Solar Tracker - Final Project

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1 Design Overview

The closed loop system is designed to maintain a solar table at an orthogonal position with respect to a light source. In other words, the sun is being tracked by the system to yield maximum output power of the photovoltaic cells. Keeping the cells perpendicular to the sun's rays allows them to trap more photons and therefore produce more power for a longer amount of time. The system executes this task using four photoresistors, or light-dependant resistors (LDRs), in an x-shape configuration to determine the altitude and azimuth of the sun or some other light source. The difference between the left and right sensors controls the azimuth angle of the assembly. Similarly the difference between the top and bottom sensors control the altitude angle. Both axis are powered by a micro servo motor that are adjusted by a pulse width modulation signal from a microcontroller. The fully assembled project can be seen in Fig.1.

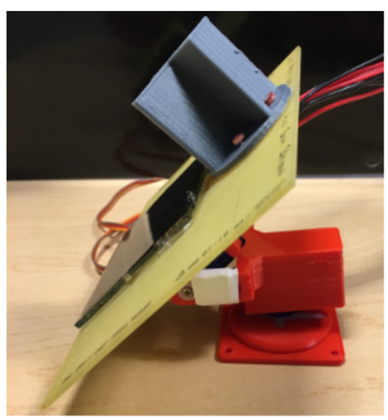

Figure 1: Isometric view of the system under test.

1.1 Design Features

These are the design features of the closed loop system:

- Serial Communication via UART
- Multi-Channel Sequence, single port analog to digital conversion sampling
- Dual-port PWM
- Proportional Control

1.2 Featured Applications

These are some featured applications that this project could support given slight modifications per application:

- Solar tracking systems
- Target lock-on systems

1.3 Design Resources

This is a quicklink to the program files for the project:

`https://github.com/RU09342-F18/intro-to-embedded-final-project-coldworldbutthesunshow`
Here are the links to 3D print the servo hub, servo mount, servo base, and light divider parts....

1.4 Block Diagram

The figure below shows that the system requires two converter subsystems. The first converter box is to calculate any discrepancies in current system status and expected output. The second is a proportional control algorithm that uses the error from the first converter to determine the conversion output to the two motors. Reference section 3.1 for a lower-level diagram.

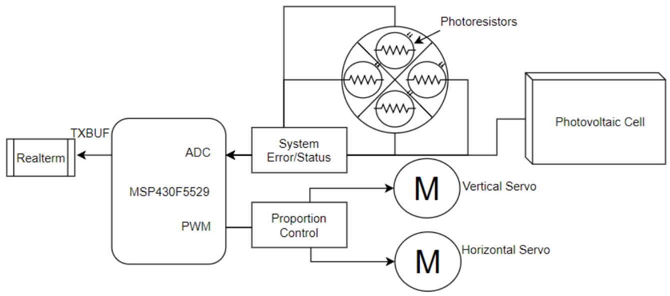

Figure 2: High-level block diagram of the closed loop system.

1.5 Board Image

The blue wires going out of the picture are data lines that are used for the PWM control and analog to digital coversion sampling.

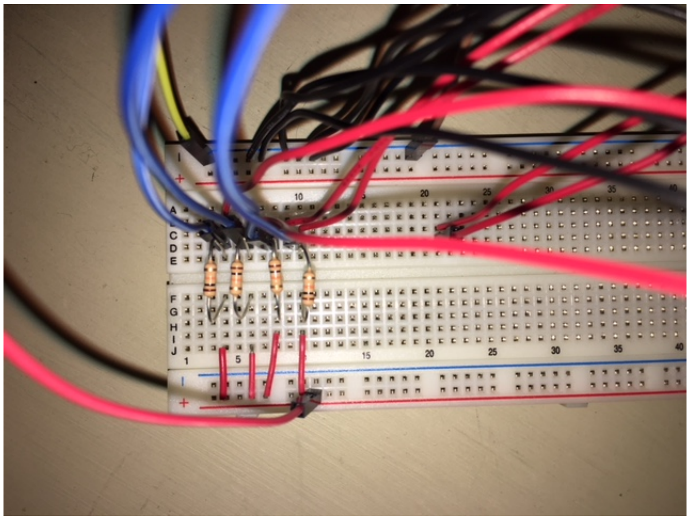

Figure 3: Photo of the Breadboard Setup

Each of the resistors on the left side of the board is a voltage divider which is in series with each of the photoresistors on the solar tracker. Each of the blue wires are connected to ADC ports on the MSP430 and are used in calculating the proportional control of the motor. As the amount of light received by the photoresistors increases the voltage received by the ADC ports increases. Since there is a divider between each of the photoresistors there is a significant difference in the amount of voltage received by the ADC ports which in turn makes our proportional control very accurate. The bottom most red wire is connected to 3.3V on the MSP430 as a reference for the voltage divider. There is also a 5V lead which connects to the motors on the solar tracker as seen in figure 4 below. At the top of the breadboard all of the connections lead to a common ground.

