that the panels reach their final predetermined location and are held there with a significant amount of force so as not to separate.

3.1.2 Discussion of Components

The final design selected utilizes a kinematic coupling component in addition to magnets. Aluminum 6061 brackets, seen below in figure 25, will be implemented along the edges of the bottom of the panels provided to us by Harris Corporation. These will be used in order to increase the stiffness of the panels as well as create a better structural connection to both the hub and the latching mechanism.

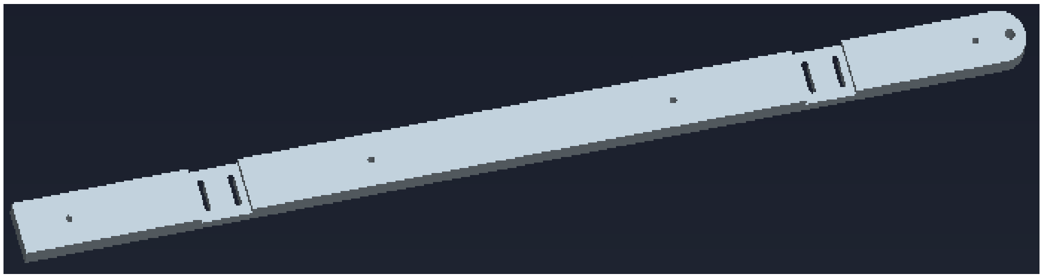


FIGURE 25: SHOWS THE ALUMINUM 6061 BRACKET THAT WILL BE APPLIED ALONG THE EDGES OF THE BOTTOM OF THE PANELS

Two of these brackets will be connected to the underside of each of the 6 panels. There will be four connections of the bracket to the panel, and the larger hole connection (seen all the way on the right in figure 25 above) will be used to connect the bracket to the hub. Connected to these slots are two aluminum 6061 armatures which can be seen below in figure 26.

FIGURE 26: SHOWS THE ALUMINUM 6061 ARMATURE WHOSE BOTTOM LEVEL WILL BE CONNECTED TO THE PANELS AND UPPER LEVEL WILL BE HOLDING THE CONE

These armatures will be connected to the slots of the brackets. The slots allow for adjustment in the final prototype in the case of misalignment. The armatures are used as supports for the cone in our kinematic coupling design. Two armatures will be fastened to the slots of the aluminum bracket using nuts and bolts. While 4 of the 6 panels will each have 2 cups and 2 cones on opposite edges, due to the nature of deployment, the first panel to reach its final position will be composed of 4 cups. Similarly, the last panel to reach its fully defined configuration will be composed of 4 cones. The cone that the upper level of this armature is supporting (seen below in figure 27) is a truncated sphere and is made of steel.

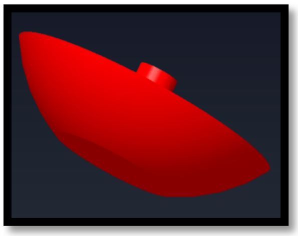


FIGURE 27: THE CONE THAT WILL BE USED IN THE KINEMATIC COUPLING DESIGN

Steel was chosen because it is a ferrous material and the cone and magnets are implemented into this design to hold the panels in their final configuration.

The first panel to reach its final position consists of 4 cups. An image of these cups can be seen below in figure 28.

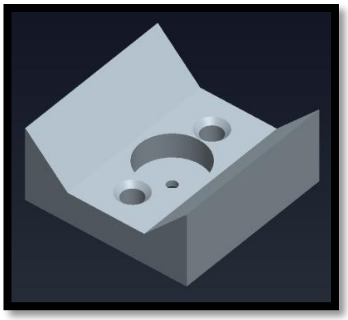


FIGURE 28: THE V-BLOCK (CUP) THAT WILL BE USED IN THE KINEMATIC COUPLING DESIGN

Once the first panel is in its final position, a second panel will then be in its linear phase of motion, moving towards the first panel. The armature is designed to hold the steel cone just off the edge of the second panel. Its geometry is designed so that as the second panel linearly approaches the first panel, the cone on the moving panel will find the cup on the stationary panel. The V-block design of the cup is very important, as it made to help guide the cone to its exact position. Once the cone has been guided into the V-block, the second panel should then be in its defined location. The larger, middle hole seen in figure 28 of the V-block above is where the magnet will be located. A picture of the magnet intended for our design can be seen below in figure 29.

FIGURE 7

It is a grade N42 neodymium magnet and has an approximate magnet pull force of 6.5 lbs. This means that if this magnet were connected to a flat steel plate, it would take a 6.5lb force (approximately 29 Newtons) acting perpendicular to this surface to pull the magnet from the plate.

Once the cone has found the V-block and been guided to its precise location, the attraction between the magnet and the cone will then hold the panel in this location. In this state, the second panel is then connected on one side, while the other end of the panel remains unconnected and consists of two cups. This can be seen below in figure 30.

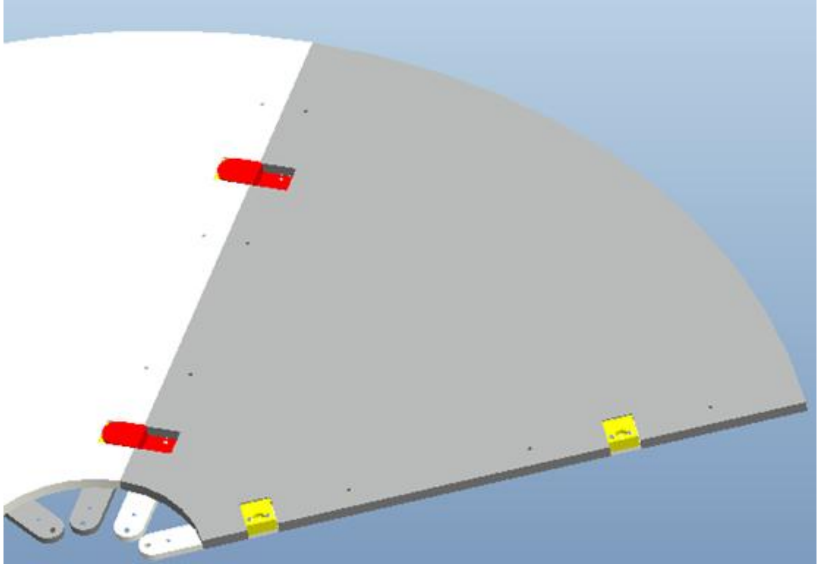


FIGURE 30: SHOWS AN ASSEMBLY OF TWO PANELS. THE PANEL ON THE RIGHT IS CURRENTLY UNCONNECTED, SHOWING TWO CUPS (YELLOW) FOR THE TWO CONES ON THE NEXT PANEL (NOT SHOWN) TO CONNECT TO

The red components in figure 30 above are the armature-cone configuration and the yellow components are the cups. As the second panel is now in its defined location, the third panel will then be in the linear phase of motion, where the two cones on its side will be moving towards the two open cups on the second panel. This process will continue to repeat itself through the fifth panel finding its final position. The only difference in the connection of the sixth panel is that its design incorporates four cones and no cups. The first panel having four cups and no cones is, essentially, what makes the overall connection of all six panels possible.

