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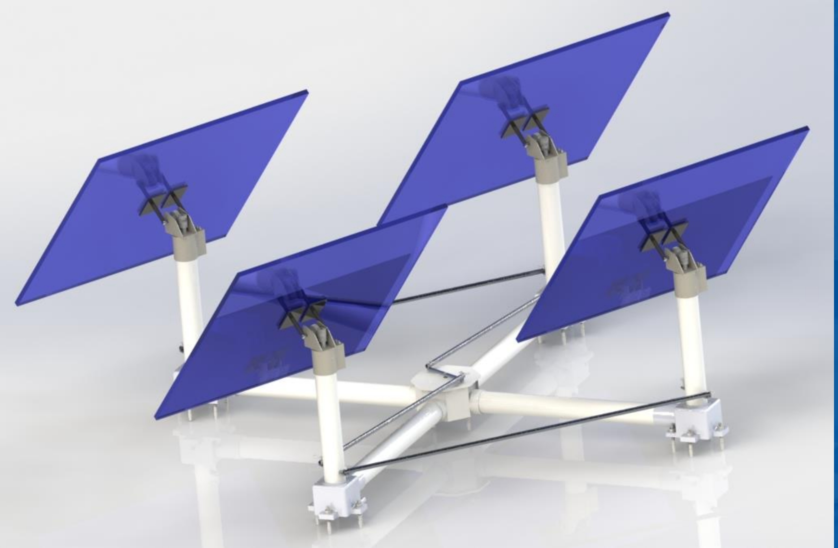
Sun Chariot

Innovative Heliostat Module Design



EML4501 Spring 2022 Section 29054

Group 9: Daniel Colbert, Daniel Corrada, Jessica Blazek, Matthew Giles, Roberto Profeta, Roni Alima, Utah Johnson

Presentation Outline

Hedgehog Concept

Product Overview

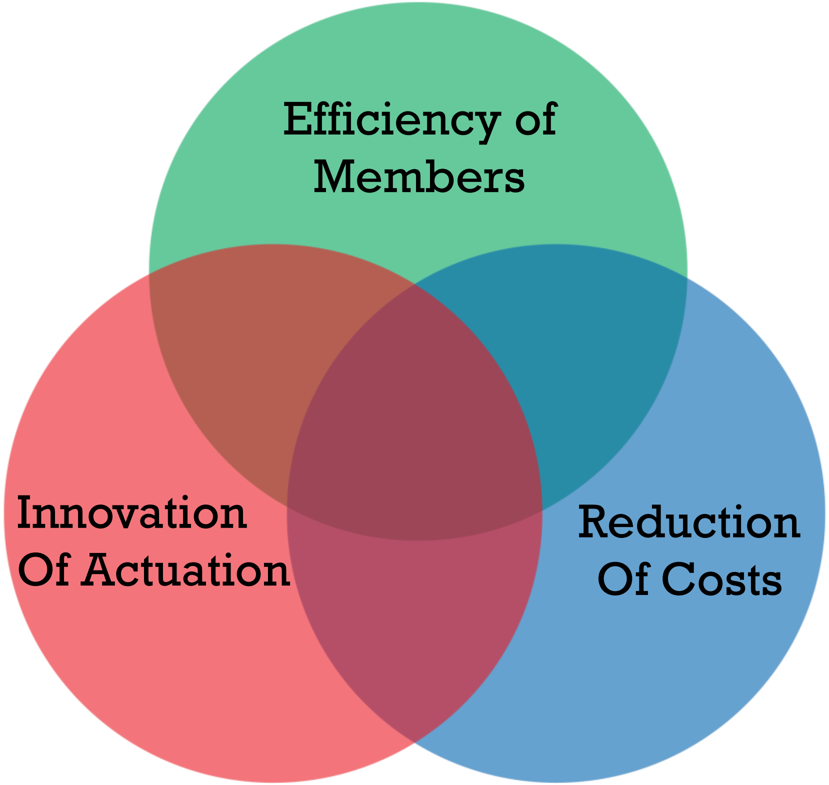
- Subsystem Identification and Key Features
- Engineering Analyses in Each Subsystem

Cost Breakdown

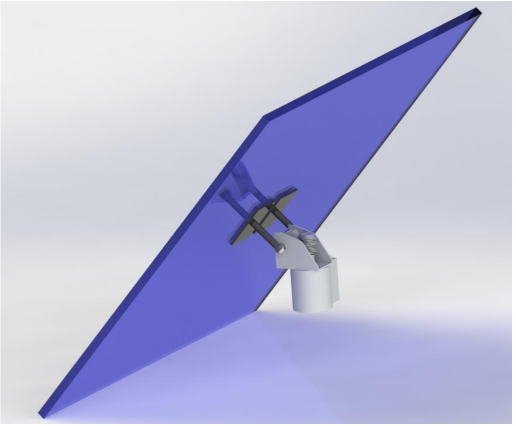
Conclusion

Hedgehog Concept

- Sun Chariot is a heliostat design marked by its novel actuation which maximizes mechanical efficiency.

