UF Herbert Wertheim College of Engineering
UNIVERSITY of FLORIDA

Hel10s Solar Solutions

Heliostat Module Design

Section 13337, Group 10

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POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

Design Motivation and Value Proposition

Most Economical Heliostat Design

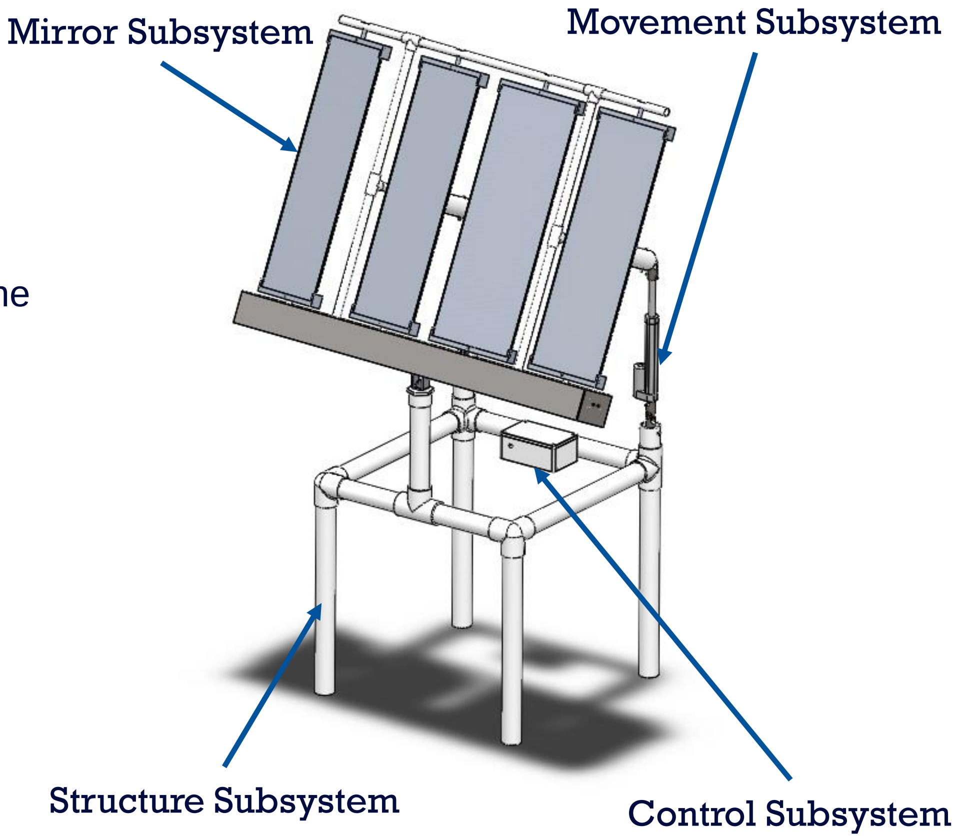
- Saves time and money
  - Low-cost OTS parts
  - PVC support structure
  - Minimize number of motors
  - Easily manufactured parts
  - Modular Design

Product Overview

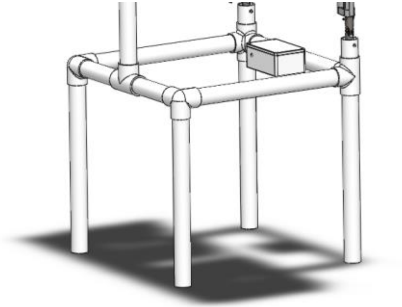
Heliostats are mirrors that move in two axes
to track the sun and focus light to a central source

Project Description

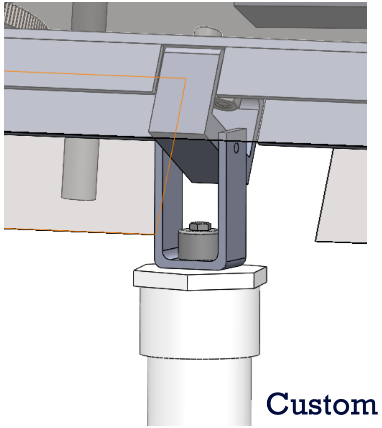
- Design a low-cost, small scale, modular tracking heliostat to be used in a larger array to generate enough solar power and heat energy to satisfy the customer's needs.
- Overall Product Dimensions
    - Height: 2.1 m
    - Width: 1.3 m



