Introduction to Engineering Design with Professional Development 1

Final Report for
SunCatcher – Solar Umbrella

Team: SunCatcher
Section 9
Instructors: Joshua L. Hurst
Tracy N. Schierenbeck
Version 2.3.e
May 8, 2013

Prepared by
Matthew Causa (2014, Industrial & Management Engineering)
Morgan Kube (2015, Environmental Engineering)
Zachary Luzinas (2014, Electrical Engineering)
John Malcovitch (2014, Mechanical Engineering)
Kerry White (2015, Industrial & Management Engineering)

Executive Summary

Over the course of the last ten weeks team SunCatcher designed and constructed the SunCatcher umbrella, a dual-use system designed to charge most USB powered devices using solar energy. The SunCatcher umbrella was designed around the idea that the user will need to charge a phone or other USB powered device while outdoors.

The design of the system was broken down into five different subsystems: the shaft and battery compartment; the mechanical design of the canopy; the canopy and solar panels; the power regulation, and the USB charging system. The solar panels are mounted on the canopy of the umbrella and the solar panels feed into the shaft of the umbrella where the circuits are. The power regulation circuit can take in any amount of power the solar panels can produce and regulate it down to charge an array of six batteries in less than four hours. This system feeds into the USB system which can take in the power from the solar panels or the batteries and regulate that power down to the recommended amount to charge an USB powered device.

The mechanical systems of the shaft were designed using fiberglass rod and were constructed to be less than five pounds and withstand winds of up to 15 miles per hour. The mechanical design of the canopy was designed so that the rods of the canopy could extend to seven feet and support the panels and canvas, while weighing less than ten pounds. The canopy needed to include the solar panels for the electrical systems and be water resistant and.

The following report places an emphasis on the design process for this final product. Everything from the project selection to the design of the project is discussed. Each decision made is supported through the use of various modeling techniques. The project was selected through the use of decision matrices while the mechanical systems were modeled in SolidWorks CAD. The electrical systems were modeled in both ORCAD PSpice and the online software CircuitLab.

The final product can be considered successful as it meets the intended requirements. The system can fully charge the chosen reference USB device to 100% in just over 2.5 hours, well under the 4 hour target. Additionally, the charging system can fully charge batteries in under three hours, less than the four hour target. Finally, the estimated production cost calculated for a mid-volume run of 10,000 units is $118, under the $150 production estimate set forth as an initial goal.

Table of Contents

1 Introduction

By: Matthew Causa

Solar technology isn't new. Its history spans from the 7th Century B.C. to today. We started out concentrating the sun's heat with glass and mirrors to light fires. Today, we have everything from solar-powered buildings to solar-powered vehicles. It seems as if inventors and innovators are constantly trying to integrate solar technologies into existing products in order to stray away from using inefficient energy that increase society's environmental footprint. One example of this is the integration of solar technology into an umbrella, or more specifically, a parasol. But why would anyone one ever want to create energy while they are trying to block out the sun?

The answer lies within the advances in modern technology; staying connected by using a phone, tablet, or computer is essential. Often, powering these devices is not difficult; just plug into the power socket in a car or into the nearest electrical outlet. There are times, however, when people choose to push beyond the limits of modern infrastructure and available power. A solar powered umbrella would allow a beach goer, camper, or hiker to stay connected by harnessing energy from the sun and transmitting it into their device.

Many of the existing products that integrate solar technology are expensive and in turn bypass a large demographic of the market. The goal of the SunCatcher is to design a solar powered umbrella that is affordable and marketable to a large number of consumers.

2 Project Objectives & Scope

Prepared by: All

Project Scope

In the 10-week allotted time, Team SunCatcher has worked to design, build and test a prototype of a solar powered umbrella. Given the project duration, certain materials and design considerations may be implemented because of limited time and resources. These modifications will be identified and justified throughout all levels of documentation.

For example, several parts of the design will be 3D printed in ABS Plastic. 3D Printing is a great way to prototype and test parts, but in order to ramp up production, a plastic injection mold would be lower manufacturing costs immensely.

A fully marketable product would require additional testing in diverse regions and environments, and would likely also require additional safety certifications from established testing laboratories. This level of testing and certification will not be executed during this project.

Additionally, full durability testing and product life-cycle analysis will not be attempted, due to the infeasibility of achieving required number of usage cycles or operational hours.

2.1 Mission Statement

Objective: To enable users to access remote power by utilizing a dual-purpose device they would otherwise use outdoors.

Table 2.1 – Mission statement

Product Description	**A solar powered umbrella that will allow the user to charge electronic devices and provide lighting at an affordable price point.**
Benefits	Allow the user to stay powered while enjoying outdoor locations without easy access to electricity.
Goals:	• Introduce a successful prototype by April 26th. • Support the design process with research and testing • Make product easy to use and affordable.
Primary Markets:	• Middle-class Beachgoers • Home Pool Owners • Cottage or lakefront owners
Secondary Markets:	• Resorts/Hotels
Assumptions:	• Rechargeable battery energy storage. • Transitional from beach to home use. • Easily transported.
Stakeholders:	• IED Project Group • MANE Department Faculty • RPI School of Engineering

2.2 Customer Requirements

Survey Results

A survey consisting of 7 questions was distributed in person and on social media hubs, receiving 166 responses. From the survey results, the group found that a large portion of consumers frequently have issues with device power: nearly 60% of respondents reported that they often or always run low on battery power when they are on the go. Additionally, many consumers enjoy using their phones or tablets and listening to music near the water. However, this may also reflect the younger population who responded to social media surveys. The project group also found that noise pollution was a valid concern for beachgoers, and that maximum volume output levels should be considered for any music system.

While a large number of respondents indicated they do not carry an umbrella to the beach, several of those non-umbrella users commented that they were excited about the concept and would use the product. This supports the development group's theory that a beach umbrella offering more utility than just shade might be successful.

Finally, the target customers for the solar umbrella are middle-class consumers who frequent beaches, pools, or lake fronts. Additionally, homeowners with pools or cottage owners are prime target customers. These last two market segments are likely underrepresented in survey results, which are skewed toward a younger age group (and thus less homeowners) by a large volume of social-network referrals.

In addition to the multiple choice responses, a comment section was included on the survey. Many respondents filled in valuable input in this section, and some of these comments were used to generate customer needs found in Table below. The corresponding target values were determined through research by members of the project group. Key metrics to the project's success, as judged by survey comments, are highlighted.

Some of the comments received from the survey included;

- "Would have to have power and be water proof, while standing up to sand and dirt."
- "Umbrella should have string-lights for nighttime usage"
- "I think buying reserve battery for my phone would cost less than the umbrella that can play music."

Based on these results there were changes made to the design of the prototype such as; night-time lighting, a tray to rest the electronic device you are charging, and waterproofing of the system.

2.3 Technical Specifications

Based on the customer requirements and breakdown of the subsystem a table of specifications was created. These specifications have been decided based on the customer feedback we received.

Table 2.3: Customer Requirements and Technical Specifications

Customer Requirement	Technical Specification	Target Value / Range
Sufficient Energy Storage	mAh	≥2400 mAh
Quick device charging	Max Output Current	≥ 500 mA
Doesn't hurt users	Safety	0 casualties
Lightweight	Pounds	< 20 lbs
Large shade area	Area	≥6 ft diameter
Inexpensive	Estimated Production Cost ($)	< $150
Sufficient lighting (night use)	Lumens	≥300 lumens
Water resistant wiring	Time withstood rain	10 minutes
Won't tip over in wind	Wind speed withstood	15 mph
Not too loud for others	Maximum sound level (dB)	~70dB

Then once these specifications were established more specific specifications for each subsystem were established. The complete list of subsystem specified technical specifications is reproduced in appendix B.

The last specification in red, regarding an audio system, was investigated for implementation, but eventually dropped by the design team due to mixed customer reactions and questionable added value to the system.

3 Assessment of Relevant Existing Technologies

By: Matthew Causa

3.1 Overview

The task of harnessing solar energy while simultaneously blocking solar radiation has been attempted by many inventors and innovators. With improvements in photovoltaic technology, gathering energy from the sun has become more efficient and less expensive.

The project team has researched US patents and other similar marketed products to their project proposal. All of the benchmarks examined have the same underlining objectives: absorb solar energy, store the energy in a rechargeable battery, and use that energy to power various devices. A sample of these patents and devices are included below.

3.2 Patents and Prior Arts

Table 3.2.1 provides an overview of relevant patents for relevant technologies. The table is followed by a more detailed synopsis for each patent.

Table 3.2.1 – Patent Research for Relevant Technologies

Competitive Product	Title / Description	Relation to this project
"Powerbrella"	Solar powered umbrella that charged a range of devices	Used to benchmark aesthetics. The company went out of business due to high product price point.
"Brookstone 9' Powered Patio & Beach Umbrella with USB Ports	Luxury umbrella designed primarily for home use.	Used to benchmark to avoid a high cost design. The company went out of business

"Solar Powered Umbrella"

On October 17th 2006, Arian Reyes and Luis Jermaine Wimbush filed US patent 2007/0283987 for the "Solar Powered Umbrella" [1]. This device aimed to block solar radiation and provide power to a range of devices (Reyes, 2007). Examples of attached devices include electric grills, electric ice coolers, radios, televisions, DVD players, portable video game consoles, fans, and possibly heater or air-conditioning units. The inventors designed the umbrella to fit onto a patio table with a stand, or be placed into the sand on the beach. Their design also include a power manager, which would be a solid state device equipped with a wattage/voltage meter. This power meter would allow the user to alternate voltages present at an outlet. Additionally, the solar cells for the invention would be located in a strip near the top of the canopy, as seen in Figure 3.2.1 below.

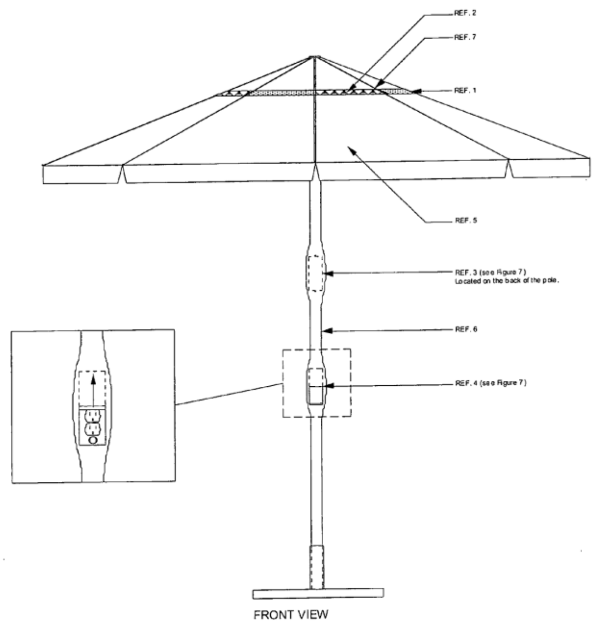


Figure 3.2.1 – Front View of "Solar Powered

Benchmarking research did not reveal any implementations, products for sale, or prototypes created by the listed inventors or the Assignee "Enlightened Innovations". The project team finds that the system design in the patent is likely not feasible, due to the high voltage output required to power heating or cooling systems, combined with the minimal surface area of PV cells on the canopy. The project team did not find any patent issued by the United States Patent and Trademark Office under the application's title or inventor names.

"Outdoor Shading Device with Renewable Power System"

On December 23rd, 2008, Wanda Ying Li filed their patent for an "Outdoor Shading Device with Renewable Power System" [2]. The system, seen in figure 3.2 below, was designed to provide outdoor shading combined with a renewable power system (solar) that included lighting, speakers, and electrical power sources. The system can be automatically adjusted toward the sun for maximum solar collection, and the entire canopy is comprised of tiny solar cell arrays. The Patent was granted in 2012 (US number 8,104,492 B2), but the complexity of the automatic alignment mechanism and full-canopy solar array would likely make this device cost prohibitive for the average consumer (Wu Wei, 2008).

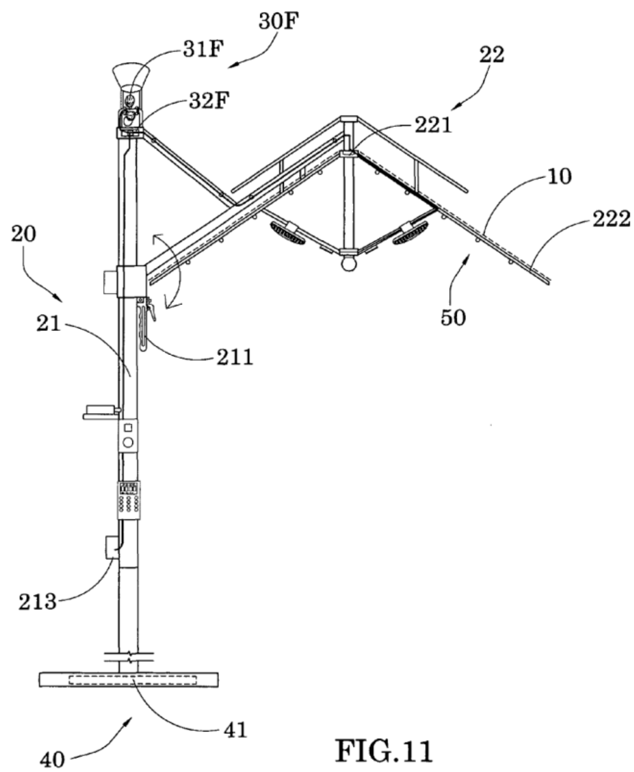


Figure 3.2.2 – Profile View of "Outdoor Shading Device with Renewable Power System" Patent

Table 3.2.2 provides an overview of competitive benchmarks. The table is followed by a more detailed synopsis for each product.

Table 3.2.2 – Competitive Benchmarking

Patent Number	Title / Description	Relation to this project
2007/0283987	"Solar Powered Umbrella"	Used to benchmark solar panel placement and integration considerations
2012/8104492B2	"Outdoor Shading Device with Renewable Power System"	Used to benchmark a dynamic solar panel system that would adjust to obtain the maximum amount of sunlight

Powerbrella

In 2008, Konarka Technologies and SKYShades entered into a joint venture and introduced the "Powerbrella" (Quick, 2009) . The solar powered umbrella was designed to provide the user shade whether they are on sand or grass while providing power via USB port or 12V ouput. The PowerBrella, seen below in figure 3.3, also featured charging capabilities without the need for solar energy, allowing the Powerbrella's rechargable batteries to be pre-charged via a home or car power socket.

Figure 3.2.3 – Promotional Image of the "PowerBrella"

The PowerBrella was introduced to a substantial press fanfare[3], but without specific details on release date or cost. Limited numbers of PowerBrella were produced, and the product never achieved market success, with units ranging from $4000 to $10000[4]. The product was also aimed at hotels and resorts, without effort to reduce the price point to market directly to consumers. Additionally, the "Power Plastic" panels at the core of the product were criticized for their short life spans and low efficiency (3%-4%, vs. 15-20% on a standard PV cell)[5]. Konarka, the producer of the panels, filed for bankruptcy in 2012, and several US SkyShades subsidiaries are also undergoing U.S. bankruptcy procedures [6].

Brookstone '9' Solar Powered Patio & Beach Umbrella with USB Ports'

The product most closely related to the project proposed by the team is available from Brookstone retailers for $399 (Brookstone, 2012). The Brookstone model, seen below in figure 3.2.4, provides similar USB charging capability, although total charge capacity and other details are not available. However, at $399, this device may be seen as a 'luxury' item priced out of reach for most consumers. The project team believes there exists a significant market opportunity for a low-cost competitor with additional features.

Figure 3.2.4 – Brookstone Solar Patio and Beach Umbrella

4 Professional and Societal Considerations

In today's fast-paced technology driven world, people like to stay connected and never miss a thing. However, using a phone or tablet so much drains the battery life very quickly. Sometimes, people are in a remote place where an outlet is not available to charge with. The SunCatcher allows people to charge their phone or tablet and stay linked in to the outside world while also enjoying the outdoors. In this way people can access power in a remote place where usually they could not.

The "SunCatcher" has many possible uses should it actually be brought to market. The umbrella could be sold to individual users for beach use or patio use. It could also be marketed to resorts or hotels to be used in mass. Another possibility is to private beaches who could rent the umbrellas to the average beach goer.

Not only is the umbrella useful, it is environmentally friendly. The beach umbrella uses solar panels to capture the energy of the sun to function, instead of using grid electricity generated by conventional, often dirtier, power sources. This lessens the impact on the environment that would usually occur when charging a phone. The batteries used in the shaft of the umbrella are rechargeable. These batteries are also selected to be NiMH, a battery chemistry that creates far less toxic production byproducts or recycling hazards compared to NiCAD batteries. The umbrella is eco-friendly and does not harmfully impact the environment from its use.

Safety precautions were taken to ensure the umbrella will not harm the user. All electrical wires were waterproofed with shrink wrap and electrical tape. The internal circuits also have multiple safety precautions built in, and redundant fail-safes. Finally, the mechanical properties have been calculated and designed to offer a large safety factor in a variety of operational conditions.

5 System Concept Development and Selection

By: John Malcovitch

The team decided on a sustainable energy project that would have specific appeal to those looking to be active outdoors. A comprehensive review of the concept development process, including several decision matrices and three compelling project candidates, is included in Appendix A of this report.

Once the 'Solar Powered Umbrella' Concept was selected by the team, many system target specifications were decided by customer requirements and the technical specifications needed to meet those requirements. Two major requirements were that the system could fully charge a smartphone with a large battery capacity, and that it could do so quickly. A third main objective was to create a system which could be scaled for volume manufacturing in order to offer the product at a mass-market price. Thus, cost-efficiency was always a concern for production models, but the actual cost metric of the prototype would not figure into the criteria for design success. Instead, the final estimated production cost was carefully researched and calculated, and the results of that exercise can be found in appendix D.

Due to the highly integrated nature of this project, many other design choices were made at the subsystem level or within working groups composed of 2-3 subsystems. Thus, the bulk of the engineering design process will be demonstrated in the Subsystem Analysis and Design section to follow.

6 Subsystem Analysis and Design

By: Matthew Causa

The umbrella will be broken up into five subsystems, with each group member in charge of a specific subsystem. The first two subsystems involve the canopy of the umbrella: Matt will be in charge of the mechanical design of the umbrella and the folding mechanism. Kerry will be in charge of the material selection and construction of the canopy. She will also be responsible for the solar panel selection, configuration, and attachment. The third subsystem, assigned to Morgan, involves the design and construction of the shaft, umbrella bases, and the battery compartment. Zach will be in responsible for the power control circuit and system wiring. John will be in charge of the USB circuit and lighting features. He will also provide CAD and LabJack support for various subsystems.

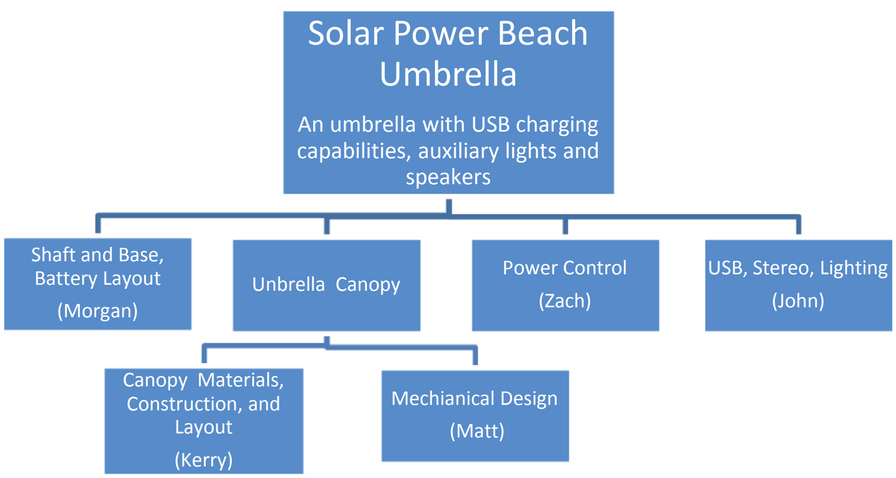


Figure 6.1 – Hierarchical Subsystem Diagram

Although the umbrella is broken down into these five subsystems, the nature of the design is fully integrated in the sense that many specifications, measurements and requirements of one subsystem affect the design considerations for one or more other subsystems. Table 6.1 illustrates subsystems that will need to integrate and work together to accomplish our overall customer requirements

Table 6.1 – Integration Considerations

How will we Integrate…	Subsystem Affected: John (USB/Aux)	Morgan (Shaft)	Matt (Canopy - Mech. Design)	Kerry (Canopy Fabric and Panels)	Zach (Control Circuit)
Shaft/ Hub Connection		x	x		
Wire Placement	x	x		x	x
Canopy attachment			x	x	
Battery compartment		x			x
USB connection	x	x			x
USB, lighting power	x				x
Lighting, speaker placement	x		x	x	
Panel attachment				x	x

A full list of interface specification is included in Appendix B. Figure 6.2 displays a functional diagram of the system, along with associated with each subsystem.

Figure 6.2 – System Functional Diagram

6.1 Subsystem 1- Shaft and Battery Compartment

Prepared by: Morgan Kube

The first design choice with the support subsystem was which material to use for the shaft construction. This application would require a material that would be strong and stiff enough to hold the weight of the canopy, yet still have room to enclose several circuits and wires. The ideal material would be low weight, low cost, high strong tensile and compressive strengths, and be resistant to corrosion and thermal softening. Additionally, the primary electrical safety safeguards were to be handled by other subsystems, but choosing a non-conductive material would add additional safety factor, since any local shorts could not be transmitted to other connection points in the shaft

An initial survey of readily available hollow tubing materials yielded three candidate materials; Fiberglass, PVC, and Aluminum. After creating a selection matrix reproduced below in Table 6.1A, the Fiber-glass hollow rods would be the best fit for the project. The specific material composition, GPO3, was very stiff, strong, and lightweight, but was also available in several wall thicknesses that would allow the shaft to be designed for an optimal strength to Inner Diameter ratio.

Table 6.1A – Material Selection Matrix

Selection Criteria	*Fiber-glass*	*PVC*	*Aluminum*
Cost (1”-2” range)	***-1***	***1***	***-1***
Tensile Strength	***0***	***-1***	***1***
Compressive Strength	***1***	***0***	***1***
Stiffness (Young’s Modulus)	***0***	***-1***	***1***
Weight (density)	***1***	***1***	***-1***
Size Availability	***1***	***-1***	***0***
Heat Resistance (softening)	***1***	***-1***	***1***
Corrosion Resistance	***1***	***1***	***1***
Electrical Insulation	***1***	***1***	***-1***
Sum of +1’s	***6***	***4***	***5***
Sum of 0’s	***2***	***0***	***1***
Sum of -1’s	***1***	***4***	***3***
Net Score	***5***	***0***	***2***
Rank	***1***	***3***	***2***
Continue?	***Yes***	***No***	***No***

Once the material was selected, the other subsystem designers were consulted to determine a minimum internal diameter for shaft. The Regulation Circuit and USB subsystems estimated that 1.6” ID would allow enough room for breadboards and the tallest electrical components. Hollow fiberglass rods were found on McMaster-Carr with a diameter of 2 inches and an inner diameter of 1.75 inches. Meeting the internal size constraint, this rod selection could be tested to ensure the stated subsystem strength goals could be met.

Because the estimated static load on the shaft was relatively small (with a target system weight of 20lbs), the chosen design metric was the shaft's ability to withstand 30 MPH winds. Though the accurate creation of these test conditions would be exceedingly difficult and outside the required realm of this project, this scenario could be used to verify the design of the shaft. To do so, the material strength ratings were obtained from the vendor (McMaster-Carr). The tensile strength of the fiberglass is listed as ranging from 10,000 psi to 15,000 psi, and the compressive strength from 35,000 psi to 39,000 psi. Thus, the respective values S_{mt}=12,500 psi and S_{mc}=37,000 psi were selected. These values were then used them to find the maximum bending stresses the shaft could withstand, and from this information and an estimated canopy geometry, the maximum wind speed could be calculated.

First, the maximum tensile stress was used to calculate maximum bending stress. This motivates the amount of force the shaft will be able to withstand without snapping. The applied force from the wind was assumed to be a point force at the top of the shaft, with a fixed base in the ground. This assumption simplifies load and aerodynamic calculations, neglecting only the drag effects of the shaft which are much smaller than those of the canopy.

This process begins with the Equation one shows the total area of the umbrella's shaft.

$$Total\ Shaft\ Area = A_o - A_i = 0.7363in^2 \qquad \text{<6.1.1>}$$

The next equation uses the shaft area and compressive strength to find a static load the shaft can withstand:

$$\sigma_{c-max} = \frac{F}{A} \rightarrow \quad F_{s_{-max}} = A_s * \ \sigma_{c-max} = \quad 27{,}243 \text{ lbs} \qquad \text{<6.1.2>}$$

This verifies that the static load rating is much larger than expected canopy weight (with a safety factor of over 450 even if a 3x stress concentration factor is included). The bending strength of the shaft can then be calculated.

Next, the maximum tensile stress is used to find a maximum theoretical bending moment in the shaft. The next equation shows that if there were 100 lbs of wind the umbrella shaft would fail and could not withstand the force.

$$\sigma_{bM} = \frac{M_b}{Z_p} = \frac{Fl}{(d_o^3 - d_i^3)/6} = \frac{(100lbs)(7ft)(\frac{12in}{ft})}{(2in)^3 \ - (1.75in)^3} = 19{,}086\,psi$$

This calculation shows that if there were 100 lbs of wind (F) applied at the top end of the shaft, the material would fail. However, this same formula can be used with the material strength rating, in order to find a maximum force.

$$M_{limit} = Z_p \times \sigma_{max} = 5{,}501lbin$$

$$F_{limit} = \frac{M_{limit}}{l} = 68.76lbs$$

Also, this calculation can be repeated with various shaft lengths to find various force limits. For a length of 36 inches (which is the length of the bottom piece of the shaft):

$$F_{limit-shaft} = \frac{M_{limit}}{l_{36}} = 152.81lbs$$

So if the umbrella were much shorter, it would be able to withstand more wind force. However, this is not a realistic solution, since no one would be able to sit under the canopy.

In order to then convert the amount of force into a wind speed the drag formula was used to calculate both the drag on the shaft and the top of the umbrella. Since the actual Reynolds number could not be determined without wind speeds, a simplified formula was used that is generally used in industry to calculate maximum wind loading for antennae or structures in winds under 200MPH[11]:

$$F = A * P_w * C_d \qquad \text{<6.1.3>}$$

Where F is wind force in lbs, A is area in square feet, P_w is Wind pressure in lbs/ft^2, and Cd is drag coefficient. Since P_w is equal to $.00256v^2$ where v is wind velocity in MPH, equation <6.1.3> can be rearranged to form:

$$v = \sqrt{\frac{F}{.00256C_dA}} \qquad \text{<6.1.4>}$$

Shaft drag:

C_d=1.2 [source]

F=$F_{lim-shaft}$ = 152.82 lbs

A=d*L = 1.16666 ft^2

$$v_{max-shaft} = 206.47\ mph$$

This predicts that extremely high wind speeds would be needed to cause the shaft alone to fail due to bending. Thus, the drag force on the umbrella will be used with formula to find the limiting wind speed. The frontal canopy area is approximated as a solid hemisphere, and the drag coefficient is overestimated as that of a sphere[12].

Umbrella drag:

F_d=68.76lbs

C_d=0.47

$A_{canopy} = \frac{\pi d^2}{8}$

$$V = 54.5\ mph$$

This result would indicate a safety factor of 3.633. However, there were some assumptions used in this calculation, such as the umbrella canopy being a full half dome. This is not the case in reality because there is no bottom to the umbrella canopy; for a hollow dome, some wind forces might act on the umbrella from below. However, canopy cutouts are being used to prevent a “parachute” effect from accumulated wind, so this effect will be neglected for now.

These equations confirm the design choices that were made would withstand the desired conditions. Once these design choices were made, sketches were made for the lengths and diameters of each piece of the shaft; shown below.

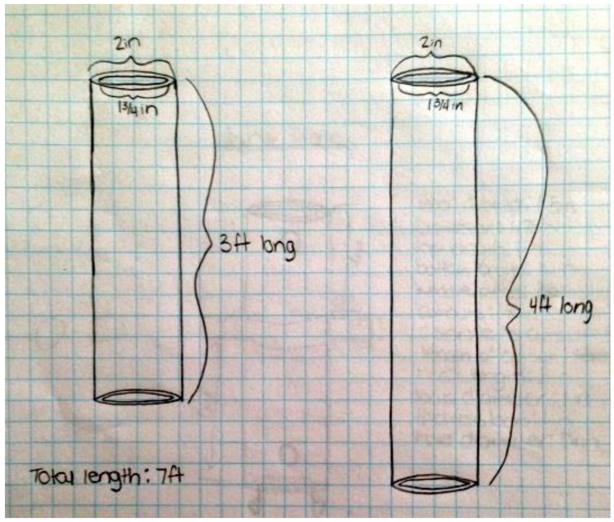


Figure 6.1.1 – Sketch of Shafts

The next choice was selecting an affordable version of these fiberglass hollow rods. There was no solution to this problem for the individual prototype, as all hollow materials with greater than 1.5” ID had a high cost per foot. However if these were being mass manufactured, the price of these rods would be much cheaper. Also, the shrinking of other subsystems such as circuits would allow smaller (and thus cheaper) rods to be used.

Also, the initial subsystem design included an umbrella tilt mechanism, in order to vary orientation angle as the angle of the sun moved through the sky. The tilt mechanisms on existing umbrellas were researched, and the assembly proved complex. No existing parts could be found that would be compatible with a 2” shaft, although two Chinese manufacturers were discovered that would produce the part in minimum runs of 5,000 units. The production of a single prototype was investigated, but this piece would require excessive labor cost to produce. When consulting the IED shop instructor on this topic, he said that the work it would require is far beyond the scope of IED and the group project. Thus, if the umbrella were to be manufactured, this piece could be integrated into the final design, but will be omitted for this prototype.

A base was also needed for holding the SunCatcher in sandy environments. An augur would hold the shaft in place securely and with a compact part, and would also make sand insertion easier. Due to the complexity of manufacturing an augur, existing product implementations were researched. A “sandgrabber” product was finally selected and ordered for this task.

Next, a solution for holding the shaft together was investigated. After finding that threading the existing shaft would thin the material and run the risk of failure, a separate joint piece was considered. Again, several materials were considered, but the additional option of 3D printing an ABS piece would allow tight fit tolerances and the integration of a USB port and phone holder. Designing the piece was not difficult; basic dimensions were found and given to a CAD modeler. The piece didn't need to be overly thick, because included holes would match up with holes in the shaft, and a bolt would be placed through to strengthen the bond. The final design is shown in the photos below. A full engineering drawing is included in Appendix I.

