Herbert Wertheim College of Engineering
UNIVERSITY *of* FLORIDA

Stellar Sunshine

A Brighter Future in Sustainable Energy

Class 13070, Section 225A, Group 3

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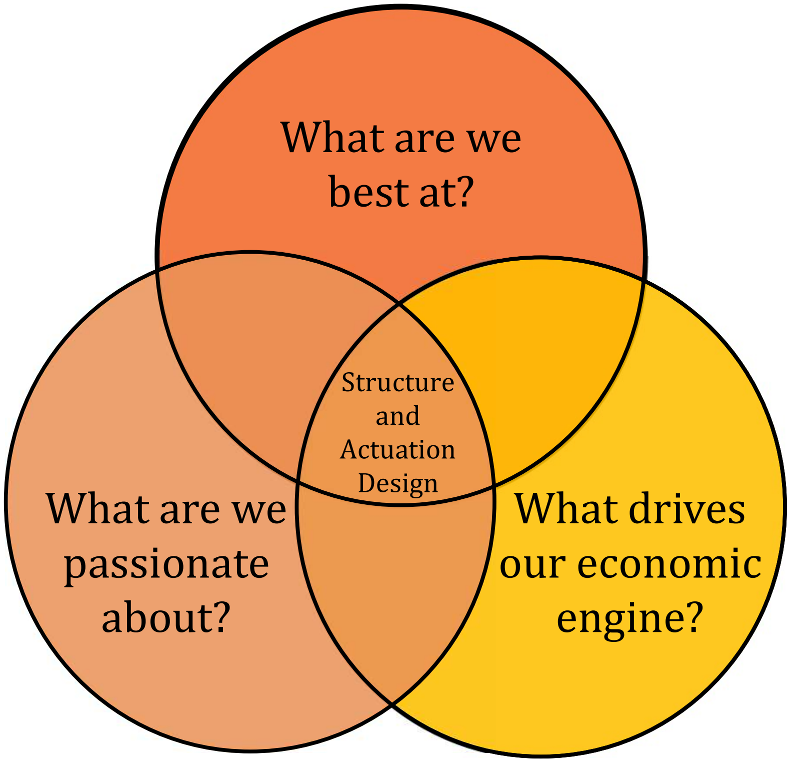
POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

- Strengths
  - Structure Mechanic, Design for Manufacture, Computer Aided Design Optimization
- Passions
  - Programming , Controls Systems, Mechanical Design, Sustainable Engrgy, Computer Aided Design
- Economics
  - Long term profit/ Module, Initial Cost/ Module



Slide 2

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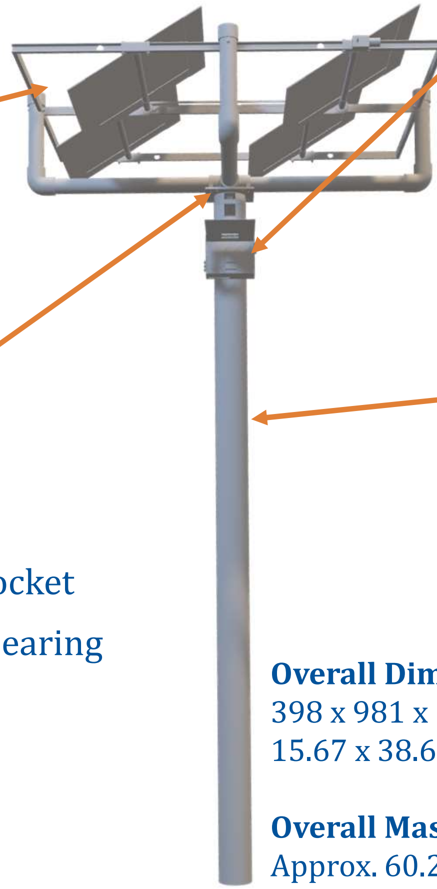

Reflective Subsystem

- Solar Mirror Film
- Adhered to steel frame

Maneuverability Subsystem

- Only two motors
  - 12V 3RPM DC
- Altitude rotation – chain and sprocket
- Azimuth rotation – Oilite thrust bearing
  - 'Lazy Susan'

Tracking Subsystem

- Arduino Uno on each Module
- Motor Encoders
  - 16 counts per revolution
  - 972 reduction ratio

Structure Subsystem

- Pressure Treated Pine
  - Driven into the ground
- PVC frame supporting heliostat mirrors

Overall Dimensions:
398 x 981 x 1210 [mm]
15.67 x 38.6 x 47.64 [in]

Overall Mass:
Approx. 60.22 [lbs]

Slide 3

SH0 Add relative dimensions
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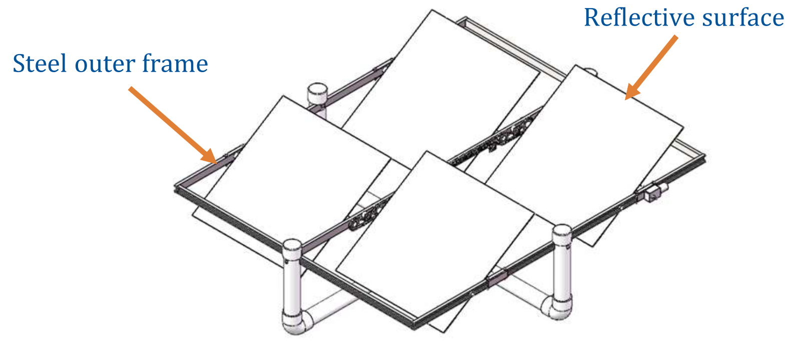
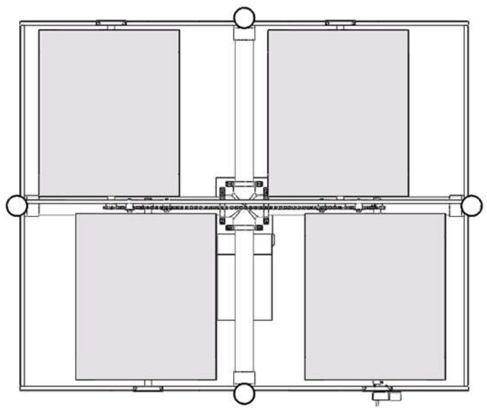
Reflective Subsystem Overview

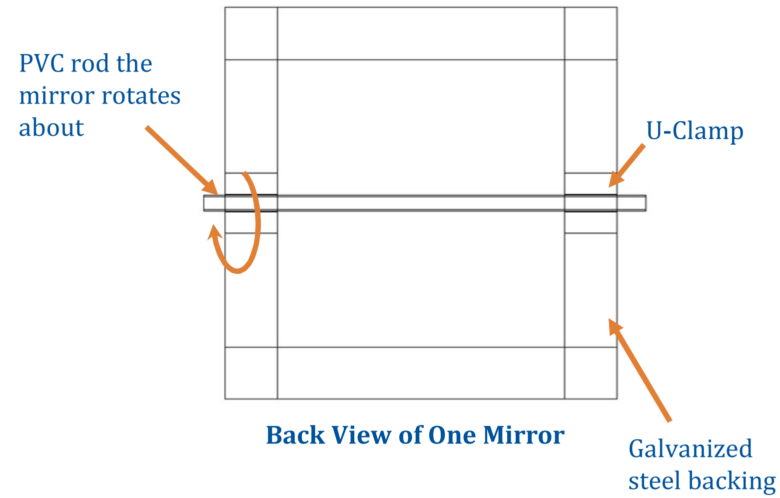
- 4 square mirrors
  - Solar Mirror Film
  - 20 GA galvanized steel backing plate
  - Low carbon steel outer frame
  - Rotates about PVC rods



Isometric View of Module



Top View of Module



Back View of One Mirror

Reflective Subsystem Customer Needs

Reflective subsystem

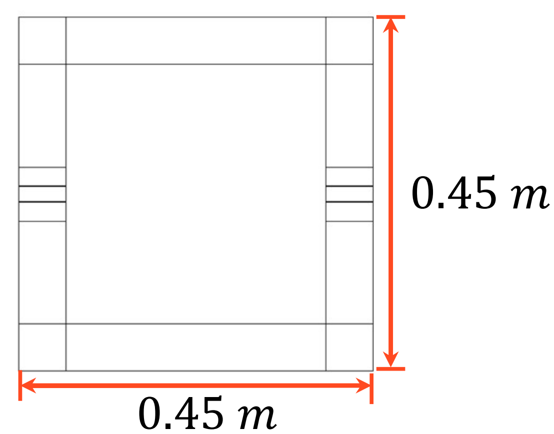
Characteristic	Need	Target
Module size	Need 2	Total collection size < 1 m^2
Heliostat number	Need 3	4-16 heliostat/ module
Self shading	Need 6	Self shading ≤ 90% time
Washable	Need 12	Withstand 2750 psi
Lifetime	Need 15	Lifespan = 20 years
Thermal power	Need 17	Input power of 1 MW
Concentration ratio	Need 18	Delievered flux ≥ 174300 W/m^2
Absorbing aperture	Need 19	≥ 90% reflective area

