Fall 12-8-2014

Team Sunflower - Solar Tracker Team 2

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MEMS 411 Final Report

Solar Panel Tracking System – Team 2

Laura Scott, Ethan Glassman, Lindsey Warden, Max Kapczynski
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5.2.3 Methodology. How, exactly, did you get the analysis done? Was any experimentation required? Did you have to build any type of test rig? Was computation used?

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6 Working prototype

6.1 A preliminary demonstration of the working prototype (this may be left blank).

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7.2.2 A link to a video clip version of 1

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8.3.2 Does your final project result align with the project description?

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8.3.5 Did your team share the workload equally?
8.3.6 Was any needed skill missing from the group?
8.3.7 Did you have to consult with your customer during the process, or did you work to the original design brief?
8.3.8 Did the design brief (as provided by the customer) seem to change during the process?
8.3.9 Has the project enhanced your design skills?
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9 Appendix A - Parts List
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12 Annotated Bibliography (limited to 200 words per entry)
1 Introduction

1.1 Project problem statement
Our design problem was to create a solar radiation tracking device. The primary goal of this device was to keep a solar panel perpendicular to the solar radiation with 95% efficiency throughout the day. The tracker had to be able to account for the sun’s seasonal angle in St. Louis, and the design would be even better if it could account for the sun’s seasonal angle at any latitude. Another important aspect of the solar tracker design was that it must be able to reset itself each day for the sunrise without human input. Other aspects to consider were weatherproofing in order to keep the device safe from the elements throughout the year as well as the ability for the device to be independent of the power grid as the entire premise of a solar panel is to create usable energy rather than consume energy.

1.2 List of team members
The list of figures and tables must be updated by you using the references tab.

2 Background Information Study

2.1 A short design brief description that defines and describes the design problem
The design problem we are confronting in this project is to build a mechanical system for a solar panel that adjusts the angle of the panel with the motion of the sun. The more perpendicular the panel is to the solar radiation, the more efficiently the panel will draw electrical energy from the sun’s light.

2.2 Summary of relevant background information (such as similar existing devices or patents, patent numbers, URL’s, et cetera)
Patent: US3311748 A

https://www.pc-control.co.uk/howto_tracksun.htm


http://renewableenergysolar.net/can-my-solar-panels-withstand-a-hail-storm/

http://energyinformative.org/solar-panels-weather/


3 Concept Design and Specification

3.1 User needs, metrics, and quantified needs equations. This will include three main parts:

3.1.1 Record of the user needs interview (Prof. Bevers)

Question: Does the tracking system have to adjust automatically for changing seasons?
Answer: The system cannot be manually changed to adjust for seasonal angle.

Q: How much visibility does the system have to have of the entire sky?
A: 360 degree visibility is best, but 180 degrees is okay.

Q: Where is the system located?
A: St. Louis

Q: How much efficiency does the solar panel have to maintain before it needs to move?
A: There is no exact requirement for efficiency, but you should calculate what it comes out to be.

Q: Does the system have to be self-powered or is an external power source acceptable?
A: It should be self powered from the energy it collects. The demo will be outside. Don’t forget that if you use a microprocessor that it needs to be supplied with power even when the system is not generating power.

Q: Does the system need to automatically reset itself each day?
A: Yes, and with no assistance.

Q: How much power does the system need to produce?
A: Enough to power itself.

Q: Where is the system supposed to be set up? Would it be free standing on the ground or on a slanted roof?
A: It would be set on the ground by itself.

Q: How ‘pretty’ does the entire construction have to be?
A: This is a prototype to prove a concept. Its not made to be ready for mass production. Aesthetics do not have to be perfect.

Q: Should the system be waterproof for weather purposes?
A: Yes, but this is not as important as the working functionality.

Q: Does the system have to portable or would it be permanent fixture?
A: The system would be a permanent fixture, but you still need to move your system for demonstration purposes.
3.1.2 List of identified metrics (units, best-worst values)

1. Is Fully Automatic (binary, 1-0)

2. Max Voltage Production (volts, 5-0)

3. Wind Speeds Tolerated (mph, 70-0)

4. Snow Build-Up Tolerated (in, 5-0)

5. Is Free-Standing (binary, 1-0)

6. Cost of Materials (dollars, 0-200)

7. Degrees of Visibility (degrees, 360-0)

8. Ground Space Needed (m2, 0-10)

9. Numbers of Motors Required (integer, 0-3)

10. Number of Moving Parts (integer, 0-20)

3.1.3 Table/list of quantified needs equations

<table>
<thead>
<tr>
<th>User Need</th>
<th>Scoring Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully Automatic</td>
<td>0.16</td>
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<tr>
<td>Self-Powered</td>
<td>0.16</td>
</tr>
<tr>
<td>Wind Durability</td>
<td>0.1</td>
</tr>
<tr>
<td>Snow Durability</td>
<td>0.06</td>
</tr>
<tr>
<td>Free-Standing</td>
<td>0.06</td>
</tr>
<tr>
<td>Cost Under $200</td>
<td>0.1</td>
</tr>
<tr>
<td>Full-View Rotation</td>
<td>0.13</td>
</tr>
<tr>
<td>Compact</td>
<td>0.11</td>
</tr>
<tr>
<td>Minimal Complexity</td>
<td>0.13</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1</strong></td>
</tr>
</tbody>
</table>
Quantified needs equation
**Nmh means normalized metric happiness

0.16(fully automatic nmh) + 0.16(self-powered nmh) + 0.10(wind durability nmh) + 0.06(snow durability nmh) + 0.06(free standing nmh) + 0.10(cost under $200 nmh) + 0.13(full view rotation nmh) + 0.11(compact nmh) + 0.13(complexity nmh) = total happiness

3.2 Four (4) concept drawings

Design 1

Motors mounted on the solar panel itself pull on each of the three cables. This raises or lowers a corner of the solar panel and provides great freedom of positioning.

This hanging design is awkward and leaves the panel swinging in the wind, which could lower efficiency or even damage the panel.
This design rotates about the center post, and has the solar panel cantilevered outward on an arm. The arm is motorized to provide elevation control. This design is exceedingly simple to plan and construct. Few moving parts would be required.