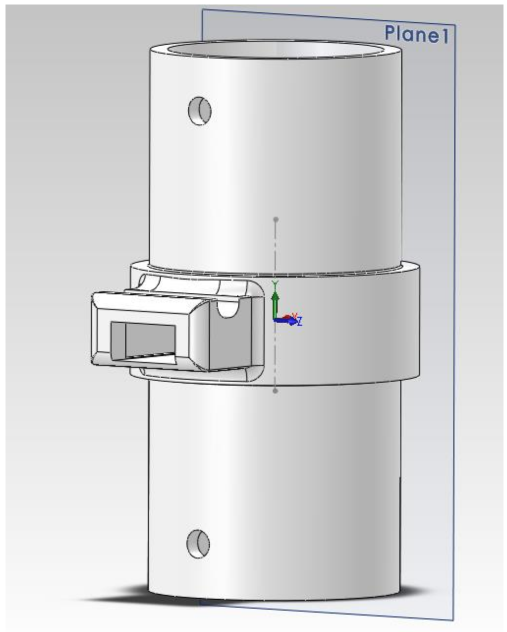


Figure 6.1.2 – Joint CAD model

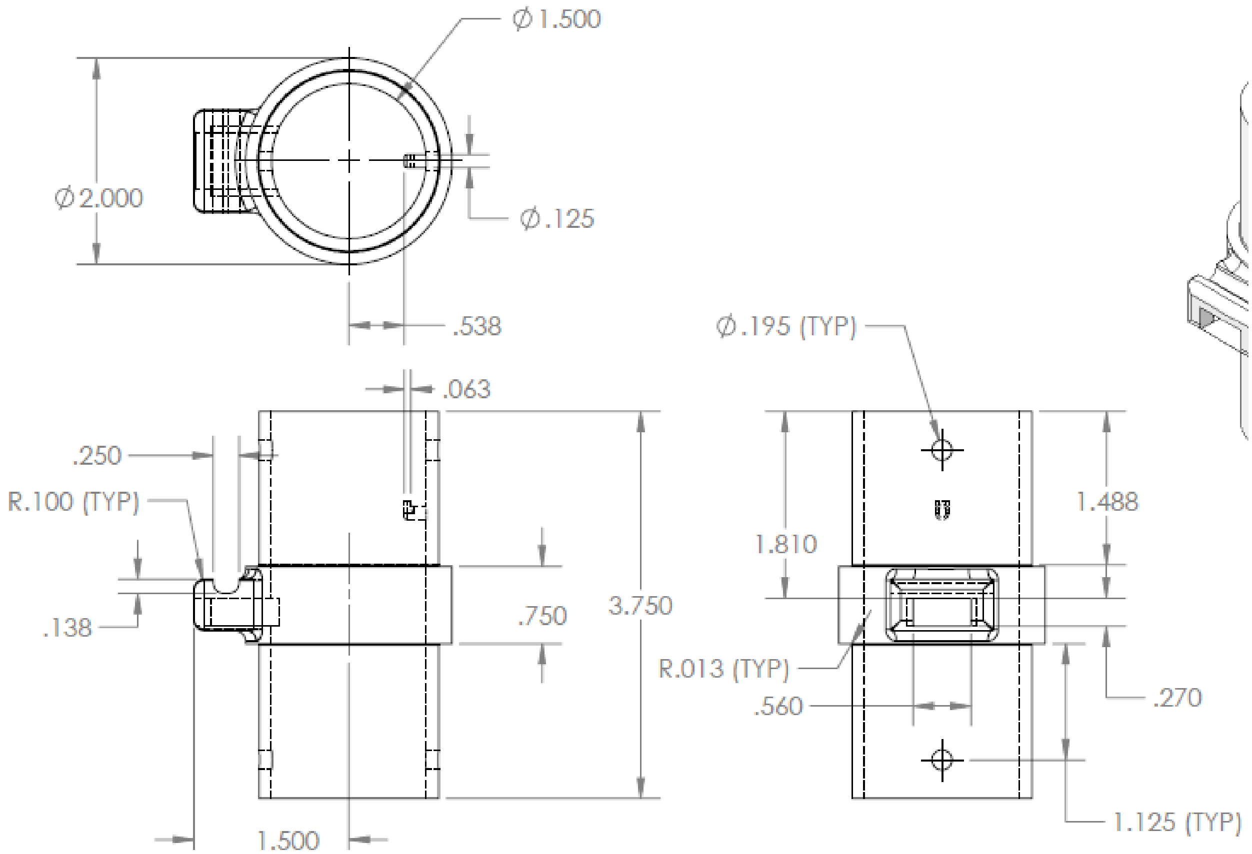


Figure 6.1.3 – Joint Dimensions

<u>Battery Compartment</u>

Once the shaft design was complete, a solution for the battery compartment needed to be found. The compartment needed to house 6 AA batteries in series, so it had to be 12 inches long as dictated by battery dimensions, and held in a linear configuration that would make efficient use of inner shaft volume. Several non-conductive materials were investigated, and 1/2" PVC was found to have an inner diameter of 0.62in, just larger than the battery dimension of 0.55in. The PVC was selected, and appropriate caps were selected. Holes were drilled through the caps of the PVC, and a scrap battery compartment was disassembled for its conductive plates. These plates were then fixed into the caps with epoxy.

Lead wires for the battery compartment were selected based on maximum current ratings and the maximum current traveling into or out of the battery compartment. The Power Regulation and USB Subsystems estimated a maximum output of 1.5A, while the Solar Panel subsystem calculated a maximum value of 2A. This was selected. A wire gauge of 20 was selected based on current capacity charts, using the values for chassis wiring[21]. Power transmission factors ratings are based on when wires are bound together in bundles and cannot dissipate heat as effectively, while chassis wiring considers wires to be "loose" and surrounded by air.

Table 6.1B

Max. Output Current	Max Input current	Wire Gauge Selected	Max Current Cap (Power Trans/Chassis)	Safety Factor
1.5A	2.0A	20AWG	1A / 11A	5.5

Throughout the process sketches were made of the product. The sketches and final product are shown in the pictures shown below in figures 6.1.4 and 6.1.5.

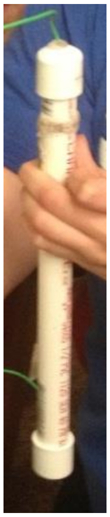


Figure 6.1.4

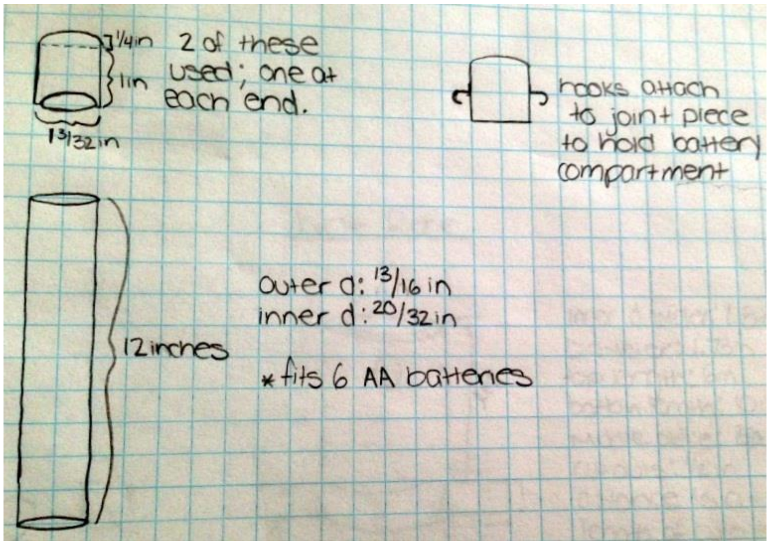


Figure 6.1.5

To test the shaft and battery subsystems, the shaft would have to prove it can support the weight of the complete system in sand. The battery compartment would have to safely support the charging and discharging of the batteries at the maximum current ratings.

The overall success of this subsystem was crucial for the success of the rest of the entire system, since the shaft houses the circuits and also connects the canopy mechanism, and the electrical functioning of the SunCatcher was totally dependent on the safe, reliable operation of the battery pack.

6.2 – Mechanical Subsystem

Prepared by: Matthew Causa

Since design of the mechanical system of the SunCatcher was complex, it will be broken down to further analyze its components. The system was comprised of 5 main components; the ribs, stretchers, a center hub, top hub, and a top cap. Figure 6.1, a 2-dimensional illustration, identifies each component of the mechanical subsystem design that will be analyzed.

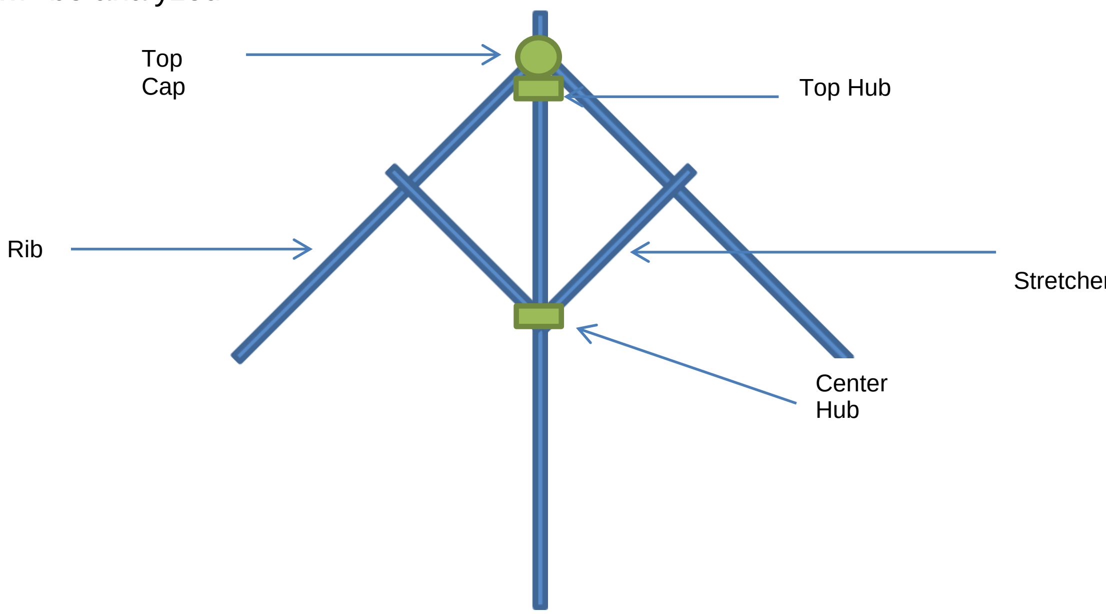


Figure 6.2.1 – 2-Dimensional illustration of Mechanical System

6.2.1 – Ribs and Stretchers

The ribs and stretchers are the “bones” of the subsystem. The ribs provide a base support for the canopy material to rest on, while the stretchers allow the ribs to expand (open the umbrella) and contract (close the umbrella). At first, the design featured a 6 rib system, but after benchmarking the mechanical canopies of other beach umbrellas, it became apparent that 8 ribs (and stretchers) were the industry standard and added strength and stability to the system ("Umbrella FAQ," 2008).

Choosing the most appropriate material was crucial; strength, flexibility, cost and conductivity were all taken into account. The material had to be strong enough to support the canopy material and solar panels and ensure robustness. Flexibility was important because if the ribs and stretchers are too rigid they cannot withstand wind resistance and additionally will not give the umbrella its “U” shape when fully extended. In order to keep costs down and profits up, the less expensive the material will aid the products marketability. Importantly, the SunCatcher has electrical wires that come in contact with the ribs and stretchers, so a non-conductive material was necessary for the safety of the user.

Wood, metal (steel and aluminum), and fiberglass were all possibilities. 3/16" diameter fiberglass rods were ultimately selected as the material that was most appropriate (McMaster-Carr, 2011). Fiberglass was the strongest, most flexible, least expensive and non-conductive. Once the material and dimensions were selected, the ribs and stretchers needed to somehow be connected to each other and to the shaft.

Connection

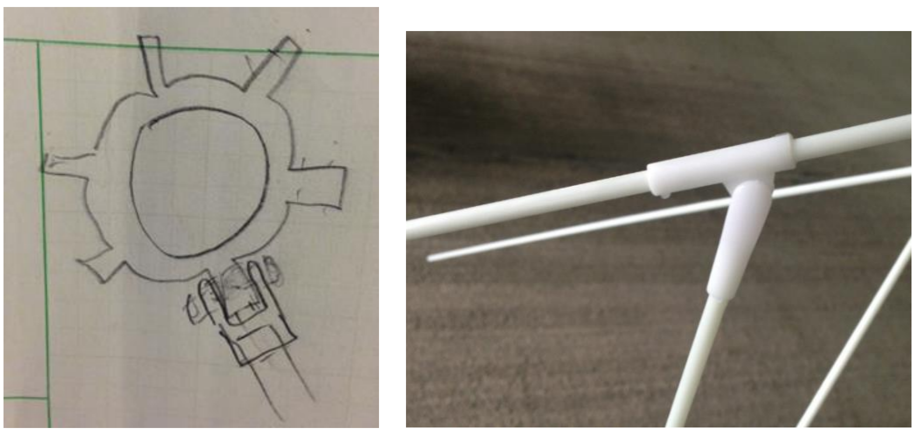


Figure 6.1.2 – Connection Sketch and Connection Final Design

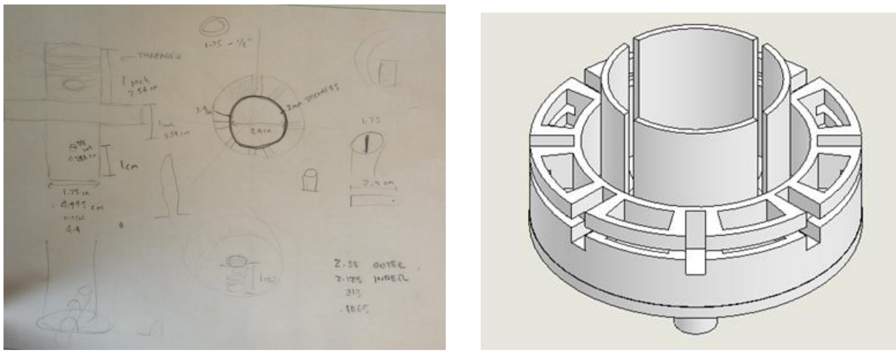
The ribs and the stretchers were connected with joiners, small jointed hinges, made out of HDPE Polyethylene. The joiner is comprised of 2 parts, one male and one female. The female portion is HDPE Polyethylene was chosen because of its large strength to density ratio and low cost. The joiner allows the ribs to be fixed to the stretchers, but still be able to change the angle between them. Without the joiners, the umbrella would not be collapsible.

The end of each rib and stretcher was capped with 1'' HDPE Polyethylene cover that has a tabbed end. The tabbed end has and 1/8" diameter hole cut out. These covers enable the ribs and stretchers to connect to the shaft, which will be discussed in more detail later in the top hub and center hub sections.

6.2.2 – Center Hub, Top Hub, and Top Cap

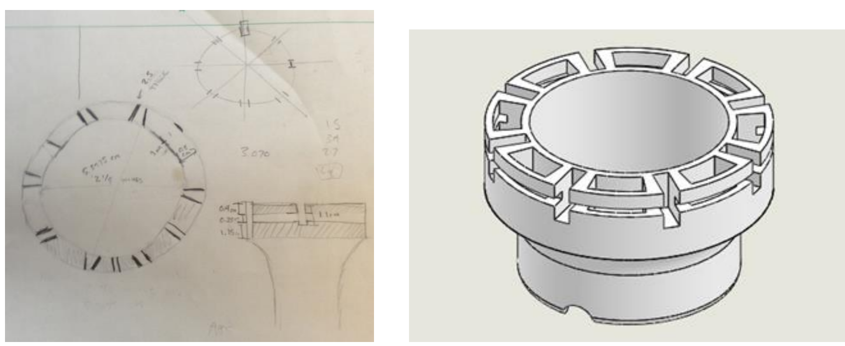
All 3 parts went through multiple design iterations and sketches. After final sketches were completed, all parts were drafted in SolidWorks. The parts were then 3D printed in ABS Plastic, which is an appropriate material for the prototype (MatWeb), but the long term manufacturing cost would be infeasible. When the SunCatcher's production gets ramped-up, a less expensive plastic, such as HDPE Polyethylene, would be injected into a mold for large scale production.

The top hub provides two main functions, a central meeting point for the 8 ribs and anchoring point for the canopy material.



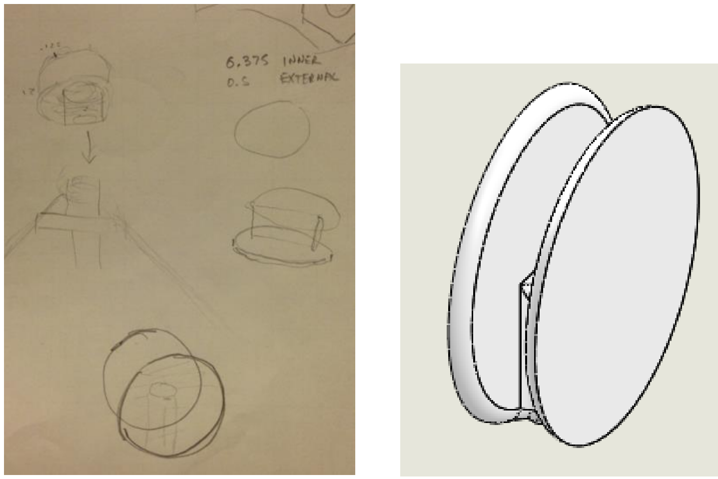
6.2.1 – Top Hub Original Sketch and Final Design

The center hub also provides two main functions, a central meeting point for the 8 stretchers and fixture for which the user of the umbrella can slide the hub up the shaft to expand the stretchers, which in turn expand the ribs.



6.2.2 – Center Hub Original Sketch and Final Design

The top cap was design to carry out two main functions, it seals the canopy material to the top hub, ensuring it will not slip off the cap mount and allows the user to disassemble the umbrella in case a part needs to be repaired or replaced.



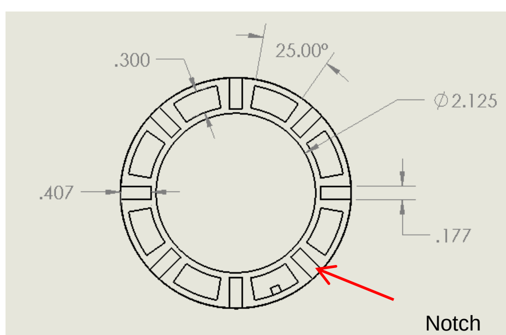
6.2.3 – Top Cap Original Sketch and Final Design

Top and Center Hub Considerations

In order to properly engineer the top hub and central hub (keeping robustness, safety, etc. in mind), extensive design considerations were required. The following considerations can be analyzed simultaneously because they are applicable to both hubs.

Notch dispersion

The 8 tab notches had to be designed exactly 45 degrees apart (from each other around the perimeter of the hub to guarantee that the system would be symmetrical. This symmetry provided even dispersion of load of canopy material and the 8 solar panels throughout the mechanical system.



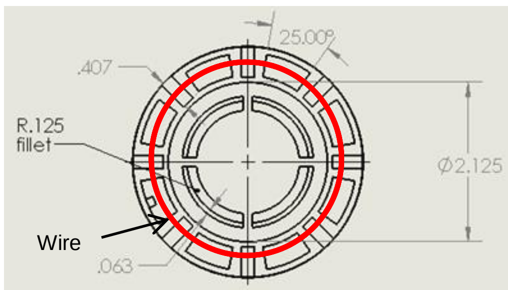
6.2.4 – Top View of the Center Hub

Notch Size

The opening of each notch had many considerations; it could not be too wide, too narrow, or the exact size of the tabbed end. If the notch was too wide, the tab would fit, but would not be constricted enough to guarantee symmetry. If the notch was too narrow, the tabbed end would simply not fit and could not be used as a central meeting point. Finally, if the notch was exactly the same size as the tabbed end, there would be friction between the two, making the umbrella difficult to open and close and over time would compromise the robustness of the design. After these considerations, the notch was designed to be 1/16th of an inch larger than tabbed end. This design of the notch kept the system symmetric, allowed the tabbed end to fit into the notch, and eliminated robustness issues.

Wire Selection & Wire Safety

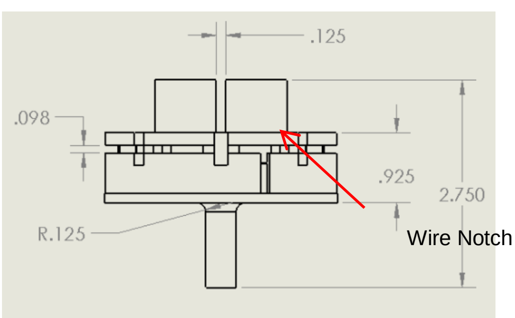
With proper notch dispersion and notch size, the tabbed ends of both the ribs and the stretchers can be fixed onto the top hub and center hub, respectively. 20 gauge, soft-tempered steel wire was threaded through the tabbed ends of the ribs and stretchers and wrap around the inner portion of their respected hubs. Zinc galvanized, soft-tempered steel wire was chosen because it has high tensile strength and yield strength and most importantly, it has malleable or "bend and stay" properties (MatWeb). Zinc galvanized was chosen over black oxide because of its non-corrosive properties. Once the wire was threaded, pliers were used to twist the wire to close the loop around each hub.

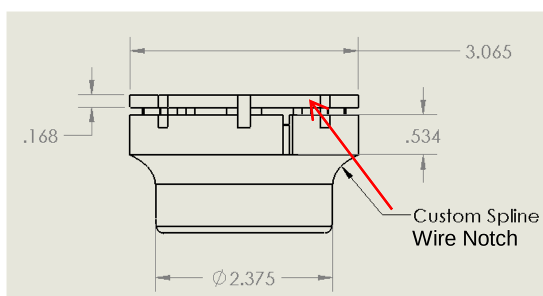


6.2.5 – Top View of the Top Hub

The wire was 7 1/2" in length which was calculated by finding the circumference of the inner diameter of each hub (6.675") plus the distance that it needed to wrap around and adding .825" to allow for twisting.

Knowing this excess, exposed steel wire would cause a safety hazard for the user, a wire notch was designed for each hub. The wire could now be pushed back into the wire notch to surround the extra, twisted wire and avoid potential injury to the user.





6.2.6 – Profile View of Top and Center Hub

Top Hub Considerations

Form Fit to Shaft

The top hub was designed to be secured to the top of the shaft. Since the shaft was designed to have a 2” outer diameter and a 1 ¾” inner diameter, the top hub was engineered to form fit 1 ½” down and around the inside of the shaft and lip over on the outer area of the shaft. After testing, the top hub did not seem to form fit around the shaft tightly enough. The hub was then secured by a ¼” threaded steel rod that went through the shaft and the top hub.

Cap Mount

A 1” cylindrical mount with a 1/4” diameter was extruded from the center of the top hub. Since the cylinder is perpendicular to the top hubs surface, a concentrated stress point was created. For the purposes of holding the canopy material, this stress point is not critical because it is not load bearing. A fillet is added for purposes of the top cap (discussed in the next section).

Center Hub Considerations

Spacing between Shaft

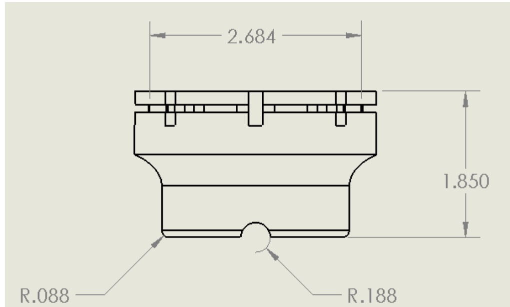
The center hub was designed to slide up and down the shaft, opening and closing the umbrella for the user. Similar to the notches in top and center hubs, the inner diameter of the center hub could not be designed too big, too small or the exact size of the outer diameter of the shaft. The inner diameter was calculated to be 2 1/16”, leaving 1/16” of leeway. This leeway decreases the possibility of friction which increases the robustness of the system.

Ergonomic Handle

The bottom 1” portion of the center hub was designed for the user to wrap their index finger and thumb around, enabling them to safely open and close the umbrella. A spline was implemented at the top of the handle design for ergonomic purposes.

Dowel and Dowel Notch

A 3/8” diameter, brushed Aluminum dowel was selected to go through the shaft and sit underneath the center hub. The dowel works against gravity to fix the mechanical system 19.62 inches from the top of the shaft. Brushed aluminum was selected because of its lightweight, low cost, and high shear strength.



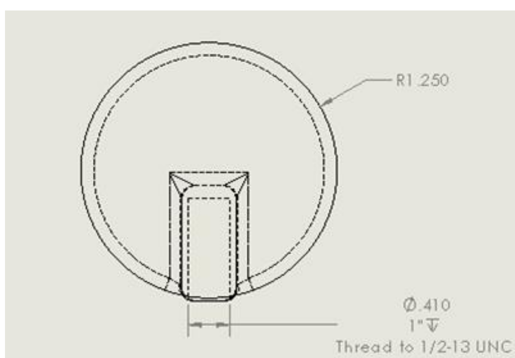
6.2.7 – Profile View of Center Hub

A semicircle with a .188 inch radius was cut out of the bottom of the center hub. This dowel notch provides a dual purpose. When the dowel sits within the notch, it prevents the center hub from being twisted which would create torsion within the system. If the dowel notch was not in place, all of the stress would be concentrated on a significantly less area.

Top Cap Considerations

Advertising Opportunity

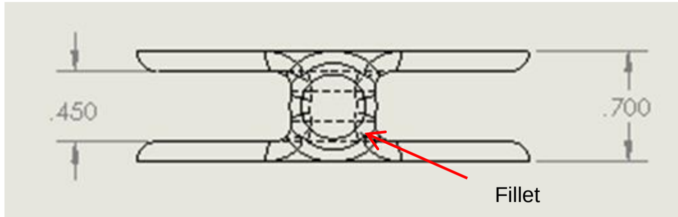
The top cap presented an opportunity to market the SunCatcher to potential customers. A 2.5” diameter vinyl logo was placed on each side of the top cap.



6.2.8 – Bottom View of Top Cap

Fillet Usage

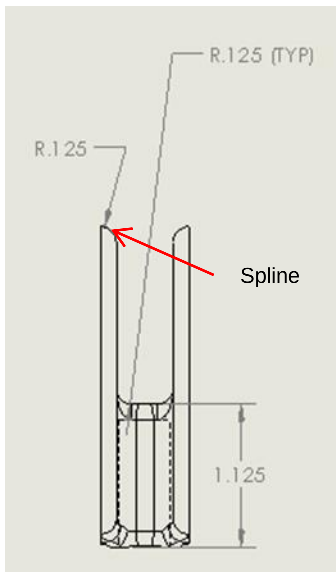
Fillets were added to the areas surrounding the two 2.5” circular plates and the female cap mount to ensure the system will be robust when the user needs to disassemble the umbrella.



6.2.9 – Bottom View of Top Cap

Spline Implementation

Splines were implemented throughout the design of the top cap. Unlike the center hub, these splines were not introduced to make the system more ergonomic, but to give the top cap a sleek, finished look.



6.2.10 – Profile View of Top Cap

6.2.3 Calculations for Specifications

Table 6.3.1 provides a breakdown of requirements of the mechanical subsystem that need to be met in order to comply with the customer requirements in Section 2.

Table 6.3.1 – Mechanical Subsystem Requirements

SunCatcher - Subsystem Techincal Specs			
Team Member/(Subsystem)	Key Function	Target Spec	How to Demonstrate
Matt (Canopy - Mech. Design)	**Weight** - lightweight to allow user to carry, open and close umbrella easily	< 5 lbs	Weigh with scale
	Portability - user can collapse the umbrella in order for easy transport and storage	Radius <4 in	Measure with calipers
	Shade Area - when umbrella is fully open, the diameter will provide shade for two people	6 ft	Measure
	Strength - Umbrella will not fail when canopy and solar panels are placed on the system	5 lbs. (Solar panels + Canopy)	Open canopy

Weight Specifications

By keeping the mechanical system to less than 5 lbs., given the estimated weights of the other subsystems, we could meet our weight specification of less than 20 lbs.

For each piece, the volume was determined by measuring with a tape measure or by information provided through SolidWorks (in the case of the top hub, central hub, and top cap).

To find the volume of the Fiberglass ribs/stretchers, Polypropylene caps, and Steel wire the length was measured with a tape measure and the diameter was measured with calipers. The volume equation for a cylinder was then applied:

$$V = \pi r^2 h$$

where r is the radius (1/2 diameter) and h is the length of the part.
By multiplying the nominal density (lbs./cubic inch) by the volume of the fiberglass rib/stretcher, the weight of the part was found. The weight was then multiplied the quantity of pieces in the system to determine the net weight for the part(s).

The volumes of the top hub, lower hub, and top cap were all determined by a feature in SolidWorks where the parts were designed. The determined volume was then multiplied by the nominal density of ABS plastic.

Table 6.3.2 – Weight Calculations

Quantity	Part Description	Diameter (inches)	Length (Inches)	Inner Diameter (inches)	Density (lbs./inch^3)	Volume (inches^3)	Weight (lbs.)
8	Fiberglass Stretcher	0.188	16.5	-	0.058	0.46	0.211
8	Fiberglass Ribs	0.188	41	-	0.058	1.13	0.525
16	Plastic Caps w/ eyelet	0.290	1	0.188	0.034	0.04	0.021
8	Polypropylene End Cap	0.290	1.25	0.188	0.034	0.05	0.013
8	Polypropylene Connector (Male)	0.350	1.25	0.188	0.034	0.09	0.023
8	Polypropylene Connector (Female)	0.350	1.5	0.188	0.034	0.10	0.028
1	ABS Top Hub	Varies	Varies	Varies	0.038	2.93	0.110
1	ABS Center Hub	Varies	Varies	Varies	0.038	2.72	0.102
1	ABS Top Cap	Varies	Varies	Varies	0.038	1.33	0.050
2	Soft-tempered Steel Wire	0.035	6.5	-	0.282	0.01	0.004

Net Weight (lbs)	1.087947808

The expected total weight of the mechanical system is 1.09 lbs., 3.91 lbs. less than the maximum target weight. When the system is complete, it will be weighed on a scale to test for accuracy.

Portability

In order to meet the customer requirement

Shade Area

The goal of this subsystem is for the canopy to have an outer radius of 6 ft. when open. In order for this to happen, the center hub must be fixed a certain distance away from the top of the shaft.