Reflective Proof of Concept – Need 2

- "Total reflector collection area of a single heliostat module is $\leq 1\ m^2$"

$$A_{mirror} = (0.45\ m)(0.45\ m) = 0.203\ m^2$$
$$A_{reflective} = 4(A_{mirror})$$

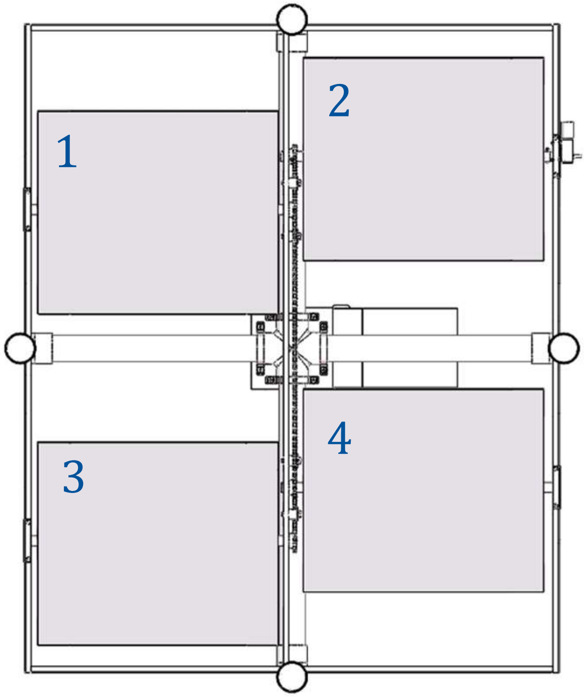
$$A_{reflective} = \mathbf{0.81\ m^2}$$



Reflective Proof of Concept – Need 3

- "Each module must be composed of 4-16 heliostats"

$$\boldsymbol{N = 4\, mirrors}$$



Reflective Proof of Concept – Need 6

- "Individual heliostat units cannot shade other heliostats in that module"
  - Average shading of heliostat module is 6.79%
    - 2x2 grid pattern of mirrors within modules reduces bending stress on mirror rods to reduce optical losses
    - Comes with trade-off of front two mirrors partially shading back two mirrors during early morning and late evening.

Reflective Proof of Concept – Need 12

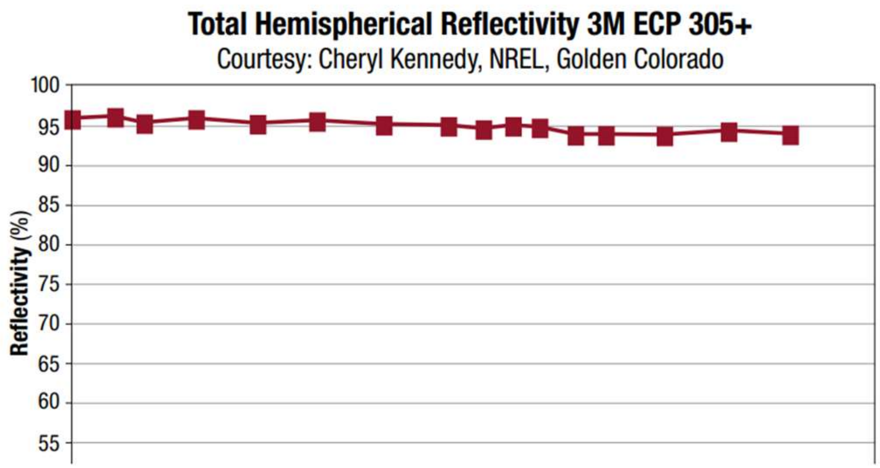
- "The reflecting surface of each heliostat must be washable using conventional cleaning methods to remove dust and residue."
  - Pressure Washing → $S_y \geq 2750\ psi$
    - Solar Film:

$$\boldsymbol{S_y = 7935\ psi}$$

    - Manufacturers recommend pressure washing to clean

Reflective Proof of Concept – Need 15

- "Operational lifetime of installation longer than 20 years"
  - Outdoor lifetime test
    - Ongoing data from 1995 -2012
      - 17 years and showed less than 3% drop
      - Will **exceed the 20-year** lifespan with high reflectivity



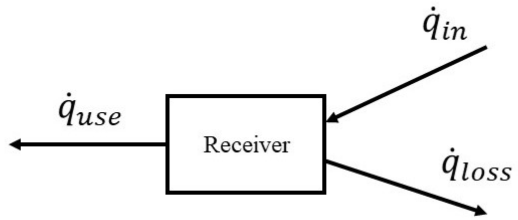
Reflective Proof of Concept – Need 19

- "The distance of the heliostat units furthest from the collector target tower must account for dispersion of reflected light from the heliostats relative to the size of the absorbing aperture of the solar receiver target."
  - Solar Film has a **Total Solar Reflectance of 94%**
    - Greater than the specified 90%

Reflective Proof of Concept – Need 17

- "The collection field delivers to a receiving tower with a concentrated focal thermal input power of 1MW for at least 1 hour each day."

$$\dot{Q}_{in} = \dot{Q}_{absorbed} + \dot{Q}_{loss}$$



$$\dot{Q}_{loss} = A_{rec}\epsilon\sigma T_{rec}^4$$

$$\dot{Q}_{loss} = (1\,m^2) * (1) * \left(5.67 * 10^{-8}\frac{W}{m^2 * K^4}\right) * (291.0\,K)^4 = 406.8\,W$$

$$\dot{Q}_{absorbed} = 1\,MW$$

$$\dot{Q}_{in} = 1000000\,W + 406.8\,W = 1000406.8\,W$$

$$N = \frac{\dot{Q}_{in}}{\dot{Q}_h} = \frac{1000406.8\,W}{132.7\,W} \approx 7539$$

Reflective Proof of Concept – Need 18

- "The collection field must always provide a solar concentration ratio greater than 1000 suns"

Defined Customer Metric:

$$C_{opt} = \frac{\dot{q}_{ave,r}}{\dot{q}_a} \geq 1000$$

$$\dot{q}_a = 174.3\ W/m^2$$

$$\therefore\ \dot{q}_{ave,r} \geq 174{,}300\ W/m^2$$

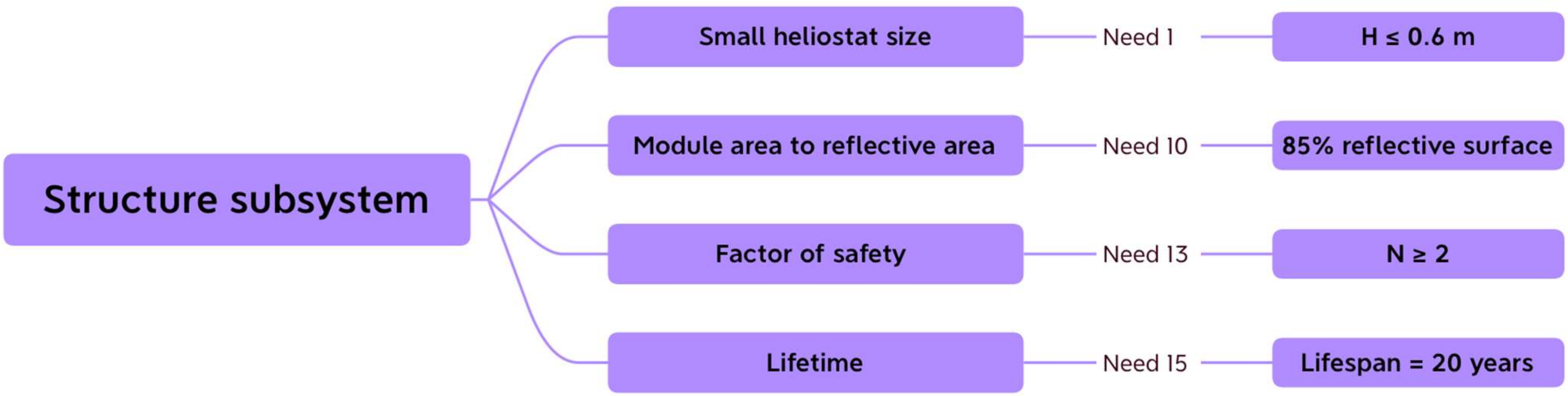
$$\dot{q}_e = \frac{G_{sc}}{4} = \frac{1367\ W/m^2}{4} \rightarrow \dot{q}_e = 174.3\ W/m^2$$

