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# Water Lenses for Low-Cost Concentrator Photovoltaics

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# Washington University in St. Louis

## SCHOOL OF ENGINEERING & APPLIED SCIENCE

*Executive Summary*

Solar energy-harvesting has been steadily improving, yet there still remains a price and efficiency barrier that prevents photovoltaic cells from becoming more commonplace. Acrylic, polycarbonate, or glass lenses and reflectors are current strategies used to increase the amount of sunlight focused onto PV cells. Concentrators and reflectors require additional costs and usually do not track with the sun to intercept direct sunlight. The purpose of S.A.L.T. is to create an affordable way of increasing light exposure by using water to refract light onto a focal line across an array of PV cells. Through FEA analysis, the shape of the membrane can be predicted for various membrane material and volumes of water. FEA analysis was also employed to determine the location of the focal line as the angle of incident light to the membrane changes. Results show the membrane will take the form of a second degree polynomial and that the focal line will lie within the bounds of the S.A.L.T. frame. The results indicate that a stationary, mounted servo will effectively allow the PV cell array to track with the focal line of refracted sunlight.

# MEMS 411: Senior Design Project
## S.A.L.T

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## 1.1    INITIAL PROJECT DESCRIPTION

Our project idea is to design and build the hardware required for a Concentrator Photovoltaics (CPV) array. The goal of SALT is to study the economic feasibility of using water lenses rather than conventional optics which are usually cost-prohibitive for these kinds of applications.

We hope to include two axes of actuation to track both the focal point and the path of the sun over the course of the day. The main goal of this project is to maximize power output while also minimizing costs.

## 1.2    EXISTING PRODUCTS

#1: Fresnel Lens CPV
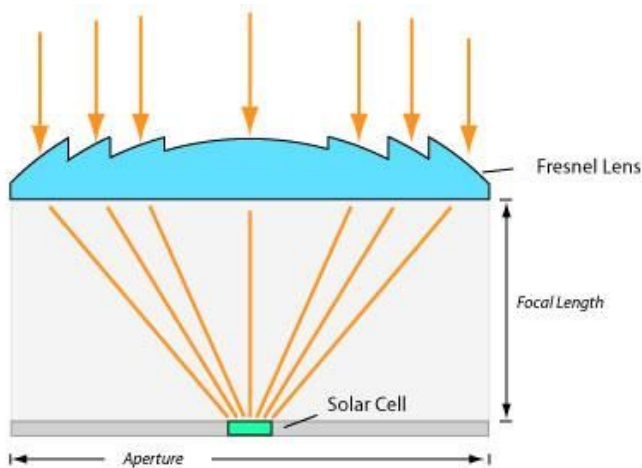


Figure 1: Light refraction on a Fresnel lens [1]

Description: Like most CPV designs, including ours, the light is focused onto a smaller high-efficiency solar panel. However this design uses Fresnel lenses to focus the incoming light, usually made of glass or acrylic. These kinds of solar panels also require 2-axis tracking since the incident rays must come in at 0 degrees incidence for the light to be focused properly.

#2 Parabolic Mirror CPV
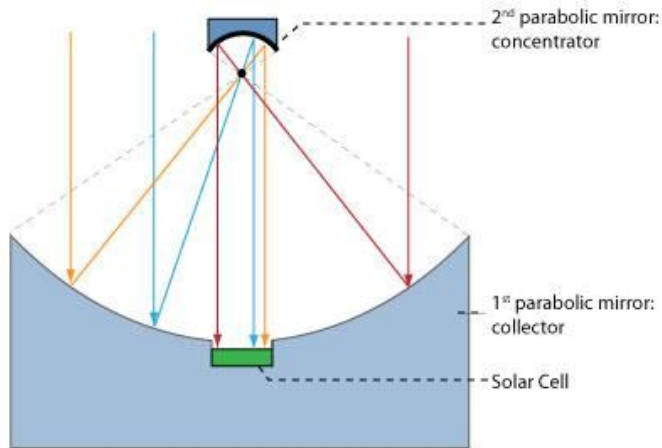
Figure 2: Refraction of light from a mirror [1]

Description: This CPV method uses reflective surfaces to focus the light onto the solar cells. Like most other CPV methods, it requires 2-axis tracking to minimize the angle of the incident rays. Similar solutions can be found in thermal solar installations, however, the main advantage of using PV cells is that PV cells are not subject to the same thermal restrictions for their light source and will still produce a reduced amount of electricity under cloudy conditions. [2]

#3 Luminescent CPV
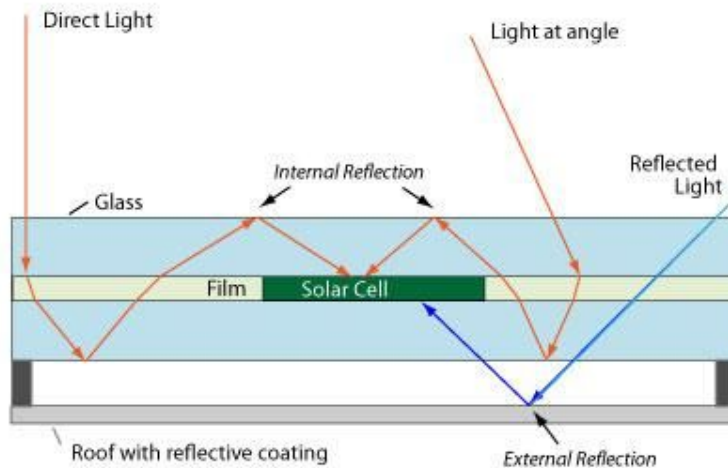


Figure 3: Path of light on a luminescence CPV [1][3]

Description: This solar CPV solution uses reflection of small optics devices to guide the light to the solar cell usually after multiple bounces. One of the main advantages of this method is that it is independent of angle of incidence, allowing it to work with both direct and diffuse light. This also means that it does not

require any kind of solar tracking and can also benefit from the efficiency improvements from using better cells in a smaller quantity to maintain the cost effectiveness of the system.

### 1.3   RELEVANT PATENTS

Patent US20090223555 A1:

https://www.google.com/patents/US20090223555

This patent describes an apparatus using Fresnel lenses to focus light on high-efficiency PV cells cooled using a special carbon-based material. This is similar in concept to our idea in the sense that they are using optics to minimize the costs coming from the solar cells.
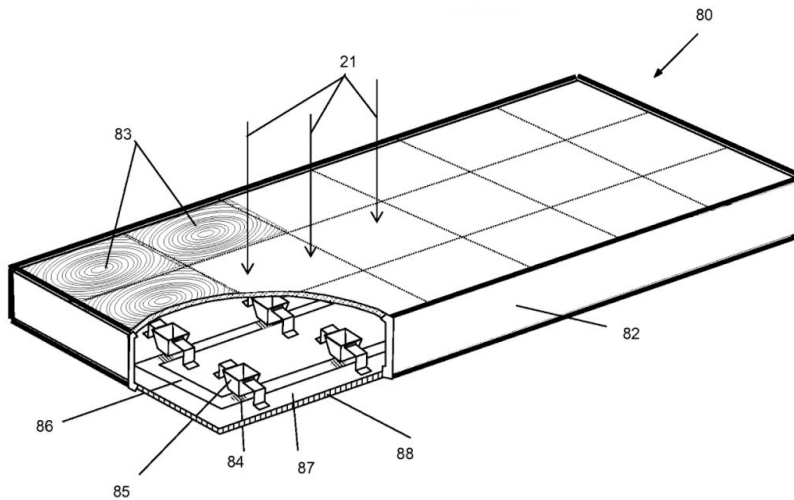


Figure 4: Patent US20090223555 schematic

Patent US20130038132 A1:

https://www.google.com/patents/US20130038132

This patent describes a CPV method meant to "make solar energy converters more energy efficient at a reasonable cost". This method uses a parabolic mirror as its main optics device (10) with secondary reflector type concentrators to once again decrease the necessary area required to be covered by solar cells. Given adequate cooling, this allows them to use a small number of high-efficiency cells to reach high efficiencies at a lower cost than simply covering the area of the main dish with solar cells.
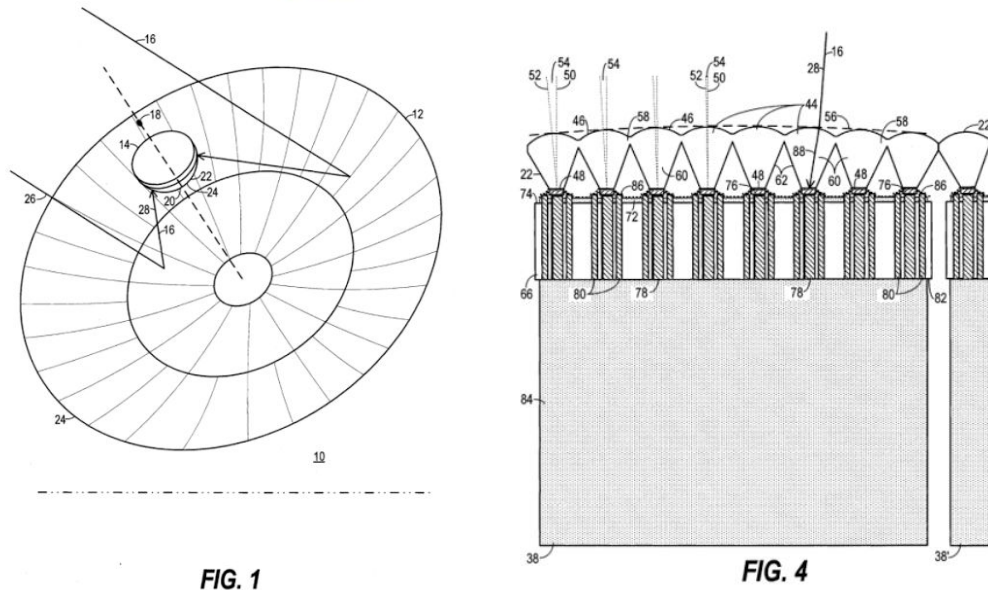
Figure 5: Patent US20130038132 Schematic

## 1.4   CODES & STANDARDS

Standard 1: IEC 61215

- Withstands 200 thermal cycles from -40C to 90C
- Hail- withstands 10 impacts from 1" hail at 52 mph
- Hot spot test - 3 cells for 1-- hrs


Standard 2: Section 605.11.1

All raceways, enclosures, junction boxes, cable assemblies, combiners, and disconnects need to be clearly labeled to indicate the presence of PV conductors The labels shall have "WARNING: PHOTOVOLTAIC POWER SOURCE" in all-white, capital letters, a minimum of 3/8 inch tall, on a red background

## 1.5   PROJECT SCOPE

"Affordable Concentrating Photovoltaics"

Our initial project idea is to design and build the hardware required for a Concentrator Photovoltaics (CPV) array. The goal of this project is to study the economic feasibility of using water lenses rather than conventional optics which are usually cost-prohibitive for these kinds of applications.

We hope to include two axes of actuation to track both the focal point and the path of the sun over the course of the day. The main goal of this project is to maximize power output while also minimizing costs.

1. Customer

Current and future PV array owners with limited financial means in remote areas where there is limited electricity demand and where getting equipment to is difficult are the intended customers for this product.

2.  Benefits to the customer

The main interest in this PV setup is the low weight and cost requirements given that the heavy elements are readily available and can likely be sourced locally.

3.  Project goals
● The solar water lens apparatus should provide an improvement in power output when compared to bare solar cells.
● Easy to put together: Can be sold as a kit or built using plans.
● Low cost: The product should fulfill those requirements at a minimal cost.
● Minimize the influence of weather and wear from normal use.

4.  What is in scope?

The optics, frame, and 1-DOF mechanical actuation are in scope

5.  What is out of scope?

The electronics (outside of PV cells and actuators) and tracking software are out of scope.

6.  Critical success factors
● Increase power output from the CPV apparatus.
● Can be actuated either by hand or using electric actuators
● Simple and reliable structure, can be assembled by the user
● Ease of use
● Robustness, requires minimal maintenance
● The lens performs well as a focusing device

7.  Project assumptions
● Water lenses are a good solution to affordable CPV arrays
● The tracking can be done manually at decent efficiency
● This solution is better than just having the cells by themselves (or can be scaled up in such a way to be able to compete with traditional solar panels)

8.  Project Constraints
● Budget: $200-$300
● Tools: Machine shop, 3d-printers, maybe the woodworking shop
● Time: 2.5 months

9.  Key deliverables

- Power output (power vs. cost)
- Ease of construction
- Simple building materials
- Weather-proof-ness (performs well in wind), how strong is it?

## 1.6 PROJECT PLANNING

Table 1: Senior design Project Gantt Chart

**MEMS 411 Senior Project** — Plan / Actual

| | ACTIVITY | START | DURATION | START | DURATION | Milestone |
|---|---|---|---|---|---|---|
| 1 | Project Statement | 1 | 1 | 1 | 1 | |
| 2 | Background Information Study | 2 | 1 | 1 | 2 | |
| 2.1 | Schedule Library Consultation | 2 | 1 | 2 | 1 | |
| 3 | Needs and Specification Study | 3 | 1 | 2 | 1 | |
| 3.1 | Call Christophe's Dad | 3 | 1 | 3 | 1 | |
| 4 | Project Scope | 3 | 1 | 3 | 1 | |
| 5 | Concept Generation | 4 | 1 | 4 | 1 | ★ 9/25 |
| 4.1 | Concept Review | 4 | 2 | 4 | 2 | ★ 9/28 |
| 6 | Concept Selection and Embodiment | 5 | 2 | 5 | 2 | ★ 10/9 |
| 6.1 | Source parts list | 5 | 2 | 5 | 1 | |
| 6.2 | Allocate budget | 5 | 1 | 5 | 1 | |
| 6.3 | Finish Part Ordering | 5 | 1 | 6 | 1 | |
| 6.4 | Turn in all check requests | 5 | 5 | 5 | 5 | |
| 7 | Research concepts | 5 | 3 | 5 | 4 | |
| 7.1 | Optimize membrane and liquid | 5 | 1 | 7 | 1 | |
| 7.2 | Optimize solar tracking | 6 | 1 | 10 | 1 | |
| 7.3 | Optimize frame design | 7 | 1 | 7 | 1 | |
| 8 | Design for X (DFX) | 7 | 3 | 8 | 4 | 11/17 |
| 9 | Prototype Demo | 12 | 1 | | | ★ 11/17 |
| 9.1 | Complete Prototype Build | 8 | 4 | 9 | 3 | |
| 9.1.1 | Frame Design | 8 | 4 | 9 | 3 | |
| 9.1.2 | Create and optimize PV cell array | 8 | 4 | 8 | 4 | |
| 9.1.3 | 1 DOF solar tracking and optimization | 8 | 4 | 8 | 4 | |
| 10 | Final Report | 15 | 1 | | | ★ 12/8 |
| 10.1 | Data organization | 13 | 1 | | | |
| 10.2 | Data analysis | 13 | 1 | | | |
| 10.3 | Data optimization | 13 | 1 | | | |
| 10.4 | Future suggestions | 14 | 1 | | | |
| 10.5 | Market analysis/Feasability | 14 | 1 | | | |
| 10.6 | Project statement check | 14 | 1 | | | |
| 11 | Final Presentation | 15 | 1 | | | ★ 12/8 |
| 12 | Teardown/Cleanup | 15 | 1 | | | ★ 12/8 |

Date columns: 08/28/17 (1), 09/04/17 (2), 09/11/17 (3), 09/18/17 (4), 09/25/17 (5), 10/02/17 (6), 10/09/17 (7), 10/16/17 (8), 10/23/17 (9), 10/30/17 (10), 11/06/17 (11), 11/13/17 (12), 11/20/17 (13), 11/27/17 (14), 12/04/17 (15), 12/11/17 (16), 12/18/17 (17), 12/25/17 (18)

## 1.7 REALISTIC CONSTRAINTS

Our design is meant to be a proof of concept project, though we still were limited and affected by a series of constraints as outlined below.

