UF Herbert Wertheim College of Engineering
UNIVERSITY *of* FLORIDA

Illumigator

Small-Scale Heliostat for Industrial Solar Processing

Section 1355, Group 5

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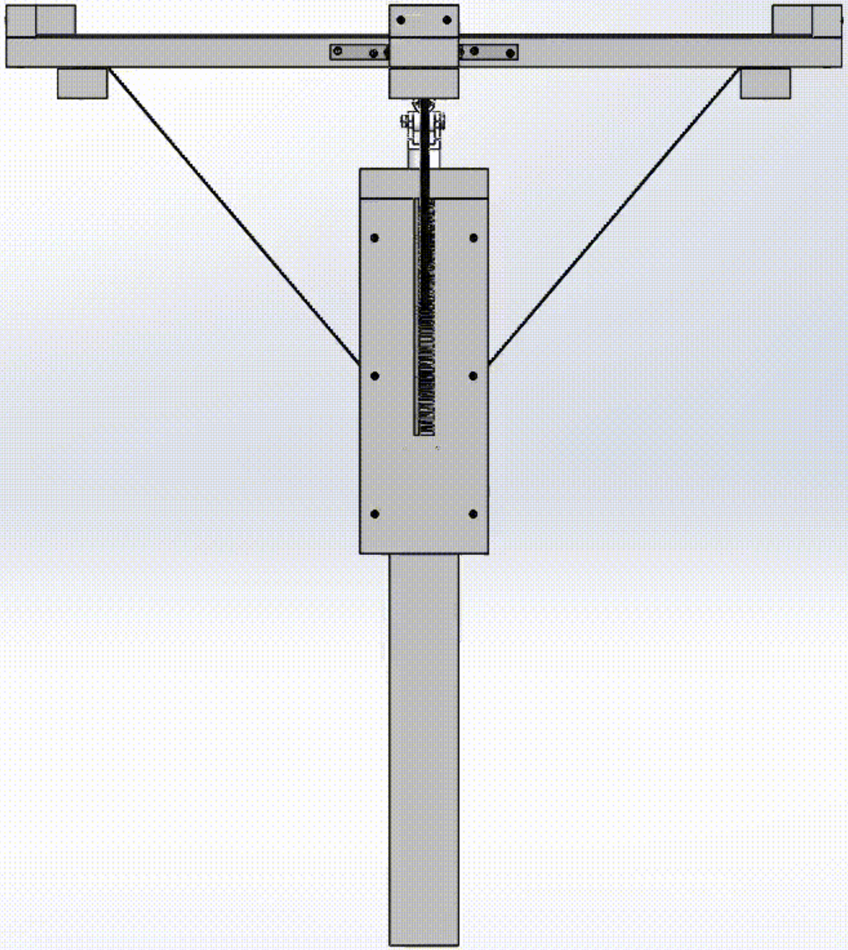
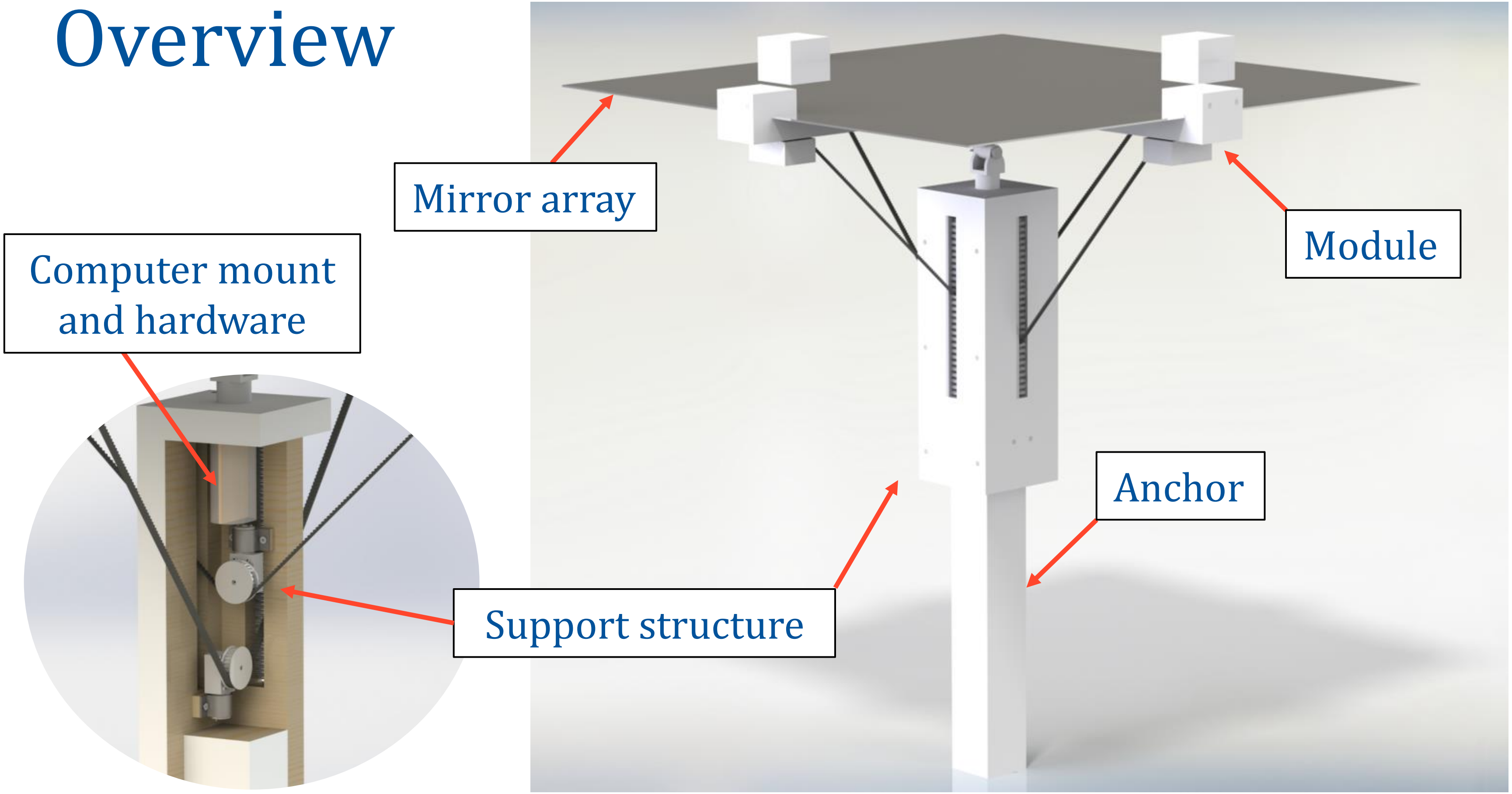
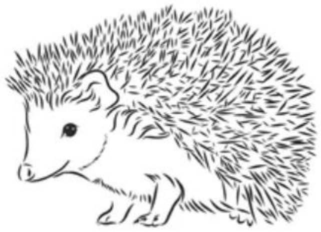
POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