3.1.3 Pros and Cons Discussion

The simplicity to this design is one of its appealing features. The panels themselves move but contain no additional moving parts as all of the components added onto the panels are securely screwed, bolted, or connected by an adhesive. Previously debated designs contained cables and additional moving parts, which increased the risk of failure of the design. This final chosen design has eliminated these increased potential failures. Additionally, in choosing magnets as the latching device, we no longer depend on the panels to exert a force in order to engage the latching mechanism. Instead, we will be utilizing the force that these magnets create to hold them in their final position, taking those potential additional stresses off of the panels. In this design the panels will reach their final state and the magnets will exert a force to compressively hold them there. Other design candidates not incorporating magnets would have no forces to keep them in their retained state.

Although this is the best design there are still a couple of draw backs. The unexplored use of magnets in space applications means that extended experimentation of the magnets for this design will be necessary. Additionally, magnets have temperature limitations. Depending on the material they are comprised of, they have a maximum temperature for which any temperature exceeding its value will demagnetize the magnet. This is a very important aspect of design that we must take into consideration. Lastly, our design utilizes the forces between the magnet and cone to hold the panels in their final configuration. A mechanical latching mechanism implemented into the design in the case that this attraction is compromised would enhance our design, however there is no such mechanical device incorporated into it at this stage.

3.1.4 Stress Analysis

The prototype proposed is not intended to be loaded beyond the weight of materials and forces applied in handling during assembly, operation and transportation. The team has identified the connection between the support brackets and the hub as the most likely component to fail due to yielding. High stresses are expected to result in this region as a result of the relatively great length of the panels compared to the area used for the hub connection. Therefore, yielding would be expected to occur as a result of a bending moment.

The following is a description of the analysis performed. First, one curved support bracket in modeled as a cantilever beam. The weight of the panel, any hardware, and any forces applied to the area of the panel are represented in the free body diagram by a single point load, P. The load is applied in the direction of maximum reaction moment. The reaction moment and shear force are calculated. Next the stress due to shear and bending at point "A" are calculated. The principal stresses at this point are derived. Finally, the Von Mises yield criterion is utilized to determine approximate yield strength. This value is then checked against a finite element model.

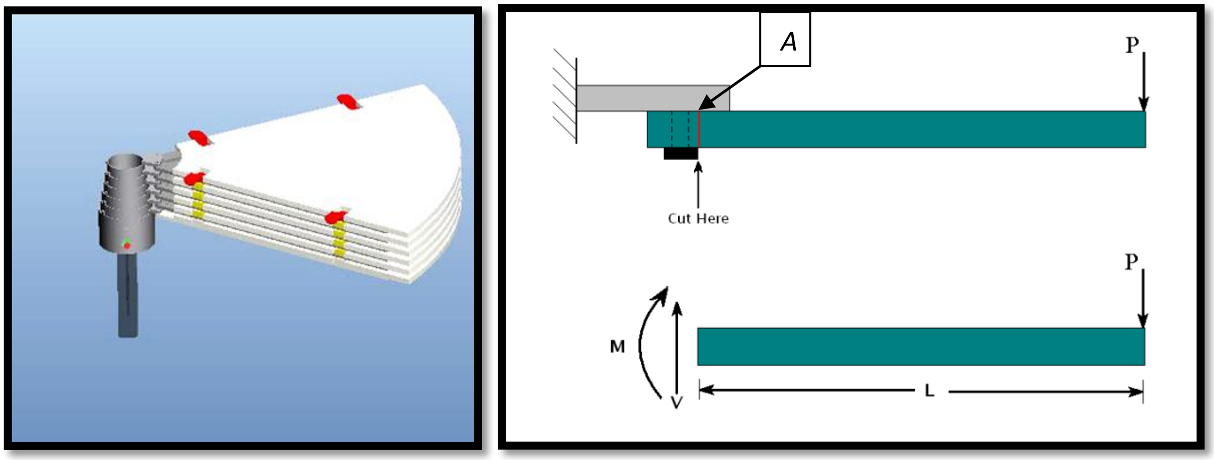


FIGURE 31: SHOWS (LEFT) THE STOWED PANEL ASSEMBLY AND (RIGHT) THE MODELING OF ONE OF THESE PANELS AS A CANTILEVERED BEAM

Applied Load: P
Reactions: M, V
Dimensions: L, A=WxH

The shear stress is given by:

—

The stress due to bending is given by:

Where:

Such that:

The Principal Stresses are given by:

The Von Mises or strain energy density yield criterion is expressed in terms of the principal stresses by:

$$\sigma_v = \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2 + 3\tau_{12}^2}$$

Therefore, the material will yield if $\sigma_v > \sigma_o$, or if the Von Mises stress surpasses the material yield strength in tension.

Substituting approximate dimensions and solving, the Von Mises stress found to be (The mathcad used for this calc is included in appendix ii):

σ_o=11.5 ksi for, L=24in, H=0.25in, W=1in, P=5lb

A finite element analysis (FEA) also predicts stresses on the order of 10-20ksi in this region. The FEA also predicts stress concentrations.