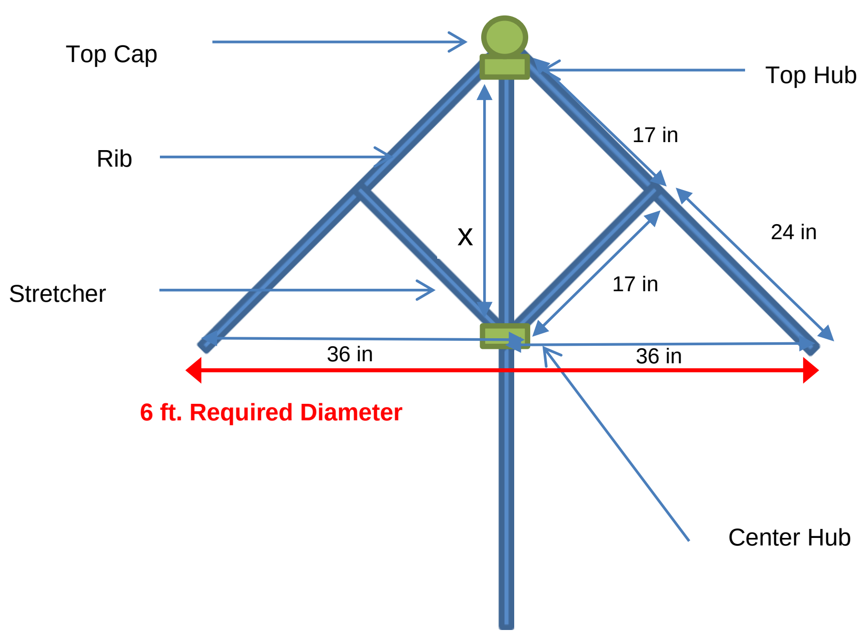


Figure 6.3.1 – Analysis of Shade Diameter

Pythagoreans Theorem was applied to find the distance x.

$$x^2 + b^2 = c^2$$

Where: b = 36 inches (half of the required diameter length),
c = 41 inches (length of a rib)

$$x^2 + (36)^2 = (41)^2$$

$$x^2 = (41)^2 - (36)^2$$

$$x^2 = 1681 - 1296$$

$$x^2 = 385$$

$$x = 19.62141687$$

In order to achieve the shade area of 6 ft., the center hub needs to be fixed approximately 19.6 inches below the top of shaft.

The outer diameter will be measured with measuring tape to test and see if the specification was met.

Strength

The SunCatcher must be able to support the canopy material and solar panels. End pockets will be fixed on to the nylon canopy material that will lie on top of the structure below. The end of each rib will be placed inside theses end pockets. As the user of the umbrella applies an upward force on the center hub, the slack in the material will decrease until the material is taut.

Once the material reaches this state, any further upward force from the user will cause the ribs of the umbrella to deflect. This deflection cannot exceed the maximum deflection for fiberglass. To test the how much the umbrella will deflect, we will assume that the weight of the solar panels and canopy material act at the end of the fiberglass rib. The beam ABC is the Rib. At Point B, there is an upward force from the stretcher. At Point C, there is a downward force from the 5 lb. (3.1 lbs. for canopy material and 1.9 for solar cells) weight.

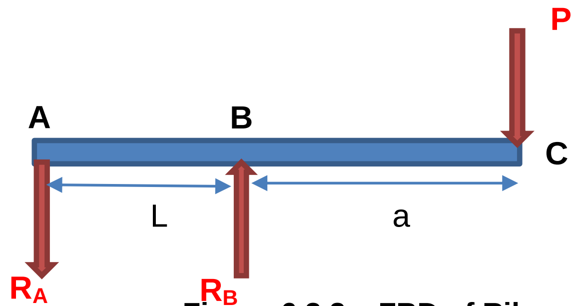


Figure 6.3.2 – FBD of Rib

Using the Free Body diagrams we get the two following reactions:

$$R_A = P\frac{a}{L}$$

$$R_B = P\left(1 + \frac{a}{L}\right)$$

Analysis is done about a Hypothetical Point D on the rib in order to get a moment equation with respect to x.

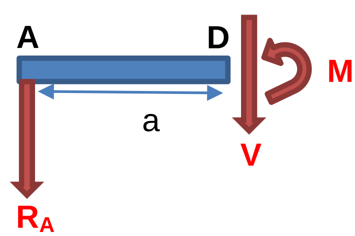


Figure 6.3.3 – Developing the Moment Equation

Taking the moment about point D gives:

$M = -P\frac{a}{L}x$ $\quad$ (0 < x < L)

Differential Equation for the elastic curve:

$$EI\frac{d^2y}{dx^2} = -P\frac{a}{L}x$$

Noting that EI (flexural rigidity) is constant, we integrate twice to find:

$$EI\frac{dy}{dx} = -\frac{1}{2}P\frac{a}{L}x^2 + C_1$$

$$EIy \quad = -\frac{1}{6}P\frac{a}{L}x^3 + C_1x \quad + C_2$$

In order to figure of the C_1 and C_2, we need to substitute in for x and y according to our boundary conditions. Since the rib is fixed at both points A and B, we can assume the deflection at those points is zero (y=0) when x = 0 (point A) and when x = L (point B).

$[x = 0, y = 0]$ $\qquad$ $C_2 = 0$

$[x = L, y = 0]$ $\qquad$ $EI(0) = -\frac{1}{6}P\frac{a}{L}L^3 + C_1L$

$$C_1 = \frac{1}{6}PaL$$

Substituting for C_1 and C_2:

$$EI\frac{dy}{dx} = -\frac{1}{2}P\frac{a}{L}x^2 + \frac{1}{6}PaL$$

$$EIy = -\frac{1}{6}P\frac{a}{L}x^3 + \frac{1}{6}PaLx$$

Divide both equations by the constant EI to obtain:

$$\frac{dy}{dx} = \frac{PaL}{6EI}\left[1 - 3\left(\frac{x}{L}\right)^2\right]$$

$$y = \frac{PaL^2}{6EI}\left[\frac{x}{L} - 3\left(\frac{x}{L}\right)^3\right]$$

The maximum deflection y_{max} occurs when the slope of the elastic curve is zero. So setting $\frac{dy}{dx}$ = 0 in the equation above, we x_m:

$$0 = \frac{PaL}{6EI}\left[1 + 3\left(\frac{x_m}{L}\right)^2\right]$$

$$x_m = \frac{L}{\sqrt{3}} = 0.577L$$

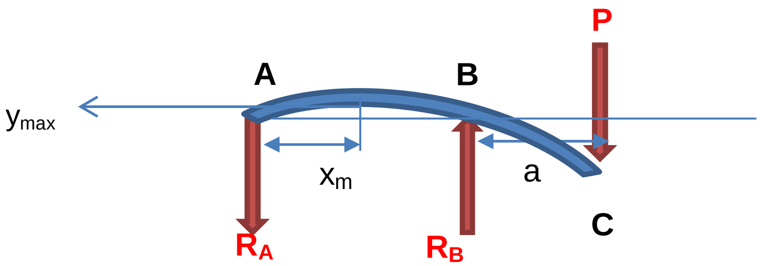


Figure 6.3.4 – Calculating the Deflection

We substitute x_m/L 0.577 into equation (4) to obtain y_{max}:

$$y_{max} = \frac{PaL^2}{6EI}[(0.577) - (0.577)^3]$$

$$y_{max} = 0.0642\frac{PaL^2}{EI}$$

Since all of the other variables in our equation are known values, we can now plug in and determine the maximum deflection. Given P = 5 lbs., a = 24 in., L = 17 in., $I = \pi\frac{R^4}{4}$, E = 2,500,000.

$$y_{max} = 0.0642\frac{(0.005\ kips)(24\ in.)(17\ in.)^2}{(2{,}500{,}000\ psi)(0.00000613\ in.^4)}$$

$$y_{max} = 0.0145\ in.$$

The maximum deflection formula in Appendix D (Mechanics of Materials, 3rd edition) of:

$$y_{max} = -\frac{ML^2}{2EI}$$

Where M = 0.005 kip*24 in, L=24 in, $I = \pi\frac{R^4}{4}$ E = 2,500,000.

$$y_{max} = |-0.4509\ in.|$$

Since the absolute value of the maximum deflection is greater than the deflection in the rib, we can be assured the system will not fail.

6.2 Subsystem 3 – Canopy Fabric and Solar Panels

This subsystem consisted of the canopy construction and layout. The material for the canopy needs to be lightweight but sturdy and UV resistant. After careful benchmarking, a nylon canvas was chosen over a canvas or polyester because it was more durable than polyester materials, but significantly lighter than the canvas[16]. Also, the nylon canvas had better mildew and moisture resistance that the canvas, and had innate UV resistant properties, rather than relying on coatings which might wear off with use [17].

The material needed to be cut and sown to achieve a 7 foot diameter. The canopy was made of two pieces sown together, but slits were left between the material to allow wind to pass through. This would reduce the effect of a strong wind on the umbrella, where wind might get trapped underneath a sealed canopy and create a parachute-like effect. Pockets were sown at the extremities of the canopy in order to attach the ribs. These will hold ribs in place securely, while also allowing the entire system to be disassembled and reassembled easily. The finished canopy fabric is displayed below in figure 6.3.1.

Figure 6.3.1 – Completed Canopy Fabric

Additionally, solar panels had to be selected to attach to the material selected. The solar panels had to provide at least 7.2 volts. Two main panel styles were researched: Glass based Photovoltaics, and flexible Photovoltaics. Some of the Pros and Cons of each are listed below in table 6.3A.

Table 6.3A – Comparison of Solar Panel Types

Rigid (Glass) PVs		Flexible PVs	
Pros	**Cons**	**Pros**	**Cons**
Lower cost	Fragile	Lightweight	Higher cost
High efficiency (~15%) [18]	Inflexible	Conforms to shape	Lower Efficiency (~7%) [19]
Longer Panel Life	Heavy		Shorter Lifespan

With these considerations, the low-cost and higher efficiency of the rigid panels trumped the weight savings and flexibility the flexible panels. Once this was determined, a panel layout had to be determined, while simultaneously accounting for different panel selections. The main choices were between a 6 rib canopy and 6 panels, or an 8 rib canopy with 8 panels. After reviewing available panel power ratings and conferring with the canopy mechanism subsystem, the 8-panel design was selected. This would allow 4 pairs of 5V panels to be wired in series-parallel to achieve a 10V output. The solar panels selected are .15m by.13m and have a capacity of 2.5 Watts (500mA max).

A canopy arrangement was chosen as illustrated below in figure 6.3.2. This keeps the panels relatively close to the shaft for wiring and support consideration, while also staying far enough down to be covered by canvas when the umbrella is folded. This will protect the panels from excess damage or wear.

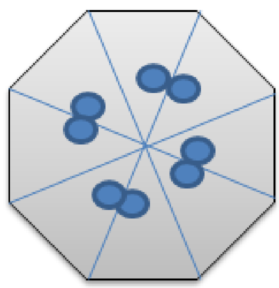


Figure 6.3.2: Solar Panel Configuration

The following figure demonstrates how the panels will be wired, and the expected output power.

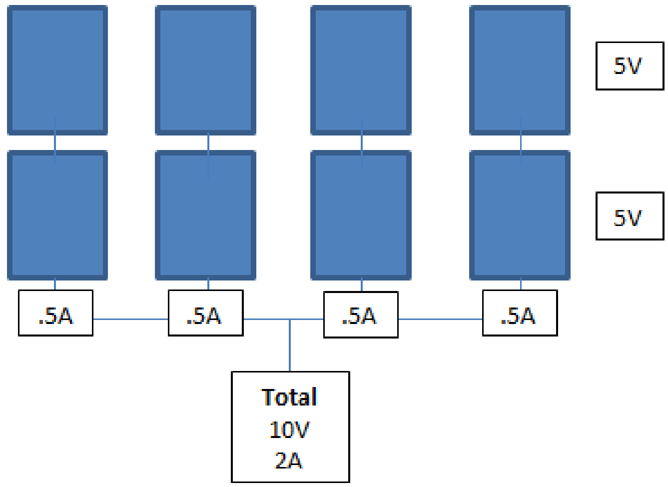


Figure 6.3.3: Solar Panel Configuration

Design Calculations

The average Solar Radiation of the sun on earth's surface is 1000 W/m² and the average rigid PV solar panel has an efficiency of 15 percent[18]. Below are the calculations for solar radiation of several different latitudes using the following equation.:

Panel Output Power = (Avg Solar Radiation at Latitude) × (Area of Panel) × (Efficiency)

At the Equator

$$\left(1000\,\frac{\mathrm{W}}{\mathrm{m}^2}\right) \times (.0195\mathrm{m}^2) \times (.15) = 2.925\ W\ per\ solar\ panel$$

Solar Radiation = $1000\ \frac{W}{m^2}$

At 30° Latitude

$$\left(866.025\,\frac{\mathrm{W}}{\mathrm{m}^2}\right) \times (.0195\mathrm{m}^2) \times (.15) = 2.53\ W\ per\ solar\ panel$$

Solar Radiation = $1000\ \frac{W}{m^2} \times (cos(30°)) = 866.025\ \frac{W}{m^2}$

At 45° Latitude

$$\left(525.32\,\frac{\mathrm{W}}{\mathrm{m}^2}\right) \times (.0195\mathrm{m}^2) \times (.15) = 1.53\ W\ per\ solar\ panel$$

Solar Radiation = $1000\ \frac{W}{m^2} \times (cos(45°)) = 525.32\ \frac{W}{m^2}$

At 60° Latitude

$$\left(500\,\frac{\mathrm{W}}{\mathrm{m}^2}\right) \times (.0195\mathrm{m}^2) \times (.15) = 1.4625\ W\ per\ solar\ panel$$

Solar Radiation = $1000\ \frac{W}{m^2} \times (cos(60°)) = 500\ \frac{W}{m^2}$

Because the umbrella is not a flat surface and is tilted at an angle, the solar radiation received is affected. The umbrella is tilted at 20 degrees and the following equations take this tilt angle, latitude, and time of year into account[19].

$$S(solarpanel) = \frac{S(horizontal) * (\sin(\alpha + \beta))}{(\sin \alpha)}$$

$$\alpha = 90° - \emptyset + \delta$$

∅ = Latitude

$$\delta = (23.45) * \sin\left[\left(\frac{360}{365}\right) * (284 + Day\ Number)\right]$$

Plot by Day at 30° Latitude

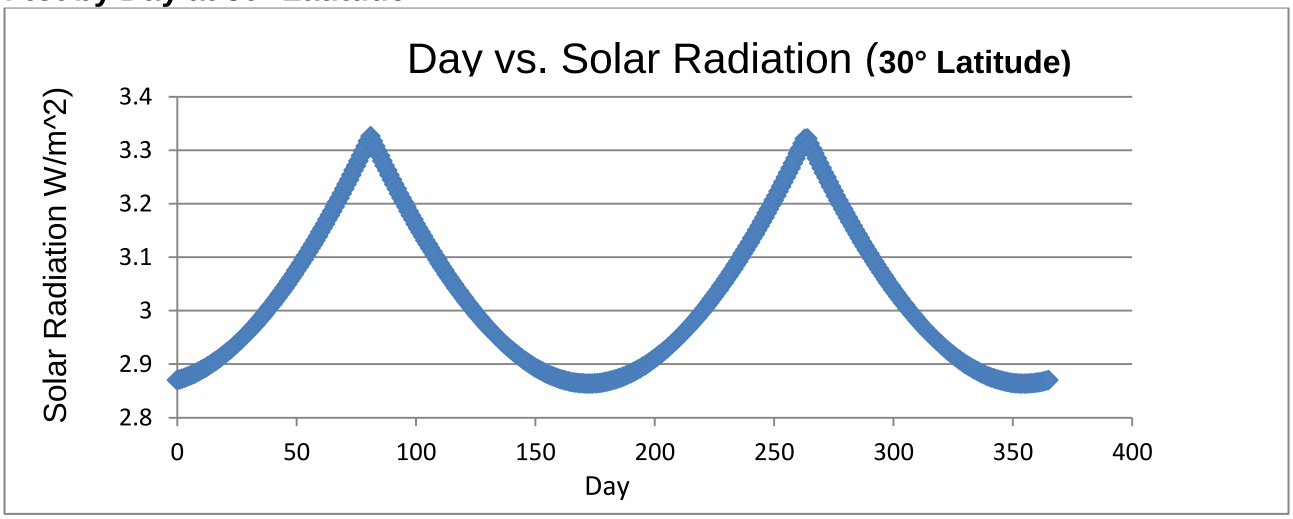


Figure 6.3.4: Plot of Solar Radiation

*Day 1 = January 1st

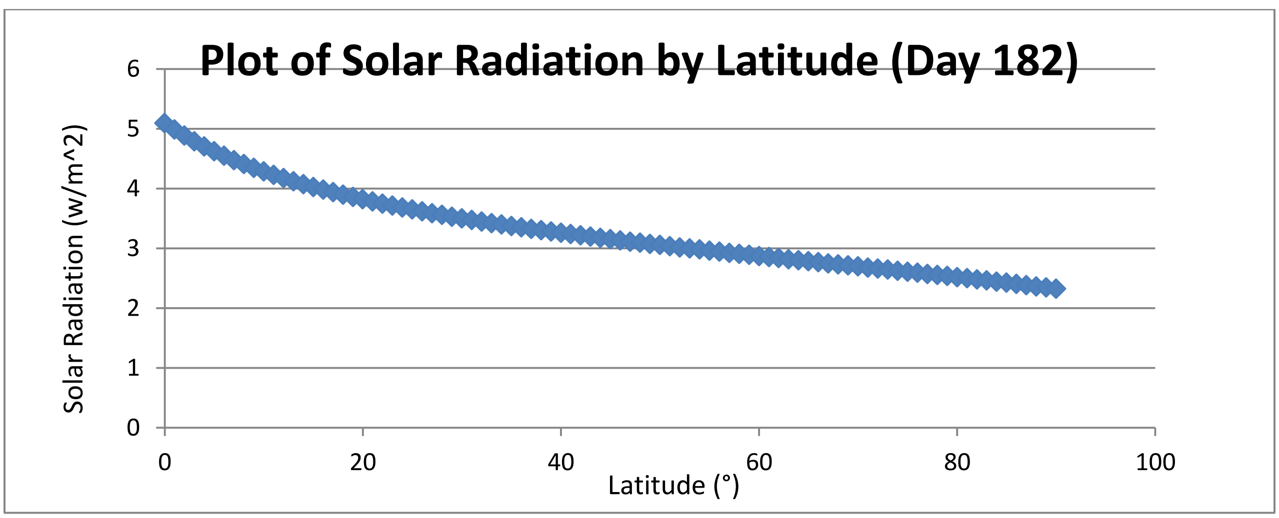


Figure 6.3.5: Plot of Solar Radiation

*using Day 182, middle of the summer

These predictions indicate that even at higher latitudes and with tilted panels, the system should receive enough solar energy to keep the panels operating near their peak output for a large portion of the day, and a majority of the year. The actual effect of tilt, cloud cover, and other shade blockage can be with the panels and a multimeter.

As seen below the final canopy sewn, the panels attached, and the wiring waterproofed. Below in figure 6.3.6 the canopy is attached to the mechanical canopy subsystem.

Figure 6.3.6: Completed Canopy fabric and solar subsystem

6.3 Subsystem 4 – Power Regulation Circuit and Battery Charging

Prepared By: Zachary Luzinas

6.3.1 Circuit Design

The main purpose of this subsystem is to regulate the power from the solar cells to charge six AA NIMH rechargeable batteries in under four hours. The voltage created by the solar cells needs to be regulated down to 7.2 volts to effectively recharge the batteries without damaging the cells from over-voltage. The regulated current from the solar cells has to recharge the battery array safely in less than four hours, as determined by customer requirements. The circuit is also designed to output a constant voltage and nearly constant current to the USB and lighting subsystem. The circuit has to therefore account for variations in the power from the solar cells. The circuit also has to be constructed to ensure safety for the user; this is done by building the circuit so it could fit within the shaft of the umbrella, follows safe circuit design, and does not contain any exposed wiring that might cause a short or fire.

The first section of the circuit has to be designed to step down the 10 volts being supplied by the solar cells to a constant 7.2 volts to charge the batteries. The simplest way to regulate a constant voltage is to design a voltage divider circuit and choose resistor values that will step down the voltage to the needed value. The largest problems with this design is the lack of control of the current and a variable output voltage if the input voltage changes. The lack of control in this design would result in harmful fluctuations in the power being supplied to the batteries and the USB circuit. The circuit design needs to have a greater level of control than the voltage divider circuit can offer.

A new circuit design was chosen after researching different components that can be used to implement simple voltage and current control. The LM317T voltage regulator is a simple component that can be easily implemented in a circuit to regulate the voltage and current of low power devices. By choosing resistance values of 6k ohms and 1k ohms, the component provides the circuit with an output voltage of 8.8 volts and a constant 1.5 amp current. This output voltage ensures the voltage reaching the batteries is a steady 7.2 volts.

The next section of the circuit ensures that there is not an overvoltage in the batteries. An overvoltage in the batteries could cause overheating and eventual failure from the battery array which could damage the USB device connected to the circuit. There is also the possibility of a fire when batteries are overcharged for prolonged periods of time. To combat this, a Zener diode is placed in parallel with the LM317T. The first Zener diode was selected to have a breakdown voltage of 8V in the original circuit. This Zener diode would act as a short that sent excess current to the ground in the circuit if the voltage in the batteries or the voltage reaching the batteries was greater than 8V. The major flaw with this design was the lack of internal impedance in the diode that would prevent the diode from burning out if it were subjected to a current in excess of 1 amp. If the diode burnt out it would have acted as a short to ground under any voltage or current condition. This would have prevented the regulated power from getting to the batteries to charge them.

To fix this problem, artificial impedance had to be installed into the circuit to allow for a controlled current flow in the Zener diode. Adding a simple resistor was considered, but the inefficiencies found in a resistor would have prevented the current from being controlled to a point where the diode would not have been burnt out in excess of 1 amp of current. The redesigned overvoltage compensator was chosen to act as a voltage dependent switch that would activate when the voltage was in excess of 8 volts.

The Zener diode was used in conjunction with a low power NPN BJT transistor and several resistors to act as a voltage dependent switch. By using a common emitter configuration with the components the switch operated with moderate amount of impedance to the system that dropped the 8.8 volts, being regulated by the lm317t, to 7.2 volts to charge the batteries. The Zener diode was wired on the base of the transistor with a small resistance that would prevent the current from burning the diode out. The switch would only activate if there was current travelling through the diode and into the base of the transistor.

The model of the overall circuit is shown below in Figure 6.4.1

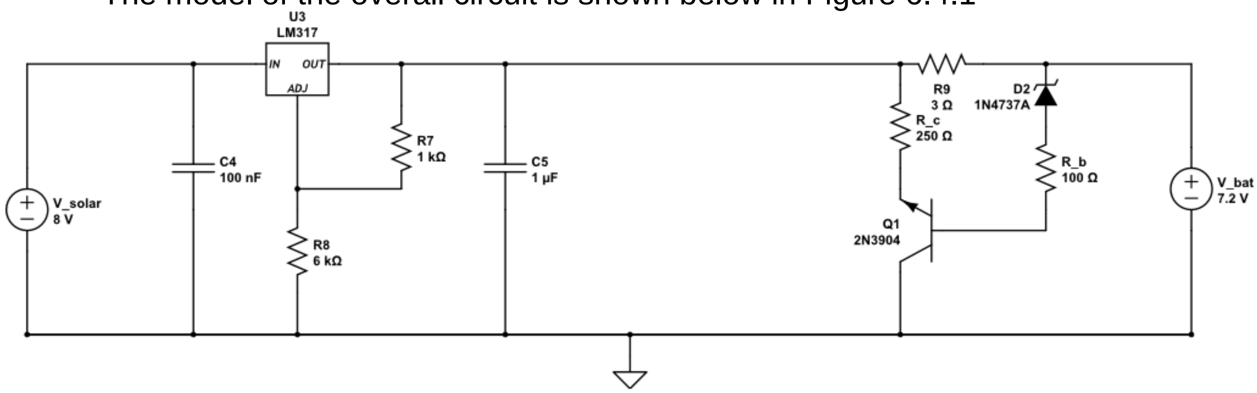


Figure 6.4.1 – Proposed Regulation Circuit

In figure 6.4.1 there are two capacitors not previously mentioned. These capacitors were used in conjunction with the LM317T to regulate the current to the previously mentioned 1.5 amps. Simulations of this circuit were carried out, and the results displayed below in figures 6.4.2 and 6.4.3.

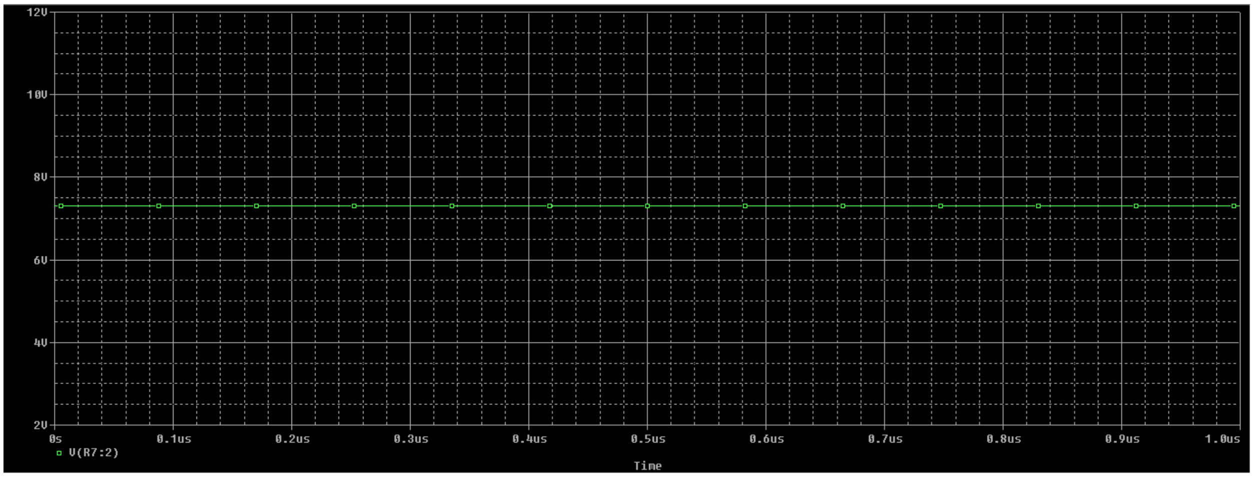


Figure 6.4.2 – Simulated Output Voltage

The circuit simulation software PSpice was used to simulate the majority of the circuits. Figure 6.4.2 shows the time domain response to the overvoltage compensator section of the circuit. The response shows a constant 7.3 volts across the batteries over the given time period.

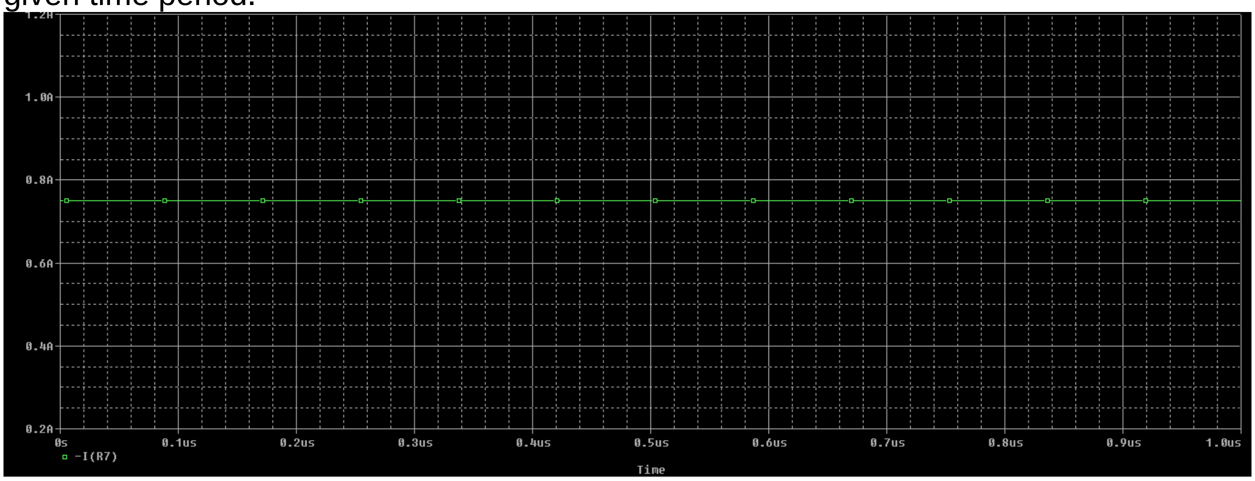


Figure 6.4.3 – Proposed Regulation Circuit

Figure 3 shows the current in the time domain that is charging the batteries over the given time period. The figure shows a constant 750 milliamp current over the time period shown.

The circuit design allows for a constant 750 milliamp current and 7.3 volts to charge the batteries as long as the voltage from the solar cells remains at 10 volts and the current remains above 1.5 amps. A multi-meter can be used to test the output at the battery compartment to verify that the output is similar to that found in the simulations.

6.3.2 Batteries

The batteries needed to be chosen to have enough capacity to charge USB powered devices with no external input from the solar cells. The USB devices to be fully charged were outlined by customer requirements, motivating the overall capacity technical specification of 2500mAh. Also, the batteries needed to have the capability of fully charging or discharging in under 4 hours

The original battery selection was Jolt 2500 milliamp hour NIMH rechargeable batteries. These batteries were selected because they were already owned by one of the project members, and they seemed to have specs that met the project requirements

For charging rechargeable batteries, the charge rate is a key metric, where

$$\text{Charge Rate C} = \frac{Capacity\ (mAh)}{Current\ (mA)}$$

Charging or discharging the Jolts in four hours would then only place them at .25C, well under the safe NIMH limit of 1C. However, after testing these batteries it was discovered that they were unable to meet their advertised capacity, and the output current fluctuated well before the voltage shoulder. To test the discharge rate a single battery was attached to a 1k ohm load resistor and allowed to discharge completely. As seen in figures 4 the discharge curve of a single battery was very unreliable. Additionally, the battery voltage dropped significantly after less than two days of being fully charged. These batteries were deemed to be too unstable to use in the circuit. The short discharge duration and lack of an overvoltage state in the batteries would negate any safeguards designed into the control circuit.

Figure 4:

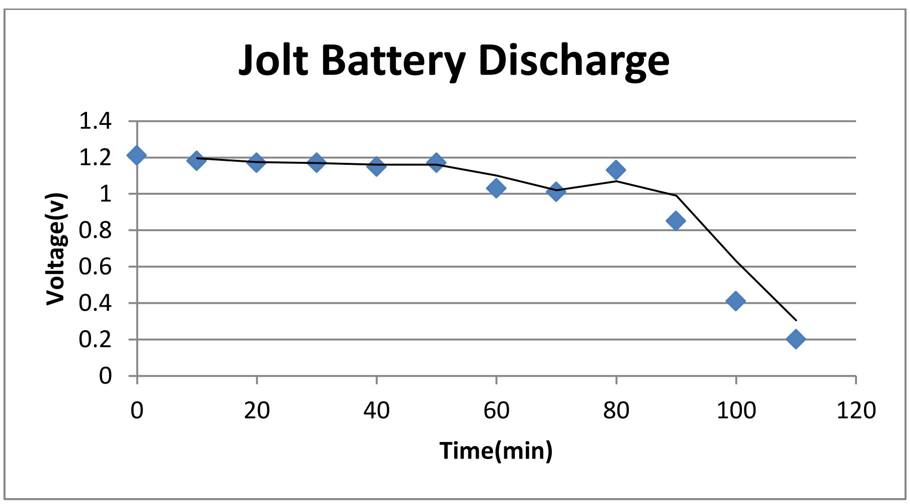


Figure 6.4.4: Battery Discharge curve for Jolt Batteries

Energizer Recharge® 2300 milliamp hour batteries were chosen to take the place of the Jolt batteries. The energizer batteries have a smaller rated capacity, but are rated for faster charging and discharging cycles. These batteries also feature a low self-discharge (LSD) chemistry, allowing the batteries to be stored for long periods of time without a significant charge drop.[TECHSHEET] This feature would enable the SunCatcher to operate effectively between longer periods when not charging directly.