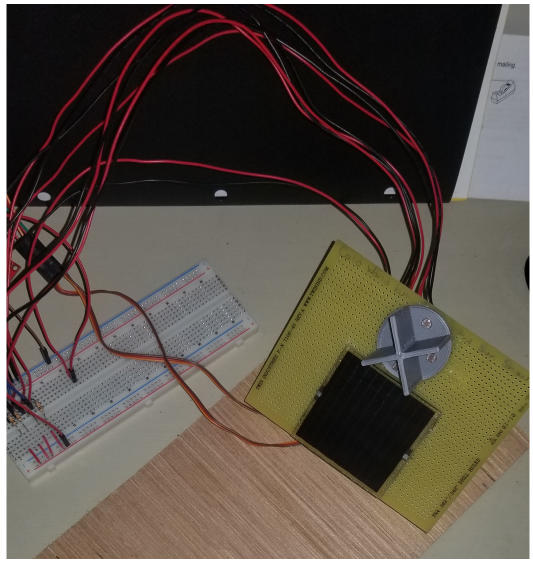

Figure 4: Photo of Breadboard and Solar Panel

2 Key System Specifications

PARAMETERS	SPECIFICATIONS	DETAILS
Azimuth	0-180°	Rotational axis of the system
Altitude	90-160°	Tilt axis, 90°is vertical
Servo PWM	5-10% duty cycle	PWM for both servos
Max Servo Voltage	5V	Separate supply from MSP

Table 1: Various parameter types required by the system

3 System Description

The main goal of this project is to create a system which points and maintains a solar panel in the direction of a light source as well as track the voltage output of the solar panel. In order to do this two motors are used in conjunction with photoresistors which track the location of the light source. Ideally the solar panel is constantly facing the light source directly and in turn the voltage output of the solar panel is constant. In a non-tracking solar panel there is a much lower efficiency than in a tracking solar panel. The photoresistors on top of the system are separated by a divider which prevents light leakage and increases accuracy of the tracking. Each of the four photoresistors are in series a 10kΩ resistor for a voltage divider topology. The output voltage of the divider is read by the onboard Analog-to-digital converter of the MSP430. Tracking calculations based off of these voltages are made and sent to the PWM control in order to turn the servos. Additionally the voltage readings taken directly from the solar panel lead is sent to TXBUF to be read and recorded with serial communication. The system and the program take the error between the values of the photoresistors and uses those to track the position of the light source using proportional control.

3.1 Detailed Block Diagram

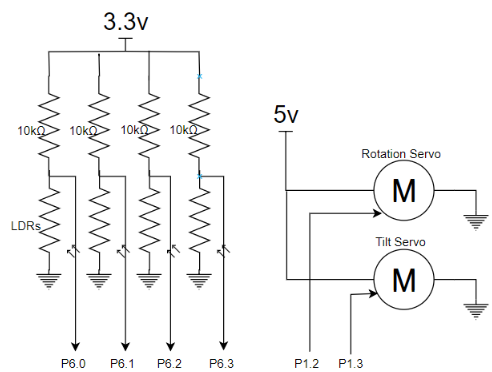

Figure 5: Detailed block diagram of the closed loop system.

The ports with directional arrows is data from/to the MSP430F5529. The grounds shown in the diagram are separate for ease of drawing, but in fact the circuit should have common ground across all devices.