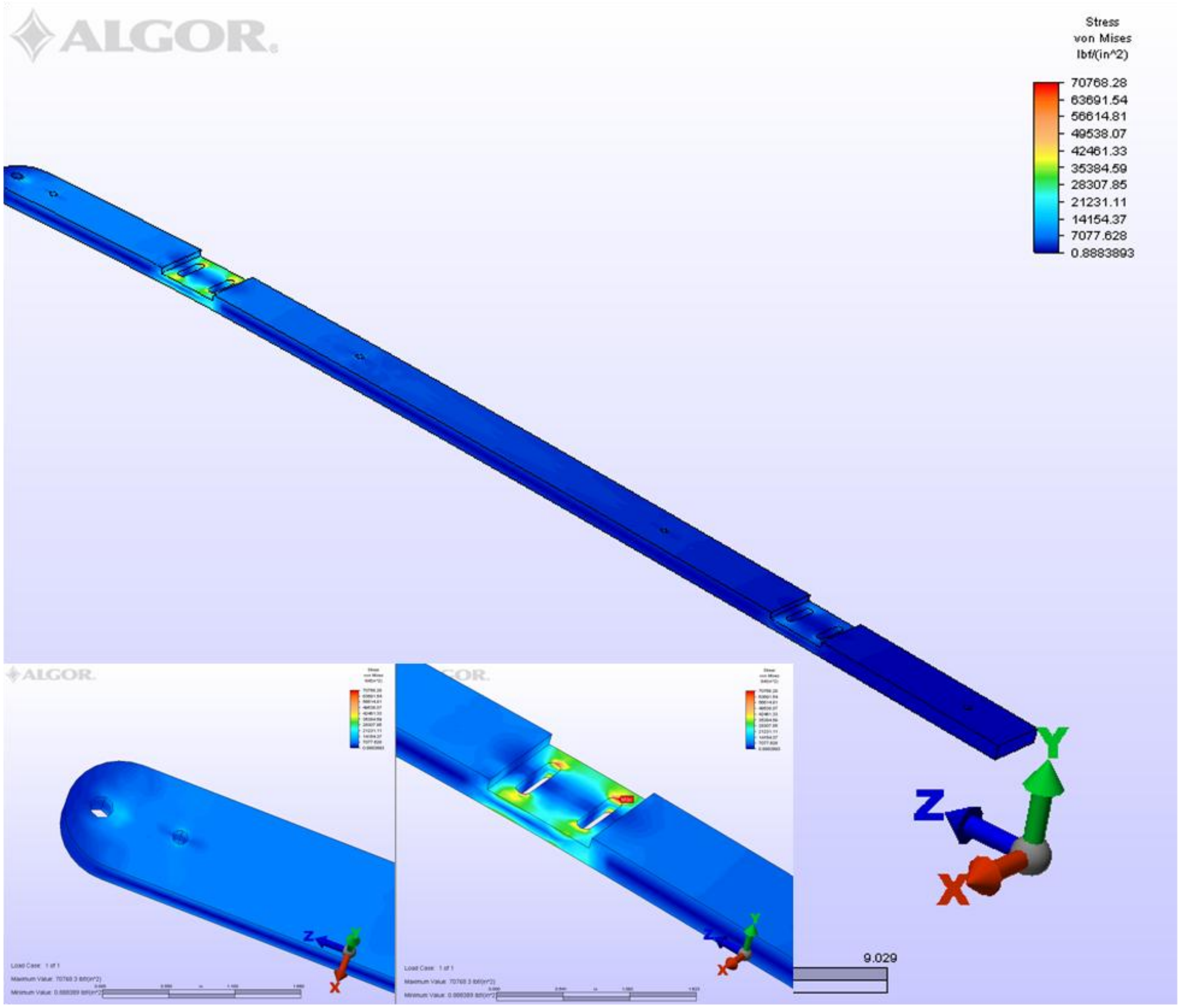


FIGURE 32: SHOWS STRESS PREDICTION IN A FINITE ELEMENT ANALYSIS OF ONE OF THE BRACKETS OF THE PANELS

3.2 Fabrication & Assembly

3.2.1 Materials Analysis and Selection

Function: Panel for Solid Reflector (acts as a beam in uniform loading)

Constraints:

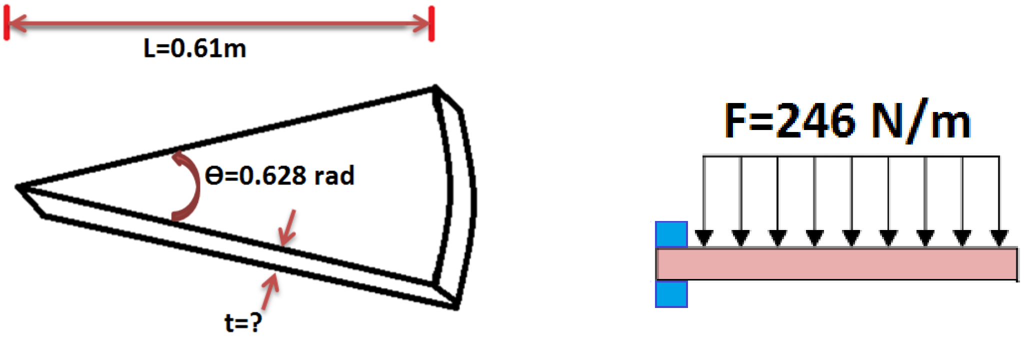


FIGURE 33 – PANEL CONSTRAINTS AND SHAPE. ON THE LEFT IS THE PANEL DIMENSIONS REQUIRED, ON THE RIGHT IS THE LOADING CONFIGURATION SEEN BY THE PANEL. THE PANEL IS LOADED AS A BEAM IN UNIFORM LOADING.

- Must not yield when F=150 N (Distributed force seen by another panel and external forces on panel. Assumed, factor of safety of 1.5).
- Must not deflect more than $\delta=6.1\text{x}10^{-3}$ meters when F=150 N. This value is not strict, but is preferred. If the panels deflect more or less, within reason (±1%), they will still be functional.
- Length of the panel is 0.61 meters.
- Each panel must span an angle of 1.047 radians (6 panels for a total of 360^{o}).

TABLE 1: LISTS THE CONSTRAINTS FOR MINIMIZING THE MASS OF ONE OF OUR PANELS

Constraint	Variable	Magnitude	Units
Force	F	150.0000	Newtons (N)
Length (radius)	r	0.6100	Meters (m)
Deflection	δ	.0061	Meters (m)
Radial span	Θ	0.6280	Radians (rad)

The objective is to minimize the mass of the panel. While minimizing cost is not an objective, it will be something to take note of as we are under a budget for our project. However, performance will not be sacrificed to save money.

Objective: Minimize mass of each panel

The free variables of the panel will be the choice of material and the panel thickness. If the panels become too thick, they will not be useful for connecting to the hub, so this will be looked at when materials are selected.

Free Variable: Material, thickness

The best materials for a light, stiff, strong panel are found by deriving the material index for each constraint. – —— is the equation for elastic bending, taken from Ashby's Appendix B.3. This equation is used to solve for the stiffness material index. Detailed derivation for the material index can be found in Appendix A.

–

—— This material index is for the stiffness constraint (Derived in Appendix A).