Two noticeable drawbacks are present though. First, the panel sweeps out a large area on the ground as it rotates, this would make it ungainly to have near trees or buildings, as a large space needs to be cleared. Second, the cantilevered arm needs to be built strongly, and there is a torque imposed upon the rotating member that controls elevation. In the cases of snow and wind loading, the connection would have to be very strong and have robust bearings capable of handling larger radial load.

Telescoping action of the two moving legs causes rotation about the ball-socket joint at the top of the fixed post.

The telescoping posts could be driven by leadscrews or some other sort of linear motor.

This design is relatively complex, and the precision leadscrews could suffer damage from wind and water.
Design 4

This panel is similar to Design 2, but the panel is moved so that its center of gravity aligns with the axis of rotation, so there is no cantilever. A counterweight at the end of the elevation arm balances out the weight of the panel, leading to balanced torques on all structural members.

Elevation and rotation are achieved similar to Design 2, with one motor controlling a rotating member for each axis.

In the cases of snow or wind loading, Design 4 should prove itself to be more robust for a lighter support structure than Design 2, in addition to sweeping out a smaller area and thus taking up less space.

Note: This design was the only one of the four that is directly inspired by real-world designs. A large amount of two-axis automatic solar tracking systems use a design that is similar to this. This design does not appear to be a hallmark of a particular company or customer need, it merely stands out as an excellent choice when a two-axis system is required.
1.1 A concept selection process. This will have three parts:

3.2.1 Concept scoring (not screening)

Design 1:

<table>
<thead>
<tr>
<th>Metric</th>
<th>Score</th>
<th>Weight</th>
<th>Total Impact</th>
<th>Happiness</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Total Impact Value</td>
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<tr>
<td>Importance Weight</td>
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<tr>
<td>Needed Helpfulness</td>
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<tr>
<td>Number of Mount Points</td>
<td>0.12</td>
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<tr>
<td>Number of Hubs</td>
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<tr>
<td>Square Meters of Ground Area</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Degrees</td>
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<td>Cost</td>
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<tr>
<td>Free Standing</td>
<td>0.05</td>
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<tr>
<td>Amount of Straw Built up foes</td>
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<tr>
<td>Wind Speeds Hodumed</td>
<td>0.03</td>
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<tr>
<td>Available Production Rate</td>
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<tr>
<td>Final Material</td>
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<table>
<thead>
<tr>
<th>Design 1: Panel Hanging from Wires</th>
</tr>
</thead>
<tbody>
<tr>
<td>Needs</td>
</tr>
<tr>
<td>-------</td>
</tr>
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<td>Security</td>
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<td>Cost</td>
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<tr>
<td>Complexity</td>
</tr>
<tr>
<td>Power</td>
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<tr>
<td>Efficiency</td>
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</table>
### Design 2: Cantilever Arm

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<tr>
<th>Metric</th>
<th>Need</th>
<th>Value</th>
<th>Units</th>
<th>Best Value</th>
<th>Worst Value</th>
<th>Actual Value</th>
<th>Normalized Metric Value</th>
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<tbody>
<tr>
<td>Fully Automatic</td>
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<td>1</td>
<td>Binary</td>
<td>5</td>
<td>70</td>
<td>5</td>
<td>1</td>
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<tr>
<td>Max Voltage Production</td>
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<td>1</td>
<td>Binary</td>
<td>5</td>
<td>70</td>
<td>5</td>
<td>1</td>
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<tr>
<td>Wind Speeds Tolerated</td>
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<td>1</td>
<td>mph</td>
<td>5</td>
<td>70</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Fully Standing</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Square meters of ground used</td>
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<td>1</td>
<td>mm²</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Number of Motors</td>
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<td>Integer</td>
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<td>0</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Number of Moving Parts</td>
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<td>1</td>
<td>Integer</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Happiness Values**

- Total Happiness Value: 0.0159
- Importance Weight (fall): 0.48
- Importance Weight (spring): 0.48
- Total Happiness: 0.0100

**Note:**

- The table above represents the evaluation of the design criteria, where each criterion is rated on a scale from 1 to 10, with 1 being the lowest and 10 being the highest. The happiness values are calculated based on the importance weights assigned to each criterion.
- The design criteria are divided into different categories: full automatic, max voltage production, wind speeds tolerated, fully standing, square meters of ground used, number of motors, and number of moving parts.
- The table includes units for each metric to provide a clear understanding of the values assigned.
- The normalized metric happiness values are calculated to compare the relative importance of each criterion.
### Final Design: The Sunflower

<table>
<thead>
<tr>
<th>Need</th>
<th>Score</th>
<th>Units</th>
<th>Smart</th>
<th>Busy</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Fully automated</td>
<td>5</td>
<td>Hour</td>
<td>5</td>
<td>5</td>
<td>Notes</td>
</tr>
<tr>
<td>2. Self-powered</td>
<td>4</td>
<td>Hour</td>
<td>4</td>
<td>4</td>
<td>Notes</td>
</tr>
<tr>
<td>3. Water detection</td>
<td>3</td>
<td>Hour</td>
<td>3</td>
<td>3</td>
<td>Notes</td>
</tr>
<tr>
<td>4. Wind direction</td>
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<td>Hour</td>
<td>2</td>
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<tr>
<td>5. Wind speed detected</td>
<td>1</td>
<td>Hour</td>
<td>1</td>
<td>1</td>
<td>Notes</td>
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<tr>
<td>6. Max wind speed reached</td>
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<td>Hour</td>
<td>0</td>
<td>0</td>
<td>Notes</td>
</tr>
<tr>
<td>7. Min wind speed reached</td>
<td>0</td>
<td>Hour</td>
<td>0</td>
<td>0</td>
<td>Notes</td>
</tr>
<tr>
<td>8. Fully automatic</td>
<td>0</td>
<td>Hour</td>
<td>0</td>
<td>0</td>
<td>Notes</td>
</tr>
</tbody>
</table>

