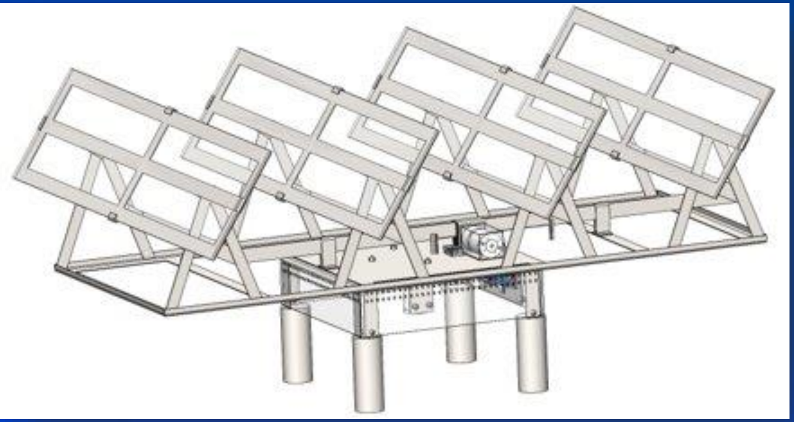
Herbert Wertheim College of Engineering
UNIVERSITY of FLORIDA

Mechanical and Aerospace Engineering

EML 4501 Mechanical Engineering Design II Spring 2022

Section: 13070 Group: 4

TM



OPERATION CONCENTRATION

Marcus Mlack, Stephen Morton, Matthew Poole, Kristin Santaniello, Jenna Scott and Joshua Watts

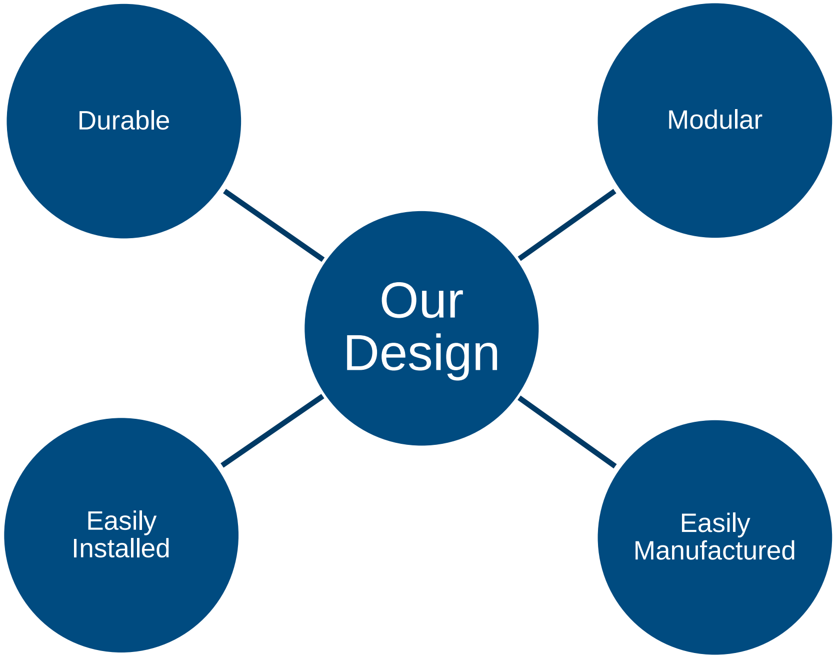
POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

Outline

- Who is Operation Concentration?
- Overview of the design and its subsystems
- Analysis of the subsystems
- Final remarks

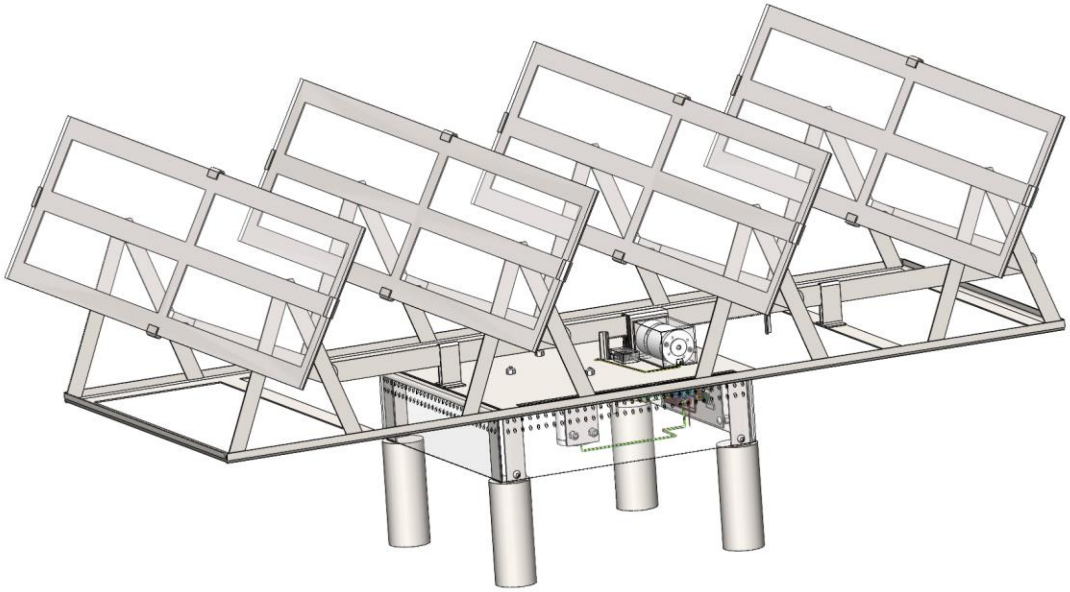
Our Principals (Hedgehog Concept)

- To create a durable, modular heliostat system with two axes of rotation that is easy to manufacture and easy to install
- We're passionate about creating something new and challenging to push what is possible



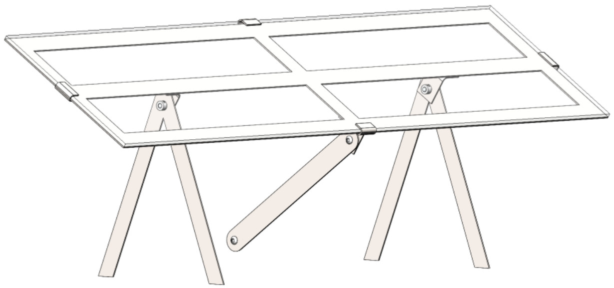
Design Overview

- Mirror Subsystem
  - 4 reflective surfaces
- Controller subsystem
  - 1 motor
  - Connecting Rod
- Heliostat Base Subsystem
  - Linkage system
  - Rotates about vertical axis
- Module Base Subsystem
  - 1 motor
  - Control Panel
    - Arduino and ESP module
  - 4 legs for support
  - Concrete posts