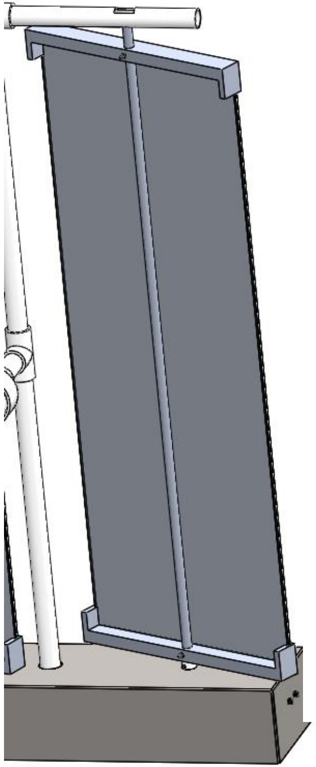
Key Features



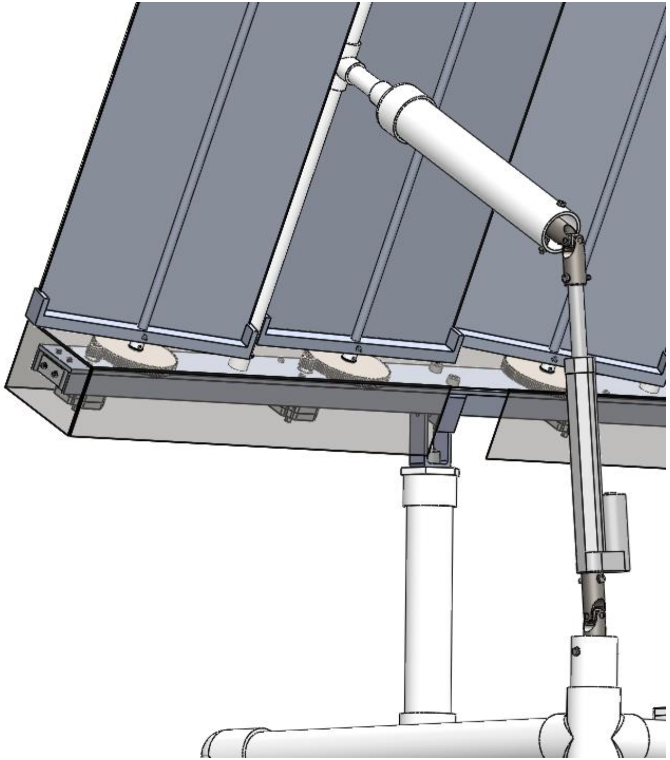
Cost-effective, Lightweight PVC frame



Custom Two-axis Joint



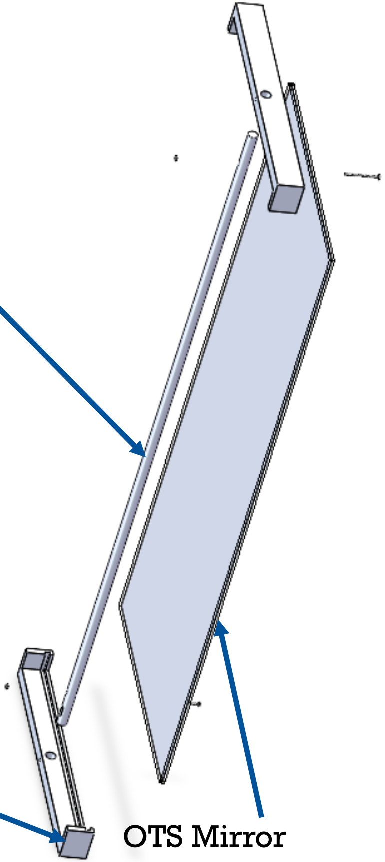
Long rectangular mirrors (OTS, no adhesive required, glass-coated)



Dual azimuthal drive (simultaneous heliostat elevation)

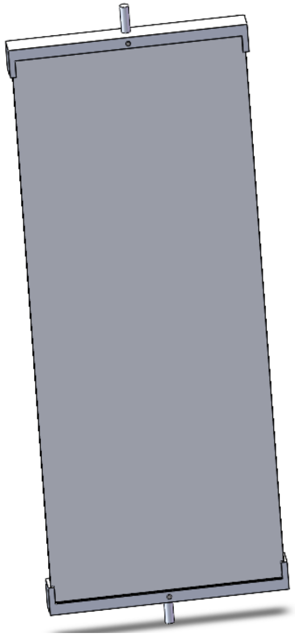
Mirror Subsystem

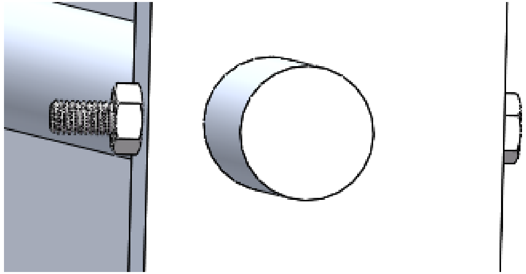
Aluminum Round Bar
- 12 mm diameter



Aluminum Slots
- Cast

OTS Mirror
- Aluminum Reflective Surface





Mirror Subsystem – Aluminum Reflective Surface

- Silver has higher reflectance (0.95-0.97), Aluminum 0.87-0.92
- Drawbacks of silver
  - More expensive
  - Surface degrades when used in heliostats
    - Darkened spots proliferate, reducing performance

Image courtesy of InnoGlass Technology

Mirror Subsystem Design Analysis

- Number of heliostat modules required, N:

Assumptions:

- Solar Flux, q = 1,000 $\frac{W}{m^2}$
- Optical efficiency, n = 0.5

Known:

- Module Collection area, A = 1 m^2
- Required thermal input power, Q = 1 MW

$N = \frac{Q}{qAn} = \mathbf{2000}$ **heliostat modules**

Gemasolar concentrated solar power project
Image courtesy of Sener Group

Mirror Subsystem Design Analysis

- Receiver area for concentration ratio > 1000:

Assumptions:

- Concentration Ratio, $CR = \frac{A_{ref}}{A_{rec}}$

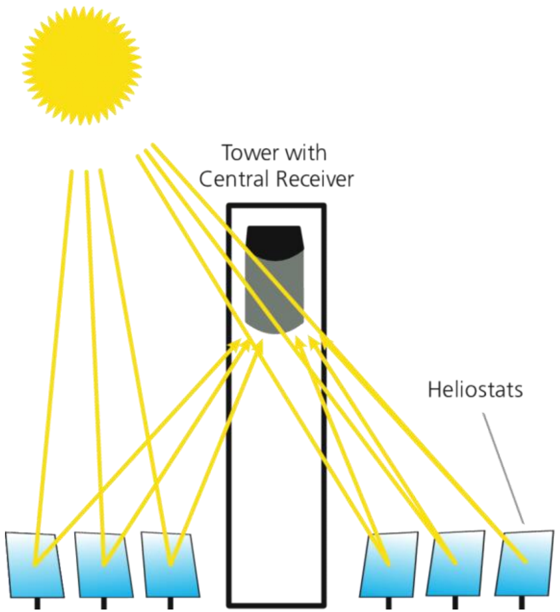
Known:

- Total reflective area, $A_{ref} = 2000\ m^2$

$$1000 > \frac{2000}{A_{rec}}$$

$$A_{rec} < 2m^2$$

$\boldsymbol{A_{rec}}$ **= 1.95 m²** to minimize losses with desired CR



Methanol production via solar reforming of methane
- Scientific Figure on ResearchGate.