### 1.7.1 Functional

Our project is meant to be scalable, yet we must keep the overall length to around 1m and the height to 1m so that we could transport it for demonstrations. Because of the set water capacity in our membrane, the focal line is modeled to be 0.6m below the bottom of the membrane. This means we must have the height of the trough be at least 0.6m plus the amount the membrane is displaced.

### 1.7.2     Safety

There is a direct safety constraint with the weight and stability of the project. Since the trough is made for outdoor use, we have to be able to protect the electronics from rain and the frame from being tipped over from wind.

### 1.7.3     Quality

PV cells start to perform poorly at high temperatures. Since we plan to focus direct solar light at small cells, an effective cooling strategy is required to maintain peak performance of the cells. Monitoring the temperature is vital in the design and maintenance of SALT.

### 1.7.4     Manufacturing

Manufacturing with ceramics and metals for the trough requires special tools. The manufacturing of the PV cell array requires use of solder and soldering iron to connect individual cells in a line.

### 1.7.5     Timing

Parts need to be able to ship quickly due to the time constraint of a semester. We must try to build early and fail quickly so that parts can be ordered earlier rather than later down the road. Testing will take a day (we are tracking the sun), as well, so we need to set aside time to commit to this.

### 1.7.6     Economic

The goal of our project is to make the cheapest functional water lens, so we are constrained on costs and will be designing to meet all our performance goals with as minimal expense as possible. This limits parts to cheaper  items such as wood, PVC, etc.

### 1.7.7     Ergonomic

We are working with a number of electronics, which can be confusing in a machine-man relationship. Therefore, we should plan our layout so that the important interfaces are clearly labeled and accessible on the top of the trough for ease of use. Warnings could be included with the sensitive arduino and wiring to further aid in the use of SALT.

### 1.7.8     Ecological

We need SALT to do more good than harm when it comes to ecology. SALT should amplify the collection of renewable energy. If it results in less power output, on average, than PV array without the water-lens then we have not met a primary goal. Direct ecological impact could also result if the focused light hits the ground and/or grass where SALT is stationed.

### 1.7.9     Aesthetic

One thing to think about is that this is a ground-based solar energy collector. Therefore, it could be included in the customer's landscape. SALT would benefit from a simple, unconvoluted aesthetic to avoid visually imposing in a yard, farm, or landscape.

### 1.7.10   Life Cycle

SALT needs direct light to focus and will obstruct diffuse light from the cells. As a result, only customers who live in areas which receive relatively high direct solar irradiance would benefit from the increased

energy output. One solution could be to include a mechanism to temporarily remove the membrane when it is partly or fully cloudy, so that the PV cells can capture diffuse light.

### 1.7.11   Legal

IEC standards require PV arrays to physically withstand thermal cycles and certain weather requirements such as hail. Therefore, performance testing will need to be included with our device so that we can match these legal standards.

## 1.8   REVISED PROJECT DESCRIPTION

From the additional information gathered during our research, we realized focal points only exist when the angle of incidence is equal to 0. This means the sun should be facing the lens directly in most CPV applications. However, we realized that with minimal modification to our initial design, we could make the trough we are using as a lens face the sun, requiring only vertical motion of the solar cells to find the focal point as the beams stretch depending on the height of the sun in the sky. This solution would address the concerns regarding the limitations of a gravity-dependent lens and the lack of control that would give us on the angle of incidence of the light. We now envision the entire assembly pivoting around one axis to face the sun, and an actuator moving the cells up or down to find the focal point as can be seen in the image above.

## 2   CUSTOMER NEEDS & PRODUCT SPECIFICATIONS

## 2.1   CUSTOMER INTERVIEWS

Table 2: Customer interview results

| Customer Data: Customer: Michel Foyer<br>Address: Manoir de Fribois, 14340 Saint Loup de Fribois, Calvados, France<br>Date: 17/08/2017<br><br>*Translated from french* | | | |
|---|---|---|---|
| **Question** | **Customer Statement** | **Interpreted Need** | **Importance** |
| After hearing about our product, what components do you think should be included? | I'm unsure whether the PV cell will be able to handle the high temperatures from magnifying | Safe way of handling overheating | 5 |
| | It has to be able to stand a lot of weather conditions and not | Weather-proof and robust | 4 |

| | have much wear and tear. I don't want to have to keep making fixes to it. | | |
|---|---|---|---|
| Now that you know a bit more, can you tell us what your thoughts on concentrator photovoltaics | Would not want to spend as much as some of the lenses on the market right now | Cost is less than a concentrator photovoltaic | 5 |
| | I don't know much but someone told me that focusing sunlight onto one spot will get you more power | Power generated is higher with our product than just with a pv cell array | 5 |
| How often would you have to move the device to a different location? | Ideally it wouldn't ever have to move, probably not too often. | Doesn't have to stay portable after installation | 1 |
| Does the device have to be pre-assembled? | Assembling isn't really an issue since you only have to do it once. As long as all the electrical parts are done it's easy. | Assembly of the structural parts is not an issue. The electrical parts need to be easy to assemble or pre-assembled. | 2 |
| Would you mind having to move the panel manually throughout the day? | That sounds like one other thing I would forget to do. If it can be done automatically I'd much prefer that. | Needs to track the sun | 4 |
| Is there any other needs that you'd like this device to fulfill? | I think my biggest concern is that I would like to see that it works and that it is more efficient than putting out bare solar panels and just as reliable | More power generated than a traditional PV cell array | 5 |
| | | Robustness | 4 |
| Any other concerns with our project? | I think that if you have a water basin with nothing covering it you might end up with insects or plants growing in your trough | Should keep wildlife out of the water lens | 3 |

## 2.2    INTERPRETED CUSTOMER NEEDS

Table 3: Interpreted customer needs

| Need Number | Need | Importance |
|:---:|:---:|:---:|
| 1 | Safe way of handling overheating | 5 |
| 2 | Robustness | 4 |
| 3 | Costs less than an expensive concentrator photovoltaic | 5 |
| 4 | More power generated than a traditional PV cell array | 5 |
| 5 | Does not need to be portable after initial setup and installation | 1 |
| 6 | Assembly of the structural parts is not an issue. The electrical parts need to be easy to assemble or pre-assembled. | 2 |
| 7 | Needs to track the sun | 4 |
| 8 | Needs to keep out bugs/plants | 3 |

## 2.3    TARGET SPECIFICATIONS

Table 4: **Target product specifications for SALT**

| Metric Number | Associated Needs | Metric | Units | Acceptable | Ideal |
|:---:|:---:|:---:|:---:|:---:|:---:|
| 1 | 1 | Temperature | K | 373K | 353K |
| 2 | 2 | Load | N | 300 | 1000 |
| 3 | 3 | US Dollars/Power Output | $/W | 1$/W | 0.8$/W |
| 4 | 4 | Power per unit surface area (of PV cells) | W/m^2 | 100W/m^2 | 200W/m^2 |
| 5 | 5 | Time to disassemble | Hours | 8 | 1 |

| 6 | 6 | Time to assemble unit | Hours | 5 | 1 |
| 7 | 7 | Ability to track sun | Y/N | N | Y |
| 8 | 8 | Sterile lens water | Y/N | Y | Y |