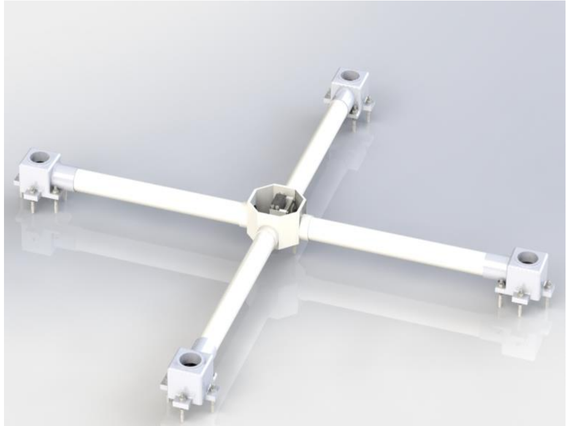


Identification of Subsystems

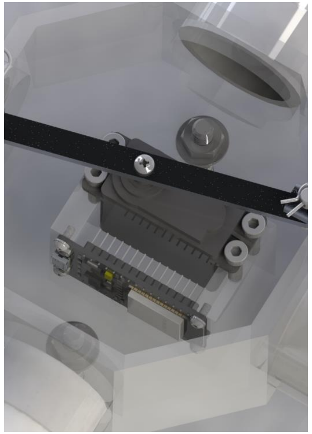


Reflector

Rotating Mechanism

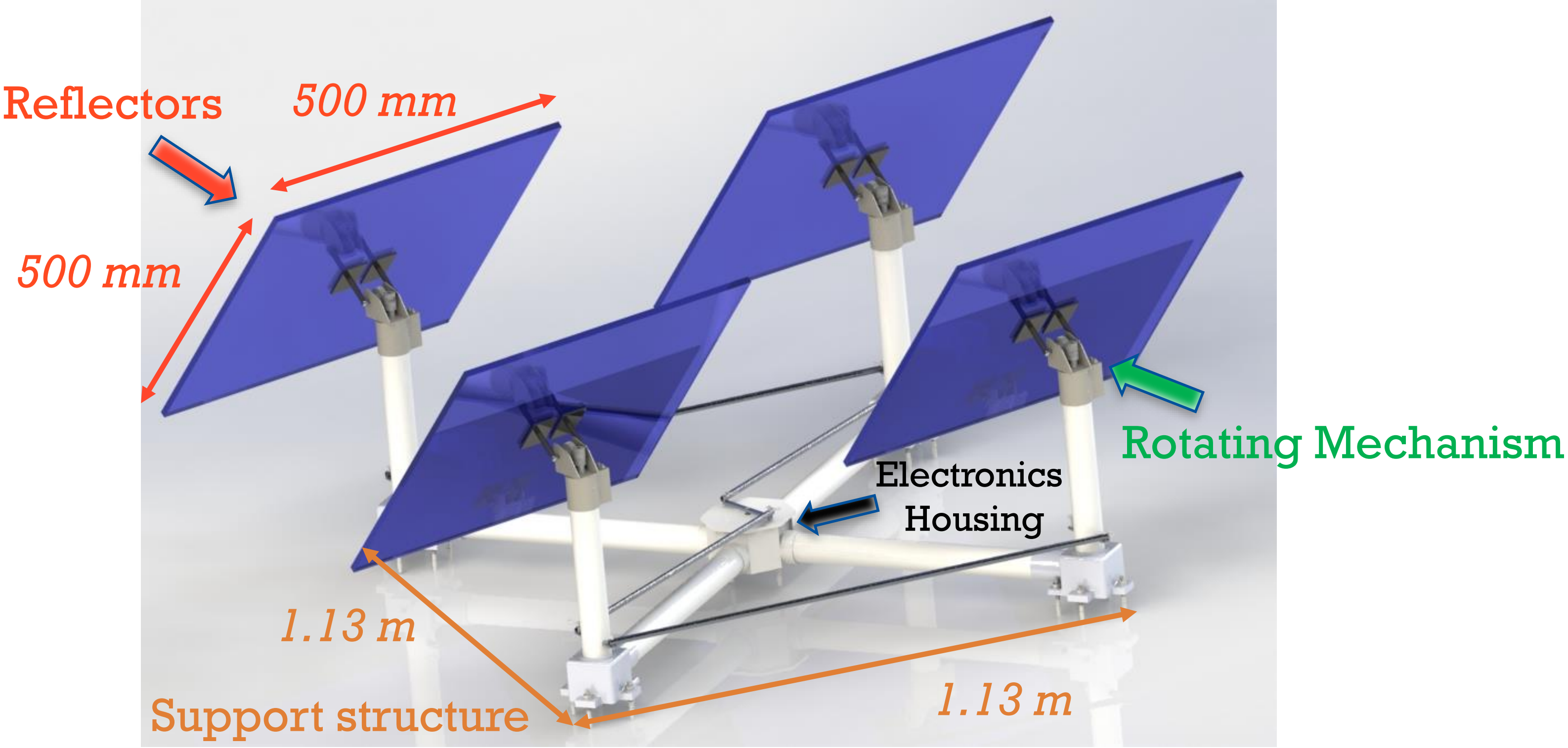


Support Structure

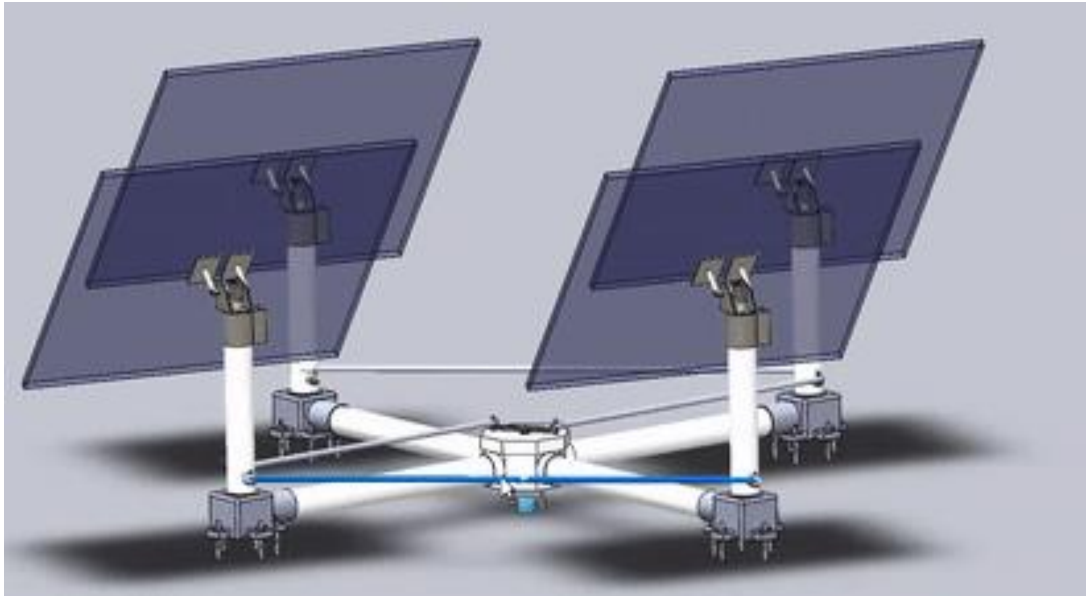


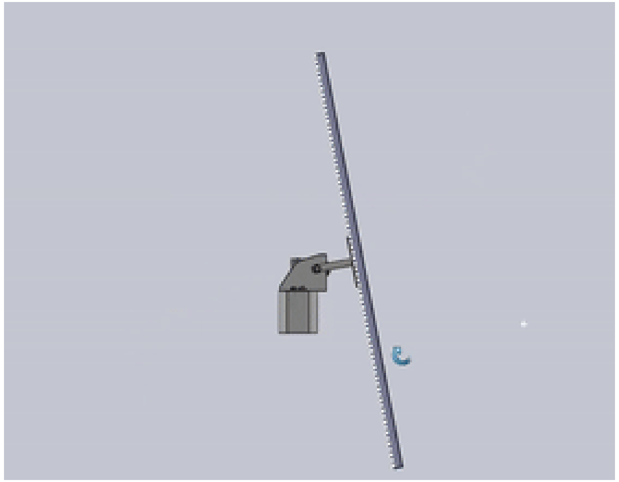
Electronics

Product Overview



Two-Axis Rotation





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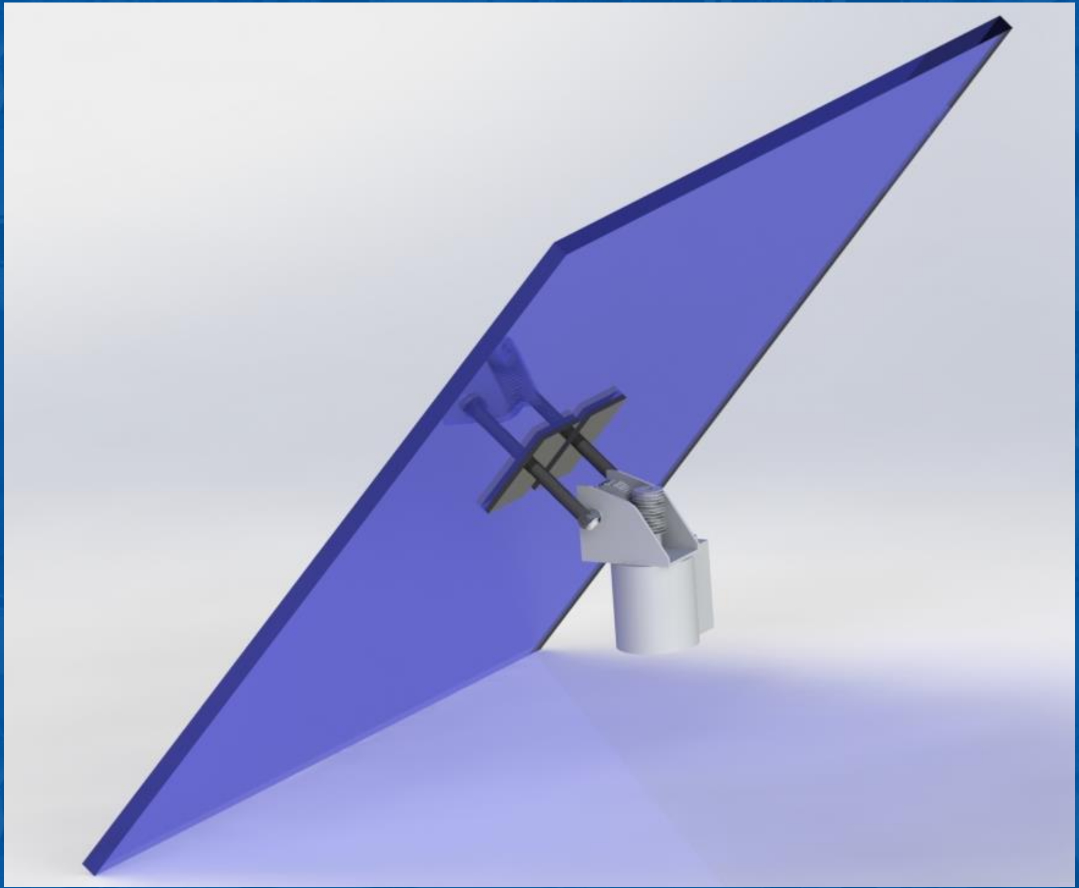
Reflector



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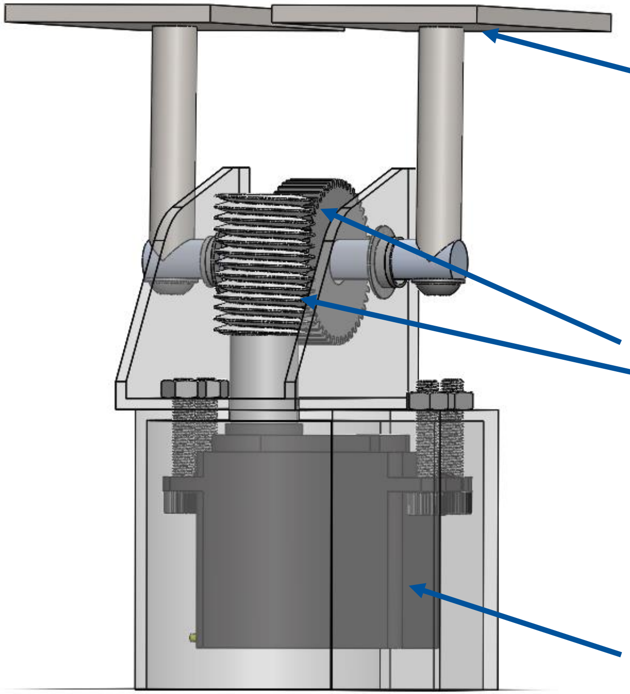
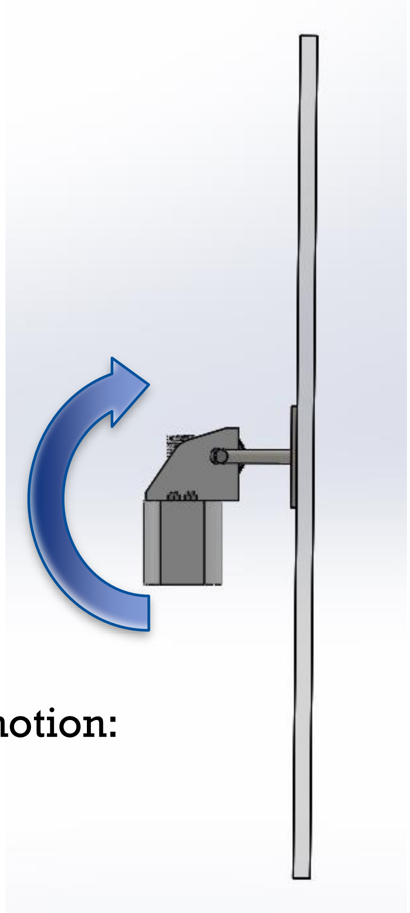
Degrees of Rotation (Major Axis)



Mirror bonds to plates with urethane

Gear reduction 48:1

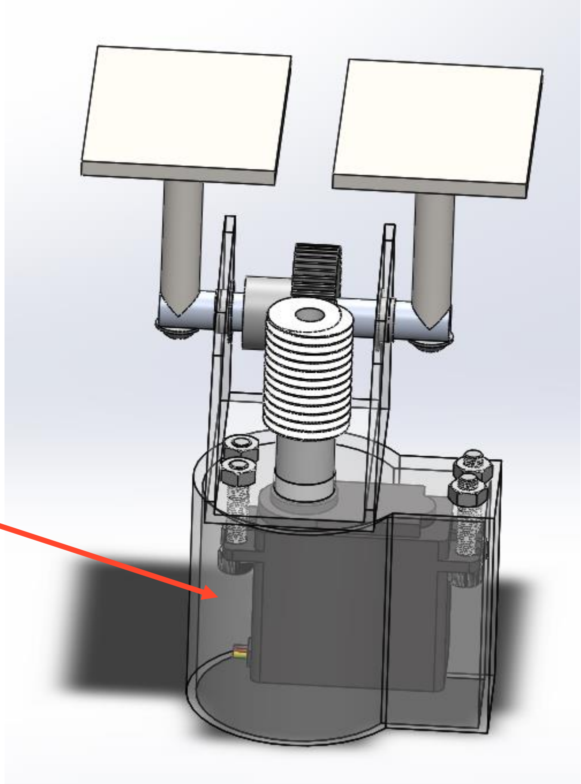
Servo resolution of ±0.144°



Full range of motion: -90° → +90°

Degrees of Rotation (Major Axis)

Torque after gear reduction: 7.01 N·m

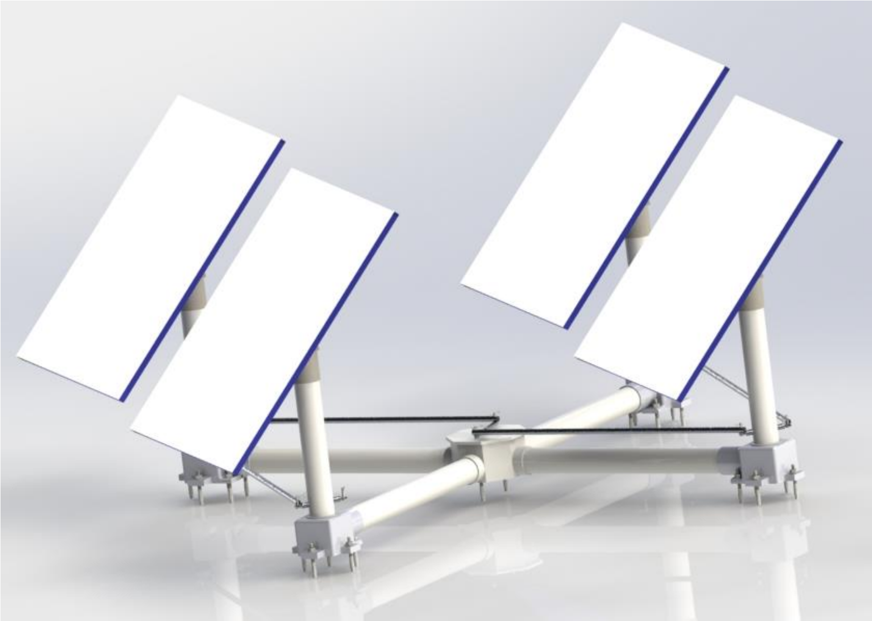


Major axis motor:
MS-R-6-40 Analog Servo

5 kg·cm max torque
4.8 Volts
360˚ rotation motor

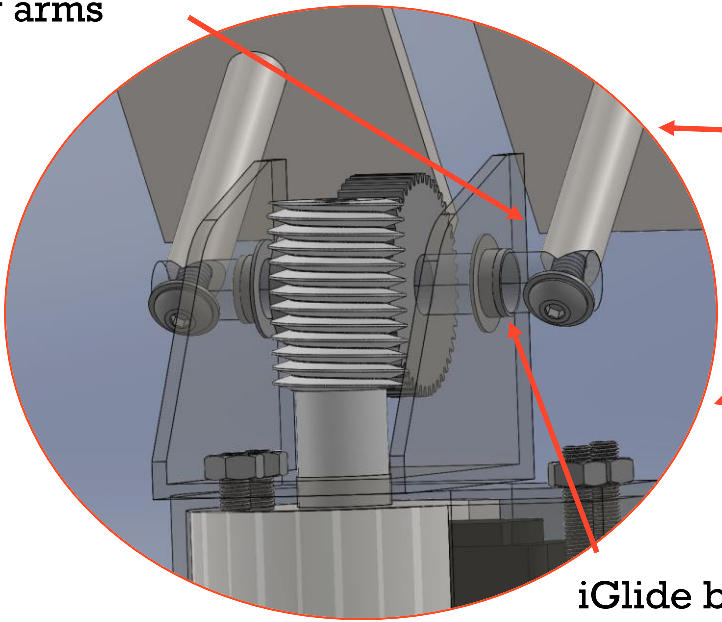
Reflector Sub-Assembly

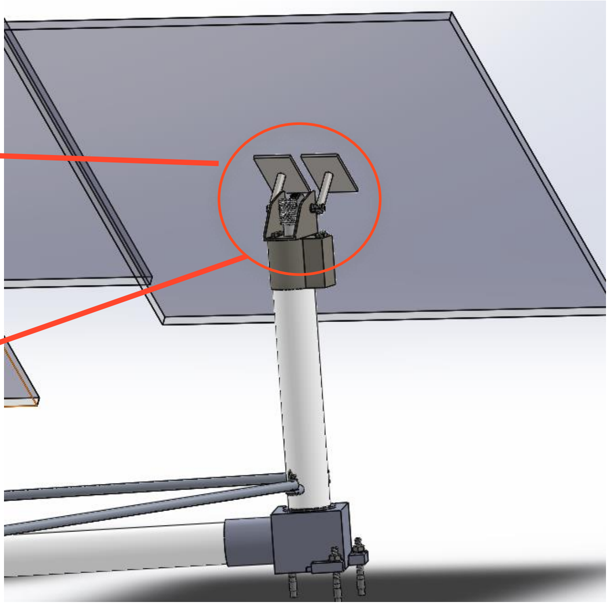
- Four Independently Moving Square Reflectors
  - $500\ mm \times 500\ mm$
- Silver-Coated Glass
- Fastened via Urethane Adhesive