**Final Score:** 20

**Total Happiness:** 0.10
Design 4:

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<tr>
<th>Metric</th>
<th>Need</th>
<th>Fully Automatic</th>
<th>3 Fully Manual</th>
<th>2 Semi-Auto</th>
<th>1 Not Auto</th>
<th>0 Not Applicable</th>
<th>Score</th>
<th>Weight</th>
<th>Total Happiness</th>
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<tr>
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<td>9</td>
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<tr>
<td>Square Meters of Ground Used</td>
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<td>Design</td>
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<td></td>
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<tr>
<td>Free Standing</td>
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<td></td>
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<td></td>
<td>5</td>
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<tr>
<td>Amount of Showbuild Up to Date and Paid</td>
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<td></td>
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<td>Wind Speeds For Used</td>
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<td>Max Volume Production</td>
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<td></td>
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<td>1</td>
</tr>
</tbody>
</table>

Total Happiness Value:
3.2.2 Preliminary analysis of each concept’s physical feasibility

Design 1:
This design has challenges stemming from the one-sided nature of the supports for the solar panel. On a calm day, this panel would still be shaded to some extent by the supporting poles, as they must be taller than the height of the panel. On a windy day, the panel could act like a sail and apply significant additional strain on the cable, but also causing the angle between the solar panel and the sun to be difficult to control. The poles would need to be sufficiently stiff to support the panel without undue bending.

Care would have to be taken in the selection of a robust cable management system, as any tangles in the wire could cause the system to lose an ability to track the sun accurately. Pulleys and counterweighted cabling would likely be necessary to reduce energy usage of the control system, as we want to maximize output power, and use a minimum amount of energy in moving the panel.

If the motors and control systems were mounted on the solar panel, it would be necessary to design a back to the panel that is sufficiently strong and rigid to support mounting of these systems to the panel without damaging the panel. It would also be necessary to provide some wiring to transfer the gathered solar energy from the panel for storage and delivery to the grid. If the motors and control system were mounted in the poles, a cabling system for transferring the solar energy from the panel to the control system would be necessary. It would also be necessary to ensure the signals from the solar tracking sensors could be polled quickly enough, and are of strong enough amplitude to get sufficiently accurate solar tracking for our desired minimum angle between panel and sun.

Design 2:
The seasonal angle adjustment would not be governed by sensor input and this could easily lead to inaccuracy. This would decrease our optimization potential. The design has the benefit (but also the drawback) of being relatively simple, and as such should not be a difficult undertaking. However, a potential design concern arises from its simplicity is that of the imbalance of the motor/drive shaft with the solar panel. The device could become top heavy if not properly counterweighted, and even if it was, the positioning of the panel relative to the motor could lead to potentially significant strain on the shaft and/or motor, particularly if rain or snow were to build up on the surface of the solar panel.

Design 3:
This design is not very practical as you would need very long drive shafts to be able to reach as many angles and directions as possible. There is the potential for the solar panel to become top heavy and disrupt the function of the motors adjusting its angle. Furthermore, at angles that vary significantly from the horizontal, the angle adjustment shafts could not be fixed relative to the support shaft, another concern to add to the complexity of the overall design. Accounting for this cheaply and effectively might be a difficult design problem to confront.

Design 4:
This design provides the shortest moment arms applied to the motor shafts, which should reduce the need for complex support systems to prevent bending or shearing the...
motor shafts. Counter weighting the solar panel will minimize stresses on the system at rest, simplifying material choices. It will be necessary to provide a robust vertical column to support the second motor and the solar panel without flexing. A relatively large bearing might be needed to ensure smooth rotation of the vertical column without applying the supporting forces to the shaft of the motors.

It will be essential to prevent back driving of the control motors, probably with worm gears, to reduce energy needed to hold the panel in a fixed location. This gearing system should also allow use of relatively weak motors, as it is not important to have high-speed motor movement.

The compact design puts control systems near the motors and solar tracking sensors, which should simplify the electronics configuration. There should be no special requirement for materials in this design, as static and dynamic forces on the components should be minimal.

3.2.3 Final summary

The winner of our concept selection process is design 4. Of all the designs it has the best long-term durability and visibility. It also has the most reasonable cost for the amount of efficiency it would allow the solar panel to produce. Design 1 is too problematic because the cables are not rigid meaning that the solar panel is easily swayed by wind. Because this design also causes the solar panel to act a sail catching any wind, the cables would have to be extremely strong to hold the forces exerted. Design 2 is eliminated due to both its over simplicity and vulnerability. Because the seasonal angle is not tracked by sensors, but rather by estimation, the efficiency is significantly less than that of design 4. Also, this design has the potential of easily becoming top-heavy due to the imbalance of the motor/drive shaft with the motor. Design 3 has been ruled out because of its lack of visibility when the sun is at low angles as well as the cost of the design. Even with very long drive shafts, the visibility would still be limited at extreme angles that other designs could see.

3.3 Proposed performance measures for the design

1. No more than 10% extraneous motor motion used per day.
2. Never goes more than ±10 degrees off of orthogonal.
4 Embodiment and fabrication plan

4.1 Embodiment drawing
## 4.2 Parts List

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<tr>
<th>Comp. Number</th>
<th>Part</th>
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4.3 Draft detail drawings for each manufactured part
4.4 Description of the design rationale for the choice/size/shape of each part

1. The stand for the device is made from 1” pipe size PVC pipe. This serves as a cost-effective, sturdy and weatherproof mount that is compatible with off-the-shelf pipe flanges (Part # 8) for simple mounting.

2. This 6V solar panel from Adafruit represents a panel that is close to wholesale-price but is available from a reputable hobby site and will be shipped from the US. It works at our necessary operating voltage of 6V, and provides 3.7W at full capacity which leaves us with a comfortable margin to operate our electronics. This panel is also waterproofed which is essential for outdoor operation.

3. McMaster offers many different sorts of pulleys for use with lots of different kinds of cable. I opted to use elastic tubing, because it can be shortened to length simply and does not require tensioners. The low load is not an issue because these pulleys are not running for a long duration and carry low loads.