# 3   CONCEPT GENERATION

## 3.1   FUNCTIONAL DECOMPOSITION
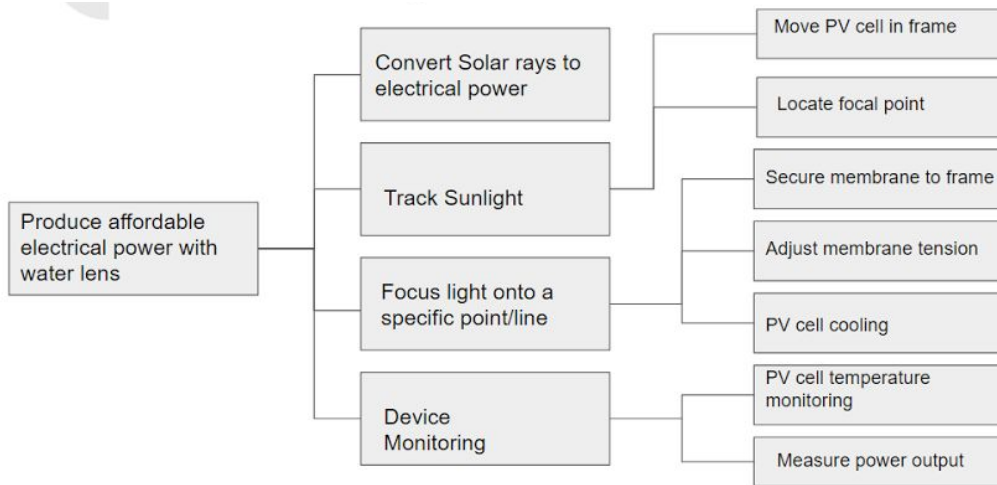


Figure 6: **Function tree for useless box**

## 3.2    MORPHOLOGICAL CHART
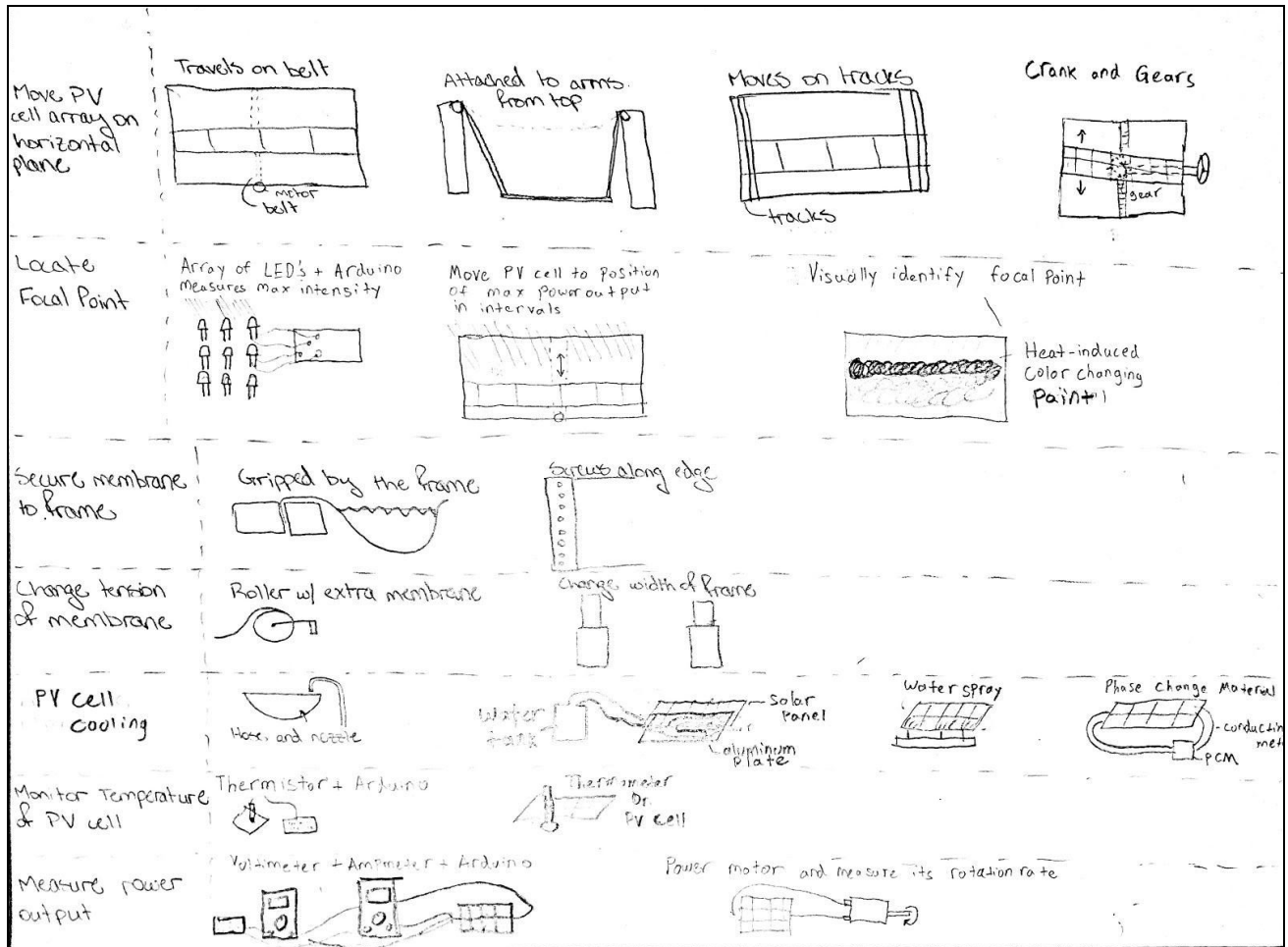


**Figure 7: Early Design Process Morph chart**

### 3.3   CONCEPT #1 – "BELT TRAVEL"
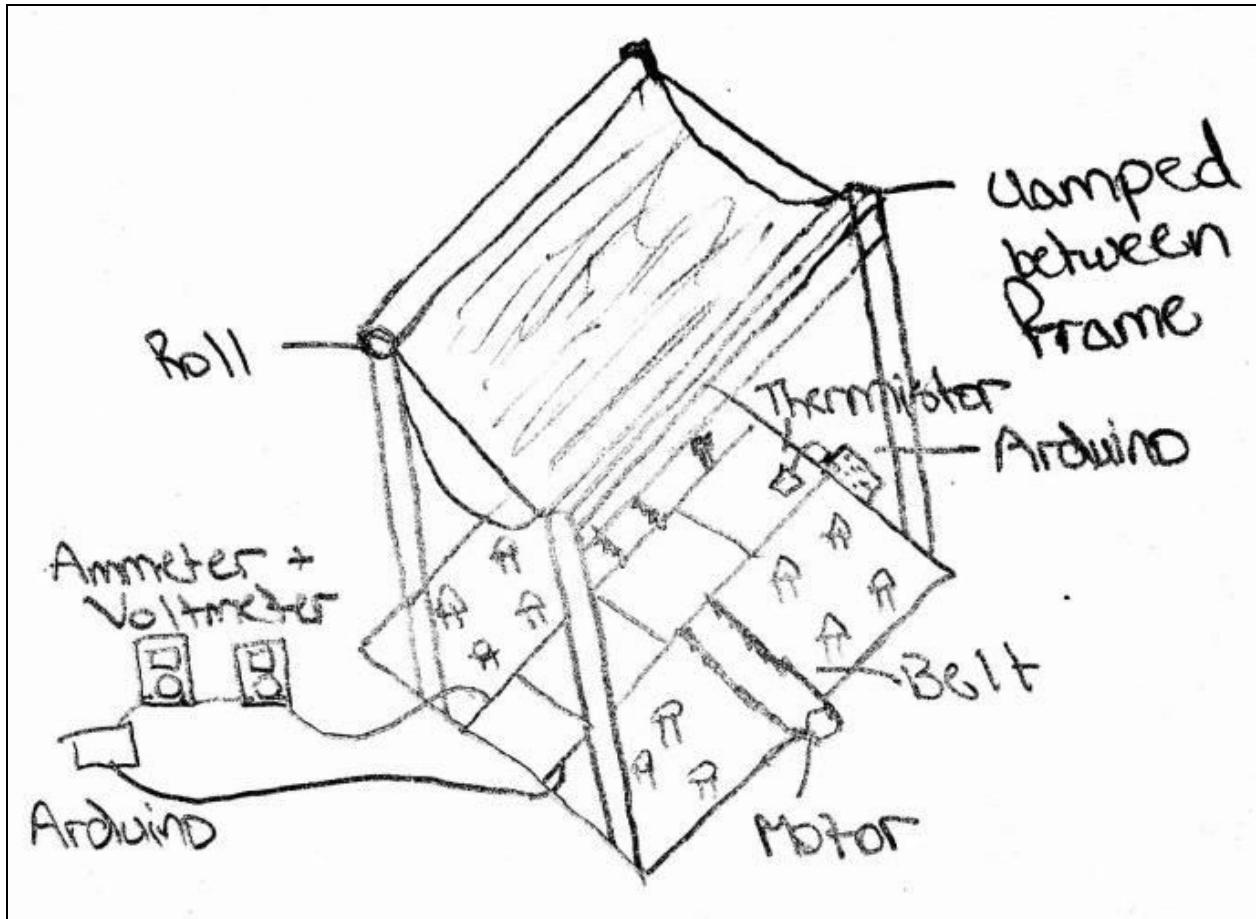


Figure 8: "Belt Travel" concept sketch

**Name:** Belt Travel
**Description:** One belt powered by a motor moving the row of PV cells in one direction back and forth. The array of LED's measuring intensity help to find the ideal place to move the PV cells. The membrane is clamped by the frame on one end and attached to a roller on the other to help control the shape of the membrane by adding or subtracting membrane material.
**Solutions from Morph Chart:** 1. Travels on belt
                         2. Array of LED's
                         3. Gripped by frame
                         4. Roller with extra membrane
                         5. Hose and nozzle
                         6. Thermistor and Arduino
                         7. Voltmeter, Ammeter, and Arduino

## 3.4    CONCEPT #2 – "CIRCULAR MEMBRANE"
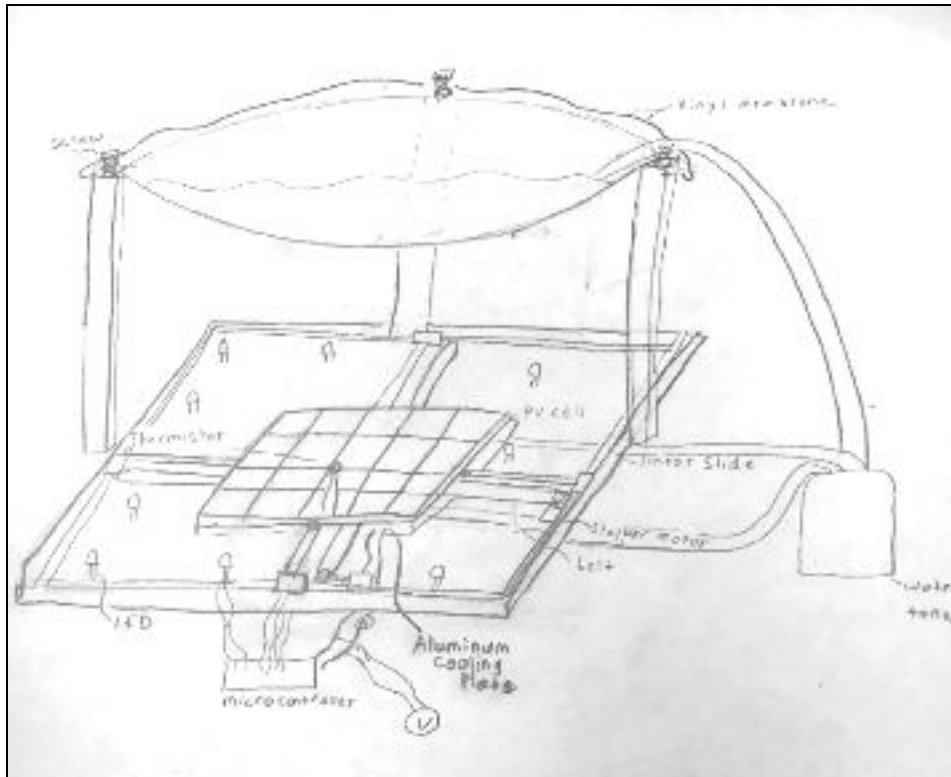


Figure 9: "Circular membrane" concept sketch

**Name:** Circular Membrane
**Description:** Two belts and four linear slides allow a PV cell, sitting on a water-cooled aluminum base, to position over a focal point. An LED array locates the position of max solar intensity. A circular membrane filled with water from a water tank focuses the light onto a 2-D array. The membrane can change shape by adding or subtracting water from tanking.
**Solutions from Morph Chart:**

1. Travels on belts
2. Arrays of LED's
3. Gripped by screws
4. No tensioner
5. Water tank and aluminum cooling
6. Thermistor and Arduino
7. Voltmeter, Ampmeter, and Arduino

## 3.5    CONCEPT #3 – "MANUAL OPERATION"
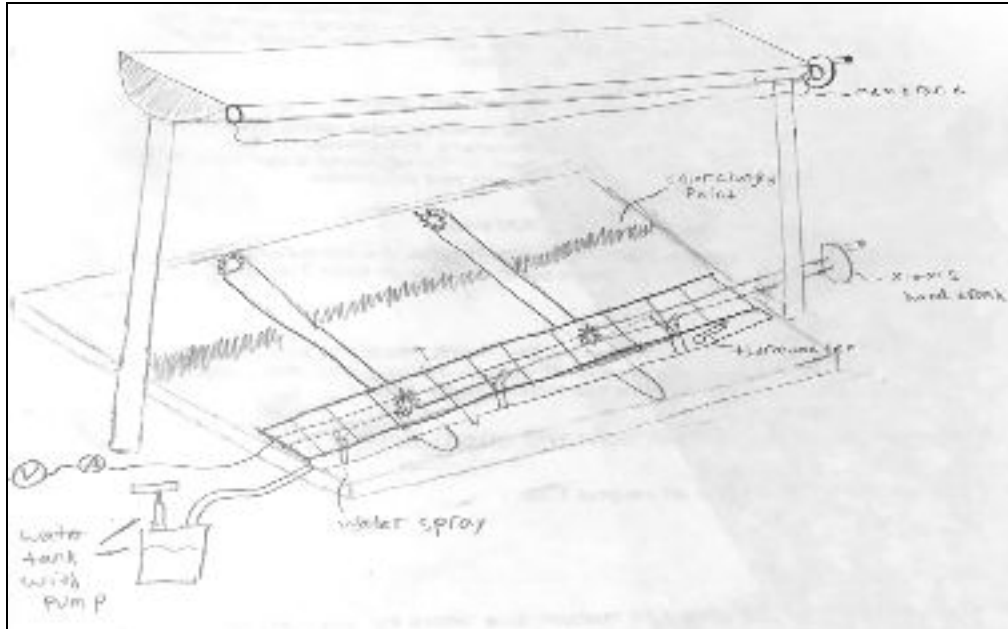


Figure 10: "Manual operation" concept sketch

**Name:** Manual Operation
**Description:** This design is intended to be more manually operated to decrease the amount of energy used in optimizing the PV cell. Cranks are used to position the solar panel and a color changing material is used to find the focal point. A trough water lens is used and a thermometer and manually operated water spray regulates the temperature.
**Solutions from Morph Chart:**

1. Crank and tracks for trough
2. Color-changing material
3. Screws along edge
4. Roller with membrane
5. Water spray
6. Thermometer
7. Read voltmeter and Ampmeter (P=IV)

### 3.6    CONCEPT #4 – "2D-CONCAVE LENS WITH 2D ACTUATION"
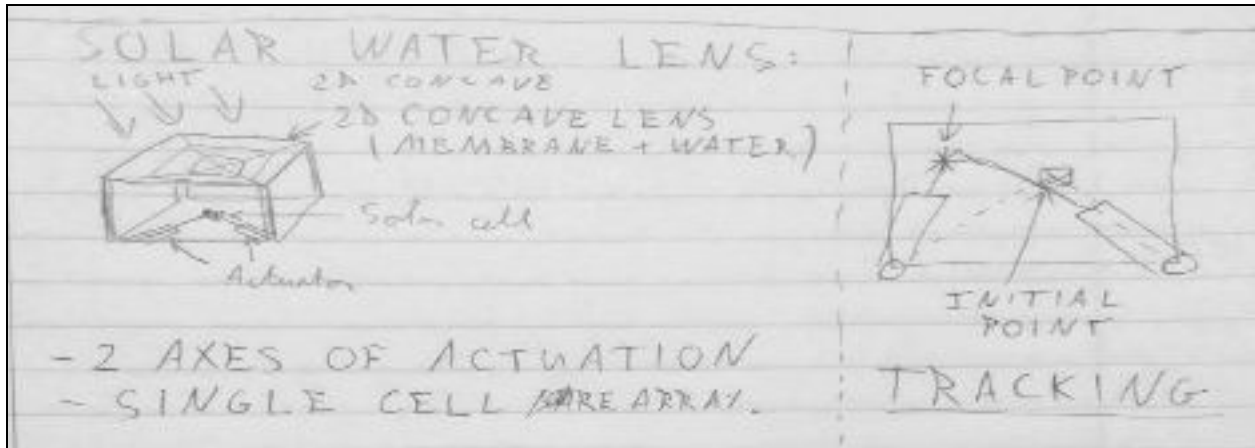


Figure 11: "2D-Concave Lens with 2D actuation" concept sketch

**Name:** 2D-Concave Lens with 2D actuation
**Description:** This design is intended to limit the amount of moving parts, and when necessary to make joints constrained translationally. This system uses two linear actuators to find the focal point generated by a 2D-concave water lens
**Solutions from Morph Chart:**
1. Screws along edge / adhesive
2. Liquid cooling (using water from lens)
3. Thermistor
4. Arduino

**3.7    CONCEPT #5 – "RADIAL MOVEMENT"**
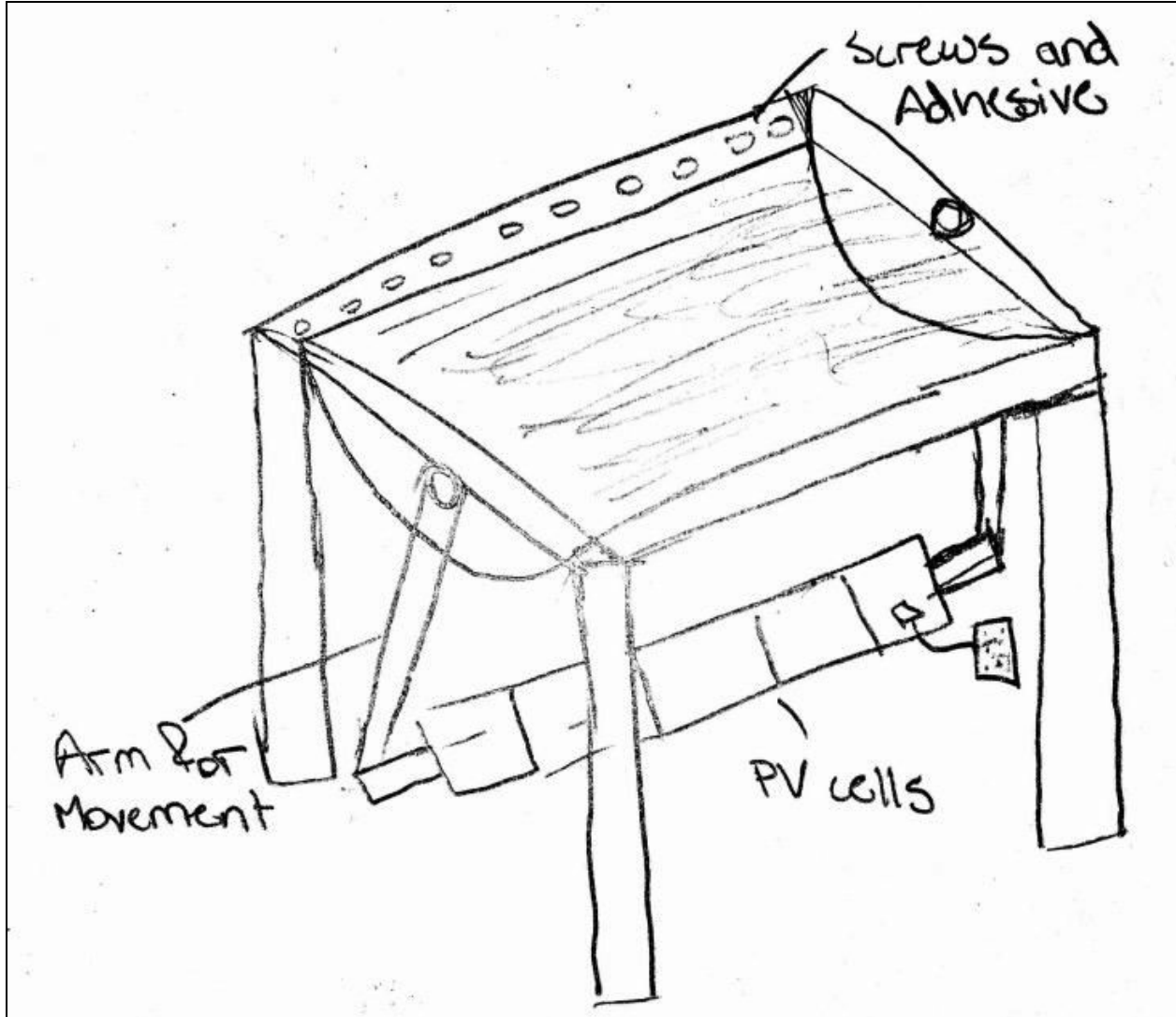


**Name:** Radial Movement
**Description:** The emphasis of this is on the radial movement of the PV cells. The focal point may not stay on a horizontal plane, so this design accounts for that. The PV cells will move on intervals based on where the sun is. Temperature and power measurements will be taken as well.
**Solutions from Morph Chart:**
1. Screws along edge / adhesive
2. Radial movement of PV cells
3. Thermistor
4. Ammeter and Arduino

