Sun Crest Inc.

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Design Specification for the *Stellar Dish: Sun-tracking Solar Cooker*

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Sun Crest Inc.

March 19, 2015

Dr. Andrew Rawicz
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RE: ENSC 305/ 440W Capstone Project Design Specification (DS) for the *Stellar Dish Sun-tracking Solar Cooker*

Dear Dr.Rawicz,

Attached is DS for Stellar Dish Sun tracking Solar Cooker. We intend to design and build a working Solar Cooker with an integrated sun tracking mechanism to harness 25% more solar power. The DS will contain detailed description of the system overview, user interaction, component/material selection, electrical, mechanical and power performance requirements. Every requirement has safety and engineering standard associated with it.

“1.5 million People die per year from respiratory diseases related to smoke inhalation, which are mostly children and women”. Using SunCrest's solar cooker will not emit toxic fumes, smokes which will alleviate the respiratory diseases. Another major problem I personally have witnessed is the development of cataract as a result of long time exposure to EMR from the firewood burning. Tenzin, one of our team members say “My grandmother actually had a cataract in her eyes for three year, which blinded her for three years”.

Sun Crest Inc. comprises of four dedicated and fully-committed 4th-year engineering students: Owen Au, Tenzin Sherpa and Imtiaz Charania. We are all motivated to design and deliver the best possible product to our clients and believe in turning idealities into reality one step at a time. Please feel free to contact Owen Au at owenau@sfu.ca

Sincerely,
Owen Au
CEO, SunCrest Inc

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1 Introduction/Background

The Stellar Dish Sun Tracking Solar Cooker is a parabolic solar cooker with sun tracking capabilities and is designed to be low-cost, affordable and efficient. The apparatus can achieve cooking temperatures of approximately 250°C on a typical sunny day at places closer to the equator. The Stellar dish is equipped with an LDR - dependent sun tracking mechanism which allows the dish to locate the sun and adjust its position to provide maximum energy efficiency. To facilitate the tracking motion, the parabolic dish is mounted on a turntable azimuthally rotated by an Arduino-controlled servo motor.

1.1 Scope

This document contains detailed functional requirements of the Stellar dish. These requirements explain the proof of concept model and also describe the production necessities for this device. The engineers at SunCrest Inc. will strictly follow these design and construction guidelines keeping safety as a first priority. This document will drive the future design of the system and our engineers will strictly make sure all of the stated requirements are considered and met in all the development stages of our product.

1.2 Intended Audience

This functional specification document is intended to be used by the members of SunCrest Inc. and as a reference for legal disputes. The project supervisor will use this document to track various phase completions. Test engineers may also use this specification as a guide to verify functionalities of the product.

1.3 Overall Design

The overall design of our sun tracker is a closed-loop feedback system in which an Arduino Uno microcontroller will control a servo motor to track the sun using a pulse-width control method. The position information of the sun is then compared to the position of the LDR sun tracker in the feedback route back into the input. If there is discrepancy between the two positions the motor will move to the position of the LDR Sun tracker. In other words, the smaller independent sun-tracker is used to fine tune position of the umbrella dish.

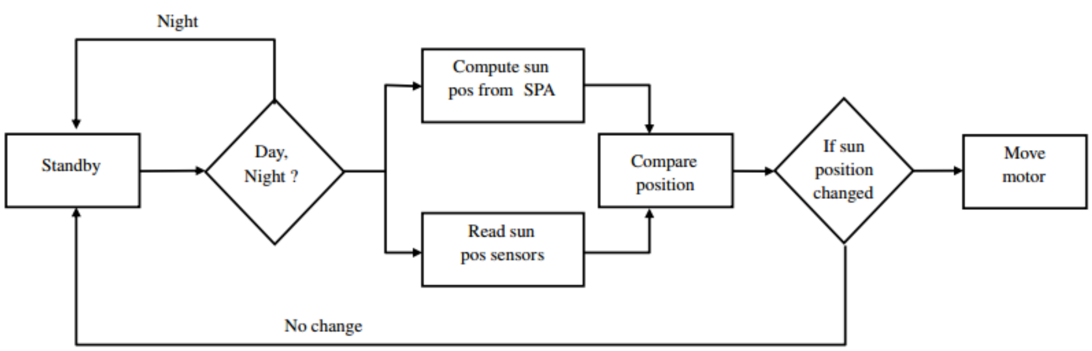

Figure 1 Flowchart describing the overall design [1].

2 Dish Design

2.1 Focal Length

As mentioned earlier, the reason behind using a parabolic dish is to focus all the reflected rays from the sun at a focal point. The dish is the most energy efficient near the focal point; hence we need to calculate the dimensions of the solar dish. F/D = 0.6, where f is the focal length of the parabolic dish and D is the diameter, is the standard whereby the focal point position is not too low that the sunlight reflected off the outer rim areas will strike the focal point at a very low angle make thermal transfer difficult [1].

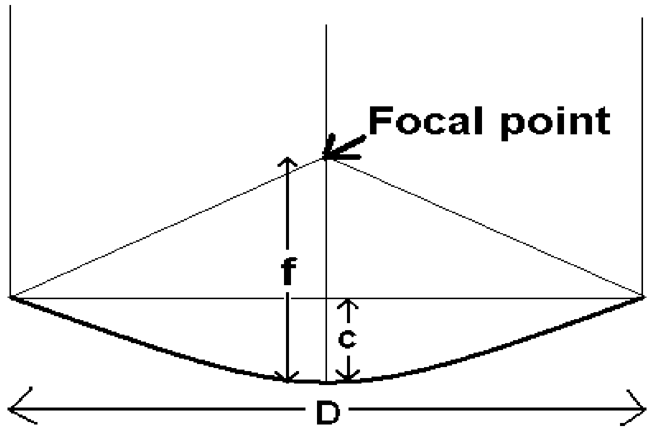

Figure 2 Image displaying Parameters of the parabolic dish [2]

Using this ratio, we solve the diameter [2].

$$C = D^2/16F$$

$$D = \sqrt{\frac{required\ power}{\pi \times solar\ constant}} = \sqrt{\frac{0.7\ kW}{\pi \times solar\ constant}} = 94cm$$

Where solar constant = $1kW/m^2$

Therefore our diameter needs to be about 1 meter wide. From these calculations, we can conclude that the focal point is at most 6 times higher than the height/depth of the dish. The minimum height than required for this design is 9.83 cm, having the focal point at 57 cm, hence it can be concluded that the focal point is 6 times the height/ depth of the dish. The surface area of a paraboloid without the base is [2]:

$$Surface\ area\ of\ circular\ paraboloid = \frac{\pi}{6} \times \frac{r}{h^2} \times \left[\!\left[(r^2 + 4h^2)^{3/2} - r^3 \right]\!\right]$$

If we put our height of 10 cm and radius of 50 cm then our surface area is .816 m^2.