Simple Pivot Mechanism

D-shaped rod supporting reflector arms





iGlide bushing surface

Solar Concentration Ratio

$$\frac{N_{reflectors} * A_{reflector}}{A_{reciever}} = SCR$$

$$\frac{4250 * (0.25m^2)}{1\ m^2} = 1063\ suns$$

Thermal Input Power

$$\eta_{heliostat} * A_{heliostat} * N_{heliostats} * \dot{Q}_{sun} = P_{thermal\ input}$$

$$0.98 * 0.25 * 4250 * 1000 = 1.04\ MW$$

Thermal Fatigue

$$\dot{Q} = h(T_{max} - T_e)$$

Glass:

$$T_{max} = T_e + \frac{\dot{Q}}{h} = 49^oC + \frac{1000\frac{W}{m^2}}{24\frac{W}{m^{2\,o}C}} = 90.6^oC$$

Reflective Silver Mirror:

$$T_{max} = T_e + \frac{\dot{Q}}{h} = 49^oC + \frac{1000\frac{W}{m^2}}{10\frac{W}{m^{2\,o}C}} = 149^oC$$

$T_{min} = -6.67^oC$ (Coldest temperature in placement location)

$$\Delta T = 107^oC - (-6.67^oC) = 97.3\,^oC$$

$$\Delta T = 149^oC - (-6.67^oC) = 155.7\,^oC$$

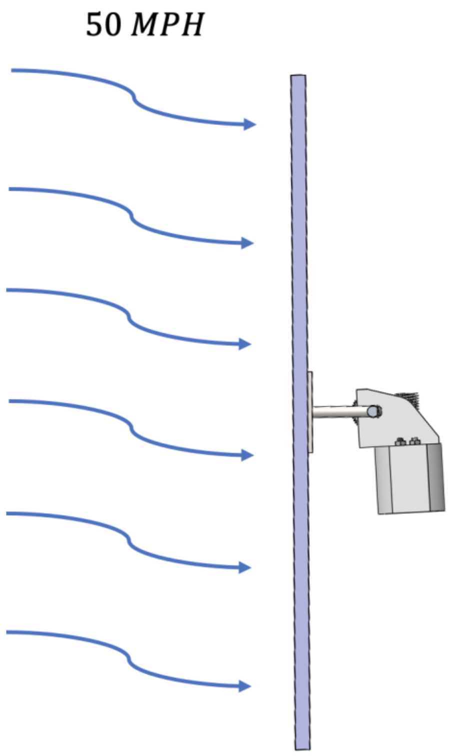
Hasselman, D. P. H., Badaliance, R., McKinney, K. R., & Kim, C. H. (n.d.). *Failure prediction of the thermal fatigue resistance of a glass - Journal of Materials Science*. SpringerLink. Retrieved April 13, 2022, from https://link.springer.com/article/10.1007/BF00540926

Otiaba, K. C., Bhatti, R. S., Ekere, N. N., Mallik, S., and Ekpu, M., "Finite element analysis of the effect of silver content for Sn–Ag–cu alloy compositions on thermal cycling reliability of solder die attach," *Engineering Failure Analysis* Available: https://www.sciencedirect.com/science/article/pii/S1350630712002166.

Drag Force on Reflector

- C_D = Drag coefficient = 1.28
- A = Frontal area = $0.25\ m^2$
- ρ = Density = $1.202 \frac{kg}{m^3}$
- v = Wind speed = $50\ MPH$ ($22.4 \frac{m}{s}$)
- F_w = Drag force on reflector

$$F_w = 0.5\rho v^2 C_D A = 96\ N$$



Reflector Bending Stress

- F_w = Reflector drag force = 96 N
- l_r = Reflector length = 0.5 m
- w_r = Reflector width = 0.5 m
- t_r = Reflector thickness = 0.005 m
- σ_r = Bending stress
- n = Factor of safety

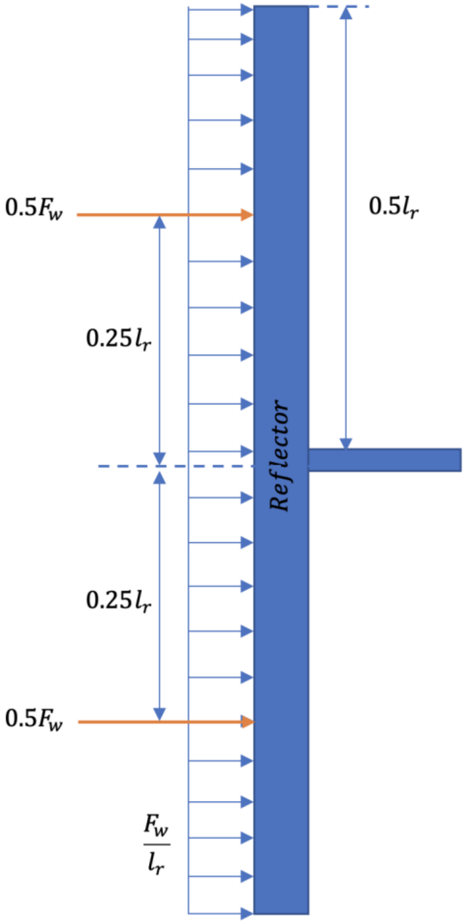
$$M_{max} = (0.5F_w)(0.25l_r) = 6\ N \cdot m$$

$$I = \frac{w_r t_r^3}{12} = 5.21 \times 10^{-9} m^4$$

$$y = \frac{t_r}{2} = 0.0025\ m$$

$$\sigma_r = \frac{M_{max} y}{I} = 2.88\ MPa$$

$$n = \frac{S_u}{\sigma_r} = 24.31$$



PP2401 Autourethane Strength

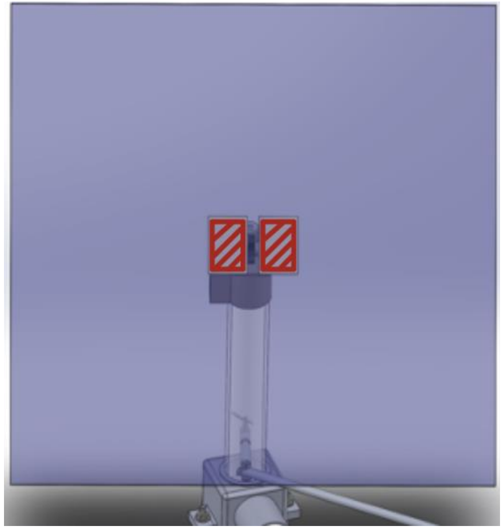
- F_w = maximum wind force = 96 N
- w = width of application = 40 mm
- l = length of application = 60 mm
- σ_y = strength of Urethane = 10.14 MPa
- A_c = contact area
- σ = maximum stress
- n = factor of safety

$$A_c = 2(w * l) = 4800\ mm^2$$

$$\sigma = \frac{F_w}{A_c} = 0.02\ MPa$$

$$n = \frac{\sigma_y}{\sigma} = 507$$

- ** High factor of safety due to large application area of Urethane (negligible effect on cost)



Customer Needs: Reflector Subsystem

Customer Need	Design Specifications	
Total reflective area ≤ 1 m^2	Total reflective area: 1 m^2	✓
Cleaning time ≤ 15 minutes	Total cleaning time: 10 min	✓
Focal thermal input power of at least 1 MW	Focal thermal input power: 1.04 MW	✓
Solar concentration ratio > 1000 suns	Solar concentration ratio: 1063 suns	✓
Reflection distance ≥ 100 m	Reflective distance 100 m	✓

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Rotating Mechanism

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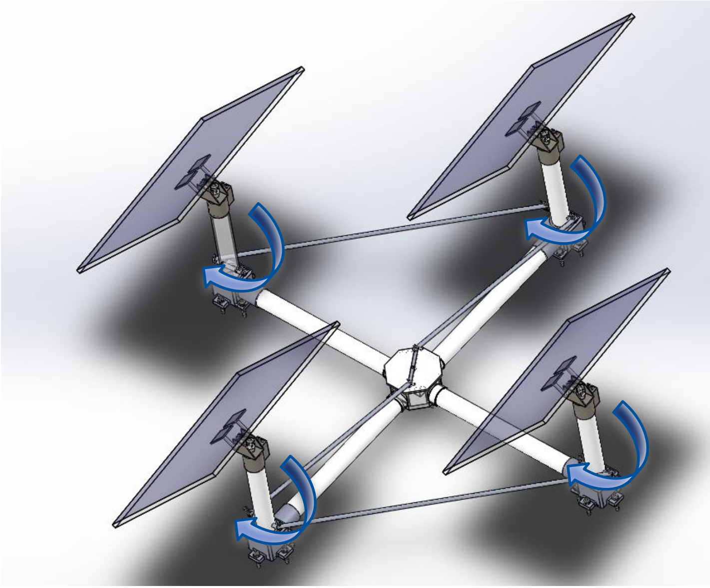
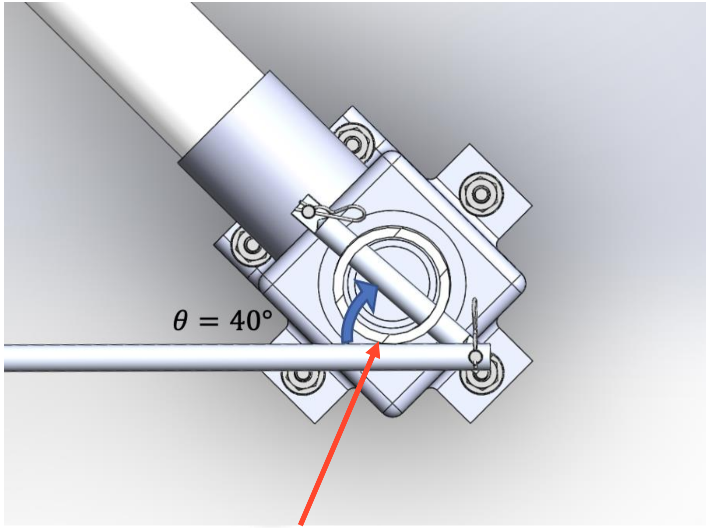
Minor Axis Rotation