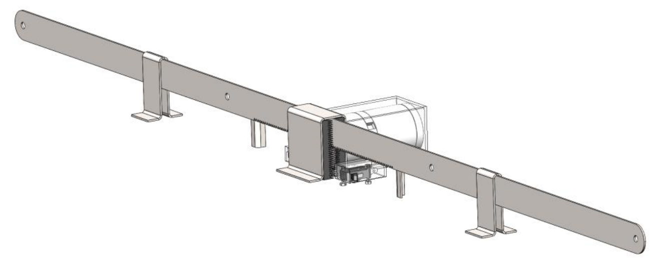


Design Overview

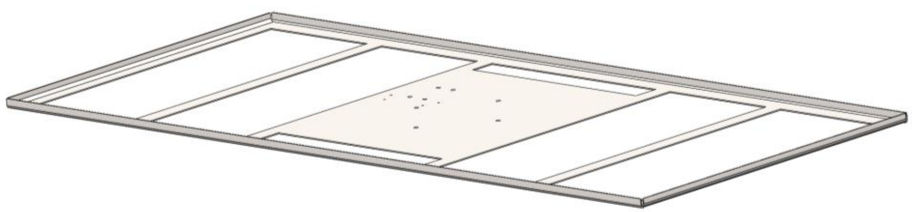
Mirror Subsystem



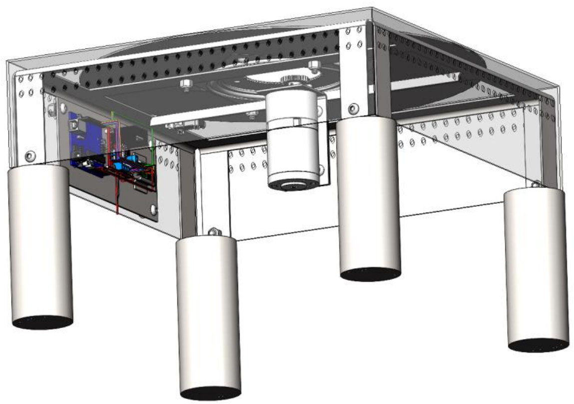
Controller Subsystem



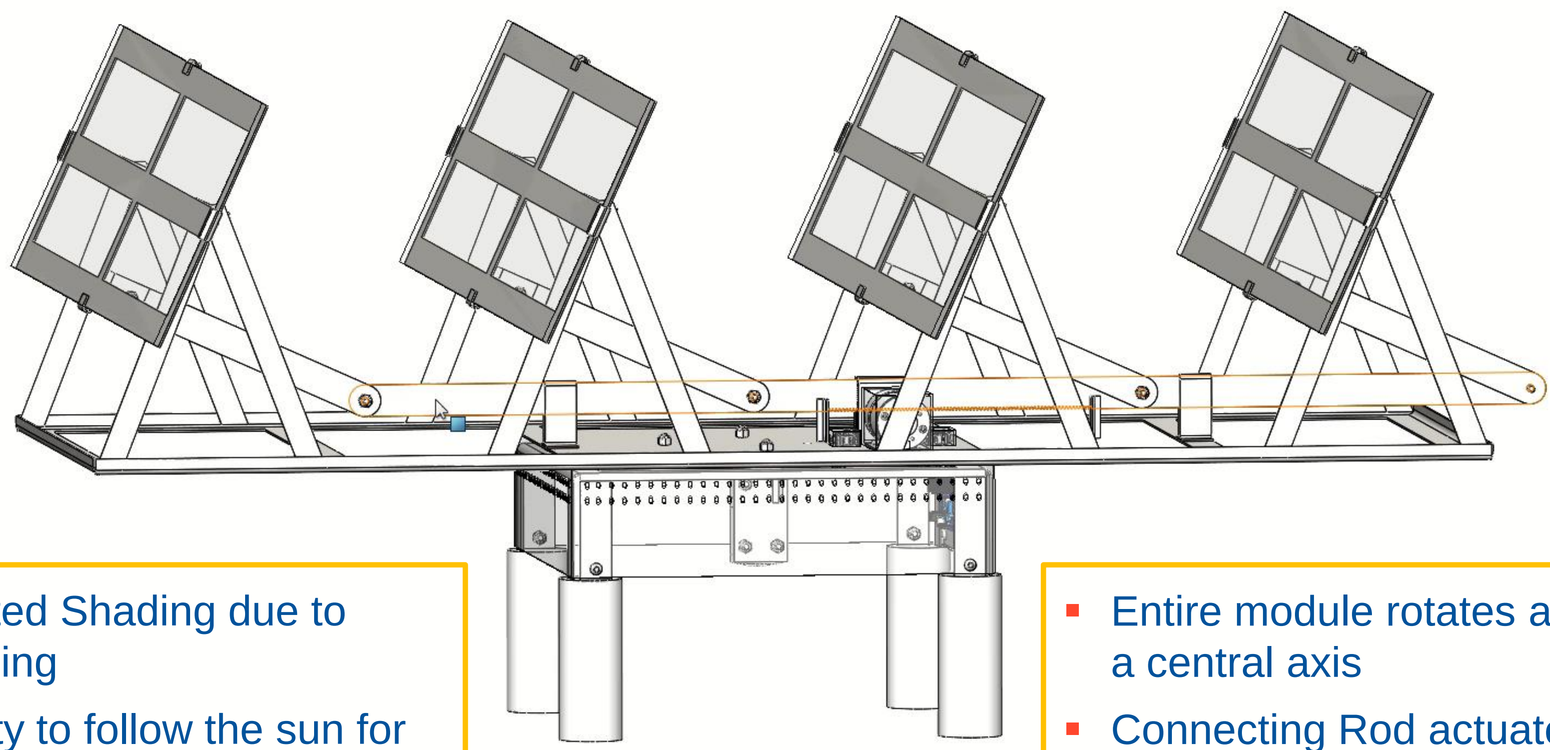
Heliostat Base Subsystem



Module Base Subsystem



Design Overview

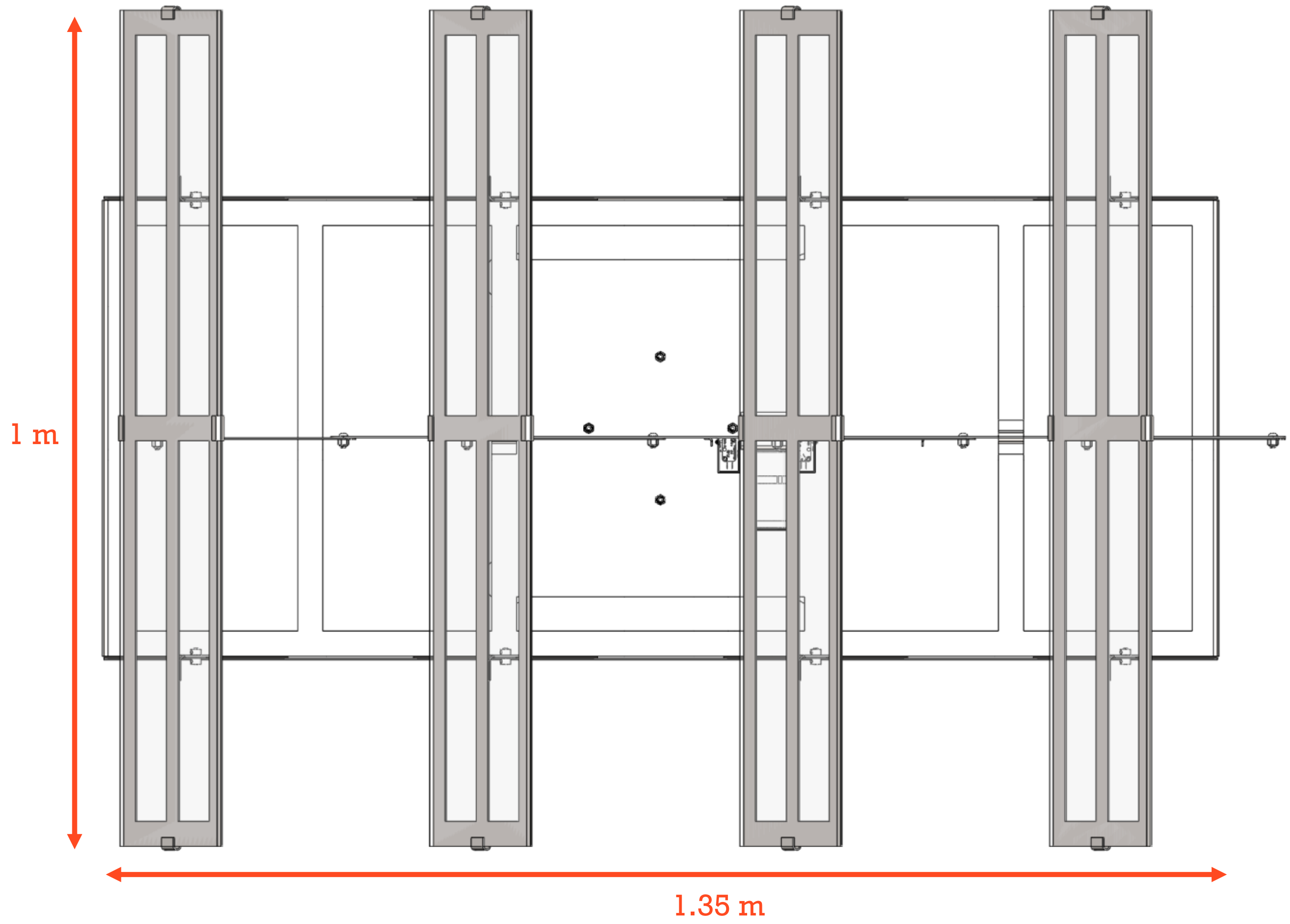


- Limited Shading due to spacing
- Ability to follow the sun for maximum energy collection

- Entire module rotates about a central axis
- Connecting Rod actuates all four mirrors together

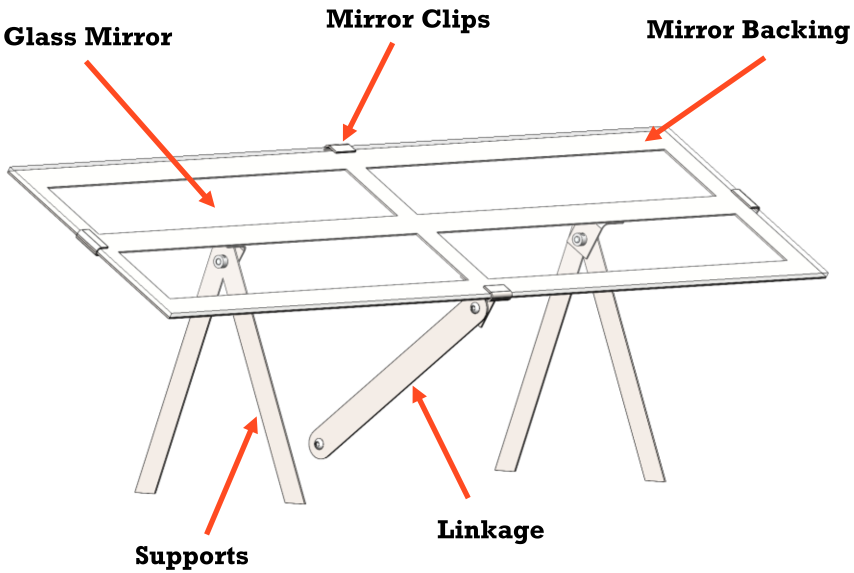
Overall Product Dimensions

- Top View
- Overall Dimensions
  - 1m x 1.35m
- The center of each module is spaced 1.7m from the nearest module

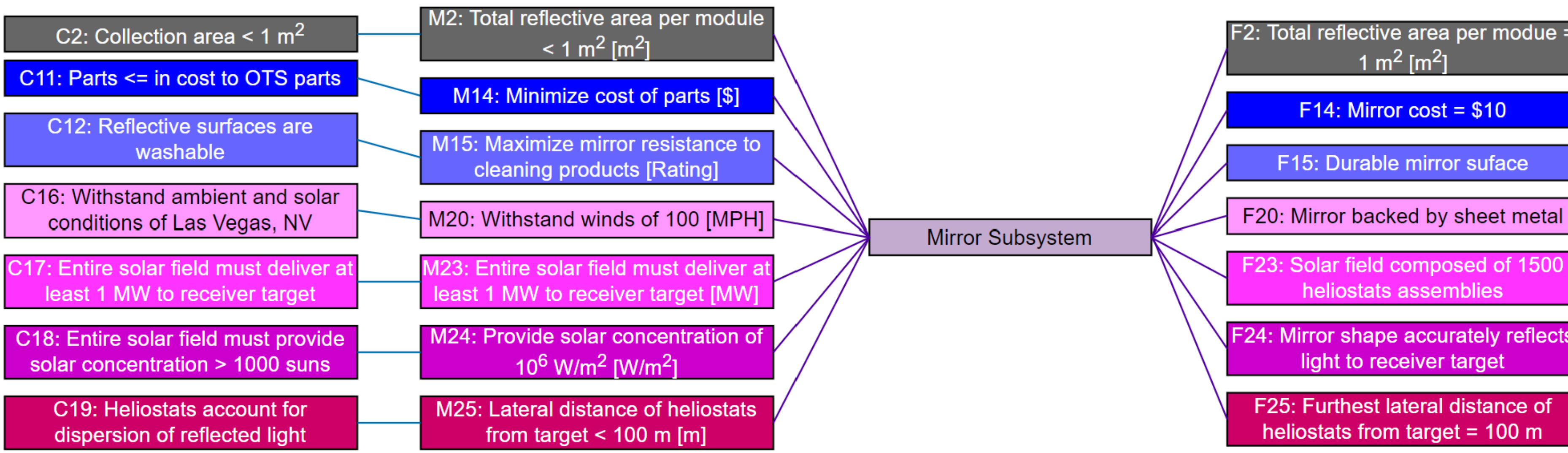


Mirror Subsystem

- Borosilicate Glass Mirror
  - 1 x 0.25 x 0.005 m
- 4 Mirror Clips
  - 0.071” thick Zinc-Galvanized Low-Carbon Steel Sheet Metal
- Mirror Backing
  - 0.015” thick Zinc-Galvanized Low-Carbon Steel Sheet Metal
- 2 V-Shaped Supports
  - 0.071” thick Zinc-Galvanized Low-Carbon Steel Sheet Metal
- Linkage
  - 0.071” thick Zinc-Galvanized Low-Carbon Steel Sheet Metal