Therefore the input energy from the sun is:

Surface area x avg. Solar Irradiance = 0.816 m^2 x 700 W/m^2 = 571 Watts. Note that from the solar irradiance values on the world map, Vancouver receives less than 700 W/m^2. In reality, our design will not receive that much power [2].

2.2 Reflective Material

Reflective material used to implement the solar dish was Aluminum since it is inexpensive and reflects approximately 80% of the sunlight [4]. According to our calculations, 80% of 0.7 kWatt energy will be reflected and merged near the focal point.

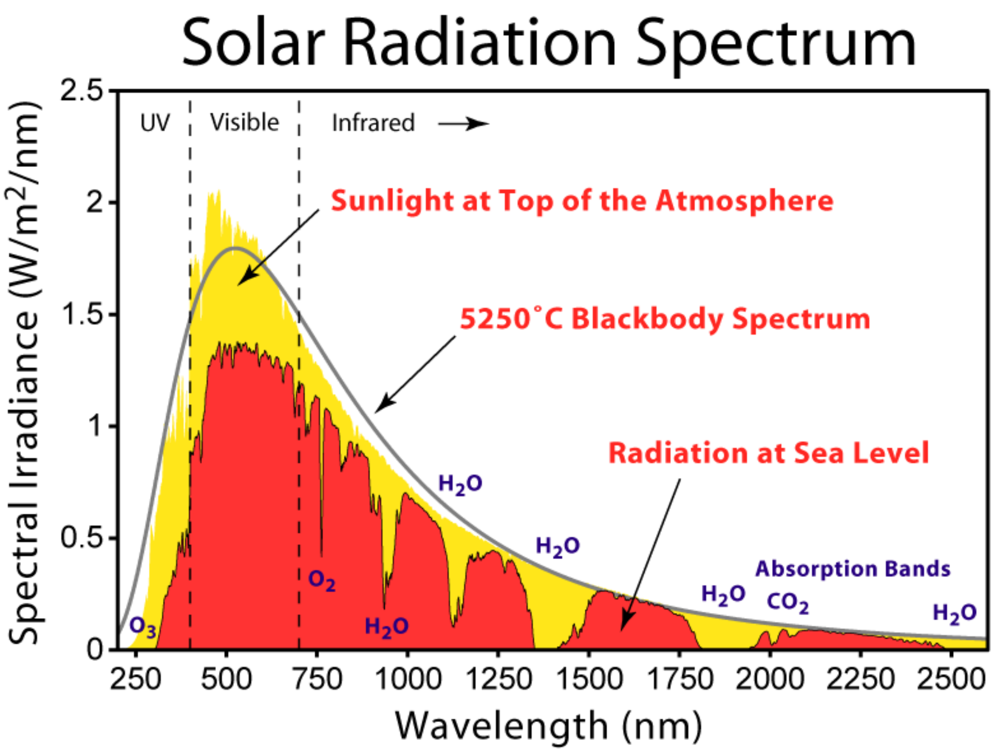

Figure 3 Image displaying various Spectral Irradiance [3]

The visible wavelengths range is between 400nm - 700nm [5]. The highest spectral irradiance is achieved from the visible and infrared spectrum. It was necessary that the material used for reflectivity has the highest reflective percentages for the spectrum ranging between 400 - 700 nm due to the fact that visible light contributes the highest spectral irradiance. From the graph below, it is obvious that Aluminum is a strong choice since it has the highest reflectivity for our design purposes. Other than reflectivity, it is also essential for our design to use inexpensiveer materials and Aluminium is the inexpensiveest and most widely available [4].

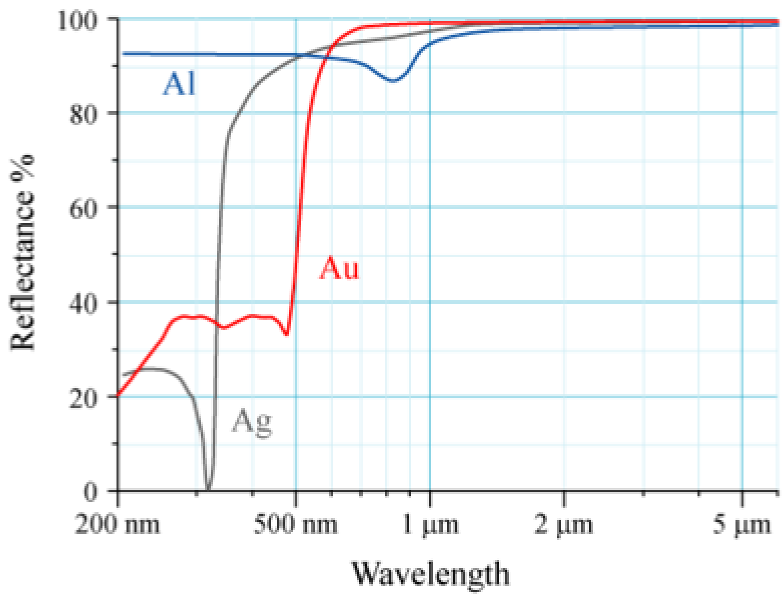

Figure 4 Image displaying Reflectivity of various metals [4]

2.3 Power Requirements

In order to power up the Arduino and the motor, the required voltage is approximately 18 Volts. The potential required to power up Arduino is 12 volts which will be powered by a battery source. The main motor requires an approximate voltage of 6 volts and the LDR suntracker servo motors will need 2 volts. The maximum power can be tested using an ammeter and following some steps provided by the Gadgetmakers blog [5].