The Illumigator



Overview


Mirror array
Module
Computer mount and hardware
Anchor
Support structure



Core Value Proposition

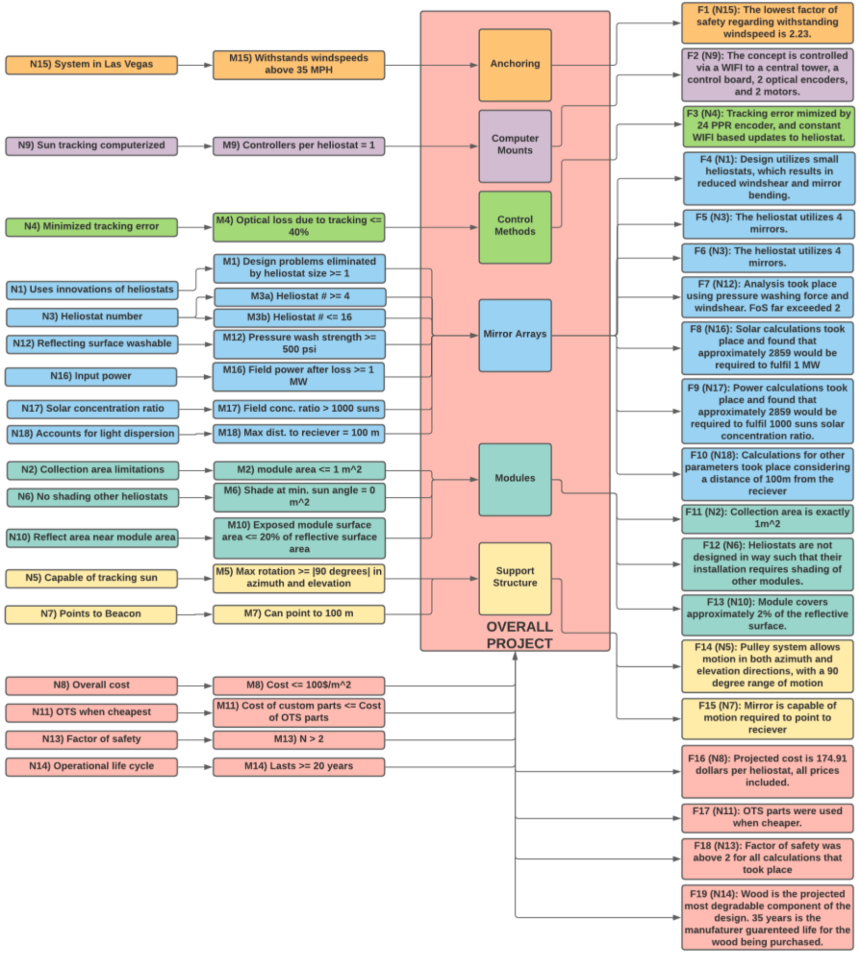
Our "Hedgehog Concept"

Skills:
- Diversity in coursework/ experience
- Creative ideation
- Synergy

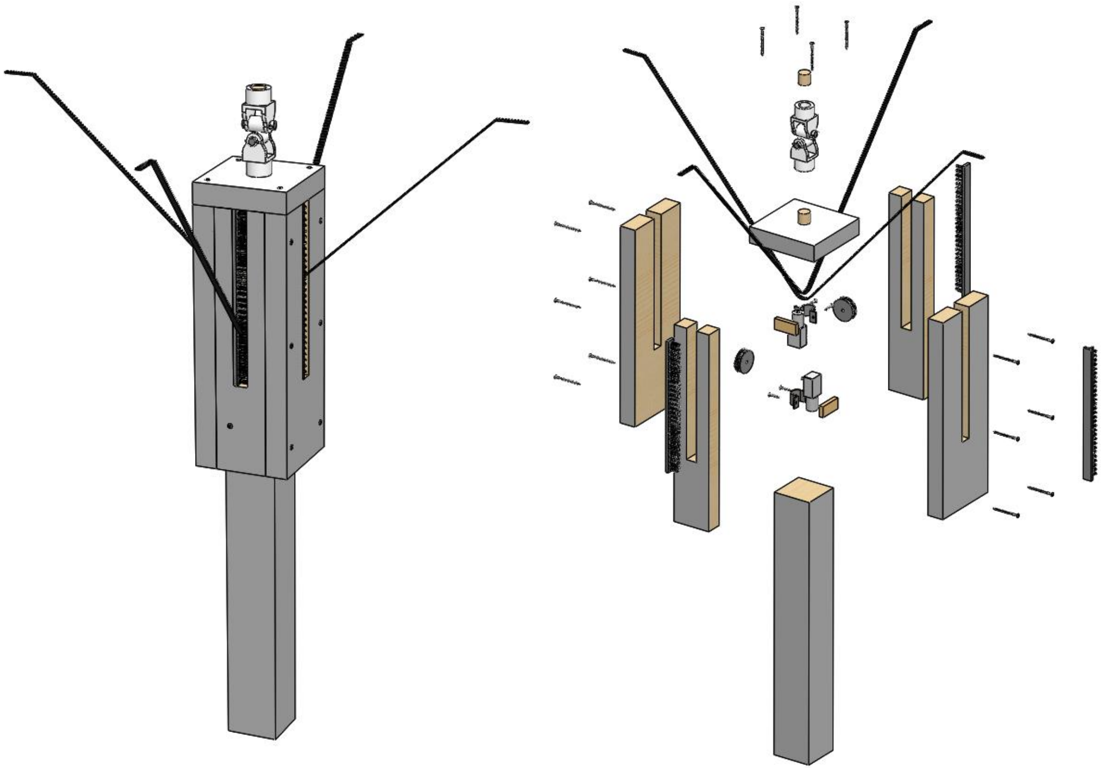
Economic drivers:
- Cost/heliostat
- Profit/MW produced

Driving passions:
- Sustainability
- Modularity
- Accessibility

Customer Needs Map



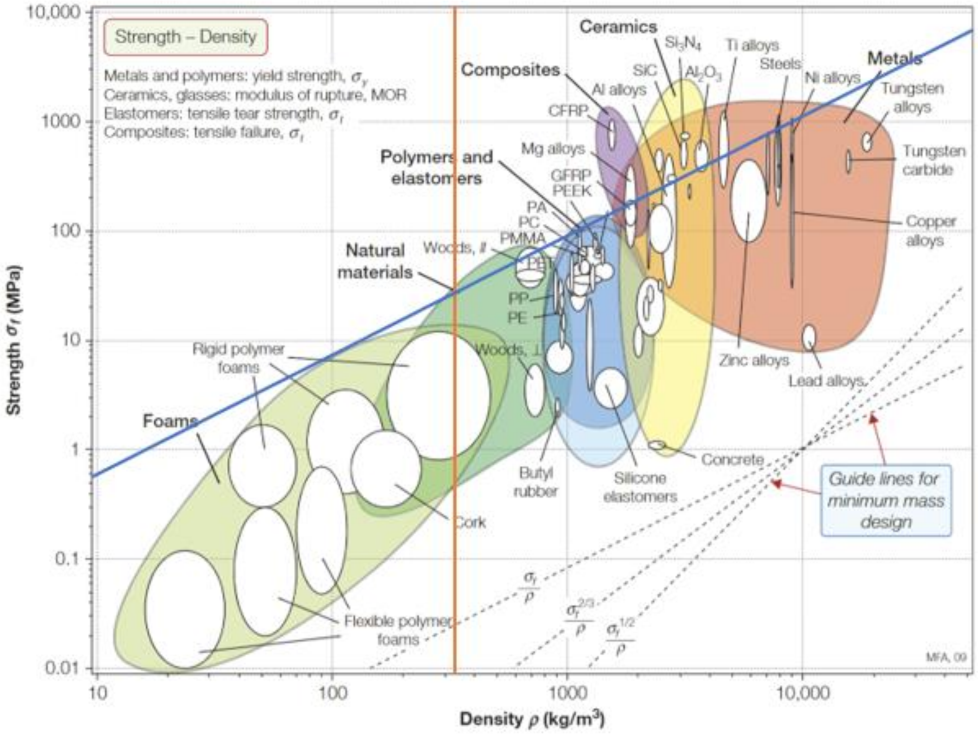
Subsystem 1+2: Support Structure/Anchor



- Primary material = pressure-treated pine wood
- 3D-printed universal joint and timing belt pulleys for module actuation
- Painted to protect from corrosion and limit interior temperature changes