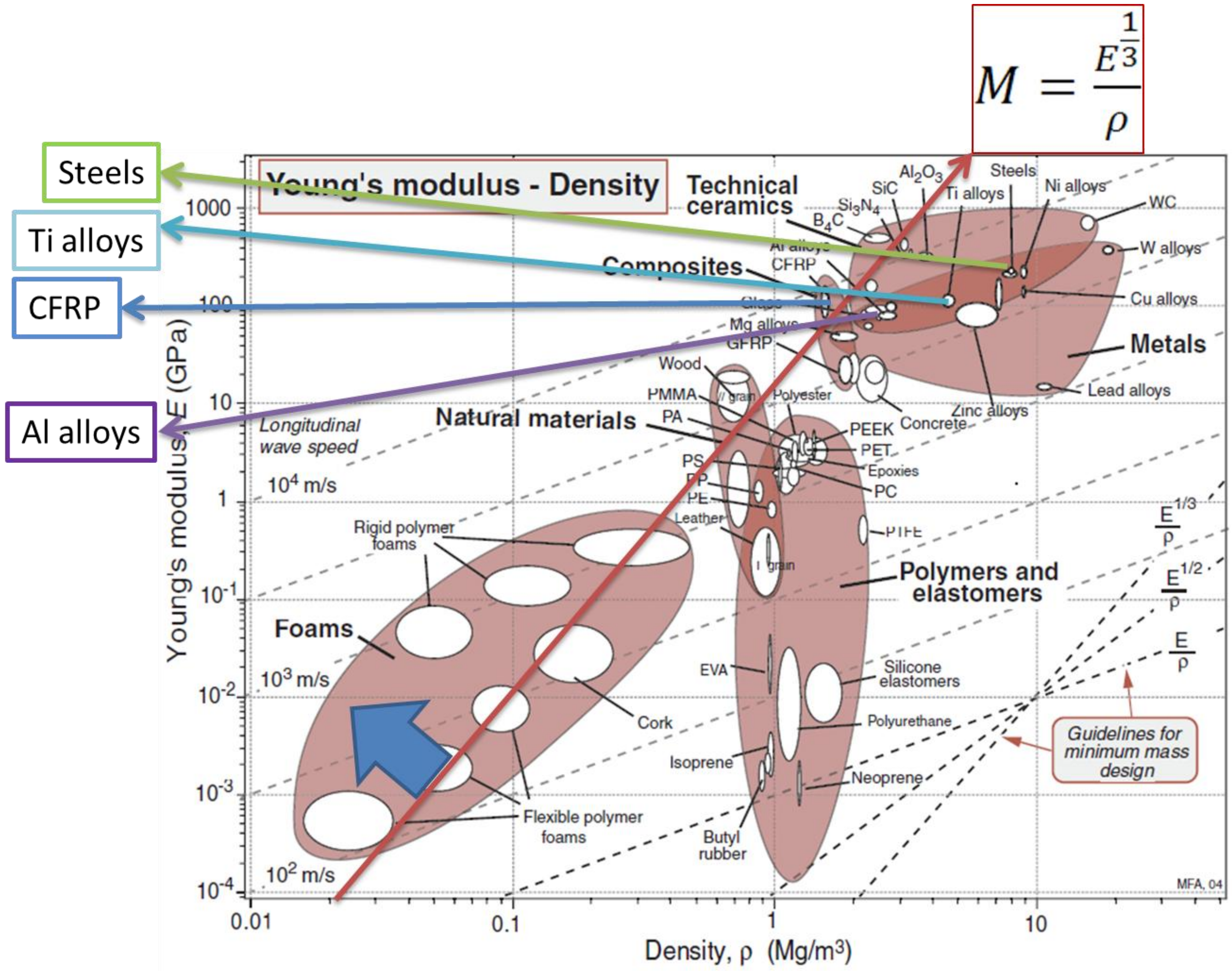


FIGURE 34: SHOWS THE YOUNG'S MODULUS- DENSITY PLOT OF VARIOUS MATERIALS FOR US TO USE IN ORDER TO SATISFY OUR MATERIAL INDEX

Materials to the top left of the material index line are the most ideal for our design specifications. Since the panel will be attached at one end and free at the other, all brittle materials will be ignored due to tension forces. No ceramic materials will be considered. No foam materials will be considered due to the high thickness that would be required for the desired stiffness. As seen from figure 34, steel, titanium alloys, CFRP, and aluminum alloys will be further investigated.

TABLE 2: SHOWS THE DENSITY, ELASTIC MODULUS AND COST FOR THE MATERIAL CANDIDATES FOR A LIGHT, STIFF PANEL

Material	Density (kg/m^3)	Elastic Modulus (GPa)	Cost ($/kg)
Steels	7,850	201-217	0.85
CFRP	1,550	69-150	42.00
Al alloys	2,700	68-82	1.60
Ti alloys	4,600	90-120	70.00

— is the equation for plastic failure of the panel, taken from Ashby's Appendix B.4.

–

—— This material index is for the strength constraint (Derived in Appendix A).

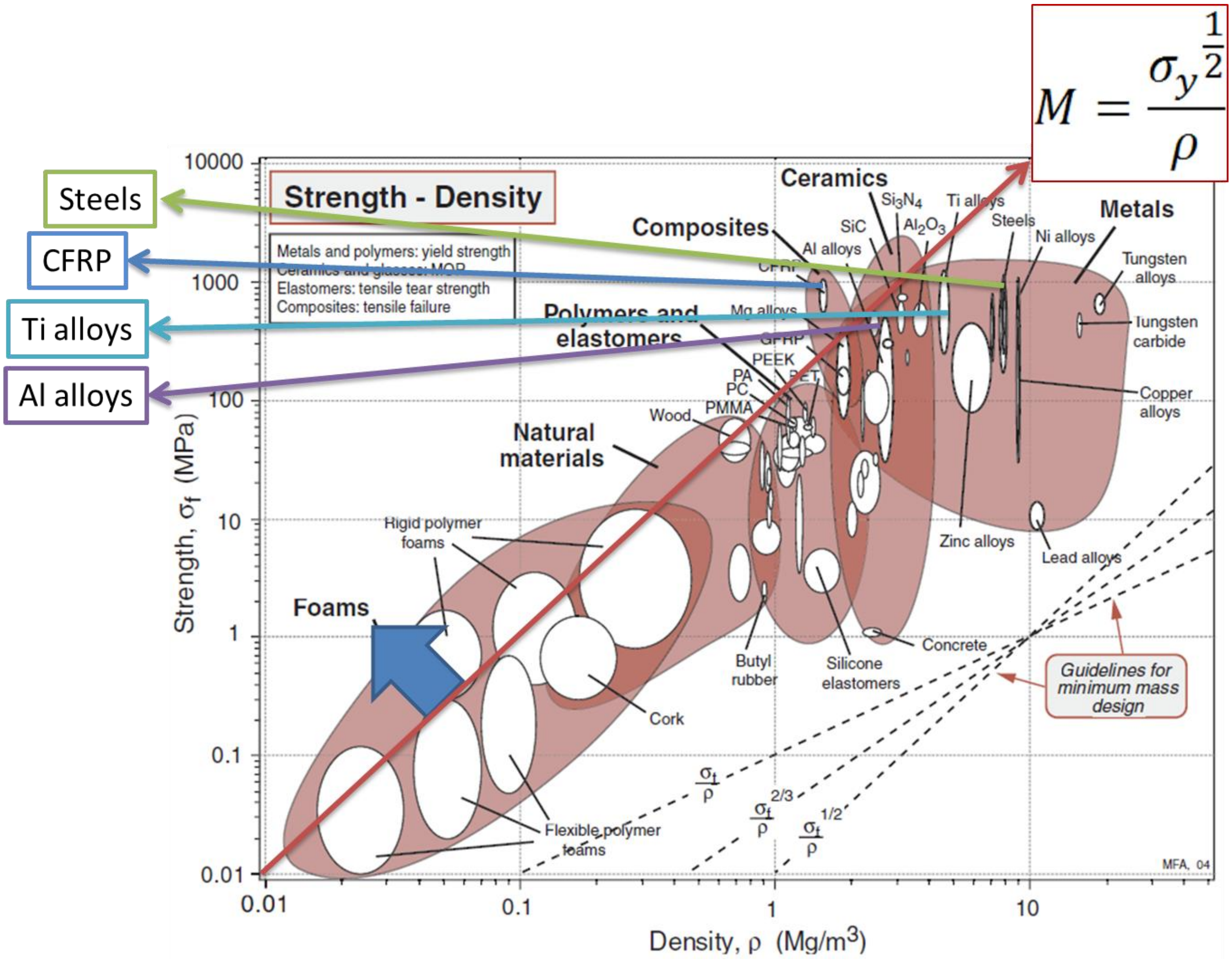


FIGURE 35: SHOWS THE STRENGTH-DENSITY PLOT FOR US TO USE IN ORDER TO SATISFY OUR MATERIAL INDEX

Materials to the top left of the material index line will be most ideal for a light, strong design. As seen in the figure above, the same materials that were stiff are also strong. Steels, CFRP, titanium alloys, and aluminum alloys will be further investigated. Again, brittle materials are neglected due to their sudden failure. Foams are not being considered for the same reasons as mentioned before; the thickness will be too large for the desired strength.