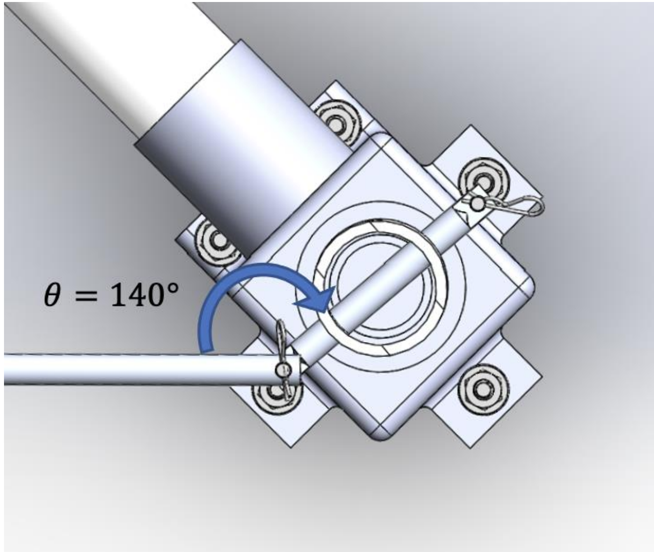
Full 100˚ rotation

Minor Axis Rotation

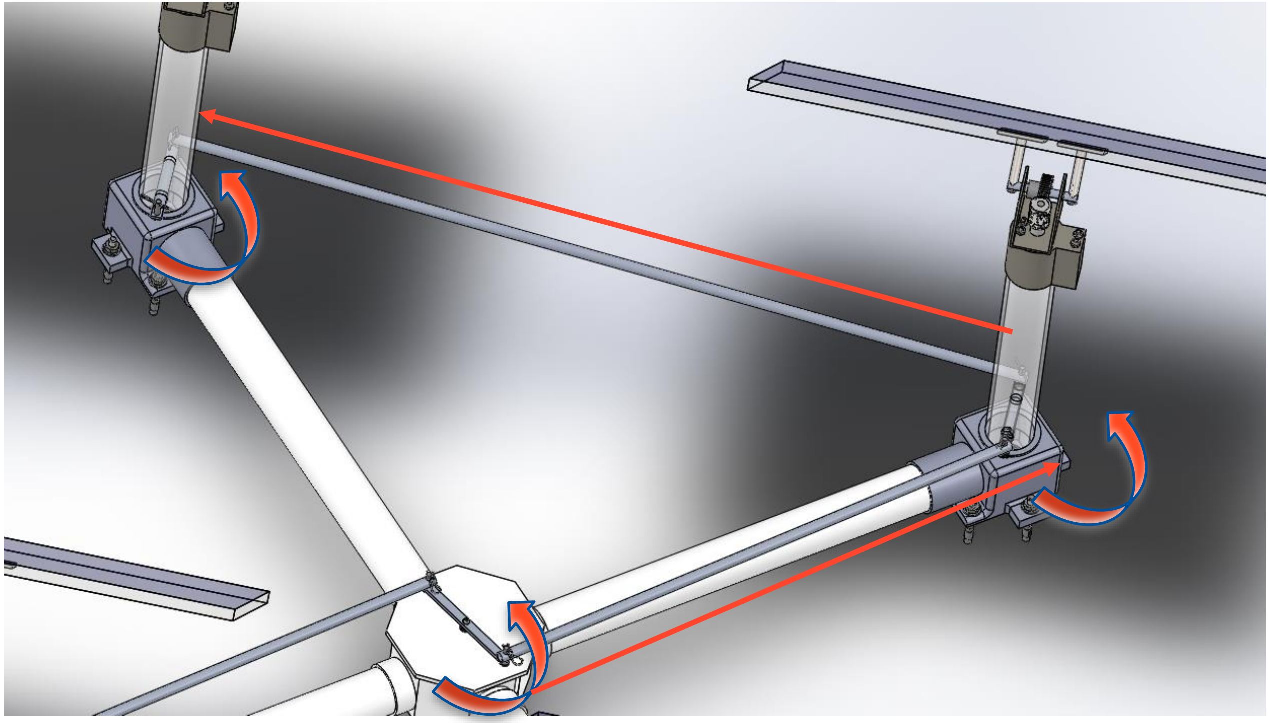


Point of contact

Full 100° rotation



Rotating Mechanism



Central Motor:
CYSS0090 Analog Servo Motor

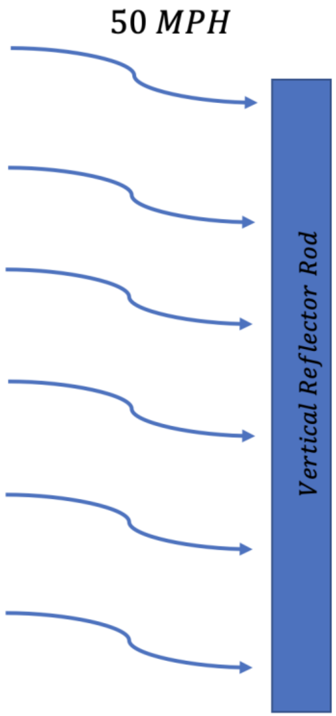
10 kg ·cm Max Torque
4.8 Volts

Drag Force on Vertical Reflector Rod

- C_D = Drag coefficient = 1.1
- d_r = Rod diameter = 0.042 m
- h_r = Rod height = 0.325 m
- v = Wind speed = 50 MPH $\left(22.4\frac{m}{s}\right)$
- ρ = Air density = 1.202 $\frac{kg}{m^3}$
- F_D = Drag force on rod
- A = Frontal area = 0.25 m^2

$$A = d_r h_r$$

$$F_D = 0.5\rho v^2 C_D A = 4.2\ N$$



Vertical Rotating Rod Stress

- h_r = Height of rod = 0.325 m
- d_r = Outer diameter of rod = 0.042 m
- r_o = Outer radius of rod = 0.021 m
- ρ = Density of air = 1.202 $\frac{kg}{m^3}$
- C_{Dr} = Reflector drag coefficient = 1.28
- C_{Dv} = Vertical rod drag coefficient = 1.1
- I = Moment of inertia = $7.9 \times 10^{-8}\ m^4$
- v = Velocity of air
- F_w = Drag force on reflector
- F_D = Drag force on rod
- M_r = Reaction moment

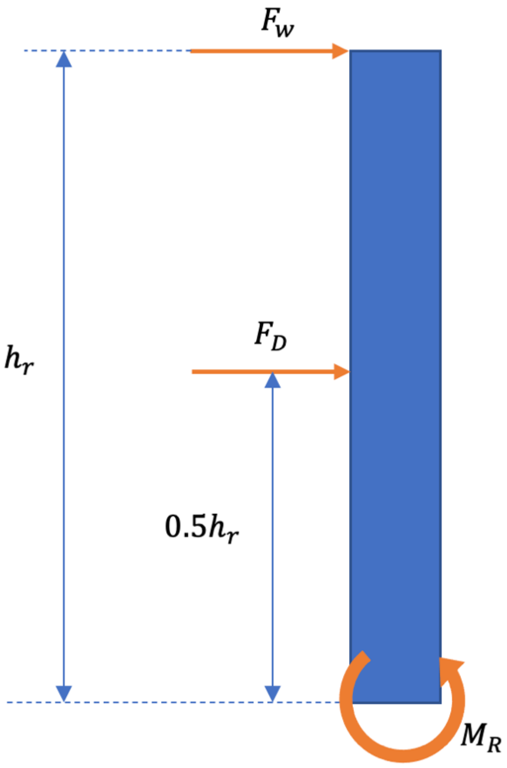
$$F_w = 0.5\rho C_{Dr} v^2 A_{ref} = 96\ N$$

$$F_D = 0.5\rho C_{Dv} v^2 h_r d_r = 4.2\ N$$

$$M_R = h_r(F_w + 0.5F_D) = 31.88\ \mathrm{N} * \mathrm{m}$$

$$\sigma_{bending} = \frac{M_R r_o}{I} = 8.48\ MPa$$

$$n = \frac{55\ MPa}{8.48\ MPa} = 6.49$$



Vertical Rotating Rod Deflection

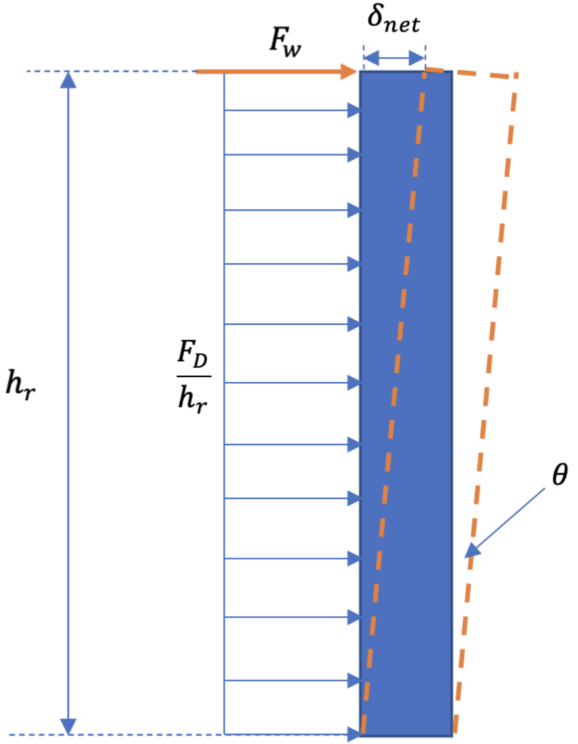
- E = Modulus of elasticity of PVC = 4.425 GPa
- δ_w = Deflection due to reflector
- δ_D = Deflection due to distributed load
- θ = Angle of deflection

$$\delta_w = \frac{F_w h_r^3}{3EI}$$

$$\delta_D = \frac{\left(\frac{F_D}{h_r}\right) h_r^4}{8EI} = \frac{F_D h_r^3}{8EI}$$

$$\delta_{net} = \delta_w + \delta_D = \frac{h_r^3}{EI}\left(\frac{F_w}{3} + \frac{F_D}{8}\right) = 3.2\ mm$$

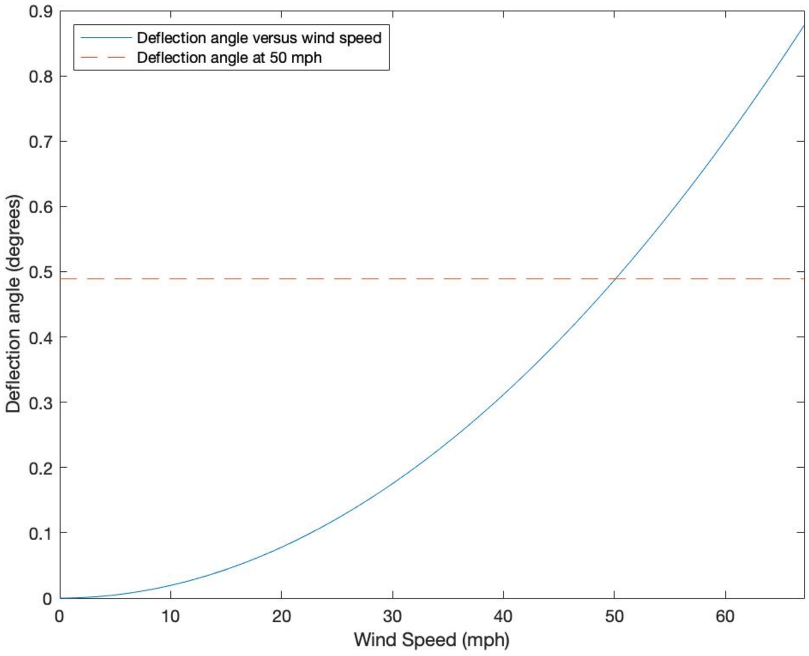
$$\theta = \tan^{-1}\frac{\delta_{net}}{h_r} = 0.49°$$



Vertical Rotating Rod Deflection (Cont.)

$$\theta_{max} = 0.29°$$

Rod Deflection at Various Speeds		
$Wind\ Speed\ (mph)$	$\delta_{net}\ (mm)$	$\theta\ (degrees)$
10	0.13	0.02
20	0.51	0.08
30	1.15	0.18
38	1.87	**0.29**
50	3.20	0.49