$$\dot{q}_r = \eta\ \dot{q}_e = (0.94)\left(174.3\frac{W}{m^2}\right) \rightarrow \dot{q}_r = 163.8\ W/m^2$$

$$\dot{q}_{ave,r} = N\ \dot{q}_r = (7539)\left(163.8\frac{W}{m^2}\right)$$

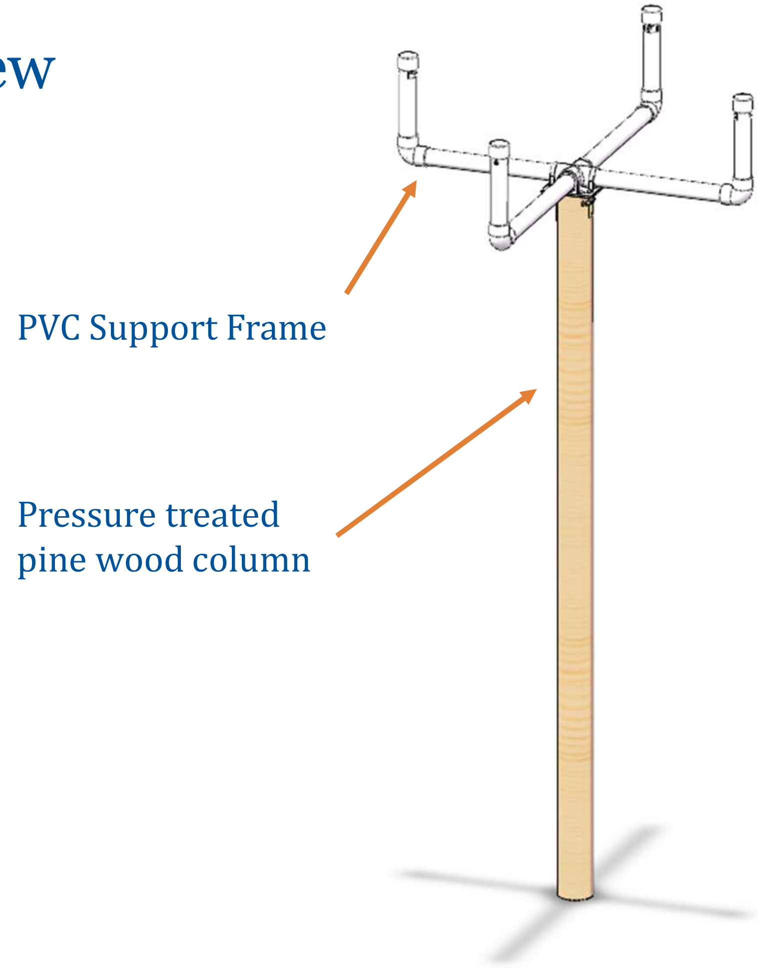
$$\rightarrow \boldsymbol{\dot{q}_{ave,r} = 1,235,205\ W/m^2}$$

Structure Subsystem Customer Needs



Structure Subsystem Overview

- Wooden Post
  - Driven into the ground
    - Stability
- PVC Heliostat support frame



Structure Proof of Concept – Need 1

- Design capitalizes on innovations enabled by small heliostat size.
  - Previous heliostat designs are 0.413 m tall
  - Final height is 0.6m

$$h_{total} = h_{PVC} + h_{wood}$$
$$= 0.29m + 0.31m$$

$$\boldsymbol{h_{total} = 0.6\ m}$$

Slide 16

PA0 Need previous heliostat heights

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Structure Proof of Concept – Need 10

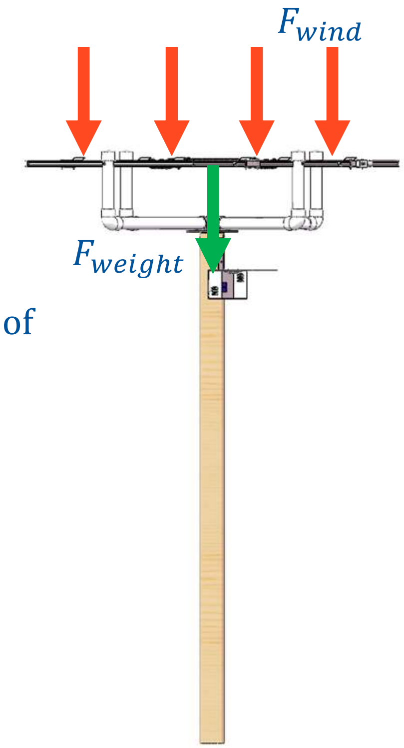
- "The total module area relative to the reflecting area should be small."
  - Defined the ratio of reflective to the whole collection field as ≥ 0.85.

$$\frac{A_{reflective}}{A_{collection}} = \frac{4(A_{mirror})}{4(A_{mirror}) + A_{structure}} = \frac{0.81\ m}{0.81m\ + 0.066\ m} = 0.92$$

$$\frac{A_{reflective}}{A_{collection}} = \mathbf{92\%}$$

Structure Proof of Concept – Need 13

- “Factor of safety must exceed $n = 2$”
  - Weight and Wind Force acting directly downward
  - Buckling Analysis, wood column – n = 1910.35



Euler Column formula, substituting second moment of area where $I = Ak^2$, k is radius of gyration. C is approximated as ¼ since it is a beam that is fixed at one end.

$$\frac{P_{cr}}{A} = \frac{C\pi^2 E}{\left(\frac{l}{k}\right)^2} = \frac{\left(\frac{1}{4}\right)\pi^2(10GPa)}{\left(\frac{0.31m}{0.0254m}\right)} \rightarrow \frac{P_{cr}}{A} = 165.65MPa$$

$$\sigma_{max} = \frac{F_{total}}{A_{cross-sectio}} = \frac{703.2N}{0.0081m^2} \rightarrow \sigma_{max} = 0.0867MPa$$

$$n = \frac{(P_{cr}/A)}{\sigma_{max}} = \frac{165.65MPa}{0.00867MPa} \rightarrow \boldsymbol{n = 1910.35}$$

Structure Proof of Concept – Need 13

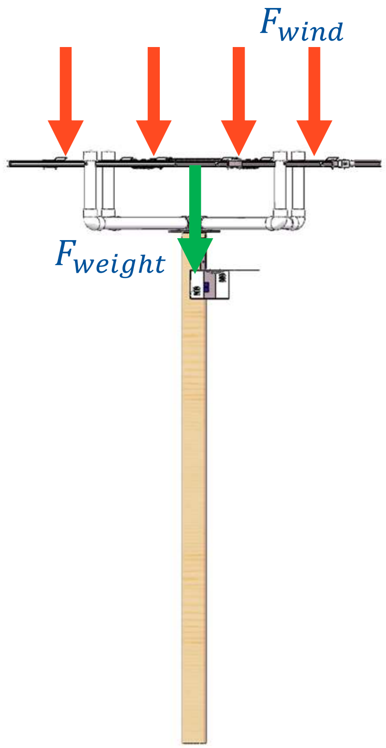
- "Factor of safety must exceed $n = 2$"
  - Weight and Wind Force acting directly downward
  - PVC Bending Analysis – n = 2.94
  - Assuming force is distributed equally amongst 4 PVC supports

$$F = F_{total}\left(\frac{1}{4}\right) = \frac{703.2N}{4} = 175.8\text{N}$$

$$M_{max} = Fd = (175.8N)(0.541m) = 95.11Nm$$

$$\sigma_{max} = \frac{M_{max}c}{I} = \frac{(95.11Nm)(0.024m)}{1.22 \cdot 10^{-7}m^4} \rightarrow \sigma_{max} = 18.71MPa$$

$$n = \frac{S_{yPVC}}{\sigma_{max}} = \frac{55MPa}{18.71MPa} \rightarrow \boldsymbol{n = 2.94}$$