3.2 Highlighted Devices

- MSP430F5529: The microprocessor contains the protocols for the ADC, PWM, and UART for the LDRS and solar cells.
- Light Dependant Resistor: A light dependent resistor, LDR, or photoresisitor is a light-controlled variable resistor. The resistance of the light dependent resistor decreases with an increase of light intensity and the resistance increases with a decrease of light intensity; photo conductivity. Four light dependent resistors were used to control the position of the solar cell.
- Micro-Servo 9G: The Servo motor was used to move the solar cell based of the PWM inputs of the light dependent resistors. Two servo motors were used; one controls the rotation of the azimuth axis and other one controlled the rotation of the altitude axis.
- Solar Cell: A solar cell, or photo voltaic cell, is an electrical device that converts the energy of a light source directly into electricity by the photo voltaic effect,

which is a physical and chemical phenomenon. The solar cell was used to produce a voltage which was recorded via UART.

3.3 Device/IC 1

MSP430F5529 Microprocessor:

The MSP430F5529 was used as the brain of the circuit. It's role is to send PWM signals to control the posisiton of each servo motor, send and receive UART messages, and read and convert the solar cell's nominal voltage to a readable value.
Pulse width modulation is used to control each of the servo motor's position to keep the solar cell centered over the light source. If the difference between the the left and right light dependant resistor is zero then the servo motor controlling the azimuth axis will not move. If the difference between the bottom and top light dependant resistor is zero then the servo motor controlling the altitude axis will not move.

```
void configurePWM()
{
   // Sets P1.2 as the output pin
   P1DIR |= BIT2;                                  // Sets P1.2 as output driver for pwm for fan speed control
   P1SEL |= BIT2;                                  // Selects the port 1.2 as the timer A output
   P1DIR |= BIT3;
   P1SEL |= BIT3;
   TA0CTL = TASSEL_1 | MC_1 | TACLR;               // Sets timerA_0 to SMCLK, up-mode, clears the register
   TA0CCR0 = 655;                                // Sets CCR0 max pwm
   TA0CCR1 = 50;                                 // Sets CCR1 to initial value of 90 degree position for base motor
   TA0CCR2 = 50;                                 // Sets CCR2 to initial value of 90 degree position for hub motor
   TA0CCTL1 = OUTMOD_7;                            // Output mode 7 reset/set
   TA0CCTL2 = OUTMOD_7;                            // Output mode 7 reset/set
}
```

Figure 6: PWM Setup.

Universal Asynchronous Receiver/Transmitter is used to send and receive signals from the MSP430F5529 to RealTerm or any serial communication firmware. The baud rate was adjusted to match the speed at which data is transferred in order to observe a readable value on the firmware. In this project a baud rate of 9600 was utilized, a Baud rate of 9600 means to have a transfer speed of 9600 bits per second achieved by clock division and modulation.

```
void configureUART()
{
    P1DIR |= BIT0;
    P1OUT &= ~BIT0;

    P4SEL |= BIT5;                              // Enables RX and TX buffer
    P4SEL |= BIT4;
    UCA1CTL1 |= UCSWRST;                        // Software reset enable
    UCA1CTL1 |= UCSSEL_1;                       // USCI clock source select - ACLK
    UCA1BR0 = 3;                                // Baud rate clock divider1 for 9600 BR
    UCA1BR1 = 0;                                // Baud rate clock divider2 for 9600 BR
    UCA1MCTL |= UCBRS_3 | UCBRF_0;              // First and second stage modulation for higher accuracy baud rate
    UCA1CTL1 &= ~UCSWRST;

    UCA1IE |= UCTXIE;                           // Enables Transfer buffer interrupt
}
```

Figure 7: UART Setup.

The Analog to Digital Converter was needed to properly analyze the input from light dependant resistor to a readable value. Each light dependant resistor is configured to its own ADC port and then compared to each other. In addition, the solar cell is also configured to its own ADC port in order to properly read the voltage produced by the solar cell. With a total of 5 individual ADC ports being used in the project In Fig.8 the various registers and control registers were initialized.

```
void configureADC()
{
    P6SEL = 0x1F;                               // Enable A/D channel inputs
    ADC12CTL0 = ADC12ON+ADC12MSC+ADC12SHT0_2; // Turn on ADC12, set sampling time
    ADC12CTL1 = ADC12SHP+ADC12CONSEQ_1;       // Use sampling timer, single sequence
    ADC12MCTL0 = ADC12INCH_0;                 // ref+=AVcc, channel = A0
    ADC12MCTL1 = ADC12INCH_1;                 // ref+=AVcc, channel = A1
    ADC12MCTL2 = ADC12INCH_2;                 // ref+=AVcc, channel = A2
    ADC12MCTL3 = ADC12INCH_3;                 // ref+=AVcc, channel = A3, end seq.
    ADC12MCTL4 = ADC12INCH_4+ADC12EOS;
    ADC12IE = 0x10;                           // Enable ADC12IFG.4
    ADC12CTL0 |= ADC12ENC;                    // Enable conversions
}
```

Figure 8: ADC Setup.