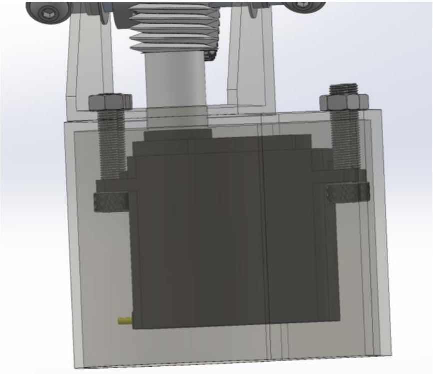
Resolution of Motor

Reflector Servo

- PW_{range} = pulse width range = $2500\mu s$
- θ_{tot} = total rotation = $360°$
- W_{db} = dead band width = $\pm 1\mu s$
- R = resolution

$$\frac{PW_{range}}{\theta_{tot}} = 6.944\mu s * degree^{-1}$$

$$R = \frac{W_{db}}{6.944\mu s * degree^{-1}} = \pm 0.144°$$

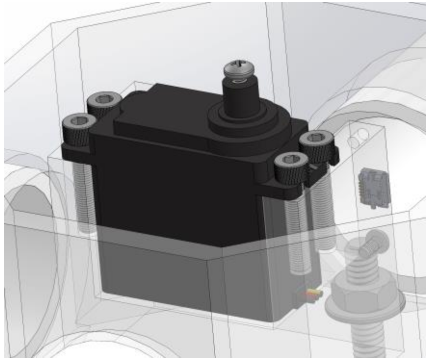


Central Servo

- PW_{range} = pulse width range = $2200\mu s$
- θ_{tot} = total rotation = $90°$
- W_{db} = dead band width = $\pm 2\mu s$
- R = resolution

$$\frac{PW_{range}}{\theta_{tot}} = 24.444\mu s * degree^{-1}$$

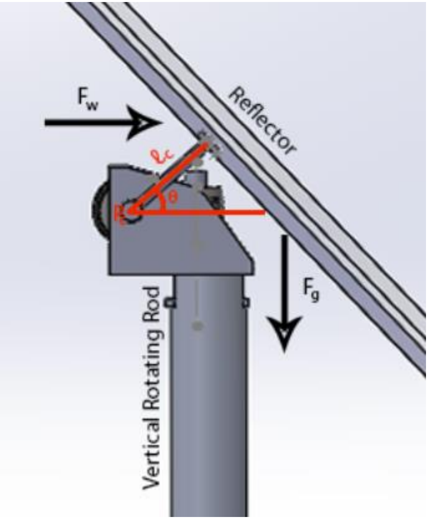
$$R = \frac{W_{db}}{24.444\mu s * degree^{-1}} = \pm 0.082°$$



Reflector Servo Torque

- $F_w = maximum\ wind\ force = 96\ N$
- $l_c = length\ of\ reflector\ support\ arm = 0.0412\ m$
- $m_r = mass\ of\ reflector = 1.35\ kg$
- $\eta_w = worm\ gear\ efficiency = 0.64$
- $G = gear\ ratio = 48$
- $T_{stall} = stall\ torque = 0.2157\ N \cdot m$
- $T_o = output\ torque$
- $\theta_r = angle\ of\ rotation$
- $T_c = torque\ applied\ to\ pinion\ rod$

Reflector Servo Torque

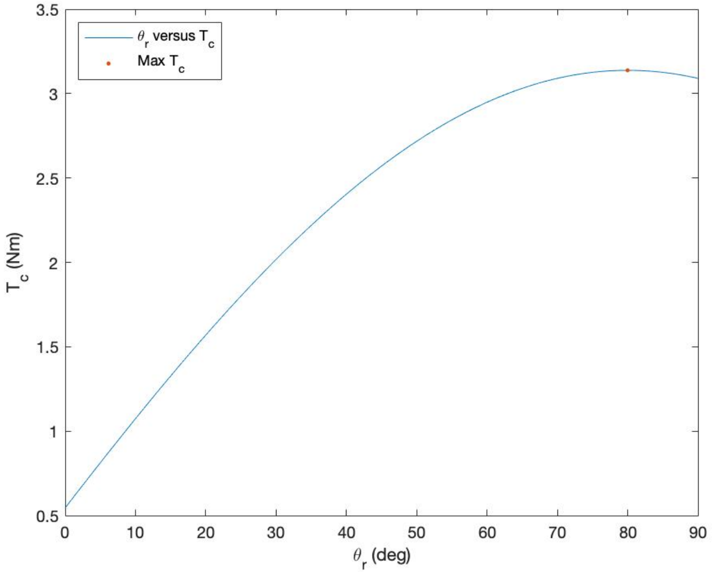


$$F_g = m_r g = 13.42\ N$$

$$T_c = F_w l_c sin\theta_r + F_g l_c cos\theta_r$$

Peak at $\theta_r = 79.9°$

$$T_c = 4.0\ N \cdot m$$



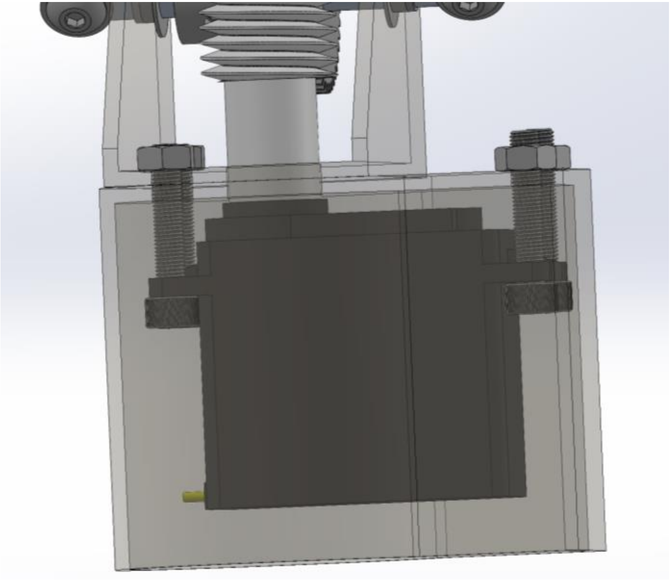
Reflector Servo Torque

$$m_w = \frac{T_o}{T_{stall}}$$

$$m_w = \eta_w G$$

$$T_o = T_{stall}\eta_w G = 6.6\ N \cdot m$$

$$T_o > T_c$$



Customer Needs: Rotating Mechanism

Customer Need	Design Specifications	
Reflect light toward 100 m tall receiver	Reflector can redirect light to >100 m height	✓
Total module cost ≤ $100/m^2$	Total module cost $301.06	✗
Automatic rotation of 180˚ laterally and 90˚ longitudinally	180˚ rotation in major axis 90˚ rotation in minor axis	✓
At least 10% cheaper than OTS	OTS parts used wherever possible	✓
Each heliostat individually rotates 180˚	Individual rotation of > 180˚	✓
Lifetime ≥ 20 years	Lifetime of 20+ years	✓

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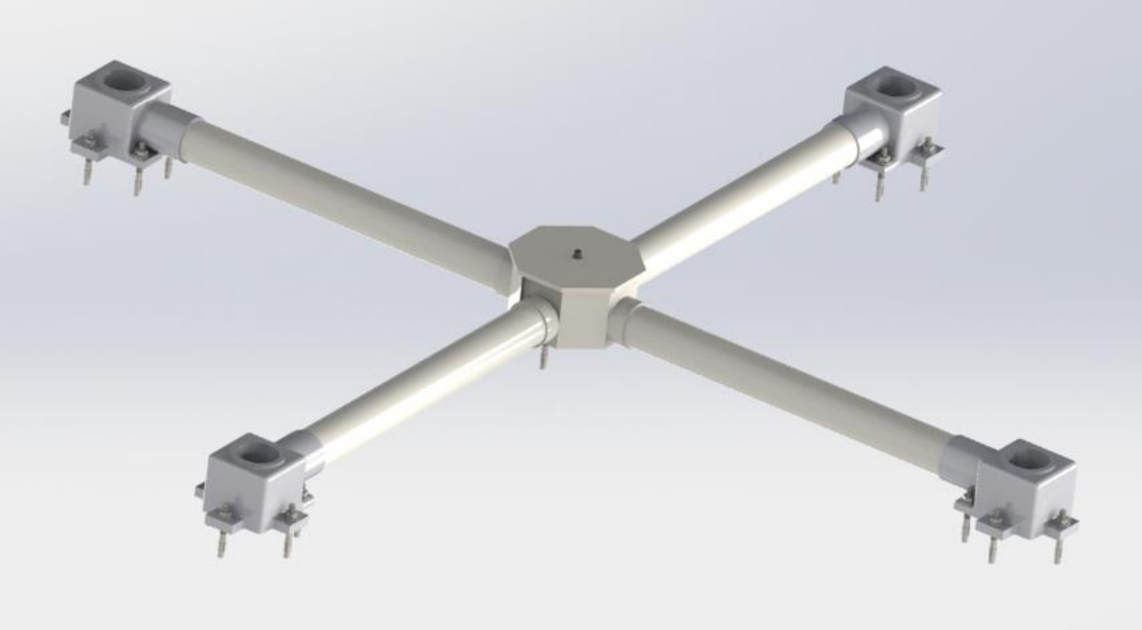
Support Structure



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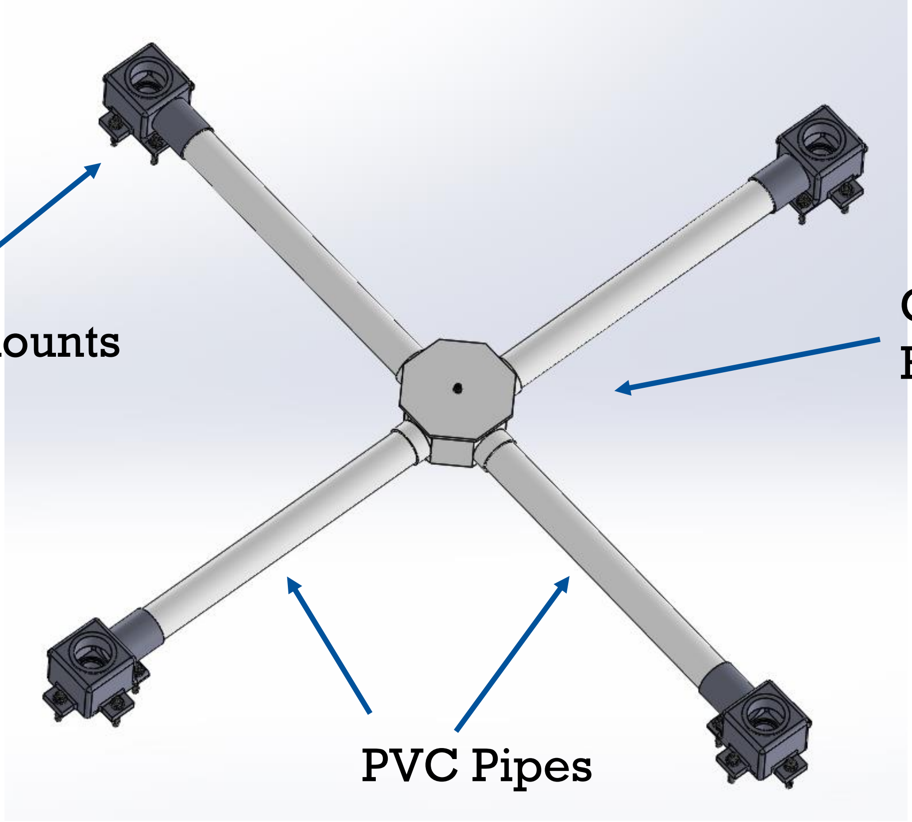
Support Structure