Customer Needs Map for Mirror Subsystem



Mirror Subsystem Analysis

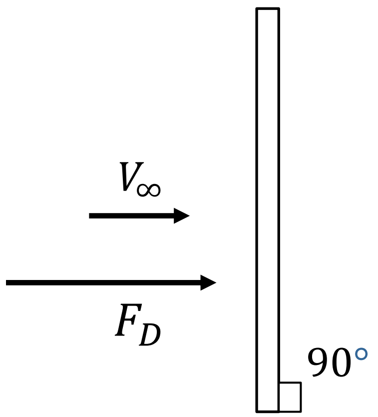
Drag Force Calculations

- Assume Mirrors are in the vertical position to maximize frontal area

$C_D = 1.98\ (For\ rlat\ rectangular\ plate\ perpendicular\ to\ the\ flow)$

$$F_D = \frac{1}{2}\rho v^2 C_D A = \frac{1}{2}\left(1.225\ \frac{kg}{m^3}\right)\left(44.7\ \frac{m}{s}\right)^2 (1.98)\left(0.25\ m^2\right) = 605.8\ N$$

$$F_{max} = F_D \times FOS = 605.8\ N \times 2 = 1211.6\ N$$



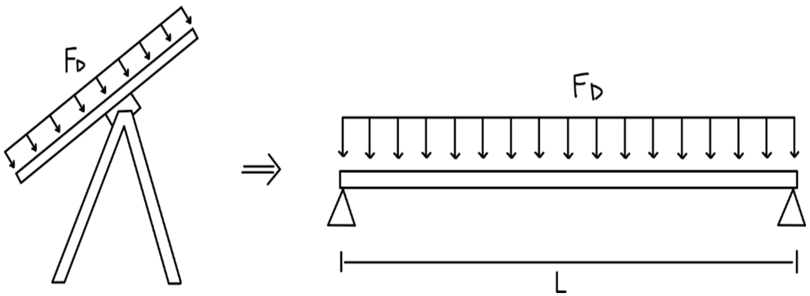
Mirror Bending Stress Calculations

- Assume Drag Force acts as a distributed load across the face of the mirror

$$M = \frac{F_{max} L^2}{8} = \frac{(1211.6\frac{N}{m})(1\ m)^2}{8} = 151.45\ \text{Nm}$$

$$I = \frac{1}{12} b h^3 = \frac{1}{12}(0.25\ m)(0.00318\ m)^3 = 6.7 \times 10^{-10}\ m^4$$

$$\sigma_f = \frac{My}{I} = \frac{151.45\ \text{Nm} \times 6.7 \times 0.00159\ m}{6.7 \times 10^{-10}\ m^4} = 359.44\ MPa$$



*Drawings not to scale

Mirror Subsystem Analysis

Downforce Calculation

- Assume mirrors at maximum lifting angle before the flow separates

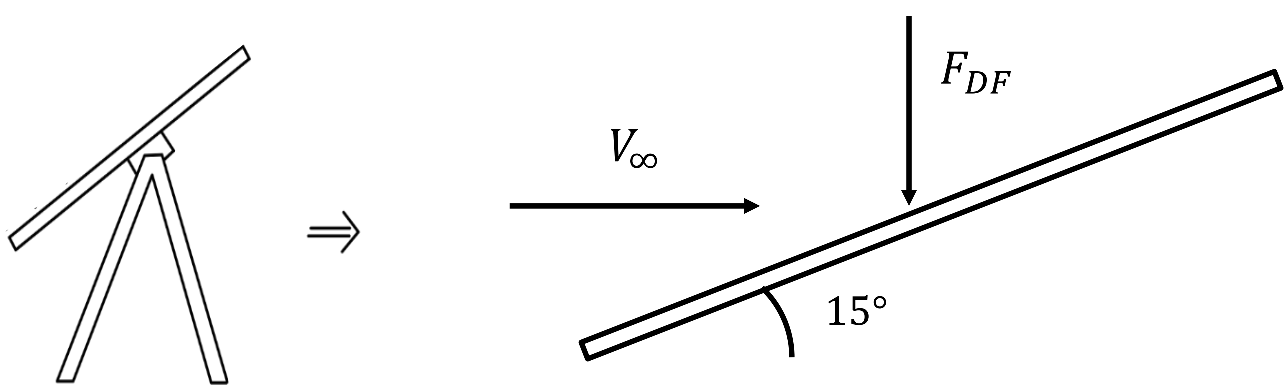
$$C_L = 2\pi\alpha \ (For\ Flat\ Rectangular\ Plate)$$

$$\alpha = 15\ degrees = 0.2618\ radians\ (Maximum\ angle\ of\ attack\ before\ flow\ separation)$$

$$C_L = 2\pi(0.218) = 1.32$$

$$F_{DF} = -F_L = -\frac{1}{2}\rho v^2 C_D A = -\frac{1}{2}\left(1.225\ \frac{kg}{m^3}\right)\left(44.7\ \frac{m}{s}\right)^2 (1.32)\left(0.25\ m^2\right) = -402.69\ N$$

$$F_{max} = F_{DF} \times FOS = 402.69\ N \times 2 = 805.38\ N$$



*Drawings not to scale

Maximum Shading

Assumptions

1. Maximum angular offset from horizontal is θ_s= 40°
2. h_s is offset from vertical by the angle 90°-θ_s
3. Mirror position at θ_s has tracking errors < 0.5°
4. A right angle is formed between the shaded regions and mirrored surfaces
5. Height of mirrors is 0.25m

Determining height of shaded region: h_s

$$\tan(90° - \theta_s) = \left(\frac{0.25m - h_s}{distance\ between\ mirrors}\right)$$

$$\tan(90° - 40°) = \left(\frac{0.25m - h_s}{0.1575m}\right)$$

$$0.1575m \times \tan(50°) = 0.25m - h_s$$

$$0.25m - (0.1575m \times \tan(50°)) = \boldsymbol{h_s = 0.0623m}$$

Determining area of shaded region per mirror: $A_{s,mirror}$

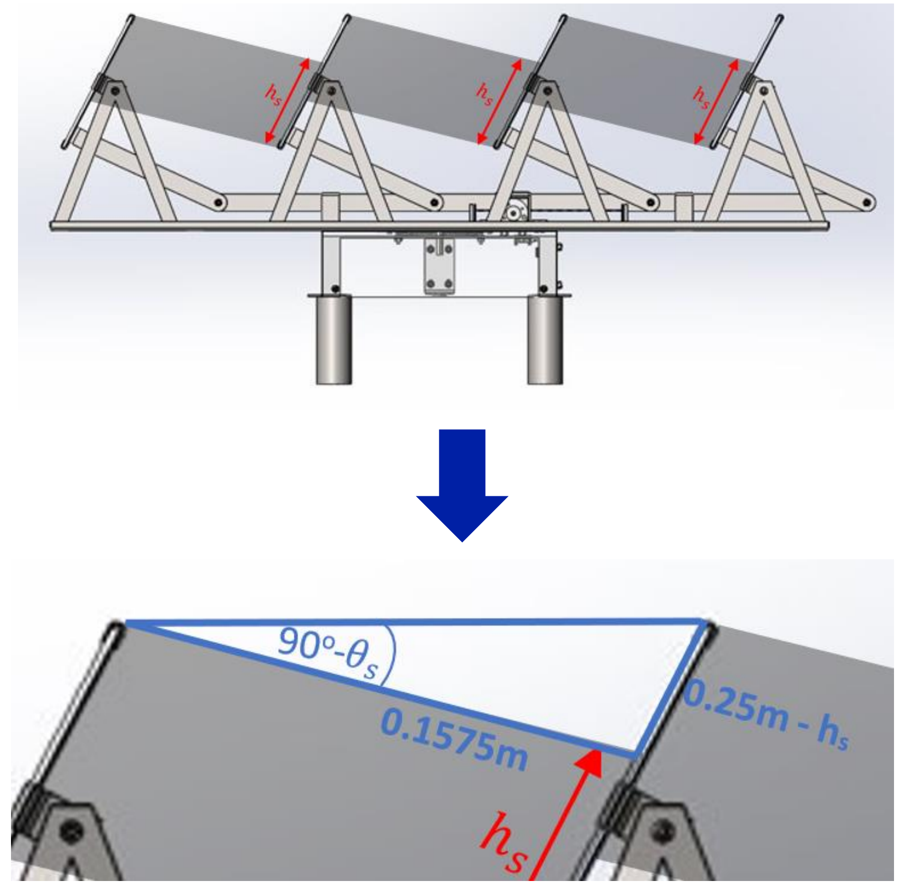
$$A_{s,mirror} = L \times h_s$$

$$A_{s,mirror} = (1m) \times (0.0623m) = 0.0623m^2$$

Determining total shaded area: $A_{s,total}$

$$A_{s,total} = 3(L \times h_s)$$

$$A_{s,total} = 3(0.0623m^2) = \boldsymbol{0.187m^2}$$

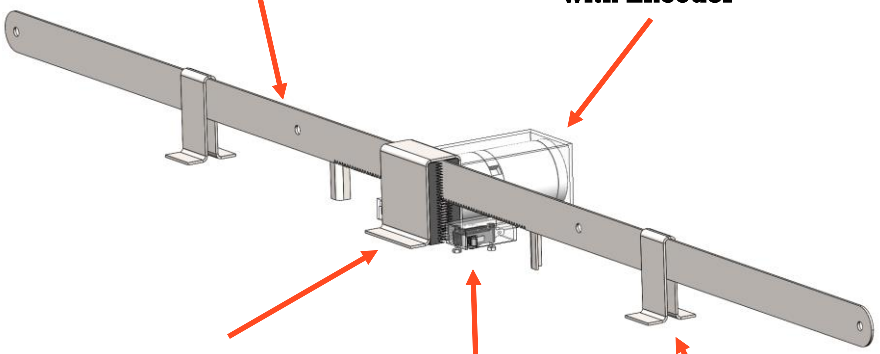


*Geometry not to scale

$$\%_s = \frac{shaded\ mirror\ area}{total\ mirror\ area} \times 100 = \frac{0.4987m^2}{4(1m \times .25m)} \times 100 = \boldsymbol{18.7\%}$$