Structure Proof of Concept – Need 15

- "Operational lifetime of the installation must exceed 20 years."
  - Wood is brittle – will not fail unless stress exceeds yield strength
  - PVC is ductile – failure due to cyclic loading
    - Number of cycles in 20 years: $N_c = 10^5$

$$S_e' = \frac{S_{ut}}{2} = \frac{58MPa}{2} = 29MPa$$

$$a = \frac{(fS_{ut})^2}{S_e'} = \frac{(0.8 \cdot 58M\quad)^2}{29MPa} = 74.24MPa$$

$$b = -\frac{1}{3}\log\left(\frac{fS_{ut}}{S_e}\right) = -\frac{1}{3}\log\left(\frac{0.8 \cdot 58M}{29MPa}\right) = -0.068$$

$$S_f = aN_c^b = (74.24MPa)(10^5)^{-0.068}$$

$$\rightarrow \boldsymbol{S_f = 33.93MPa}$$

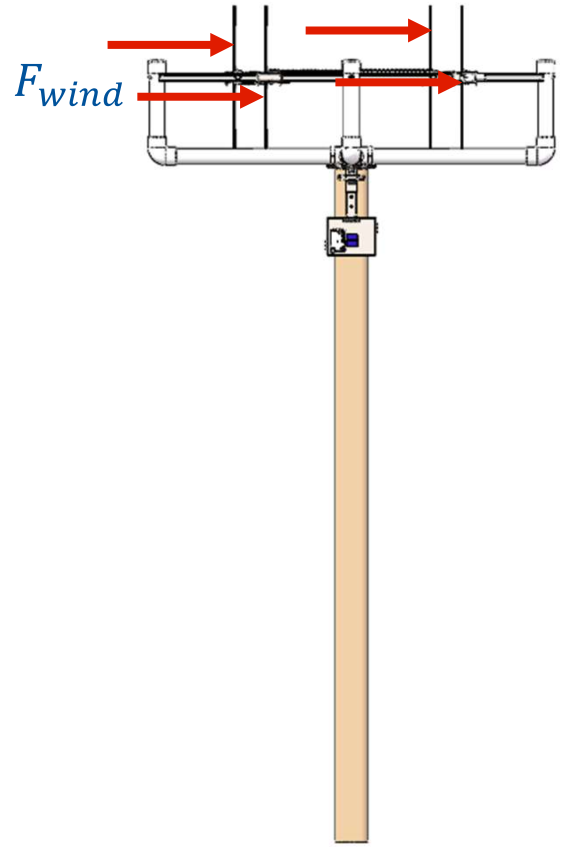
From previous slide:

$\sigma_{max} = 18.71\ MPa$

$\boldsymbol{S_f > \sigma_{max}}$ ∴ **Lifespan > 20+**

Structure Proof of Concept – Need 16

- "The system operates under ambient and solar conditions in Las Vegas, NV."
  - Maximum temperature is 47.8°C
    - PVC has a maximum operating temperature of **60**°C
  - Maximum wind speed is 90 *mph*
    - Additional factors of safety for the structural components



Structure Proof of Concept – Need 16

- Wind Verification
  - Bending Factor of Safety for Wood Column

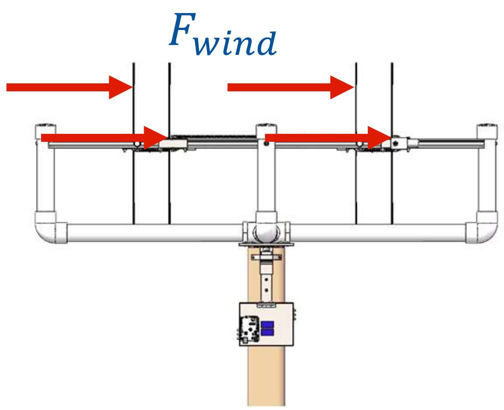
$$F_{total} = 4F_d = 4(174.52N) = 698.1N$$

$$M = F_{total}(l) = 698.1N(0.6m) \rightarrow M = 418.85Nm$$

$$\sigma_{max} = \frac{Mc}{I} = \frac{M\left(\frac{d}{2}\right)}{\frac{\pi d^4}{64}} = \frac{32}{\pi d^3}M = \frac{32}{\pi(0.102m)^3}(418.85Nm)$$

$$\rightarrow \sigma_{max} = 4.02MPa$$

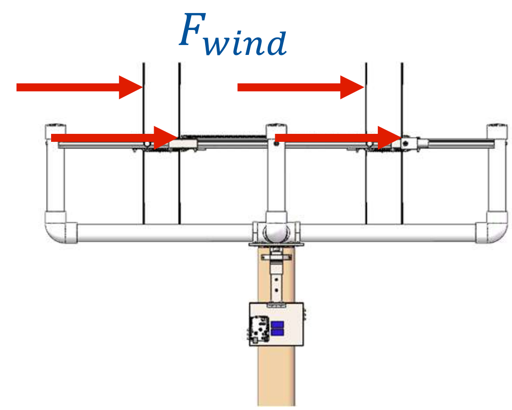
$$n = \frac{S_{ut,wood}}{\sigma_{max}} = \frac{35MPa}{4.02MPa} \rightarrow \boldsymbol{n = 8.706}$$



$n \gg 2$ ∴ Safe

Structure Proof of Concept – Need 16

- Wind Verification
  - Bending Factor of Safety for PVC Frame
  - Assume force is distributed equally among all 4 PVC frame supports



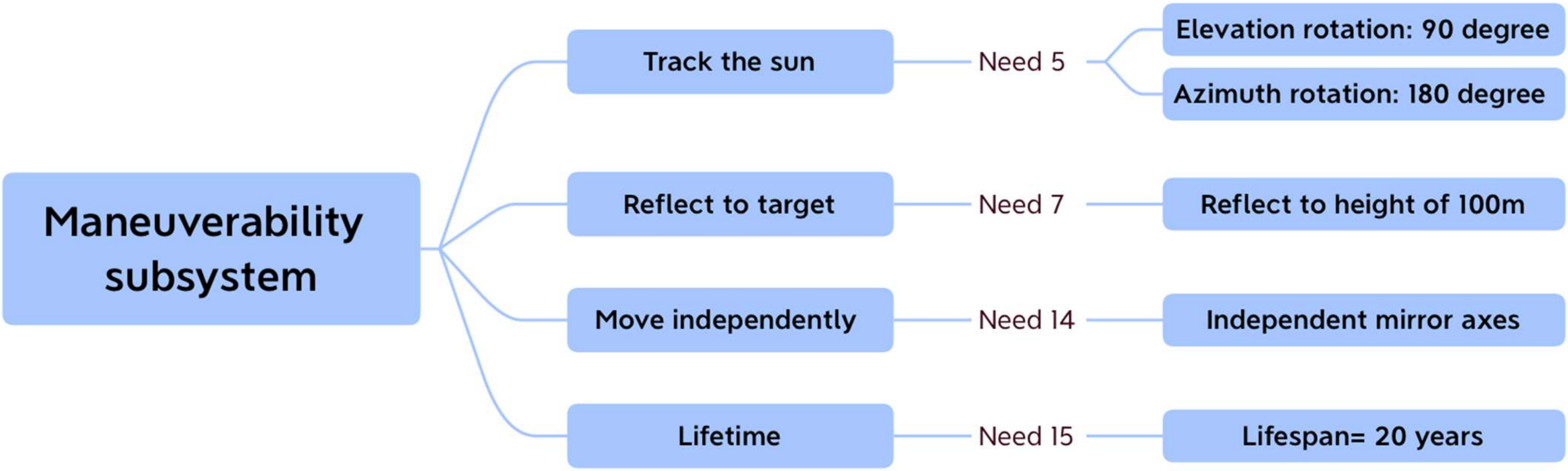
$$M = F_{total}(l) = 174.52N(0.29m) \rightarrow M = 50.6108Nm$$

$$\sigma_{max} = \frac{Mc}{I} = \frac{50.6108Nm(0.024m)}{1.22 \cdot 1\ ^{-7}m^4} \rightarrow \sigma_{max} = 9.956MPa$$

$$n = \frac{S_y}{\sigma_{max}} = \frac{55MPa}{9.956MPa} \rightarrow \boldsymbol{n = 5.524}$$