Support Structure/Anchor Material Selection

- Low Cost and density
- Modular
- >20-year lifetime
- Ashby analysis



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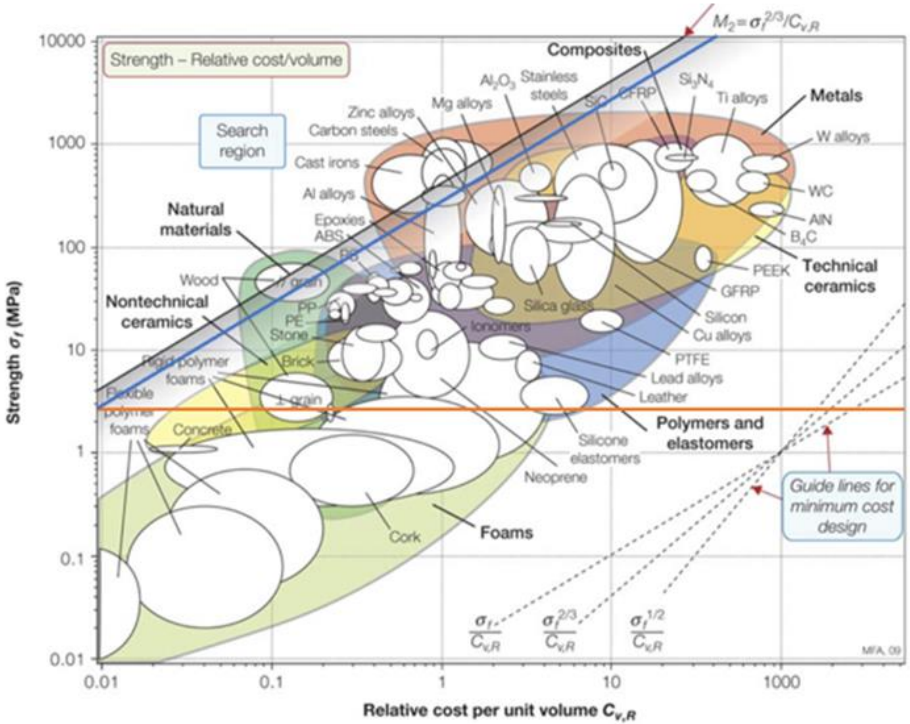
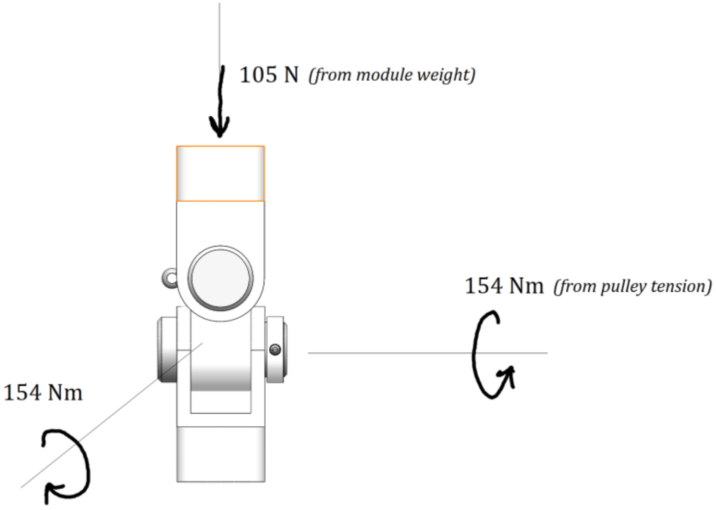


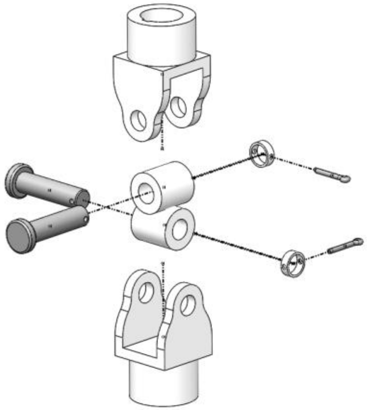
Support Structure Analysis: U-joint

$$\sigma_{y,1} = \frac{P}{A} = \frac{105\ N}{0.00051\ m^2} = 205.9\ kPa$$

$$\sigma_{y,2} = \frac{My}{I} = \frac{154N * \left(\frac{.0254m}{2}\right)}{\frac{\pi}{64} * .0254m^4} = 97.79\ MPa$$

$$\tau = \frac{Tc}{J} = \frac{154N * \left(\frac{.0254m}{2}\right)}{\frac{\pi}{32} * .0254m^4} = 47.86\ MPa$$

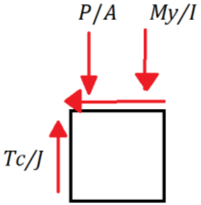




$$center = \frac{98\ MPa}{2} = 49\ MPa$$

$$radius = (47.86^2 + 98^2)^{\frac{1}{2}} = 109.06\ MPa$$

$$\sigma_a = 158.06\ MPa, \qquad \sigma_b = -60.6\ MPa$$



Brittle Failure Criteria

1004 steel UTS= 565 MPa

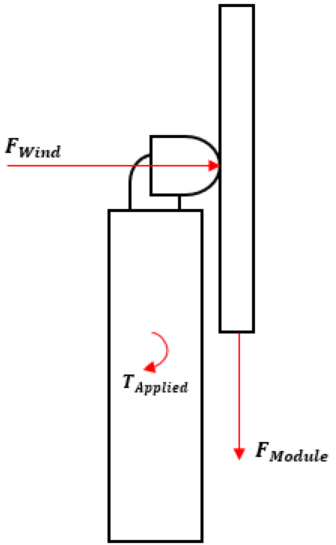
Max normal stress criterion:

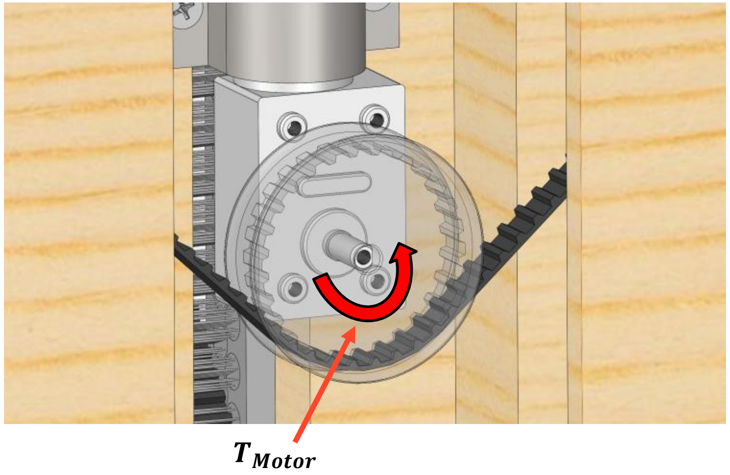
$$n_1 = \frac{565}{158.06} = 3.57, \quad n_2 = \frac{565}{60.6} = 9.32$$

Coulomb-Mohr criterion:

$$n = \left(\frac{158.06 + 60.6}{565}\right)^{-1} = \mathbf{2.58}$$

Support Structure Analysis: Minimum Factor of Safety





Material mass and volume:

$$M_w = \rho_w * V_w$$
$$V_w = l * w * h$$

$$V_{w1} = 0.0889 * 0.0381 * 1.076 = 0.00364\ m^3$$
$$V_{w2} = 0.0889 * 0.041275 * 0.0381 = 0.000140\ m^3$$
$$V_{w3} = 0.0889 * 0.0381 * 0.0508 = 0.000172\ m^3$$