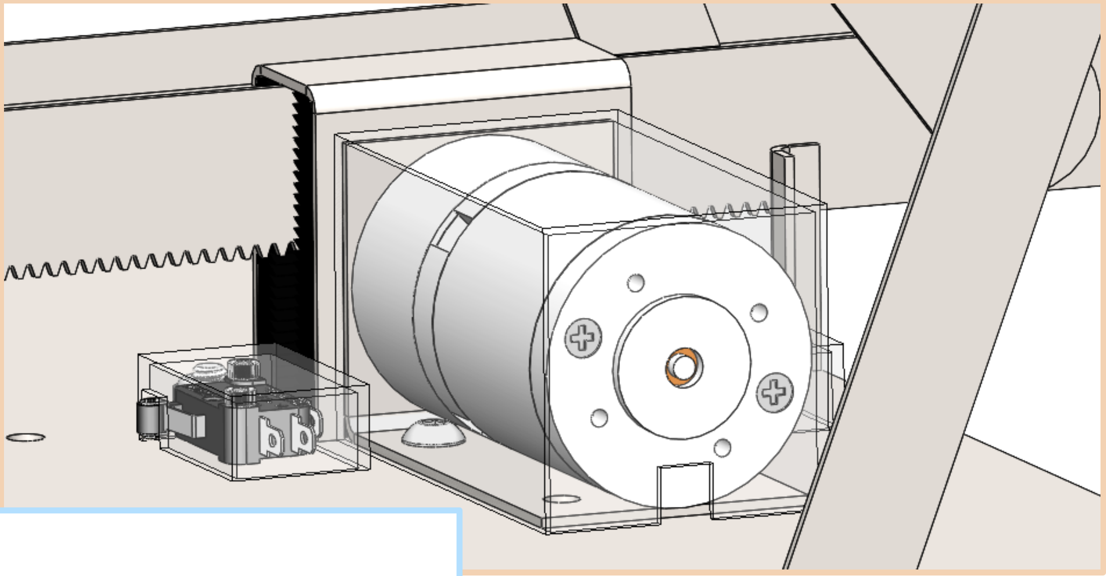
Controller Subsystem

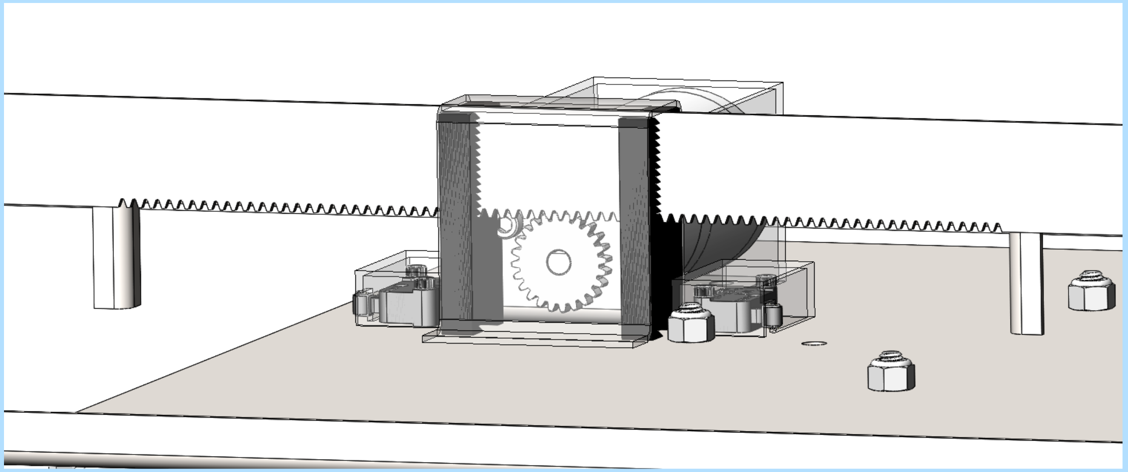
- Connecting Rod
  - 0.071” thick Zinc-Galvanized Low-Carbon Steel Sheet Metal
- 16.7 RPM Cytron Motor with Encoder
  - Shielding Case Polyethylene Sheet
  - 810 Counts Per Revolution
- Protective Brush
  - Silicone Weather Stripping Brush
  - Brush holder
    - 0.071” thick Zinc-Galvanized Low-Carbon Steel Sheet Metal
- 2 Limit Switches
  - Shielding Case Polyethylene Sheet
- 2 Rod Guides
  - 0.071” thick Zinc-Galvanized Low-Carbon Steel Sheet Metal



Controller Subsystem Close Ups

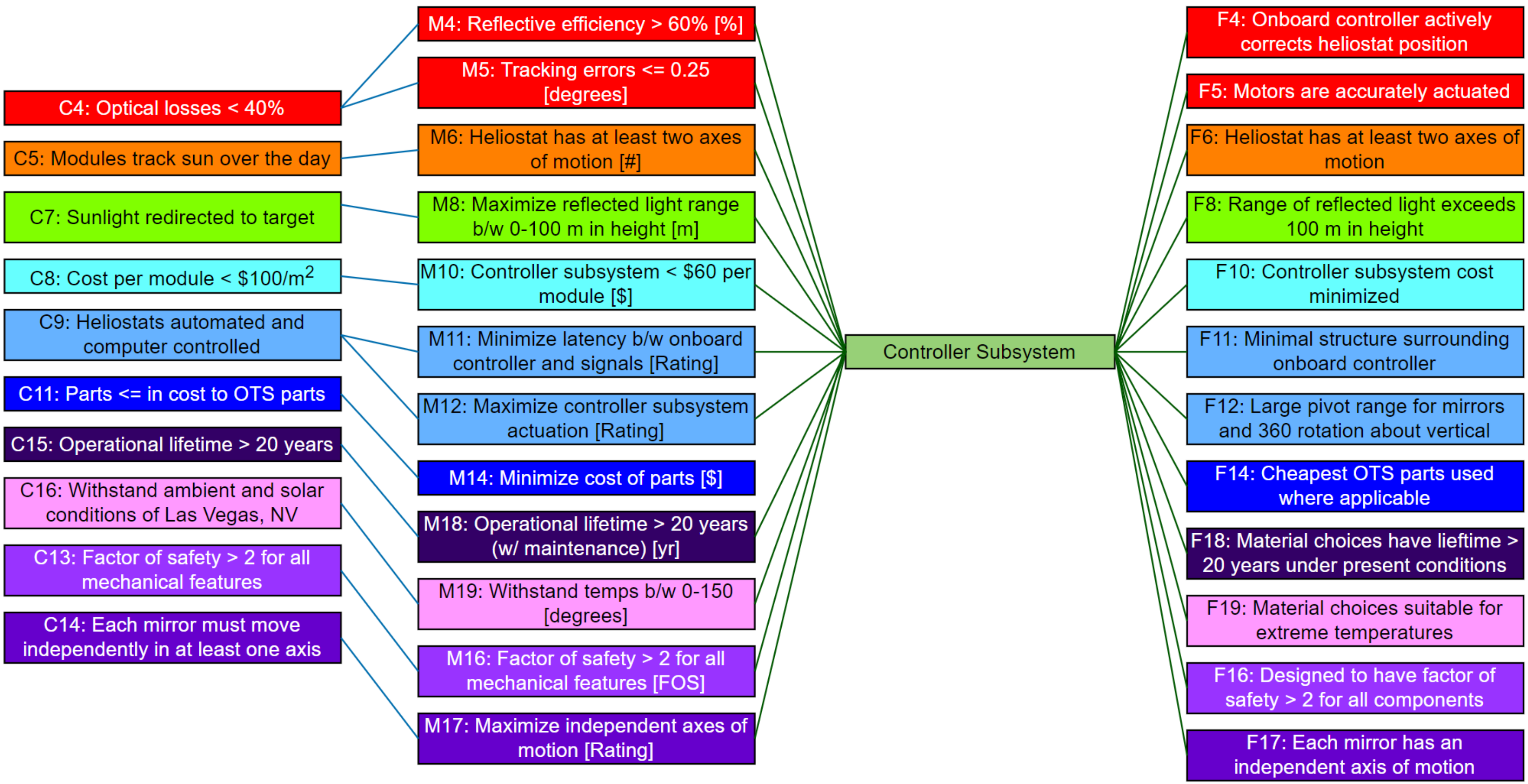
- Motor
- Protective Case
- Brush





- Connecting Rod
- Limits Switches and their Stoppers

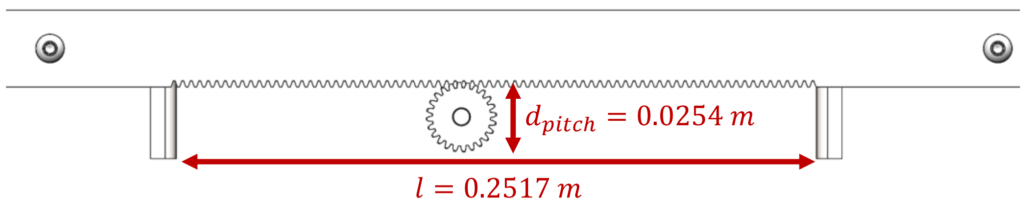
Customer Needs Map for Controller Subsystem



Controller Subsystem Analysis

Motor Torque Calculations

- Assume reset takes 600 seconds, starting from rest



$$v_{rod} = \frac{\Delta l}{t} = \frac{0.2517\ m}{600\ s} = 4.195 \times 10^{-4}\ m/s^2$$

$$a_{rod} = \frac{\Delta v_{rod}}{t/2} = \frac{4.195 \times 10^{-4}\ m/s^2}{300\ s} = 1.398 \times 10^{-6}\ m/s^2$$

$$F_{rod} = m_{rod} a_{rod} = 0.97899\ kg\left(1.398 \times 10^{-6}\ m/s^2\right) = 1.369 \times 10^{-6}\ N$$

$$M = F_{rod}\frac{d_{pitch}}{2} = \left(1.369 \times 10^{-6}\ N\right)\left(\frac{0.0254}{2}\ m\right) = 1.739 \times 10^{-8}\ Nm$$

$$\omega = \frac{v_{rod}}{r_{pitch}} = \frac{4.195 \times 10^{-4}\ m/s}{0.0127\ m} = 0.033\ rad/s$$