3.4 Device/IC 2

Micro-Servo 9G:

Two servos were used to control the tilt and rotation of the solar hub. The servos are controlled by the micropressor via pulse width modulation. The desired pulse width is determined by an algorithm based on the voltage output of the LDRs. The PWM signal is a 50Hz signal with a 5-10% duty cycle. In other words, the total period of the signal is 20ms and the time on can be within 1ms to 2ms. If the time on is 1ms the position of the servo is at 0°, if the time on is 1.5ms the position is at 90°and so on. A visual representation of the required PWM signal for the servo is in Fig.9.

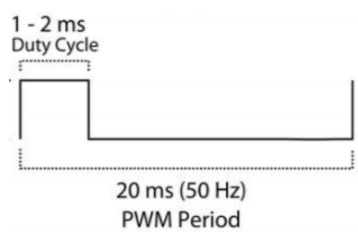

Figure 9: PWM signal of micro-servo SG90

4 SYSTEM DESIGN THEORY

The system in this project is responsible for maintaining a solar cell at a specified position. The position of the panel with respect to the sun is determined by four LDRs. These LDRs act as the balance system. If one photoresistor is receiving more light, the system must adjust to account for this difference. The photoresistors are arranged in a voltage divider topology, and each voltage output of the dividers is then converted to a digital value using the onboard ADC. The resultant of the changing resistance of the light dependant resistors can be calculated for servo motor control using equations 1, 2, and 3.

$$VoltageDivider : ADC = 5V * \frac{10k\Omega}{R_{Photoresistor} + 10k\Omega} \tag{1}$$

$$VoltageDividerDifference : Diff = ADC1 - ADC2 \tag{2}$$

$$P - Control : MotorPosition = CurrentMotorPosition + (Diff * K_p) \tag{3}$$

The variable K_p is the proportionality constant which can be tuned to the optimal nominal value for a specific application. In the case of this system, less twitch of the motors and smoother movements was observed with a K_p less than 0.0025.

4.1 Design Requirement 1

Positioning the Solar Cell:

The main objective is to maintain the orthogonality of a solar cell positioned in the direction of a light source, even if that source is moving; like the sun. The nominal resistance of the light dependant resistors determines the output voltage of the voltage divider which is logged by the 12-bit ADC. The four voltages are compared in a manner that the opposing sensor, left from right, are evaluated. If the difference is not equal to zero the motor will act accordingly to maintain orthogonality. This behavior is executed using proportion control since PI control is not necessary in this application due to the nature of the slow, consistent ”traveling” sun.

4.2 Design Requirement 2

Serial Communication:

In order to easily communicate and receive information from the solar monitor it is necessary to send data through serial communication. Although UART was implemented, the serial communication with the MAX7221 to 7-seg display was also attempted. In order to output using serial communication it is necessary to set up Master Out Slave In (MOSI), Chip Select (CS) and clock (CLK) ports. This can be seen in the image below.

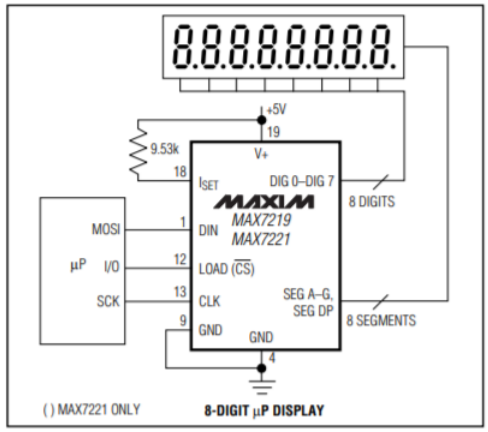

Figure 10: Schematic of MAX7221 Interfacing with MSP430 and 7-SEG Display

When the MSP430 is ready to send a signal it turns off the CS bit and the MOSI port sends a 16 bit signal to the MAX7221 over the course of 16 clock cycles. After the 16 clock cycles are complete the CS signal is turned off again. The 7-segment display which was used only contained digits as opposed to the eight displayed in the figure. Each of the LEDs on the 7-segment display has an anode and a cathode. The MAX7221 A through G pins were connected to the A through G anodes on the 7-segment display and the first three digit pins on the MAX7221 were connected to the gates of three transistors which each connected the digit cathodes on the 7-segment display to ground. This allows for each digit to be sent individually.