Running the same discharge test as featured in figure 4, the Energizer batteries yielded a much more stable discharge curve, seen in figure 5. The overvoltage "shoulder" is also readily apparent at the left side of the graph.

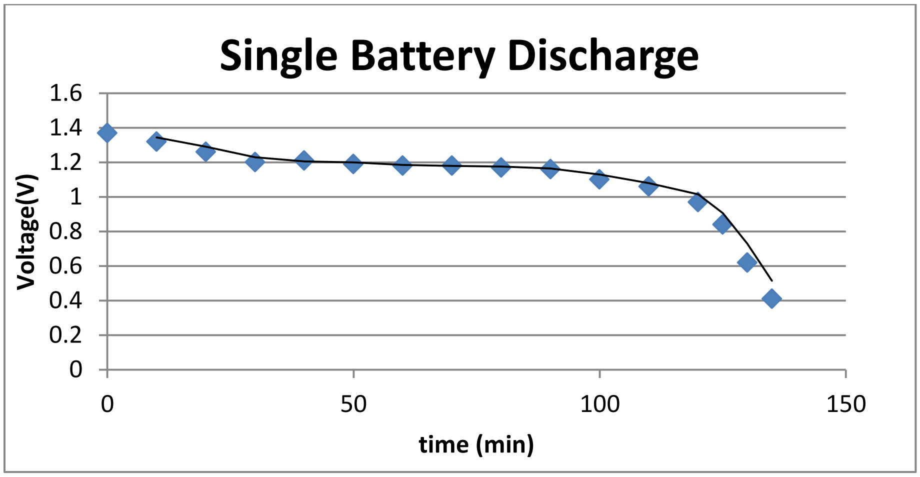


Figure 6.4.5: Battery Discharge curve for Energizer Batteries

To test the charging duration of a single battery, the battery had one amp driven through it. A load resistor was used to prevent the current from burning up the battery. By supplying 1 amp the battery should be charged in 2.3 hours. Figure 6 shows the charging curve for the single battery.

Figure 6:

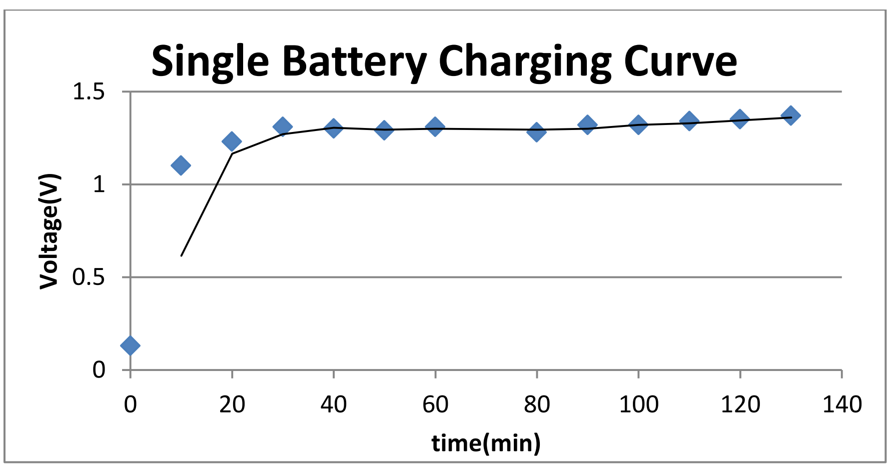


Figure 6.4.6: Battery Charge curve for Single Energizer Battery

To simulate the conditions of the battery array within the umbrella, six batteries had to be tested under similar conditions. Figure 7 shows the discharge of six batteries on a 7.2 ohm load. The load was chosen so the batteries would supply a near constant 1 amp current to the load. This would allow the batteries to discharge fully in 2.3 hours.

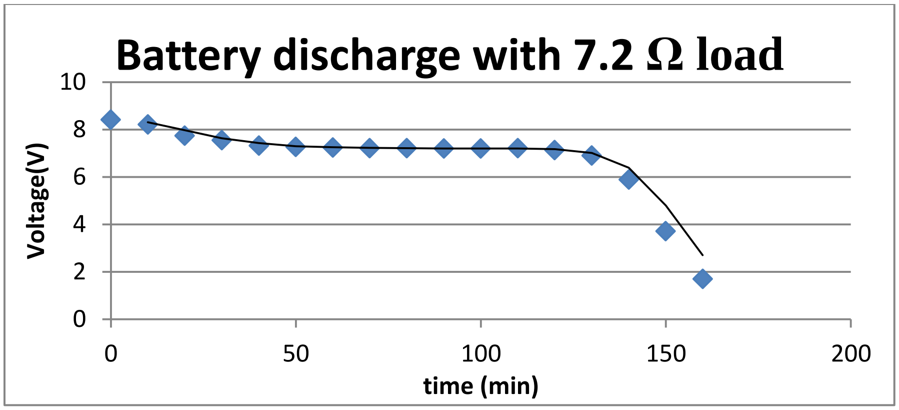


Figure 6.4.7: Battery Discharge curve for 6 Energizer Batteries

To charge the six batteries, a 1 amp current was driven through them, like in the test above. Figure 8 shows the six battery's charging curve. Again the batteries were connected to a load resistor to prevent any damage as a result of an uncontrolled current. Under the 1 amp current the batteries should have charged entirely in 2.3 hours. The results seen below in Figure 6.4.8 took slightly longer, possibly due to charging inefficiencies in either the battery or the charging circuit.

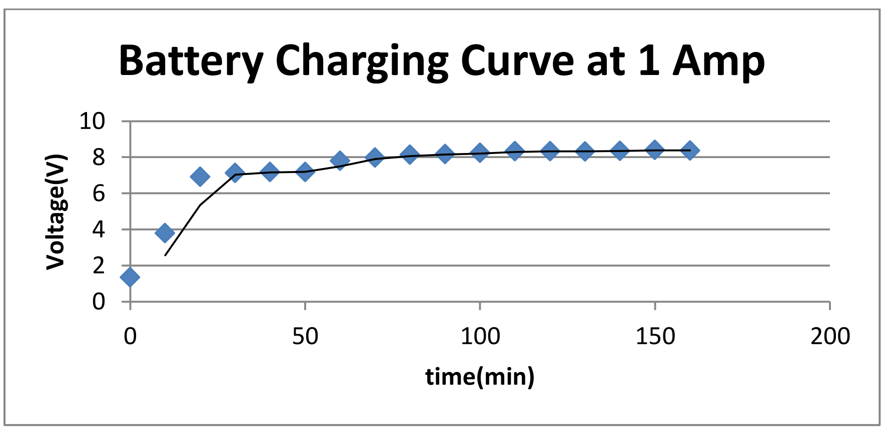


Figure 6.4.8: Battery Charge curve for 6 Energizer Batteries

6.4.3 Boost Converter

The previous circuit design was created assuming the voltage of the solar cells will remain fairly constant. In case this did not occur, a boost converter was designed to regulate a constant output voltage of 10 volts and a constant current of 1.5 amps, assuming the input current was greater than 1.5 amps. The boost converter was designed with the assumption that the voltage of the solar cells would vary from 8 volts to 10 volts and that the current would not remain at a constant 2 amps.

The voltage of the boost converter is controlled using the LM555 timer to control the duty cycle and switching frequency of the power MOSFET switch. The power

MOSFET used was the IRF150 which is an ideal MOSFET to use for low power switching applications. The switching frequency varied from 2000 hertz at an 8 volt input to 1190 hertz at a 9 volt input. Figure 9 shows the simulated boost converter circuit in the CircuitLab program.

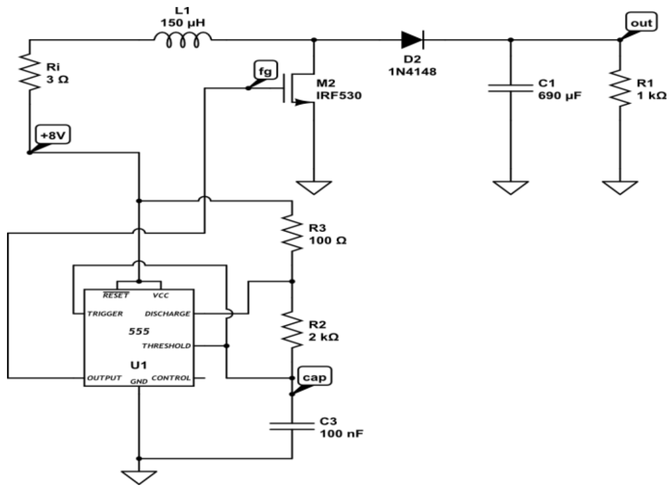


Figure 6.4.9: Boost Converter Schematic

The calculated critical inductance of the converter is 90 microhenries and the minimum capacitance is 571 microfarads. These values were calculated to keep the converter out of the discontinuous conduction mode. This mode occurs when the inductor discharges before the end of the switching cycle and it can create problems in the circuit. Ideally the inductor should fully discharge right at the end of the switching cycle.

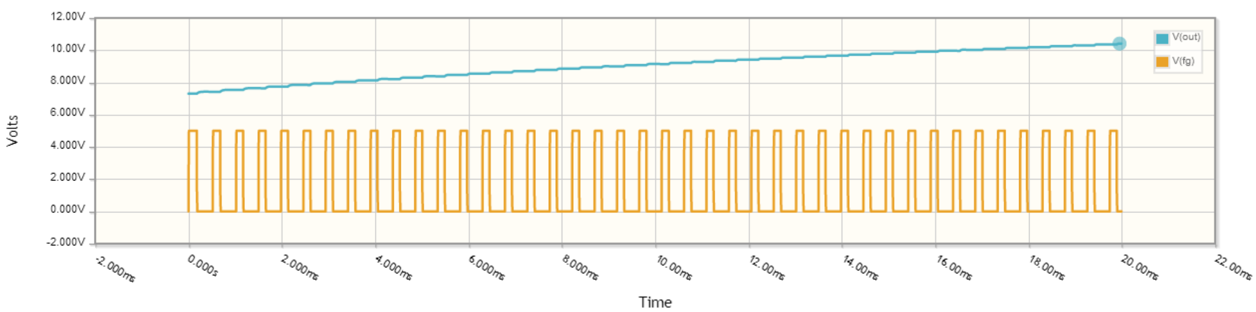


Figure 6.4.10: Discharging Voltage Simulation

Figure 10 shows the voltage across the switch (V(fg)) as well as the output voltage of the boost converter simulated in CircuitLab. The 8 volt input is increased to just above 10 volts in the simulation.
Figure 11:

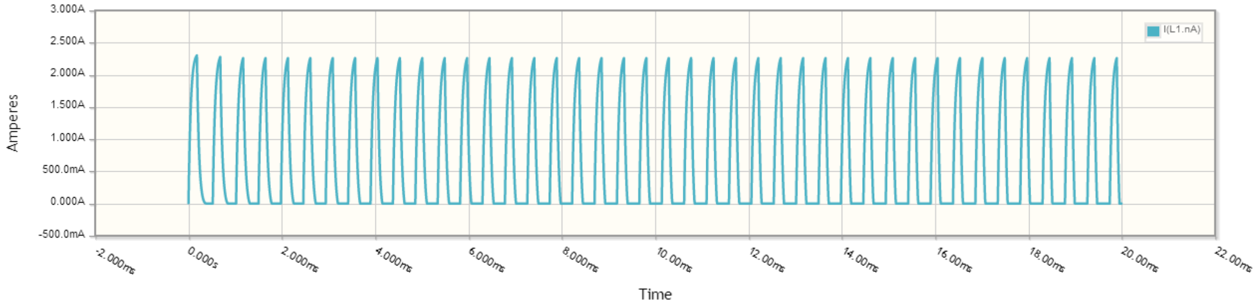


Figure 6.4.11: Discharging Current Simulation

Figure 11 shows the inductor current over the same time period as the simulation in figure 10. The simulation shows the effect of line commutation on the system which is something that was not accounted for in the calculations of the converter.

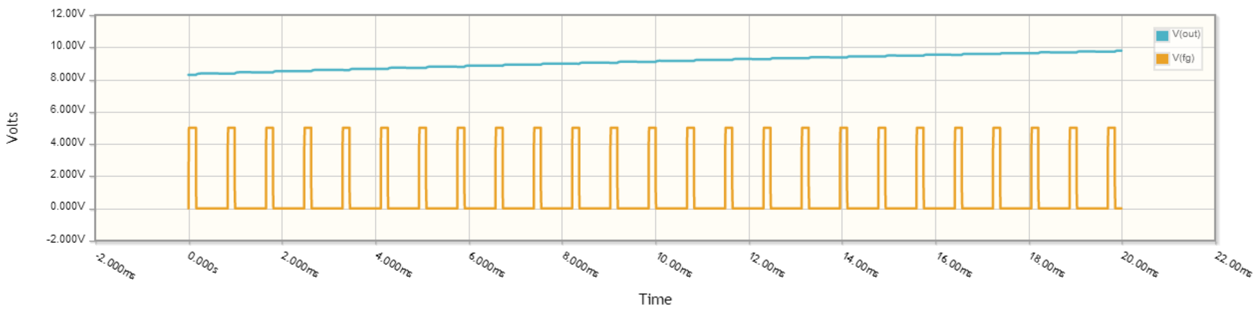


Figure 6.4.12: Discharging Simulation, 9V

Figure 12 shows the output voltage and voltage across the switch at a 9 volt input. The output goes to 10 volts at a slower pace than at the 8 volt input. The frequency of the switch is noticeably smaller but the duty ratio of the switch is larger than the switch at the 8 volt input.

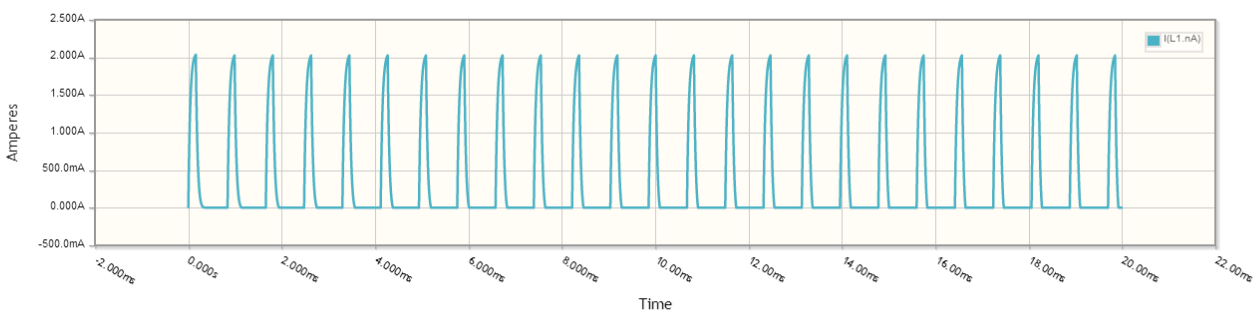


Figure 6.4.13: Discharging Simulation – Maximum current

Figure 13 shows the inductor current during the same time interval as the simulation above. The maximum current is smaller than at the 8 volt input and the effects of the line commutation have a greater effect on the circuit.

After testing, the boost converter was not included in the overall circuit of the system. The uncontrolled line commutation as well as the large current requirements made the boost converter less than ideal for the safe operation within the circuit. Also, the only controlled power sources available to test the converter had a limit of 1 amp, and the converter requires at least 1.5 amps to operate. This gave results that were inconclusive because the output voltage was staying just below the input voltage. This was cause for reasonable concern as to the operation of the converter so the converter was removed from the circuit. Additionally, solar panel testing (mentioned 6.3) demonstrated that the panel outputs stayed near a constant 10V, so the additional boost converter was not necessary to system operation.

6.4 Subsystem 5 – USB Charging Circuit and Lighting

Prepared By: John Malcovitch

The foremost goal of this project is to provide power to mobile devices, and so it is critical that the USB circuit actually works to charge devices. The USB Charging circuit subsystem is delineated from the Collection/storage circuit subsystem after the battery module: the USB subsystem energy directly from the 7.2V battery source and regulates the output to 5V. A second, parallel tap for the lighting circuit draws 7.2V and converts it down to 6V using a cheaper, though less efficient, circuit.

One main consideration for this subsystem is available energy at the batteries vs. energy available for the USB and lighting systems. The system technical specifications include:

- Will fully charge iPhone 4S battery (reference)
  - Requires 1420 mAh delivered through USB
- Provides lighting for at least 4 hours after full phone charge
  - Requires $E \geq 4hours * I_{lighting} + 1420\text{mAh}$

The first specification creates technical requirements due to the Apple iOS charging protocol, and also helps create a target system energy capacity for the other subsystems. The second requirement may slightly increase the energy requirement, but it also serves as a constraint on the choice of lighting elements once the system's battery selection has been made.

Additionally, inefficiencies must be taken into account to present a more accurate value for available energy. Nickel Metal Hydride batteries, as selected for this project, exhibit anywhere from 25% to 45% inefficiency in charging and discharging; an efficiency value of 66% will be used for this project until test data is available from selected batteries [1]. Also, for this subsystem, the batteries will be assumed to be fully charged, so inefficiencies on the charging side will not be considered. This leaves the available energy capacity, which for the USB portion can be expressed with the following:

$$E_{cap} = (Q_{mAh} * V)/1000 = (2500mAh * 7.2V)/1000 = 18\text{ Wh}$$

$$E_{avail} = E_{cap} * \eta_{discharge} * \eta_{reg}$$

$$E_{avail} = 18\text{Wh} * .66 * .93 = 11.048\text{ Wh} = \mathbf{2209.7\ mAh\ @\ 5V}$$

In these equations, η_{reg} is the efficiency of the power regulating circuit, governed largely by the efficiency of the DC-DC converter (specified by manufacturer). The selected converter is specified at 93% efficiency, and the energy values for the selected batteries are included above. This would appear to fulfill the requirement of having at least 1420 mAh at 5V available for the USB charger, which leaves available energy for the lighting circuit:

$$E_{light} = E_{cap} * \eta_{discharge} * \eta_{lights} - E_{USB}$$

$$E_{light} = 18\text{Wh} * .66 * .95 - (1420\text{mAh})(5V) = 4.186\text{Wh (or) } \mathbf{697mAh\ @\ 6}\boldsymbol{V}$$

This 697 mAh available for lighting is calculated using lighting materials that operate at 6V, and a conservative 95% efficiency estimation that is lower than the calculated efficiency with a simple voltage divider.

<u>USB Circuit:</u>

As mentioned previously, the USB charging circuit must obey certain protocols in order to charge certain devices. While pins 1 and 4 provide the 5V supply that actually charges a device, pins 2 and 3 are data lines used to send “handshake” signals in PCs and digital devices. The USB pin map for three common connectors is seen below.

Pin	Name	Cable color	Description
1	VCC	Red	+5 VDC
2	D-	White	Data -
3	D+	Green	Data +
4	GND	Black	Ground

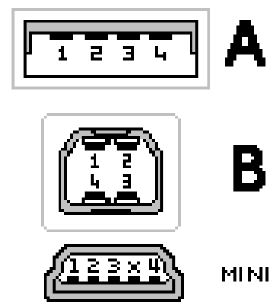


Figure 6.5.1: USB Pin Map[21]

Certain consumer devices are known to limit charging compatibility using these data-lines. In 2004, Apple began to include sensors in iPod Minis and other iDevices that required a certain voltage present on the data-lines before charging[14]. This was nominally to prevent device damage when attempting to charge with an inappropriate power supply. Beginning in 2007 with the introduction of the iPhone, the data-line signal was revised to require 2.0V on both the D- and D+ lines. This sent devices a signal that they were connected to a dedicated charger, and could draw 500 mA. Later standards increased the current capacity up to 2A for devices with larger batteries, such as the iPad.

To begin the circuit design, the group decided that the charger must supply a minimum of 500mA in order to charge Apple devices, requiring 2.0V signals present at both data lines. In order to do that, a resistance divider was created using high-value in order to minimize power loss. A simple voltage divider formula was used as follows:

$$V_{out} = V_s \frac{R_1}{R_1 + R_2} \quad \rightarrow \quad R_2 = \frac{V_s}{V_{out}} R_1 - R_1$$

Setting R1 equal to an arbitrary value such, such as 50kΩ yields:

$$R_2 = \frac{5V}{2V} 50\text{k}\Omega - 50\text{k}\Omega = 75\text{k}\Omega$$

Since 75kΩ and 49.9kΩ resistors are readily available, these values were accepted. Additionally, this divider circuit would only result in an ideal power loss of

$$P_{loss} = V_s I_{loss} = V_s\left(\frac{V_s}{R_t}\right) = \frac{5V^2}{75\text{k}\Omega + 49.9\text{k}\Omega} = \mathbf{2.00 * 10^{-4}\ W}$$

Using this Voltage divider as a basis for the USB charger, a circuit was designed around it. A DC-DC converter was chosen to step down the voltage from 7.2V at the batteries to 5V for the USB. The main motivation for this converter is the efficiency of available modules, such as the 93% efficiency of the unit chosen. Additionally, capacitors C1 and C2 were used to smooth the input and output ripple currents of the converter. The values of C1 and C2 were selected as specified in the datasheet for the V7805-1000 DC-DC converter [4]. The circuit is also fused to prevent damage to the connected device in any current spike, and a 5.1V Zener diode is incorporated to protect the circuit from overvoltage. The final circuit schematic is as follows:

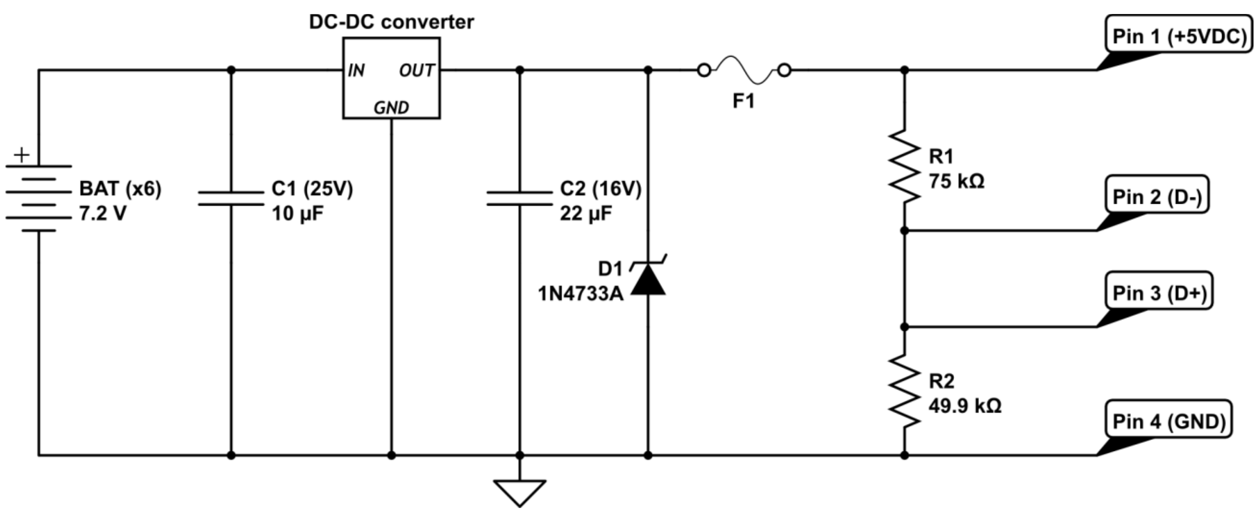


Figure 6.5.2: Complete USB Circuit, Mark I

During preliminary testing, this circuit charged iPhones, iPods, and Android Smartphones at 500mA. However, the Apple iPad (3rd Gen) would not accept this circuit as a charging source. This would effectively preclude owners of a market leading device from successfully using this device.

The circuit design was revisited, and a second set of data-line voltages was found that would enable the iPad to draw suitable charging current. This charger would also operate as a "fast charger" for other devices such as iPhones and compatible Android phones, allowing a current output of up to 1A. The initial DC/DC converter used in the first circuit had a maximum operating current of 1A, so a different DC/DC converter was ordered that would support up to 1.5A, preventing any undue chance of component damage. Additionally, the fuse was moved ahead of the converter as an extra safeguard. The biggest difference in this second circuit, shown below in figure 6.5.3, is the addition of a second voltage divider circuit that supplies 2.76V at the 'Data-' line.

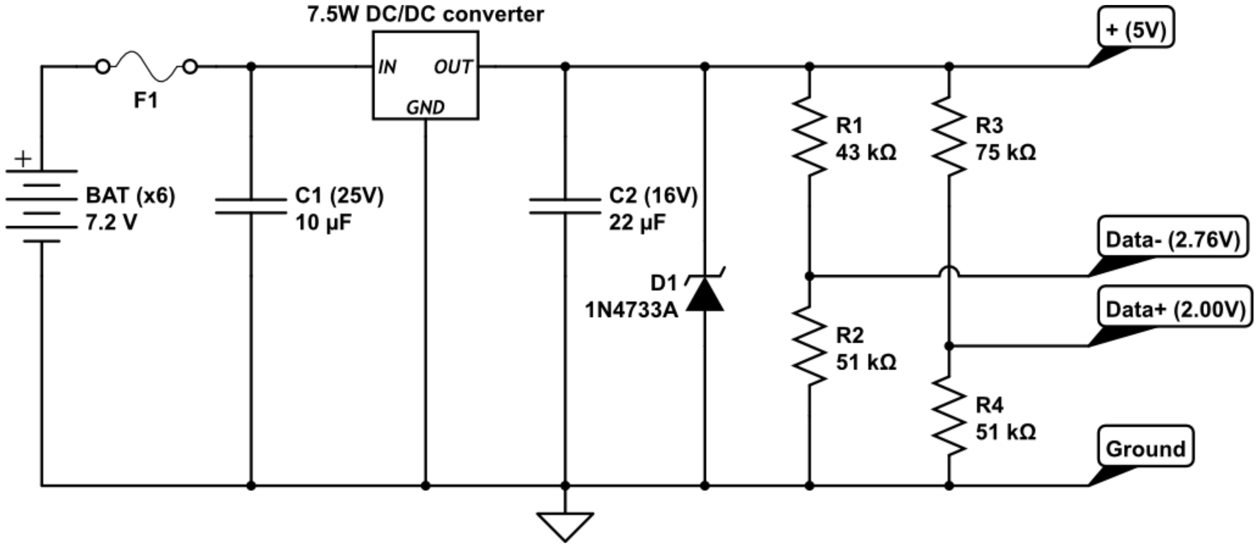


Figure 6.5.3: Complete USB Circuit, Mark I

This circuit, built and tested on a protoboard, proved to successfully charge all test devices including the iPad. The circuit is displayed on the protoboard in figure 6.5.4 below.

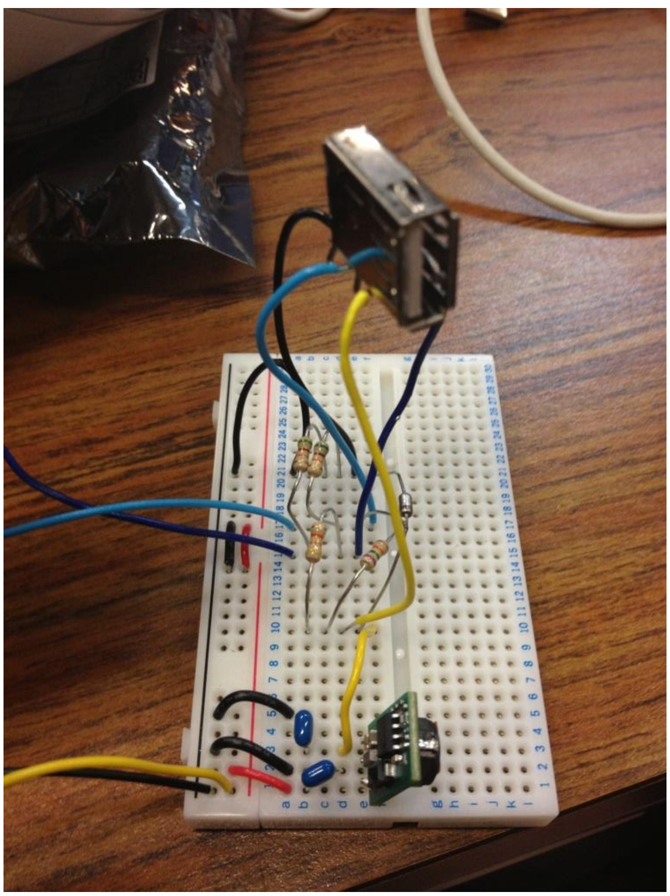


Figure 6.5.3: Complete USB Circuit, Mark II

Lighting:

To design the lighting system, an efficient illumination source that operated on less than 7.2V was required. This narrowed the range of possible solutions to LED arrays or LED light-strips. LED strips or “light strings” were selected due to their wider illumination area, compared to spot LEDs (as common in flashlights). The spot lighting would be more efficient at focusing light for tasks such as reading, but would require frequent manual adjustment. The LED array would distribute light more evenly, which would be more suitable to casual reading or tasks, and also provide greater ease of use for the end user.