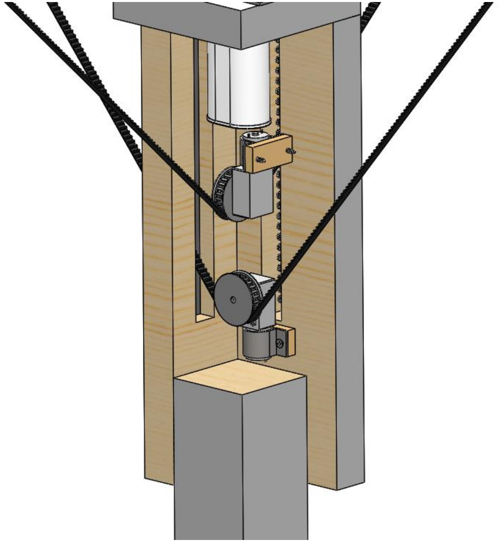
$$M_w = 350\frac{kg}{m^3} * 1.1649\ m^3 = 2.985\ kg$$
$$M_g = \rho_g * V_g = 2200\frac{kg}{m^3} * 1m^2 * 0.003175m = 6.985\ kg$$
$$M_{total} = M_g + M_w = 9.97\ kg \Rightarrow F_{mod} = \mathbf{97.8\ N}$$

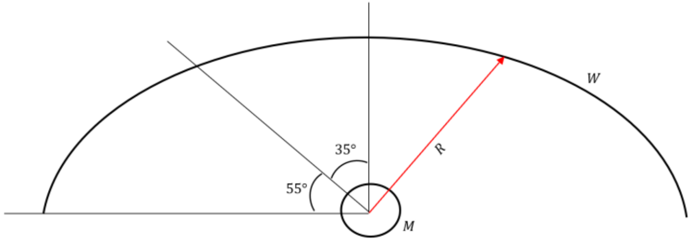
Applied force and torque:

$$F_{wind} = A * P * C_d$$
$$P = 0.613V^2 = 0.613 * 15.65^2 = 150.14\ N/m^2$$
$$F_{wind} = 1 * 150.14 * 1.4 = 210.19\ N$$
$$\Rightarrow F_{total} = F_{wind} + F_{mod} = \mathbf{308\ N}$$

$$T_{applied} = F_{total} * \frac{D}{2} = 308 * \frac{0.044602}{2} = \mathbf{6.87\ N * m}$$
$$N = \frac{T_{stall}}{T_{applied}} = \frac{44.145}{6.87} = \mathbf{6.43}$$

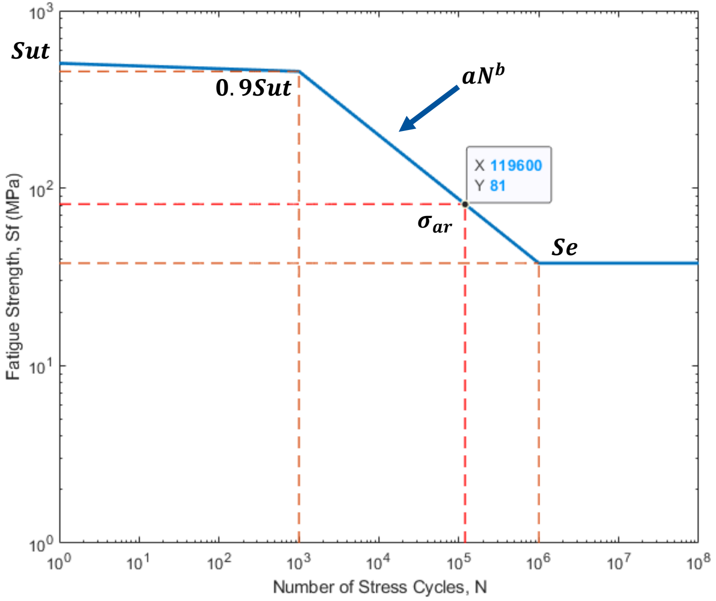
Support Structure Analysis: Motor Lifetime





- Dual motors for azimuth and elevation angles
- $\frac{Cycles}{day} = \frac{Arc\ length\ W}{Circumference\ M} = \frac{R\theta}{\pi D}$
- Top motor: $\frac{0.4569\ m}{0.165\ m} * 2 \sim \frac{6\ cycles}{day}$ = 43,800 cycles at 20 years
- Bottom motor: $\frac{0.5210\ \mathrm{m}}{0.165\ m} * 2 \sim \frac{7\ cycles}{day}$ = 51,100 cycles at 20 years

Support Structure Analysis: Motor Lifetime



- $\sigma_{ar} = aN^b \Rightarrow N = \left(\frac{\sigma_{ar}}{a}\right)^{\frac{1}{b}}$
- $a = \frac{(0.9S_{ut})^2}{S_e} = \frac{(0.9*505)^2}{37.8} = 5470.8$
- $b = \frac{-1}{3}\log\left(\frac{0.9S_{ut}}{S_e}\right) = \frac{-1}{3}\log\left(\frac{0.9*505}{37.8}\right) = -0.360$
- $S_e = k_a k_b k_c k_d k_e k_f * 0.5S_{ut} = .807(.997)(.590)(1.00)(.814)(.387) * 252.5$

k_a = Surface factor
k_a = Size factor
k_a = Loading factor
k_a = Temperature factor
k_a = Reliability factor
k_f = Miscellaneous factors (plating, surface imperfections, frettage, etc.)

- $\tau = \frac{Tc}{J} = \frac{6.87(.003)}{(1.27*10^{-10})} = 162.283 \Rightarrow \sigma_{ar} = \frac{162.283-0}{2} = 81.142\ MPa$
- $N = \left(\frac{81.142}{5470.8}\right)^{\frac{-1}{0.360}} = 119{,}560\ cycles$

Support Structure Analysis: Interior Heat Transfer

$$P = VI \triangleq q = 58.9\ W$$

$$qR = T_i - T_j$$

1. Ambient air:

$$Re = \frac{ux}{\nu}$$

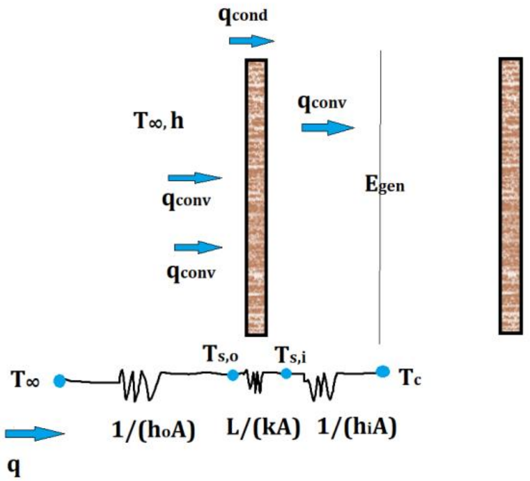
$$Nu = 0.332(Re)^{\frac{1}{2}}(Pr)^{\frac{1}{3}}$$

$u = 15.6\ m/s$, $T\infty = 320.8\ K$

→ *$T_{s,o} = 317.3\ K$, $T_{s,i} = 298.6\ K$*

Operating temperatures:

- *Motor: -30 to 70°C*
- *Controller: -40 - 85°C*



2. Iterative process to determine T_c

Guess T_c

$$Ra = \frac{g\beta(T_c - T_{s,i})D^3}{\nu\alpha}$$

$$\overline{Nu_L} = 0.68 + \frac{0.67Ra^{\frac{1}{4}}}{\left(1 + \left(\frac{0.492}{\text{Pr}}\right)^{\frac{9}{16}}\right)^{\frac{4}{9}}} = \frac{hL}{k}$$