TABLE 3: SHOWS THE DENSITY, YIELD STRENGTH AND COST FOR THE MATERIAL CANDIDATES FOR OUR LIGHT, STRONG PANEL

Material	Density (kg/m^3)	Yield Strength (MPa)	Cost ($/kg)
Steels	7,850	400-1,100	0.85
CFRP	1,550	550-1,050	42.00
Al alloys	2,700	30-500	1.60
Ti alloys	4,600	250-1,245	70.00

To find the best material it is necessary to examine both material indices individually, and then pick a material that is both strong and stiff, while selecting the lowest possible density. A table has been built to show the mass of the best materials that satisfy the constraints.

TABLE 4: SHOWS THE MASS (DUE TO STRENGTH) OF THE BEST MATERIALS THAT SATISFY THE CONSTRAINTS OF STRENGTH

Material	Density (kg/m^3)	Yield Strength (MPa)	Mass due to strength (kg)	Thickness (m)
Steels	7,850	400	1.36	0.0015
Al Alloy	2,700	30	1.71	0.0054
CFRP	1,550	550	0.23	0.0013
Ti alloy	4,600	250	1.01	0.0019

TABLE 5: SHOWS THE MASS (DUE TO STIFFNESS) OF THE BEST MATERIALS THAT SATISFY THE CONSTRAINT OF STIFFNESS

Material	Density (kg/m^3)	Elastic Modulus (GPa)	Mass due to stiffness (kg)	Thickness (m)
Steels	7,850	200	5.51	0.0060
Al Alloy	2,700	68	2.72	0.0086
CFRP	1,550	69	1.55	0.0086
Ti alloy	4,600	90	4.22	0.0079

The stiffness is the limiting constraint in this case, and all the masses for the stiffness design are more than the mass required for the strength design. Because of this, our panels will be stronger than required. To meet the constraint of deflecting no more than 6.1×10^{-3} meters only the mass in the stiffness table will be used.

CFRP is the lightest material that satisfies the stiffness requirement, but aluminum is much cheaper and the mass gained due to cost saved is appropriate for our senior design budget. Due to budget restraints and no loss in performance, aluminum will be chosen as the material for the panel prototype. Due to aluminum's low density, low cost, stiffness, and strength, it will also be used for the cone's armature as well as the v-block. The cone must contain iron to work with the attraction of the magnet; therefore, steel will be used.

TABLE 6: SHOWS THE SIZE AND MASS OF EACH ALUMINUM COMPONENT

Aluminum Parts (Quantity of 1)	Density (—	Elastic Modulus (GPa)	Yield Strength (MPa)	Length (m)	Thickness (m)	Volume (m^3)	Mass (kg)
Panel Bracket	2,700	68-82	30-500	61.00×10^{-2}	6.35×10^{-3}	$8{,}600 \times 10^{-6}$	26.6×10^{-2}
Cone Armature	2,700	68-82	30-500	5.08×10^{-2}	2.54×10^{-3}	4.92×10^{-6}	1.33×10^{-2}
V-block	2,700	68-82	30-500	5.08×10^{-2}	12.70×10^{-3}	18.8×10^{-6}	5.08×10^{-2}

TABLE 7: SHOWS THE SIZE AND MASS FOR THE STEEL CONE

Steel Parts (1 part)	Density (—	Elastic Modulus (GPa)	Yield Strength (MPa)	Diameter (m)	Volume (m^3)	Mass (kg)
Cone	7,850	201-217	400-1,100	25.4×10^{-3}	34.3×10^{-6}	2.69×10^{-2}

3.2.2 Consolidated List of Materials (CLM)

TABLE 8: SHOWS A CONSOLIDATED LIST OF THE MATERIALS REQUIRED FOR OUR DESIGN

Component	Specifications	Vendor	Price per unit	Quantity	Sub Total
Neodymium Magnet	1/8" OD x 1/16" ID x 1/16" thick	K&J Magnetics, Inc.	$0.79 - $3.75	12	$9.48 - $45.00
Cone	Steel	Bal-tec	$9.90 - $31.50	12	$118.80 - $378.00
Aluminum 6061 (Bracket)	1/4" x 1" x 6'	McMaster Carr	$16.02	5	$80.10
Aluminum 6061 (V-block)	1/2" x 1" x 3'	McMaster Carr	$17.23	1	$17.23
Sheet Aluminum (Z-Arm)	0.10” thick, 12” x 24” plate	Speedy Metals	$16.85	3	$50.55
Screws	1/8", Flat Head, pack of 100	Home Depot	$4.65	1	$4.65
Bolts	1/8“, pack of 100	Home Depot	$4.24	1	$4.24
Epoxy	1.7 oz, Clear	The Binding Source, LLC	$15.52	1	$15.52
				TOTAL:	**$300.57 – $595.29**

Table 8 above shows a detailed list of all of the materials we will need for our design. We will be buying aluminum bars and sheets to machine the brackets, V-blocks and Z-arms. We have provided a price range for the cones. The final pricing on this component will depend on the degree of machining incorporated into their design. For example, we can buy solid spheres of steel for $9.90 per unit and machine them ourselves or we can buy spheres that have been truncated and threaded for $31.50 per unit. We want to minimize our overall cost, so buying the solid spheres and machining them ourselves is preferred. However, we are going to consult a machinist before any purchasing of the spheres takes place to inquire how difficult it will be to machine them ourselves to the desired dimensions. In the worst case scenario that they will be too difficult to machine with minimal inaccuracies, we will take the upper limit of their pricing into our total spending. Even in such a case, we fall far below the allotted $2,500 budget. Thus, we have left room open in our budget to potentially purchase and experiment with various magnets.

3.2.3 Fabrication Procedures

Part fabrication process:

TABLE 9: SHOWS METHOD FOR MACHINING OUR BRACKET, ARMATURE, CONE AND V-BLOCKS

Process	**Shape (3D Solid)**	**Mass (1-5 kg)**	**Thickness (5-12 mm)**	**Batch Size (1-20)**
Conventional Machining	**YES**	**YES**	**YES**	**YES**

Bracket, Armature, Cone, and V-block fabrication:

Conventional machining is the best choice for fabrication. Aluminum and steel are the only materials that require modifications and are easily fabricated. Florida State University's machine shops will be used for all part machining. Any other fabrication processes would not be feasible consider the batch size is less than 100 units and our team's access to the university's machine shop is readily available.