An LED strip was chosen based on both weather resistance and component cost. This strip was tested and found to output ample light for casual reading in a totally darkened room. However, this strip operates in a very narrow range between 5V – 6V, with very little visible light at 5V. Thus, a divider circuit is required to supply the lighting strip with 6V. Utilizing the formula used previously,

$$R_2 = \frac{7.2V}{6V} 810\text{k}\Omega - 810\text{k}\Omega = 162\text{k}\Omega$$

This formula was iterated several times in order to arrive at a commonly available resistor values, and a 160 kΩ is the closest available value. This yielded a predicted 6.0124V at the output of the divider circuit, which was found to be tolerated by the LED array. The original lighting circuit schematic is displayed along with the USB block and battery in the figure below:

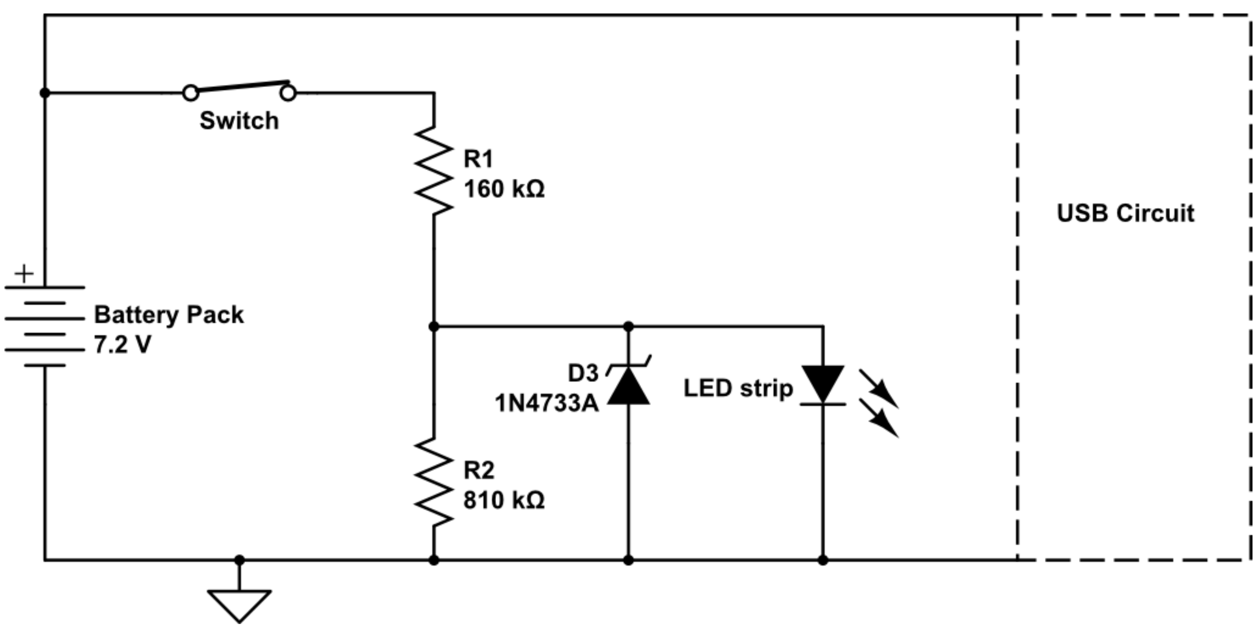


Figure 6.5.4: Original Lighting Circuit

This circuit proved insufficient, however, as the actual voltage present at the voltage divider tap only reached a maximum of 5.35V, even when the circuit was driven directly by constant voltage source. After checking all the wiring and troubleshooting, the Electrical Engineering student in charge of Power Regulation was consulted. This student pointed out that the difficulty could be caused by the very high resistor values. The dividers were redesigned using available low-value resistors, and testing showed the circuit had exactly 6.00V present at the lighting tap. A schematic of the final lighting circuit is included below in figure 6.5.4.

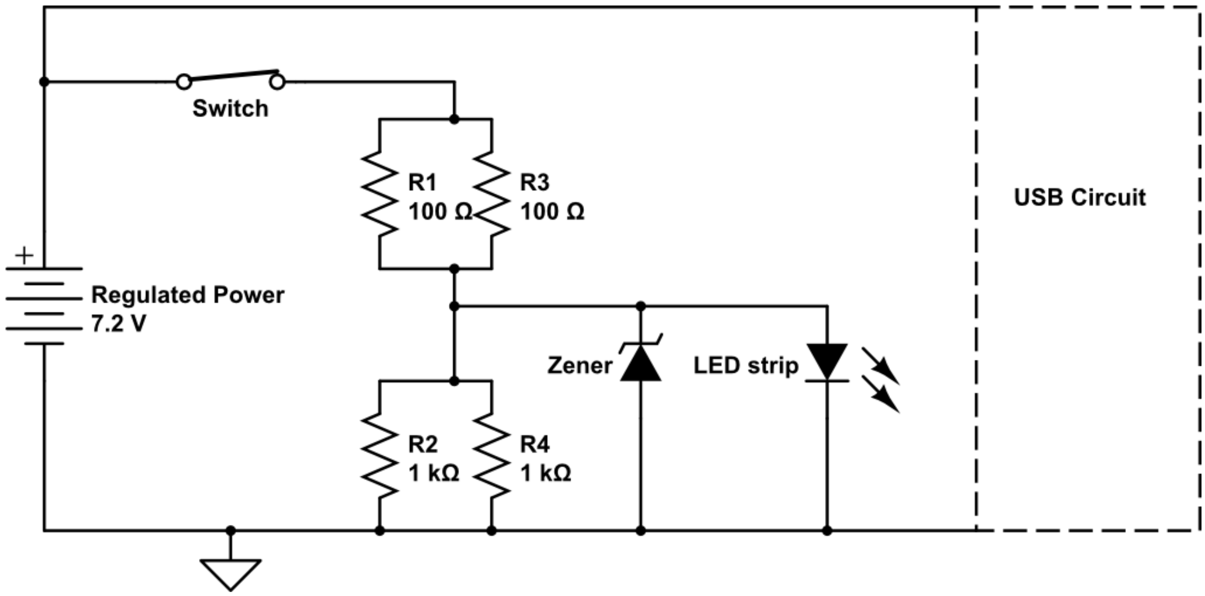


Figure 6.5.4: Final Lighting Circuit Design

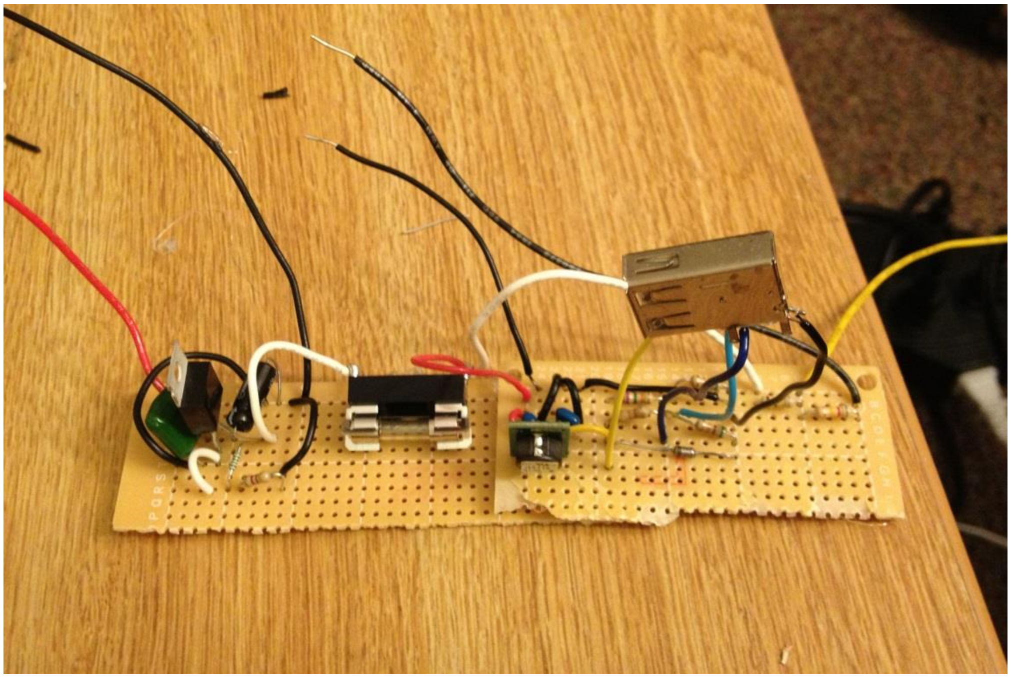


Figure 6.5.5: Constructed Power Regulation, USB, and Lighting Circuits

The charging and lighting circuits both worked as intended. A spare USB cord was cut open to allow voltage data to be collected for the charging circuit, and a bench-top power supply could be used to measure real time current output. The lighting output can be tested either using an expensive piece of precision equipment, known as an integrating sphere, or with a low-tech 'pass/fail' method such as a readability test in a dark room. Some photography enthusiasts refer to a method of calculating EV settings in order to determine a lumen rating, but the validity of this experimental method is unknown.

The LED lighting strip produced enough light to read sheets in a totally blackened room, as displayed in figure 6.5.6 below.

Figure 6.5.6: Dark Room Readability testing

However, when attempting to use the "EV" method while the lights were mounted on the final system, the calculations yielded Lumen values between 1-3 lumens. For reference, a relatively low power 40W incandescent bulb is rated at 500 lumens. This seems to indicate that the EV method is inaccurate, at least with the camera equipment used to carry out the test. A final image of the lighting testing is shown below in figure 6.5.7.

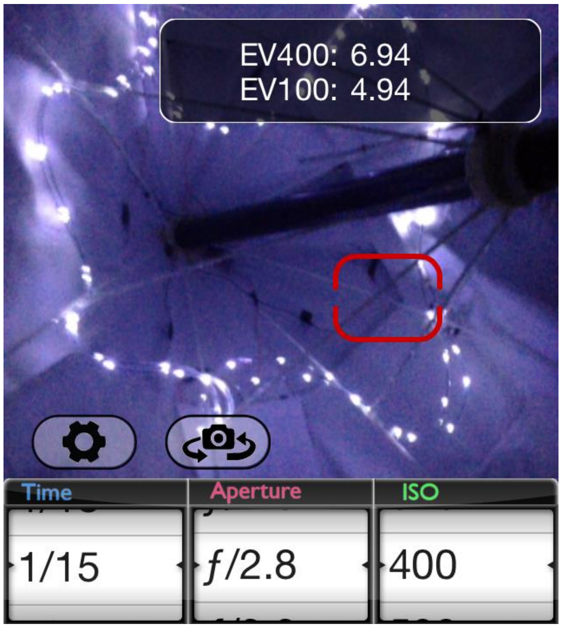


Figure 6.5.7: EV Exposure-to-lumen test method

7 Results and Discussion

7.1 Results

System testing began with the solar panels. The team first needed to establish whether they would produce a constant voltage or constant current. If they produced a constant voltage as suspected, their sensitivity to clouds, angular orientation to sun had to be tested. Voltage testing was completed using a LabJack writing data to a basic PC UI. The panels were then wired to the LabJack in a number of different arrangements. Some of the data from these tests are represented in following graphs.

Figure 7.1.1: Solar Panels and LabJack arrayed for testing

In the first set of tests, illustrated below in figure 7.1.2, the voltage is tracked as a single canopy is rotated through various angular orientations to the sun. This data is typical of other results from different panels, showing that the voltage remains constant regardless of position or partial blockage.

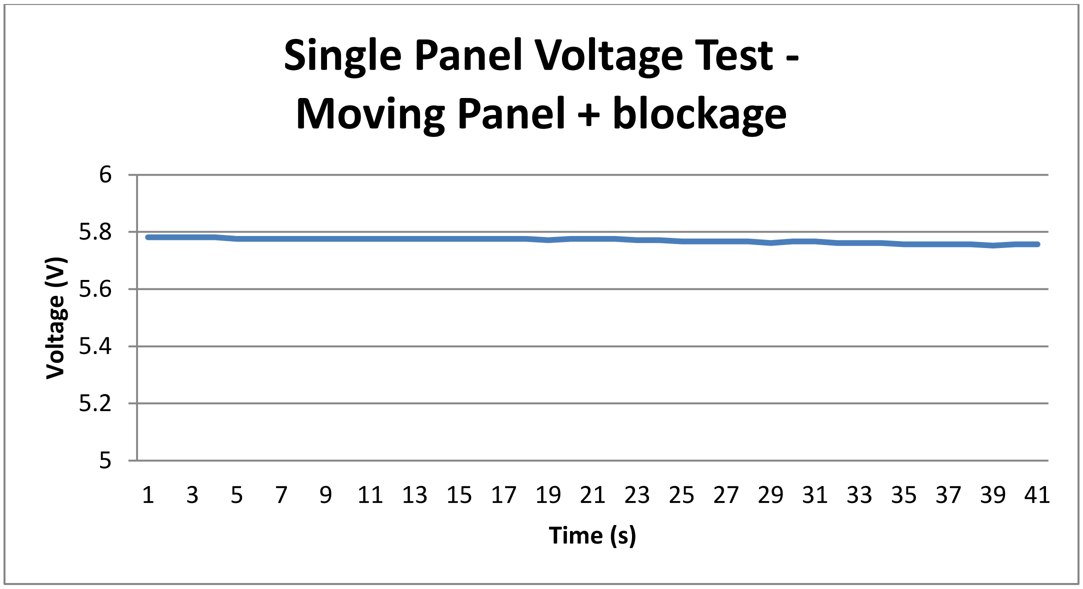


Figure 7.1.2: Single panel rotation and partial shade

In another test, several panels at the same angle were left outside for over 7 minutes to track voltage consistency. It is apparent from the results in figure 7.1.3 that the output voltages track well together. There is an unusual dip around the 6 minute mark that could not be fully explained. However, the observer will note that the Y axis is magnified so that the complete scale ranges from 5V to 6V. This is only a momentary 3.5% dip, and the output voltage still stays above the 5V nominal rating.

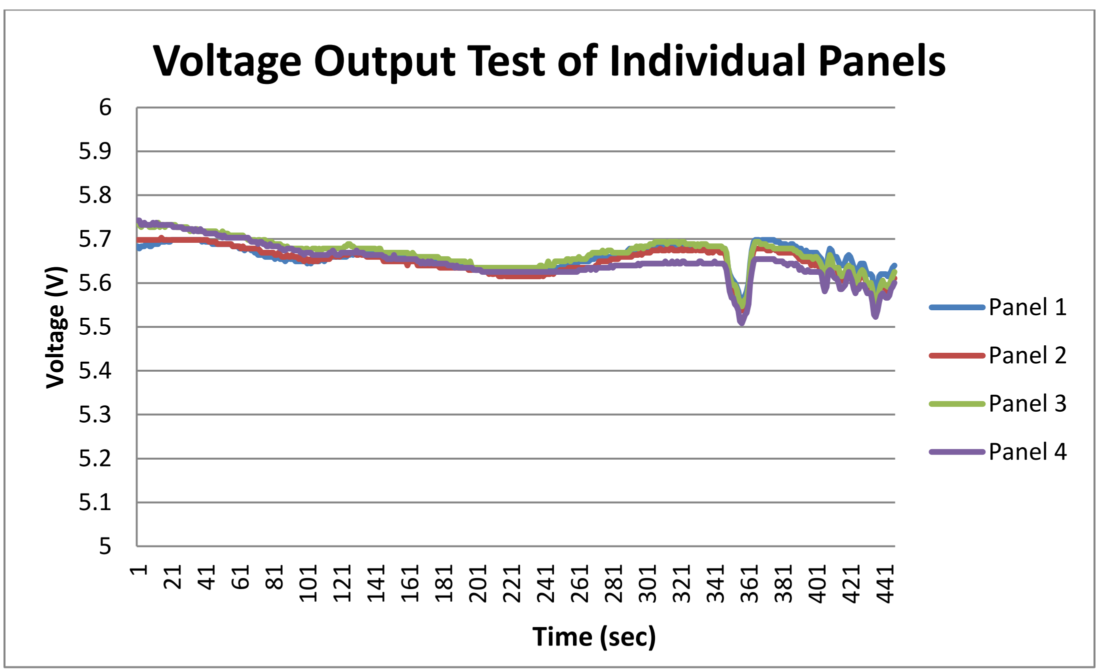


Figure 7.1.3: Voltage Consistency test

Another set of data includes one column of values for two panels hooked in series. By placing the panels in series, the panels produced a very constant voltage around 11V. This is represented below in figure 7.1.4. These readings had to be taken with a multimeter, since the experimenters discovered the LabJack has a maximum input voltage of 10V. This resulted in spreadsheets of data with a constant 9.995117 V.

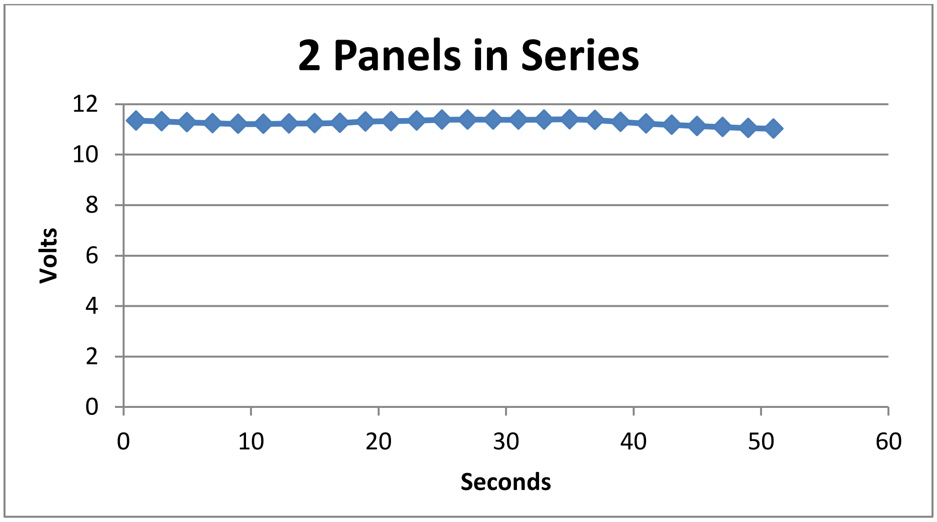


Figure 7.1.4: Series panel voltage testing

Tests were performed to test the current. These data show the current output is highly dependent on a range of variables such as cloud cover, and partial shade. Different conditions were noted during data recording, and key points were noted on graphs below. All tests were done with a multimeter, since the LabJack could not handle the amount of current produced by the panels. Recordings were taken every 5 seconds or so and entered into a spreadsheet.

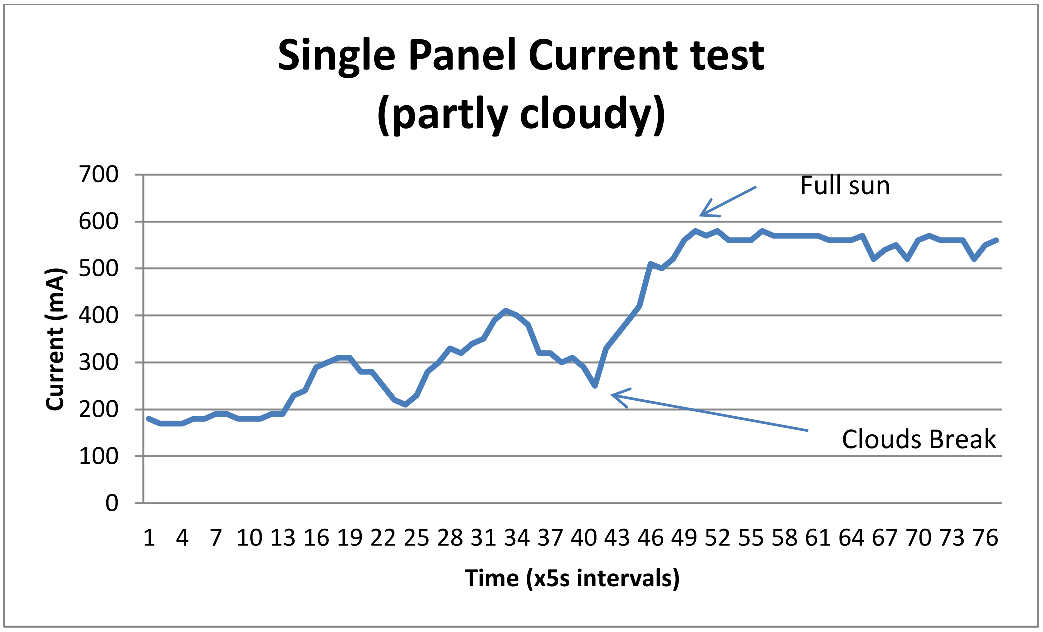


Figure 7.1.6:

The test in figure 7.1.4 above shows the current output while the cloud cover varies. Note that the x-axis is counting intervals, and thus these are 76 readings at 5 seconds intervals (slightly over 6 minutes testing). The next test, represented in figure 7.1.6 below shows 2 panels tested in series and the effects of rotation away from the sun. There is also a stretch where one of the panels was blocked by a shadow cast by the tester's hand.

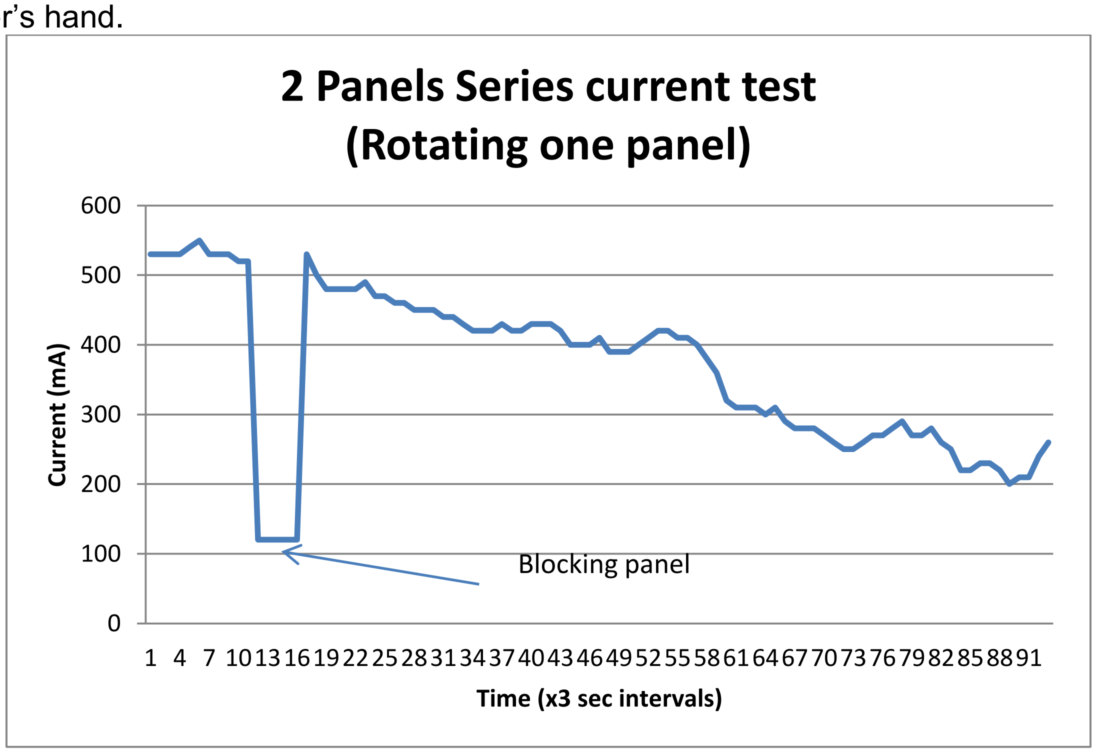


Figure 7.1.7:

The next graph in figure 7.1.7 shows the effect of blockage only on 2 panels in series. It is shown that covering one panel eliminates most of the current output. The first blockage portion reducing current to about 120mA occurred when holding a hand about 5 inches above one panel, still allowing some sunlight to strike the panel. The next reductions represent the total covering of one or two panels by holding a flat object over the entire panel surface.

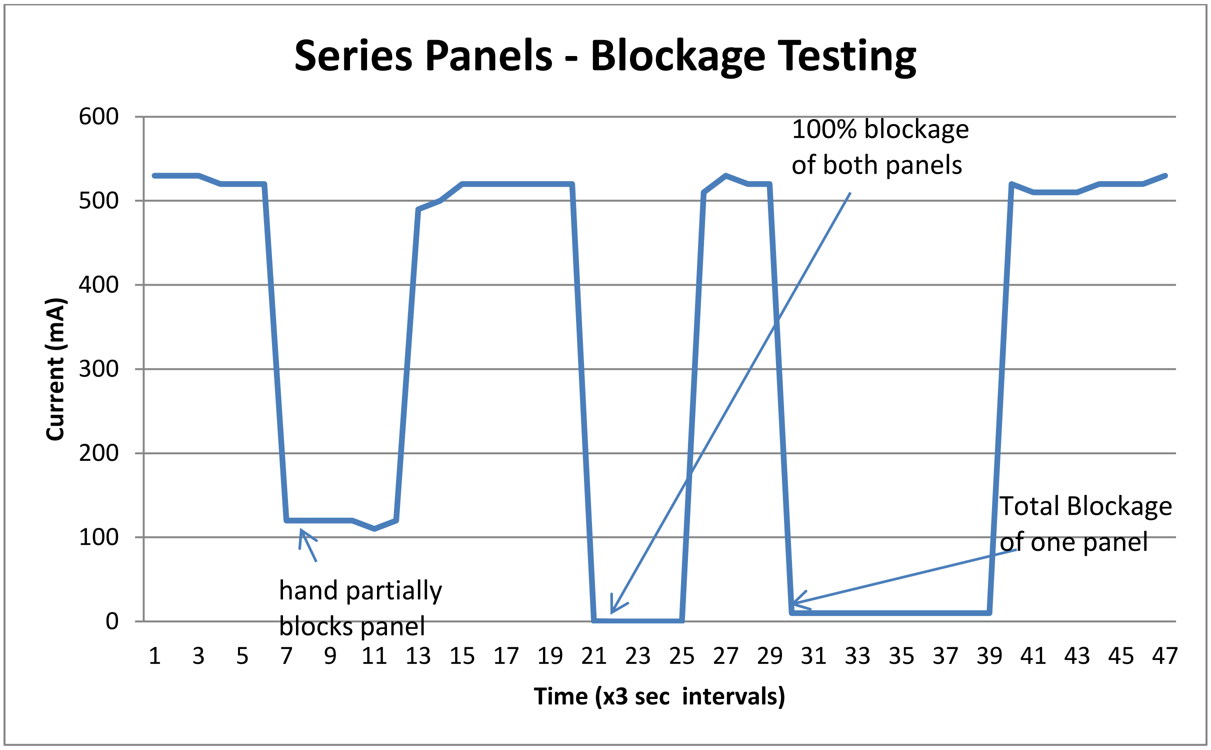


Figure 7.1.8:

These tests were done on individual panels, since the panel wiring needed to be waterproofed after the full assembly of the umbrella. Measuring the current for the full system would have required cutting into main transmission wiring and putting Ammeter (multi-meter) in series, which could have provided electrical hazard once reassembled.

The USB Charging subsystem was also tested thoroughly once the final circuit design was constructed. First, the circuit was tested with nearly all of the USB devices available to the experimenters. The results of the charging success are recorded in Table 7.1A below.

Table 7.1A – Device charging compatibility

Device	Charge Successfully?
iPhone 4S	√
iPad 3rd Gen	√
Motorola Droid (Android Smartphone)	√
iPod Nano	√
Bluetooth Headset	√
Sony PS3 Controller	√
iPhone battery charger (portable)	√
FitBit health tracker	√
Potato	X
iPhone 5	√

The USB Charger thus proved it was nearly universally compatible as a charger. However, more in depth data was desired for certain devices. The subsystem designer tested this by using a bench-top power supply that could be set to hold a precise output voltage, and then display the current drawn. This apparatus was then connected to the input of the USB circuit at the DC/DC converter, and a device was plugged into the USB socket. The test was started at 7.2V, swept up until 10V, and then swept down again to 4.8V. Readings were taken in 0.1V increments, after readings stabilized. The first device tested was the iPhone 4S, as seen below in figure 7.19.

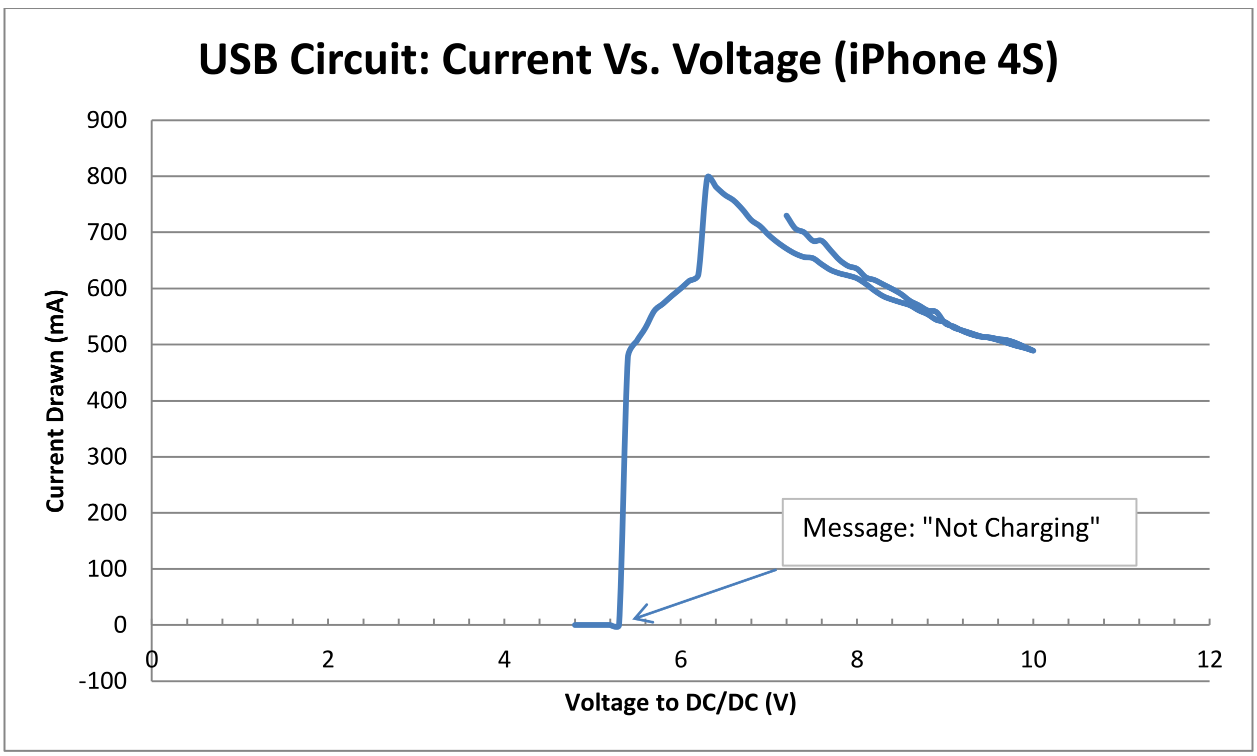


Figure 7.1.9: Output Current vs. Input Voltage graph for iPhone 4S

The iPhone 4S seems to draw the most current when the USB circuit has a 6.2V input. The exact mechanism for this is unclear, as the output of the USB+ pin remains at a steady 4.9V throughout. The explanation likely likes in the current handling characteristics of the DC/DC converter, and how it adjusts current to maintain a steady voltage. It is interesting to note that the curve did not follow quite the same path when retracing 10V to 7.2V as it did when sweeping up. Also, the phone indicated that it was still charging until the output current dropped to absolute zero (5.2V).

The same test was then conducted on the iPad 3rd Gen, viewed below in figure 7.10.