$n \gg 2$ ∴ Safe

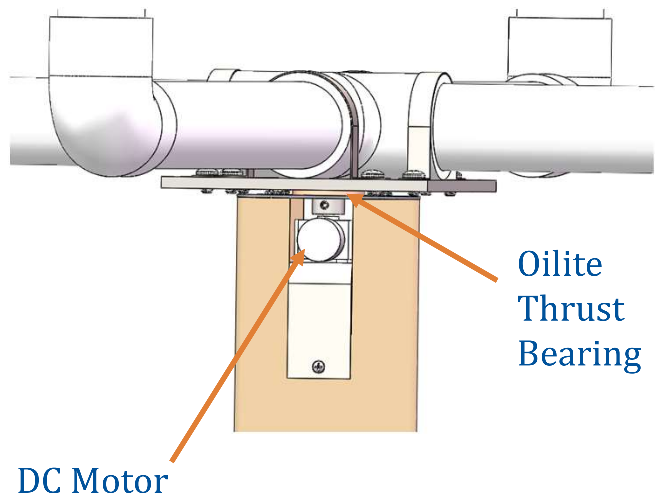
Maneuverability Subsystem-Customer Needs



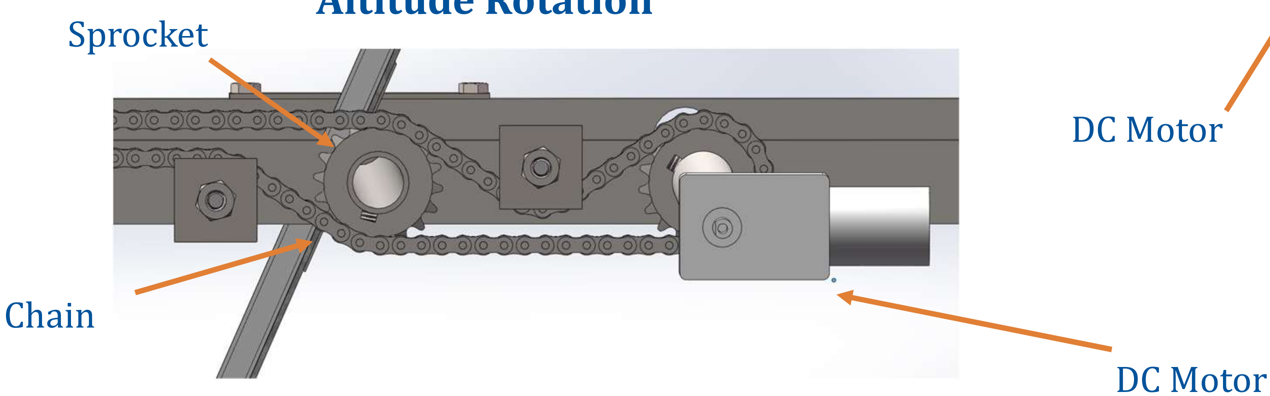
Maneuverability Subsystem Overview

- Two DC motors
  - Oilite Thrust Bearing
  - Chain and sprocket design
    - 360° of freedom in both rotational directions

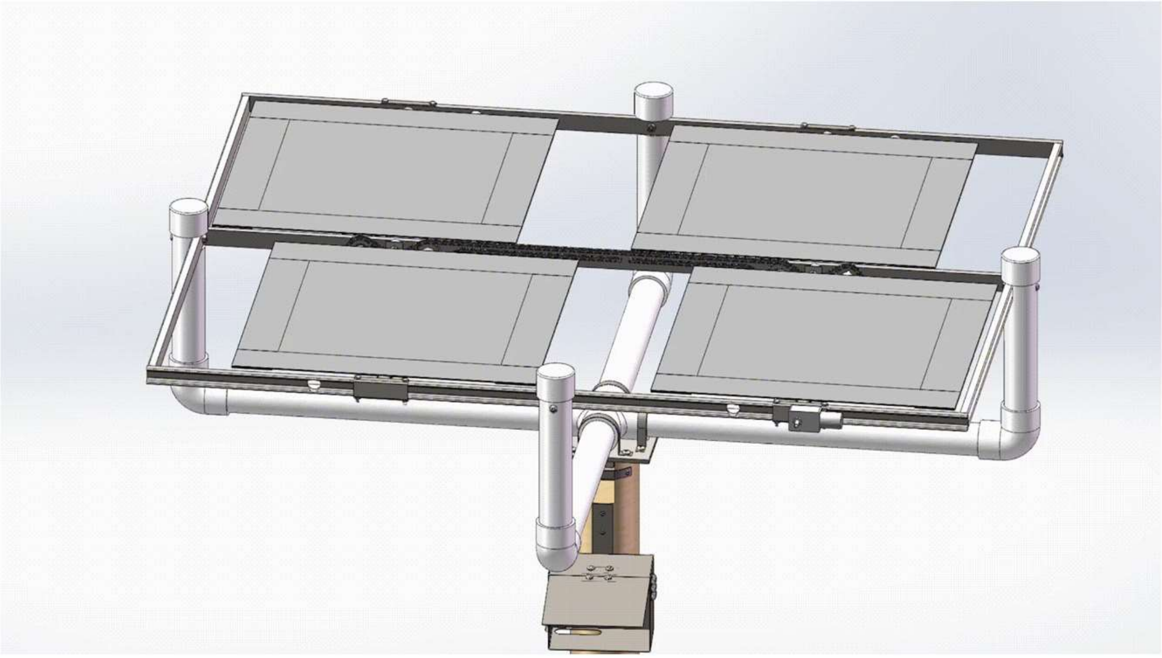
Azimuth Rotation



Altitude Rotation



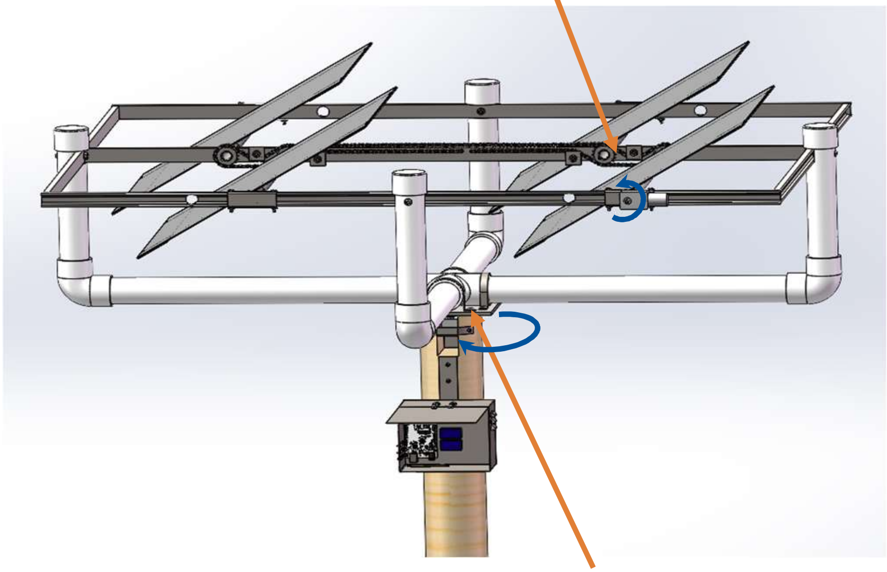
Rotation Animation



Maneuverability Proof of Concept – Need 5

- "Each module must be capable of tracking the sun throughout the day."
  - All mirrors have 360° of freedom in both azimuth and elevation directions.