Mirror Subsystem Design Analysis

- Mirror wind loading

Assumptions:

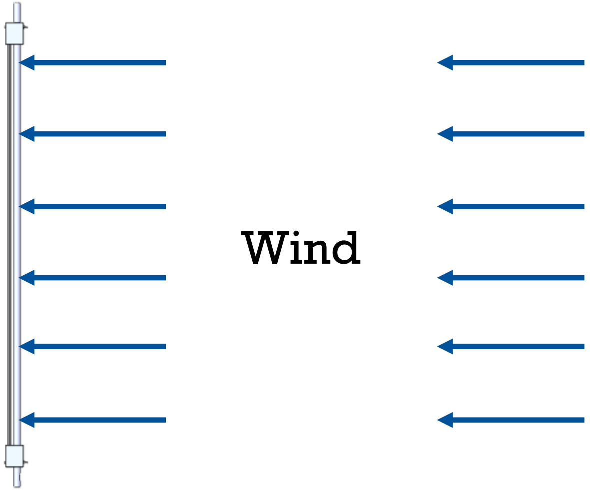
- Max operating wind speed of 35 MPH (15.65 m/s)
- Wind load perpendicular to mirror
- Tensile strength of glass set at 7 Mpa
- Density of air = 1.225 $\frac{kg}{m^3}$

Wind load calculation:

- $q = \frac{1}{2}\rho V^2 = \mathbf{150\ Pa}$

Max stress and deflection:

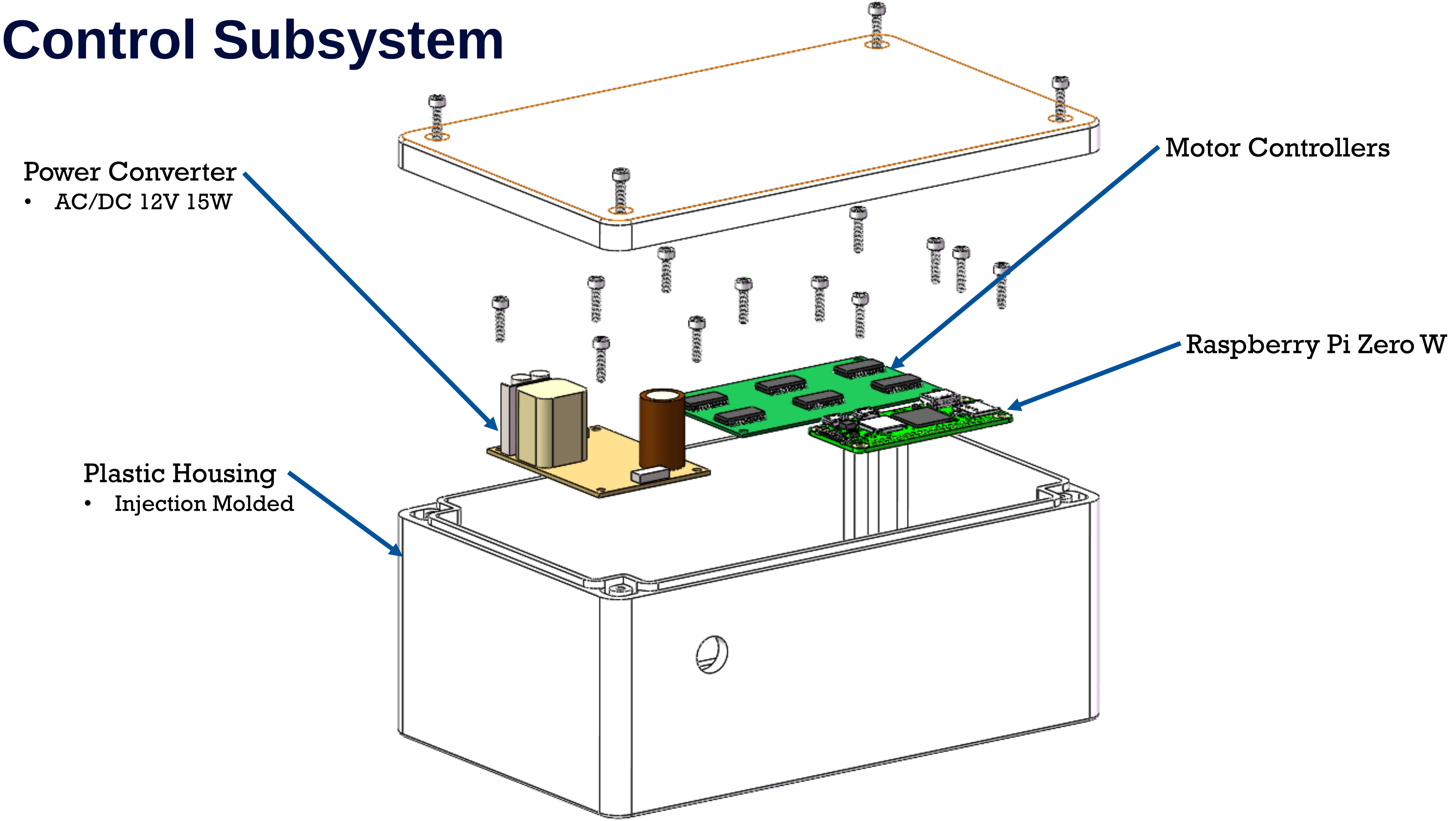
- $\sigma_{max} = \frac{\beta q b^2}{t^2} = \mathbf{0.2718\ MPa}$
- $\delta_{max} = \frac{-\alpha q b^4}{E t^3} = \mathbf{11.87\ \mu m}$