4. This length of 2” base aluminum U-channel was chosen because this is one of the few parts that needs to bear significant load and must be stable. The .25” wall thickness ensures stability, and the width spreads the load out on the pulley beneath it. I chose a short leg length of 1” and then opted to bolt on separate plates, because of the prohibitive cost of U-channel with large leg lengths.

5. This pulley accepts the elastic belt I will use to drive the rotation. The reduction ratio between the two pulleys is not critical, but any small reduction will be favorable. The outer diameter was really chosen because it matches the size of the Lazy Susan bearing that the pulley will be permanently epoxied onto.

6. This bearing really lets the design come together. This design needs to support axial and radial loads of approximately the same magnitude, meaning a larger bearing to spread the load out is ideal. The bearing has mounting holes and a large surface facilitating easy integration into the design. The lazy susan bearing rides on ball bearing races, providing very smooth rotation.

7. This plate is another one of the few load-bearing parts of the design. I judged ⅛” plate to be insufficiently rigid for the load that it will be carrying. ¼” plate will provide ample strength. This plate offers mounting points for the Lazy Susan bearing, the stand flange, and the rotation motor all in one part. Previous designs had multiple parts and brackets all bolted to each other to provide the same function, but this single-plate mounting does the job easily and cheaply. No manufacturing processes more complex than simple drilling is required to create this part.

8. This unthreaded PVC pipe flange serves as the mounting part for both the Part 7 and the base plate. The flange can be securely cemented to the PVC stand, offering a simple and robust way to mount the project to the baseplate. The flanges come with ½” bolt clearance holes, and the same holes are drilled into Part 7 and the baseplate to mount the parts together.

9. These plates rise up several inches from the legs of Part 4, providing space to let the main beam elevate vertically. The plates are only ⅛” aluminum, but as the loads are primarily vertical and longitudinal, not transverse, there will be no risk of excess loading.

10. This motor will power the elevation of the panel as the sun rises and falls through the seasons. This motor was picked because of the lower price and the availability of a plastic case that slides
over the motor and provides robust mounting holes. This will anchor the motor securely to Part 9 and let it move the panel without fear of loosening or failing.

11. This motor will rotate the pulleys at the base, providing the daily back-and-forth action that will be the bulk of the device’s motion. This motor has a sealed steel planetary gearbox and tough construction. Because of the lack of documentation concerning mounting holes on the motor, I have elected to secure the motor to the mounting plate with zip-ties that will place the motor unit under some stress. The tough construction makes this design possible. Nearly any 6V sealed geared motor can be substituted for this particular unit, but this was an affordable example from a trusted hobby site, so that is why I chose this particular unit.

12. This part serves two purposes: First, it accommodates two set-screws that grip the keyed shaft of the elevation motor. Second, it has four clearance holes that will let four #10 bolts secure the elevation beam to the motorized shaft. This connection is very strong and secure and will offer great protection against failure. The main shaft diameter is 0.25”, this diameter offers enough space for the set-screws to gain traction. The flange diameter is 0.75”, this is the minimum diameter that allows use of a #10 screw. A larger flange diameter would necessitate larger and more expensive aluminum bar stock, as well as more troublesome manufacturing.

13. This lightweight, cheap nylon flanged sleeve bearing will ensure low-friction operation of the elevating shaft, without the price and weight of a ball bearing. The elevation shaft spends so little time in motion that this sleeve provides all the smoothing necessary.

14. The motor must be stood off of the elevation plate by a small distance, in order to accommodate the flanged sleeve. These simple aluminum spacers serve this task.

15. This steel ring snaps onto a groove in Part 16 and keeps the flanged sleeve on its side securely in place.

16. This part serves much the same purpose as Part 12 but does not need to transmit motor power. Thus, it serves only to offer a second mounting point for the #10 screws that secure Part 12 through the beam.

17. This bent sheet metal part secures the solar panel strongly to the motorized beam. The bracket will be permanently epoxied to the back of the solar panel, and leaves enough space for the panel’s power wires. It extends a small distance above the panel, this space is to be used for sensor mounting points.

18. Electronics box from McMaster is ideal for protecting delicate electronics from weather. We want to be able to drill holes easily for bringing power and photoresistor wires into and out of the control system. Plastic box is economical and is threadable and easily modified to provide mounting points for the electronics.

19. This base board is a simple Masonite slab. The stock is very economic and provides a large, stable base that is easily drilled and cut. Outdoor performance is acceptable in the short term, but for long-term use in damp environments a better material will be chosen.

20. These are two 6-32 threaded rods that serve as secure mounting posts for the cable ties that will secure the rotation motor to the rotation plate.

21. This is the third major load-bearing part in the design. This box beam is taller than it is wide, providing beneficial strength against the weights of the panel and counterweight. Aluminum provides better strength than any plastic, and is available cheaply in the sizes necessary. A
smaller beam could be used and still be safe against the stresses involved, but would significantly complicate efforts to mount the motor securely. This larger beam is a simple and robust solution.

22. These angled aluminum brackets will serve to mount the panel to the beam. The stock is inexpensive and will accept #10 screws to securely mount these parts together.

23. The counterweight assembly is composed of four 0.25” thickness mild steel plates, chosen for their high density and low cost. These four plates are dimensioned and placed in order to properly balance out the weight of the solar panel and mounts on the other end of the beam. The design allows individual counterweight plates to be slipped on and off easily, if the design requirements change in the future.

24. Battery Charger: Simple, robust battery charging unit. Designed for simple addition of battery charging to any electrical system. Requires 5V input to charge, with 3.3v and 5v outputs to power the Arduino (3.3 - 12v input)

25. Battery:

   Arduino - 15mA when active, 5mA when in sleep mode. Assume 10% of daytime (assume ~10 hrs) is duty cycle. Power usage is 15 mA * 1 hr + 5 mA * 23 hr = 360 mAh/day.

   Motors - Assume stall current of 500 mA for 1 hr, 5% of stall current on average during 23 hr downtime. Power usage is 500 mA * 1hr + 25 mA * 23 hr = 1075 mAh/day.