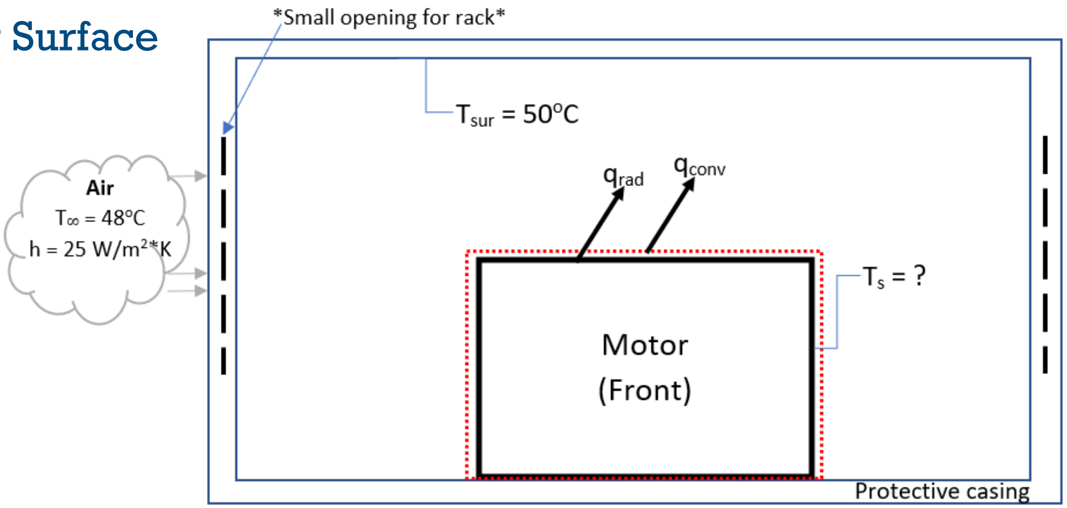
Power Calculation

$$P_{min} = M\omega = \left(1.739 \times 10^{-8}\ Nm\right)(0.033\ rad/s) = 5.265 \times 10^{-7}\ W$$

Controller Subsystem Analysis

Heat Transfer Analysis of DC Motor Surface

Assumptions
1. Surface Thermal Emissivity ε = 0.83
2. Motor L = 0.0762 m, Motor D = 0.0508 m
3. Steady-state system
4. System Efficiency ~ 0.8
5. Air travels trough small opening for rack
6. Outer casing heated to T_{sur} = 50°C from solar radiation



Conservation of total energy

$$\frac{dE_{st}^{tot}}{dt} = \dot{E}_{in}^{tot} - \dot{E}_{out}^{tot}$$

Conservation of thermal/mechanical energy

$$\dot{E}_{in} - \dot{E}_{out} + \dot{E}_{gen} = 0$$

Relationship between mechanical/electrical power

Mechanical work — Heat leaving motor — Electrical power

$$\dot{W} - q - P = 0$$

$$q = \dot{W} - P$$

$$P = \dot{W}\eta_{motor}$$

*Minimum power needed to start movement

$$q = P\left(\frac{1}{\eta_{motor}} - 1\right)$$

$$q = (1.74 \times 10^{-6} J)\left(\frac{1}{0.8} - 1\right) = 4.35 \times 10^{-7} W$$

Application of Rate Equation

$$q = q_{rad} + q_{conv} = A[q"_{rad} + q"_{conv}]$$

$$q = \left[\pi DL + \frac{\pi D^2}{4}\right]\left[\varepsilon\sigma(T_s^4 - T_{sur}^4) + h(T_s - T_\infty)\right]$$

$$4.35 \times 10^{-7} W = \left[\pi(0.0508m)(0.0762m) + \frac{\pi(0.0508)^2}{4}\right]\left[\varepsilon\sigma(T_s^4 - T_{sur}^4) + h(T_s - T_\infty)\right]$$

$$3.06 \times 10^{-5}\frac{W}{m^2} = \left[(0.83)\left(5.67 \times 10^{-8}\frac{W}{m^2}\right)(T_s^4 - 1.088 \times 10^{10}K^4) + \left(25\frac{W}{m^2K}\right)(T_s - 321K)\right]$$

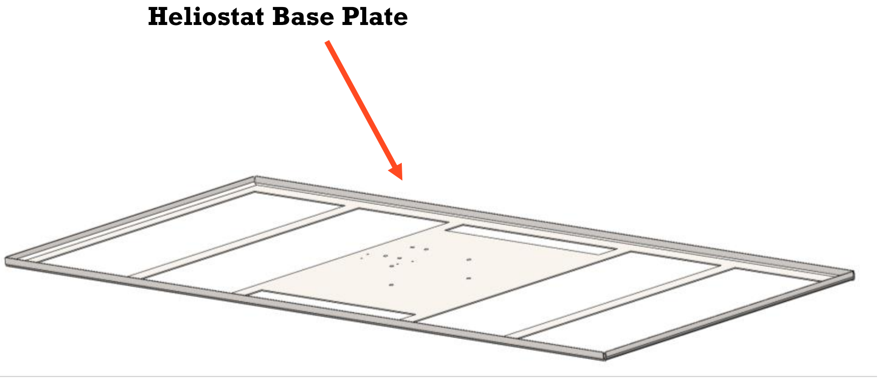
$$T_s = DC\ motor\ surface\ temp. = 321.4K = \mathbf{48.4°C}$$

- Component is not at risk of overheating

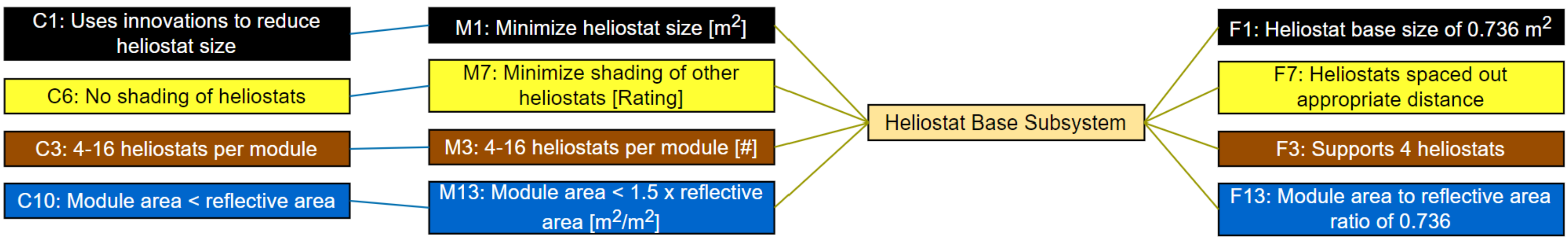
*Drawings not to scale

Heliostat Base Subsystem

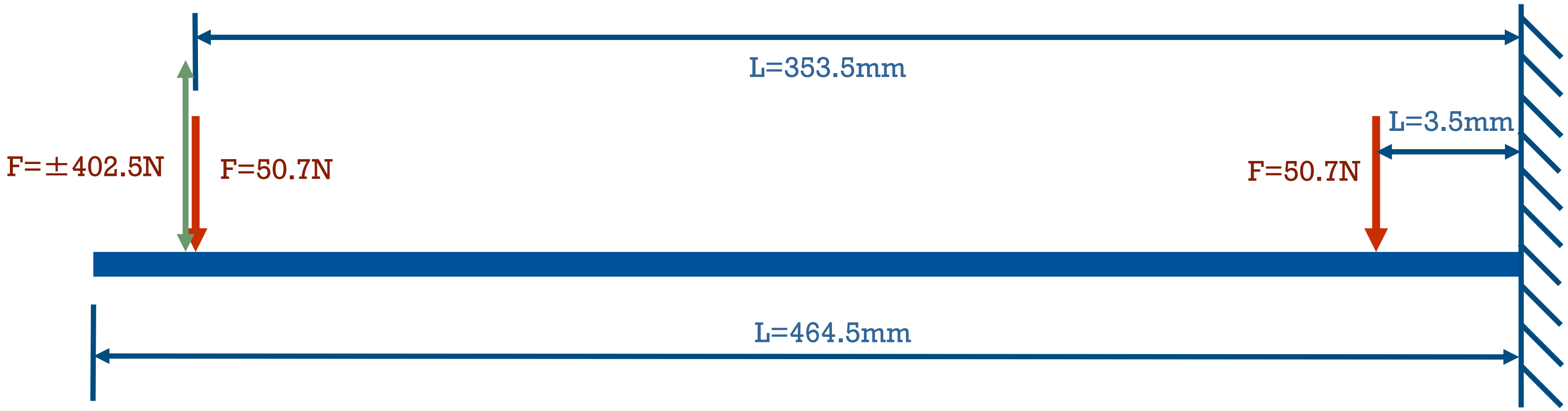
- Heliostat Base Plate
  - 0.071” thick Zinc-Galvanized Low-Carbon Steel Sheet Metal
  - 1.33 x 0.545 m rectangular shape with cutouts
  - Edges are bent up by 15 mm for strength



Customer Needs Map for Heliostat Base Subsystem



Heliostat Base Subsystem Analysis



Conservative Cantilever Beam approximation of the heliostat base

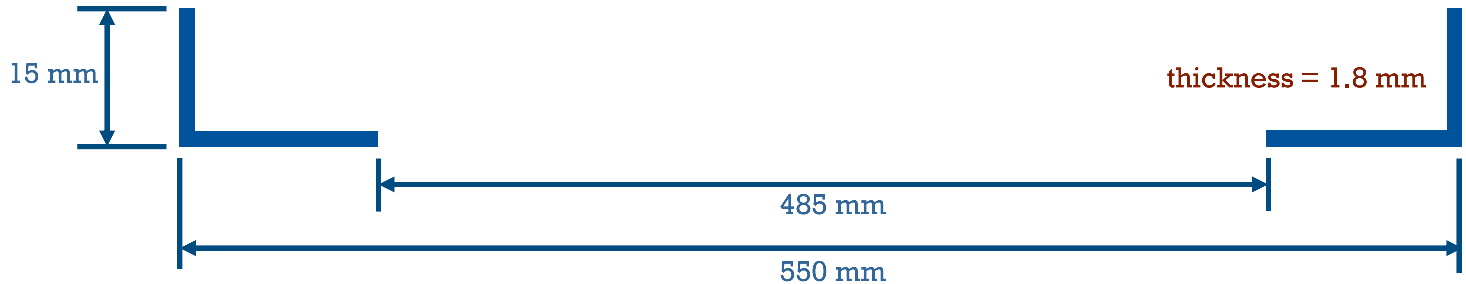
F_1 and F_2 are forces from the weight of heliostats. F_d is the max downforce experienced by the mirrors by the wind.