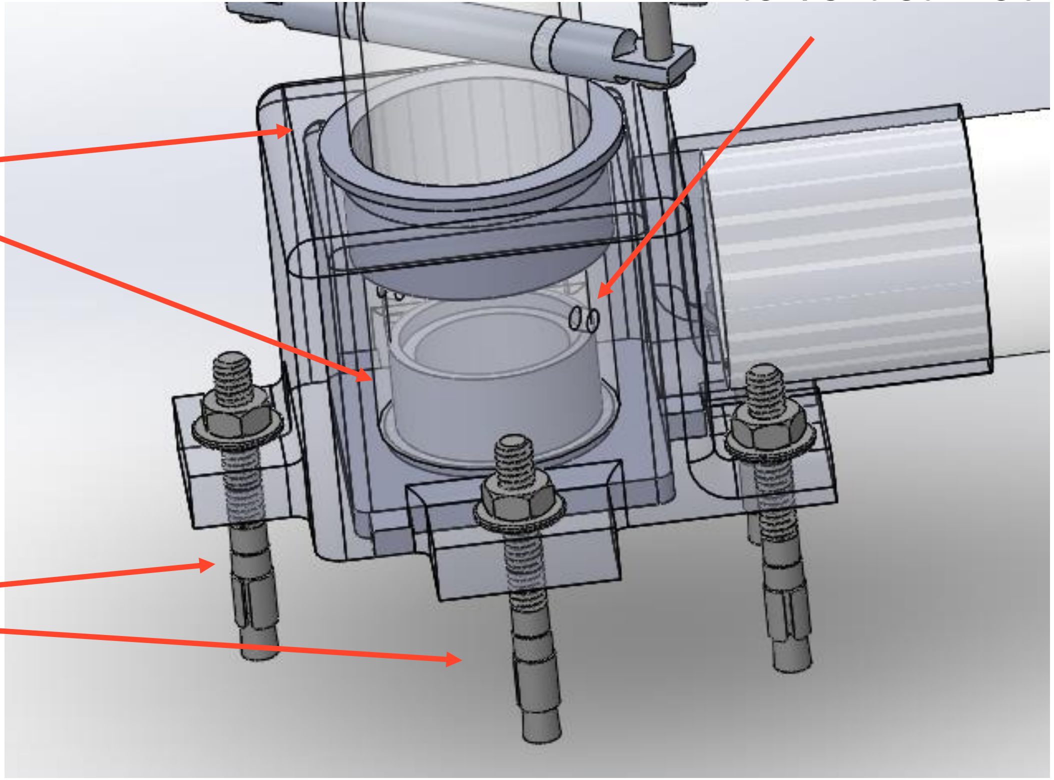


Corner Support Base

Hole for wire access into vertical rod

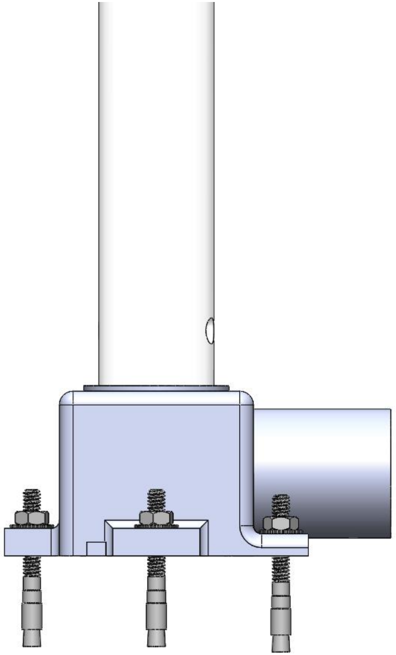
iGlide HPP bushings

Concrete anchor bolts



Base Flange Stress

- F_w = Drag force on reflector = 96 N
- F_D = Drag force on rod = 4.2 N
- h_r = Height of rod = 0.325 m
- w_b = Width of base = 0.07071 m
- l_f = Length of flange = 0.01588 m
- w_f = Width of flange = 0.0317 m
- t_f = Thickness of flange = 0.01 m
- M_A = Moment about point A (see fig.)
- σ_f = Flange bending stress
- σ_y = PETG Yield stress



Base Flanges Stress Cont.

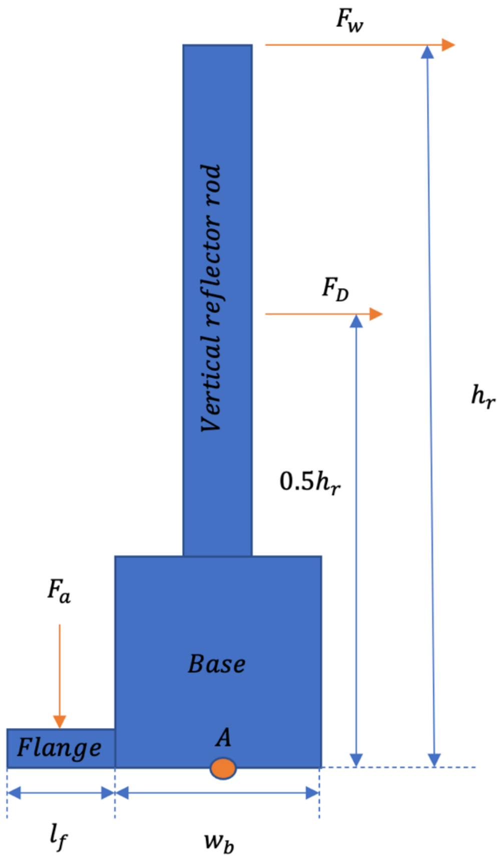
$$\sum M_A = F_a(0.5w_b + 0.5l_f) - F_w h_r - F_D(0.5h_r) = 0$$

$$F_a = \frac{h_r(F_w + 0.5F_D)}{0.5(w_b + l_f)} = 736.4\ N$$

$$M = 0.5F_a l_f = 5.85\ N * m$$

$$\sigma_f = \frac{My}{I} = \frac{My}{\frac{w_f t_f^3}{12}} = 11.7\ MPa$$

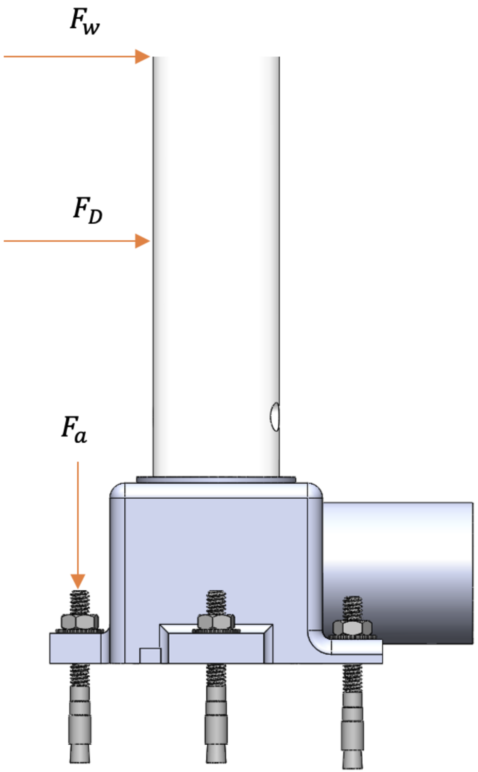
$$n = \frac{\sigma_y}{\sigma_f} = 4.27$$



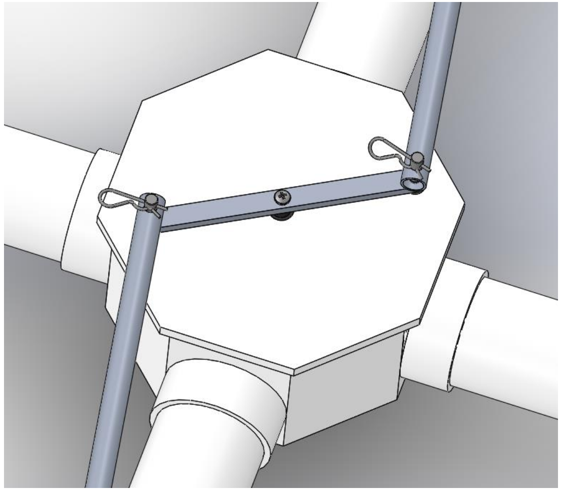
Anchor Strength

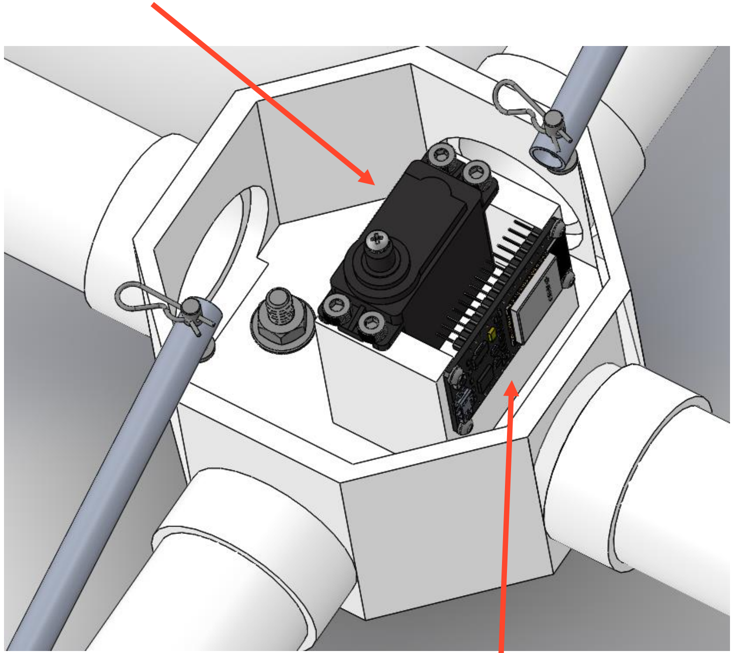
- From flange analysis, F_a = 736.4 N
- Pull-out strength of S_p = 2135.15 N
- Safety Factor of 2.90, assuming load on one anchor

$$n = \frac{S_p}{F_a} = 2.90$$



Middle Junction





Customer Needs: Support Structure

Customer Need	Design Specifications	
Heliostat area ≤ 0.25 m^2	Single heliostat area 0.25 m^2	✓
Heliostats per module = 4 to 16	4 heliostats per module	✓
Shading acceptable 60 min after dawn and 60 min before dusk	Designed to minimize shading within constraints	✓
Total module area ≤ 2 m^2	Total module area 1.35 m^2	✓
Factor of safety N ≥ 2	All factors of safety >> 2	✓
Withstand weather conditions to at least 25% waterproofing	All materials water resistant and passed thermal analyses	✓

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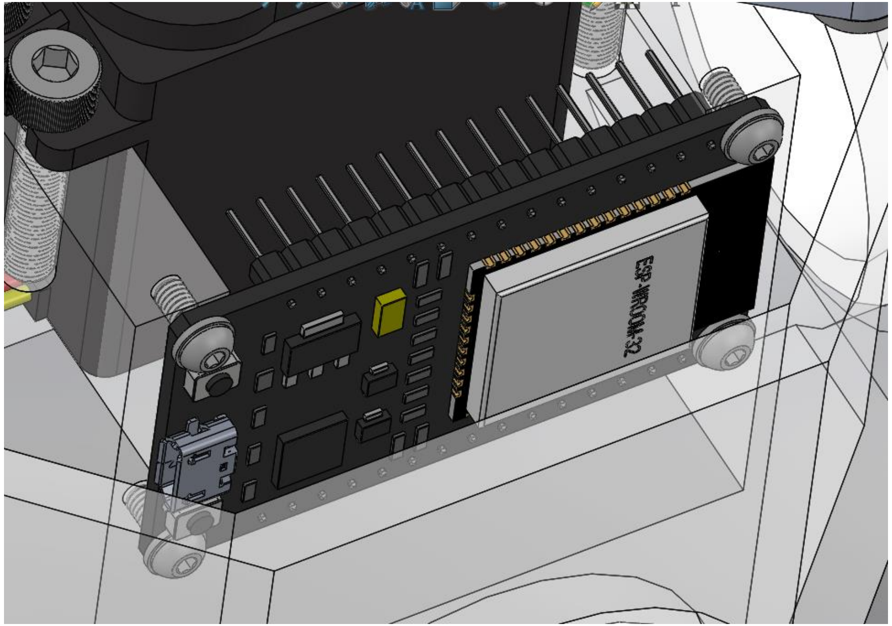
Controls & Electronics