   Motor controller - Quiescent current max = 32 mA. Assume only when in use during 1 hr/day duty cycle. Min is 7mA, assume 23 hr. 32 mA * 1hr + 7 mA * 23 hr = 193 mAh/day.

   Battery charger - Quiescent current is 55uA. Assume 24h use, 55uA * 24 = 0.77 mAh/day.

   Total energy = 360 + 1075 + 193 + 0.77 mAh/day = 1628.77 mAh/day.

   Worst case, 2 days without sun * factor of safety of 2, 6500 mAh

26. Arduino Pro 328: Provides industry leading support for introductory electronics projects. Abundant code and examples available with many of the Sparkfun products, simplifying the integration of mechanics and embedded control system. Full size Arduino boards such as the Pro 328 provide 6 analog and 14 digital I/O pins, with 6 PWM outputs, as well as a dedicated USB port for connecting to a computer for programming and a dedicated power port. Provides a robust central computing platform, ideal for real-time processing of our 4-8 analog photocells. It is relatively easy to use a digital analog converter chip to expand available analog inputs. 3.3 - 12v input makes it simple to power directly from the 5v output of the battery charger circuit. 40mA outputs sufficient to power motor controller.

27. Photocell: Low cost passive light sensor. Resistance changes based on incident light, via a roughly linear response. Requires no energy to track the sun, has ~50ms response time, which is well more than sufficient for sun tracking over 1 day timescales.
28. Motor Controller: 2A outputs are more than sufficient for 500mA stall current motors. By using a shield, the motor control circuit is mechanically supported, and loose wires are minimized, simplifying electronics box layout and reducing likelihood of electronics malfunctions.

29. Elevation Motor: Simple, high-torque, slow motors. We are moving a solar panel ~180 degrees in ~10 hours, which requires minimal speed. By utilizing a gear motor, backdriving of the motors is unlikely, which allows us to completely turn off the motor driving system during the downtime between updating the sun position, reducing energy usage of the control system.
5 Engineering analysis

5.1 Engineering analysis proposal

5.1.1 Form, signed by section instructor

Experimental analysis:
- Project: Solar Tracking Device
- Names: Laura Scott, Ethan Glassman, Lindsey Warden, Max Kapaernsky

INSTRUCTOR: J. Beyer

The following engineering analysis tasks will be performed:

Before:
- Mechanical Analysis:
  - Moving part interference analysis
    - Interface analysis in solid works
    - Motion analysis in solid works
  - Panel view angle analysis based on St. Louis latitude
    - Calculated necessary maximum view angles based on seasonal solar movement
  - Motor ratio analysis
    - Using calculations for view angles and solar movement, calculate necessary rotational motor speed
    - Gear ratio analysis
    - Torque analysis
  - Wind speed durability analysis based on St. Louis weather
    - FEA test in solid works based on average wind patterns
  - Temperature Analysis
    - Analysis of possible extreme temperatures on materials used

- Control System Analysis:
  - Block Diagram Analysis
  - Layout block diagram of feedback system
  - Battery life analysis
    - Average power use analysis
    - Maximum battery life in sleep mode, active, and worst case
  - Voltage and Current Analysis
    - Part compatibility analysis
    - Motor drive analysis

After:
- Mechanical Analysis:
  - Moving part interference analysis
    - Physical test of interfering structures
  - Back drive prevention analysis
    - Apply simulated wind

- Control System Analysis:
  - Battery life analysis
    - Disconnect solar panel from system to see how long battery lasts
    - Analyze ability of system to charge battery faster than draining it by recording battery voltage output before and after running system
5.2 Engineering analysis results

5.2.1 Motivation. Describe why/how the before analysis is the most important thing to study at this time. How does it facilitate carrying the project forward?

**Motivation**

From a mechanical engineering standpoint, the two facets of our prototype that demand the most attention are moving part interference analysis and motor ratio analysis. The solar tracker contains many components moving in two degrees of freedom. The motion must be unrestricted or the solar panel will be unable to see all sections of the sky. Unexpected collision of moving parts could also bring about damage or failure of components. Our prototype has two motors, one for rotating the panel and another for changing its elevation. Both must have enough torque to reliably perform these tasks. The result of this selection has come down to the choice of fixed-ratio gearbox offered with the motor chosen.

5.2.2 Summary statement of analysis done. Summarize, with some type of readable graphic, the engineering analysis done and the relevant engineering equations

**Summary Statement of Analysis Done**

Motor ratio analysis demanded a small amount of math in order to plan. We began under the assumption that we were working with a motor at 6V, and that the required rotational speed was negligibly small. To perform our analysis we modeled the weight of the solar panel (not including counterweight) as a mass M with a weight Mg, at the end of a beam of length d. Using the torque found, we searched for a motor that provided this torque in a convenient and affordable package.

The following equations were used to model our torque requirements:

\[ \tau = \frac{VI}{\omega} \]
Torque generated by an electric motor at operating voltage V, drawing current I, running at rotational speed \( \omega \).

\[ \tau = \frac{Mg}{d} \]
Torque required to rotate a point mass M at the end of a beam of length d.
5.2.3 Methodology. How, exactly, did you get the analysis done? Was any experimentation required? Did you have to build any type of test rig? Was computation used?

Methodology
Proper interference modeling began at the design stage. When we drew out the designs on paper and then moved them into CAD, every part and sub-assembly we put together was dimensioned to ensure compatibility. The initial expectation was that the beam holding the panel would not need to make a complete rotation; instead we designed it so it would only need to elevate a modest 75 degrees above horizontal. That was initially thought to be enough, and would keep the assembly compact and parts small and cheap.

For the motor ratio analysis, we computed the necessary motor torques using the above equations. We modeled the load that the system would have to lift, Mg, as the weight of the solar panel at the end of a cantilever beam of length, d, which we measured at the distance from the axis of rotation to where the panel was mounted on the arm.

5.2.4 Results. What are the results of your analysis study? Do the results make sense?

Results of Analysis

Interference
When assembling the prototype, we only experienced one problem that could not have been foreseen from the planning requirements. We did not adequately allocate space in some parts for fasteners. We had one other interference issue, but that was not a failure to meet previous requirements. We decided later that we should in fact aim to have the beam rotate a full rotation, instead of stopping at 75 degrees above horizontal. We measured the clearance that existed and calculated the new clearance that would be required.