### 3.8    CONCEPT #6 – "1D-CONCAVE LENS 1D LINEAR ACTUATION "
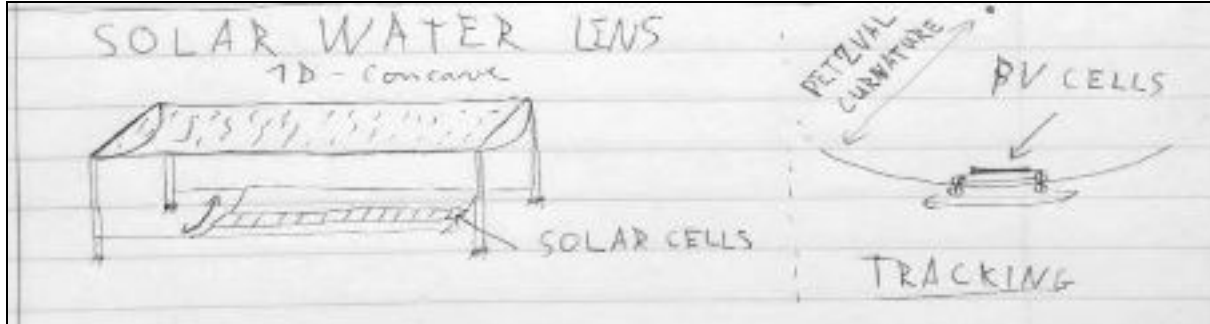


Figure 12: "1D-Concave Lens 1D Linear Actuation" concept sketch

**Name:** 1D-Concave Lens 1D Linear Actuation
**Description:** This design is intended to limit the amount of moving parts even more, and allows us to cut out one axis of actuation by making a slight sacrifice in efficiency. This system uses a single stepper motor to move the panels to position the solar cells array (made of cells placed in a line) on the line of maximum irradiation corresponding to the focal points of the lens, which only focuses the light in one dimension.
**Solutions from Morph Chart:**
1.   Pinched membrane in the frame to adjust.
2.   Liquid cooling (using water from lens) running underneath cells
3.   Thermistor
4.   Arduino

# 4 CONCEPT SELECTION

## 4.1 ANALYTIC HIERARCHY PROCESS AND CONCEPT SCORING MATRIX

Table 5: Analytic Hierarchy Process

| | Mechanical safety | Cost of components | Move PV Cell Array | Locate Focal Point | Secure membrane to frame | Change tension of membrane | PV cell cooling | Monitor temperature of PV cell | Measure power output | Robustness | Ease of Electrical Assembly | Row Total | Weight Value | Weight (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mechanical safety | 1.00 | 5.00 | 1.00 | 1.00 | 3.00 | 9.00 | 3.00 | 7.00 | 1.00 | 3.00 | 3.00 | 34.00 | 0.16 | 16.08% |
| Cost of components | 0.20 | 1.00 | 0.33 | 0.20 | 0.20 | 3.00 | 1.00 | 1.00 | 0.20 | 1.00 | 1.00 | 8.13 | 0.04 | 3.85% |
| Move PV Cell Array | 31/12 | 3.00 | 1.00 | 1.00 | 1.00 | 7.00 | 1.00 | 5.00 | 1.00 | 3.00 | 5.00 | 24.00 | 0.11 | 11.35% |
| Locate Focal Point | 1.00 | 5.00 | 1.00 | 1.00 | 1.00 | 9.00 | 5.00 | 5.00 | 1.00 | 3.00 | 5.00 | 32.00 | 0.15 | 15.13% |
| Secure membrane to frame | 0.33 | 5.00 | 1.00 | 1.00 | 1.00 | 9.00 | 7.00 | 5.00 | 0.33 | 3.00 | 3.00 | 32.67 | 0.15 | 15.44% |
| Change tension of membrane | 0.11 | 0.33 | 0.14 | 0.11 | 0.11 | 1.00 | 5.00 | 0.33 | 0.14 | 0.33 | 0.20 | 7.62 | 0.04 | 3.60% |
| PV cell cooling | 0.33 | 1.00 | 0.33 | 0.20 | 0.14 | 3.00 | 1.00 | 1.00 | 0.20 | 1.00 | 0.33 | 8.21 | 0.04 | 3.88% |
| Monitor temperature of PV cell | 0.14 | 1.00 | 0.20 | 0.20 | 0.20 | 3.00 | 1.00 | 1.00 | 0.20 | 1.00 | 0.20 | 7.94 | 0.04 | 3.76% |
| Measure power output | 1.00 | 5.00 | 1.00 | 1.00 | 3.00 | 7.00 | 5.00 | 5.00 | 1.00 | 3.00 | 5.00 | 32.00 | 0.15 | 15.13% |
| Robustness | 0.33 | 1.00 | 0.33 | 0.33 | 0.33 | 3.00 | 1.00 | 1.00 | 0.33 | 1.00 | 1.00 | 8.67 | 0.04 | 4.10% |
| Ease of Electrical Assembly | 0.33 | 1.00 | 0.20 | 0.20 | 0.33 | 5.00 | 3.00 | 5.00 | 0.20 | 1.00 | 1.00 | 16.27 | 0.08 | 7.69% |
| | | | | | | | | | | | Column Total: | 211.50 | 1.00 | 100% |

Row criterion is _____ than/as column criterion

Numerical ratings: 9 -- Extremely more important
7 -- Very strongly more important
5 -- Strongly more important
3 -- Moderately more important
1 -- Equally important
1/3 -- Moderately less important
1/5 -- Strongly less important
1/7 -- Very strongly less important
1/9 -- Extremely less important

Table 5: Concept Scoring Matrix

| | | Alternative Deisgn Concepts | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Belt Travel | | Circular Membrane | | Manual Operation | | 2-D actuation | | Radial Movement | | 1-D Actuation | |
| Selection Criterion | Weight (%) | Rating | Weighted | Rating | Weighted | Rating | Weighted | Rating | Weighted | Rating | Weighted | Rating | Weighted |
| Mechanical safety | 16.08 | 3 | 0.48 | 3 | 0.48 | 3 | 0.48 | 2 | 0.32 | 5 | 0.80 | 5 | 0.80 |
| Cost of components | 3.85 | 2 | 0.08 | 2 | 0.08 | 3 | 0.12 | 2 | 0.08 | 4 | 0.15 | 4 | 0.15 |
| Move PV Cell Array | 11.35 | 2 | 0.23 | 2 | 0.23 | 3 | 0.34 | 2 | 0.23 | 5 | 0.57 | 4 | 0.45 |
| Locate Focal Point | 15.13 | 1 | 0.15 | 1 | 0.15 | 3 | 0.45 | 4 | 0.61 | 1 | 0.15 | 1 | 0.15 |
| Secure membrane to frame | 15.44 | 5 | 0.77 | 3 | 0.46 | 3 | 0.46 | 3 | 0.46 | 5 | 0.77 | 4 | 0.62 |
| Change tension of membrane | 3.6 | 2 | 0.07 | 3 | 0.11 | 3 | 0.11 | 2 | 0.07 | 2 | 0.07 | 3 | 0.11 |
| PV cell cooling | 3.88 | 4 | 0.16 | 4 | 0.16 | 3 | 0.12 | 2 | 0.08 | 2 | 0.08 | 4 | 0.16 |
| Monitor temperature of PV cell | 3.76 | 3 | 0.11 | 4 | 0.15 | 3 | 0.11 | 2 | 0.08 | 2 | 0.08 | 2 | 0.08 |
| Measure power output | 15.13 | 3 | 0.45 | 3 | 0.45 | 3 | 0.45 | 2 | 0.30 | 4 | 0.61 | 4 | 0.61 |
| Robustness | 4.1 | 2 | 0.08 | 1 | 0.04 | 3 | 0.12 | 1 | 0.04 | 5 | 0.21 | 4 | 0.16 |
| Ease of Electrical Assembly | 7.69 | 1 | 0.08 | 1 | 0.08 | 3 | 0.23 | 2 | 0.15 | 2 | 0.15 | 1 | 0.08 |
| Total score | | 2.504 | | 2.268 | | 2.647 | | 2.221 | | 3.279 | | 3.125 | |
| Rank | | 4 | | 5 | | 3 | | 6 | | 1 | | 2 | |

**4.2    EXPLANATION OF WINNING CONCEPT SCORES**

The "Radial Movement" concept allows the solar cell to move as simply as possible on 1 axis of rotation. The movement is by two servos and the PV cells will move in an arc in order to track with the movement of the focal point of the lens. Due to its simplicity, there is less safety risk, lower structural costs and slightly easier to wire than its other electrically-actuated counterparts. The ability to locate the focal line is very low due to the concept's spaced out LED array. A temperature-dependent colored material on the bottom would clearly locate the focal line and minimize electrical assembly, but it would lack the ability to communicate that information to the servos that run the rotating arm.

**4.3    EXPLANATION OF SECOND-PLACE CONCEPT SCORES**

The key difference between the "Radial Movement" concept and the "1-D Actuation" concept is how the solar panels would move to readjust to a new focal point/line. "1-D Actuation" uses a single stepper motor attached to the PV cell cartridge to move itself along an arc of "Petval" curvature (to track with the focal point throughout the day). This form of actuation is a little more complicated than simply attaching an arm to a servo (as in "Radial Movement"), as it requires a belt to move along and more of a load on the motor to stay in place. In addition, the membrane is secured to the frame, which is simpler and easier to adjust than by using lots of screws (as in "Radial Movement"). Ultimately, "Radial Movement" was the better choice due to its reliability in moving the PV cell.

**4.4    EXPLANATION OF THIRD-PLACE CONCEPT SCORES**

The "Manual Operation" concept acted as our standard and basis for all of the other rankings. This is because it is the easiest structure to visualize in use. Ultimately, we would not use Manual Operation for customer use because it would require the customer to move the PV cells regularly to track with the sun, which is a severe inconvenience. Yet, even so, a pure mechanically controlled setup provides several key advantages. There is no electrical assembly, component cost mostly goes towards the frame, and a temperature-induced color changing material would be much safer, robust and simpler to assemble than an LED array for focal line tracking. The toughest part to control is the cooling of the PV cell. Because there is no electrically-activated cooling when the PV cell gets too hot, it would be imperative for someone to constantly watch the thermostat and to be ready to spray the cells with water.

### 4.5    Summary of Evaluation Results

      After performing the analytic hierarchy process, we found the mechanical safety to be the most important criteria. Afterall, safety is most important especially when focusing light and heat. Next, the ability to measure power output and to locate and track with the focal point are essential to the goal of maximizing power output of with SALT. Our winning result seems to be the most capable of locating and tracking with the focal point, while also containing the fewest parts. The fully mechanical frame (our scoring standard) has a desirable ease of assembly and PV cell movement, yet is not practical for a user. Though, some mechanical elements may be transferred to our final project; a manual water cooling pump could be a simple solution to an overheating PV cell. The concepts ranked 4-6 had a complexity that was out of scope and relied on intricate electrical assembly and was not conducive to generating the highest power output possible.

# 5 EMBODIMENT & FABRICATION PLAN

## 5.1 ISOMETRIC DRAWING WITH BILL OF MATERIALS



| ITEM NO. | PART NUMBER | QTY. |
|----------|-------------|------|
| 1 | PVC tri-corner | 4 |
| 2 | PVC_Short | 8 |
| 3 | PVC_Long | 2 |
| 4 | PVC y-coupler | 6 |
| 5 | Servo_adapter | 2 |
| 6 | Servo_body | 2 |
| 7 | Servo_horn_and_linkage | 2 |
| 8 | Flat_plate | 1 |
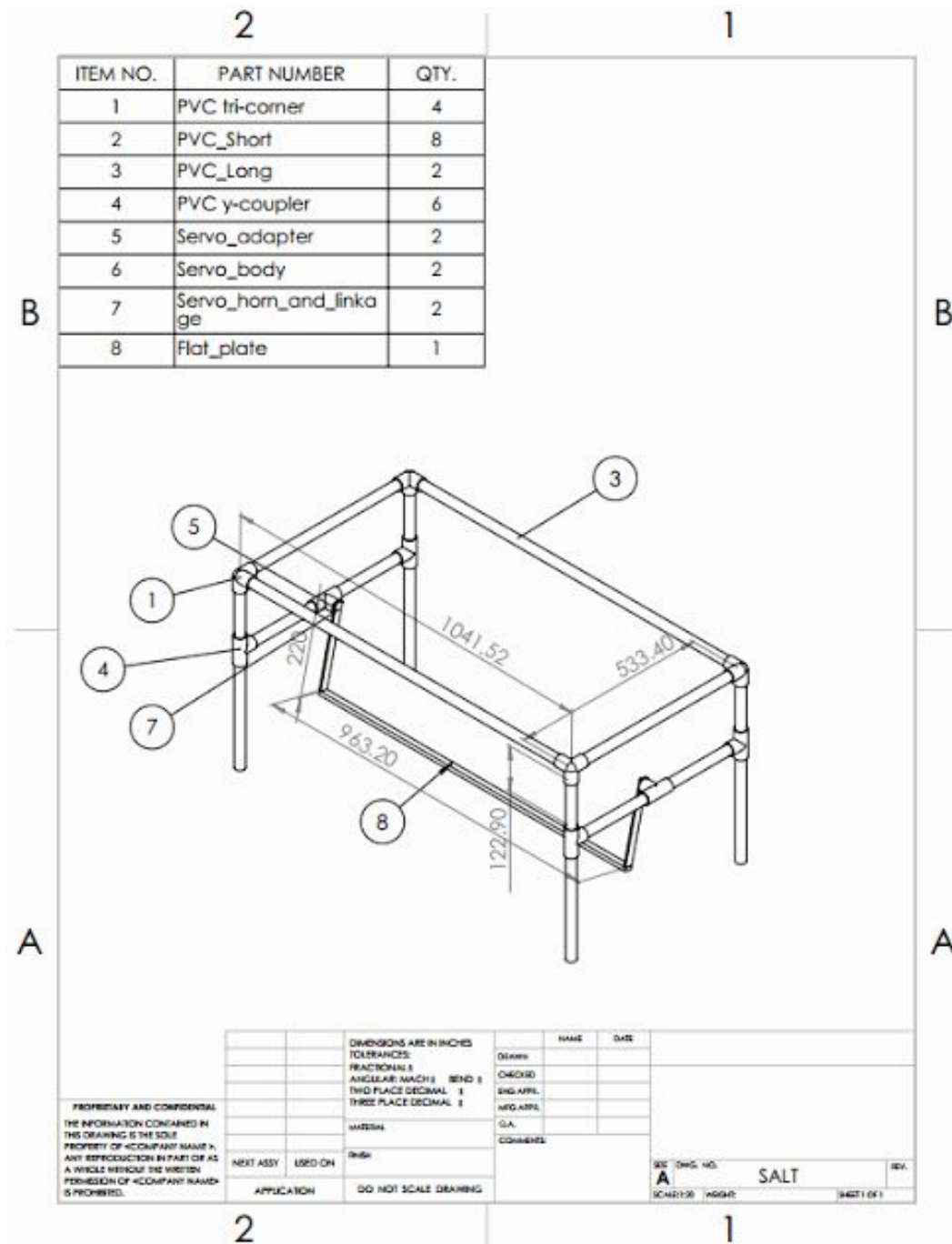
Figure 13: Isometric Drawing with Bill of Materials