3.2.4 Magnet Selection

In selecting the magnets for our design, we focused on permanent magnets. There are four types of permanent magnets

- Ceramic
- Alnico (a combination of aluminum, nickel and cobalt)
- Samarium Cobalt
- Neodymium Iron Boron

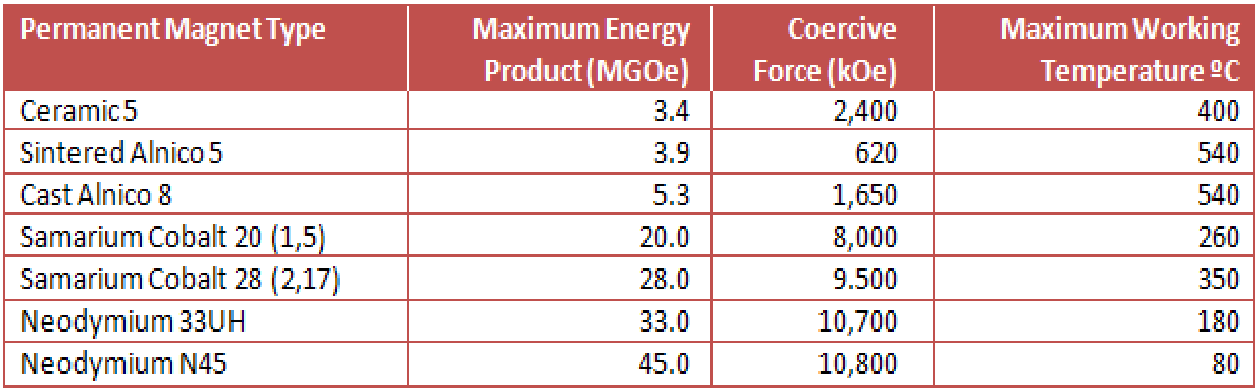
In analyzing these magnets against each other, we focused on three aspects of their design:

- Maximum Energy Product
    - This is the amount of magnetic field passing through a magnet per unit volume
    - It measures the performance of a magnet, the higher the maximum energy product, the stronger the magnet
- Coercive Force
    - This is the amount of force required to demagnetize a magnet
    - It is the resistance of the magnet
- Maximum Working Temperature
    - Also referred to as the Curie Temperature

- A magnet exposed to a temperature above its maximum working temperature will demagnetize

Table 10 below shows values for these three qualities for at least one of each type of permanent magnet.

TABLE 10: SHOWS THE COMPARATIVE CHARACTERISTICS WE USED TO SELECT OUR PERMANENT MAGENT

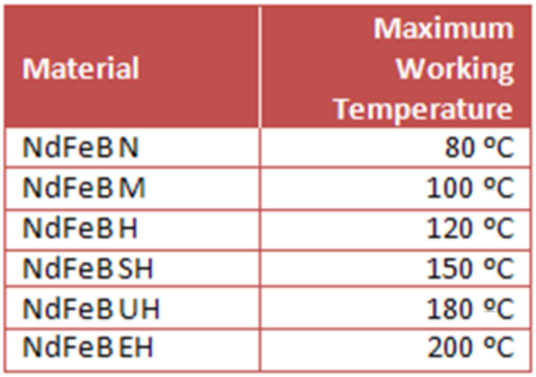


Permanent Magnet Type	Maximum Energy Product (MGOe)	Coercive Force (kOe)	Maximum Working Temperature ºC
Ceramic 5	3.4	2,400	400
Sintered Alnico 5	3.9	620	540
Cast Alnico 8	5.3	1,650	540
Samarium Cobalt 20 (1,5)	20.0	8,000	260
Samarium Cobalt 28 (2,17)	28.0	9.500	350
Neodymium 33UH	33.0	10,700	180
Neodymium N45	45.0	10,800	80

Despite their high maximum working temperatures, ceramic and alnico magnets have a low maximum energy product and coercive force. For that reason we ruled them out as candidates and focused on samarium cobalt and neodymium magnets.

Samarium cobalt magnets possess a high maximum working temperature, energy product and coercive force whereas neodymium magnets possess the highest energy products and coercive forces with only a moderate Curie temperature. Different grades of neodymium magnets possess higher Curie temperatures (as can be seen below in table 11).

TABLE 11: SHOWS THE MAXIMUM WORKING TEMPERATURES FOR VARIOUS TYPES OF NEODYMIUM MAGNETS



Material	Maximum Working Temperature
NdFeB N	80 ºC
NdFeB M	100 ºC
NdFeB H	120 ºC
NdFeB SH	150 ºC
NdFeB UH	180 ºC
NdFeB EH	200 ºC

Both samarium cobalt magnets as well as neodymium magnets are brittle in nature and therefore aren’t strong mechanically. Neodymium magnets are slightly mechanically stronger than samarium cobalt magnets and are more cost effective, delivering higher amounts of energy per unit volume. For these reasons, we selected a neodymium magnet to use in our design.

Temperatures in space are significantly more drastic than here on earth. Since space is a vacuum, heat transfer occurring through space are solely due to radiation. Thus, the exposed temperature of a material in space is dependent on that materials absorptivity and emissivity, along with its orientation to the sun. The magnets incorporated into our design are encased in other materials. Bare metals in space can be coated with a transparent Teflon material, which increases the materials emissivity and maintains its already relatively low absorptivity. In doing so, the exposed temperature of the metals remains in the range of -129 to 120 degrees Celsius. We are only concerned with the upper limit of this temperature range. Neodymium SH, UH, EH and possibly H would all be good candidates to send into space. However, due to the increased price and reduced availability of these types of magnets, we have decided on a neodymium magnet of grade N42. Since we are demonstrating our prototype on earth, the maximum temperature limitation shouldn’t be a factor. By using a neodymium magnet similar to the one we would want to use in space, we aim to get the same results.

FIGURE 8

Figure 36 above shows our chosen neodymium magnet of grade N42. This magnet has an outside diameter of 0.5 inches, thickness of 0.125 inches and a 0.25 inch by 0.125 inch 90 degree countersunk hole in its center to connect it to the V-block in our assembly.

3.2.5 Assembly Procedures

4 of the panels each consist of:

- 2 brackets
- 2 cone-armatures
- 2 cones
- 2 V-blocks
- 2 magnets
- 4 nuts
- 4 bolts
- 11 screws

Of the remaining two panels, one consists of 4 V-blocks and no cones, while the other consists of 4 cones and no V-blocks. The remaining components of the panels are identical to the first 4. Once the provided panels have been connected in sets of 2 using an epoxy adhesive, our new panels can then be assembled. Using the views in figure 37 below as a guide, the procedure of assembly for each of the four identical panels is as follows:

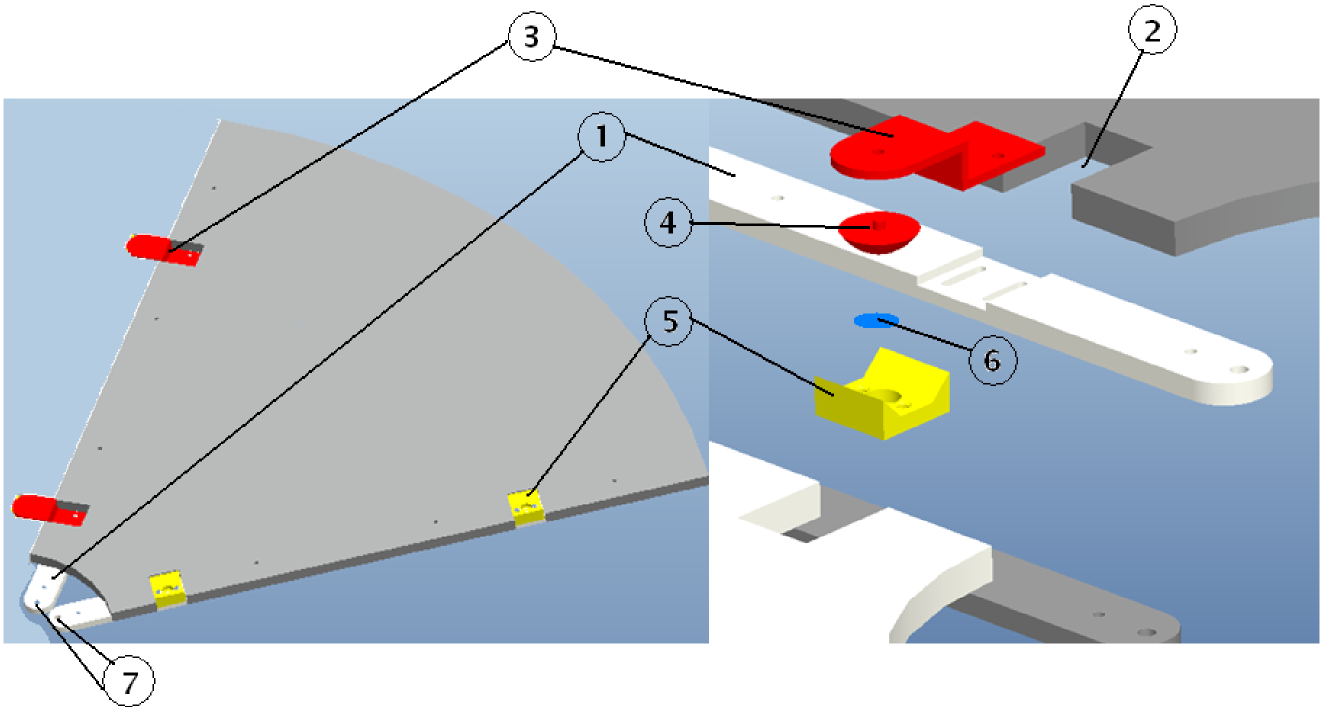


FIGURE 37: SHOWS THE VARIOUS COMPONENTS OF OUR DESIGN. THE COMPONENTS ARE NUMBERED FOR EASIER ASSEMBLY.

1) Connect the brackets (1) to the underside of each panel using three screws per bracket
    - Two brackets per panel on opposing edges
    - Two small sections of material (2) from each opposing edge of the provided panel must be removed to expose the slots in the brackets (1)
        - Four sections of material(2) removed per panel
2) Looking at the left edge of the panel, connect the base of the Z-arm (3) to each of the newly exposed slots on the bracket (1) using 2 nuts and 2 bolts
    - Two Z-arms on left edge of each panel
3) Connect the cone (4) to the upper level of each of the two Z-arms (3) using a bolt
    - One cone (4) per Z-arm
    - Two cones (4) per panel
4) Looking at the right edge of the panel, connect the V-blocks (5) to the newly exposed slots on the bracket (1) using 2 nuts and 2 bolts
    - 2 V-blocks (5) on right edge of each panel
5) Connect the magnet (6) to the center hole in the base of each of the two V-block (5)
    - One magnet (6) per V-block
    - Two magnets (6) per panel

For the first panel (the panel connected to the outermost ring of the hub), which contains four cups and no cones, the procedure is as follows:

1) Connect the brackets (1) to the underside of each panel using three screws per bracket
    - Two brackets per panel on opposing edges
    - Two small sections of material (2) from each opposing edge of the provided panel must be removed to expose the slots in the brackets (1)
        - Four sections of material (2) removed on the panel
2) For both edges of the panel, connect a V-block (5) to each of the newly exposed slots on the brackets (1)
    - Two V-blocks (5) per edge
    - Four V-blocks (5) on the entire panel
3) Connect the magnet (6) to the center hole in the base of each of the four V-blocks (5)
    - One magnet (6) per V-block
    - Four magnets (6) on the entire panel

Lastly, for the last panel (the panel connected to the innermost ring of the hub), which contains four cones and no cups, the procedure is as follows:

1) Connect the brackets (1) to the underside of each panel using three screws per bracket
    - Two brackets per panel on opposing edges
    - Two small sections of material (2) from each opposing edge of the provided panel must be removed to expose the slots in the brackets (1)
        - Four sections of material (2) removed on the panel
2) For both edges of the panel, connect the base of the Z-arm (3) to each of the newly exposed slots on the bracket (1) using 2 nuts and 2 bolts
    - Two Z-arms (3) per edge
    - Four Z-arms (3) on entire panel
3) Connect the cone (4) to the upper level of each of the Z-arms (3) using a bolt
    - One cone (4) per Z-arm
    - Four cones (4) per panel

Once all six panels have been assembled, they can then be connected to the hub using a nut and bolt in the exposed hole (7) on the bracket. There are two connections to the hub per panel.

Section 4 – Testing & Conclusions

4.1 Prototype Analysis

4.2 Conclusions

4.1 Prototype Analysis

4.1.1 Goals of Analysis

The overall goal at hand is to create a working prototype for a solid reflector deployment mechanism. With this prototype we aim to demonstrate the mechanical ability of our latching mechanism to engage during deployment and securely hold our six panels in a final, flush configuration for a prolonged period of time. Once the prototype has been assembled, analysis on the mechanism will take place. From this analysis we aim to:

- Find the minimal load for separation of the panels
- Evaluate the ability of our panels to self align using our kinematic coupling design
- Evaluate and experiment the hold of our chosen magnets
- Evaluate the forces exerted by the panels during deployment

4.1.2 Types of Tests

Testing will begin towards the end of January and continue through February.

Proposed tests

- Finding the minimal load for separation of the panels:
  - Determine the direction of loading and minimum load magnitude required to separate panels
  - Apply a various range of loads (approximately 1 to 5 lbf) to the end of the panels to experiment with their yield strength
- Evaluate the ability of our panels to self align:
  - The slots in the brackets of our design allow for alterations to the positioning of the v-blocks and z-arms
    - Strain panels into misaligned configurations. Determine maximum misalignment direction and magnitude where panels do not realign
- Evaluate and experiment the hold of our chosen magnets
  - Do the magnets securely hold the panels in their intended final positions?
    - Is there any gapping?
  - Approximately how much force needs to be applied in order to separate the panels
- Evaluate the forces exerted by the panels during deployment
  - As the panels are being linearly translated, how much force is each panel exerting?
    - Is this force great enough to engage a mechanical latch?

As experimentation and analysis take place, alterations and modifications to the original design of the latching mechanism may be necessary.

4.2 Conclusions

4.2.1 Strengths and Weaknesses of Design

Design Strengths:

- Passive
    - No power required for panels to interlock
- Simple
    - No moving parts to fail
- Reliable
    - Panels will not fail to interlock due to design
- Secure
    - Once interlocked, panels remain locked due to magnetic forces
- Modifiable for prototype testing
    - Design can be updated or changed if prototype fails

Design weaknesses:

- No mechanical latch
    - Panels can be forced apart by high external forces acting upon panels
- Unexplored use of magnets in space
    - Operation time indefinite
    - No documentation of magnet use in space

4.2.2 Recommendations for Future Efforts

Incorporate a mechanical latch to ensure the panels remain interlocked after deployment. Preferably the latch would engage as soon as the panels successfully deployed and would not require any complicated parts that could fail. Further investigation is still underway for possible mechanical latches that can be used with our coupling mechanism.