3 Mechanical Design

3.1 Motor

The basic driving mechanism of the rotary system is enforced by the Hitec HS-785HB sail winch servo modified with the SPG785A Servo Power Gearbox from Servocity. For our purpose we require extremely low RPM, with high torque, given the requirement and the price constraint we settled on using this particular motor with a 7:1 gear ratio. Following are the motors diagrams and related schematics [6].

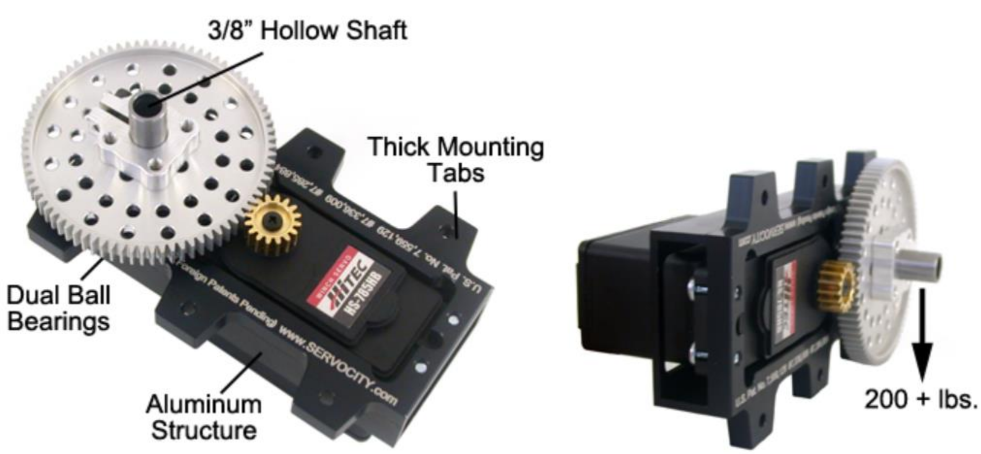

Figure 5 Motor Required for Sun Tracker design

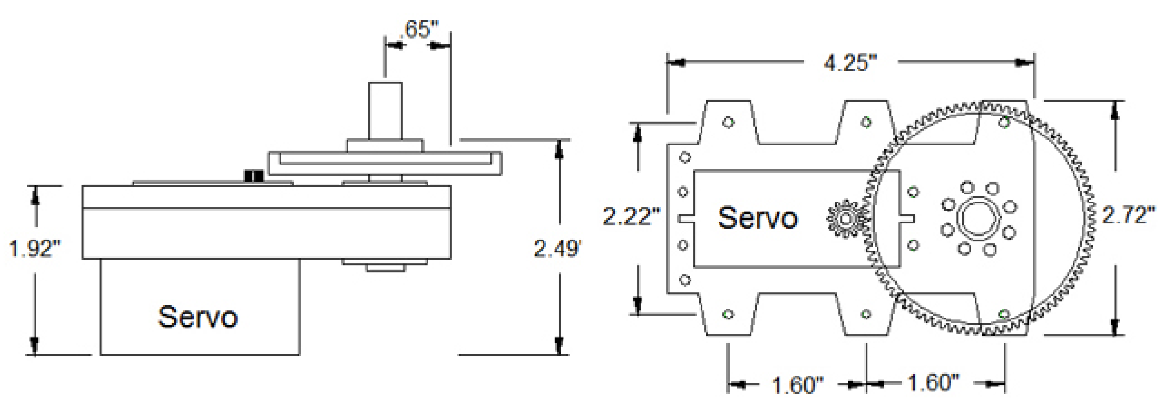

Figure 6 Dimensions of the motor [6]

The data specification of the HS-785HB sail winch servo provides us with a lot of crucial information needed to plan our design [6]. The custom servo that we brought has an added gear configuration (highlighted in yellow above) which will give it a 7:1 mechanical advantage for torque. Our standalone servo is rated at 183 oz-inch torque at 6v and applying the 7:1 ratio gear, the torque will be 1281 oz-inch.

The position movement of this servo is dependent on pulse-width control. It is provided that the operating travel is 1.75 turns for every one side pulse travelling from 1500 µsec to 1900 µsec. What this means is that changing the width of the signal pulses sent from 1500 µsec to 1900 µsec will cause the servo to turn 1.75 rotations. This is the essence of pulse-width control; altering the width of the pulse will cause the servo to move to a new position. The rotational span of the original unmodified servo is 630 degrees (1.75 turns) but with the 7:1 gear, the maximum rotational span of the servo becomes 630 degrees divided by 7 which is equal to 90 degrees from the neutral position, however, this is good enough for building a sun-tracker. Therefore the maximum rotational span of our servo is 180 degrees. The rotation span of the servo is demonstrated below in the picture (ignore the time values).

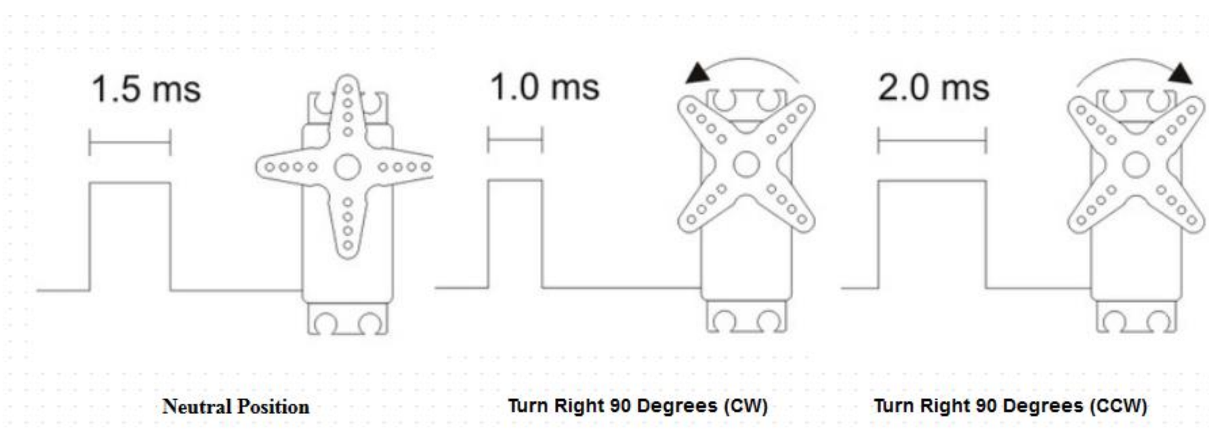

Figure 7 Motor response for PWM

3.2 Force Analysis of the Food Supporting Structure

This design is fairly straight forward since it only requires withstanding a vertical force exerted by the food on the stand. The maximum weight that can be placed on the stand was designed to be 19.6 N. The free body diagram and the calculations are provided in the figure below.