## 5.2    EXPLODED VIEW
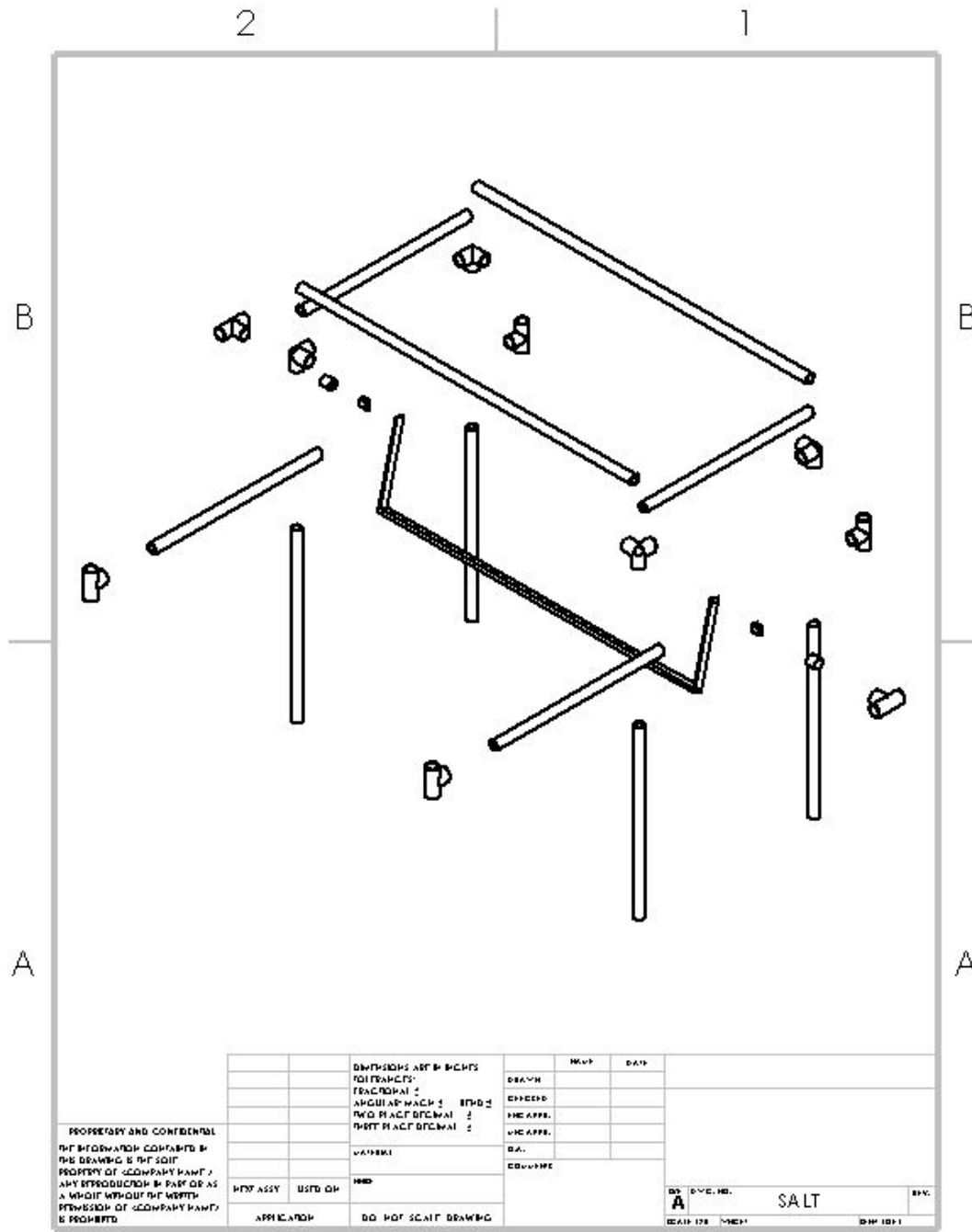


Figure 14: Exploded View

## 5.3    ADDITIONAL VIEWS
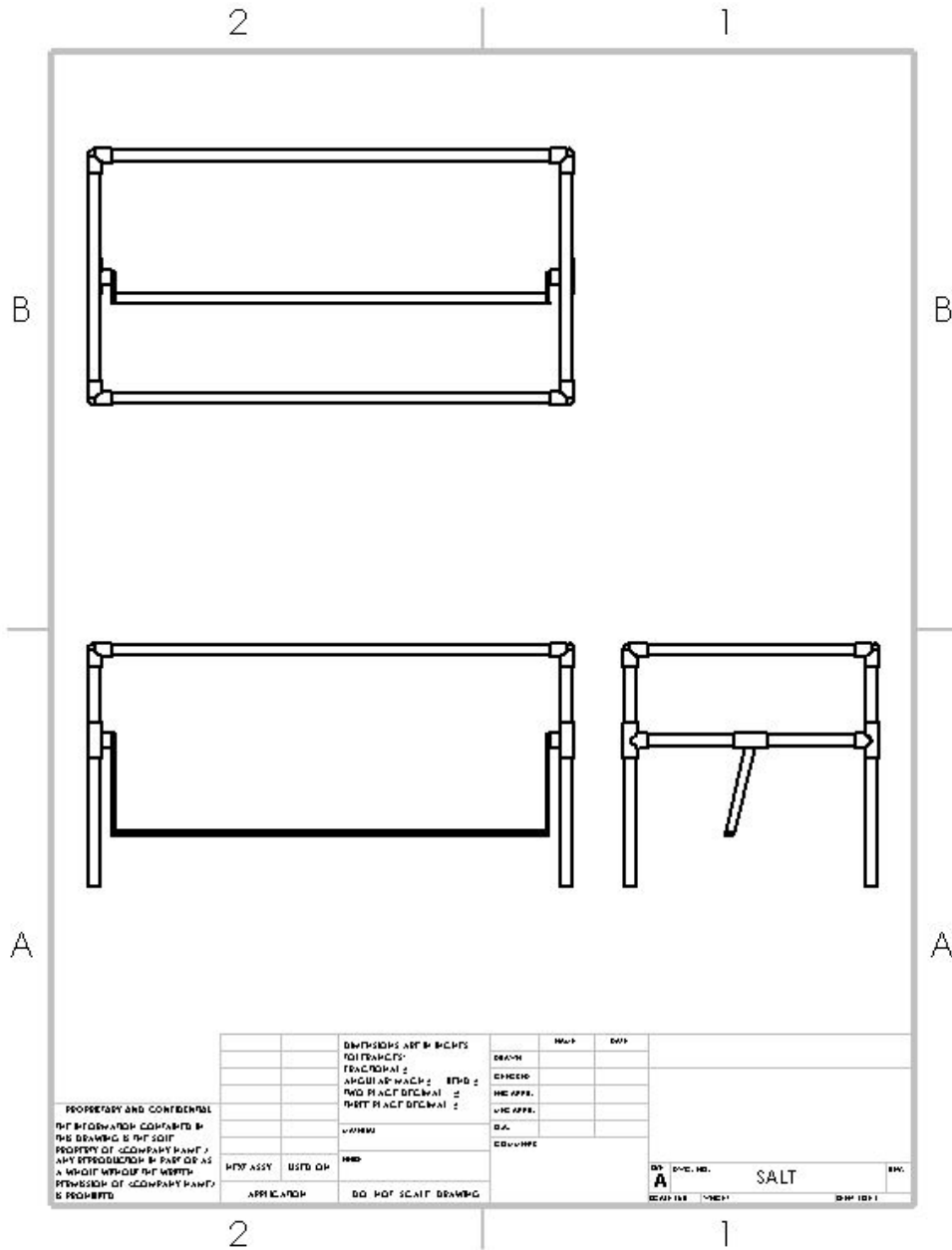


Figure 15: Additional Views

# 6    ENGINEERING ANALYSIS

## 6.1    ENGINEERING ANALYSIS RESULTS

### 6.1.1    Lens Shape Analysis
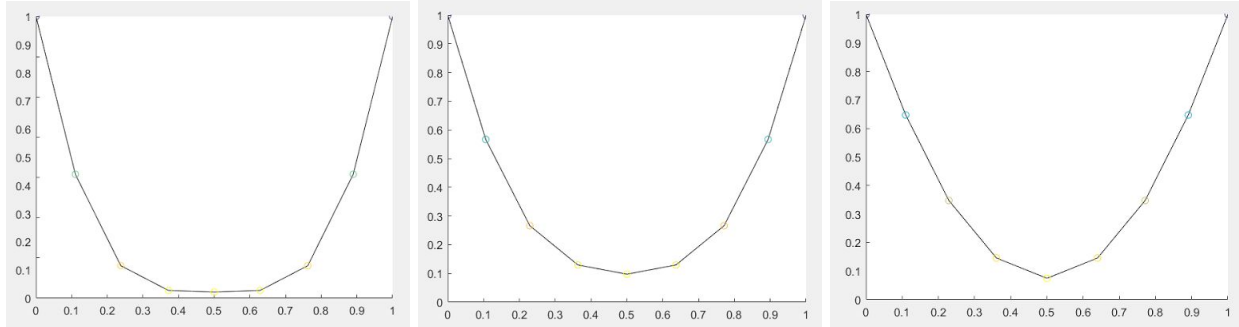


Figure 16: Lens Animation (axes not to scale)

#### 6.1.1.1    Motivation

Given inconclusive research on the shape of a fluid filled flexible membrane, we decided that it was necessary to verify the approximate shape of the lens. The results of this analysis will later be used to simulate the optical properties of the lens in the second part of our engineering analysis.

#### 6.1.1.2    Summary Statement of the Analysis

The results of the analysis showed that a simple second degree polynomial (with the odd term equal to zero since the lens is symmetrical) can adequately approximate the shape of our lens (see figure below).
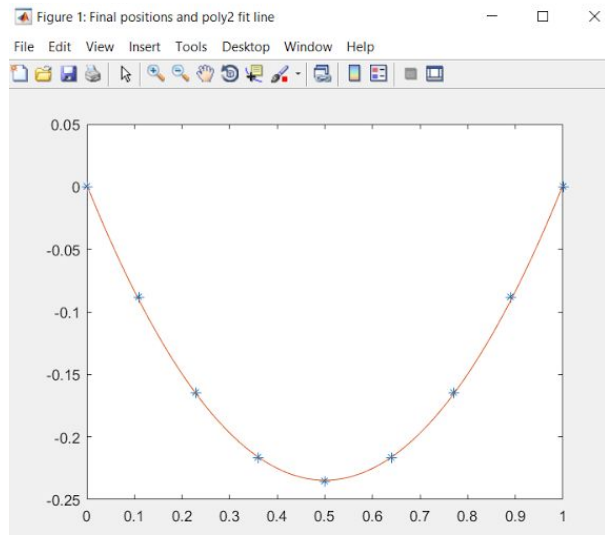


Figure 17: Lens 'final' shape and Poly2 fit

Note: The code for this simulation is included in Appendix D.

### 6.1.1.3    Methodology

We conducted a finite element analysis of the effects of hydrostatic pressure on a flexible membrane held on two sides. This matlab script calculates the forces exerted on each element and displaces them accordingly to attempt to find steady state. This is done by taking into account the hydrostatic pressure and the tension in the membrane and the script runs until the average displacement of each point passes a lower bound. The equations used were simply newton's second law, "F = ma", the equation for hydrostatic pressure "F = ρgzA", and the force caused by strain "$F = E A \Delta L \div L$".

### 6.1.1.4    Results

These results are consistent with the shape observed in our prototype and when used in conjunction with our lens focal analysis tool, these results seem to accurately predict the shape of our lens.

### 6.1.1.5    Significance

While this simulation does not give us a mathematically exact solution, we believe that the results of this analysis show that the final shape of the membrane can be accurately approximated to a second degree polynomial.

## 6.1.2    Lens Focal Analysis
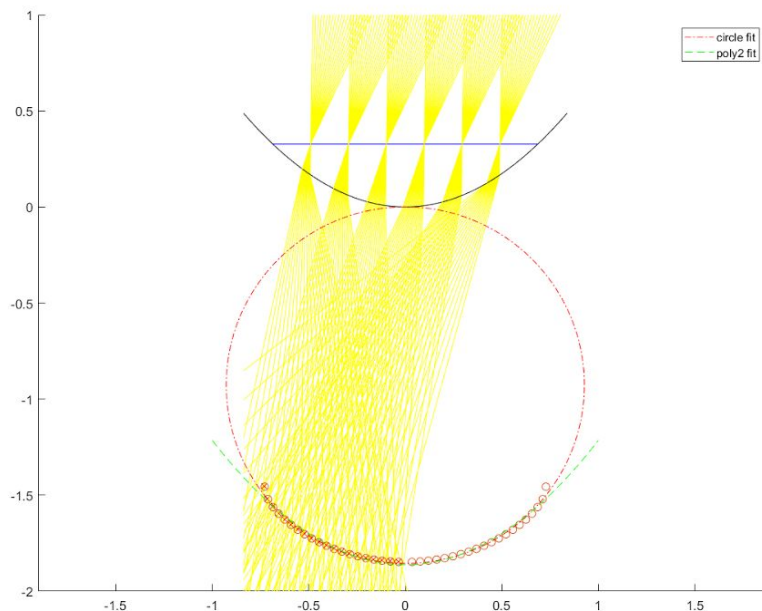


Figure 18: Finding the Petzval curvature using circle fit

### 6.1.2.1    Motivation

The main challenge when designing water lenses comes from the imperfect focusing of incident rays. Since the membrane does not have a constant curve, the focal point does not exist. Instead, an area of higher light concentration can be observed and the goal of this simulation tool is to estimate the location of the point of maximum irradiance.

### 6.1.2.2    Summary Statement of the Analysis

This simulation tool accurately approximates the location of the focal point from what we have tested on our prototype, and has allowed us to save time adjusting the membrane and confirm prior hypotheses concerning how well this lens can focus incoming light rays.



Figure 19: Focal point simulation at 0, 10 and 20 degrees angle of incidence
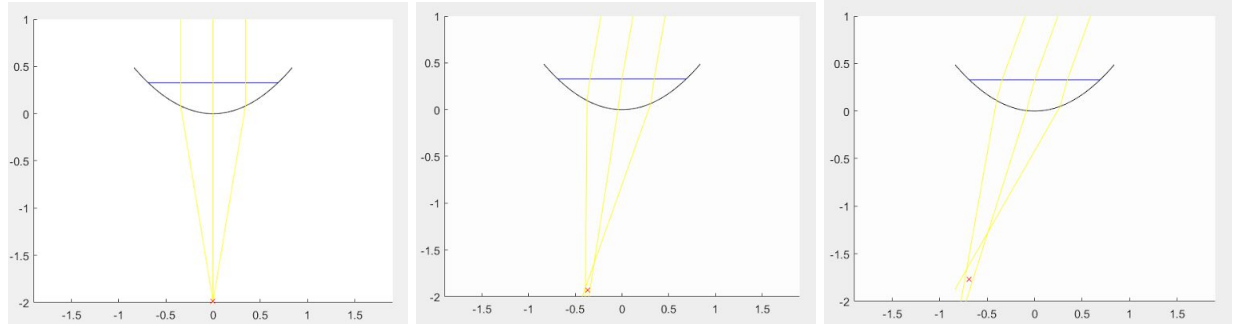
Note: The code for this simulation is included in Appendix D.