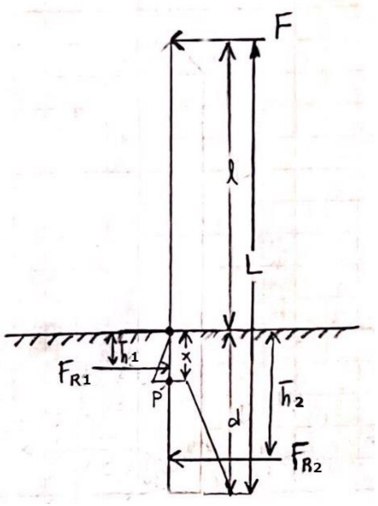
$$q = h(T_c - T_{s,i})$$

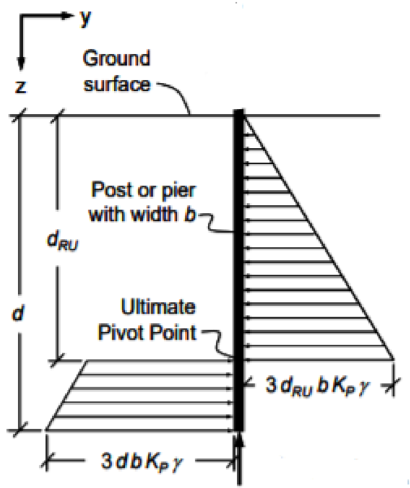
→ *$T_c = 310.6\ K =$ **37.45°C***

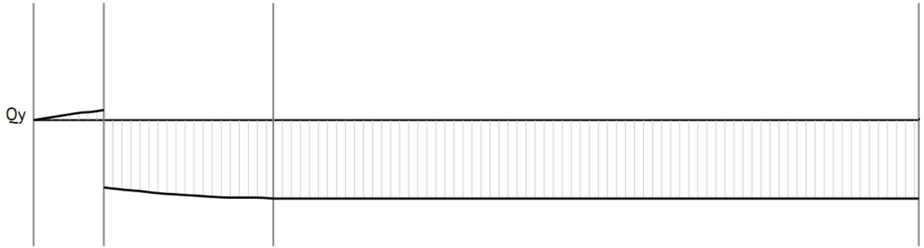
Anchor Analysis: Statics

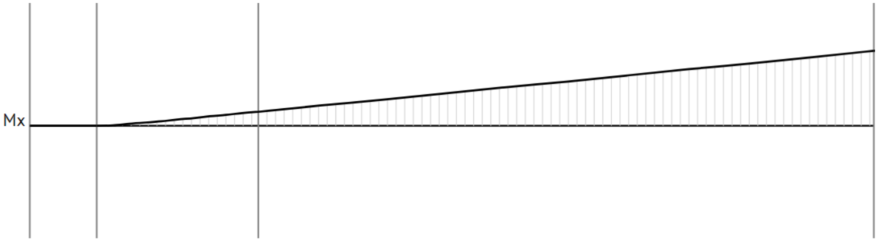
- d = depth = 0.3048 m
- d_{RU} = pivot depth = 0.2155 m
- B = post width = 0.1016 m
- Kp = coefficient of passive earth pressure = 3.690
- γ = moist unit weight = 16677 N/m^3

- $F_{max} = \frac{K_p \gamma w d^3}{3(l+x)}$ =170.83 N









Customer Needs: Support Structure

5. Dual-axis solar tracking

7. Can point to receiver 100 m away

11. Utilizes OTS parts, and custom parts when cheaper

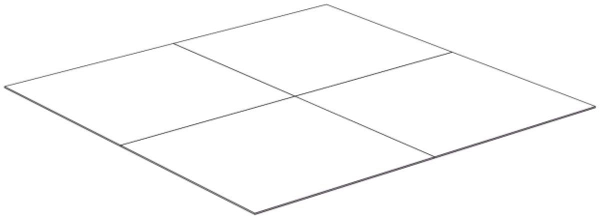
13. High factor of safety

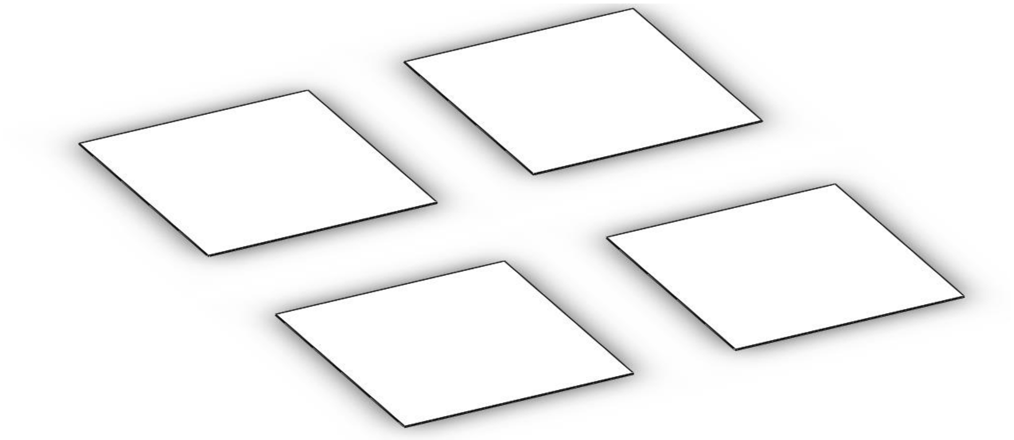
14. High operational lifetime

Customer Needs: Anchor

15. Allows heliostat to withstand Las Vegas wind speeds

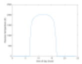
Subsystem 3: Mirror Array





- 4 total OTS mirrors per heliostat
- Minimal tracking error
- Customer needs addressed:
- Lift force of 33.756 lbs from maximum wind speed of 35 *mph*

Mirror Array Analysis: Maximum Receiver Temperature



Max temperature = 2022 K (winter solstice)

Absorption efficiency

Useful power output (W)

Stefan-Boltzmann constant

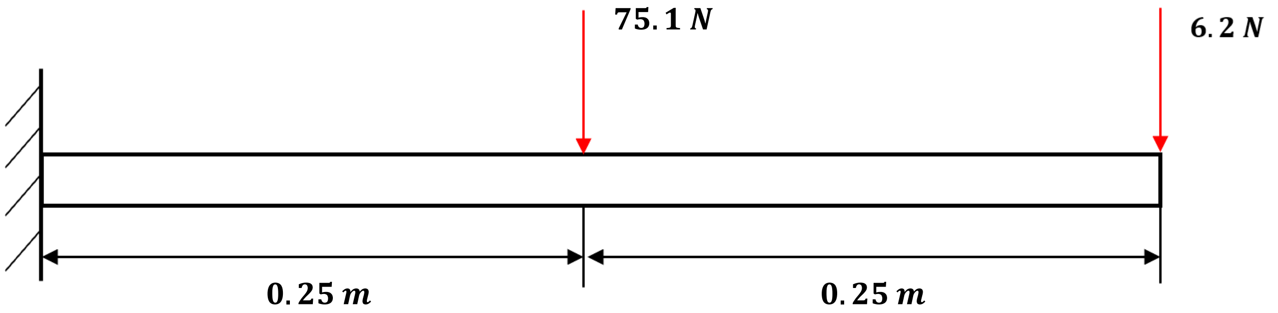
$$\eta_{abs} = \frac{Q_{use}}{Q_{solar}} = 1 - \frac{\sigma {T_r}^4}{G_t C} = 0$$

Power from solar irradiation (W)