Controls and Electronics

- ESP8266 Wi-Fi enabled microcontroller
- 5.5 Volt power supply
- Safe Operating Temp. Range: -40 °C to 125 °C



Microcontroller Thermal Analysis

- k = thermal conductivity constant = $0.2 \frac{W}{mK}$
- h = convective coefficient of air = $10 \frac{W}{m^2K}$
- σ = Stefan Boltzmann constant = $5.67 \times 10^{-8} \frac{W}{m^2K^4}$
- ϵ = emissivity = 0.84
- Δx = total length in contact with surface = 48 mm
- T_{surr} = ambient air temperature = 338.08 K
- q''_{cd} = conductive heat flux
- q''_{cv} = convective heat flux
- q''_{r} = radiative heat flux
- T_s = surface temperature

Microcontroller Thermal Analysis

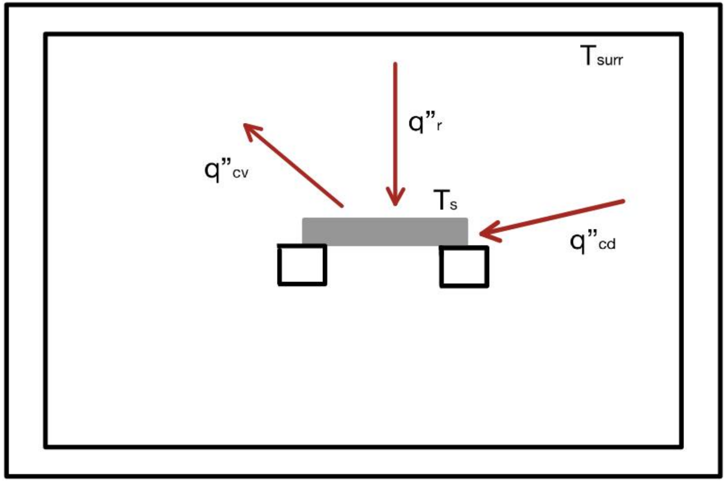
$$q''_{cd} + q''_{cv} + q''_{r} = 0$$

$$q''_{cd} = k\frac{\Delta T}{\Delta x}$$

$$q''_{cv} = h(T_s - T_{surr})$$

$$q''_{r} = \epsilon\sigma(T_s^4 - T_{surr}^4)$$

$$\therefore T_s = 357.251\ K = 84.25\ °C$$



Maximum operating temperature, $T_{max} = 125°C$

Customer Needs: Controls & Electronics

Customer Need	Design Specifications	
Critical tracking error $\leq \pm 0.25^{\circ}$	Servo motor resolution of $\pm 0.144^{\circ}$	✓
Active for 8.8 hours daily	Wifi enabled microcontroller can track at all hours of the day	✓

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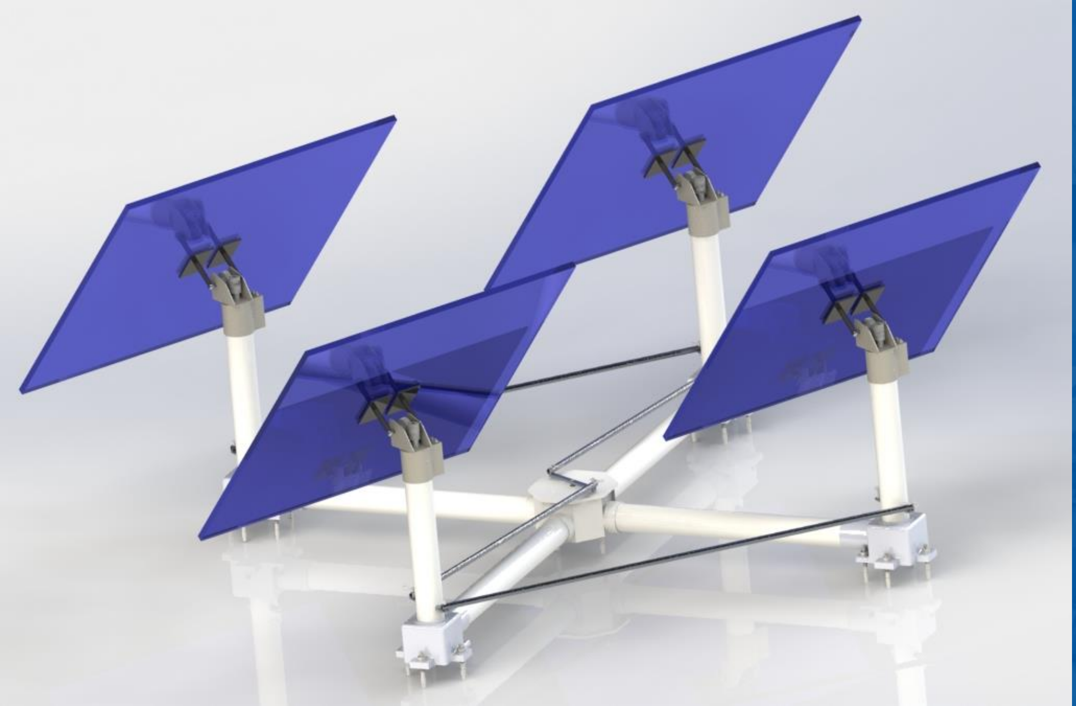
Full Assembly



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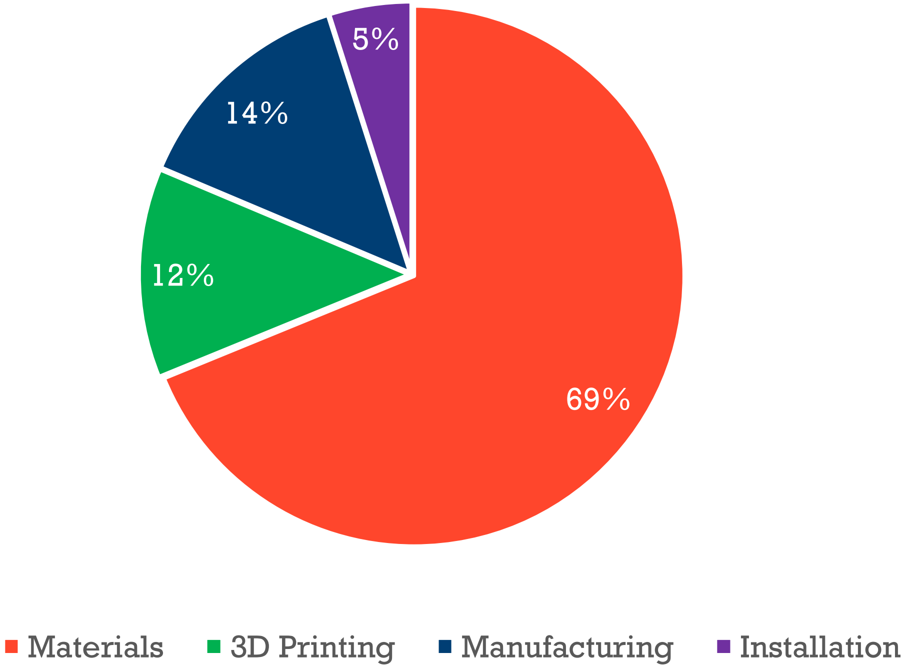
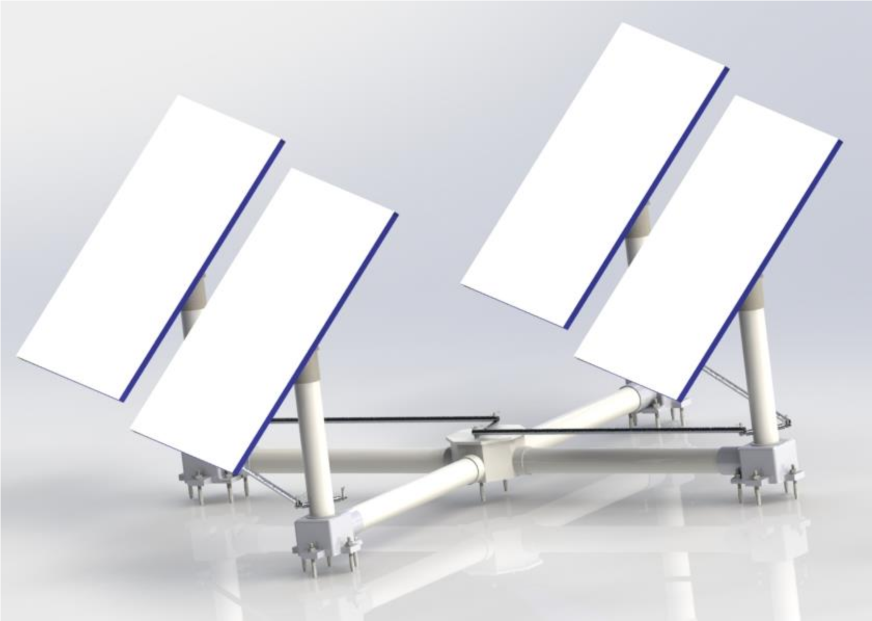
Cost Breakdown

Category	Cost
Materials	$205.83
3D Printing Components	$37.47
Manufactured Parts	$41.08
Installation	$14.70
Total	**$301.06**



Prototyping Defense

- Modularity
- Low Number of Actuators
- Small Footprint Ratio
- Easily Sourced Materials
- Multipurpose Usage of Members



Thank you for attending our presentation!