### 6.1.2.3    Methodology

The matlab script was coded symbolically to allow easy modification of membrane shape and simpler mathematical manipulation of the various light ray paths, the use of tangents for our calculations does lead to limitations in terms of acceptable inputs for the angle of incidence, however, given that we are using this tool to provide approximate results and given our extrapolation of the petzval curvature of our focal plane from a finite set of calculated focal points, this was deemed sufficient for our use case.

### 6.1.2.4    Results

This simulation tool confirms our initial hypothesis concerning the lack of mathematical focal point, instead, we can find an area of maximum solar irradiance which we approximated to the average position of the intercepts of the exiting light rays. This yields fairly consistent results at low angles of incidence but will cause issues at higher angles as diverging rays will create outliers.

### 6.1.2.5    Significance

This analysis has already been used for our prototype and would allow us to calibrate our lens to different latitudes and could form the basis of a model predictive control system if we were to choose that method to control our tracking system.

## 6.2    PRODUCT RISK ASSESSMENT

### 6.2.1    Risk Identification

Risk Name: Frame Failure

Description: SALT is designed to be easy to assemble and lightweight. We are using primarily PVC for the frame. Since SALT will be used outside, the PVC could be susceptible to weather damage and may lose its structural integrity.

Impact: 5. If the frame does collapse, water could pour out of the membrane and cause water damage. In addition, the frame could cause physical damage to the electronics and to any users.

Likelihood: 2. The likelihood of failure of the frame is low because we are using wood legs to hold up the frame to hold a relatively small weight of water. Even if one leg fails, three others remain to provide support. In addition, it is often easy to tell whether wood is rotting, splitting or cracking.

Risk Name: Membrane Failure

Description: The membrane of SALT is a flexible vinyl material that is susceptible to stretching as well as puncture. Since the weight of the water is on the membrane, we worry about the strength of the membrane. We also worry about anything puncturing the membrane, since one small puncture will create a rip and spill all of the water.

Impact: 5. If the membrane does fail, water could pour out of the membrane and cause water damage. In addition, the frame could cause physical damage to the electronics and to any users.

Likelihood: 3. The likelihood of this failure is medium because our membrane does stretch a lot and we cannot control something puncturing it; we can only minimize the problem. We have covered the electronics with plastic to minimize the impact of this happening.

Risk Name: Heat from Focused Light

Description: The water-filled membrane concentrates solar radiation to a focal line. If there is high solar radiation and not sufficient cooling to the PV cells, this can result in heat damage to the PV cells and even to the mounting platform for the cells.

Impact: 5. The PV cells are the most essential pieces to our power-generating project and therefore this is an impactful risk that affects the core purpose of SALT. In addition, our frame is wood and could potentially catch fire and cause damage to people and property.

Likelihood: 4. PV cells start to fail around 100 degrees Celsius and the level of radiation focused through SALT can change throughout the day and from day to day. If the cooling does not change accordingly, there is a very real risk of PV cell heat damage.

Risk Name: Water Contamination

Description: Since SALT is outside, we worry about our water being contaminated and this contamination affecting the cooling of our PV cells, since our cooling water comes from the water in the membrane.

Impact: 3. Contaminated water will affect the specific heat of our water which would reduce the cooling effectiveness. Debris in the water could also block water flow into the cooling pipes. Both of these situations would reduce the cooling effectiveness of our cooling pipes which could allow the PV cells to reach dangerous and potentially harmful temperatures.

Likelihood: 2. The likelihood of this happening is low because we will minimize this risk by treating our water with chlorine or a similar chemical and adding a cover to our membrane to not allow any debris to fall in.

Risk Name: Tipping

Description: SALT could tip over due to the user bumping it, wind, or any other unexpected external force.

Impact: 5. If a big enough force were applied, SALT could tip over on its side, yielding SALT uneffective. If this happened the water would spill out, the PV cells would be facing sideways, and the frame could potentially break.

Likelihood: 3. We are unable to calculate the max force that will be exerted on SALT by inclement weather, so we can a=only account for a reasonable value.

Risk Name: Wire damage
Description: Though the PV cells and Arduino will be in an enclosure, the wires that lead out of the device to whatever need to be powered would be exposed to weather elements.
Impact: 4. Torn or damaged wires can cause fire damage and harm electronics and surrounding property.
Likelihood: 2. Most people use underground PVC conduits to house wires coming out of their house. This type of protection will cause exterior wire damage to be unlikely.
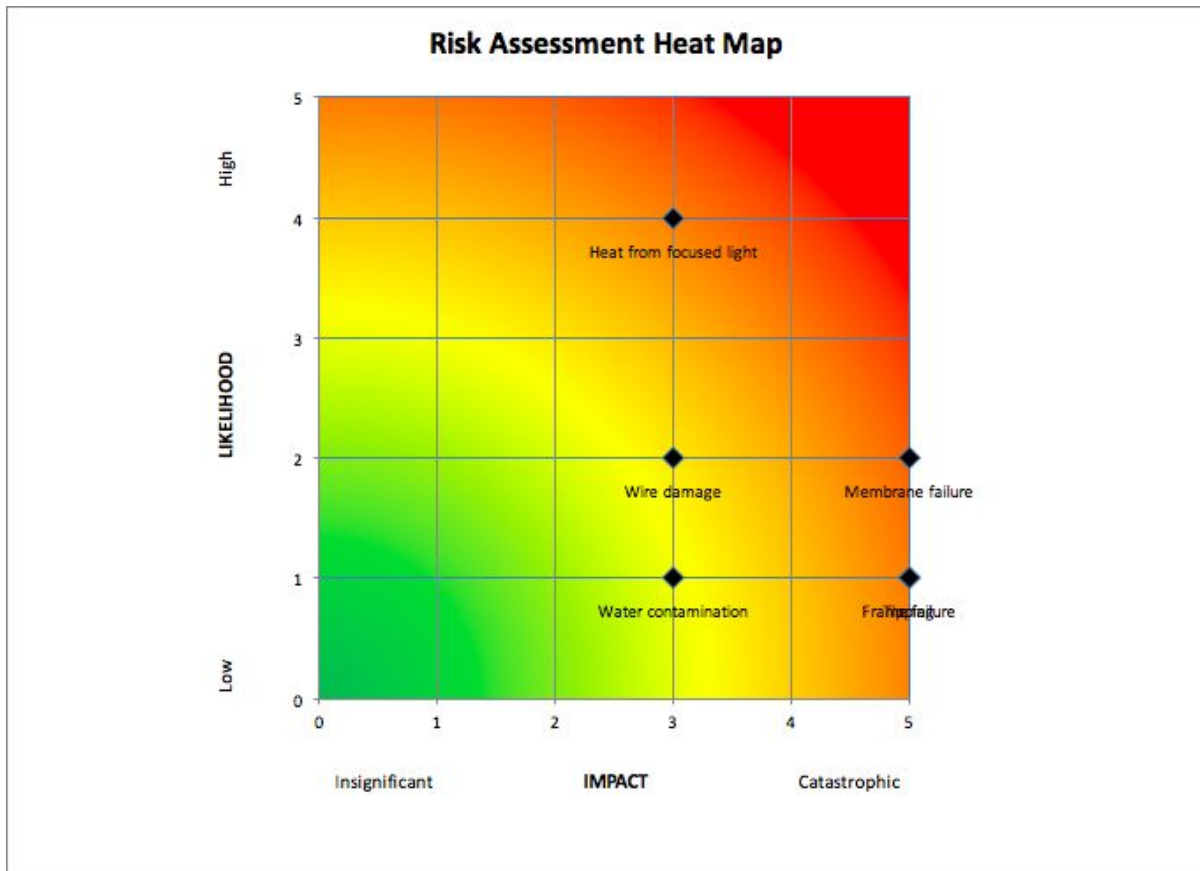
### 6.2.2    Risk Heat Map



Figure 20: Risk assessment heat map

### 6.2.3    Risk Prioritization

1. Heat from focused light
2. Membrane failure
3. Wire damage
4. Tipping and frame failure
5. Water contamination

As we can see from our heat map, the overheating of the PV cells are the highest risk factor. Next risks are membrane failure, wire damage, frame failure, tipping, and water contamination in that order. We will use this list to prioritize which risks we minimize first. We will start by implement our cooling system of running water through copper pipes so that our PV cells do not overheat and cause damage to SALT and the surroundings.

# 7  DESIGN DOCUMENTATION

## 7.1  PERFORMANCE GOALS

1. S.A.L.T. will double the power output when compared to conventional PV arrays.
2. S.A.L.T. will weigh less than 10 kg/m^2 of area.
3. S.A.L.T. will keep the PV cell to a temperature no greater than 100 degrees Celsius.
4. S.A.L.T. will not tip if tipped 5 degrees and released and corrects itself to 190% power when compared to conventional PV arrays within one minute.
5. S.A.L.T. will be able to produce 50% more power than a similar array without tracking over the course of 2 hours.

## 7.2  WORKING PROTOTYPE DEMONSTRATION

### 7.2.1  Performance Evaluation

Our prototype performed like we expected. We showed that the PV cell underneath the water lens does output more power than a PV cell away from the water lens. Our prototype met our weight performance goal even with wood parts rather than PVC pipes. The temperature of the PV cell turned out not to be as large of an issue as we expected during our prototype demo, but we made improvements on this performance goal by adding an air heatsink underneath our PV cell for our final presentation. We showed in our prototype demo that our PV cell array can correct back to the position of maximum light after shifted slightly by using the photoresistors and arduino code on the PV cell array arm.
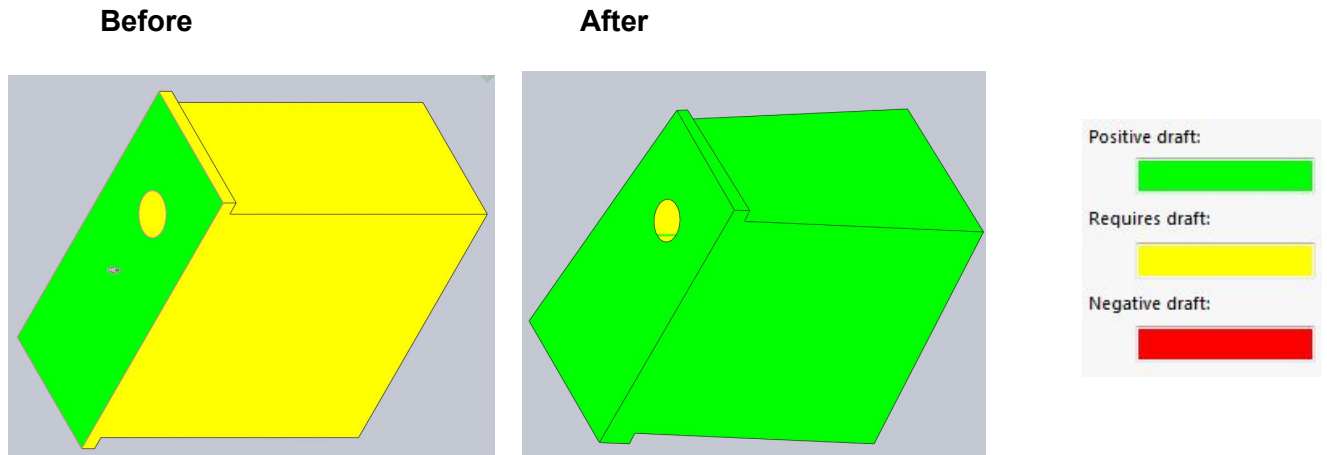
### 7.2.2  Working Prototype – Video Link

https://youtu.be/0wOqaWTZMaA

### 7.2.3  Working Prototype – Additional Photos

https://drive.google.com/open?id=1s713HkoStO5GvZTLhbsSZZa73AV432o4

# 8   DISCUSSION

## 8.1   DESIGN FOR MANUFACTURING – PART REDESIGN FOR INJECTION MOLDING

### 8.1.1   Draft Analysis Results

**Before**                                      **After**



**Figure 21:** Before and After images of a servo body using SolidWorks draft analysis and featuring. Image generated using snipping tool.

### 8.1.2   Explanation of Design Changes

The servo body, before drafting, contains sharp 90 degree edges, which would be hard to remove if injection molded. In SolidWorks, a three degree draft angles were added to protrude the front edge. Also, a three degree draft angle was added to the top face that increased the width, but does not affect our function. The sides of the servo were drafted out similar to the front face and our part "After" ended up with more positive draft angles making it easier to remove from injection molding.

## 8.2   DESIGN FOR USABILITY – EFFECT OF IMPAIRMENTS ON USABILITY

### 8.2.1   Vision

Since SALT is autonomous, visual impairment will not affect the usability of SALT. There are two situations that visual impairment could come into play. During setup of SALT, a visual impairment will make it difficult to assemble SALT, but it will not be impossible since we have no repeat pieces, so all pieces are unique and have a specific spot on SALT. A visual impairment will also affect any maintenance that is done on SALT since problems with the electronics will be hard to sense with a visual impairment.

### 8.2.2   Hearing

SALT runs using a giant servo to actuate a lever arm. When the servo is carrying too large a load, or if it is malfunctioning, it sometimes gives off a high-pitch buzz. People with

hearing impairments, such as presbycusis, may not be able to hear this sound which indicates a malfunction.

### 8.2.3    Physical

A physical impairment may affect the setup of SALT since we do have a large and cumbersome frame, but it would not affect usability. Once again, maintenance issues might be harder to solve with a physical impairment. We hope to minimize this issue by providing reliable and durable parts. We can also provide shipping and transportation options to the location of where SALT will be placed. These options can include delivery to the door and assistance to carry or wheel SALT to its final location.

### 8.2.4    Language

A language impairment will affect the usability the least because none of our parts are language specific. All of our measurements were in imperial units and we can provide an instructional video of the assembly to aid anyone with a language impairment.If we were to create a manual for the setup, we would use pictures instead of words to mediate this issue.

#### OVERALL EXPERIENCE

### 8.2.1    Does your final project result align with the initial project description?

Our final project does align with our initial project idea. We did not manage to fully implement the concept into a working product, but as this was more of a proof of concept, we think it successfully showed both the advantages and limitations of our design.

### 8.2.2    Was the project more or less difficult than you had expected?

As with any project, there are design decisions we wish we could have made with more thought put into them, and we think that the time constraint limited us in investigating such issues further. However, we think we had a good grasp of what the project would entail from the start, and our concept selection helped with mitigating issues due to complexity.