Irradiation on tilted surface (W/m^2)

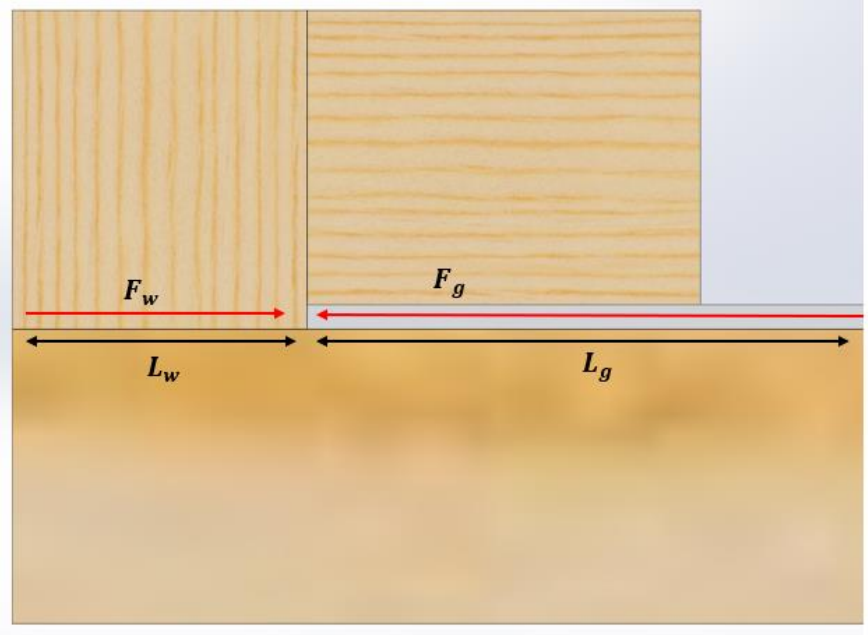
Solar concentration ratio

Mirror Array Analysis: Wind Shear and Cleaning



- $P * \frac{A}{2} = 150.14 \frac{N}{m^2} * 0.5\ m^2 = 75.1\ N$
- $A = \pi r^2 = \pi(0.762)^2 = 1.824\ mm^2$
- $F = \sigma A = 3.4\ MPa * 1.824\ mm^2 = 6.20\ N$
- $\sigma_1 = \frac{6FL}{bh^2} = \frac{6(75.1)(0.25)}{(0.0889)(0.0413)^2} = 0.743\ MPa$
- $\sigma_2 = \frac{6FL}{bh^2} = \frac{6(6.2)(0.25)}{(0.0889)(0.0413)^2} = 0.0613\ MPa$
- $\sigma_{total} = \sigma_1 + \sigma_2 = 0.8043\ MPa$
- $N_{mod} = \frac{2.31}{0.8043} = 2.87, \sigma_{total} \ll S_{ut\,glass} = 1000\ MPa$

Mirror Array Analysis: Thermal Expansion



Glass:

$$\alpha_g = 0.55 * 10^{-6}\ /°C$$

$$\Delta T = +13\ °C$$

$$\Delta l = \alpha_g L_g \Delta \mathrm{T} = (0.55 * 10^{-6}\ /°C)(0.5)(13) = 3.575 * 10^{-6}\ \mathrm{m}$$

$$\varepsilon = \frac{\Delta l}{l_0} = \frac{3.575 * 10^{-6}}{0.5} = 7.15\ \mu m$$

$$\sigma_{dt} = E_{glass}\varepsilon = 74.8\ GPa\ * 7.15\ \mu m = \mathbf{534.82\ kPa}$$

Wood:

$$\alpha_w = 0.58 * 10^{-6}\ /°C$$

$$\Delta T = +13\ °C$$

$$\Delta l = \alpha_w L_w \Delta \mathrm{T} = (0.58 * 10^{-6}\ /°C)(0.0381)(13) = 2.873 * 10^{-6}\ \mathrm{m}$$

$$\varepsilon = \frac{\Delta l}{l_0} = \frac{0.2873\ \mu m}{0.0381\ m} = 7.53\ \mu m$$

$$\sigma_{dt} = E_{wood}\varepsilon = 10\ GPa\ * 7.53\ \mu m = \mathbf{75.3\ kPa}$$

Customer Needs: Mirror Array

1. Area = 1 m^2

3. Each module must be composed of 4-16 heliostats

12. Reflecting surface must be washable

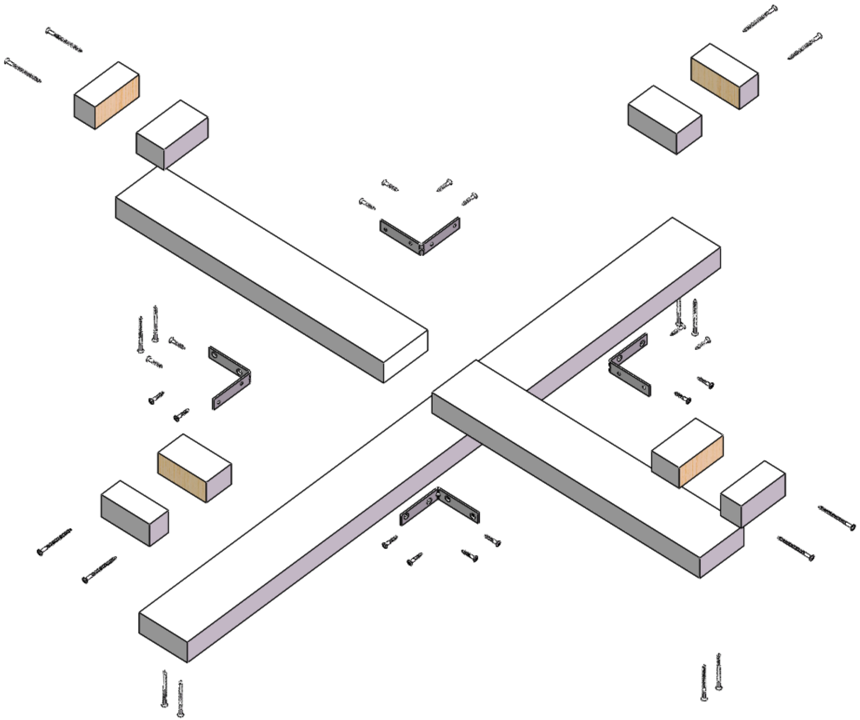
16. Focal thermal input power of 1 MW after losses

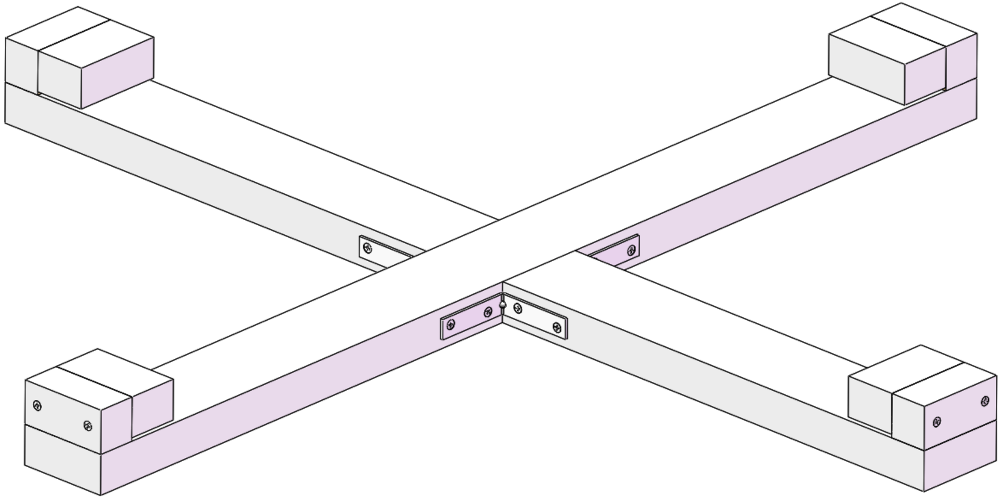
17. Solar concentration ratio is greater than 1000 suns