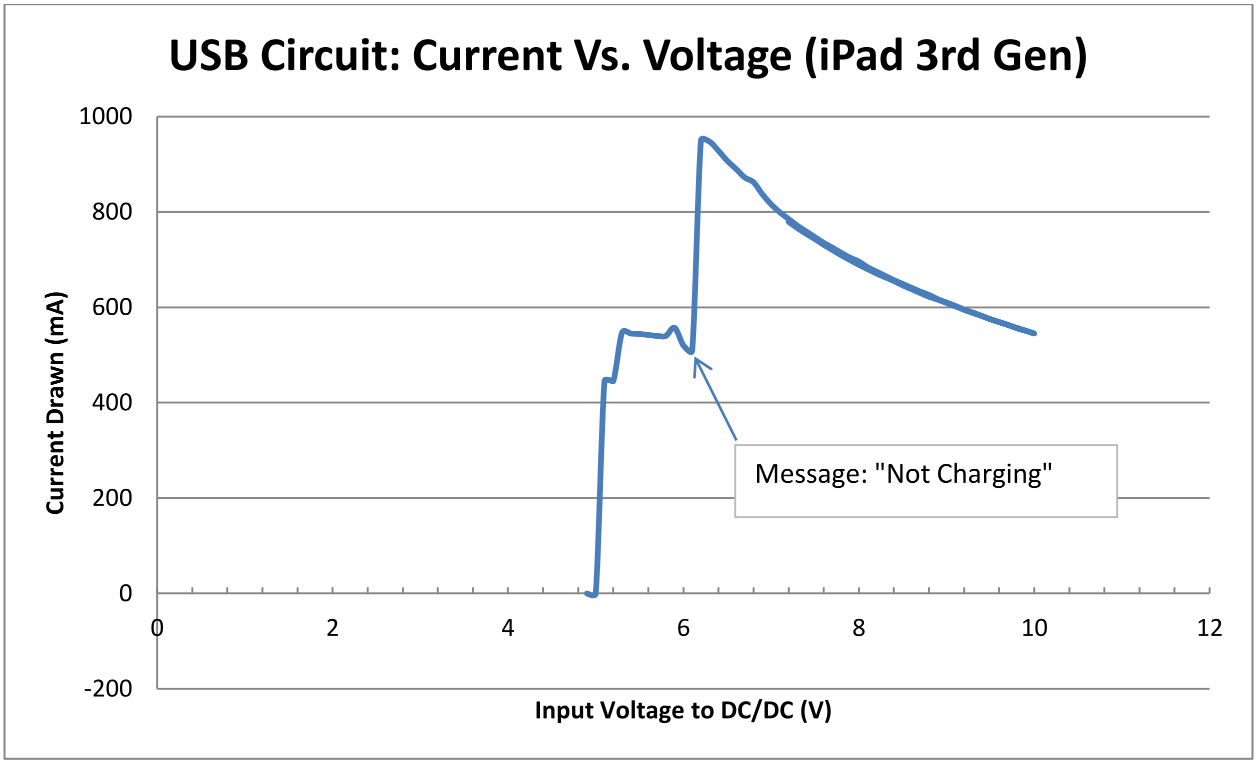


Figure 7.1.10: Output Current vs. Input Voltage graph for iPad 3rd Gen

For this test, the iPad drew nearly the exact same current on the initial sweep up/sweep down trace between 7.2V and 10V. However, 6.2V was the lowest voltage where the iPad reported charging; at 6.1V, the current drawn dropped dramatically, and the iPad displayed a “Not Charging method”. The iPad continued to draw current until 5.1V, however. Additionally, while the iPhone could be started at a low voltage (0-4V) and ramped up until a charging message appeared, the iPad would only display “not charging” if the voltage ever dipped below 6.2V, until the plug was removed and reinserted with a proper voltage. This may explain the “finicky” nature of the iPad charging: if the voltage dipped even for a fraction of a second, the iPad would not indicate charging until plugged in anew. This might cause non-charging status if the battery pack is shaken during operation.

With baseline data established from individual subsystems, the overall system could be assembled and tested against goal metrics. First, figure 7.1.11 below shows that the iPhone 4S (reference phone) is fully charged from 0% to 100% in less than 3 hours. Elapsed charging time is plotted on the X axis, and both voltage and % charge are plotted on different Y-axes. It is clear how the battery voltage drops off very quickly and then stays around a constant 7.3V. Also, the phone initially charges at a very consistent rate, but then starts to slow down around the 85% charged mark. The load voltage starts to creep back up, indicating that the iPhone may be using some software commands to draw less current as it approaches full charge. The final voltage (7.35 V) indicates that the batteries are still above nominal charge, and have more energy to supply to devices.

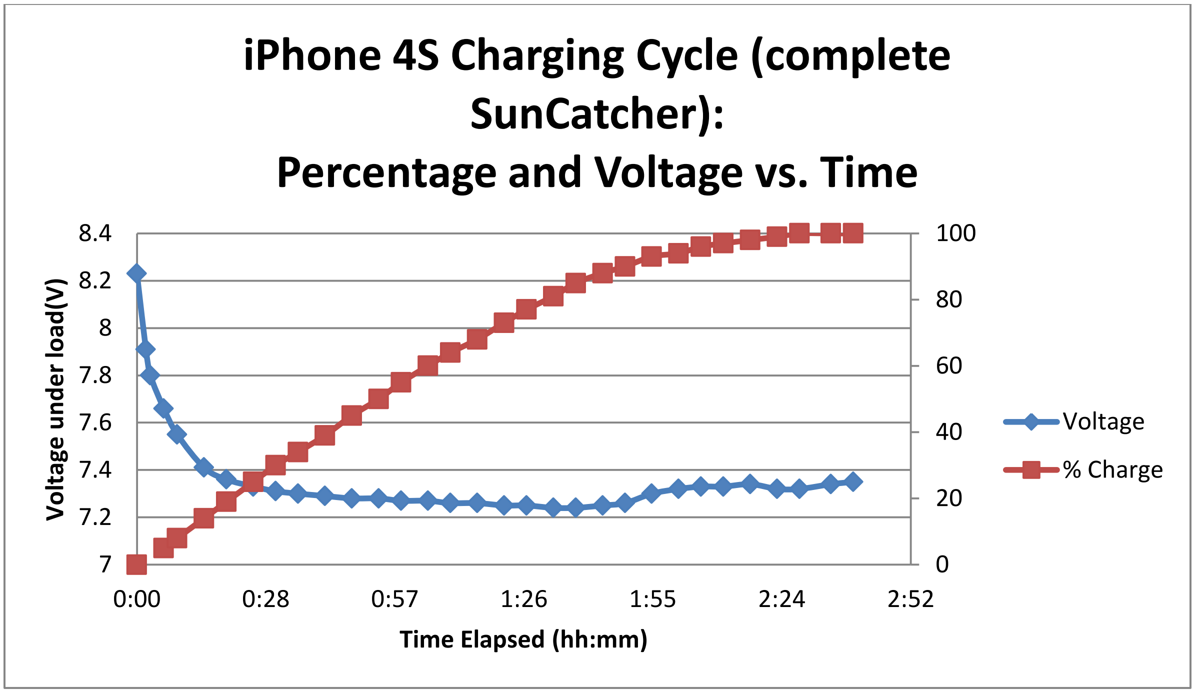


Figure 7.1.11: iPhone 4S Full charge cycle

This test was done by attaching voltmeter to either end of battery pack, and then plugging in a completely dead iPhone to be charged. Manual readings were taken from voltmeter and iPhone every 5~6 minutes. This measurement could not be automated, since there was no practical way to record the iPhone charge percentage other than an experimenter sitting there taking readings. Bluetooth and WiFi were turned off for this test, the screen brightness set to 30%, and the screen turned off after every percentage reading.

After the panels and iPhone were tested, the complete system was tested for battery charge rate in mid-day sun. For this test, the system was set up outside in a sunny field. An initial

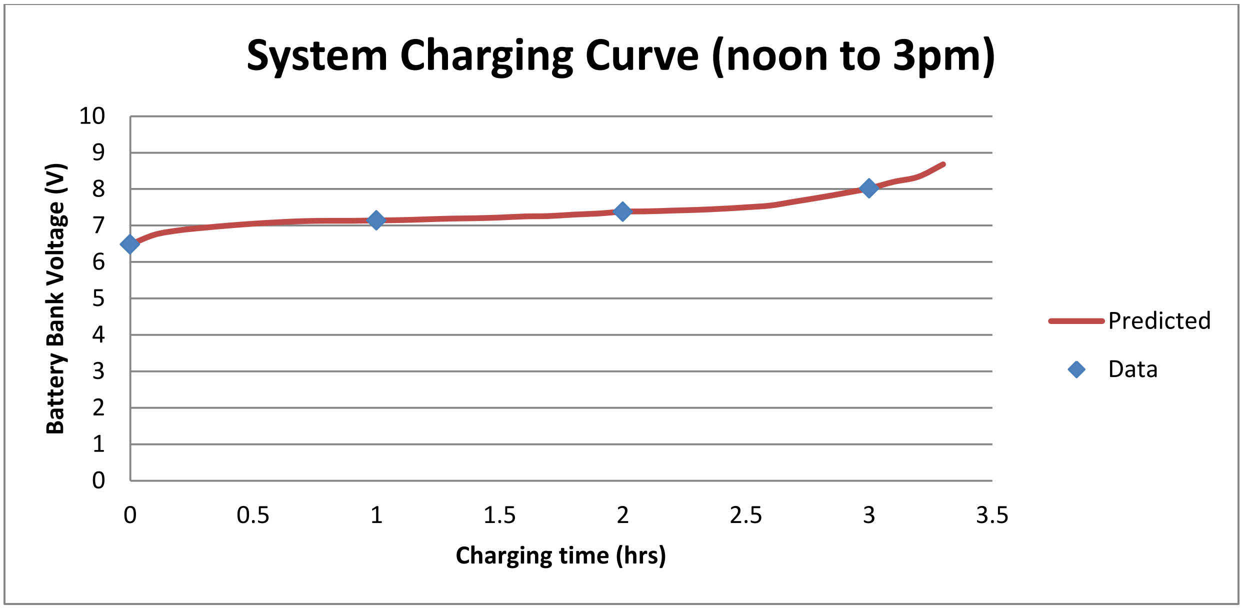


Figure 7.1.12: System Battery Full Charge Cycle

All of these tests led to a successful prototype that will be able to charge any electronic device that can connect with a USB cord. A summary table of the system performance is displayed below in figure 7.1B.

Figure 7.1B: Final Performance Metrics

Customer Requirement	Technical Specification	Target Value	Actual Value	Success?
Sufficient Energy Storage	mAh	≥ 2400 mAh	> 2800 mAh (Upper limit?)	√~
Quick device charging	Max Output Current	≥ 500 mA	1.0A max	√
Doesn't hurt users	Safety	0 casualties	0 casualties	√
Lightweight	Pounds	< 20 lbs	11.55 lbs	√
Large shade area	Area	≥6 ft diameter	6.00 ft	√
Inexpensive	Estimated Production Cost ($)	< $150	$118.02	√
Sufficient lighting (night use)	Lumens (or readability Test)	≥ 300 lumens	Dark Room Readability	√~
Water resistant wiring	Time withstood rain	10 minutes	5 minutes under hose	~
Won't tip over in wind	Wind speed withstood	15 mph	Needs testing apparatus	~

√ = Goal Met ~ = Further testing required

Open Issues:

There are a few additional tests which would have yielded valuable insight for the project had the project duration been longer. Some of these tests include:

*Effect of seasonal solar variation on panel output
*Effect of moisture contact (due to humid environment, not direct water)
*Full lighting testing using appropriate equipment (integrating sphere)
*Full stability in deep sand, wind speeds
*Complete Charging curves for more devices (iPad, iPod Nano, Android phones)
*Absolute figure on system battery charge capacity.

7.2 Significant Technical Accomplishments

The team members were able to develop skills with many different software and hardware tools that individuals had never used before. For many team members, SolidWorks was a brand new tool. Team members were able to explore the software and learn effective, technical design and analysis techniques that will be valuable in several engineering disciplines.

The project also helped students further develop knowledge in strength of materials. Since all parts of the system were load bearing to a certain extent, the team had to be wary of stress, strain, and deflection in each subsystem and the overall system. The complexity of several of the force and displacement interactions also gave students an exercise in deciding how to effectively simplify a complex model, while still obtaining valid results.

Many of the students were also able to develop either electrical connection skills, or further work on skills in circuit design and analysis. The electrical challenges presented in this project spanned a range of difficulty that allowed students of different EE exposure to learn new concepts and abilities.

8 Conclusions

By: Matthew Causa

Every member of Team SunCatcher learned valuable lessons from the 10-week long project, not only in the design process, but in working with a diverse team. Coming up with a great idea is not easy. Even harder than that is guiding an idea through the engineering process to become a well-designed product.

The final product performed very well, at met all primary target specifications. The system can fully charge the chosen reference USB device to 100% in just over 2.5 hours, well under the 4 hour target. Additionally, the team set out to design a charging system that could fully charge batteries in under four hours, and the final system can be fully charged in approximately three. Finally, the estimated production cost, calculated for a mid-volume run of 10,000 units, is $118, under the $150 production estimate set forth as an initial goal. The only specifications not explicitly met would require additional testing to verify, such as wind-speed resistance.

In order to meet customer requirements and technical specifications thoroughly (and efficiently), all team members had to communicate effectively and divide the workload in a manner that would leverage individual member strengths. These two factors were the keys to our overall success as a team, and to the technical success outlined above. The SunCatcher prototype was designed, built, and validated on time and met all customer requirements and testable technical specifications.

9 References

[1] Flexural Strength Testing of Plastics. (n.d.). *Online Materials Information Resource - MatWeb*. Retrieved May 9, 2013, from http://www.matweb.com/reference/flexuralstrength.aspx

[2] GPO-3 Flame and Track Resistant Fiberglass Mat Reinforced from Red Seal. (n.d.). *Red Seal Electric Company*. Retrieved May 9, 2013, from http://www.redseal.com/non-metallic-insulation-products/gpo-3.aspx

[3] MatWeb - The Online Materials Information Resource. (n.d.). *Online Materials Information Resource - MatWeb*. Retrieved May 9, 2013, from http://www.matweb.com/search/datasheet.aspx?matguid=d606019e896d44ea9099bdab91787664&ckck=1

[4] How to charge Nickel Metal Hydride Batteries. . (n.d.). *PowerStream*. Retrieved May 9, 2013, from http://www.powerstream.com/NiMH.htm

[5] AEI. (n.d.). *ACE EVERT*. Retrieved May 9, 2013, from http://aceevert.com/faq.html

[6] ASM Material Data Sheet. (n.d.). *ASM*. Retrieved May 9, 2013, from http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061t6

[7] Diodes, p. (n.d.). Solar Radiation on a Tilted Surface | PVEducation. *PVEducation*. Retrieved May 9, 2013, from http://www.pveducation.org/pvcdrom/properties-of-sunlight/solar-radiation-on-tilted-surface

[8] Don't Be a PV Efficiency Snob | Do the Math. (n.d.). *UC San Diego - Department of Physics*. Retrieved May 9, 2013, from http://physics.ucsd.edu/do-the-math/2011/09/dont-be-a-pv-efficiency-snob/

[9] How to replace a fiberglass rib. - YouTube. (n.d.). *YouTube*. Retrieved May 9, 2013,

from http://www.youtube.com/watch?v=NG1yvlBX79o

[10] McMaster-Carr. (n.d.). *McMaster-Carr*. Retrieved May 6, 2013, from http://www.mcmaster.com/#birch-wood/=mmeel4

[11] Cox, R., & whole, w. d. (n.d.). Wind Loads. Amateur Radio Station K7NV . Retrieved April 4, 2013, from http://k7nv.com/notebook/topics/windload.html

[12] Drag Coefficients . (n.d.). Engineering ToolBox . Retrieved April 7, 2013, from http://www.engineeringtoolbox.com/drag-coefficient-d_627.html [12] McMaster-Carr. (n.d.). *McMaster-Carr*. Retrieved May 6, 2013, from http://www.mcmaster.com/#8549kac/=mo3hpc

[13] MiaSole Sets Flexible PV Efficiency World Record at 15.5 Percent. (n.d.). *Green Tech Media*. Retrieved May 1, 2013, from http://www.greentechmedia.com/industry/read/miasole-sets-flexible-pv-efficiency-world-record-at-15.5-perc-93083/

[14] MintyBoost - The mysteries of Apple device charging. (n.d.). *limor*. Retrieved May 9, 2013, from http://www.ladyada.net/make/mintyboost/icharge.html

[15] Nylon Properties |Technical Information (Polyamide). (n.d.). *Plastic Lab Supplies | Plastic Labware*. Retrieved May 9, 2013, from http://www.dynalabcorp.com/technical_info_nylon.asp

[16] PVC Polyvinyl Chloride Detailed Property Chart. (n.d.). *TexCal Wire and Cable* . Retrieved May 9, 2013, from http://www.texwire.us/cablewire/pvcproperties.html

[17] Polypropylene, Polyester, and Nylon: More Than You Ever Wanted to Know. (n.d.). Retrieved May 9, 2013, from http://www.qualitylogoproducts.com /blog/polypropylene-polyester-nylon-guide-to-materials/

[18] Solar Panel Efficiency Ratings and Comparison Table. (n.d.). *Solar Energy Facts-All About PV Power*. Retrieved May 9, 2013, from http://www.factsaboutsolarenergy.us/solar-panel-efficiency.html

[19] Solar Panel Types & Application... Does It Really Matter Which One I Choose? | Solar Stik. (n.d.). *Solar Stik - The New Generator* | *Solar Stik*. Retrieved May 9, 2013, from http://www.solarstik.com/stikopedia/solar-stiktm-system-overview/choosing-power-generators/amorphous-vs-cigs

[20] Solar Radiation at Earth. (n.d.). *Windows to the Universe*. Retrieved May 9, 2013, from http://www.windows2universe.org/earth/climate/sun_radiation_at_earth.html

[21] USB Pinout - Connector Wiring for USB A, USB B, and Mini USB Interfaces. (n.d.). Retrieved April 3, 2013, from http://www.connections-usa.com/usb_pinout.html

[22] Wire Gauge and Current Limit Table. (n.d.). *Cables & Connectors, Inc*. Retrieved April 12, 2013, from http://www.cablesandconnectors.com/wiregauge.html

[23] Wood Strengths. (n.d.). *WoodWorkWeb*. Retrieved May 9, 2013, from http://www.woodworkweb.com/woodwork-topics/wood/146-wood-strengths.html

[24] Wood Strengths and Stiffness. (n.d.). *pdf file*. Retrieved May 9, 2013, from www.fpl.fs.fed.us/documnts/pdf2001/green01d.pdf

[25] Non-isolated switching regulator. (n.d.). *CUI INC.*. Retrieved May 9, 2013, from www.cui.com/Product/Resource/DigiKeyPDF/V78XX-1000.pdf

[26] Nylon Rod, u. t. (n.d.). McMaster-Carr. *McMaster-Carr*. Retrieved May 9, 2013, from http://www.mcmaster.com/#8628K66

[27] *Injection molding cost estimator*. (n.d.). Retrieved from http://www.custompartnet.com/estimate/injection-molding/

10 Appendix A: Selection of Team Project

Prepared By: Kerry White

A mind-map was used to highlight several possible elements involved in solving the problem of generating remote power, as seen above in figure 10.1.

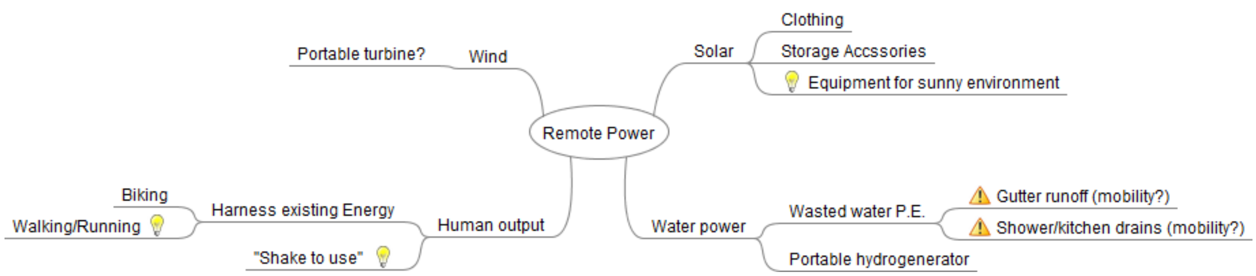


Figure 10.1: Problem Mind-Map

The results of the mind-map were used to create a concept combination table, found in Table 10.1 below.

Table 10.1: Concept Combination Table

Remote energy			
Power source	***Collect Energy***	***Store Energy***	***Apply Energy***
Human output	Magnet -> current	Battery pack	Device charging
Sun	Photovoltaic	Capacitor Bank	Lighting
Wind	Turbine	Direct output	Music systems

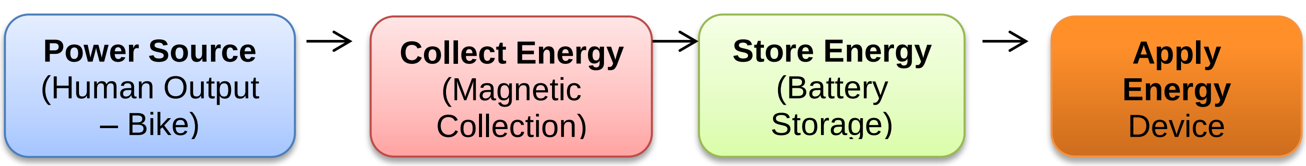
After combining a power source, way to collect, store and apply energy, five solution concepts were generated and the most promising were entered into a concept solution matrix, shown in table 10.2.

Table 10.2: Concept Selection Matrix

Selection Criteria	Concepts (1 = Good, -1 = Poor)				
	Bike powered charging module	**PV Backpack**	**PV Umbrella**	**Motion charged hiking stick**	**Bike mounted mini-turbine**
Estimated Efficiency	-1	0	1	0	-1
Safety	-1	0	1	1	-1
Estimated User Base	1	1	1	-1	0
Subsystem Division	1	-1	1	1	0
Weight/Portability	1	1	0	1	1
Existing availability	0	-1	1	1	1
Modeling Complexity	0	1	0	0	1
Build Complexity	1	1	-1	0	0
Net Score	**2**	**2**	**4**	**3**	**1**
Rank	**4**	**3**	**1**	**2**	**5**
Continue?	Y	Reject	Y	Y	

Although the PV charging backpack ranked 3rd in the selection matrix, the group decided that the backpack did not have enough possible subsystems to be considered an option. Also, after benchmarking research, hundreds of units were found online already available for low cost. Thus, the next highest ranked concept, the bike-powered charging module, was chosen for further investigation.

Concept One: Bike Powered Charging Module



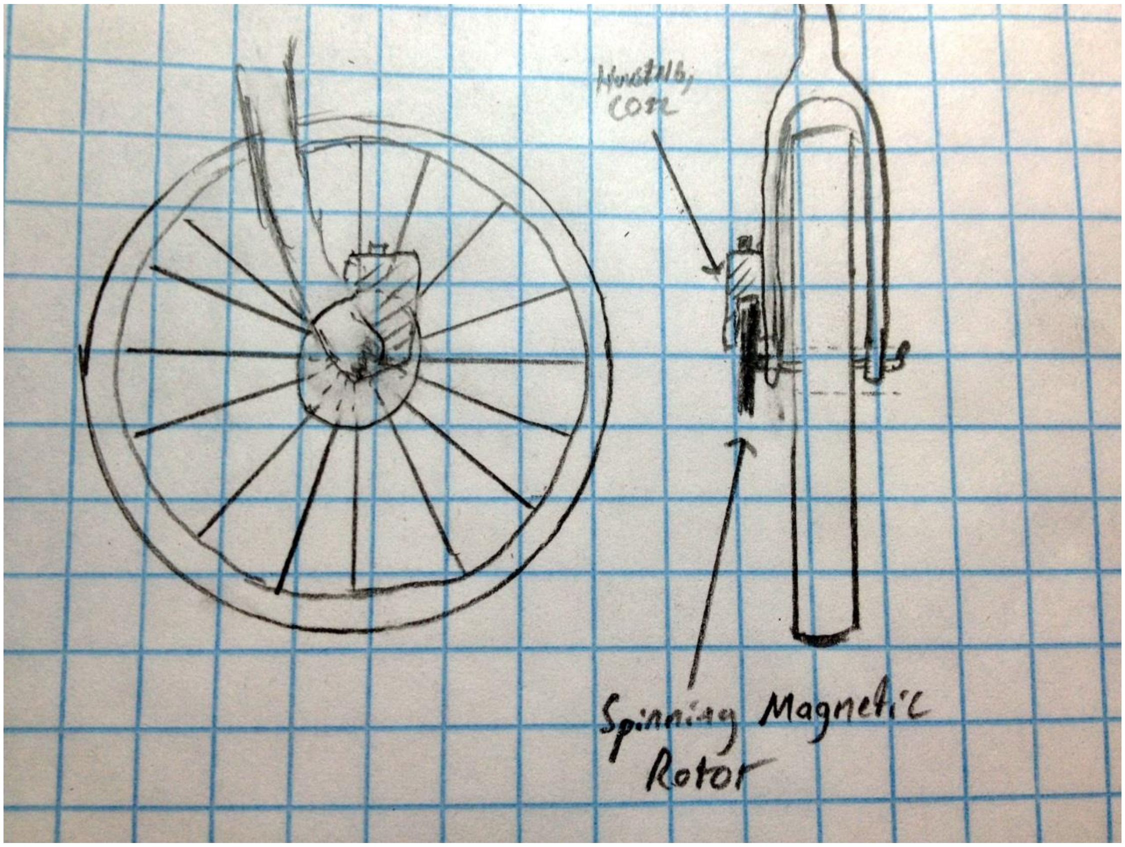
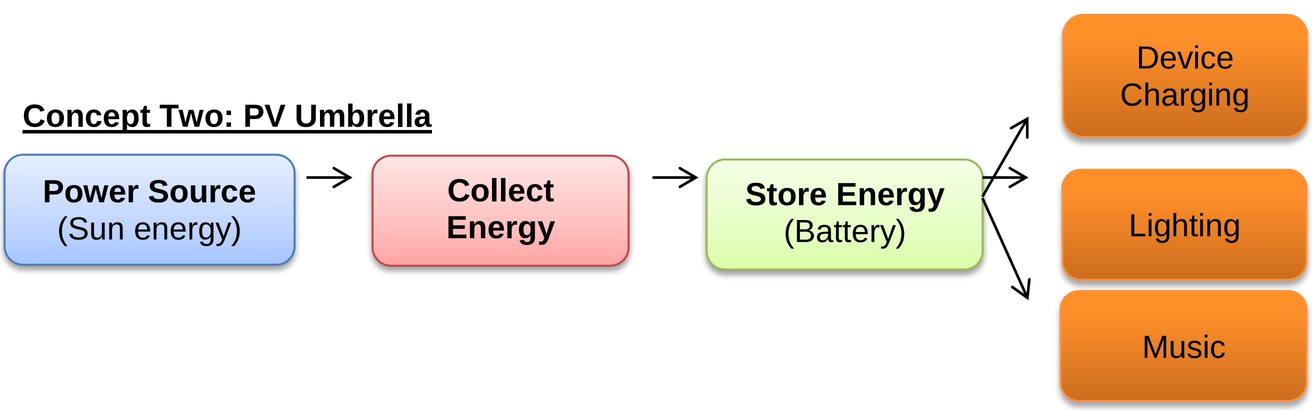


Figure 10.2- Bike powered charger module sketch

The bike powered charging module would generate an electric current as a spinning magnetic disk attached to the wheel passed through a coil module attached to the front fork. The energy would be stored in compact batteries, such as CR2032 watch batteries. A USB port would provide a charge to a connected device.

<u>Concept Two: PV Umbrella</u>



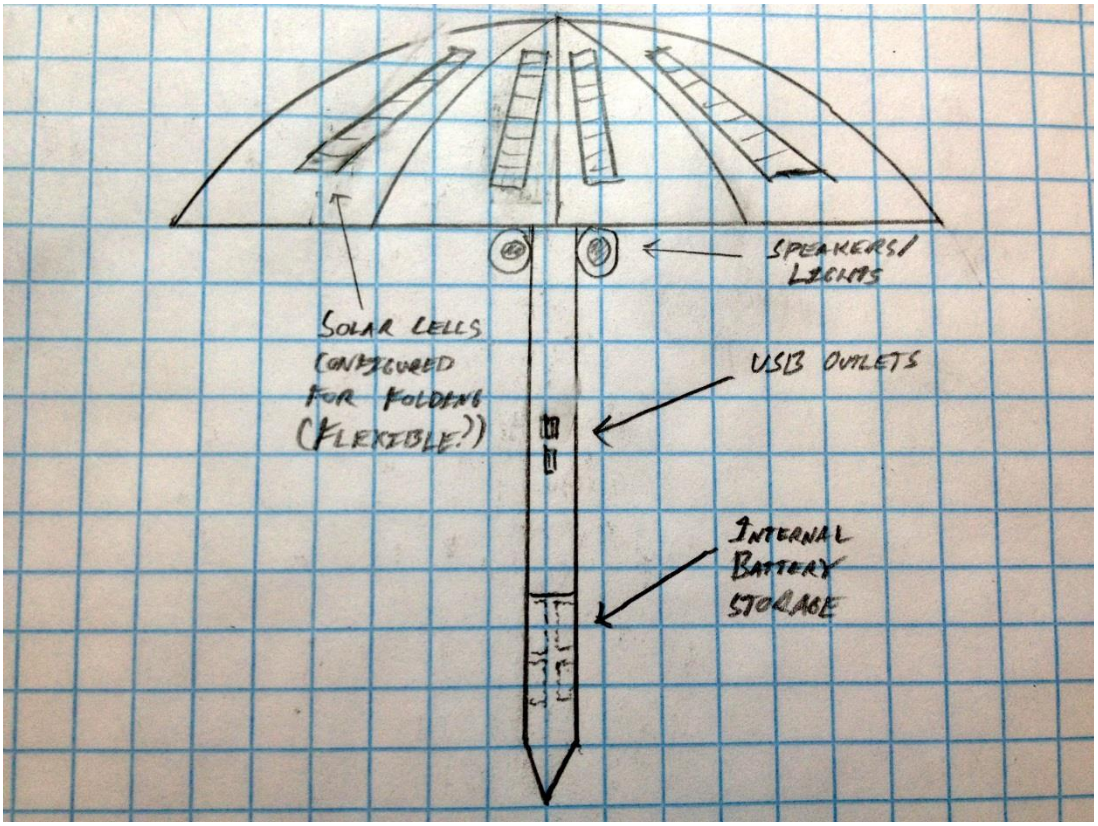
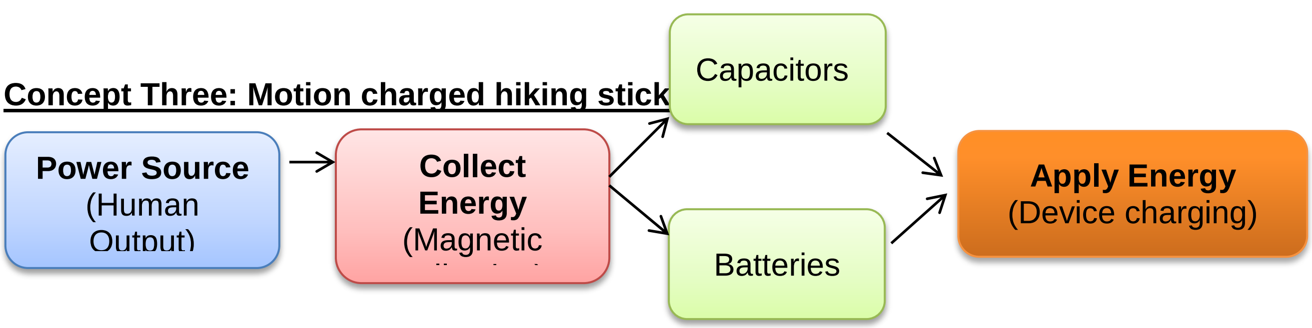


Figure 10.3- PV Umbrella sketch

For the PV umbrella concept, a standard beach umbrella would be created to hold several photovoltaic cells on the canopy. These would then charge a battery bank stored in the shaft, which would provide current to USB outlets on the shaft. Additional mounting points and wiring for lighting or speaker systems could be attached to the canopy.