### 8.2.3    In what ways do you wish your final prototype would have performed better?

Our main difficulties lied in producing usable arrays of solar cells with the desired arrangement. We were lacking proper equipment to solder the cells together and probably could have used nickel tabs and specialised flux pens to facilitate the soldering process.

We also had more minor issues with electronics such as one of our two servos failing, prompting us to replace it with a bearing since a single servo was sufficiently powerful for the task.

### 8.2.4    Was your group missing any critical information when you evaluated concepts?

An important issue that arose during prototype testing was the effects of the incidence of the sun due to the inclination of the earth. This means we likely would still need a second axis of actuation if we wanted fully automated tracking throughout the year.

### 8.2.5    Were there additional engineering analyses that could have helped guide your design?

A full 3D ray tracing analysis would have helped with the design of our trough, but was beyond our capabilities and did not fit our time constraints. We might have been able to find specialized software but did not think it was necessary given the assumptions made that the sun would be mostly following an arc directly overhead.

### 8.2.6    How did you identify your most relevant codes and standards and how they influence revision of the design?

To find existing codes and standards, we looked at online databases through Washington University's library website. We requested access to the IEC (International Electrotechnical Commision) standards database to search relevant standards. A standard was found that a PV-mounted device must be able to withstand 200 thermal cycles from -40C to 90C, which influenced our decision to include heat sinks for our cells.

### 8.2.7    What ethical considerations (from the Engineering Ethics and Design for Environment seminar) are relevant to your device? How could these considerations be addressed?

The main ethical concern is the life cycle environmental costs of this product, the main concern being the use of plastics such as PVC, which is not always sourced from regulated sources or disposed of correctly. However these issues are partially mitigated by the fact that rigid PVC is recyclable which would lessen the environmental impact of our design.

### 8.2.8    On which part(s) of the design process should your group have spent more time? Which parts required less time?

We could have spent more time on the building portion of the project. Lots of time was dedicated to the engineering analysis because we could not start building until part were received. While the engineering analysis helped us figure out where to mount our PV array, we could have made considerable more progress through trial and error if we were able to prototype sooner.

### Was there a task on your Gantt chart that was much harder than expected? Were there any that were much easier?

The "designing and creating the PV cell array" task was more troublesome than expected. The PV cells were so fragile that you could break them by picking them up. In addition, soldering wires to the cells took much longer than expected because the solder would not stick easily to the cells.

Optimizing the membrane and liquid was fairly easier than expected. It was easy to see where the focal line was while filling the membrane with water.

### 8.2.9    Was there a component of your prototype that was significantly easier or harder to make/assemble than you expected?

The most difficult component to assemble was the membrane. We had to have uniform membrane length spanning from one end of the trough to the other otherwise the lens would not focus the light onto a clean

line of uniform width. This was the most challenging part to assemble but could be done by being methodical and patient.

### 8.2.10 If your budget were increased to 10x its original amount, would your approach have changed? If so, in what specific ways?

We would likely have swapped out the flexible membrane for a hard plastic vacuum-formed transparent plastic. In addition, we would have bought tabbed solar cells to easily connect the cells in an array.

### 8.2.11 If you were able to take the course again with the same project and group, what would you have done differently the second time around?

We would have selected a concept much earlier on than what the course calendar set it to and built a simple prototype to identify and resolve issues that only showed up with a physical manifestation of our design concept.

### 8.2.12 Were your team member's skills complementary?

There was a good amount of diversity of skills within our team. Christophe is fluent in Matlab and performing mathematical and engineering analyses. Deep has a great ability to visualize how different parts will interact within the assembly, while making sure the project is aesthetically appealing. Adam is a skeptic and was able to point out flaws in the design/build of our project.

### 8.2.13 Was any needed skill missing from the group?

Our team had membres with a wide variety of skills and what skills one lacked was easily found in the other members of the team.

### 8.2.14 Has the project enhanced your design skills?

This design project was a good exercise in managing a project from start to finish with strict deadline. We feel like it mostly made us feel more confident in taking on such projects with smaller teams and powering through moments of doubts concerning our design when the build quality is not as good as we want it to be. We've learned to pay more attention to detail, which is sometimes difficult when you are also managing the bigger picture and working under tight deadlines.

### 8.2.15 Would you now feel more comfortable accepting a design project assignment at a job?

This design experience complemented our past experience with personal and extracurricular projects and did help towards being more comfortable working with new tools, as well as being more comfortable learning to use new skills, to complete a project.

### 8.2.16 Are there projects you would attempt now that you would not have attempted before?

This class helped with learning about electronics and using arduinos and sensors for actuation. We also learned about different analysis methods such as ray tracing and coding finite element analysis tools. I think this can be extremely helpful tools for a wide range of projects involving any kinds of optics, mechatronics, or even simple analysis of complex systems.

## 9        APPENDIX A - PARTS LIST

Table 6: Parts list

| Part | Link | Price |
|------|------|-------|
| Servo | https://hobbyking.com/en_us/hobbykingtm-hk15338-giant-digital-servo-mg-25kg-0-21sec-175g.html | $ 16.16 |
| 1in PVC | http://www.homedepot.com/p/1-in-x-10-ft-PVC-Schedule-40-Plain-End-Pipe-531194/202280936 | $ 3.28 |
| PVC Tri-elbow | http://www.homedepot.com/p/Formufit-1-in-Furniture-Grade-PVC-3-Way-Elbow-in-White-4-Pack-F0013WE-WH-4/205749287?MERCH=REC-_-NavPLPHorizontal1_rr-_-NA-_-205749287-_-N | $ 8.76 |
| PVC Tee | http://www.homedepot.com/p/DURA-1-in-Schedule-40-PVC-Tee-C401-010/100347502?MERCH=REC-_-NavPLPHorizontal1_rr-_-NA-_-100347502-_-N | $ 1.28 |
| Wood (36ft 2x4) | http://www.homedepot.com/p/WeatherShield-2-in-x-4-in-x-12-ft-2-Prime-Cedar-Tone-Ground-Contact-Pressure-Treated-Lumber-253928/206967773 | $ 24.51 |
| Solar cells (different type) | https://smile.amazon.com/Aoshike-1-5x1-2inch-Polycrystalline-Silicon-Charger/dp/B01NBL6TGW/ref=sr_1_10?ie=UTF8&qid=1507518903&sr=8-10&keywords=1x3+solar+cell | $ 13.89 |
| Solar cells | https://smile.amazon.com/Aoshike-78x19mm-3x0-75inches-Polycrystalline-Silicon/dp/B01N7J9V25/ref=sr_1_3?ie=UTF8&qid=1507518903&sr=8-3&keywords=1x3+solar+cell | $ 8.95 |
| Silicon Wire (Red) | https://hobbyking.com/en_us/turnigy-high-quality-20awg-silicone-wire-20m-red.html | $ 7.50 |
| Silicon Wire (Black) | https://hobbyking.com/en_us/turnigy-high-quality-20awg-silicone-wire-20m-black.html | $ 7.24 |
| Servo Extension leads | https://hobbyking.com/en_us/60cm-servo-lead-extention-futaba-26awg-10pcs-set.html | $ 4.33 |
| Arduino | https://smile.amazon.com/HiLetgo-ATmega328P-Development-Compatible-Microcontroller/dp/B01AR7YJ3O/ref=sr_1_5?s=industrial&ie=UTF8&qid=1507949020&sr=1-5&keywords=arduino | $ 7.49 |
| Light sensors | https://smile.amazon.com/a13081500ux0353-Photoresistor-Resistors-Light-Dependent-Resistance/dp/B00H4ZSGXC/ref=sr_1_7?ie=UTF8&qid=1507948975&sr=8-7&keywords=photoresistor | $ 3.35 |
| Current Sensor | https://www.sparkfun.com/products/8883 | $ 11.95 |
| | **Total** | $ 118.69 |

## 10    APPENDIX B - CAD MODELS
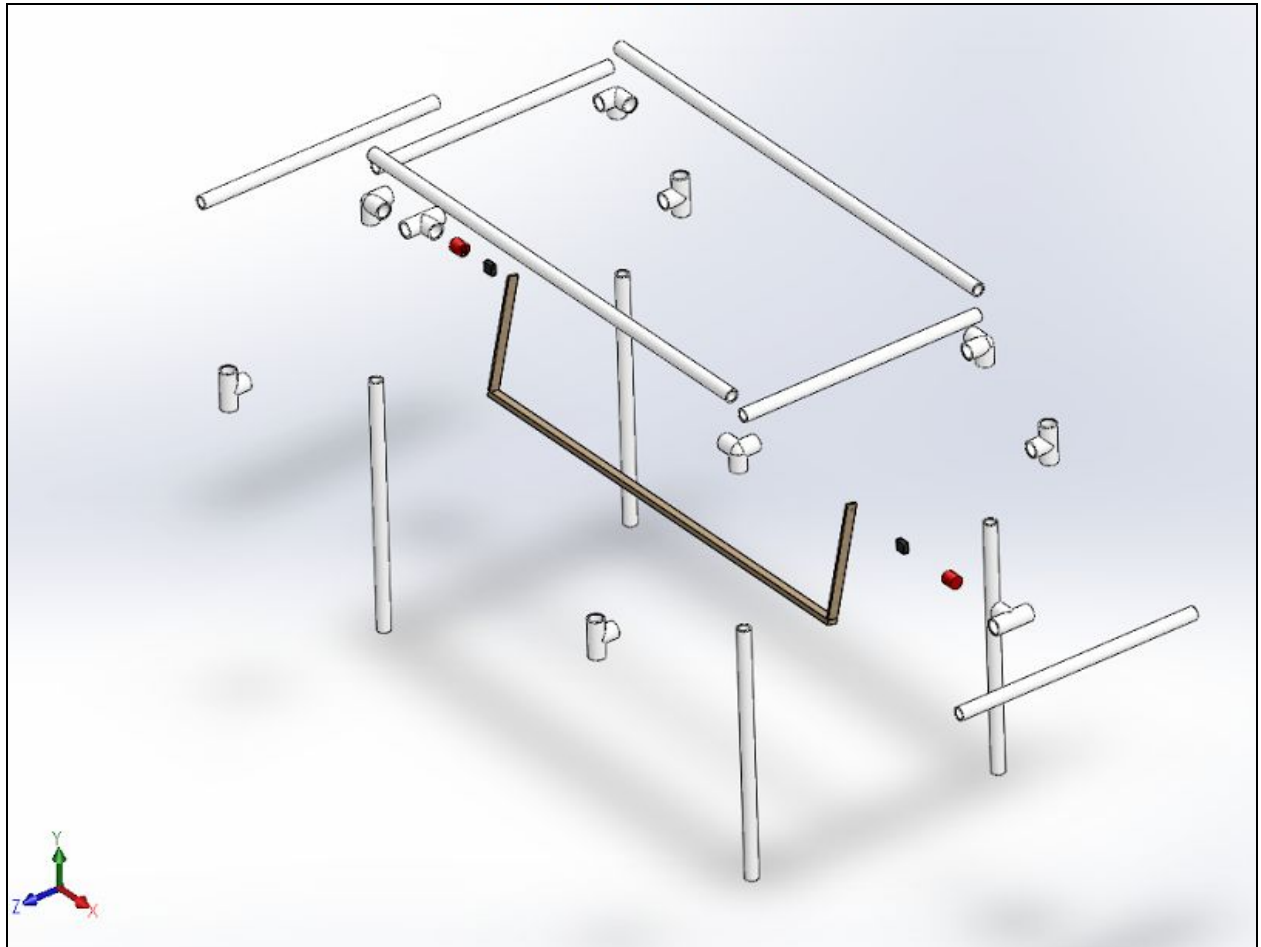


Figure 22: Final assembly exploded view render
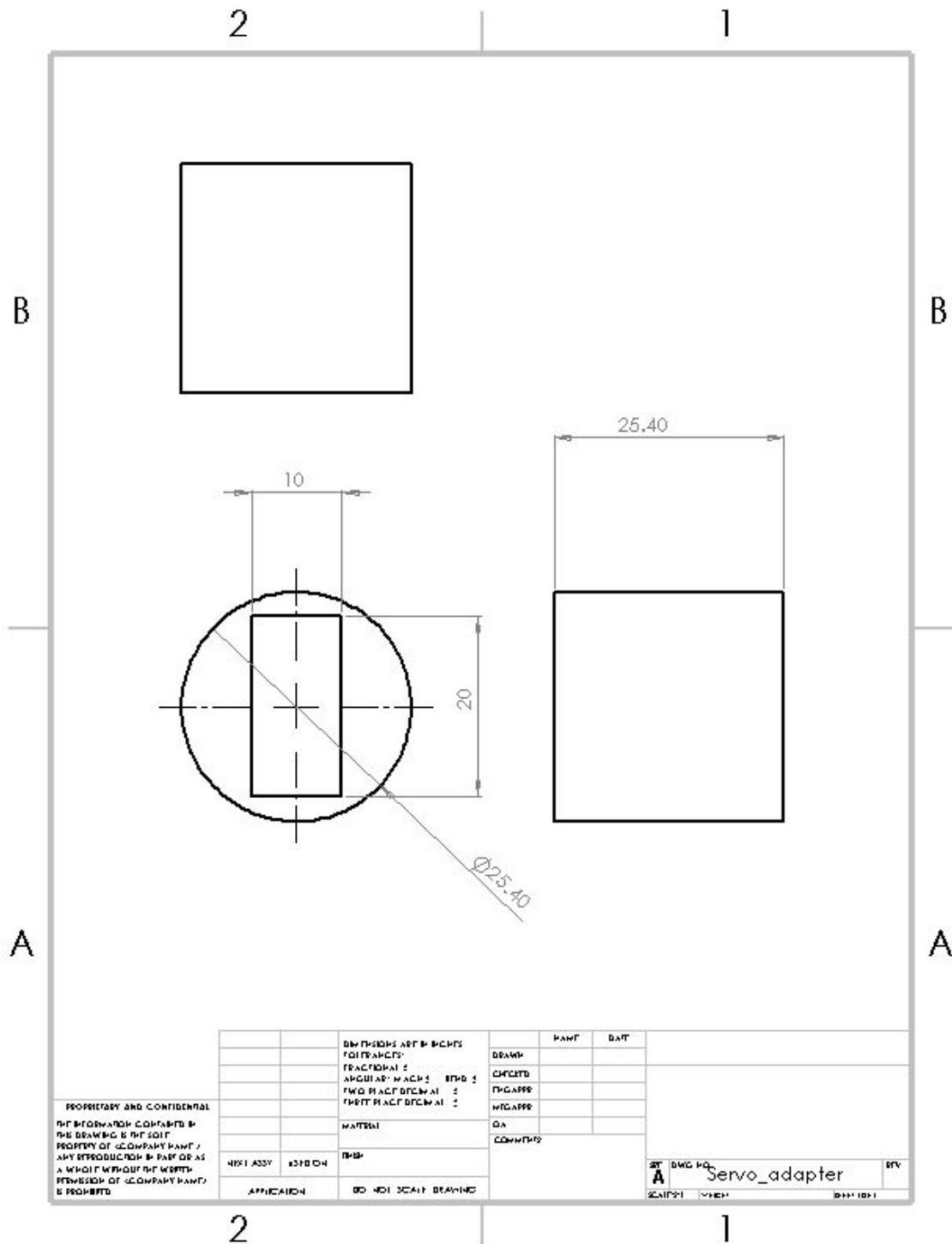
Figure 23: Servo adapter dimensions