$$M_{max} = \Sigma Fx = F_1x_1 + F_2x_2 + F_dx_d = 160400\ Nmm$$

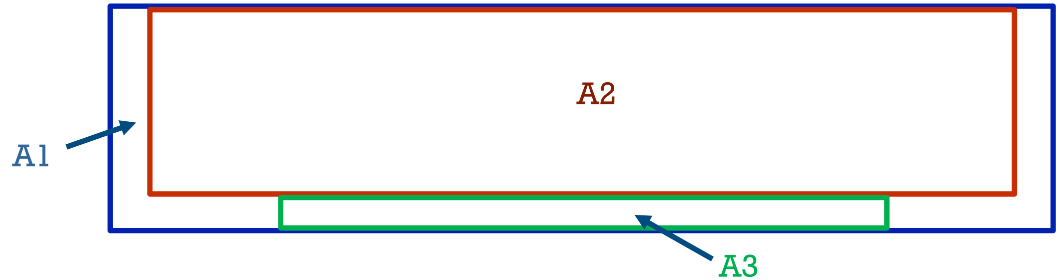
$$M_{min} = \Sigma Fx = F_1x_1 + F_2x_2 - F_dx_d = -124200\ Nmm$$

*Drawings not to scale

Heliostat Base Subsystem Analysis



Cross sectional diagram of weakest point



Centroid calculation

$$\bar{y} = \frac{A_1 y_1 - (A_2 y_2 + A_3 y_3)}{A_1 - (A_2 + A_3)} = 3.066 \text{ mm}$$

$$y = 15 - \bar{y} = 11.93 \text{ mm}$$

Second Moment of Inertia

$$I = \frac{1}{12} b_1 h_1^3 + A_1 d_1^2 - (\frac{1}{12} b_2 h_2^3 + A_2 d_2^2 + \frac{1}{12} b_3 h_3^3 + A_3 d_3^2) = 99413.99\ mm^4$$

Bending Stresses

$$\sigma = \frac{My}{I} \qquad \sigma_{max} = \frac{M_{max} y}{I} = 19.26\ MPa \qquad \sigma_{min0} = \frac{M_{min} y}{I} = -14.91\ MPa$$

*Drawings not to scale

Heliostat Base Subsystem Analysis

Cyclic Loading

$$S_{ut} = 635\ MPa$$

Equivalent Completely Reversed Stress (σ_{AR})

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} = 17.08$$

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} = 2.17$$

$$\sigma_{AR} = \frac{\sigma_a}{1 - \frac{\sigma_m}{S_{ut}}} = 17.14$$

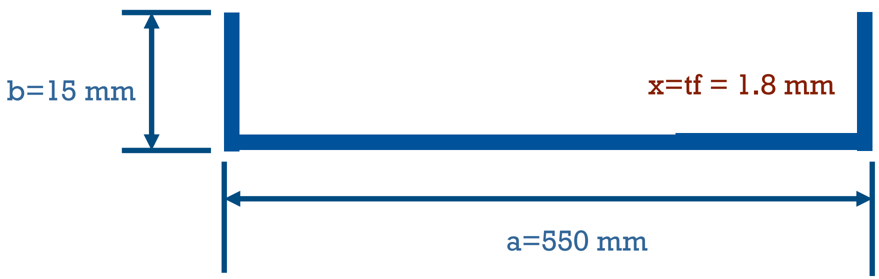


Diagram for equivalent diameter

Marin Factors and Endurance Limit Calculation

$$S_e' = 0.5 S_{ut} = 317.5\ \text{MPa}$$

$$k_a = 4.51 S_{ut}^{-1.265} = 0.816$$

$$d_e = 0.052\text{xa} + 0.1\text{tf}(\text{b} - \text{x}) = 53.9$$

$$k_b = 1.24 d_e^{-0.107} = 0.809$$

Endurance Limit

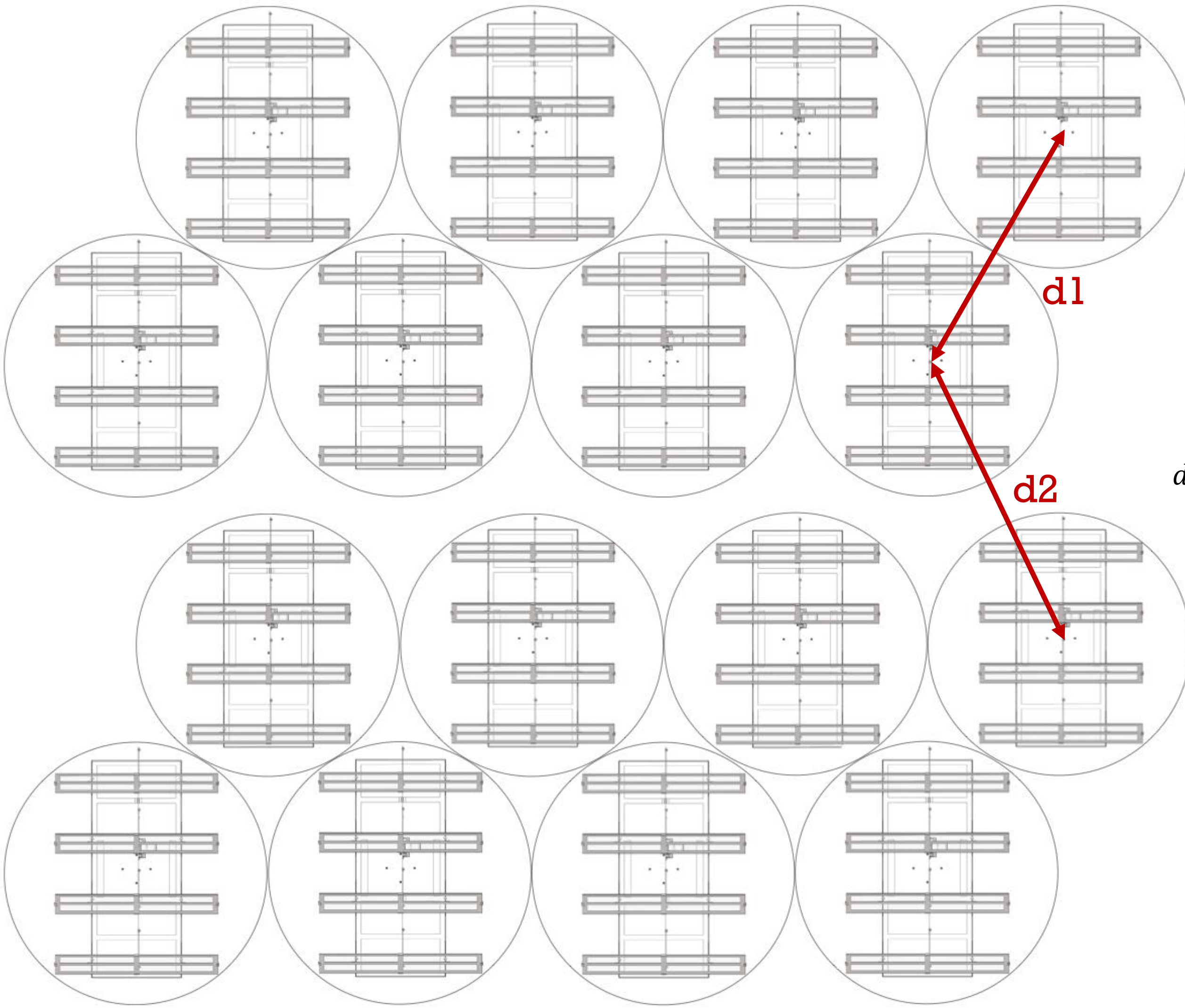
$$S_e = S_e' k_a k_b = 209.5\ MPa$$

Factor of Safety for Infinite Life

$$\eta = \frac{S_e}{\sigma_{AR}} = 12.23$$

*Drawings not to scale

Heliostat Base Subsystem Analysis

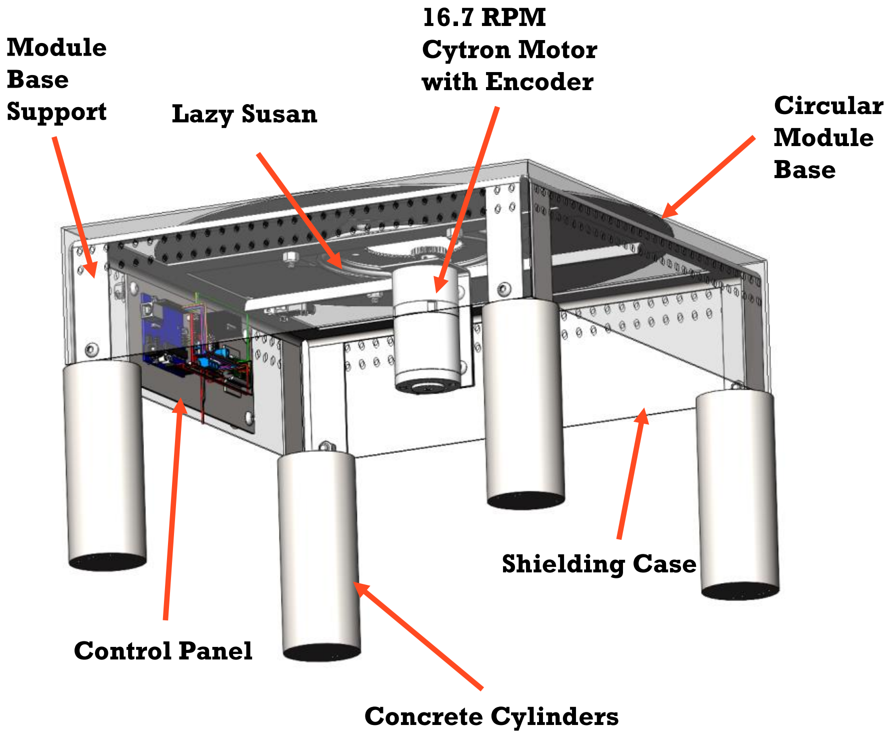


$$d_1 = 1.7m$$

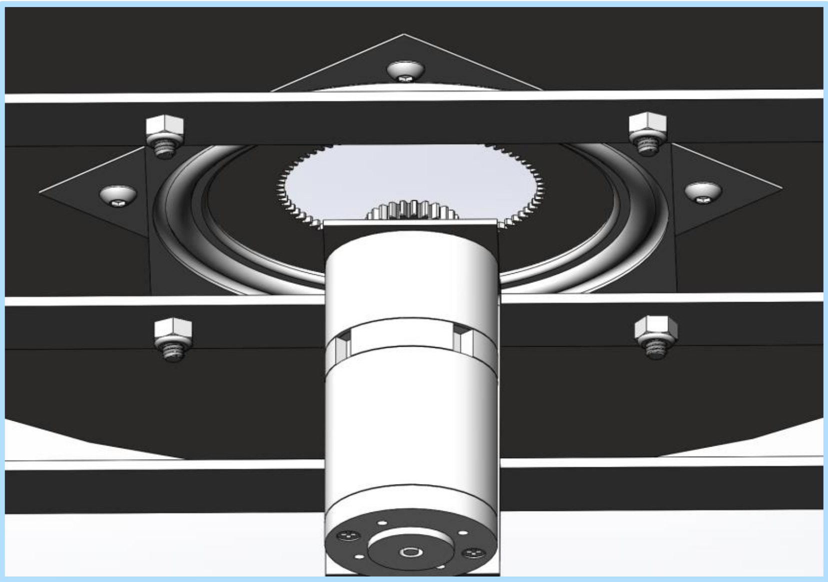
$$d_2 = \sqrt{d_1^2 + \left(\frac{d_1}{2}\right)^2} = 1.9m$$