Motor Torque
When we solved the problem of interferences, both of the motors were still struggling to move the panel as designed. At first we thought this only to be an error in our torque calculations, but it turned out to be from a combination of problems. While those problems were chiefly electrical in nature, we also found out that a miscommunication lead to calculations for our motors running at 6V, an improper assumption. Even at 6V, the elevation motor showed an unacceptable amount of backlash. We found that at the actual operating voltage, 5V, the motors did not provide enough torque.
Panel View Angle

We initially anticipated to have to analyse seasonal patterns of the sun’s angle, if we were to implement solar tracking without sensor input. Since we used pairs of active sensors, we track the sun absolutely, regardless of season. Therefore we developed past the need for this analysis criterion and is no longer necessary.

Wind and Weather Durability

We performed cursory mathematical tests to test the response of the system to wind loading. Other than possible loss of petals and leaves, at the scale we are working at we anticipate no adverse effects due to wind loading, even in high winds (~40mph).

Temperature Analysis

We specified an operating temperature range of -10 to 100 degrees Fahrenheit. We enforced this operating capability by selecting electronics and materials that performed adequately in such conditions. We were unable to test the full range, but we did perform testing from 20 to 70 degrees Fahrenheit and the Sunflower performed flawlessly.
Control System Block Diagram Analysis

![Control System Block Diagram]

Power Analysis

**Arduino** - 15mA when active, 5mA when in sleep mode. Assume 10% of daytime (assume ~10 hrs) is duty cycle. Power usage is 15 mA * 1 hr + 5 mA * 23 hr = 360 mAh/day.

**Motors** - Assume stall current of 500 mA for 1 hr, 5% of stall current on average during 23 hr downtime. Power usage is 500 mA * 1hr + 25 mA * 23 hr = 1075 mAh/day.

**Motor controller** - Quiescent current max = 32 mA. Assume only when in use during 1 hr/day duty cycle. Min is 7mA, assume 23 hr. 32 mA * 1hr + 7 mA * 23 hr = 193 mAh/day.

**Battery charger** - Quiescent current is 55uA. Assume 24h use, 55uA * 24 = 0.77 mAh/day.

**Total energy** = 360 + 1075 + 193 + 0.77 mAh/day = 1628.77 mAh/day.

Choose: 2000 mAh Lithium Ion 3.7 V one-cell battery

**Maximum Battery Life, Standby**

Total current, 12 mA. Runs for 165 hours at standby.

**Maximum Battery Life, Active Usage/Expected Case:**

Average current, 70 mA. Runs for 30 hours at expected current without charging.

**Maximum Battery Life, Worst Case Usage:**

Total current, 1100 mA. Runs for 2 hours at full stall current.

5.2.5 Significance. How will the results influence the final prototype? What dimensions and material choices will be affected? This should be shown with some type of revised embodiment drawing. Ideally, you would show a “before/after” analysis pair of embodiment drawings.

**Significance**

Changed requirements led to some changed parts, to resolve both interference and motor problems. There were a couple reasons behind each change, mostly were communication problems.
not engineering analysis problems. The issue we had making clearance for fasteners could be solved by small modifications to existing parts. No new parts needed to be made but the CAD files for the modified parts have since been updated for consistency. Also to allow the beam to make a full rotation, we took the clearance values that we calculated and we fabricated new parts that allowed these clearances. The designs have been updated to accommodate these new parts as well, as can be seen in the following figure.

To solve the motor torque problems, we had to purchase new motors that would give us enough torque. The choice of these motors reflected our new insight into the electrical and mechanical conditions of our prototype. Confident in our choice, we built the new parts that were required to mount these new motors and have them power the elevation of the beam and rotation of the assembly.

5.2.6 Summary of code and standards and their influence. Similarly, summarize the relevant codes and standards identified and how they influence revision of the design.

**Codes and Standards**

In the design and construction of this prototype, we did not encounter design decisions that would warrant the need for attention to a particular set of standards or codes.
6 Working prototype

6.1 A preliminary demonstration of the working prototype (this section may be left blank).

6.1.1 Initial Prototype
Earliest motor/movement testing, no sensors implemented, repetitive test code only:

https://www.youtube.com/watch?v=JByRkfSPUHk

Early sensor tracking testing:

https://www.youtube.com/watch?v=hkyKDW0CW8w
6.2 A final demonstration of the working prototype (this section may be left blank).
6.3 At least two digital photographs showing the prototype
6.4 A short videoclip that shows the final prototype performing
6.5 At least four (4) additional digital photographs and their explanations

The assembled system under initial real world testing.
Front and rear facing photocells visible.
The undecorated system with mechanics on display.
The electronics components (brains) on display.
7 Design documentation

7.1 Final Drawings and Documentation

7.1.1 A set of engineering drawings that includes all CAD model files and all drawings derived from CAD models. See Appendix C for the CAD models.
Tapped Setscrew Hole - Drill 0.089 Tap 4-40, offset the tap hole 45 degrees from the throughholes in the body.

Motor Adapter Shaft
7.1.2 Sourcing instructions
All of our parts were sourced either from McMaster or Sparkfun as indicated in our bill of materials. Stock materials were obtained from the machine shop stockpile.

7.2 Final Presentation

7.1.3 A live presentation in front of the entire class and the instructors (this section may be left blank)
7.1.4 A link to a video clip version of 1
7.3 Teardown

TEARDOWN TASKS AGREEMENT

PROJECT: Solar Tracker 2
(Team Sunflower)

INSTRUCTOR: Prof. Beverly

NAMES:
Lindsey Walker
Laura Scott
Ethan Glassman
Max Kaczmarski

The following teardown/cleanup tasks will be performed:

- We are keeping the hardware
- No disassembly needed
- No parts list left

- We worked outside of 411 areas
- No further cleanup required
Instructor comments on completion of teardown/cleanup tasks:

Instructor signature: [Signature]  Print instructor name: [Name]
Date: 12/8/14

(Group members should initial near their name above.)
8 Discussion

8.1 Using the final prototype produced to obtain values for metrics, evaluate the quantified needs equations for the design. How well were the needs met? Discuss the result.