Equation inputs:

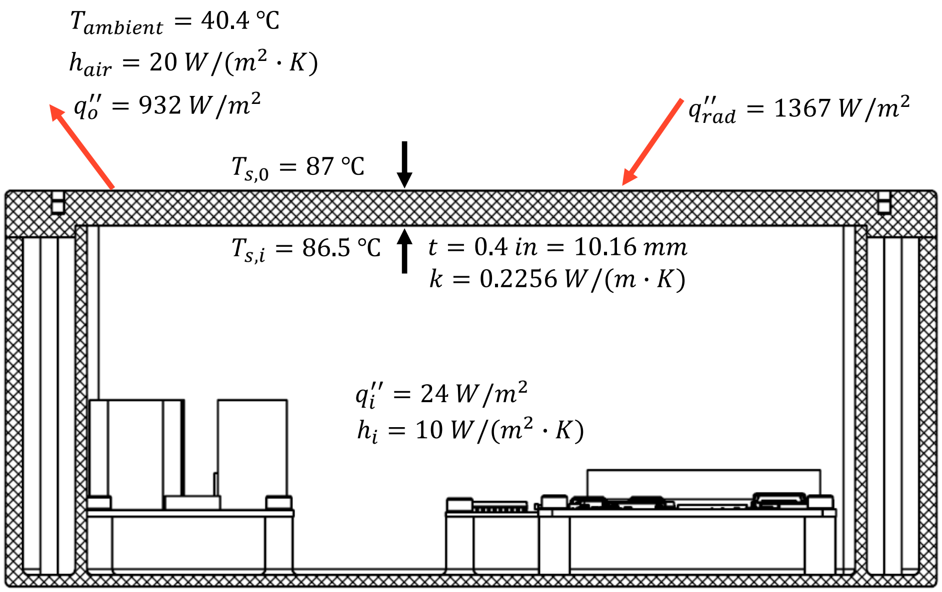
- β = 0.668
- α = 0.1236
- b = 312.5 mm
- t = 6 mm
- E = 68.935 GPa

Control Subsystem

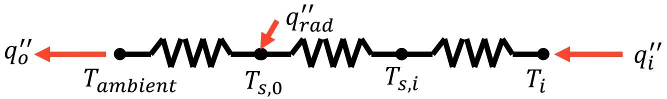


Controller Subsystem Design Analysis

- Interior Temperature
  - G = 1367 W/m^3
  - σ = 5.67 × 10^{-8} W·m^{-2}·K^{-4}
  - $T_{s,i}$ = 86.5 °C
  - **T_i = 83.2 °C**



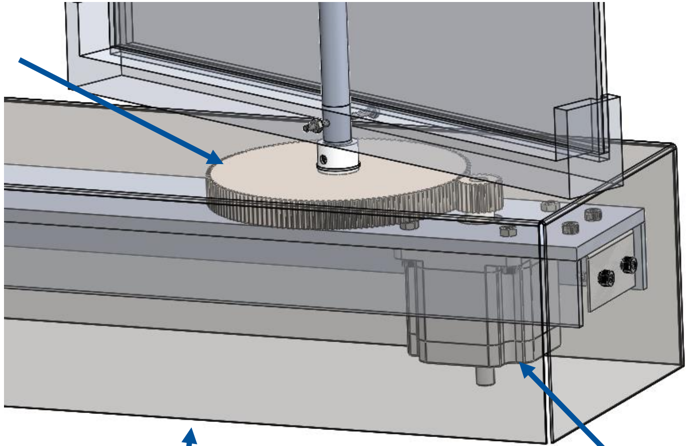
$$q''_o + q''_{rad} = h_{air}(T_{s,o} - T_{ambient}) + \varepsilon\sigma T_{s,o}^4 - \alpha G$$



$$q''_i = \frac{T_{s,o} - T_{s,i}}{t/k} = \frac{T_{s,i} - T_i}{1/h_i}$$

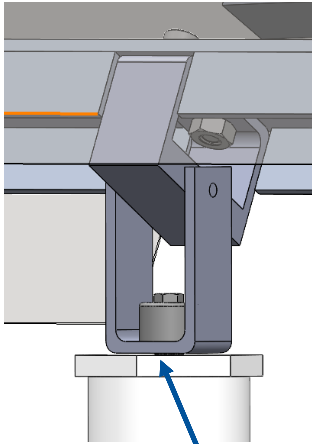
Movement Subsystem

Gears

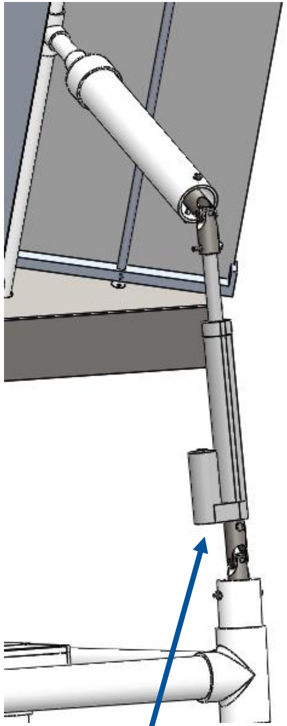


Protective housing

Stepper motors
- Azimuth of each mirror
- 200 steps/revolution



Custom two-axis joint



Linear actuators (12-inch extension)