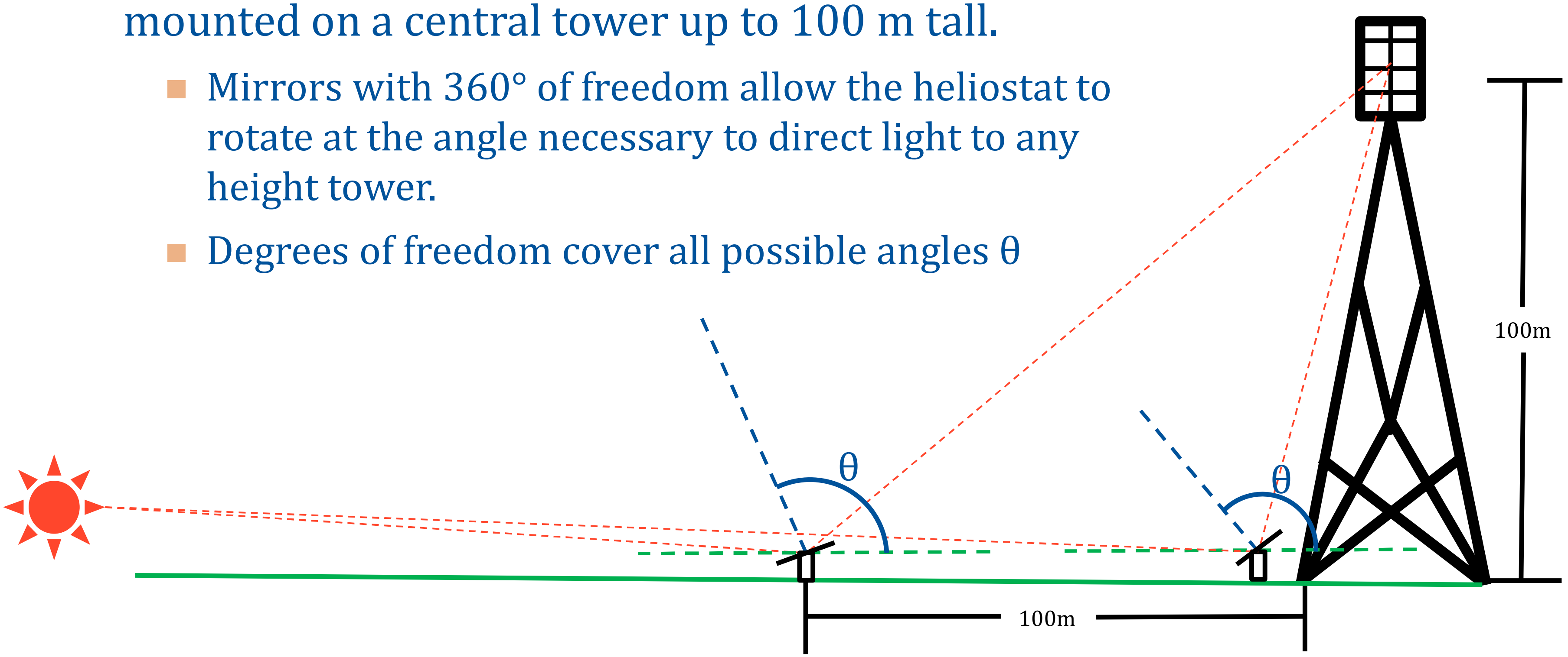
rotate 360° in elevation



rotate 360° azimuthally

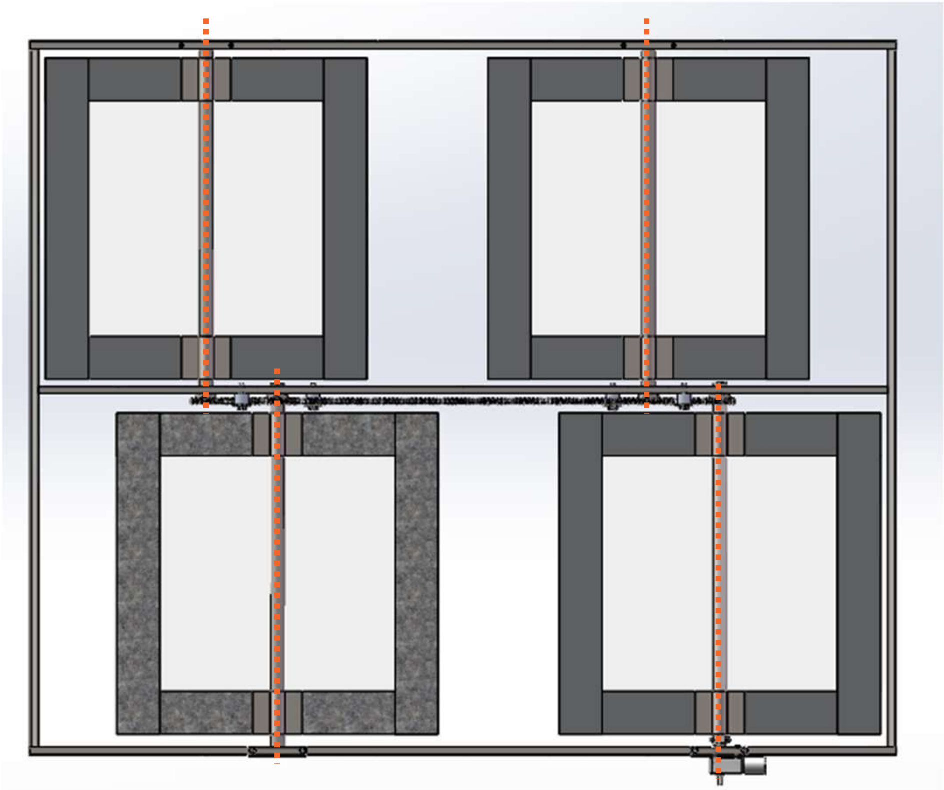
Maneuverability Proof of Concept – Need 7

- Modules must redirect sunlight to a receiver target mounted on a central tower up to 100 m tall.
  - Mirrors with 360° of freedom allow the heliostat to rotate at the angle necessary to direct light to any height tower.
  - Degrees of freedom cover all possible angles θ



Maneuverability Proof of Concept – Need 14

- "Each mirror in a module must move independently of all other mirrors in its module in at least one axis."
  - Each mirror moves independently in elevation rotation



Maneuverability Proof of Concept – Need 15

- "Operational lifetime of the installation must exceed 20 years."
  - Service Life = 1000 h at the specified 3 rpm

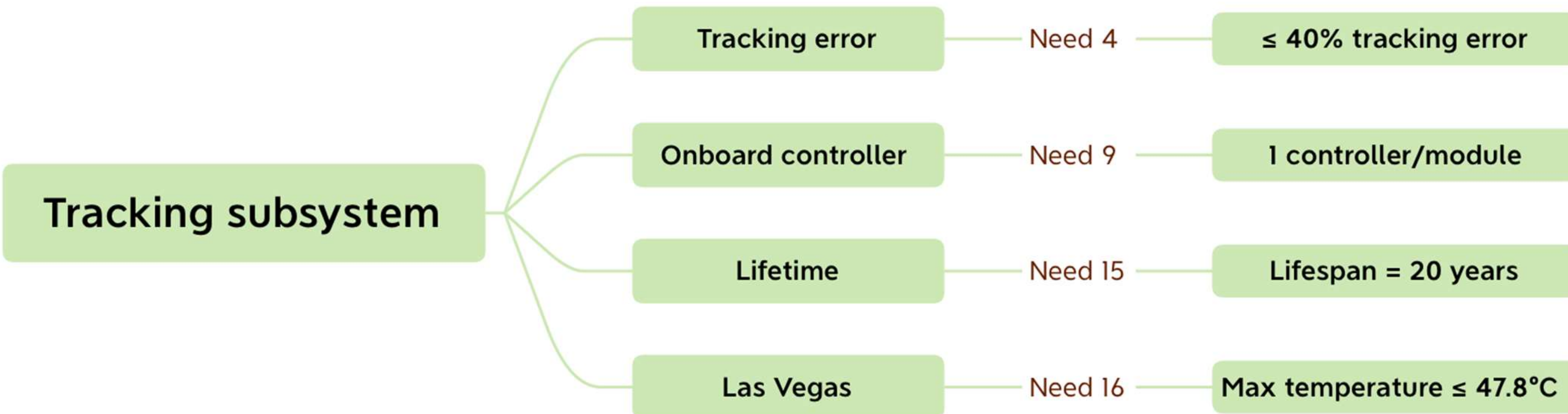
$$1000\ hours\left(\frac{3\ rev}{min}\right)\left(\frac{60min}{hour}\right) \rightarrow N = 180{,}000\ rev$$