On the initial design, we grossly underestimated the cost of the system. We stated that the counterbalanced design would cost just $100, but our costs ended up about $300. Otherwise, our final prototype met or exceeded the best expected values for each metric. Overall, we feel that the design turned out well.

8.2 Discuss any significant parts sourcing issues? Did it make sense to scrounge parts? Did any vendor have an unreasonably long part delivery time? What would be your recommendations for future projects?

We did not have any sourcing issues. It did not make sense for us to scrounge parts like our motors because of our specific electronic configuration. Or parts were ordered from McMaster and Sparkfun. Both vendors got us the correct parts in a within a week of ordering. We did scrounge a lot of our machined materials because they were mostly small pieces that can be found in the stock of the machine shop on campus. Our recommendation for future projects would be to order extra parts for the electronic components in case something is damaged and there is not enough time to order more. For instance, an extra Arduino could be ordered for the class if someone's is defective or gets shorted.

8.3 Discuss the overall experience:

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

Mechanically we found the project to be more difficult than we originally thought with lots of small moving pieces and the compactness of the design. The electronics were...
more straightforward to work with than we thought they would be. The Arduino was extremely easy to work with.

8.3.2 Does your final project result align with the project description?
Yes, our final project aligns with the project description. Our prototype is able to track the sun and automatically deal with the sunrise and seasonal angle adjustment. The only part that we changed slight was that our weather proofing was not extremely robust.

8.3.3 Did your team function well as a group?
Our team worked almost perfectly together. We worked well ahead of time to avoid last minute stress and all used our different strengths to complement each other. We had a lot of fun.

8.3.4 Were your team member’s skills complementary?
Yes. Each of us is strong in a different area whether it be machining, electronics, coding, or organization. We chose our group to be diverse so that we were not lacking in any essential skill.

8.3.5 Did your team share the workload equally?
We tried to share the workload equally as best as possible, but sometimes projects were better suited to only have one person working at a time. Some of those projects took longer than others depending on the complexity.

8.3.6 Was any needed skill missing from the group?
We were not missing any skills because we planned to be a group based on our diverse skill set.

8.3.7 Did you have to consult with your customer during the process, or did you work to the original design brief?
Mostly we worked to the original design brief because it was a straight forward project and Professor Bever gave us clear design goals to reach.

8.3.8 Did the design brief (as provided by the customer) seem to change during the process?
No, the design brief stayed consistent throughout the process.

8.3.9 Has the project enhanced your design skills?
Yes. We are now more confident integrating electronic and mechanical systems as well as building compact mechanical systems.

8.3.10 Would you now feel more comfortable accepting a design project assignment at a job?
Yes. We are now more able to clearly record and articulate the work that we have done.
8.3.11 Are there projects that you would attempt now that you would not attempt before?
Yes. We feel more comfortable approaching mechatronics projects after integrating these systems successfully.

9 Appendix A - Parts List

<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART NAME</th>
<th>Material</th>
<th>QTY.</th>
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<td>Stand</td>
<td>PVC</td>
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<tr>
<td>2</td>
<td>Adafruit 417 Panel</td>
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<tr>
<td>3</td>
<td>Small Pulley</td>
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<tr>
<td>5</td>
<td>Driven Pulley 9466T63</td>
<td>Delrin</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Lazy Susan 6031K160</td>
<td>Stainless Steel</td>
<td>1</td>
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<td>7</td>
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<td>Aluminum 6061</td>
<td>1</td>
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<tr>
<td>8</td>
<td>Pipe Flange</td>
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<tr>
<td>12</td>
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<td>Aluminum 6061</td>
<td>1</td>
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<tr>
<td>13</td>
<td>Elev. Sleeve Bearing 6389K231</td>
<td>Nylon</td>
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<tr>
<td>16</td>
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<td>Counterweight</td>
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### 10 Appendix B - Bill of Materials

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**Total Price** $267.62

11 Appendix C - CAD Models

Please refer to the file archive “Total Assembly.zip” on the File Exchange for full access to CAD models

Page 70 of 77
and assemblies. The archive contains a SolidWorks Pack-and-Go assembly and is ready to extract and then open in a SolidWorks client.

Appendix D - Code

https://github.com/efinkg/TeamSunflower/blob/master/FirstPrototypeCode_WhileLoops/FirstPrototypeCode_WhileLoops.ino

```c
#include <avr/interrupt.h>
#include <avr/power.h>
#include <avr/sleep.h>

//Motor A is rot
//Motor B is elev

//PWM Pins
const int pwn_rot = 3; //PWM control for motor outputs 1 and 2 is on digital pin 3
const int pwn_elev = 11; //PWM control for motor outputs 3 and 4 is on digital pin 11
const int dir_rot = 12; //direction control for motor outputs 1 and 2 is on digital pin 12
const int dir_elev = 13; //direction control for motor outputs 3 and 4 is on digital pin 13

//Sensor Pins
const int east_sensor_pin = A3; //analog pin 0
const int west_sensor_pin = A4; //analog pin 1
const int top_sensor_pin = A2; //analog pin 2
const int down_sensor_pin = A1; //analog pin 3
const int back_sensor_pin = A0; //analog pin 4

//Battery Input Directly to show if we're charging or not
const int battery_pin = A5; //Battery input

//End Stop Pins
const int westbutton_pin = 6; // The number of the east endstop pin
const int eastbutton_pin = 7; // The number of the west endstop pin
const int toptopbutton_pin = 5; // The number of the top endstop pin
const int bottombutton_pin = 4; // The number of the bottom endstop pin

//Instatiate sensor values
int west_sensor_value = analogRead(west_sensor_pin);
int east_sensor_value = analogRead(east_sensor_pin);
int top_sensor_value = analogRead(top_sensor_pin);
int down_sensor_value = analogRead(down_sensor_pin);
```
int back_sensor_value = analogRead(back_sensor_pin);
int battery_sensor_value = analogRead(battery_pin);

int difference_threshold = 5;
int is_bright = 40;