Module Base Subsystem

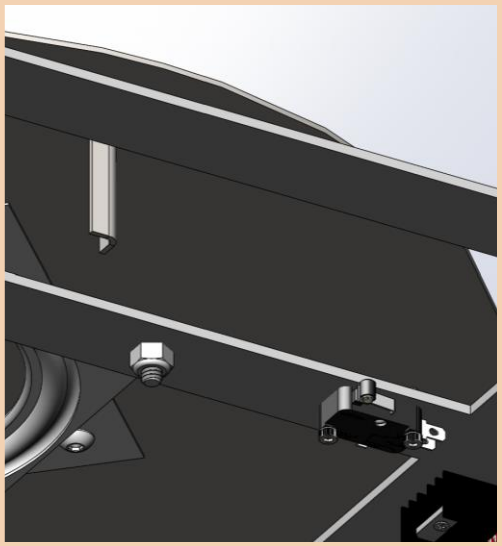
- Module Base Support
  - 0.071” thick Zinc-Galvanized Low-Carbon Steel Sheet Metal
- Lazy Susan
  - 500lb capacity
- 16.7 RPM Cytron Motor with Encoder
- Circular Module Base
  - 0.071” thick Zinc-Galvanized Low-Carbon Steel Sheet Metal
- Control Panel
  - Arduino Uno, 12V motor driver, esp-w2 microcontroller with WiFi capabilities
- Concrete Cylinders
- Shielding Case
  - Polyethylene Sheet with slits for ventilation



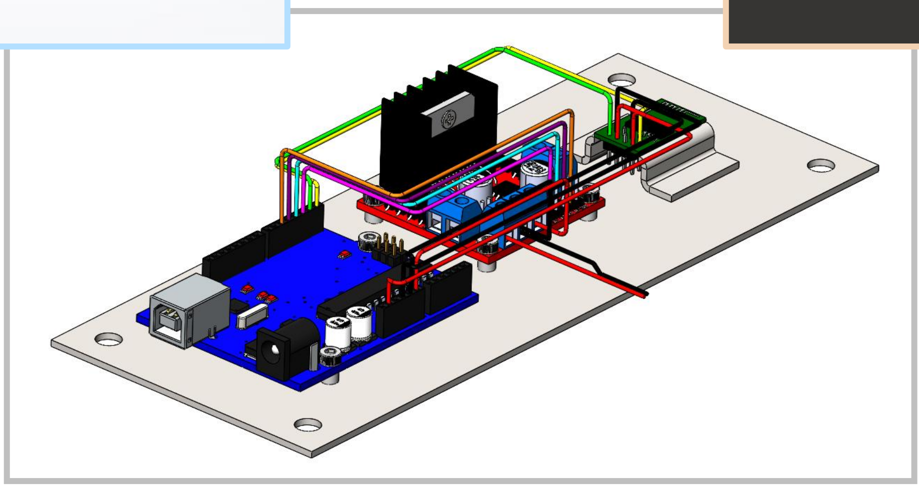
Module Base Subsystem Close Ups



- Motor
- Lazy Susan
- Circular Module Base



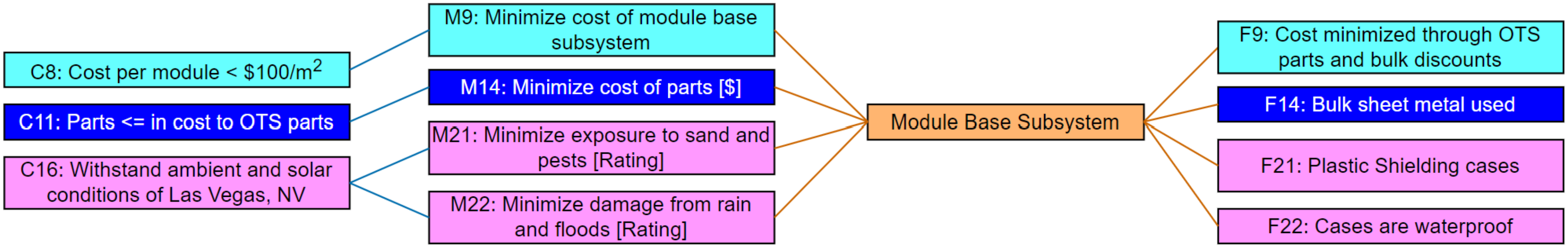
Limit Switch and its Stopper



Control Panel

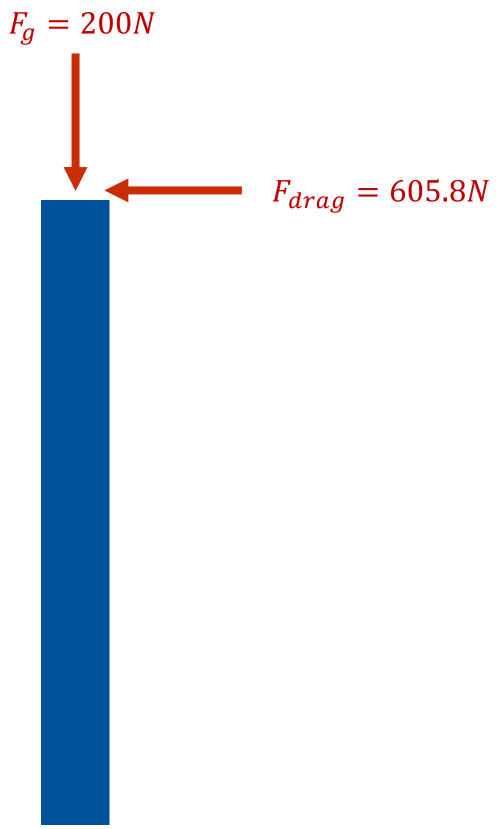
- Accuracy < 0.5°
- Wi-Fi Capabilities
- Encoders to track Position

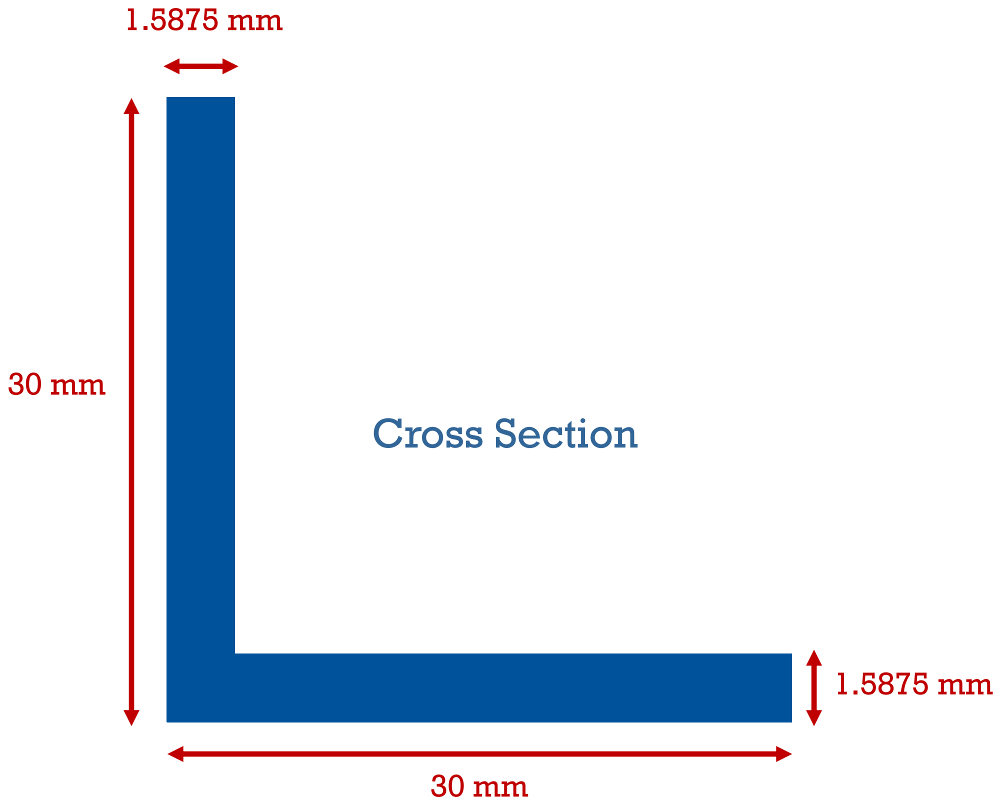
Customer Needs Map for Module Base Subsystem



Module Base Subsystem Analysis

Leg Stress Calculations





Module Base Subsystem Analysis

Leg Stress Calculations Cont.