  - 180,000 cycles till failure
  - Assume 1 cycle each day

$$180{,}000\ cycles\left(\frac{day}{1\ cycle}\right)\left(\frac{1\ year}{365\ days}\right)$$

$$= \mathbf{493\ years \gg 20}$$

Tracking Subsystem-Customer Needs



Slide 31

SH0 Fix the spelling of Las Vegas
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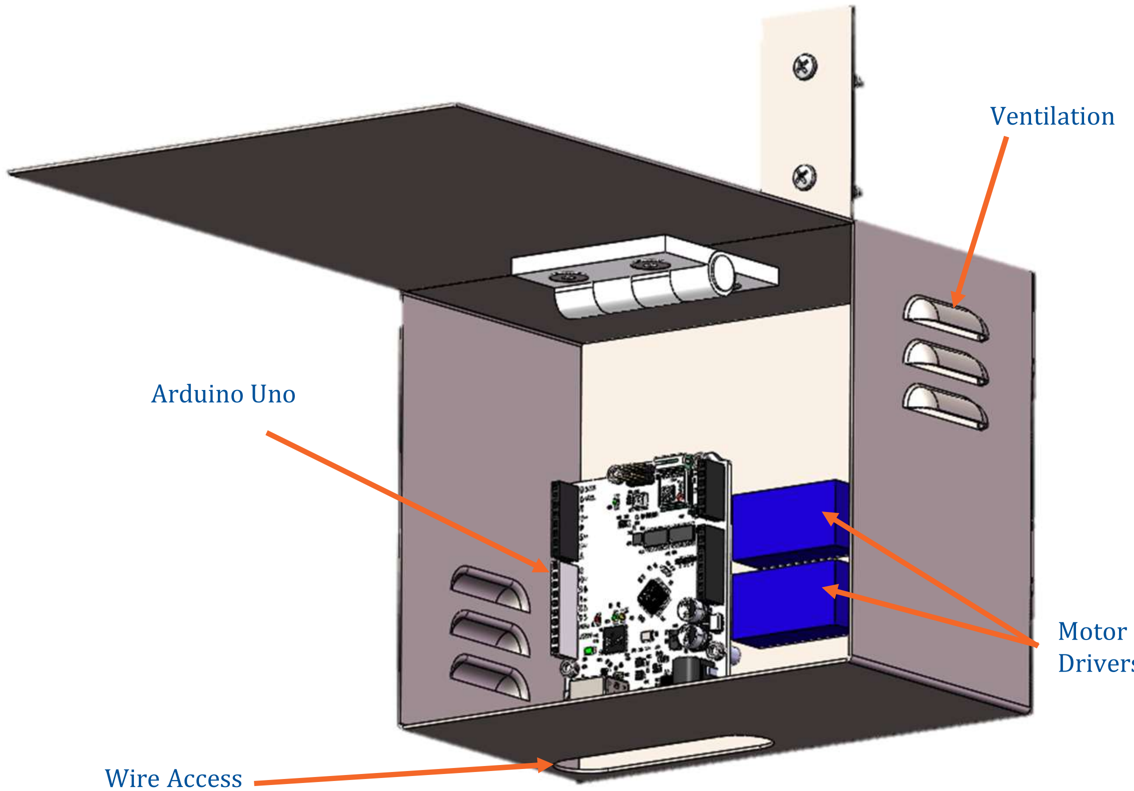
Tracking Subsystem Overview

- Motor Encoders
  - 16 counts per revolution
  - 972 Reduction Ratio



Tracking Proof of Concept – Need 4

- "Modules mitigate optical losses from tracking errors less than 40%."
  - Motor accuracy: 16 counts/rev, 971-reduction ratio

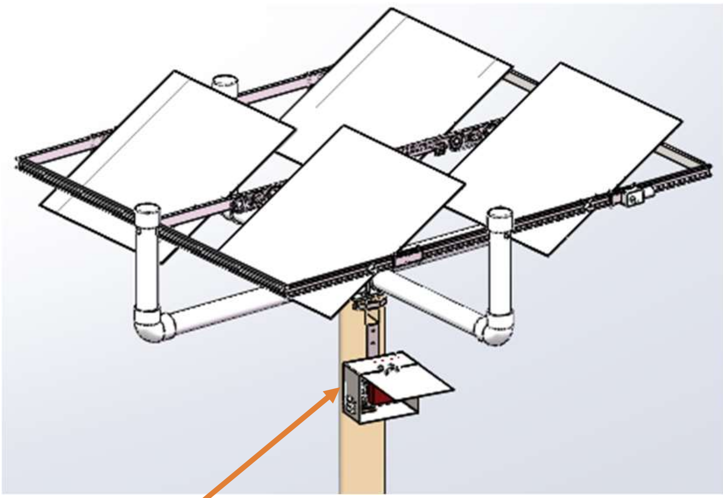
$$\left(16\frac{counts}{rev} * 971\right)^{-1} = 6.43 * 10^{-5}\frac{rev}{count}$$

$$6.43 * 10^{-5}\frac{rev}{count} * \frac{2\pi\ rad}{1\ rev} * \frac{180°}{\pi\ rad} = 0.023° \longrightarrow Tracking\ error \leq 40\%$$

$$Accuracy = \pm 0.023° \leq \pm 0.25°$$

Tracking Proof of Concept – Needs 9 & 15

- “Sun tracking by modules is automated and computer controlled with an onboard controller”
  - Each module has one onboard controller
- “Tracking lifetime exceeds 20 years”
  - Motor driver seller claims unlimited lifetime
  - Arduino Lifetime:
    - Rule of thumb for electrolytic capacitors:
      - Life doubles with drop of 10°C
      - Arduino: 5000 h at 105°C
      - Worst case temperature exposed to Arduino: 52°C

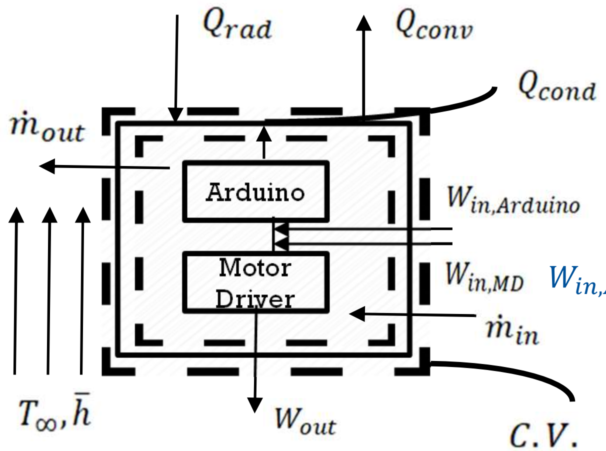


$$105°C - 52°C = 53°C \longrightarrow 5000\,h * 2^{5.3} \approx 197000\,h$$

$$197000\,h * \frac{1\ day}{24\ h} * \frac{1\ year}{365\ days} \approx 22.5\ \text{years}$$

Tracking Proof of Concept – Need 16

- “The system operates under ambient and solar conditions in Las Vegas, NV.”
  - Maximum temperature is 47.8°C
- Free convection and radiation
  - Steady state conditions, no heat transfer resistance or thermal mass in wall
  - Maximum operational temperature for Arduino and motor drivers: 85°C



Energy Balance:

$$W_{in} - W_{out} + Q_{in} - Q_{out} + \sum \dot{m}_{in}\left(h + \frac{V^2}{2} + gz\right) - \sum \dot{m}_{out}\left(h + \frac{V^2}{2} + gz\right)$$

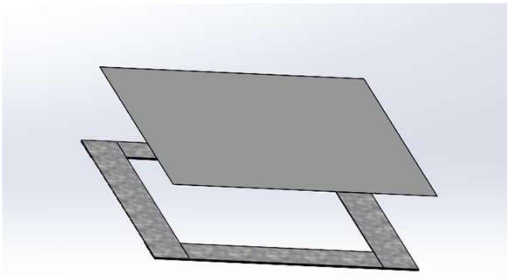
$$W_{in} - W_{out} - (Q_{conv} - Q_{rad}) + \dot{m}_{in}(c_p T_\infty) - \dot{m}_{out}(c_p T_i) = 0$$

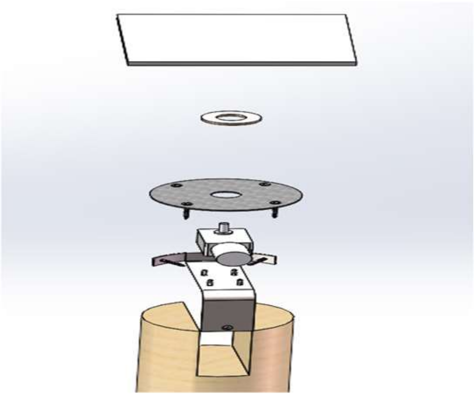
$$W_{in,Arduino} + W_{in,MD} - 2W_{out,motor} - \bar{h}A_{conv}(T_i - T_\infty) + \sigma F_{ij} A_{rad}(T_{sun}^4 - T_i^4) + \dot{m}c_p(T_\infty - T_i) = 0$$