Movement Subsystem Design Analysis

- Diameter of Joint Pin

Assumptions:

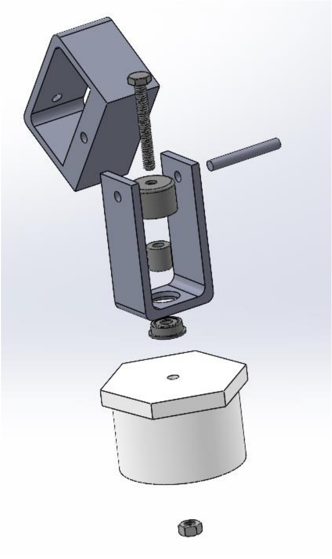
- Simply supported beam

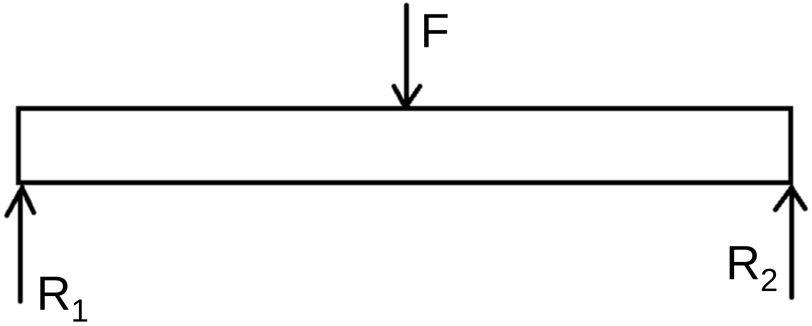
Known:

- 6061 Aluminum, σ_{yield} = 276 MPa
- Total mirror frame weight = 27.88 kg
- Length of pin = 45 mm

Bending moment analysis results

- $D_{min} = \left(\frac{8FL}{\pi \sigma_{yield}}\right)^{\frac{1}{3}}$ = **5.33 mm**
  - For factor of safety = 2
- Actual pin diameter = **6 mm**





Movement Subsystem Design Analysis

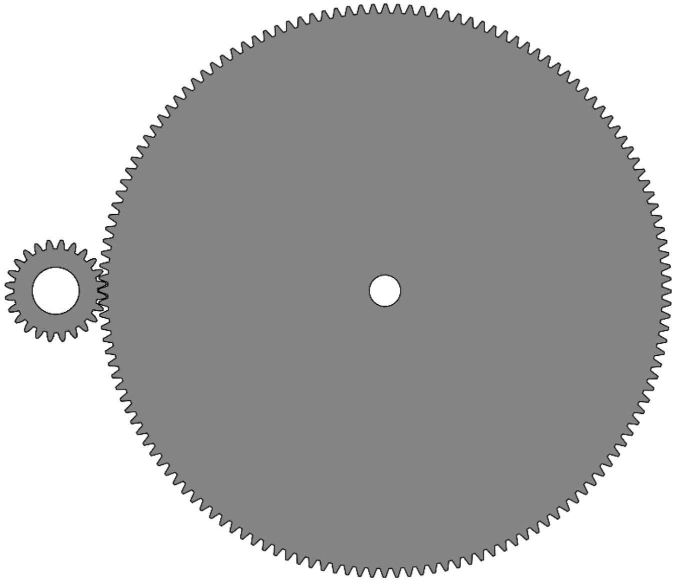
- Stepper Motor Gear Ratio

Known:

- Distance from furthest heliostat = 141.42m
- Motor step size = 1.8°,
  - $\Delta x_{1.8}$ = (141.42 m) tan(1.8°) = 4.44 m/step
- Desired step size = 0.3° ,
  - $\Delta x_{0.3}$ = (141.42 m) tan(0.3°) = 0.74 m/step

Required gear ratio = 6

- Gear 1
  - 0.75 in. diam
  - 24 teeth
  - 32 teeth/in. pitch
- Gear 2
  - 4.5 in. diam
  - 144 teeth
  - 32 teeth/in. pitch
- $G = \frac{N_2}{N_1} = \frac{144}{24} = \mathbf{6}$



Movement Subsystem Design Analysis

- Motor Mount

Known:

- Mass of components
- Length = 1320 mm
- Load = 47.6 N at end

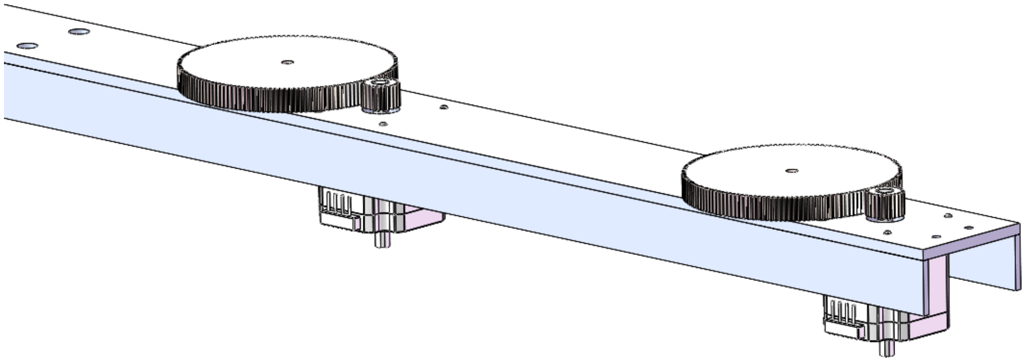
Maximum deflection 1 mm

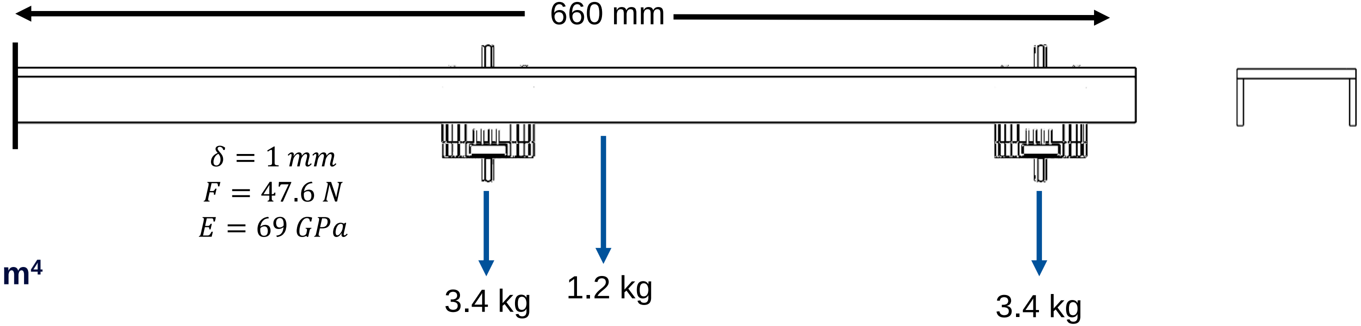
- Mass of components
- Length = 1320 mm

$$\delta = \frac{FL^3}{3EI}$$

$$I = \frac{FL^3}{3E\delta} = 66107\ mm^4$$

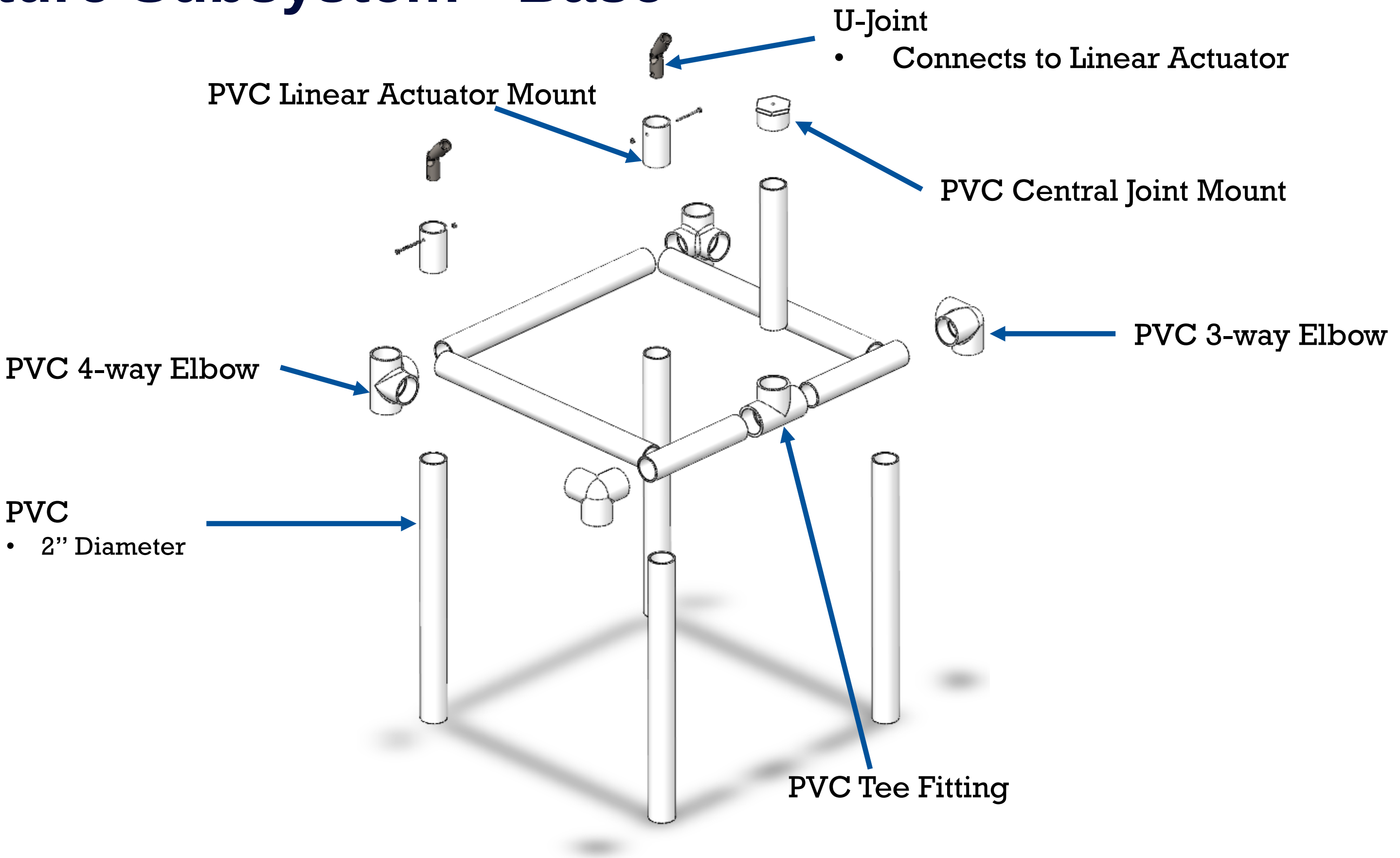
- Designed ***I* = 70,064 mm^4**



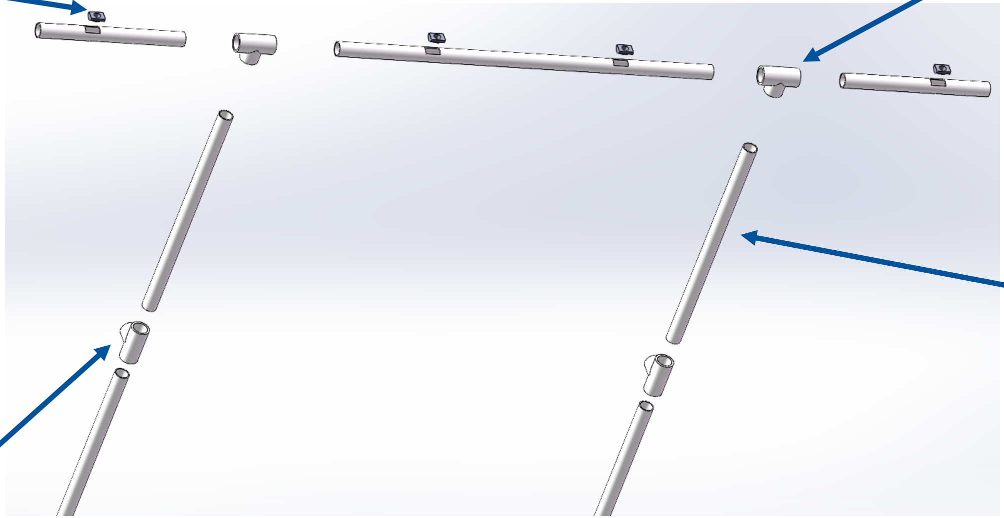


$$\delta = 1\ mm$$
$$F = 47.6\ N$$
$$E = 69\ GPa$$

Structure Subsystem - Base



Structure Subsystem – Upper Crossbar



Delrin Bushing

PVC Tee Fitting

PVC
- 25 mm Diameter

PVC Linear Actuator Mount

Structure Subsystem Design Analysis

Bending stress on PVC at U-joint:

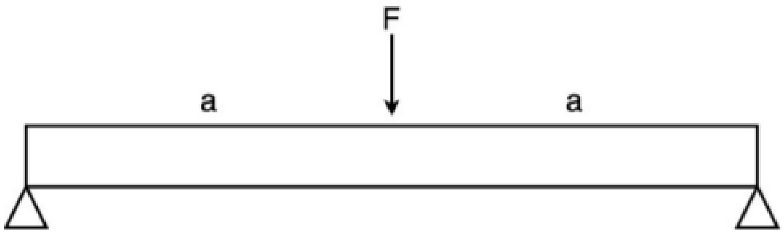
- 273.5 load from mirror assembly (27.88 kg)
- Length = 284.4 mm
- Inner radius = 25.995 mm