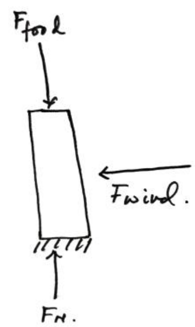

Figure 8 Free body diagram for Food support

If designed correctly, the only force required to balance the weight of the food is F_n which in our design is equal to 19.6N

$$\sum F_x = F_{wind} = 0.$$

$$\sum F_y = F_N = F_{food}.$$

$$= \boxed{2 * 9.8 = F_N}.$$

The only horizontal force acting on the apparatus are natural forces, such as wind. Since there is no acceleration of this apparatus, there is no counter force required to balance these natural forces.

3.4 Force Analysis of Beam Connected to the Motor

There are several forces that need to be considered in order to build a statically and dynamically stable device. The analysis on the beam/ turntable is the most important because there is a motor torque acting on the beam from one end and meanwhile from the other end, a smooth rotation is required while the dish is mounted. For simplicity, motor torque is renamed to T, the forces acting at that joint are Fx and Fy. The force that the dish exerts at point B is named as F_d. The figure below displays the free body diagram of the forces acting upon the beam.

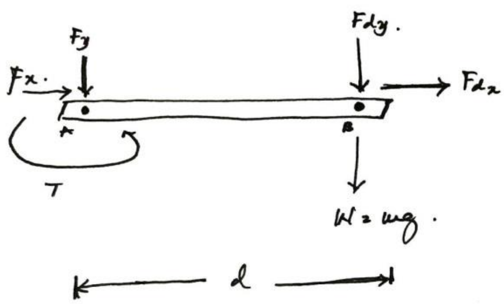

Figure 9 Free body diagram of the beam

The angular velocity required to track the sun is very low, since it rotates at a speed of 2.5 degrees per 10 minutes. For this reason we assume that our design is static which leads to simpler Statical analysis. The following image displays the calculations required for our design.

$\Sigma F_x = 0$, Assumption since angular velocity very low.

T_m = Motor Torque.

d = length of the beam.

F_d = dish force.

F = pin joint motor connection.

$$\Sigma F_x = F_x = -F_{dx}.$$

$$\Sigma F_y = F_y = -F_{dy} - Mg.$$

$$\Sigma T_A = T_m + \left(-\left(F_{dy} + Mg\right)\right) * d = 0.$$

$$\frac{T_m}{d} = \left(F_{dy} + Mg\right), \quad \frac{T_m}{d} - Mg = F_{dy}$$

$$\boxed{F_{dy} = \frac{T_m}{d} - Mg}$$

$$F_y = -F_{dy} - Mg = -\left(\frac{T_m}{d} - Mg\right) - Mg.$$

$$F_y = -\frac{T_m}{d} + Mg - Mg$$

$$\boxed{F_y = -\frac{T_m}{d}}$$

According to these calculations, the pin at point A should be able to withstand a stress of F/A and pin B should be able to hold F_d /A. The design should not malfunction provided left extra room for some environmental forces. There are no forces in the horizontal direction; this might not always be true because some areas around the Equator encounter heavy wind flow.

4 Sun Tracking

The rate at which the sun-tracker should rotate is calculated below:

$$\text{Angular Velocity} = \frac{360°}{24\,hrs} = \frac{15°}{1\,hr} = \frac{0.25°}{1\,min} \times \frac{10}{10} = \frac{2.5°}{10\,min}$$

The reason for multiplying by 10 is because tracking the sun every minute is power consuming and harder to implement so we decided to track the sun every 10 minutes.

In the design of our parabolic solar concentrator, solar energy collected can be modeled as indicated by the figure below [1], hence we set our tolerance to be less than 0.5 to optimize the energy efficiency [4].

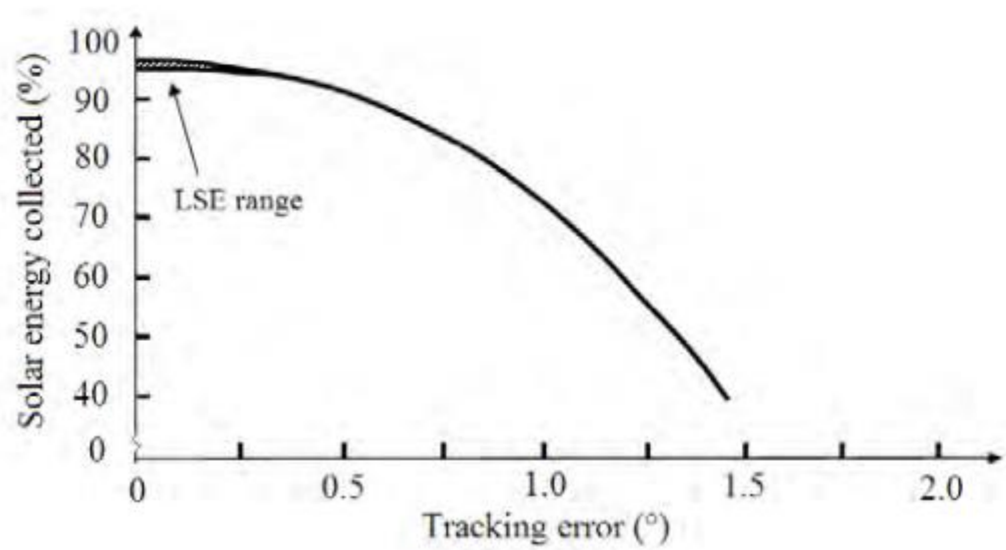

Figure 10 Solar Energy collected vs Tracking Error [4]

4.1 LDR Sun-tracker Algorithm

LDR closed loop control : The closed loop feedback control system consists of four LDRs mounted on a circular card-board which senses the amount of light falling on the top-right, top-left, bottom left and bottom right corners. The operation of the LDR sun-tracker is described by the algorithm procedure below.