4.3 Design Requirement 3

Proportional Control System:

The heart of the tracking system is the proportion control subsystem. This subsystem is responsible for calculating and delivering the proper PWM signal to each servo motor and subsequently moving the system. In other words, the proportional control's task is to keep the error of the system, difference in target resistance and true resistance, at zero by correcting for changes in position of the light source. This concept is generally referred to as negative feedback. The proportional control loop calculates this error every sample period and is multiplied by a controller gain, or proportion constant. This constant can be fine tuned during testing depending on the type of servo motor being used as some are more powerful than others. Typically, the product of the error and constant are biased by some null value but in this project we didn't utilize the controller bias null value. However, since there was a significant deadzone for the motors which were used there was no need to deadzone manually. The code for the proportional control can be found below in figure 11.

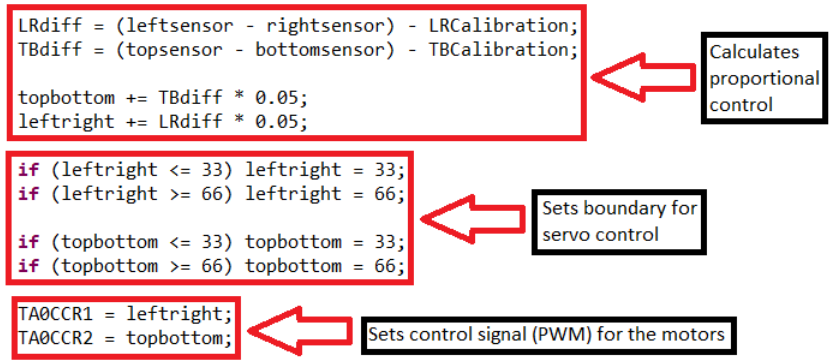

Figure 11: Code for Proportional Control of Servo Motors

In the first two lines in figure 11 the difference between the voltage on the right sensor and the left sensor are found and offset by a calibration value which is found by calibrating the system. The system can be calibrated by pointing a direct light source straight into the sensor and pressing button P1.1 on the MSP430. After this the difference which is multiplied by the proportional constant (0.05) is added to the current motor position which is represented by topbottom and leftright. After this the boundaries for the motor position are enforced with several if statements. Next the position is sent to the motor in the form of a PWM signal.

5 Getting Started/How to use the device

In order to use this device set up the circuit in figure 2 with the servo motors connected to a 5V power supply and the voltage divider is connected to the 3.3V power supply and connect them both with a common ground. After this the sensors must be calibrated. In order to calibrate the sensors ideally the solar tracker should be put in a dark or dimly lit environment with a single light source directly pointed at the device at a distance of around one to two meters. Once the light source is in place press button P1.1 and the sensors will be calibrated. Next just place the solar tracker out in the sun and let the solar tracker track the sun. Additionally if the user wants to track the voltage output of their solar panel Realterm must be used. Further details of the RealTerm setup can be read in section 6.

6 Getting Started Software/Firmware

In order to interface with the solar tracker and receive information about the voltage output of the solar panel Realterm must be set up properly. In order to do this first the baud rate needs to be set to 9600 within Realterm. The communication port found within the device manager menu within the control panel of your computer will indicate the port that the MSP430 is instantiated to. This must to be set to the corresponding port on Realterm. Also, the display must be set to unit8, or unsigned integers of 8 bits, and half duplex checked off. After the program is flashed to the board, the circuit is fully and properly built, and the program is running Realterm should automatically be receiving the voltage values of the system. In Fig.12 below is an example of how a serial communication software setup should look.

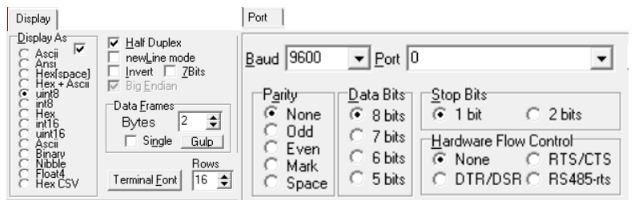

Figure 12: Realterm setup of display and port menus where Port 0 is the port that the board is connected to in the user's computer.