- Normal Stress Calculations

$$\bar{y} = \frac{A_1 y_1 + A_2 y_2}{A_1 + A_2} = \frac{(1.5875\ mm)(30\ mm)(15\ mm) + (30\ mm - 1.5875\ mm)(1.5875\ mm)(\frac{1.5875}{2}\ mm)}{(1.5875\ mm)(30\ mm) + (30\ mm - 1.5875\ mm)(1.5875\ mm)} = 8.0899$$

$$I = \frac{1}{12} b_1 h_1^3 + A_1 d_1^2 + \frac{1}{12} b_2 h_2^3 + A_2 d_2^2$$

$$= \frac{1}{12}(1.5875\ mm)(30\ mm)^3 + (30\ mm)(1.5875\ mm)(15\ mm - 8.0899\ mm)^2 + \frac{1}{12}(30\ mm - 1.5875\ mm)(1.5875\ mm)^3$$

$$+ (30\ mm\ - 1.5875\ mm)(1.5875\ mm)\left(8.0899\ mm - \frac{1.5875}{2}\ mm\right)^2$$

$$= 8256.52\ mm^4$$

$$\sigma_n = \frac{F_g}{4A} = \frac{200\ N}{(1.5875\ mm)(30\ mm) + (30\ mm - 1.5875\ mm)(1.5875\ mm)} = 2.1568 \text{ Mpa}$$

Module Base Subsystem Analysis

Leg Stress Calculations Cont.

- Bending Stress Calculations

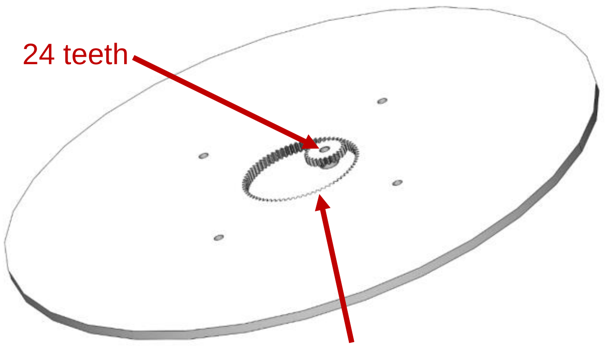
$$M = \frac{F_{drag}}{4} h = \frac{605.8\ N}{4}(100\ mm) = 15145\ Nmm$$

$$\sigma_b = \frac{My}{I} = \frac{(15145\ Nmm)(0.79375\ mm)}{8256.52\ mm^4} = 1.456\ MPa$$

Factor of Safety

$$N = \frac{S_{sy}}{\sigma_n + \sigma_b} = \frac{490\ MPa}{2.1568\ MPa + 1.4559\ MPa} = 135.6$$

Module Base Subsystem Analysis



Motor Torque Calculations

- Assume reset takes 600 seconds at the end of each day
- Assume the motor starts from rest

$$\frac{N_i}{N_o} = \frac{24\ teeth}{72\ teeth} = \frac{1}{3}$$

$$\omega_o = \frac{\Delta\theta}{t} = \frac{2\pi\ rad}{600\ s} = 0.01047\ rad/s$$

$$\alpha_o = \frac{\Delta\omega_o}{t/2} = \frac{0.01047\ rad/s}{300\ s} = 3.49 \times 10^{-4}\ rad/s^2$$

$$\omega_i = 3\omega_o = 3(0.01047\ rad/s) = 0.03142\ rad/s$$

$$\alpha_i = \frac{\Delta\omega_i}{t/2} = \frac{0.03142\ rad/s}{300\ s} = 1.05 \times 10^{-4}\ rad/s^2$$

$$M = I\alpha_i = 4.02\ kg * m^2(1.05 \times 10^{-4}\ rad/s^2) = 4.2 \times 10^{-4}\ Nm$$

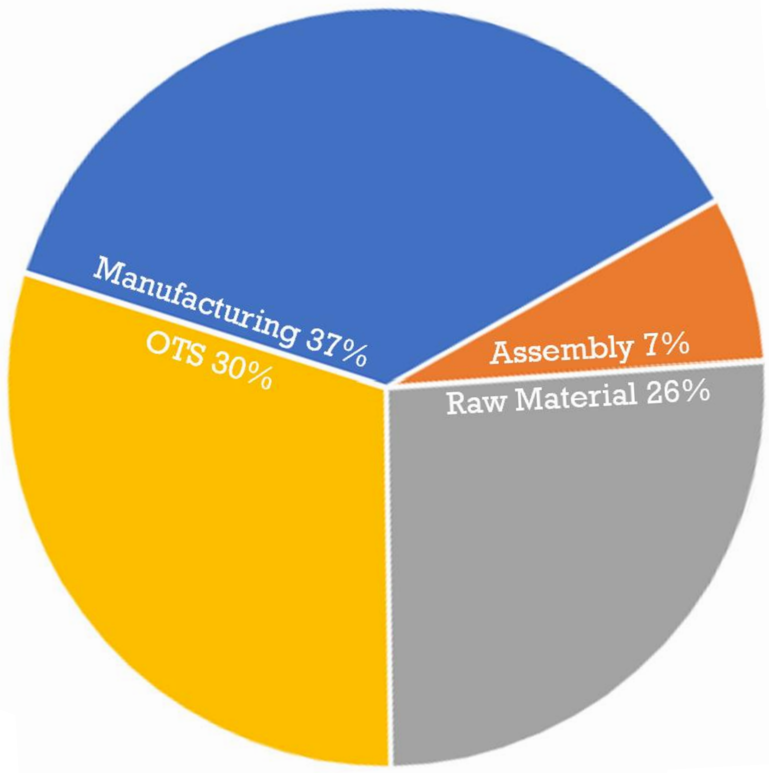
Moment of Inertia I Calculated through SolidWorks

Power Calculation

$$P_{min} = M\omega_i = 4.2 \times 10^{-2}\ Nm(0.03142\ rad/s) = 1.32 \times 10^{-2} W$$

Cost Summary – Entire Heliostat Field

Category	Cost	Color
Manufacturing	$186.53	
Assembly	$35.72	
Raw Material	$130.87	
OTS	$151.68	
Modified OTS	$0.00	
Energy	$0.02	
Total	**$504.82**	



Lifetime Summary

Although our cost is high, our design's lifespan is predicted to be well over 20 years

Brushless DC Motors have estimated lifespans of 10,000 hours

Our motors will have lifespans of approximately 68.5 years

Borosilicate Glass is highly resistant to thermal stresses

It has an extremely low coefficient of thermal expansion

Most of our design is made from sheet metal parts

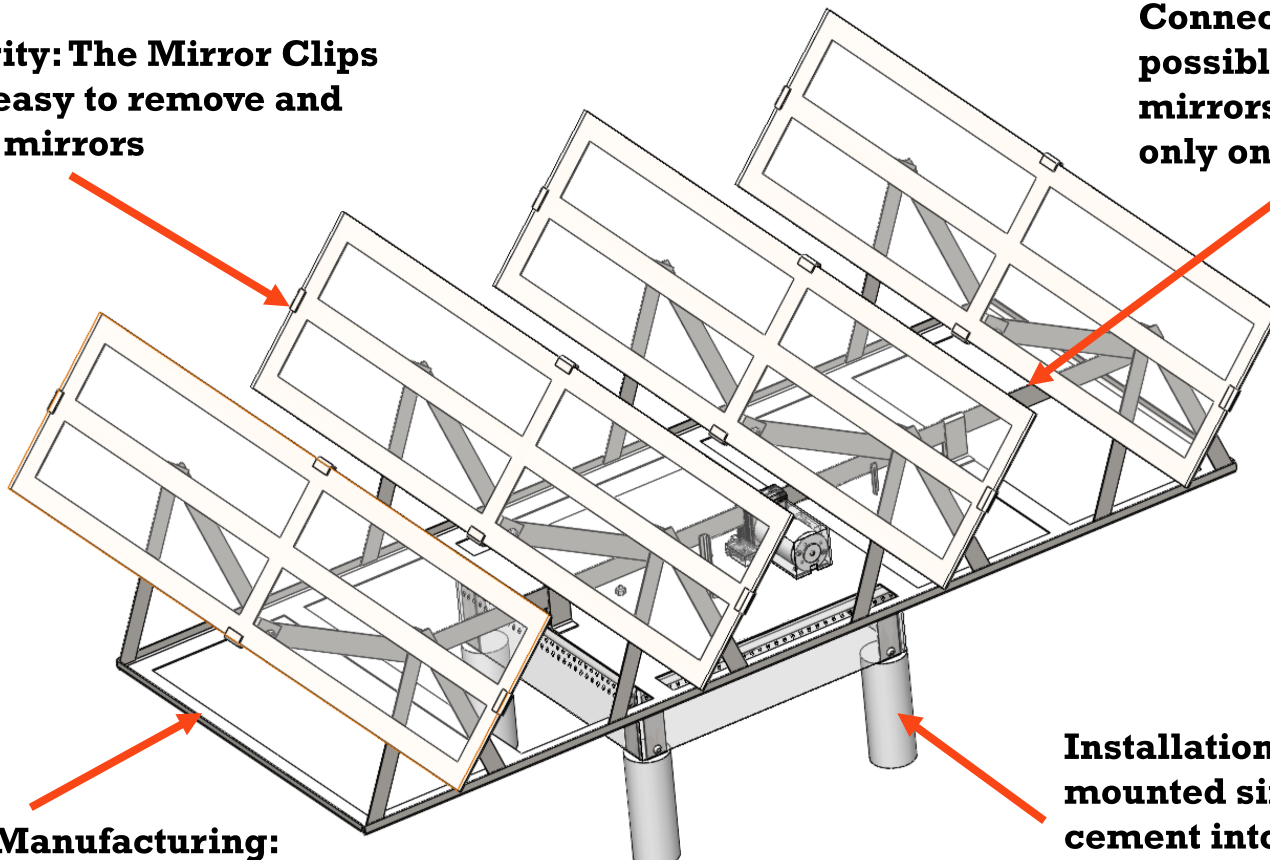
These parts are designed for infinite life, as shown in our analyses

Herbert Wertheim College of Engineering
MECHANICAL AND AEROSPACE ENGINEERING
POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

Design Highlights and Key Features

Modularity: The Mirror Clips make it easy to remove and reattach mirrors

Minimal Actuation: The Connecting Rod makes it possible to rotate four mirrors with the use of only one motor



Durability/Manufacturing: Most of the design is made from the same type of sheet metal

Installation: The module is mounted simply by pouring cement into four holes where the module base goes into the ground

Conclusion

Operation Concentration has designed a product that is

- Easy to manufacture due to the simple materials and techniques
- Quickly installed on the site of the solar farm
- Lower cost than heliostats on the market today
- Modular design to allow for faster maintenance

Thank you to the UF Department of Mechanical and Aerospace Engineering as well as our corporate sponsors!

UF Herbert Wertheim College of Engineering
UNIVERSITY *of* FLORIDA

Questions?

™