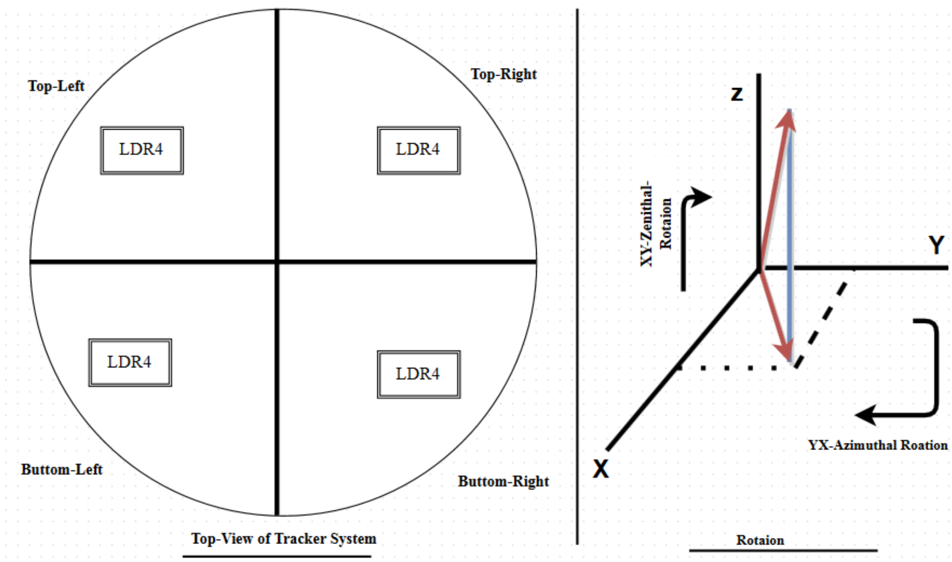

Figure 11 LDR's

Basic algorithm:

1) Four LDRs senses the light intensity
2) Compute the total intensity
3) If the total difference between intensities is within 70% of each other, that is if the analog voltages fed into the Arduino range between 30% of each other, t is something then switch to time control.
4) The measurements are fed into four analog Arduino input

   Compute the average:

- Right average: LDR1 and LDR4
- Left average : LDR2 and LDR3
- Top average : LDR1 and LDR2
- Bottom average: LDR4 and LDR3

- Find the difference:

  Diff1: Top average - Bottom average

  Diff2: Right-average - Left average

5) Feed the Diff1 and Diff2 into the Arduino to drive the zenithal and azimuthal motors

4.2 Pulse-Width Controlled Sun Tracking

As mentioned above, pulse-width control will be the method of choice for adjusting the servo position. The specified operating travel displacement of 1.75 turns per 400 µsec from the data specification (found in appendix) means that our pulse-width control time span is 800 µsec from 1100 µsec to 1900 µsec. We will be sending a signal pulse with such a length that will cause the servo to turn 2.5 degrees every 10 minutes which is the standard speed for sun-tracking [5].

To find the needed pulse width to turn 2.5 degrees, we note that the servo rotates 180 degrees in the 800 µsec control time span.

$$\text{Therefore, } \frac{180°}{800\mu\text{sec}} = \frac{2.5°}{\textit{needed pulse width}}$$

so the needed pulse width = 11.11 µsec. This means to achieve 2.5 degrees of rotation every ten minutes, we will increase the pulse width by 11.11 µsec every ten minutes until we reach the max pulse width 1900 µsec associated with the max angle position of the servo.

Instead of supplying the servo with constant DC voltage to operate, we can save power by using Pulse-width modulation or PWM to power the servo. PWM provides the servo with the necessary voltage only a portion of the time every period cycle known as the duty cycle. For example if we use 25% duty cycle, we can save 75% of the power every period cycle.

5 Software Design

5.1 Intensity Control

The software will follow a simple set of steps, when the weather is sunny, LDR readings are fairly different. A two page flowchart provided below describes the LDR sun-tracking algorithm in section 4.1 which will be implemented in Arduino.