Concept Three: Motion charged hiking stick



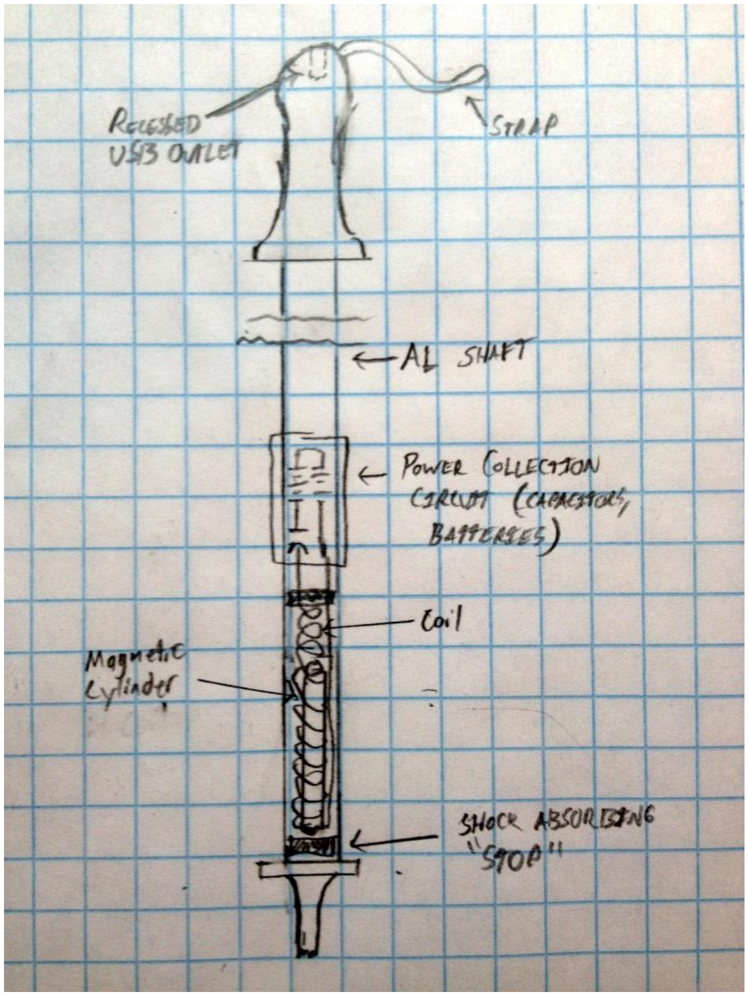


Figure 10.4- Motion-powered hiking stick sketch

The motion powered hiking stick would feature a cylindrical rare earth magnet nested inside of a coil loop. The motion of this magnetic field within the loop would generate a current sent to a power collection circuit. The circuit would feature capacitors in order to capture the rapid field fluctuations, and then offload charge to batteries for higher energy density. Shock absorbers would limit the boundaries of the magnetic cylinder travel. The entire generation system would be mounted within a non-magnetic aluminum trekking pole. A USB port on the handle would allow users to charge devices.

Table 10.2: Concept Scoring Matrix

Remote Energy, Dual-Use Concepts						
Weight	Bike-powered charging module		PV Umbrella		Motion-charged hiking stick	
	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
0.15	2	0.3	3	0.45	2	0.3
0.1	2	0.2	3	0.3	4	0.4
0.15	3	0.45	3	0.45	2	0.3
0.15	3	0.45	4	0.6	2	0.3
0.15	3	0.45	2	0.3	4	0.6
0.2	4	0.8	4	0.8	5	1
0.05	2	0.1	4	0.2	1	0.05
0.05	3	0.15	2	0.1	2	0.1
1	2.9		3.2		3.05	
	3		1		2	
	N		Develop		N	

After weighting certain criteria that the group valued more and inputting the three concepts into another selection matrix, the group chose to develop the PV umbrella further.

11. Appendix B: Customer Requirements and Technical Specifications

Prepared by: Morgan Kube

Table 11.1: Survey Questions

Question 1:	How often do you use electronics by the pool/beach?
Question 2:	How often does your battery run low?
Question 3:	Do you enjoy listening to music at beach/pool?
Question 4:	Do you bring an umbrella to the beach/pool?
Question 5:	Age group?
Question 6:	Would you want your umbrella to play music?
Question 7:	Does other people's music at the beach bother you?

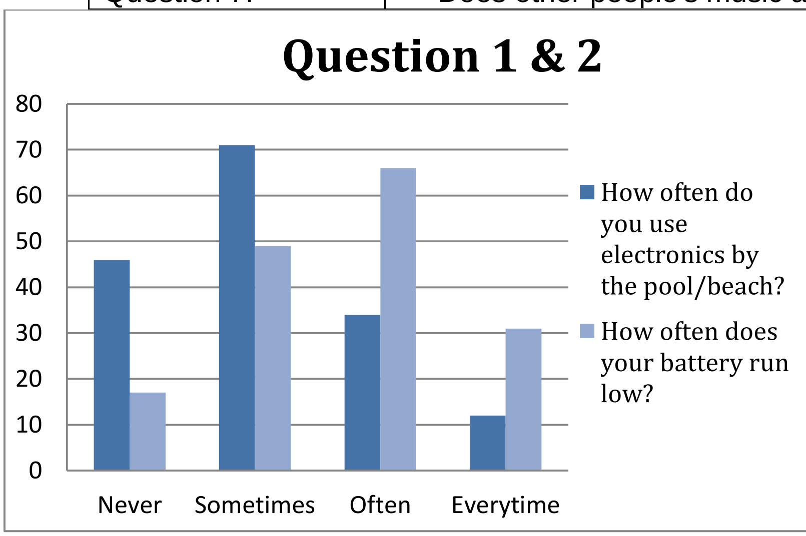


Figure 11.1a: Graph of Questions 1 & 2

	Question 1	Question 2
Never	46	17
Sometimes	**71**	49
Often	34	**66**
Every time	12	31

Figure 11.1b: Response Data for Questions 1 & 2

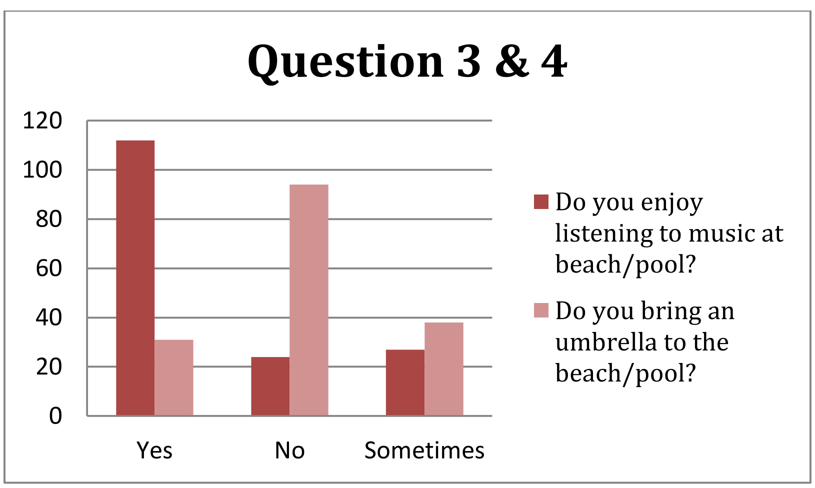


Figure 11.2a: Graph of Questions 3 & 4

	Question 3	Question 4
Yes	112	31
No	24	94
Sometimes	27	38

Figure 11.2b: Response Data for Questions 3 & 4

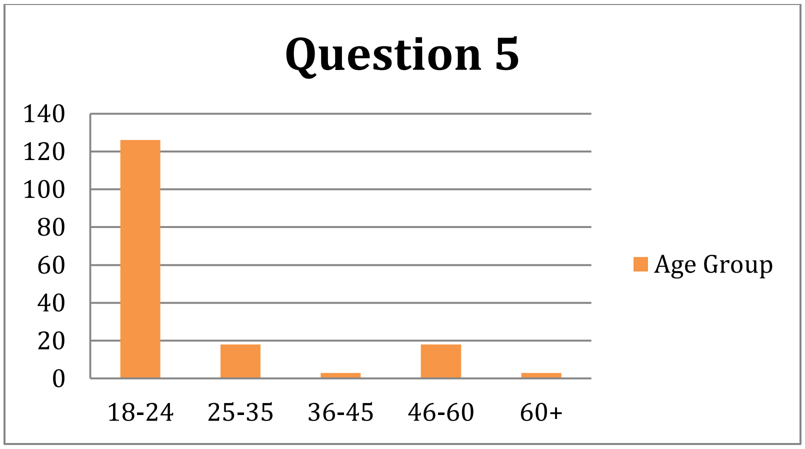


Figure 11.3a: Graph of Question 5

	Question 5
18-24	126
25-35	18
36-45	3
46-60	18
60+	3

Figure 11.3b: Response Data for Question 5

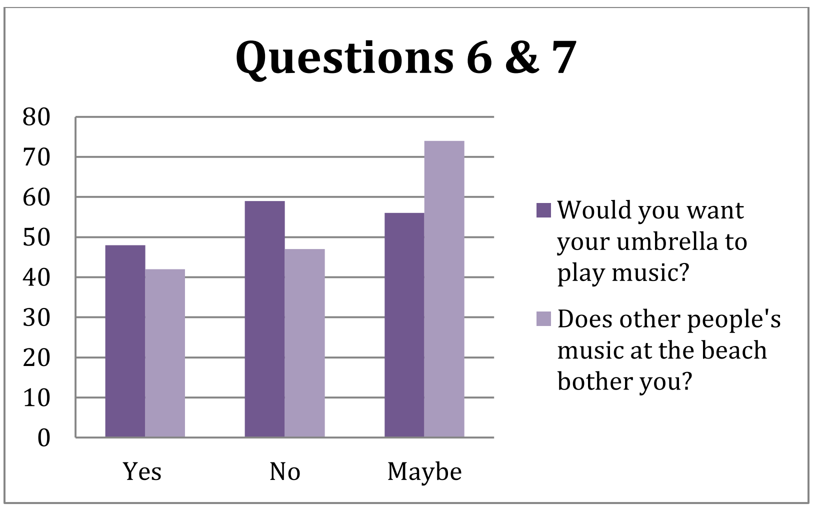


Figure 11.4a: Graph of Questions 6 & 7

	Question 6	Question 7
Yes	48	42
No	59	47
Maybe	56	74

Figure 11.4b: Response Data for Questions 6 & 7

In the table below the specific specifications for each subsystem are listed, these were the specifications that were demonstrated in Milestone 2.

Table 11.2 – Subsystem Technical Specifications

SunCatcher - Subsystem Techincal Specs			
Team Member/(Subsystem)	Key Function	Target Spec	How to Demonstrate
John (USB/Aux)	USB charging of multiple devices	Minimum current: 500mA; iPhone 4s charge in 4 hours	Charge with various devices; time iPhone charge, measure percentage batt. Gain, extrapolate time to full
	Audio Speakers	>55 dB without distortion; Max SPL <70dB	Audio Test suites (SPL- 1khz @1m)
	Lighting	300 lumens, 4 hours operation	demo: readability
Morgan (Shaft)	Weight	Less than 5lbs	Scale
	(Wind resistance)	Greater than 20 mph	Equations/simulation (Report)
	Tilt various angles	Up to 45 degrees	Actually tilt to block sunlight
	Shaft diameter, length	2", 7'	Calipers, Tape Measure
Matt (Canopy - Mech. Design)	Weight	<10 lbs	Scale
	Portability	Radius <3 in. diameter when closed	Tape Measure
	Shade Area	7' diameter canopy	Measure
	Strength	5lb add'l point load from outer edge	Demonstration
Kerry (Canopy Fabric and Panels)	Water resistance	Water resistant for 10 minutes	Place in Shower for 10 mins, then test
	Current provided	800mA to 2A	Multimeter
	Voltage	Minimum of 6V	Volt Meter
	Uv Resistant	Greater than 80%	Justify (Report)
Zach (Control Circuit)	Battery charge time, capacity	Full charge in 4 hours, min: 2500mAh	Testing results (Report).
	Energy Output	minimum: 700 mA @ 6V	Multimeter

These are some of the key features of each subsystem, that if someone else were to build our umbrella these are what would instruct them to do so.

The pictures below show the weight of Morgan's shaft, the first picture shows the weight of the top of the shaft and the next is the bottom of the shaft. The total weight is 4.95 pounds. Under Morgan's specifications there is tilting listed as a specification. The umbrella does not actually tilt though due to the added complication it would add to the manufacturing of the prototype.

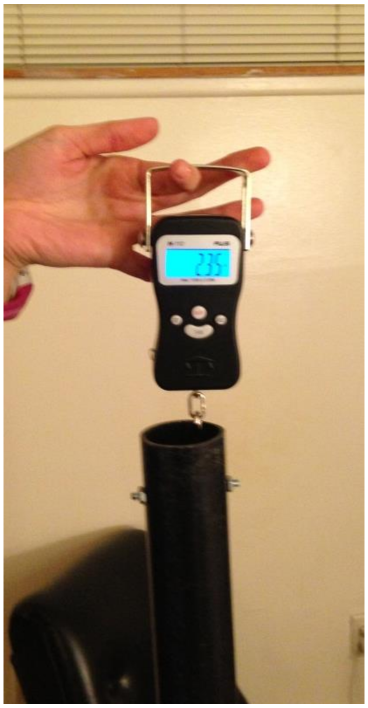


Figure 11.6 – Shaft Weight

These are pictures of Kerry's wiring and her canopy, in order to make the wires water resistant, there was shrink wrap heated around where the wires were soldered together. Electrical tape was then used to further insulate the edges of the shrink wrap. Not visible in the picture are the solar panels placed next to the ribs of each section on the canopy. The wires from the panels then run under the center of the canopy and are soldered together. Also, to ensure extra water resistance, the wire joints were hot glued in place to the canopy where the heat shrink/tape joints were made.

Figure 11.7 – Canopy Wiring

12. Appendix C: Gantt Chart

Prepared by: John Malcovitch

Team SunCatcher's Gantt Chart was often updated to include individual task breakdowns for Subsystems and Deliverable Milestones. This proved useful to the team members, and could be readily referenced as a persistent online document. However, this also results in a Gantt chart with many rows, and the document is actually taller than it is wide. This provides a representation challenge, as the document cannot be "compressed" with a weekly view.

In order to fully present all of the tasks and dates on the Gantt Chart, the Chart has been split into three main "phases" as seen in figures 12.1 through 12.3 below. Figure 12.1 shows the initial planning tasks and task owners, and includes preparation of Milestone I materials. Figure 12.2 lists the majority of the tasks, encompassing all subsystem development and integration up through the final demonstration. Figure 12.3 includes the breakdown of tasks for the final presentation and design review report.

Overall, the detailed task breakdown on the chart was useful, but some of the initial estimates for task time were made hastily, putting team members at a disadvantage almost immediately. Some subsystems had tasks ordered in straight consecutive days for several weeks, and once the reality of other coursework and commitments began to reappear, it became difficult to members to reorganize and catch up with their Gantt tasks.

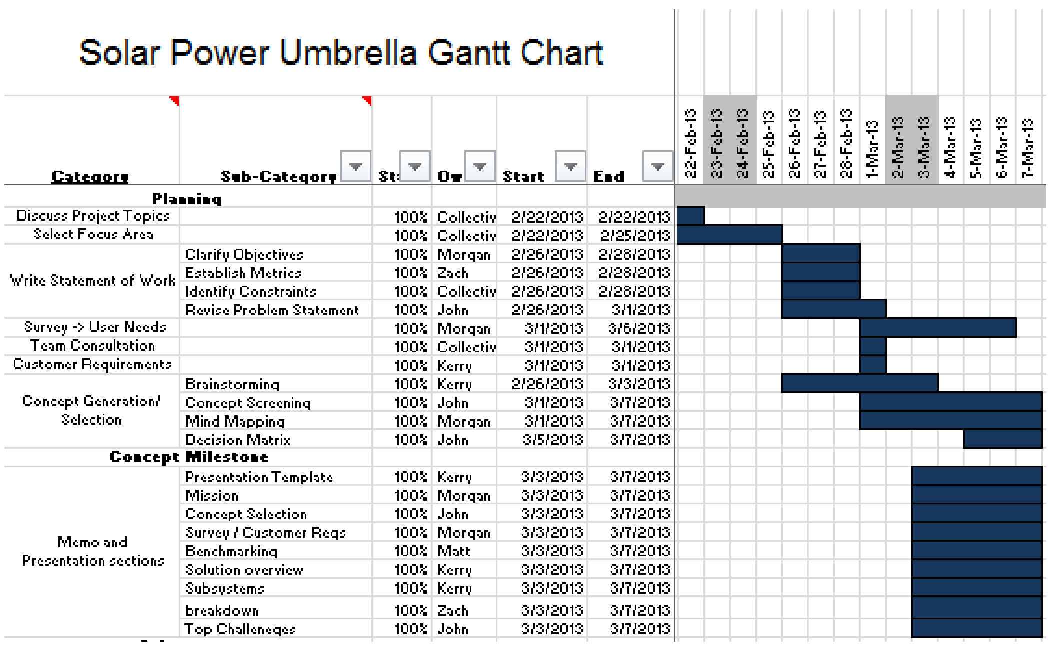


Figure 12.1 – Initial planning through Milestone I

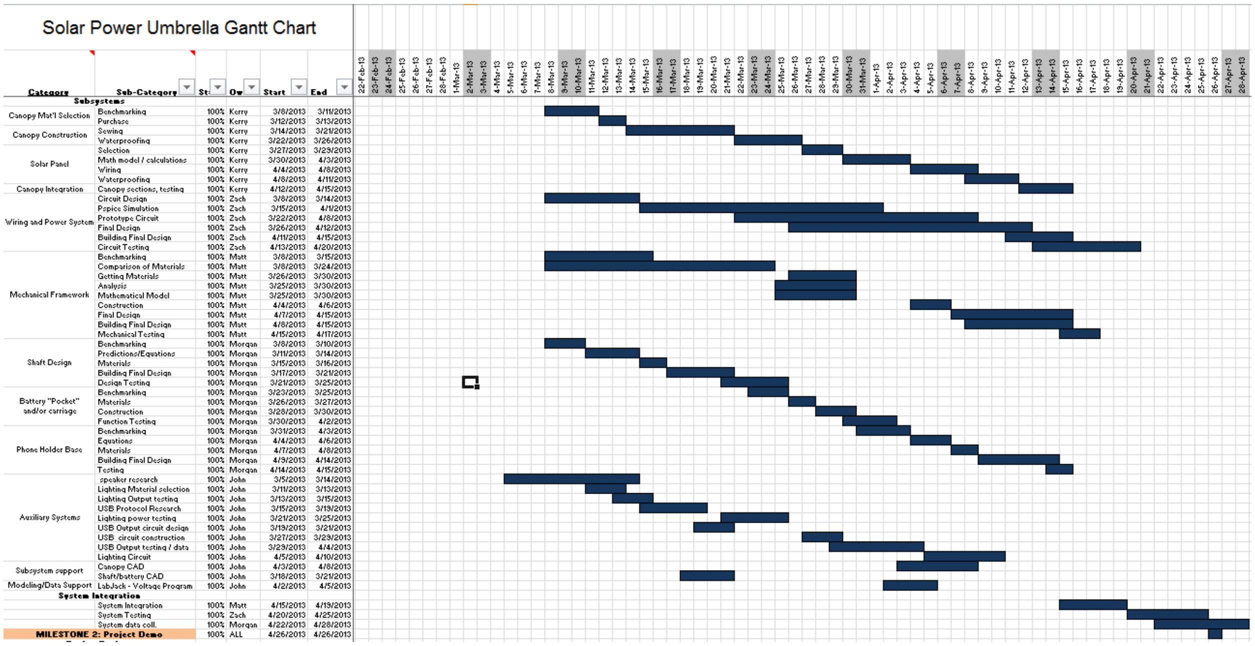


Figure 12.2 –Subsystem Development through Milestone II

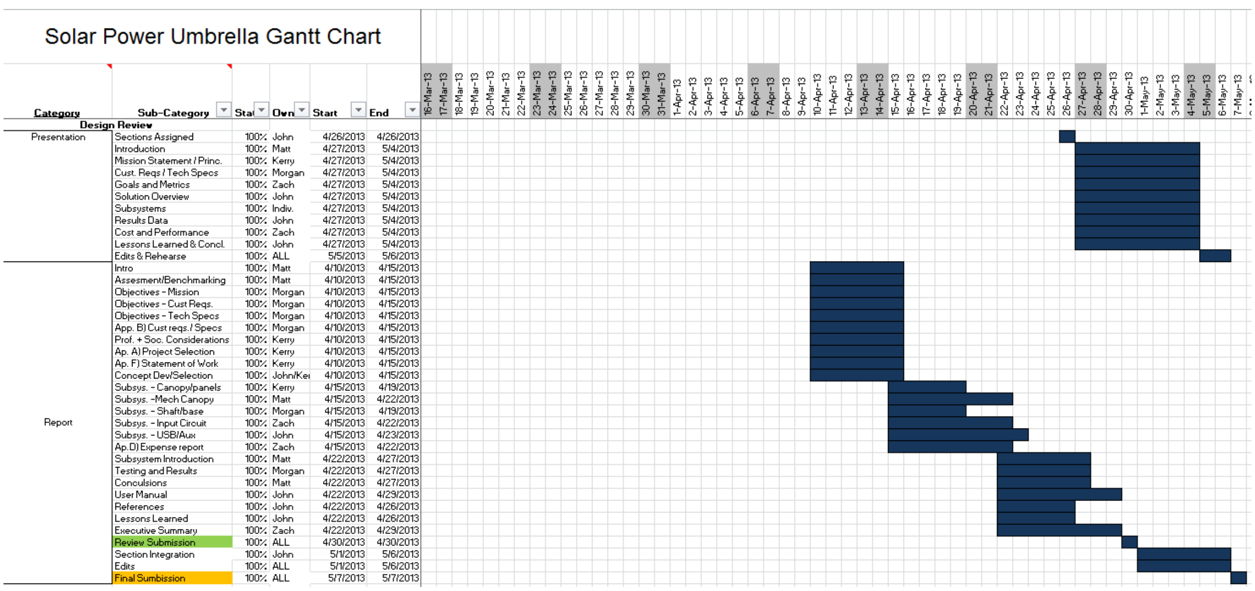


Figure 12.3 –Milestone III Presentation and Report Preparation

12. Appendix D: Expense Report

Table 13.1: Cost Analysis Prepared by: Zach Luzinas

Item	QTY	Unit Price	Subtotal	Shipping	Est. Bulk Manf. Cost @ 10k units	Source
USB adapter	1	$ 2.62	$ 2.62	-	$ 0.30	Bulk price
LED lights	1	$ 20.00	$ 20.00	-	$ 4.50	Component price est
USB sync	1	$ 2.00	$ 2.00	-	$ 0.50	Bulk
Speakers	1	$ 9.00	$ 9.00	$ 5.00	$ -	
Electrical Components	16	$ 1.40	$ 22.04	$ 4.00	$ 3.70	Bulk Pricing
DC/DC converter 7.5W	1	$ 4.30	$ 4.30	$ 2.95	$ 3.60	Bulk Pricing (250+)
DC/DC converter 5W	1	$ 7.82	$ 7.82	-	$ -	
Solar Panels	9	$ 8.00	$ 72.00	-	$ 17.36	Bulk price (vendor est)
Canopy Fabric	1	$ 19.00	$ 19.00	-	$ 5.80	Bulk Price
Waterproof Fabric Spray	1	$ 6.00	$ 6.00	-	$ 0.04	Bulk price per oz.
Waterproof Loctite epoxy	1	$ 5.00	$ 5.00	-	$ 0.11	Bulk price per oz.
Electrical Grade Fiber Glass 6ft	1	$ 38.50	$ 38.50	$ 13.50	$ 13.00	BulkPrice/Size Reduction
Electrical Grade Fiber Glass 3ft	1	$ 23.10	$ 23.10	-	$ 11.00	Bulk Price/Size Reduction
Umbrella Anchor	1	$ 12.95	$ 12.95	-	$ 3.24	Injection Mold Est
8 Energizer AA batteries	1	$ 18.04	$ 18.04	-	$ 13.00	Bulk Price
Printed Shaft Joint	1	$ 30.00	$ 30.00	-	$ 2.61	Injection Mold Est
AA battery holder	1	$ 2.79	$ 2.79	-	$ 0.30	
10 ft 3/16'' fiberglass rods	6	$ -	$ -	$ -	$ 1.20	Production Estimate
Top Hub	1	$ 30.27	$ 30.27		$ 2.66	Injection Mold Est
Central Hub	1	$ 28.10	$ 28.10	-	$ 2.60	Injection Mold Est
Top Cap	1	$ 13.74	$ 13.74		$ 2.25	Injection Mold Est
780 pin PCB	3	$ 3.50	$ 10.50	-	$ 0.50	Bulk Price
Misc. Hardware	8	$ 2.38	$ 19.43	-	$ 2.25	Rough estimate
TOTAL:			**$ 397.19**	**$ 25.45**	**$ 90.52**	

The manufacturing costs for the umbrella can be broken down into three different subsets: The direct materials costs, the direct labor costs, and the manufacturing overhead. Table 13.1 is a cost breakdown for the individual materials purchased that were used to construct the umbrella. Table 13.1 also includes cost estimates for small volume production run of 10,000 units. These estimates were obtained either with bulk pricing, injection mold pricing calculators, or estimated material cost for in house manufacture. Below is an analysis of the direct materials costs as well as ways to reduce this cost.

A significant portion of the costs came from spending money on duplicate items to ensure the umbrella would be operational. The additional solar panel, the extra batteries, and other unused components increased the overall cost of the system. These expenses could have been avoided at the risk of having the umbrella not work if spares could not be obtained to cover a component failure in time. Expenses could have also been reduced through the use of lower grade materials. However, the use of lower grade materials could have resulted in the failure of the umbrella.

These expenses above should not be viewed as an overall cost of the system in an industrial setting. The majority of costs above are variable costs that change when the materials are bought in bulk. The cost of the system would be far less in a mass production setting. The costs of the fiber glass rods, the electrical components, as well as the miscellaneous hardware would be significantly reduced if bought in bulk.

The overall cost of the umbrella would also be minimized after reducing of the size of the circuit as well as switching prototype 3D printing to a low cost injection mold manufacturing process. If the size of the circuits were reduced, the diameter of the shaft could also be reduced to reflect this change. For example the price of 1” fiberglass tubing is less than 37% of the cost of 2” tubing. This cost reduction does not consider any bulk discount. Also, this reduction in shaft diameter of the shaft would correlate to a smaller cost for the hub and joint materials that mate to the shaft. The four 3D printed parts totaled $102.10 in prototyping cost. However, if using plastic injection molding, that would be reduced by over 90% (for the existing design sizes). An injection mold cost calculator was used to estimate total cost for these parts (including tooling, machine wear, and production costs[27]. These four printed parts were estimated to total just $10.12. A screenshot of one of these calculators is reproduced below in figure 13.1.

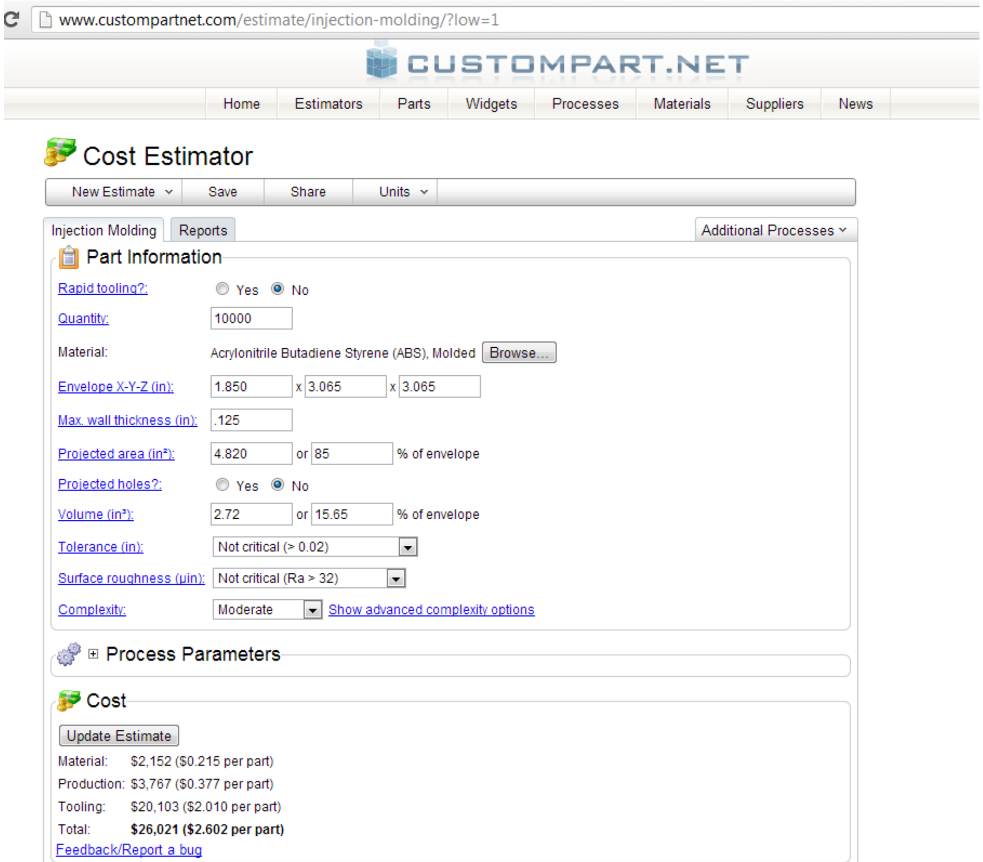


Figure 13.1 – Injection Molding Cost Calculator Example

Below, Table 13.2 indicates the total estimated manufacturing costs of the system. The manufacturing costs are considered only for the construction of approximately 10,000 units. These costs were calculated by researching the various costs of the materials needed to build the umbrella. The manufacturing overhead of the system was found by looking at the two major cost drivers, the costs of materials as well as the direct labor costs. The manufacturing overhead was calculated by assuming 90 percent of the labor costs added with 10 percent of the materials costs would give an approximation of the overhead costs.