6.1 Hierarchy Chart

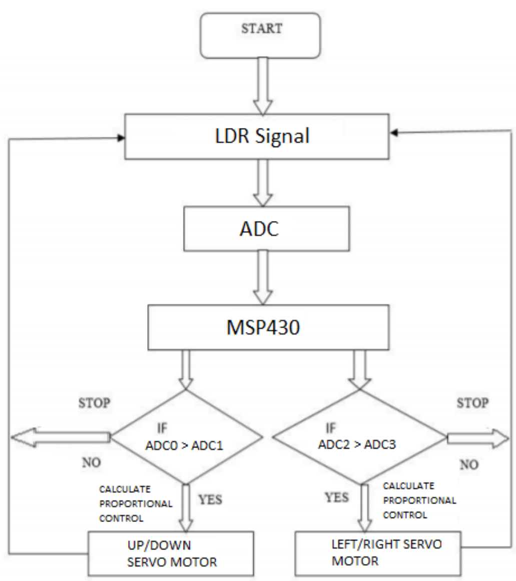

Figure 13: Hierarchy Chart of the Closed Loop System.

6.2 Test Data

In the figures below are the curves of the voltage readings from the solar cell under test. The test consisted of an artificial light that panned across the solar cell 180°over a 20 second period. This test was done while the tracking system was on and while it was off. In Fig.14 the system tracking is turned on and it is apparent that the voltage reading reaches max voltage, under artificial light intensity, much sooner than that of the non-tracking system in Fig.15. In addition to that, it stays at max voltage for a much longer period of time further maximizing total power output. Hence, the balancing of the four sensors allows for the solar cell to maintain an orthogonal angle with respect to the sun. A resultant of this is that the solar cell will produce more peak power for an extended period of time throughout the day.