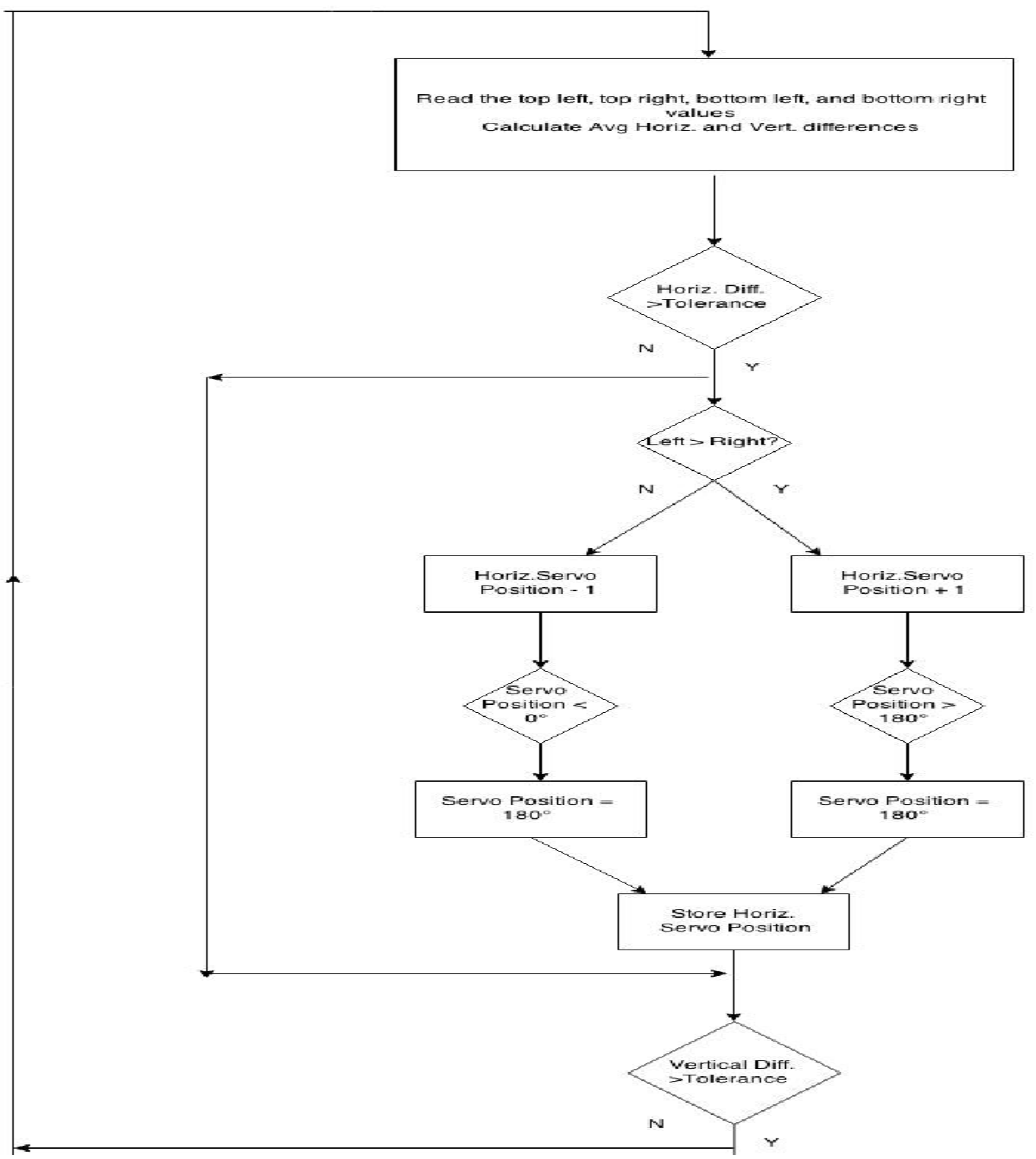

Figure 12 Flowchart for Intensity controlled suntracking

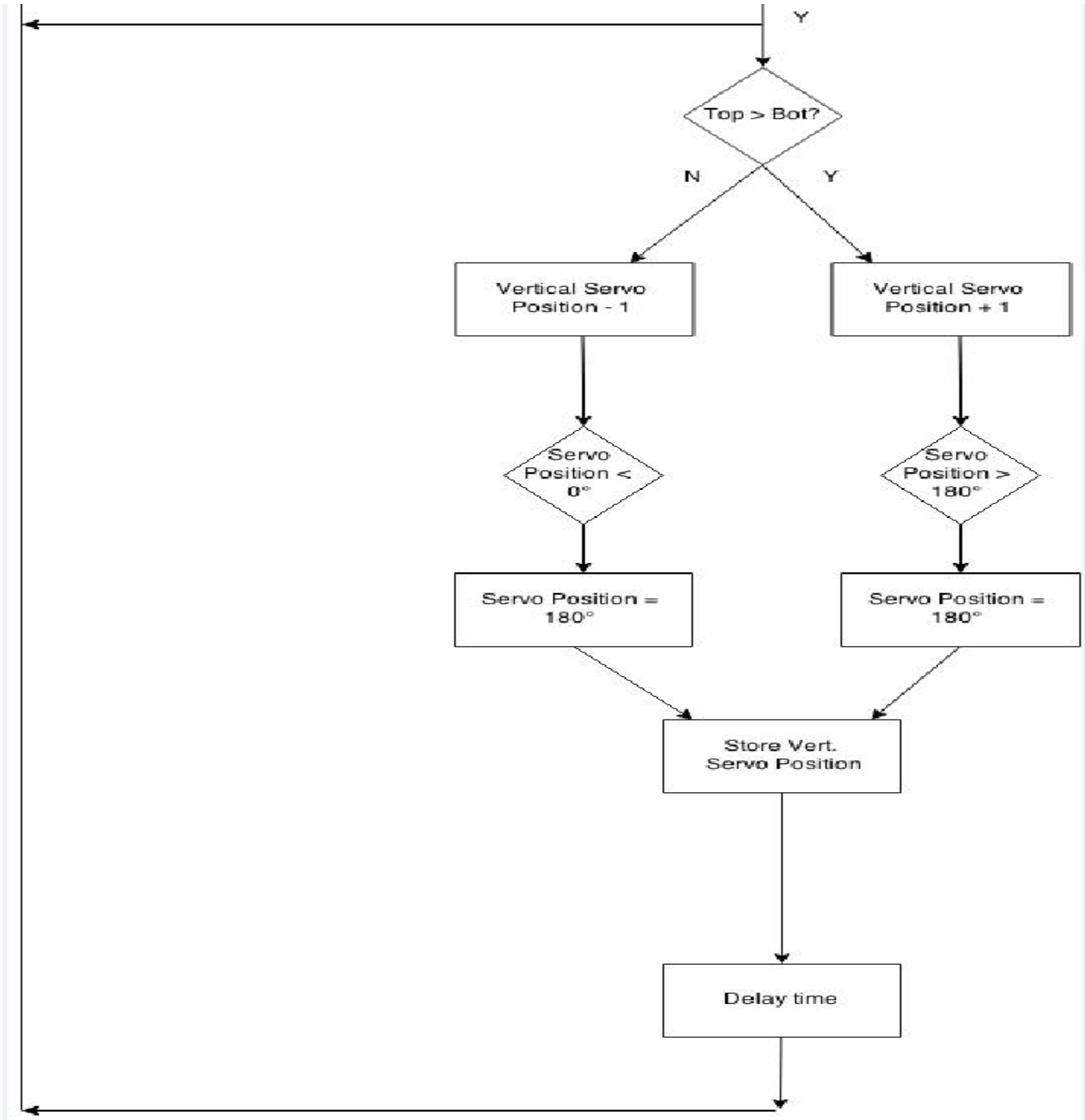

Figure 13 Flowchart Continued

6 Hardware Design

6.1 LDR circuit

The hardware required for processing power, including the circuit that is necessary to power the motor, connecting the LDR's to the analog pins is displayed below.