Table 13.2: Variable Costs

Variable Costs	Cost
Materials (Mechanical)	$47.06/unit
Materials (Electrical)	$13.1/unit
Solar Cells	$2.17/solar cell
Batteries	$13.0 / unit
Direct Labor Costs	$10/unit
Manufacturing Overhead	$17.50
Total Costs	$118.02/unit

Appendix E: Team Members and Their Contributions

10.1 - Team Member 1 – Morgan Kube

"For this project I contributed my subsystem as well as certain sections in the memo. For my subsystem I spent a lot of time in the shop to drill holes and cut the shaft. Also I helped a lot with the integration of the whole system. I helped Kerry sew the pockets on the canopy for Matt's ribs to slip into as well as gluing the solar panels onto the canopy.

As for the sections I did for the memo, I wrote my subsystem, the customer requirements, testing and results, and appendix B."

10.2 - Team Member 2 – Kerry White

"My subsystem involved the canopy construction. This meant I picked out the canopy material and cut and sowed it together and added pockets to fit onto the ribs of Matt's system. I also was in charge of selecting solar panels that would give us enough voltage and current and wiring (and soldering) them together. I also had to attach them to the canopy.

My other job was to be in charge of meetings. I created a Google calendar that marked all of our meetings and created a to-do list for each one. I also kept an attendance record and made sure we had all the materials we needed for class."

10.3 - Team Member 3 – Matthew Causa

"My individual contribution to this project, for the most part, was the design of the mechanical subsystem of the canopy. Also, I was the teams' integrator, provided useful benchmarking techniques, sought out possible marketing possibilities and was responsible for writing certain parts of the technical memo.

As the team integration specialist, I played a major role in making sure we were all on the same page in terms of measurements and specifications. Since my subsystem was essentially the body of our project, I was in constant communication with both Morgan for shaft considerations and Kerry for considerations with the canopy material.

I was in charge of the benchmarking prior "Solar power umbrellas" to see what the team could implement to make our design successful and prevent making similar design mistakes.

I believed that the SunCatcher had the opportunity to "self-advertise" so; I integrated our company logo (which Kerry designed) into the design of the "Top Cap" in my subsystem.

I was in charge of writing 4 parts of the technical memo; Introduction, Assessment of Relevant Existing Technologies, Subsystem Introduction, (beginning of section 6), and Conclusion."

10.4 -Team Member 4 –Zachary Luzinas

"During the project I used my strong background in electronics to design solutions to the problems faced by the team. I was able to use my knowledge of diodes to construct a voltage controlled switch within the design of my circuit to prevent an overvoltage within the batteries. I also used my knowledge of power electronics to design a boost converter circuit. I also used my background in soldering and circuit design to construct the circuits to fit within the diameter of the shaft of the umbrella. Using a strong background with programs such as PSpice I was able to recreate and simulate my circuit designs to gain accurate data. I also attempted to remain realistic goals throughout the project and work within the constraints given to me. I attempted to complete all of the tasks throughout the project by the deadlines set by the team."

10.5 - Team Member 5 – John Malcovitch

"My primary responsibility during this project was the design, construction, and testing of the USB charging mechanism. I also designed the lighting circuit and system, which was not as involved a design challenge. Additionally, I acted as "support staff" to help other subsystems with CAD modeling, data collection, and calculation design, while ensuring those teammates still took the lead in the design process. I also took an active role in system integration. Due to my position as a Design lab TA, I also advised my teammates and others in the appropriate use of machine tools, soldering, and fabrication methods.

For the final report, I was tasked with the USB subsystem section, Lessons Learned, and System Concept Development sections, along with the User Manual. I was also responsible for integrating the individual sections into the final report, and I contributed editing, sourcing, and calculation verification for several sections.

Finally, for project management, I worked to develop task breakdowns and stick to our Gantt Schedule to stay on track during the initial (planning and subsystem construction) phases of the project. I also helped review subsystem calculations and testing design to ensure useful predictions and results could be obtained. During the last two weeks of the semester, other team-mates also stepped up to help steer the presentation and final report to successful completion."

11 Appendix F: Original Statement of Work

Prepared by: Everyone

Team: Solar Powered Umbrella
Matt Causa, Morgan Kube, Zachary Luzinis, John Malcovitch, Kerry White

Semester Objectives:

1. Design and build a working device that is efficient, cost effective, and differentiated from existing products or concepts.
2. Perform design analysis using assorted engineering tools to help make the product the more efficient and robust before construction begins.
3. Develop a design that is easily accessible to mass market and useful at beach or home.
4. Integrate subsystems to create seamless user experience.
5. Collect, analyze data for system operation and efficiency.
6. Present design demonstration and create a thorough, well-written final memo to summarize project results.

Approach:

The group will design and build a prototype of a solar powered umbrella that will allow both charging devices via USB and auxiliary functions such as music playback and lighting. This product will be developed by a project team, with each member in charge of planning and developing a subsystem. Team members will also collaborate throughout the project to align the designs of corresponding subsystem components. Through analysis and testing, the group will aim to create an efficient, low cost prototype of a device that could be mass-produced and capitalize on market opportunity.

Deliverables and Dates:

- Finish customer requirements/technical specifications (3/5)
- Milestone one: memo and presentation (3/8)
- Begin prototype development; sketches, pictures, materials (3/16)
- Have subsystems built and ready for testing (4/1)
- Informal subsystems presentations (4/8)
- Milestone two: project demonstrations (4/26)
- Milestone three: design review presentation (5/7)
- Design review technical memo (5/9)

12 Appendix G: Professional Development - Lessons Learned

The group developed many technical skills during the execution of this project. Just as importantly, however, the group also learned a number of lessons about project management and successful team dynamics (and not only from positive experiences). In this appendix, several points are mentioned that might benefit a team embarking on a similar engineering design project.

<u>Keep – "Working Groups"</u>

Trying to schedule meetings with the entire group is indeed brutal, and the "all hands on deck" meetings became more rare throughout the semester. However, the formation of working groups was a key to keeping all subsystems developing on time. Individuals with interfacing subsystems would meet up at various points to focus on issues between their systems. This was especially important due to several joint decisions which had to be decided between teams ("who moves first?"), but it also allowed for more focused, productive small meetings.

<u>Problem: Gantt Chart Deadlines</u>

Ever since the group's Gantt chart was first created, there were issues with keeping it up to date. Many of the initial subsystem tasks were entered onto the chart without consideration of other coursework or scheduled events, and it became very difficult for those members to catch up with their subsystem peers.

<u>Keep: Deadline\Quality Assurance Managers</u>

While the previous point may point to scheduling problems, one important tool for getting back on track was appointing a group member to be in charge of deadlines and quality assurance. There was therefore accountability for group members who fell behind on scheduled tasks, who were then held to getting caught up with the team schedule. Also, the Deadline Manager position is not necessarily enjoyable, but also creates a sense of ownership for one individual to keep the entire team up to date.

<u>Try: Google Docs</u>

Some team members have used Google Docs in the task and found it lacking due to formatting errors and other functionality limitations. However, the final assembly of the report resulted in a large number of "Conflicted Copy" file extensions, due to different members trying to work on the same file at one time in DropBox. Occasionally, one member might get entirely "locked out" of a document that is read only and only accessible from a certain computer, where that file may not even be in active use. The use of Google Docs to simultaneously edit a large report might save time and enhance collaboration. However, formatting would still need to be adjusted using traditional word-processing suite.

Keep: Team DropBox

Despite the ‘conflicted copy’ issues previously mentioned, a team DropBox folder was very useful for organizing and sharing data, photos, and documents. The DropBox kept team members constantly up to date and able to easily reference progress of interconnected subsystems in a working group.

Problem: Shipping and Rapid Prototyping times

Despite leaving ample lead time for part delivery and Rapid Prototyping, unforeseen hiccups still caused the team delays in subsystem construction and testing. Reputable sites like Amazon and McMaster Carr were very reliable, and offered cheap or free shipping. Chinese vendors selling on eBay proved to be the slowest shippers, having sent some items “surface” despite advertised expedited shipping policies. One charger, a $2 cable, took 5 weeks to be delivered from Hong Kong (with free “7-14 day” shipping).

One of RPI’s 3D plotters also went offline, and required the outsourcing of part designs off campus. This caused a delay in receiving initial parts, and also created a backlog that lasted until the end of the semester. One critical component (Joint piece) experienced 2 print failures, and was actually picked up the morning of demonstration as an incomplete job and manually separated from support material.

Try: Prototype Design with greater emphasis on testing data access

The group designed much of their project with safety and waterproofing in mind. However, during testing, the lack of access ports made effective data collection very difficult without partial system disassembly at each data point. While a design can be proven strong for a “manufacturing version”, a prototype would benefit from trading some features for data-collection facilitation.

13Appendix H: User Manual

<Note: Proper Illustrations would be crucial for successful User Manual. Scope of this appendix is limited to copy only. Also, a quick-connect wiring harness would be included in consumer version for ease of setup. >

Congratulations on your purchase of the SunCatcher Solar Power Umbrella!

You can look forward to years of safe, reliable charging for all of your outdoor power needs. Please familiarize yourself with this manual in order to maximize your enjoyment of this product.

Table of Contents

PARTS INCLUDED:

The SunCatcher comes partially assembled for your convenience. In the package, you will find the following components. Please check to ensure all parts are included before you begin assembly.

1X Upper Shaft Hub With Circuit Assembly

1X Lower Shaft and Joint piece

1X Preassembled Canopy Skeleton

1X Fabric Canopy and Panel Structure

1X Battery pack Cap

6X AA Rechargeable Batteries in pouch

1X Sand grabber

1XCanopy

Additional Hardware: 3X 2.5” Threaded Rods, 1x 2.0” threaded rod, 6x ¼-20 Bolts, 1x 2” Aluminum Washer, 1X Device Charging Holster

SETUP:

1) Thread the quick-connect wiring harness attached to upper shaft and circuit portion through bottom hub of the canopy skeleton. Push through the access hole at the top of upper shaft.

   <STEP1.JPG>

2) Slide upper hub of mechanical canopy down over the top of upper shaft portion. Align the through holes of upper shaft and top hub. Insert the shortest threaded rod (2”) through the holes to prevent the top hub from rotating or sliding off the shaft.

   <STEP2.JPG>

3) Slide the Canopy fabric with attached panels over the top hub. Gently bend the stretcher ribs and insert into the canopy pockets as shown below. Place the 2” washer over the top hub extension, and screw the Canopy cap down snugly to fasten canopy fabric in place.

   <STEP3.JPG>

4) Attach quick-connect harness from the upper shaft to the top quick-connect from the Panels. Attach the quick-connect terminal from the lighting cord to the corresponding jack on the quick-connect harness.

   <STEP4.JPG>

5) Insert AA batteries into battery compartment, aligning all with correct polarity according to markings on battery compartment. Attach the wire clip to (-) terminal as shown below. Fasten battery compartment to the inside of shaft as shown.

   <STEP5.JPG>

6) Slide bottom shaft over joint piece. Align holes and insert 2.5” threaded rod through holes. Gently tighten nuts until finger tight. Insert sand grabber at bottom of base, and repeat fastening step with threaded rod and bolts.

   <STEP6.JPG>

Your SunCatcher is now ready for use.

OPERATION:

1) Find suitable location to anchor SunCatcher. Sand grabber performs best in sand or loose soil. Align canopy for maximum sun blockage and best system charging. Apply downward pressure to shaft and twist lower shaft until top sand grabber blade is level with sand or soil.

2) Slide lower hub up above the dowel hole. Place dowel through hole and lower hub to support canopy.

3) SunCatcher will automatically begin charging internal battery storage. To charge a device, connect USB cable to port on shaft joint and connect device.

4) Hang device charging holster from shaft joint to hold devices.

5) To operate lighting, press switch attached to canopy stretcher. Repeat to turn off.

6) To collapse SunCatcher, press bottom hub up and remove dowel.

7) When transporting SunCatcher, ensure solar panels are facing canopy material for damage protection. For added protection and convenience, contact SunCatcher dealer about optional Carrying Sling (Part# 60786).

SAFETY PRECAUTIONS:

Ensure sand grabber base is fully inserted into ground before operation. Do not attempt to use on hard surface without optional Patio Base.

SunCatcher wiring and components are rated for 10 minutes of full rain exposure. In case of inclement weather, move SunCatcher to sheltered area. Never attempt to disassemble unit in wet conditions.

Never cut modify wiring in any way. Contact service hotline immediately if wiring damage is found.

Check polarity of batteries before initial operation. Attempting to use SunCatcher with reversed polarity may damage the rechargeable batteries.

Do not use modified or damaged USB cords. Shorting the connection can result in rapid heat buildup or fire.

Do not store outside in damp, moist conditions.

Do not store outside in direct sunlight. May affect appearance of canopy fabric.

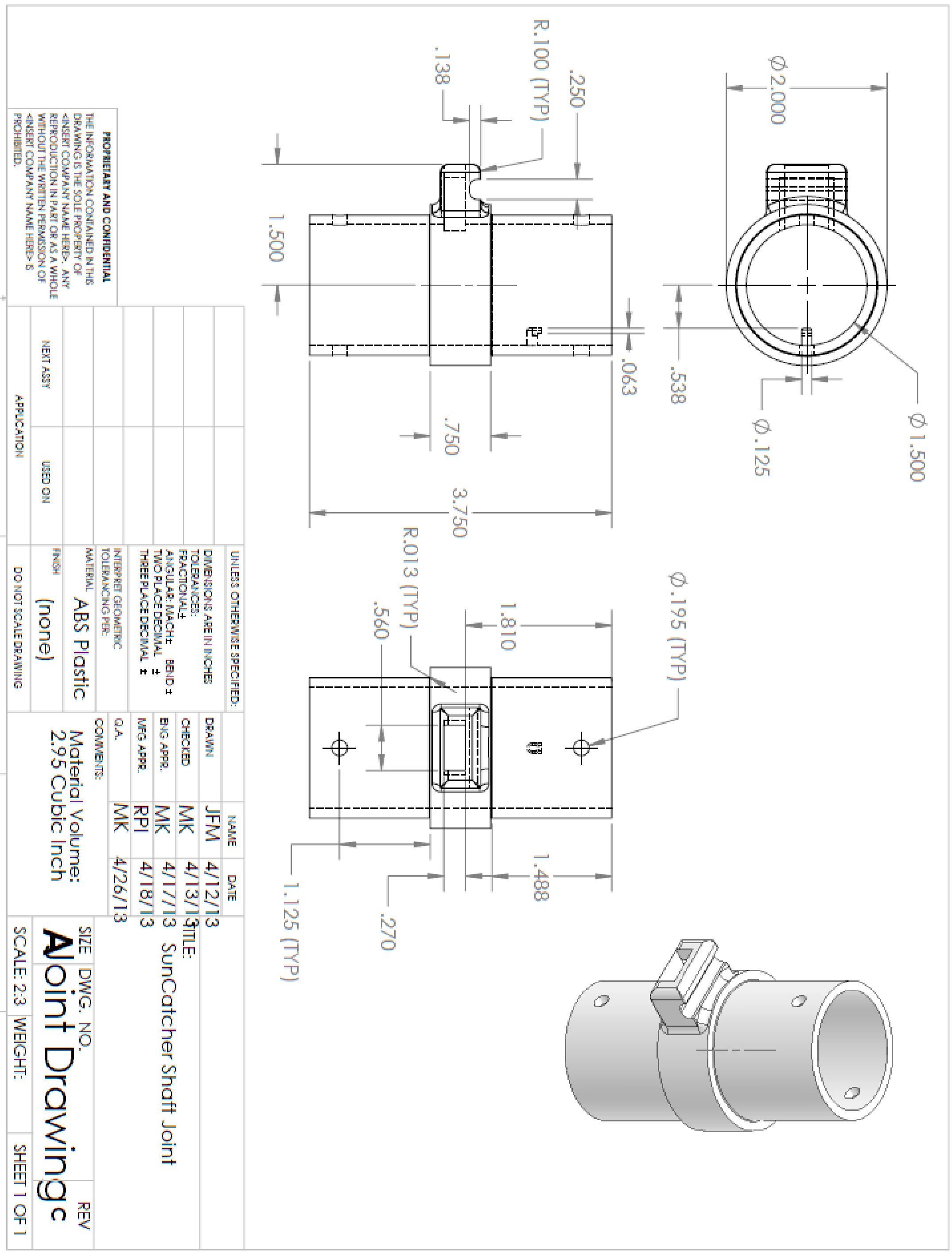
Unclip battery compartment connection when storing SunCatcher for extended periods of time.

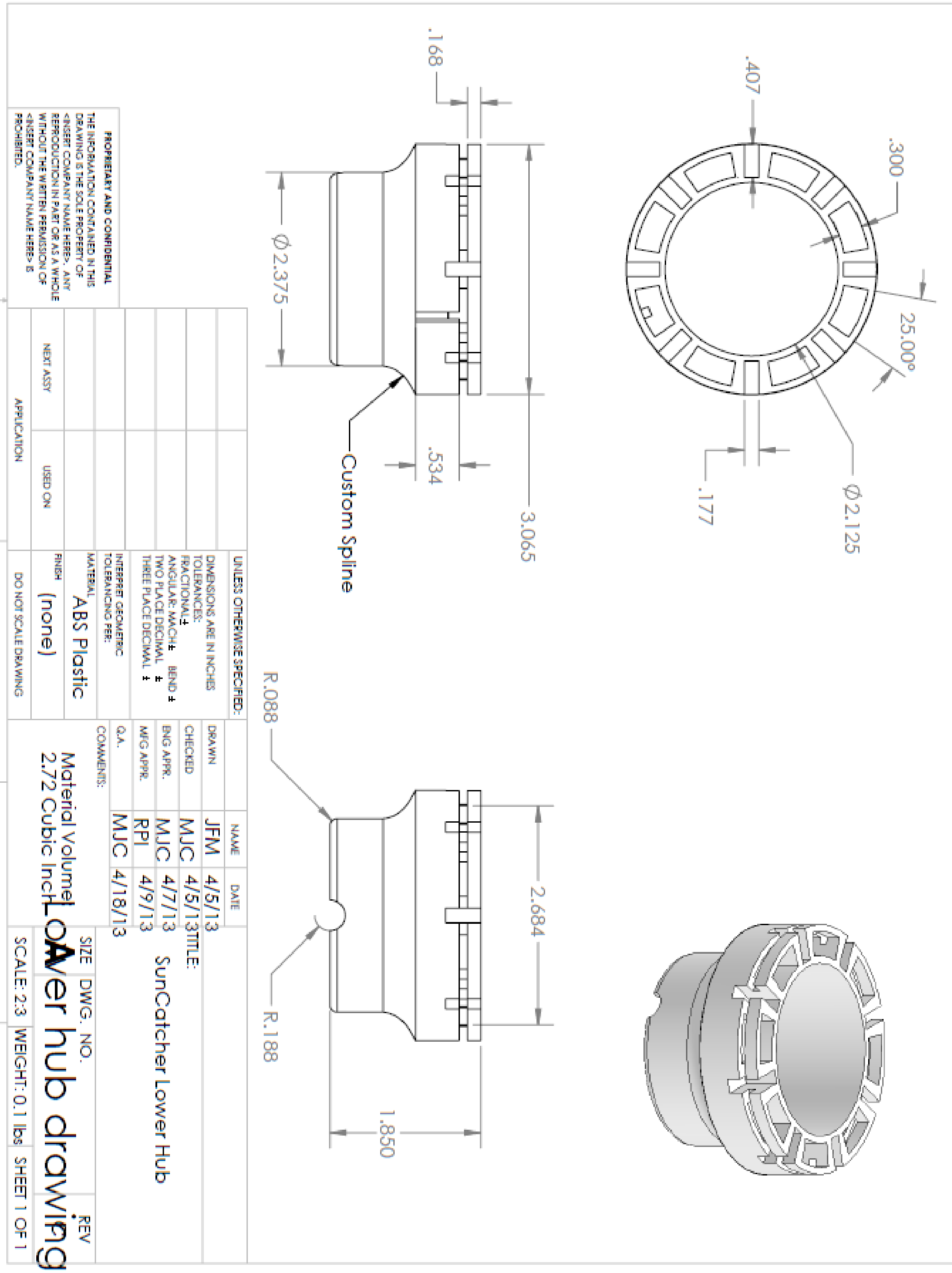
TROUBLESHOOTING

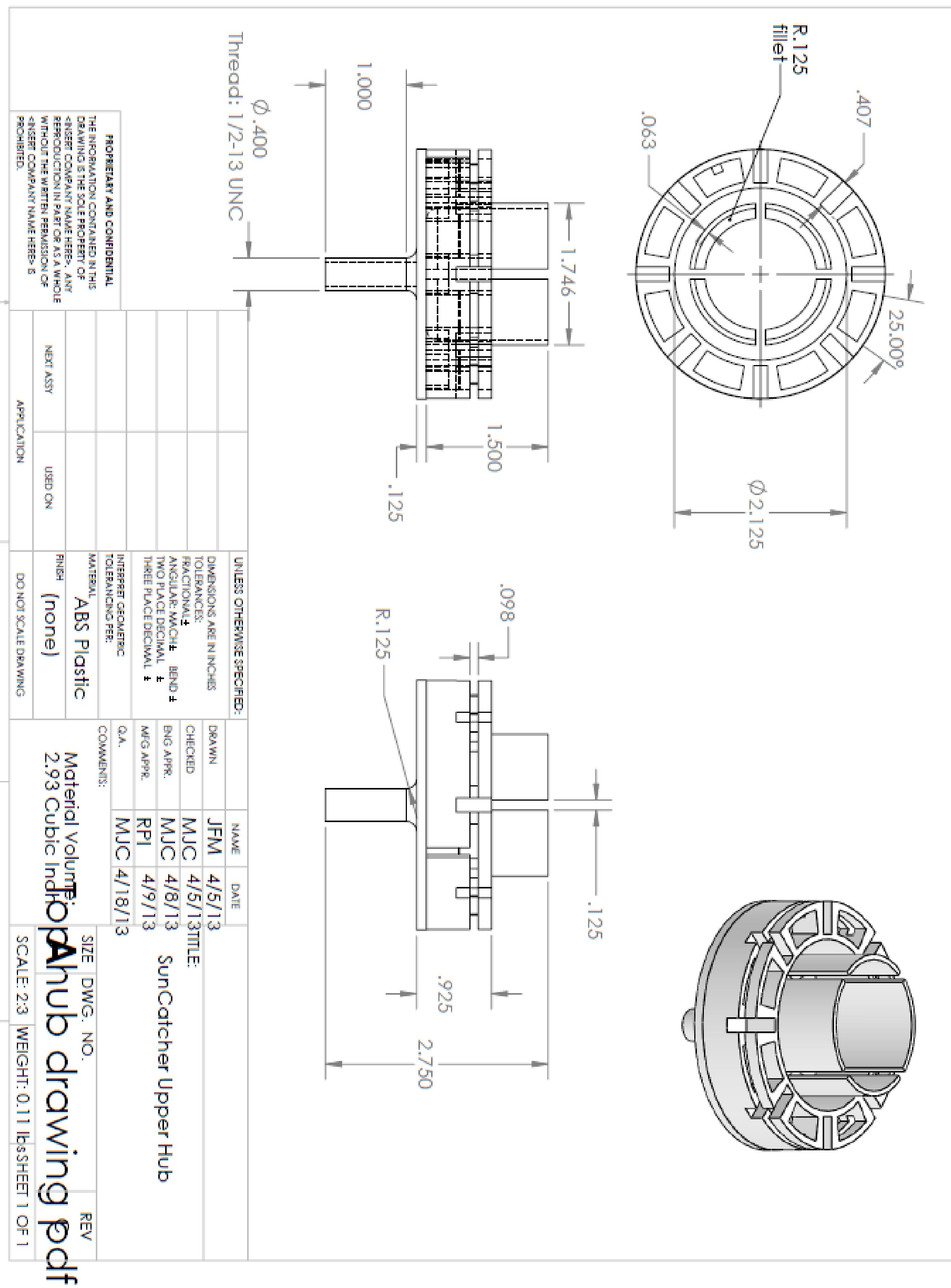
Problem	Possible Solution
Lighting system does not illuminate with button press.	a) Check battery polarity in battery case. b) Charge SunCatcher before operation c) Ensure quick-connect is inserted into wiring harness.
SunCatcher is wobbly at beach.	Ensure sand grabber is fully inserted into sand. Press and rotate until top blade is level with sand line.
SunCatcher charges slowly while outdoors.	a) Check that SunCatcher is free from shade coverage. b) Align canopy toward sun for maximum charge.
USB Device will not charge.	a) Ensure USB cable is fully inserted into USB jack on shaft joint. b) Low system charge. Place outside in full sun to recharge system.
Potato will not charge.	Potato is not supported. Please see device compatibility list on packaging.
I have broken a piece, or I still cannot resolve my issue.	Please contact SunCatcher Service department at 1-800-Sol-Watt for further assistance or Warranty Repair

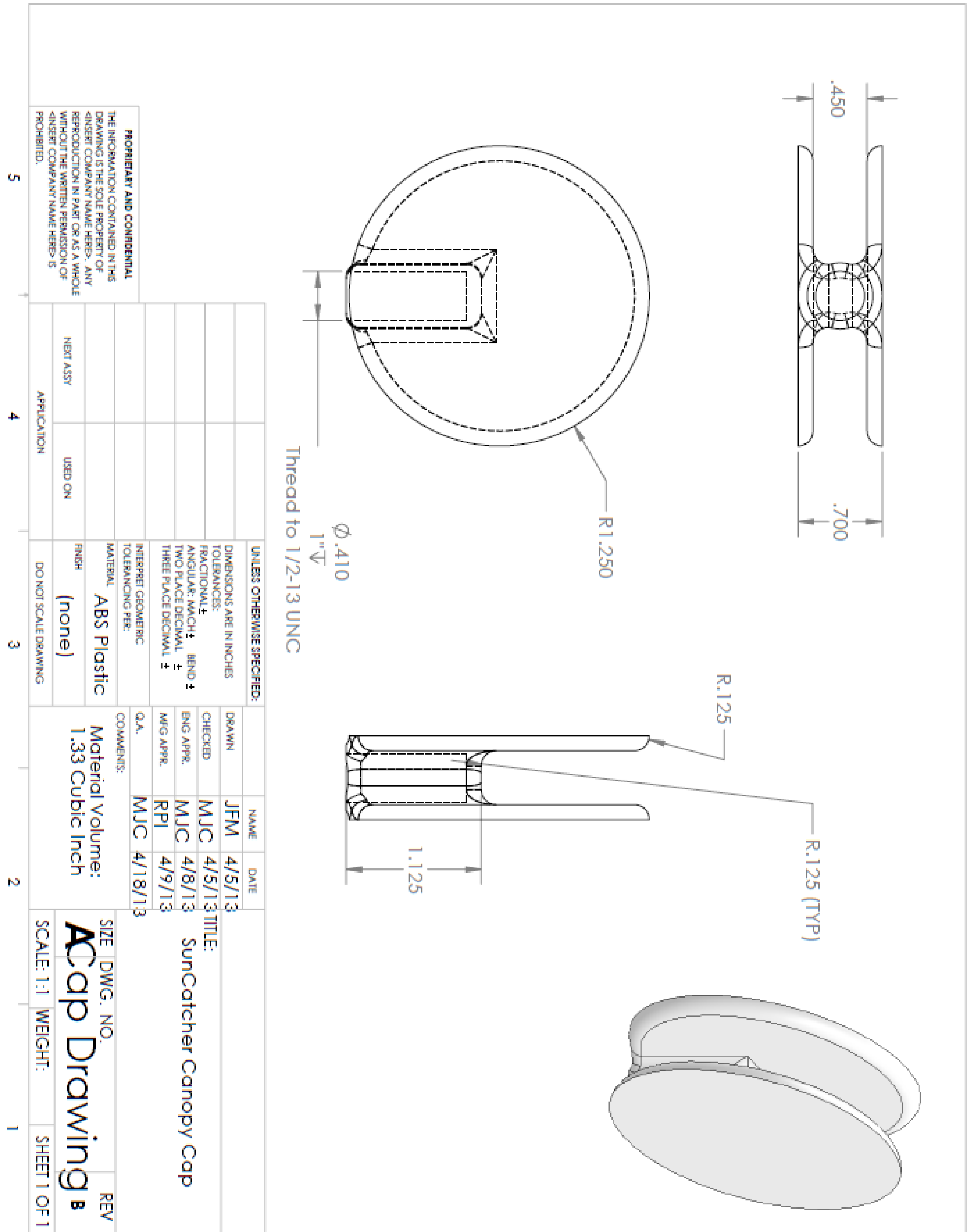
14 Appendix I: CAD Drawings

Prepared by: John Malcovitch




.407
.300
25.00°
Ø2.125
.177
.168
Ø2.375
.534
3.065
Custom Spline
R.088
R.188
2.684
1.850
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ABS Plastic
FINISH
(none)
DO NOT SCALE DRAWING
NAME DATE
DRAWN JFM 4/5/13
CHECKED MJC 4/5/13
ENG APPR. MJC 4/7/13
MFG APPR. RPI 4/9/13
Q.A. MJC 4/18/13
COMMENTS:
Material Volume
2.72 Cubic Inch
TITLE:
SunCatcher Lower Hub
SIZE A
DWG. NO.
Lower hub drawing
REV
SCALE: 2:3
WEIGHT: 0.1 lbs
SHEET 1 OF 1
5
4
3
2
1


R.125
fillet
.407
.063
25.00°
Ø2.125
1.746
1.500
.125
1.000
Ø.400
Thread: 1/2-13 UNC
.098
R.125
.125
.925
2.750
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ABS Plastic
FINISH
(none)
DO NOT SCALE DRAWING
NAME DATE
DRAWN JFM 4/5/13
CHECKED MJC 4/5/13
ENG APPR. MJC 4/8/13
MFG APPR. RPI 4/9/13
Q.A. MJC 4/18/13
COMMENTS:
Material volume:
2.93 Cubic Inches
TITLE:
SunCatcher Upper Hub
SIZE DWG. NO. REV
A
Top hub drawing pdf
SCALE: 2:3 WEIGHT: 0.11 lbs SHEET 1 OF 1
5
4
3
2
1



.450
.700
R1.250
Ø.410
1" ↧
Thread to 1/2-13 UNC
R.125
R.125 (TYP)
1.125
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ABS Plastic
FINISH
(none)
DO NOT SCALE DRAWING
NAME
DATE
DRAWN JFM 4/5/13
CHECKED MJC 4/5/13
ENG APPR. MJC 4/8/13
MFG APPR. RPI 4/9/13
Q.A. MJC 4/18/13
COMMENTS:
Material Volume:
1.33 Cubic Inch
TITLE:
SunCatcher Canopy Cap
SIZE
DWG. NO.
A
Cap Drawing
REV
B
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1