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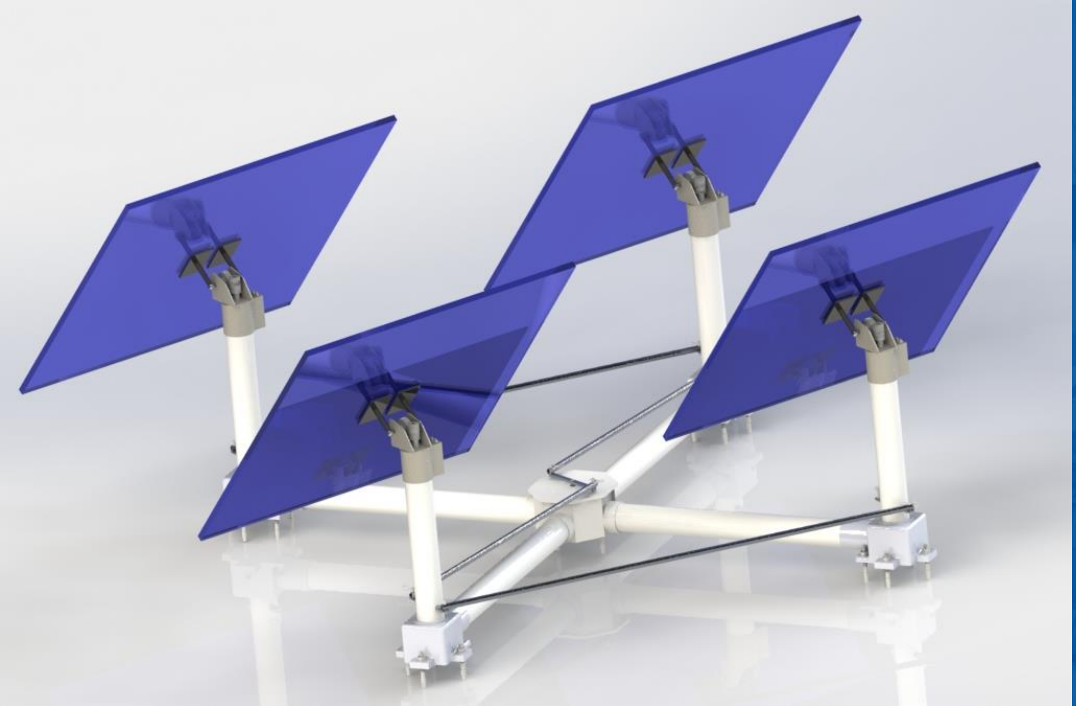
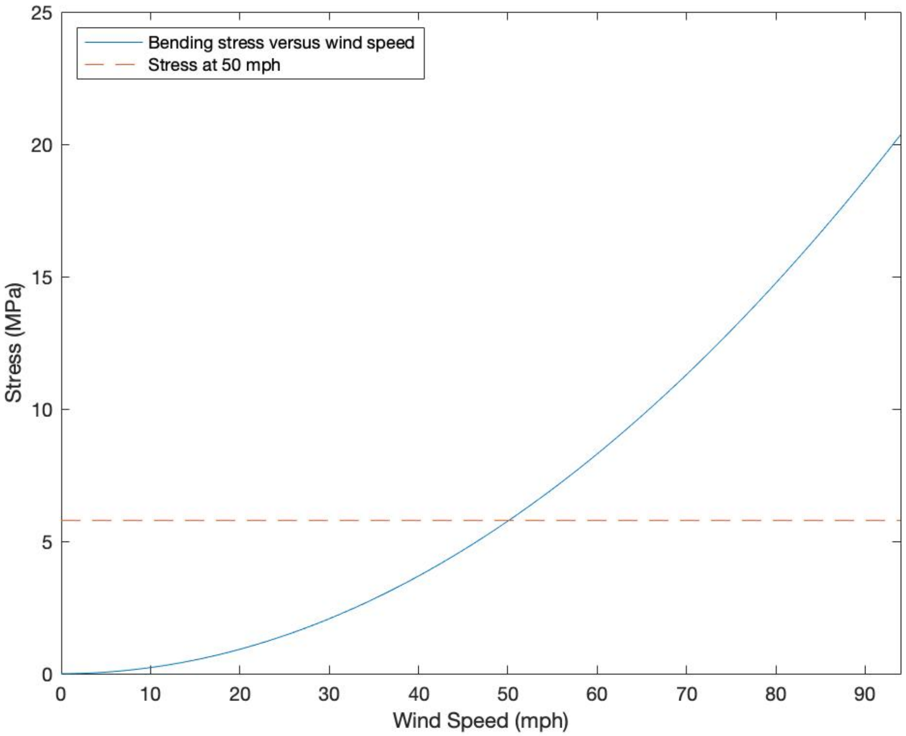
Appendix



Reflector Bending Stress Plot



Vertical Reflector Rod Wind Force

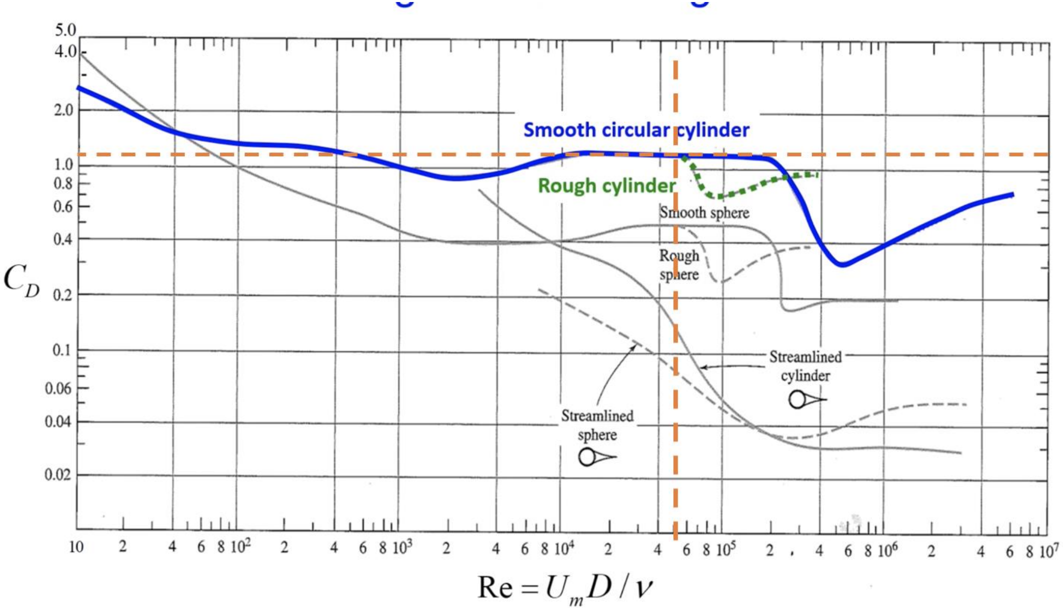
- $\rho = \text{density of air} = 1.202\ kg/m^3$
- $\mu = \text{dynamic viscosity of air} = 1.825 \times 10^{-5} kg/m \cdot s$
- $h_r = \text{height of rod} = 0.325\ m$
- $d_r = \text{diameter of rod} = 0.042\ m$
- $v = velocity = 50\ MPH = 22.4\ \frac{m}{s}$
- A = frontal area
- $C_d = \text{coefficient of drag}$
- $F_D = \text{drag force}$
- $Re = \text{Reynold's number}$

Vertical Reflector Rod Drag Force

$$A = h_r d_r = 0.01365\, m^2$$

$$Re = \frac{\rho v d_r}{\mu} = 61687.25$$

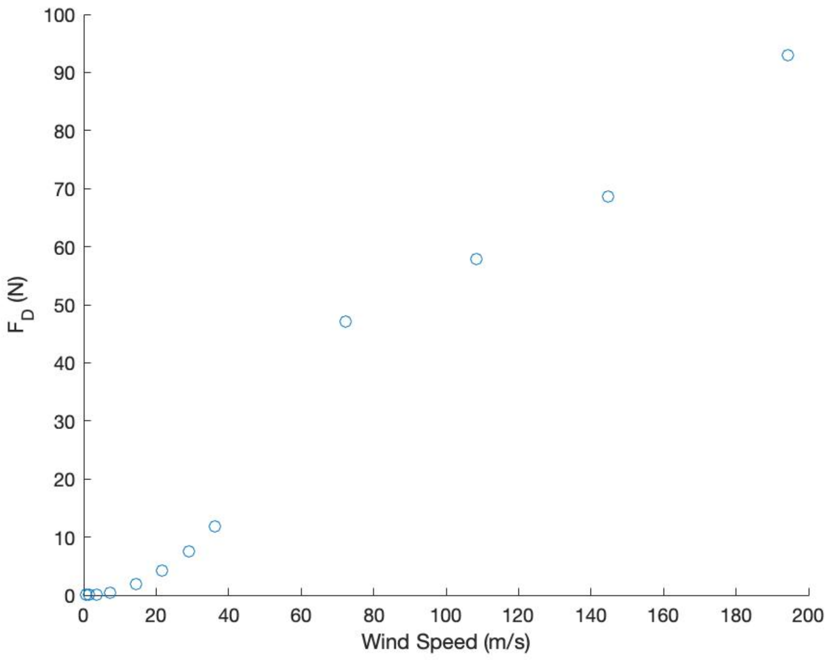
$$F_D = 0.5\rho C_D v^2 A = 4.2\ N$$



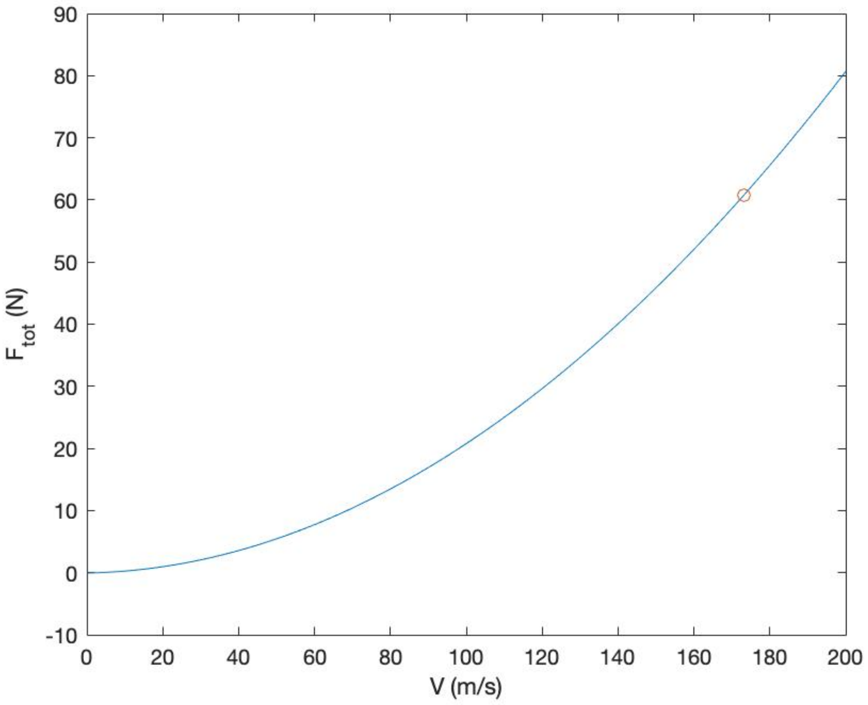
Vertical Reflector Rod Wind Force

Selected Re and C_D pairs	
Re	C_D
2×10^3	0.8
4×10^3	0.9
10^4	1.1
2×10^4	1.1
4×10^4	1.1
6×10^4	1.1
8×10^4	1.1
10^5	1.1
2×10^5	1.1
3×10^5	0.6
4×10^5	0.4
5.3748×10^5 *	0.3

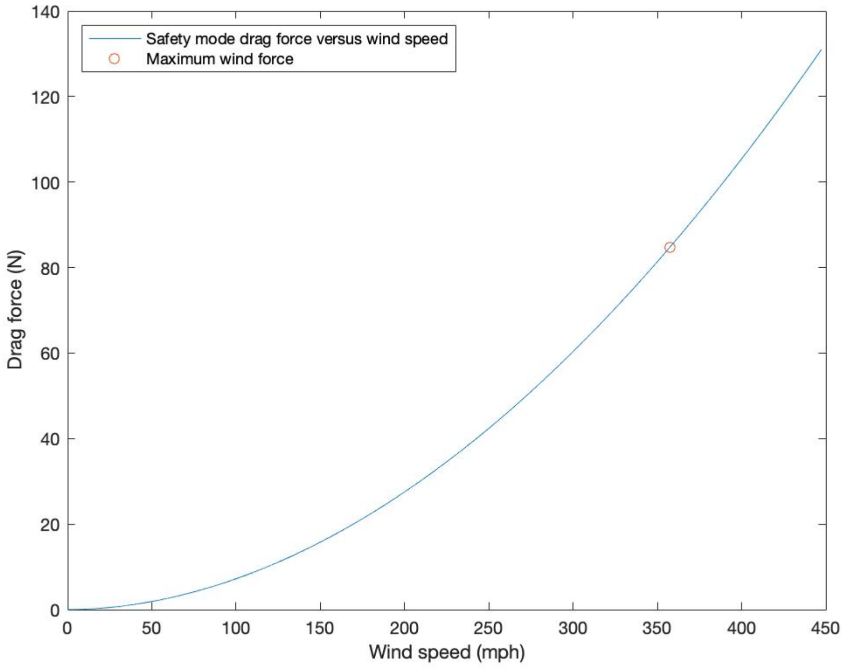
* Final value is Re_{max}



Vertical Reflector Rod Wind Force



Safety Mode Wind Speed



Anchor Strength (Cont.)

- Anchor shear strength of S_s = 1401.19 N
- Safety Factor of 13.98, assuming load on one anchor

$$\sum F = 0 \rightarrow F_s = F_w + F_D$$

$$F_s = 96\ N + 4.2\ N = 100.2\ N$$

$$n = \frac{S_s}{F_s} = 13.98$$