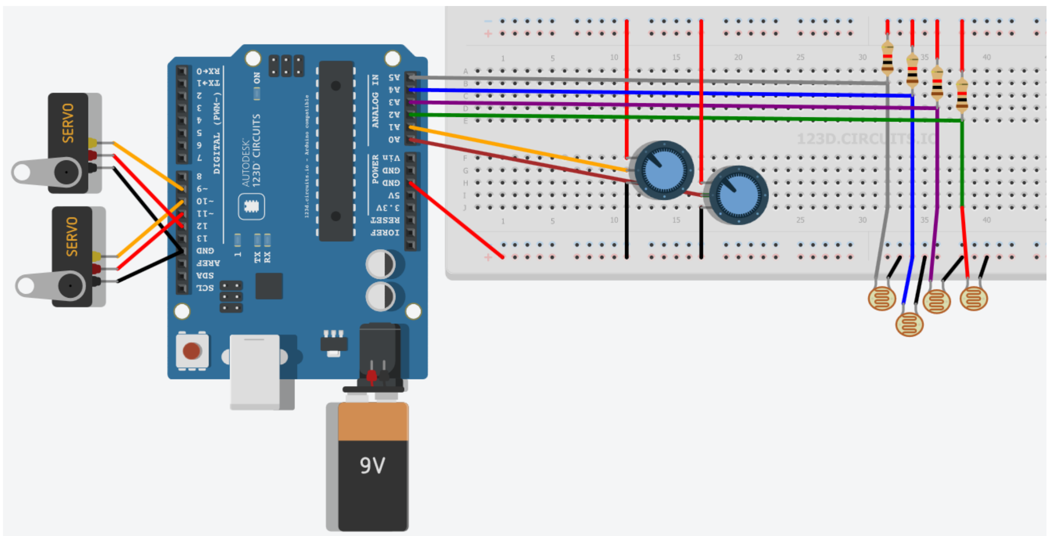

Figure 14 LDR circuit layout

These analog pins, A01 - A05 are connected with four 10kOhm resistors which are necessary in order to serve as a voltage divider. The voltage device is necessary to prevent the processor from short circuiting, which can damage the hardware. After reading the resistances using A01- A05, these values are converted into digital signals which can then be displayed on the Arduino's terminal. The digital values are than manipulated using the software as discussed in section 5. One potentiometer is needed to adjust the tolerance stated in the flowchart for the differences in LDR values if necessary. The other potentiometer is for adjusting the delay time after all actions are executed in the loop.

6.2 Light Intensity Conversion Circuit

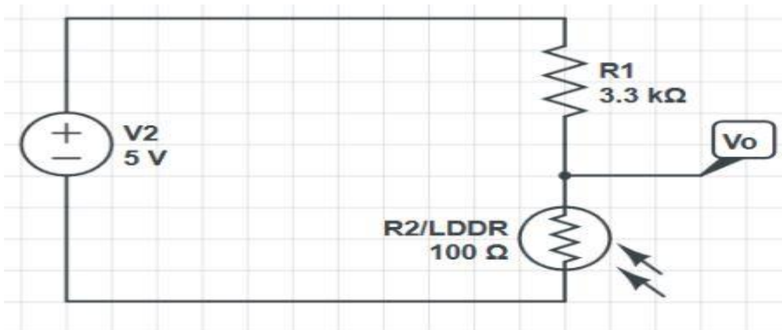

Figure 15 Light intensity conversion circuit

This voltage divider circuit converts the resistance output of the LDRs into light intensity values. The light intensity lux is given by the equation $\frac{500}{R_L}$ for a typical LDR resistor.

The voltage of the LDR resistor Vo is calculated as follows:

$$V_O = \frac{5R_L}{R_L + 3300}$$

$$R_L V_O + 3300V_O = 5R_L$$

$$3300V_O = 5R_L + V_O R_L$$

We can then get the R_L equation which we will substitute into the lux equation above.

$$R_L = \frac{3300V_O}{5 + V_O}$$

$$\frac{500}{Lux} = \frac{3300V_O}{5 + V_O}$$

$$Lux = \frac{2500 + 500V_O}{3300V_O} = \frac{25}{33V_O} + \frac{5}{33}$$

This equation is reasonable because the voltage and therefore the resistance of the LDR is inversely proportional to the light intensity.

7 Rotating Mechanism

7.1 Servo Motor

7.1.1 Torque

The Servo motor used in our design has a maximum torque of 9 N.m where the required torque for our design purposes as per earlier calculations is Fy*d where Fy corresponds with the weight of the umbrella and d is the distance between the umbrella and the motor. The mass of the beam for calculation purposes is considered negligible, which in practise would be untrue. Typical aluminum foil weighs between 0.01 - 0.02 Kgs when wrapped around an umbrella and umbrella by itself weighs 1.4 kgs. Hence the minimum torque required becomes

$$Torque = (1.4 + 0.02)kgs \times 9.8\frac{m}{s^2} \times 1m = 13\ N.m$$

The minimum distance from the motor to the umbrella can be decreased in order to achieve in order for the design to function with the given motor torque. Hence the new calculations becomes

$$Distance = \frac{9N.m}{(1.42 \times 9.8\frac{m}{s^2})kg} = 0.65\ m$$

7.1.2 Angular Velocity

The required angular velocity our design requires is approximately 2.5°/10 minutes and the minimum provided by servo motor is 5 revolutions per minute. In order to obtain the design parameters, gears may be used. The calculations are provided below.

$$Provided := 78260°/10\ minutes$$

$$Required := 2.5°/10\ minutes$$

$$Gear\ Ratio := 1{:}9000$$

The gear ratio required to slow down the motor in order to achieve the design specification is too high. There are two possible ways to decelerate the RPM. The first one is 3D printing a gear with 9000 teeth or controlling the motor using Arduino's PWM.