18. Accounts for light dispersion

Subsystem 4: Module

- Primary material = wood
- Lightweight, capable of dual-axis solar tracking
- Clamps to secure mirrors





Module Analysis: Shading Between Units

Determining Reflective Area

$$A_{rec} = \frac{Q}{q} = \frac{power\ input}{solar\ flux}$$

$$\frac{A_{heliostats}}{A_{rec}} = C = 1000$$

→ 2859 heliostats of 1 m^2 area

Shading Between Mirrors

0.018 m^2 shaded by clamps

→ **2913** heliostats of 1 m^2 area, or decreased receiver size

Shading Between Heliostats

$$field\ size = \frac{1}{2} * [\pi(100\ m)^2] = 15708\ m^2$$

$$\frac{15708\ m^2}{2913\ heliostats} = \mathbf{5.4\ m^2}\ per\ unit$$

→ Sufficient spacing, no shading in field

Module Analysis: Lift Force

The following formula defines the wind pressure on the heliostat module:

$$P = 0.00256 * v^2$$

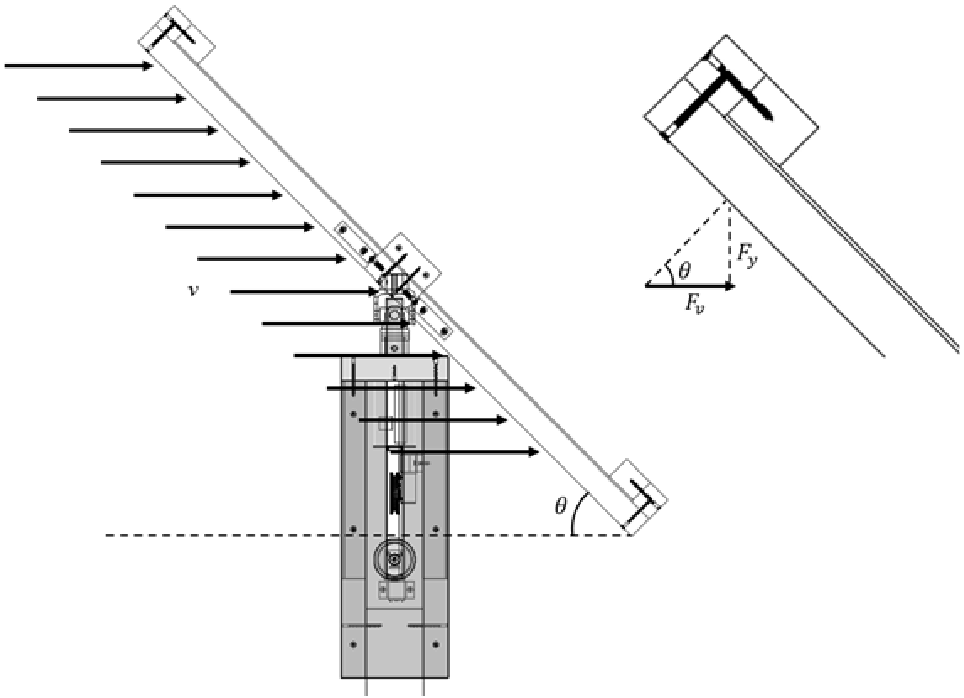
$$P = \frac{F}{A}$$

Vertical Lift Force:

$$F_y = 0.00256 * v^2 * A * \tan(\theta)$$

Assuming an angle of 45°, a wind speed of 35 mph, and a module area of 1 m^2 or 10.7639 ft^2, the vertical force is then:

$$F_y = 0.00256 * (35\ mph)^2 * (10.7639\ ft^2) * \tan(45°) = \mathbf{33.756\ lbs}$$



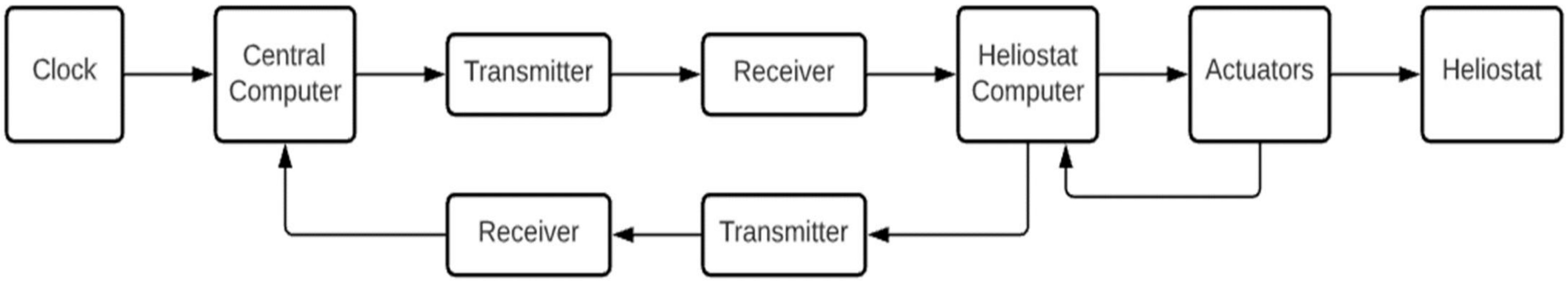
Customer Needs: Module

2. No mirror shading within heliostat

6. No shading between heliostats

10. Exposed module area < 20% reflective area

Subsystem 5: Control System



- Feedback control with inputted solar data
- Receives information from central computer
- Continual closed loop system between actuators and heliostat ensures long-lasting accuracy