4.2.3 Closing Comments and Conclusions

Once the prototype is built, a lot of testing will be conducted on the effectiveness of the magnets and the design concept selected. Due to the design being highly modifiable, any changes that need to be made will be considered and implented appropriately. The prototype will help us optimize the design and test means of mechanically latching the panels after deployment.

Appendices and References

i. Annotated Bibliography

ii. Additional Tables & Figures

iii. Health and Safety Plan

i. Annotated Bibliography

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ii. Additional Tables & Figures (Appendix A)

Stiffness limited design:

– — where C=8

Plugging in —

Where

–

Therefore —

Solving for m for mass stiffness design: — — and —

Strength limited design:

— where C=2

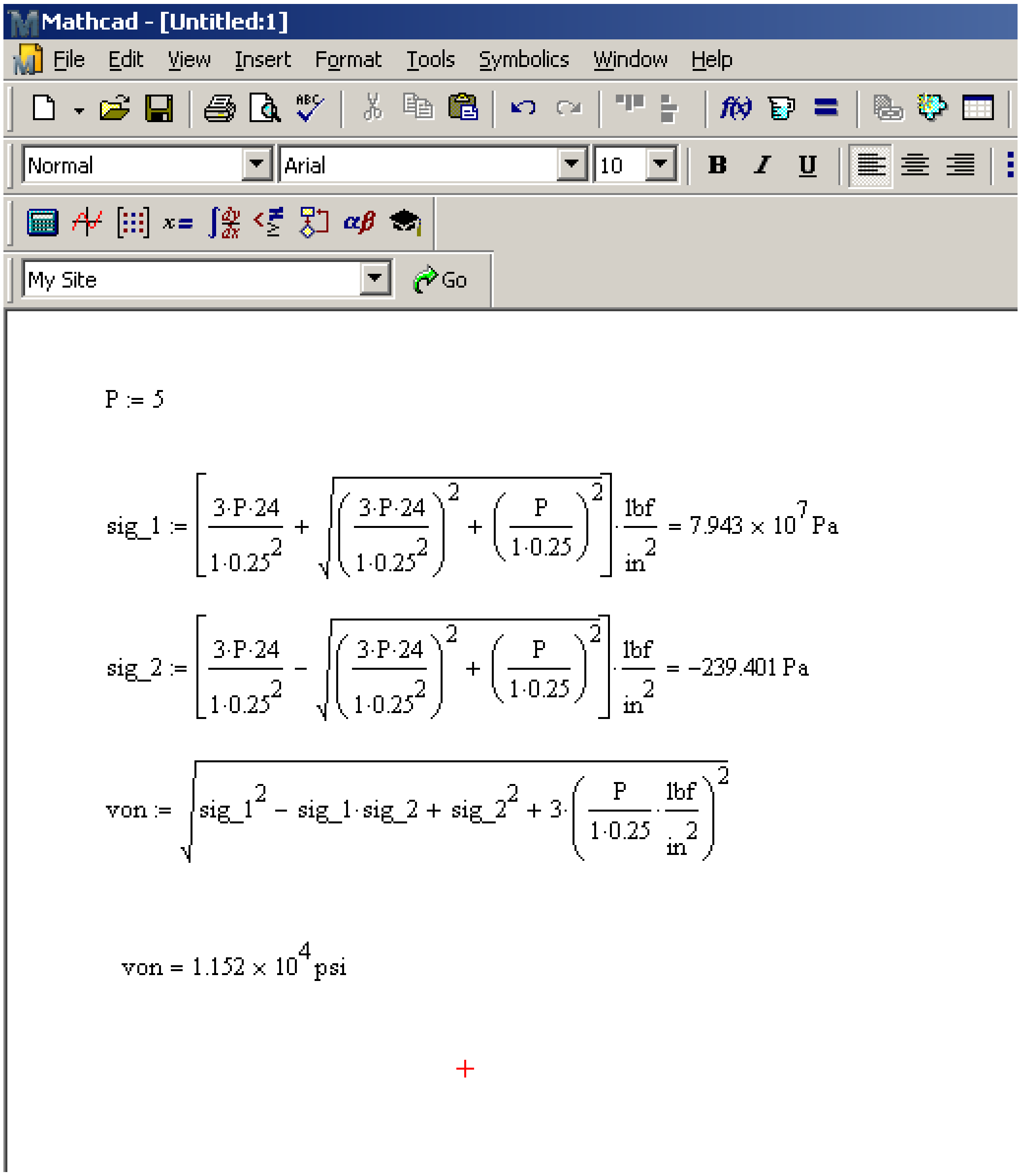
Plugging in —

Where

–

Therefore —

Solving for m for mass strength design: — — and —



$P := 5$

$$sig\_1 := \left[\frac{3\cdot P\cdot 24}{1\cdot 0.25^2} + \sqrt{\left(\frac{3\cdot P\cdot 24}{1\cdot 0.25^2}\right)^2 + \left(\frac{P}{1\cdot 0.25}\right)^2}\right]\cdot\frac{lbf}{in^2} = 7.943\times 10^7\,Pa$$

$$sig\_2 := \left[\frac{3\cdot P\cdot 24}{1\cdot 0.25^2} - \sqrt{\left(\frac{3\cdot P\cdot 24}{1\cdot 0.25^2}\right)^2 + \left(\frac{P}{1\cdot 0.25}\right)^2}\right]\cdot\frac{lbf}{in^2} = -239.401\,Pa$$

$$von := \sqrt{sig\_1^2 - sig\_1\cdot sig\_2 + sig\_2^2 + 3\cdot\left(\frac{P}{1\cdot 0.25}\cdot\frac{lbf}{in^2}\right)^2}$$

$$von = 1.152\times 10^4\,psi$$

iii. Health and Safety Plan

Due to the scale and nature of this project, there is minimal risk of any kind. However, with any design, risk assessment is still necessary. With this design there are two main concerns in the use of magnets:

1) Risk of pinching
2) Risk of chipping

Both of these risks increase as the size of the magnets being used increases. Due to the small dimensions of our magnets, neither of these risks pose too great of a threat, however it is still important to be aware of these potential concerns.

In the case that someone's finger or skin is pinched, a brass wedge should be inserted in between the magnets to remove the pressure and withdraw the hand or skin from the vicinity. Simply attempting to pull a member out from between the magnets (or in our case, the magnet and cone) will increase the force being exerted on it while simultaneously decreasing the area over which the pinching is occurring. This, overall, increases the added pressure on the hand or skin and is best relieved by simply using a wedge before attempting to release the member.

Chipping is a second risk when using magnets. Different magnet types have different material properties and some are more prone to chipping than others. Being fully aware of the type of magnet and its material properties is important with this design. Although with our design the magnets should not be exhibiting any high mechanical loads, if deemed necessary protective eyewear may be used.