8 Test Plan

8.1 Motor/Rotation Test

Conditions

The motor rotation tests will be fairly straight forward, after making the final assembly, apply voltage with the required duty cycle and observe the final design

- If the motor produces a stuttering sound, the motor is not getting enough power or it has been overloaded.
- Test to observe if the motor rotates exactly 90 degrees when a pulse of 400 μsec is applied as discussed in the data specification.

Expected Results

- What we expect after applying this test is that the motor provides a torque of 9 N.m, which is required to move the solar dish.
- The motor will rotate with an angular velocity of 2.5 degrees/ 10 minutes.

8.2 Temperature Test

Testing the temperature can be done during the initial stages of building the prototype by placing a wireless temperature sensor near the focal length of the dish.

Expected Results

- Reaches 200° C at the focal point.

8.3 ASAE Solar Cooker Performance Test

We will follow the recording procedure from the ASAE standards test which is as follows:

"The average water temperature (C) of all cooking vessels in one cooker shall be recorded at intervals not to exceed ten minutes, and should be in units of Celsius to the nearest one tenth of a degree. Solar insolation (W/m^2), ambient temperature (C), and wind speed (m/s) shall be recorded at least as frequently. Record and report the frequency of attended (manual) tracking, if any. Report azimuth angle(s) during the test. Report the test site latitude and the date(s) of testing [7]".

- The cooking power will be calculated based the equations provided the by the standards test set by the ASAE in various weather conditions and day temperatures

8.4 Software Test

Using Arduino's PWM, our test engineers will program the motor such that the required RPM is achieved. The software can be tested using high level programming languages, measuring the duty cycle by observing the graphs, tweaking the code and obtaining the expected results. The LDR's will also be tested using software; this will be done so by displaying the intensity values on Arduino's terminal.

Expected Results

- The PWM test will result with the motors rotation. The motor should rotate minimally, since the desired angular velocity/ RPM is minimal.
- The LDR software test will provide different resistances, if the two LDR's are placed further apart and display similar values when tested together.

9 Conclusion

The Sun Tracking Solar cooker product designed by the team at SunCrest Inc is intended to provide sufficient solar energy for cooking purposes targeting areas that are under developed with abundance of sunlight At such places where energy is limited, sun tracking solar cooker is easy to implement, since it saves time and provides an easy and efficient way to cook. The solar tracker built in the cooker enables it to cook with more energy efficient than a manual solar cooker.

To implement such a system, the design specifications detailed in this document closely captures the functional requirements originally outlined. The overview of the system clearly illustrates the purpose of solar cooking, how it is built and energy calculations. The proof-of-concept prototype is intended to demonstrate the sun tracking solar cooker while the commercialized product will feature enhanced capabilities with a sleek final finish. Current constraints on implementing a complete product are primarily minimal time resources. Beyond this, the document also highlights the selection process of each component justifies its use through its capabilities and financial convenience.

The company aims to present a functioning product applying to the proof-of-concept model by April 13, 2015. The attached test plan will be a assessment tool to verify the operation of the system.

References

[1] Prinsloo, G. (n.d.). Sun Tracking. In *Solar Tracking* (pp. 50-100).

[2] Determining the focal length of a parabolic dish (axi-symmetric, circular). (n.d.). Retrieved March 4, 2015, from http://www.satsig.net/focal-length-parabolic-dish.htm

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[5] Optical Power Measurement. (n.d.). Retrieved March 19, 2015, from http://home.earthlink.net/~apptechy/OpticalMeasure/OpticalMeasure.htm

[6] SPG785A Top Mount. (n.d.). Retrieved March 1, 2015, from https://www.servocity.com/html/spg785a_top_mount.html#.VQesleE3020

[7] CCT test protocol (n.d.). Retrieved March 19, 2015 from http://solarcooking.org/asae_test_std.pdf

Appendix

PREPARED BY JUN HEE, LEE
UPDATE:FEB 20, 2003

GENERAL SPECIFICATION OF HS-785HB WINCH SERVO

1. TECHNICAL VALUE

CONTROL SYSTEM	:+PULSE WIDTH CONTROL 1500usec NEUTRAL	
OPERATING VOLTAGE RANGE	:4.8V TO 6.0V	
OPERATING TEMPERATURE RANGE	:−20℃ TO +60℃(−46℉ TO +86℉)	
TEST VOLTAGE	:AT 4.8V	AT 6.0V
OPERATING SPEED	:1.68sec/360° AT NO LOAD(1.4sec/100mm)	1.38sec/60° AT NO LOAD(1.1sec/100mm)
STALL TORQUE	:11kg.cm(152.75oz.in)	13.2kg.cm(183.31oz.in)
STANDING TORQUE	:8.8kg.cm(122.20oz.in)/5° HOLD OUT	10.5kg.cm(145.81oz.in)/5° HOLD OUT
IDLE CURRENT	:8mA AT STOPPED	8mA AT STOPPED
RUNNING CURRENT	:230mA/60° AT NO LOAD RUNNING	250mA/60° AT NO LOAD RUNNING
STALL CURRENT	:1500mA	1800mA
DEAD BAND WIDTH	:5usec	5usec
OPERATING TRAVEL	:1.75turns/ONE SIDE PULSE TRAVELING 1500 TO 1900usec	
DIRECTION	:CLOCK WISE/PULSE TRAVELING 1500 TO 1900usec	
MOTOR TYPE	**:CORED/METAL BRUSH**	
POTENTIOMETER TYPE	:6 SLIDER/INDIRECT DRIVE	
AMPLIFIER TYPE	**:ANALOG AMPLIFIER**	
DIMENSIONS	**:59x29x50mm(2.32x1.14x1.96in)**	
WEIGHT	**:110g(3.88oz)**	
BALL BEARING	:DUAL/MR106	
GEAR MATERIAL	:HEAVY DUTY RESIN	
HORN GEAR SPLINE	:24 SEGMENTS/ø5.76	
SPLINED HORNS	**:QUARTER SCALE/Q-I, Q-O, Q-X**	
CONNECTOR WIRE LENGTH	:300mm(11.81in)	
CONNECTOR WIRE STRAND COUNTER	:60EA	
CONNECTOR WIRE GAUGE	**:22AWG**	