After an iterative process, The inside box temperature was found:

$$T_i = 78.4°C < 85°C$$

Design Highlights



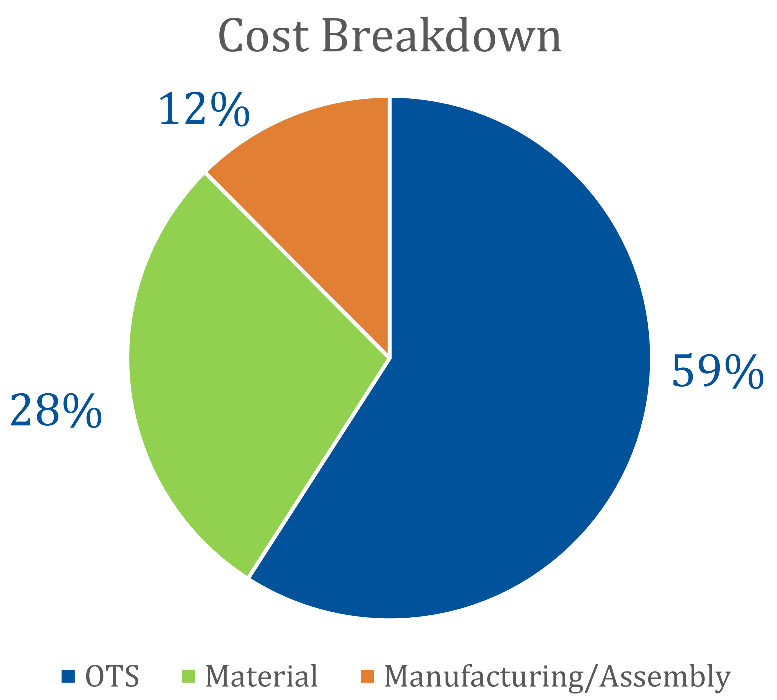


Unique Features

- Reflective
  - Solar film with galvanized steel frame
- Maneuverability
  - Sprocket and chain drive
- Structure
  - Oilite bearing

Cost Summary

Expense Type	Cost
OTS	$166.43
Raw Materials	$80.14
Manufacturing / Assembly Labor	$35.07
Total:	**$281.64**



Conclusion

- Design points:
  - Four independent square heliostats in a pattern to mitigate self-shading
  - Effective motors and controller system to accurately track the sun
  - Utilizes long-lasting materials that are unlikely to fail

Prototyping for EML4502

- Design utilizes space with small reflective surface to reduce shading between heliostats
- Uses two motors efficiently with high accuracy
- Inexpensive installation process with a wooden post

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UNIVERSITY of FLORIDA

Thank You!

Questions?

POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

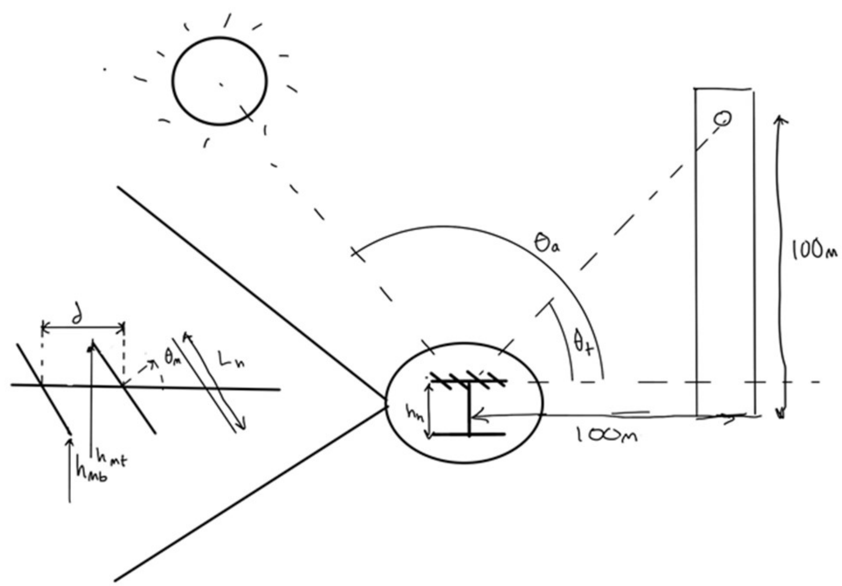
Appendix-Shading

$$\theta_t = \tan^{-1}\left(\frac{h_d}{L_t}\right)$$

$$\theta_m = \frac{\theta_s + \theta_t}{2}$$

$$h_b = \frac{h_m + L_m}{2\sin(90 - \theta_m)}$$

$$x = \frac{\left(-\frac{h_d}{2} - \left(\frac{d_b - L_m}{2\cos(90 - \theta_m)}\right)\right)}{\tan\theta_a + \tan(90 - \theta_m)}$$



Appendix-Shading cont'

$$d_s = |x| - (d_b - L_m \cos(90 - \theta_m))$$

$$L_s = \frac{d_s}{90 - \theta_m}$$

$$S = \frac{L_s}{L_m}$$

$$S_{avg} = \int_{15}^{90} \frac{\left(\frac{S}{2} + \frac{S}{4}\right)}{2} dS$$

Appendix – Structure

Force on each heliostat due to drag. Density of air for Las Vegas conditions was used.

$$F_{drag} = \frac{1}{2}\rho v^2 A c_d = \frac{1}{2}\left(1.225\frac{kg}{m^3}\right)\left(40.2336\frac{m}{s}\right)^2 (0.1089m^2)(1.98) \rightarrow F_{drag} = 174.52N$$

Total force acting directly downwards on the heliostat.

$$F_{total} = 4F_{drag} + F_{weight} = 4(174.52N) + 5.1428N \rightarrow F_{total} = 703.2N$$

Second moment of area for PVC frame supports.

$$I = \frac{\pi}{64}\left(D_o^4 - D_i^4\right) = \frac{\pi}{64}[(0.048m)^2 - (0.041m)^2] = 1.22 \cdot 10^{-7}m^4$$

Farthest distance from the central axis for PVC frame supports.

$$c = \frac{D_o}{2} = \frac{0.048m}{2} \rightarrow c = 0.024m$$

Appendix-Heat Transfer

$g = 9.81 \frac{m}{s^2}$
$\beta = 3.07 * 10^{-3}\ K^{-1}$
$T_\infty = 300.3\ K$
$T_{sun} = 5772\ K$
$F_{ij} = 0$
$L = 0.1466\ m$
$\nu = 1.85 * 10^{-5} \frac{m^2}{s}$
$\alpha = 2.63 * 10^{-5} \frac{m^2}{s}$
$k = 0.0282 \frac{W}{m * K}$
$\sigma = 5.67 * 10^{-8} \frac{W}{m^2 * K^4}$

$Ra = 1.0 * 10^7$
$Nu_L = 30.4$
$\bar{h} = 5.84 \frac{W}{m^2 * K}$
$\rho = 1.075 \frac{kg}{m^3}$
$V = 9.2\ mph$
$A_{slot} = 2.49 * 10^{-4}\ m^2$
$A_{rad} = 0.0264\ m^2$
$A_{conv} = 0.0660\ m^2$
$W_{in,Arduino} = 2\ W$
$W_{in,MD} = 540\ W$
$W_{out,motor} = 1.32\ W$

$$Ra = \frac{g\beta(T_i - T_\infty)L^3}{\nu\alpha}$$
↓
$$Nu_L = 0.54(Ra)^{1/4}$$
↓
$$\bar{h} = \frac{Nu_L k}{L}$$

g: acceleration due to gravity
β: coefficient of thermal expansion
T_∞: average temperature outside
T_{sun}: temperature of the surface of the sun
F_{ij}: viewing factor for radiation
$L = r_i$: length of the longest side of the box
r_j: radius of the sun
L: distance from the heliostat to the sun
ν: kinematic viscosity at average T
α: thermal diffusivity at average T
k: thermal conductivity at average T
σ: Stefan − Boltzmann constant
Ra: Rayleigh number
Nu_L: Nusselt number
$\bar{h}$: average heat transfer coefficient

$$F_{ij} = \frac{1}{2}\left\{\left(1 + \frac{1 + \left(\frac{r_j}{L}\right)^2}{\left(\frac{r_i}{L}\right)^2}\right) - \left[\left(1 + \frac{1 + \left(\frac{r_j}{L}\right)^2}{\left(\frac{r_i}{L}\right)^2}\right)^2 - 4\left(\frac{r_j}{r_i}\right)^2\right]^{\frac{1}{2}}\right\}$$

$r_j = 6.96 * 10^8\ m$
$r_i = 0.1466\ m$
$L = 1.497 * 10^{11}\ m$