- Outer radius = 30.165 mm of PVC

$$M = \frac{1}{2} Fa = 77.8\ Nm$$

$$y = R_o = 0.030\ m$$

$$I = \frac{\pi}{4}\left(R_o^4 - R_i^4\right) = 2.92 * 10^{-7} m^4$$

$$\sigma_b = \frac{My}{I} = \mathbf{8.05\ MPa}$$



- Yield strength of PVC = 55.2 Mpa
- Beam factor of safety = **6.86**

Structure Subsystem Design Analysis

Radiative heat flux on PVC

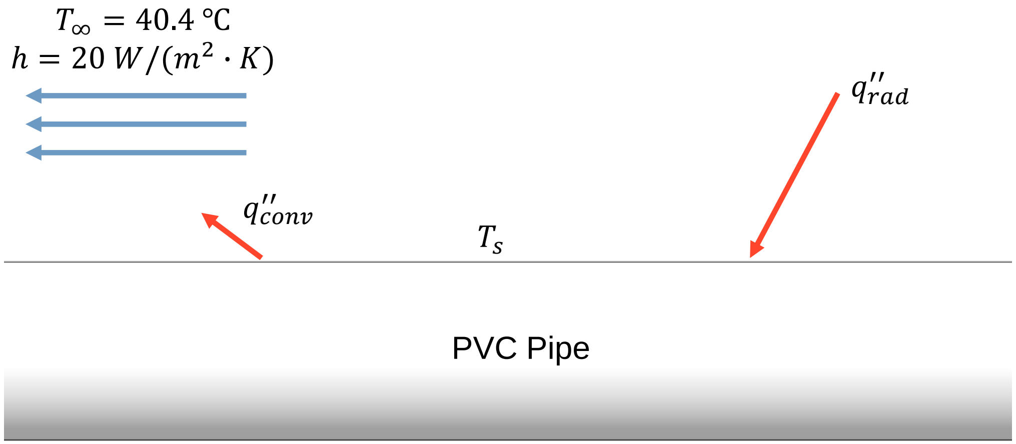
- $q'' = q''_{conv} + q''_{rad} = h(T_s - T_\infty) + \varepsilon\sigma T_s^4 - \alpha G$
- $q''_{rad} = 1367\, W m^2$
- $G = 1367 \frac{W}{m^2}$
- $\sigma = 5.67 * 10^{-8}\, W m^{-2} K^{-4}$

For white acrylic paint:

- $\varepsilon = 0.9$
- $\alpha = 0.26$

PVC operating temperature = 60 ℃

- $T_s = 87$℃



Structure Subsystem Design Analysis

Wind force lifting the assembly up

Assumptions:

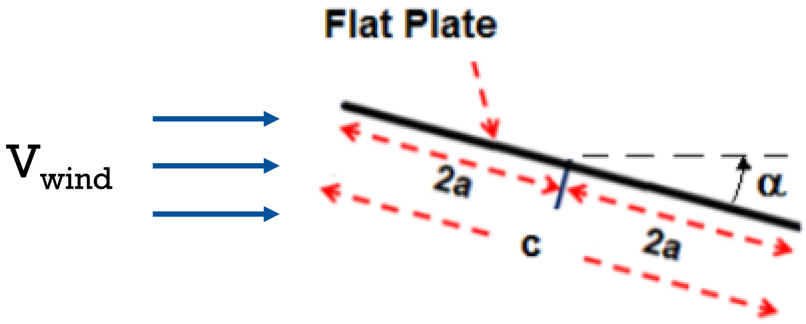
- Max angle of attack in safe position = 0.5°
- Mirrors modeled as flat plates
- Max possible wind speed = 40.2 m/s
- Lift coefficient, $C_L = 2\pi * 0.0087$
- Density of air = 1.225 $\frac{kg}{m^3}$
- Lift area = 1 m^2

Lift force calculation:

- $F_L = C_L\left(\frac{1}{2}\rho V^2\right)A = \mathbf{54.11\ N}$

Module weight:

- Mass = 27.88 kg, weight = 273.5 N

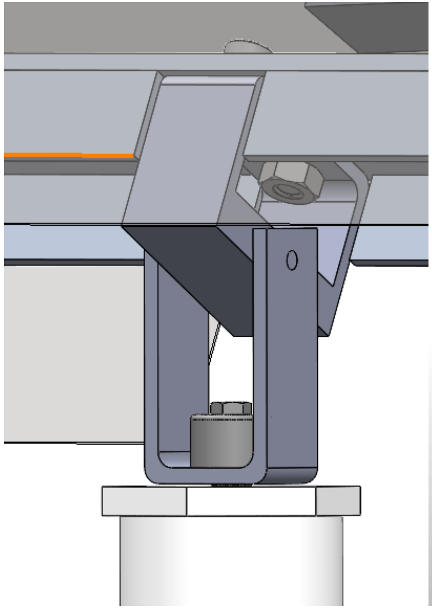


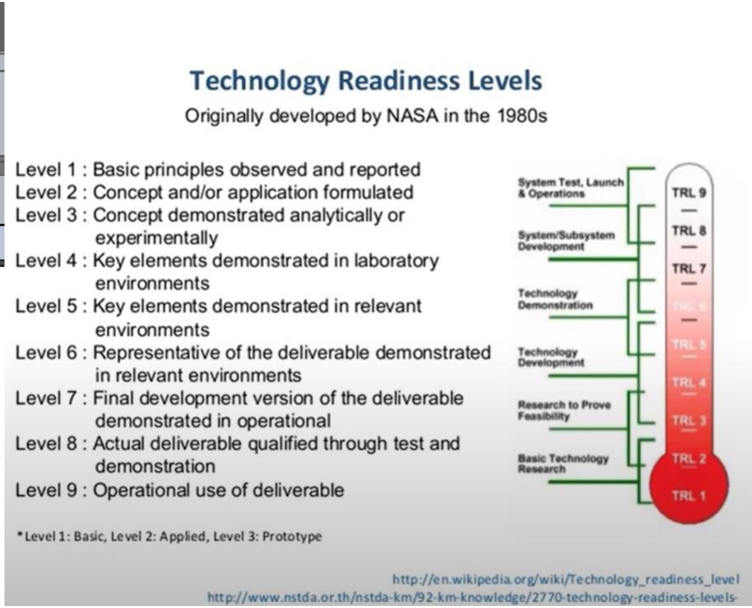
Cost Table Summary

Category	Prototype Price	Mass Production Price
OTS Parts	$248.78	$143.09
Modified OTS Parts	$2.46	$1.85
Raw Materials	$67.88	$13.94
Manufacturing Labor	$41.45	$25.11
Assembly Labor	$12.36	$12.36
Energy Consumption	$0.16	$0.16
Total	**$373.08**	**$196.50**

Technology Readiness Level (TRL)

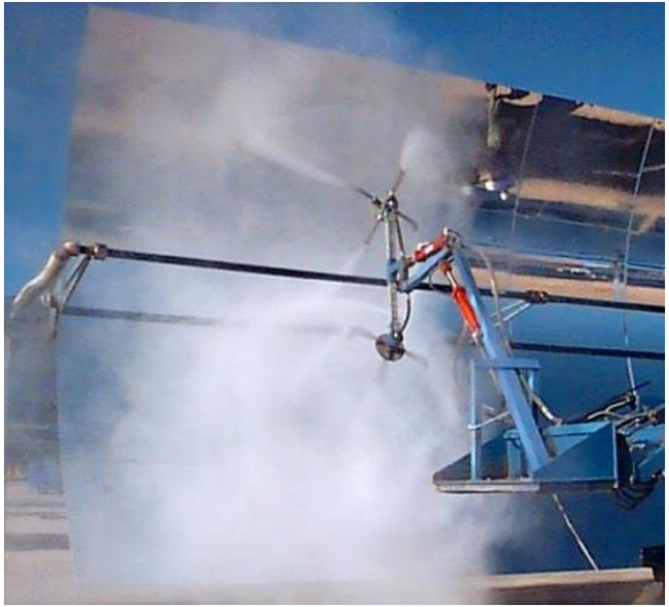
- Critical components
  - Custom U-joint
- At level 3 currently
  - Concept demonstrated analytically





Mirror Surface Cleaning

- At least 95% reflectance must be recovered
- A research study found that a high pressure (>500 PSI) stream of water recovered 95% reflectance.



Power cleaning of heliostat mirrors
Image courtesy of Arpsolar

Summary

PVC frame

- Low cost
- Easy to manufacture

Low number of motors per mirror

- 4 stepper motors, 2 linear actuators

High Precision Mirror Control

- Two modes of azimuth rotation
- Stepper motor reduction increases accuracy

Conclusion

- Low cost
- Easy to manufacture
- Q&A