# 11    APPENDIX C - CODE

## 11.1 Lens Shape Analysis Code:

```
%% Christophe Foyer 2017
% Finite element water trough simulation tool

%% ABOUT

% This program makes the assumption the through is constantly filled to the
% brim, this means it can't really be used to simulate an entire trough but
% can still be used to validate shape assumptions for the lens portion of
% this project.

% Disclaimer: this does not solve for the transient response of the system.

%% Init

clear

%% Settings

Mod_E_Membrane = 1.5E9; %Just make it large, it shouldn't deform too much
m_per_l = 2; %keep this to 1 probs
thickness = 0.0001;
rho = 999;
grav_const = 9.81;
point_num = 19; %odd numbers work much better stability-wise
disp_tol = 0.0005; %when to stop the simulation (im meters)
length_mult = 1.2; %slop added to distance between sides
dt = 0.002; %trial and error for stability
length = 1; %distance between sides
maxLoops = 5000; %maximum loops before returning results

%% Initialize points

x = linspace(0,length,point_num);

%start with a curve
syms x_sym
func = symfun((1.2*x_sym)^4,x_sym);
y = linspace(0,0,point_num);
for i = 1:point_num
        y(i) = func((x(i)-0.5*length))-func((-0.5*length));
end

%% move point proportionally to force (assume linearity)

delta_disp_avg = disp_tol*2; %initialize it to a value that works
step = 1; %init

while (delta_disp_avg >= disp_tol) && (step <= maxLoops)
```

```
%plot
hold on;
plot(x(step,:),y(step,:),'k');
scatter(x(step,:),y(step,:),[],-y(step,:))
frames(step) = getframe;
clf;
%increment step
step = step+1;

%import current coordinates
x_curr = x(end, :);
y_curr = y(end, :);
%init new ones (will overwrite)
x_next = x_curr;
y_next = y_curr;
%calculate force on each point (fixed ends)
for point = 2:(point_num-1)
%calculate force vector from previous point
dist_prev = sqrt((x_curr(point)-x_curr(point-1))^2 +
(y_curr(point)-y_curr(point-1))^2);
    if dist_prev > length_mult*length/point_num
            slope = (y_curr(point)-y_curr(point-1))/(x_curr(point)-x_curr(point-1));
            F1_x =
-abs(cos(atan(slope))*sign(slope)*(dist_prev-length_mult*length/point_num)*thickness*Mod_E_Mem
brane);
            if x_curr(point) < x_curr(point-1)
            F1_x = -F1_x;
            end
            F1_y =
-abs(sin(atan(slope))*sign(slope)*(dist_prev-length_mult*length/point_num)*thickness*Mod_E_Mem
brane);
            if y_curr(point) < y_curr(point-1)
            F1_y = -F1_y;
            end
    else
            F1_x = 0;
            F1_y = 0;
    end
    %calculate force vector from next point
    dist_next = sqrt((x_curr(point)-x_curr(point+1))^2 +
(y_curr(point)-y_curr(point+1))^2);
    if dist_next > length_mult*length/point_num
            slope = (y_curr(point)-y_curr(point+1))/(x_curr(point)-x_curr(point+1));
            F2_x =
abs(cos(atan(slope))*sign(slope)*(dist_next-length_mult*length/point_num)*thickness*Mod_E_Memb
rane);
            if x_curr(point) > x_curr(point+1)
            F2_x = -F2_x;
            end
            F2_y =
abs(sin(atan(slope))*sign(slope)*(dist_next-length_mult*length/point_num)*thickness*Mod_E_Memb
rane);
            if y_curr(point) > y_curr(point+1)
            F2_y = -F2_y;
            end
    else
            F2_x = 0;
```

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```
            F2_y = 0;
        end
        %calculate force vector from water
        hydro_p = -y_curr(point)*rho*grav_const;
        F_buoy = (hydro_p)*length_mult*length/point_num; %not accurate when untensioned but
that's fine
                %find avg slope
        slope_orth =
-1/(1/2*((y_curr(point)-y_curr(point-1))/(x_curr(point)-x_curr(point-1))+(y_curr(point)-y_curr
(point+1))/(x_curr(point)-x_curr(point+1))));
        F_buoy_x = -cos(atan(slope_orth))*F_buoy*sign(slope_orth);
        F_buoy_y = -sin(atan(slope_orth))*F_buoy*sign(slope_orth);
        %calculate membrane weight
        F_grav_x = 0;
        F_grav_y = -m_per_l*grav_const;
        %calculate new position
        x_next(point) = x_curr(point)+((F1_x+F2_x+F_buoy_x+F_grav_x)/m_per_l*(dt^2)/2);
        y_next(point) = y_curr(point)+((F1_y+F2_y+F_buoy_y+F_grav_y)/m_per_l*(dt^2)/2);
        end
        x = [x; x_next];
        y = [y; y_next];
        %delta_disp_avg = disp_tol*2; %debugging
        delta_disp_avg = sum(((((x(step,:)-x(step-1,:)).^2 +
(y(step,:)-y(step-1,:)).^2)).^(1/2))/(point_num-2)/dt %#ok<NOPTS>
end

delete(findall(0,'Type','figure'))

%plot fit
figure('Name','Final positions and poly2 fit line');
coefs = polyfit(x(end,:),y(end,:),2);
plot(x(end,:),y(end,:),'*',0:0.01:1,polyval(coefs,0:0.01:1),'-')

%play movie
figure('Name','FEA Animation');
movie(frames,1000,100);
```

## 11.2 Lens Analysis Code:

### 11.2.1 DrawLens.m

```
%% Christophe Foyer 2017
%% This script draws the lens and tries to find the focal point

%You can change the shape of the lens by changing the waterline_fun and the
%lens_fun functions.

%% Setup
clear
format SHORTENG
figure('Name','Lens Simulation');
drawnow;
%profile on
```

```matlab
%% Variables
volume = 0.3; %m^2, not really volume since this is 2d %calculate the water line from volume
membrane_length = 2; %m %calculate the x_range from length
stretch_coef = 1.2; %non-dimensional multiplier thing
ray_num = 8; %how many rays are drawn

%% Optics variables
angle_of_incidence = 2; %degrees (breaks the code at EXACTLY 0 deg...)
refr_index_fluid = 1.33;
refr_index_air = 1.00029;

%% Script

% figure setup
hold on
ylim([-2 1]) %constant y range
axis equal

% convert variables
angle_from_horizontal = (90-angle_of_incidence)/360*2*pi;

%% Membrane shape
syms x
lens_fun = symfun((x/stretch_coef)^2,x); %make sure it's symmetrical and starts at 0
syms y
F = solve(x==lens_fun(y),y);

% solve for membrane range
disp('solving for membrane range')
syms B
x_range = double(solve(int(sqrt(1+diff(lens_fun)^2),0, B)==membrane_length/2,B));

% plot membrane
fplot(lens_fun, [-x_range, x_range],'k')
drawnow;

% find water level from volume
syms WL
waterlevel = solve(int(abs(F(1)),0,WL)==volume/2, WL);

% solve for waterlevel intercepts
disp('solving for waterlevel intercepts')
waterlevel_fun = symfun(waterlevel,x);
S = double(solve(waterlevel_fun==lens_fun,x));
water_range = [S(1),S(2)];

% check for water overflow
if waterlevel > lens_fun(x_range)
        error('Water level too high.')
end

% plot water line
plot(water_range,ones(size(water_range))*waterlevel,'b')
drawnow;

% set light ray entry points
ray_entry = linspace(S(1),S(2),ray_num+2);
```

```matlab
ray_entry = ray_entry(2:end-1);

%% Find entering rays function
disp('finding entering ray symbolic functions')
ray_funs_entering = sym('x', length(ray_entry));
for i = 1:length(ray_entry)
        syms x
        ray_function = symfun((x-ray_entry(i))*tan(angle_from_horizontal)+waterlevel,x);
        ray_funs_entering(i) = ray_function;
end

% plot entering light rays
for i = 1:length(ray_entry)
        fplot(ray_funs_entering(i), [ray_entry(i), x_range],'y')
        drawnow;
end

%% Find refracted rays
disp('finding refracted ray (first refraction) symbolic functions')
ray_funs_refr1 = sym('x', length(ray_entry));
ray_exit_1 = zeros(1,length(ray_entry));
ray_angles_1 = zeros(1,length(ray_entry));
for i = 1:length(ray_entry)
        %define domain
        domain = [-x_range, ray_entry(i)];
        % get angle of incident ray
        syms x
        angle = func_angle(ray_funs_entering(i), waterlevel_fun, domain, x);
        % find outgoing angle
        refr_angle = asin(sin(pi/2+angle)*refr_index_air/refr_index_fluid);
        angle_out = angle_from_horizontal-angle+(pi/2-refr_angle);
        % add symbolic function to vector
        ray_funs_refr1(i) = symfun((x-ray_entry(i))*tan(angle_out)+waterlevel,x);
        % solve for intercept
        Sol = double(solve(ray_funs_refr1(i)==lens_fun,x));
        point = domain(1)-1; %make it outside the domain
        for j=1:length(Sol)
        if domain(1)<=Sol(j) && domain(2)>=Sol(j) && Sol(j)>point
                point = Sol(j);
        end
        end
        % throw error if no points are found
        if point == domain(1)-1
        error('No intercepts inside domain')
        end
        % add to vector
        ray_exit_1(i) = point;
        ray_angles_1(i) = angle_out;
        % plot ray
    fplot(ray_funs_refr1(i),[point,ray_entry(i)],'y')
        drawnow;
end

%% Find refracted rays 2 (probably has issues)
disp('finding refracted ray (second refraction) symbolic functions')
ray_funs_refr2 = sym('x', length(ray_entry));
for i = 1:length(ray_entry)
```

```matlab
        %define domain
        domain = [-x_range, ray_exit_1(i)];
        % get angle of incident ray
        syms x
        angle = func_angle(ray_funs_refr1(i), lens_fun, domain, x);
        %find angle of tangeant
        tang_lens = diff(lens_fun);
        %find lens angle from horizontal
        angle_lens = func_angle(tang_lens,symfun(0*x,x), [-Inf,Inf], x);
        % find outgoing angle
        refr_angle = asin(sin(pi/2-angle)*refr_index_fluid/refr_index_air);
        angle_out = pi/2+ray_angles_1(i)+angle-refr_angle;
        % add symbolic function to vector
        tang_ray_1 = diff(ray_funs_refr1(i));
        %calculate ray functions
        ray_funs_refr2(i) = symfun((x-ray_exit_1(i))*tan(angle_out)+lens_fun(ray_exit_1(i)),x);

        tang_ray_2 = diff(ray_funs_refr2(i));
        try
        if tang_ray_2 > 0
                draw_domain = [-x_range,ray_exit_1(i)];
        else
                draw_domain = [ray_exit_1(i),x_range];
        end
        % plot ray
        fplot(ray_funs_refr2(i),draw_domain,'y')
        drawnow;
        catch
        disp('Error drawing ray, skipping...');
        end
end

%% Plot Focal Point Approximation

disp('locating focal point (approx.); works better at low angles, includes outliers')
%Find ray intercepts
x_Points = zeros(length(ray_entry));
y_Points = zeros(length(ray_entry));
for i = 1:length(ray_entry)
        for j = 1:length(ray_entry)
        if ray_funs_refr2(i) ~= ray_funs_refr2(j)
                syms x
                x_Points(i,j) = double(solve(ray_funs_refr2(i)==ray_funs_refr2(j), x));
                y_Points(i,j) = double(subs(ray_funs_refr2(i),x,x_Points(i,j)));
        end
        end
end

%find distances
dist_mat = ((x_Points).^2+(y_Points).^2).^(1/2);

%remove outliers
%outlier_mat = abs(isoutlier(dist_mat)-1); %only works in matlab 2017
outlier_mat = abs(zeros(length(ray_entry))-1);

%update to remove outliers
x_Points = x_Points.*outlier_mat;
```

```matlab
y_Points = y_Points.*outlier_mat;

%find average
focal_x = sum(sum(x_Points))/(sum(sum(outlier_mat))-length(ray_entry));
focal_y = sum(sum(y_Points))/(sum(sum(outlier_mat))-length(ray_entry));

%plot the point
plot(focal_x,focal_y,'rx')
drawnow;

%for debugging
%profile viewer
```

## 11.2.2 Func_angle.m

```matlab
%% Christophe Foyer 2017
%% angle calculation function

function angle = func_angle(ray_fun, lens_fun, domain, symvar)

%assuming negative slope rays (could check later)

%find intercept points
Sol = double(solve(ray_fun==lens_fun, symvar)); %symvar symbolic variable (usually x)

%remove points outside domain and keep largest one (valid assumption?)
point = domain(1)-1; %set outside domain
for i=1:length(Sol)
        if domain(1)<=Sol(i) && domain(2)>=Sol(i) && Sol(i)>point
        point = Sol(i);
        end
end

%Throw error if no points are found
if point == domain(1)-1
   error('No intercepts inside domain')
end

%find differentials
diff_ray = diff(ray_fun);
diff_lens = diff(lens_fun);

%find tangents
tang_ray = diff_ray; %only works for straight lines (aka light rays here)
tang_lens = diff_lens(point);

%calculate angle (do we want absolute values)
%angle=atan((tang_ray-tang_lens)/(1+tang_ray*tang_lens));

%calculate angles (no absolute values
angle = -(atan(tang_ray)-atan(tang_lens));

end
```

## 12    ANNOTATED BIBLIOGRAPHY

1)  "Concentrated Solar Power Experiment with a Fresnel Lens." *Concentrated Solar Power Experiment with a Fresnel Lens*, rimstar.org/renewnrg/concentrated_solar_power_diy_with_fresnel_lens.htm. This is a DIY guide to setting up a fresnel lens for a photovoltaic array. It also is a guide for setting up testing equipment to measure power output.

2)  "Concentrating Photovoltaics." *Concentrating Photovoltaics: Solar Power*, www.greenrhinoenergy.com/solar/technologies/pv_concentration.php. This resource gave background on existing concentrating photovoltaics (CPV). This site also informed potential cooling possibilities for our cells.

3)  "MICRO-OPTICAL TANDEM LUMINESCENT SOLAR CONCENTRATOR." *ARPA-E*, 11 Feb. 2016, arpa-e.energy.gov/?q=slick-sheet-project%2Fmicro-optical-tandem-luminescent-solar-co ncentrator. This site provided benefits and drawbacks from using a luminescent solar concentrator for photovoltaics.

4)  "SOLAR DEATH RAY WATER Aqua Lens with 1/3 Kilowatt Heat Energy Grid Free Energy." *YouTube*, YouTube, 5 June 2011, www.youtube.com/watch?v=eeSyHgO5fmQ. This video was inspiration for our whole project. It gave the proof that we could focus light for increased energy output.