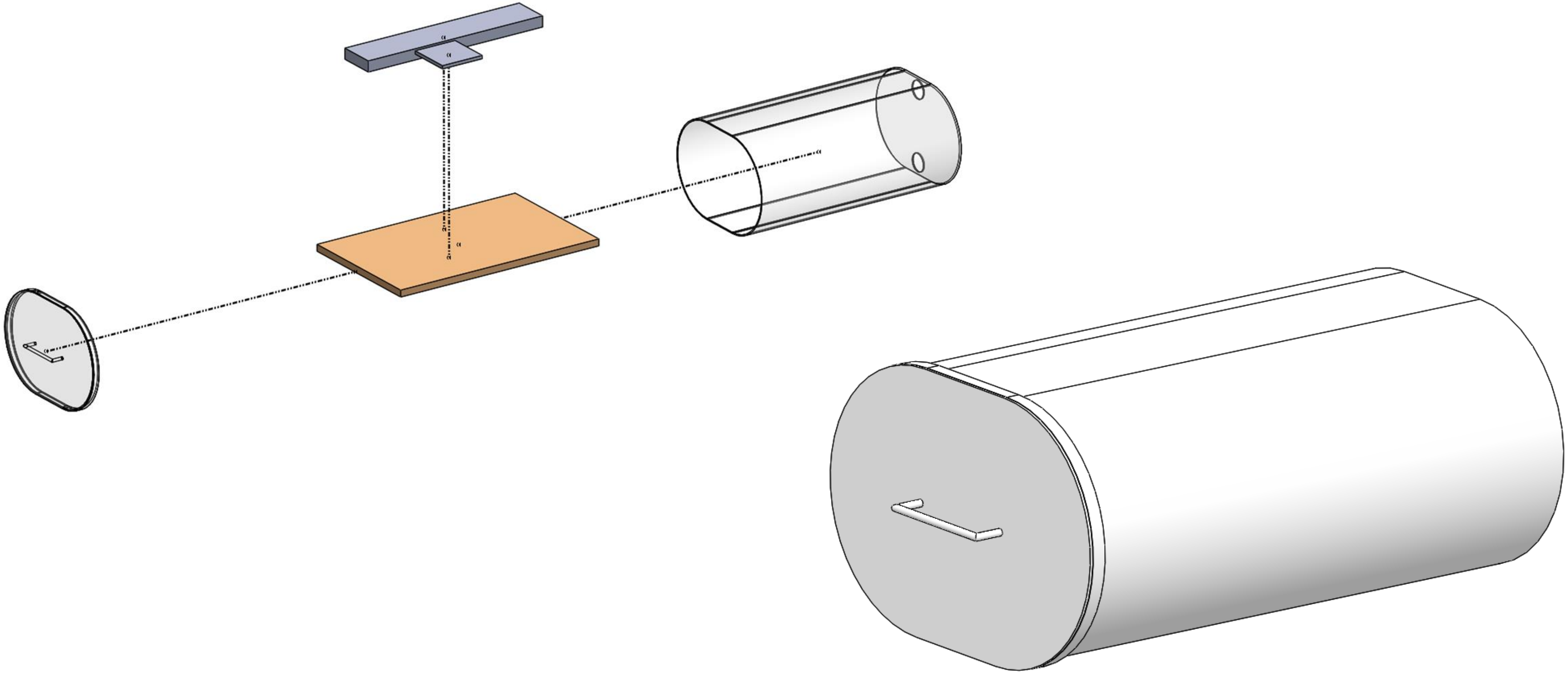
Customer Needs: Control System

4. Encoder allows for minimal tracking error

5. Built-in dual-axis solar tracking

14. Feedback control = high operational lifetime

Subsystem 6: Hardware Mount



Customer Needs: Hardware Mount

9. Allows for computerized tracking via central computer

11. Utilizes OTS parts, besides custom mounting platform

Unique Features

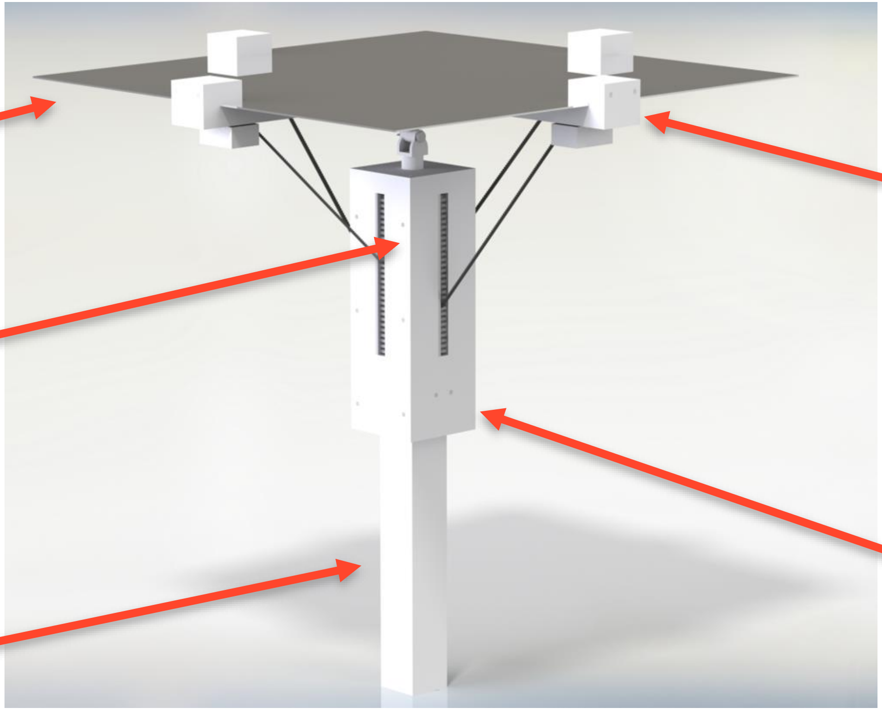
- Painted Pressure-Treated Wood
- Pulley Belt System
- Internally mounted components

Material Cost Table: Subsystem Breakdown

Mirror array: **~$21.48** (4 mirrors, per manufacturer quote)

Computer mount and hardware: **~$16.81** (Integrated RISC WIFI board, 24 PPR encoders, motor driver, wiring, fasteners)

Anchor: **~$5.13** (custom cut pine wood, fasteners, paint)



Module: **~$17.42** (Wood, corner brackets, wood screws, paint)

Support structure: **~$65.62** (Wood, OTS brush/wood screws/pulley, timing belt, 3D printed u-joint, 6V 6 RPM DC worm gear motors, paint)

Cost Table Summary: Full Assembly

Factor	Estimated Cost (USD)	Source or Justification
Raw materials	126.46	Lowest-cost OTS parts or stock material
Manufacturing	30.40	Gator Motorsports manufacturing costs sheet
Assembly	8.25	Boothroyd and Dewhurst assembly time estimation
Energy Consumption (single-family home)	$1322.12 / month	Customer, fuel, nonfuel, and demand charge rates from NV Energy

Cost Summary: Facility Energy Consumption

$$C_e = e_c + e_f + e_{nf} + e_d$$

$$energy\ cost = customer\ charge + fuel\ charge + non\ fuel\ charge + demand\ charge$$

$$e_c = \frac{\$5.75}{month}$$

$$e_f = \frac{\$0.08101}{kWh} * 4798 \frac{kWh}{month} = \frac{\$388.69}{month}$$

$$e_{nf} = \frac{\$0.16}{kWh} * 1000\ kW = \$160$$

$$e_c = \frac{\$0.16}{kWh} * 4798 \frac{kWh}{month} = \frac{\$767.68}{month}$$

Total = **$1322.12/month**

Technology Readiness Levels

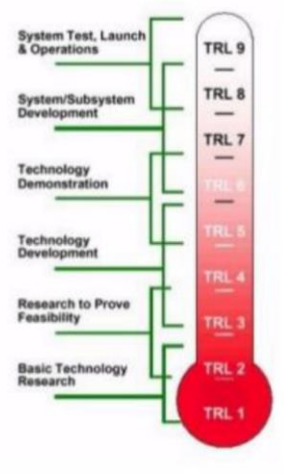
At this stage, our project is within this range

TRL 3 based on lowest component rating

Technology Readiness Levels

Originally developed by NASA in the 1980s

Level 1 : Basic principles observed and reported
Level 2 : Concept and/or application formulated
Level 3 : Concept demonstrated analytically or experimentally
Level 4 : Key elements demonstrated in laboratory environments
Level 5 : Key elements demonstrated in relevant environments
Level 6 : Representative of the deliverable demonstrated in relevant environments
Level 7 : Final development version of the deliverable demonstrated in operational
Level 8 : Actual deliverable qualified through test and demonstration
Level 9 : Operational use of deliverable



*Level 1: Basic, Level 2: Applied, Level 3: Prototype

http://en.wikipedia.org/wiki/Technology_readiness_level
http://www.nstda.or.th/nstda-km/92-km-knowledge/2770-technology-readiness-levels-

Adapted from:
Martin, Shawn K. "Technology Readiness Levels from a Practitioner's Point of View." 29 Nov. 2021. Lecture.

Why our design?

- Our design offers cheap and readily available material that can be sourced locally.
- Our design is highly manufacturable, requiring minimal tooling to produce.
- Our design is simply operated with little maintenance.
- Easily scalable prototype to downsize

Questions?