//Initialize states
int eastbutton_state = 0;         //east button initialization
int westbutton_state = 0;         //west button initialization
int topbutton_state = 0; //top button initialization
int bottombutton_state = 0;        //bottom button initialization
int val = 0;     //value for fade

void setup()
{
  Serial.begin(9600);
  pinMode(pwn_rot, OUTPUT);  //Set control pins to be outputs
  pinMode(dir_rot, OUTPUT);
  pinMode(pwn_elev, OUTPUT);  //Set control pins to be outputs
  pinMode(dir_elev, OUTPUT);
  pinMode(eastbutton_pin, INPUT);
  pinMode(westbutton_pin, INPUT);
  pinMode(topbutton_pin, INPUT);
  pinMode(bottombutton_pin, INPUT);
}

void loop()
{
  go_west();
  go_up();
  
  update_sensors();
  float voltage = battery_sensor_value*(5.0/1023.0);

  numCycles = 0;
  while(numCycles<5){

    if((back_sensor_value-average_value())>difference_threshold && eastbutton_state==LOW){
      while(east_sensor_value<is_bright && eastbutton_state==LOW){
        update_sensors();
        Serial.println(east_sensor_value);
      }
    }
  }
}
rotate_east();
}
Serial.println("Go east to catch the sunrise.");
}

while((east_sensor_value-west_sensor_value)>difference_threshold && eastbutton_state==LOW){
  update_sensors();
  rotate_east();
  Serial.println("Go east.");
}

while((west_sensor_value-east_sensor_value)>difference_threshold && westbutton_state==LOW){
  update_sensors();
  rotate_west();
  Serial.println("Go west.");
}

while((top_sensor_value-down_sensor_value)>difference_threshold && topbutton_state==LOW){
  update_sensors();
  elev_up();
  Serial.println("Elevate up");
}
while((down_sensor_value-top_sensor_value)>difference_threshold && bottombutton_state==LOW){
  update_sensors();
  elev_down();
  Serial.println("Elevate Down");
}
numCycles++;
}

numCycles = 0;

stopped();  // stop for 2 seconds
sleepNow();
}

void update_sensors(){
  //Look at all photosensors
  west_sensor_value = analogRead(west_sensor_pin);
  east_sensor_value = analogRead(east_sensor_pin);
  top_sensor_value = analogRead(top_sensor_pin);
  down_sensor_value = analogRead(down_sensor_pin);
back_sensor_value = analogRead(back_sensor_pin);

average_value();

//Check the battery voltage
battery_sensor_value = analogRead(battery_pin);

//Look at endstops
westbutton_state = digitalRead(westbutton_pin);
eastbutton_state = digitalRead(eastbutton_pin);
topbutton_state = digitalRead(topbutton_pin);
bottombutton_state = digitalRead(bottombutton_pin);
}

void sleepNow()
{
  // Choose our preferred sleep mode:
  set_sleep_mode(SLEEP_MODE_IDLE);  //Save...MOST OF THE POWER

  // Set sleep enable (SE) bit:
  sleep_enable();

  // Put the device to sleep:
  sleep_mode();

  Serial.println("Goodnight Team Sunflower :) ");

delay(10000);

  Serial.println("HI GUYS!");

  // Upon waking up, sketch continues from this point.
  sleep_disable();
}

int average_value(){
  int averagevalue =
  (west_sensor_value+east_sensor_value+top_sensor_value+down_sensor_value)/4;
  //Serial.println(averagevalue);
  return averagevalue;
}
void go_east() // no pwm defined
{
    digitalWrite(dir_rot, LOW);  //Reverse motor direction, 1 high, 2 low
}

void go_up() // no pwm defined
{
    digitalWrite(dir_elev, HIGH);  //Reverse motor direction, 3 low, 4 high
}

void go_west() // no pwm defined
{
    digitalWrite(dir_rot, HIGH);  //Set motor direction, 1 low, 2 high
}

void go_down() // no pwm defined
{
    digitalWrite(dir_elev, LOW);  //Set motor direction, 1 low, 2 high
}

void rotate_west() // full speed go_westward
{
    digitalWrite(dir_rot, LOW);  //Reverse motor direction, 1 high, 2 low
    analogWrite(pwn_rot, 200);    //set both motors to run at (100/255 = 39)% duty cycle
}

void rotate_east() //full speed backward
{
    digitalWrite(dir_rot, HIGH);  //Set motor direction, 1 low, 2 high
    analogWrite(pwn_rot, 200);    //set both motors to run at 100% duty cycle (fast)
}
void elev_up() //full speed go_westward
{
    digitalWrite(dir_elev, HIGH);  //Reverse motor direction, 3 low, 4 high
    analogWrite(pwn_elev, 200);
}

void elev_down() //full speed backward
{
    digitalWrite(dir_elev, LOW);  //Set motor direction, 3 high, 4 low
    analogWrite(pwn_elev, 200);
}
void stopped() //stop
{
    digitalWrite(dir_rot, LOW); //Set motor direction, 1 low, 2 high
    digitalWrite(dir_elev, LOW); //Set motor direction, 3 high, 4 low
    analogWrite(pwn_rot, 0);    //set both motors to run at 100% duty cycle (fast)
    analogWrite(pwn_elev, 0);
}

void stop_rot()  //stop motor A
{
    analogWrite(pwn_rot, 0);
}

void stop_elev()  //stop motor B
{
    analogWrite(pwn_elev, 0);
}

12 Annotated Bibliography (limited to 150 words per entry)

"Do I Need to Prepare Solar Panels for a Storm?" Renewable Energy Corporation


"How to Create a Solar Panel That Tracks the Sun." PC Control Learning Zone. N.p., n.d. Web. 31 Aug. 2014. This source gave us the idea for the arrangement of the photo sensors on our design. This site also gives an example of code that can be used to control motion of the panel based on analog inputs.

Energy Informative. N.p., n.d. Web. 31 Aug. 2014. This web post discusses weather considerations that go into the design of certain solar panels and addresses concerns that owners might have about potential weather damage.