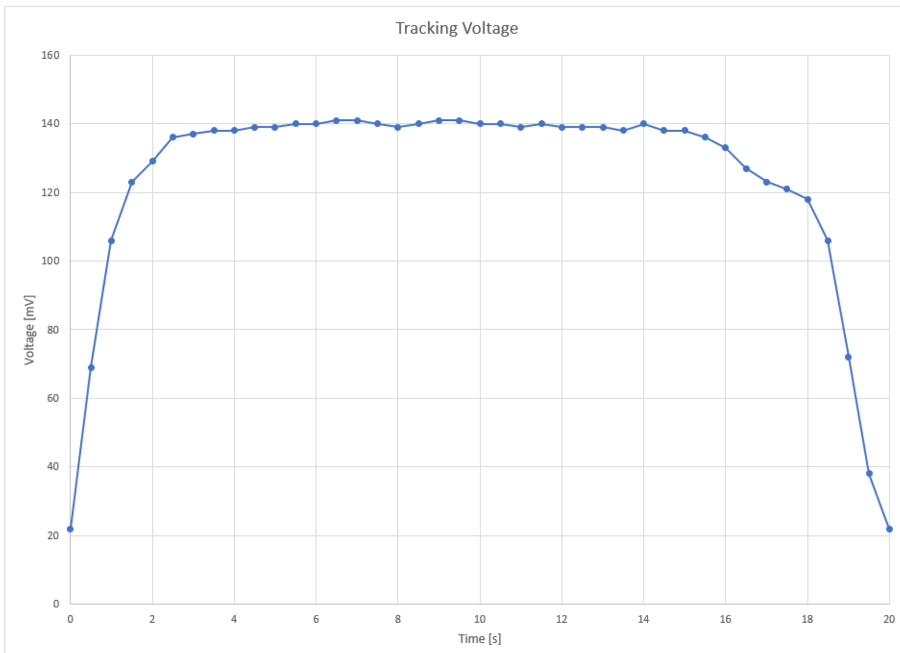

Figure 14: Realterm test data while system tracking is on

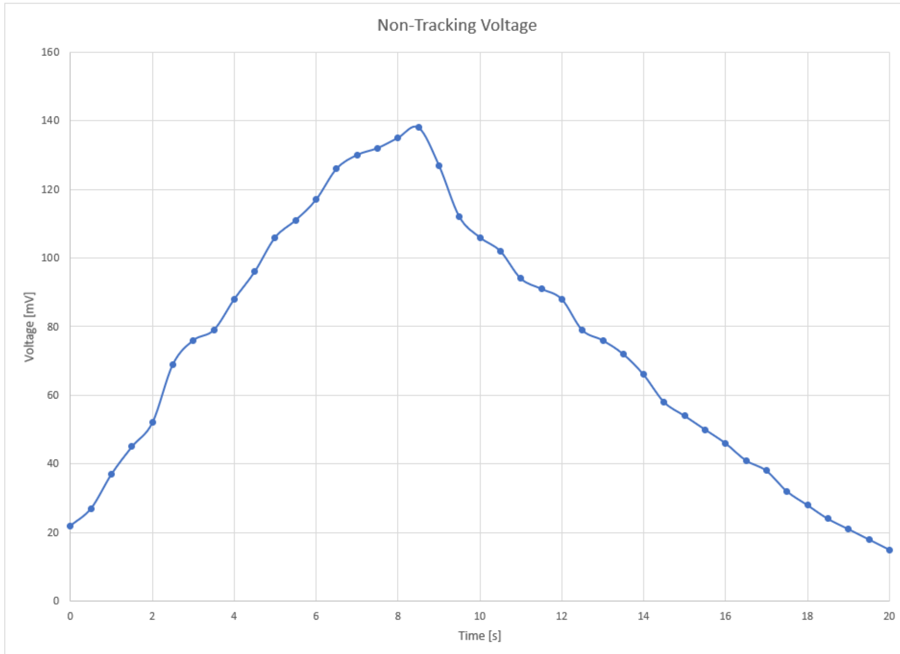

Figure 15: Realterm test data while system tracking is off

6.3 Systemic Errata

The tracking system in general has a few errors that cause system failure. The first and most obvious is when the motor reaches it's full range of motion in either direction, especially in the tilt servo, the motor gets stuck and needs external assistance to get moving again. This is most likely a resultant of lower quality mechanical components, faulty motors, or a combination of the two. Most of the time, however, this stuck position most commonly occurs in the tilt servo. The design of the pan tilt in Fig.18 doesn't allow for the table to tilt to a position parallel to the ground. This could also be another reason why the motor is getting stuck and this aspect of the project would be reevaluated in future work. Furthermore, the environment in which the system is being test has a great effect on the performance of the tracking. If there are reflective surfaces or multiple sources of light intensity the tracking will tend to be jittery and unpredictable. Even the calibration parameter doesn't entirely negate these errors. A suitable environment to test the system is in an open area with minimal obscurities and one light source to prevent imbalances. Also, it is worth noting that consistently identical photoresistor characteristics are ideal for high accuracy. The vast difference in the proportionality of light intensity to nominal resistance between the four separate photoresistors caused some discrepancies in actual results and expected results. Overall, the tracking system performed well but has many possible improvements.

6.4 Bill of Materials

- 4 - 10kΩ 1/4W resistor
- 2 - Micro servo motor SG90
- 1 - MSP430F5529 Launchpad kit
- 4 - light dependant resistors
- 1 - 3D printed Pan tilt connector
- 1 - 3D printed Pan tilt base
- 1 - 3D printed Pan tilt platform
- 1 - 3D printed light divider
- 1 - Solar Cell
- 1 - Perforated board

7 Appendix

7.1 Appendices A

Below is a quick link to the datasheet of the servo motors used in this project. `http://www.ee.ic.ac.uk/pcheung/teaching/DE1_EE/stores/sg90_datasheet.pdf`

7.2 Appendices B

Below is a quick link to the datasheet of the light dependant resistors used in this project. `https://www.sunrom.com/get/443700`

7.3 Appendices C

Below is a quick link to the users guide for the MSP430F5529 launchpad. `http://dev.ti.com/tirex/#/DevTool/MSP-EXP430F5529/?link=Device20Documentation2FMSP430I`
`6XX2FMSP430F55292FUsers20Guide`

7.4 Appendices D

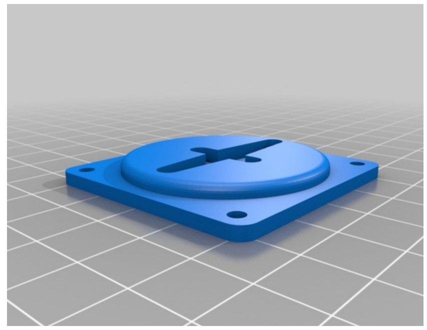

Figure 16: 3D printed Platform

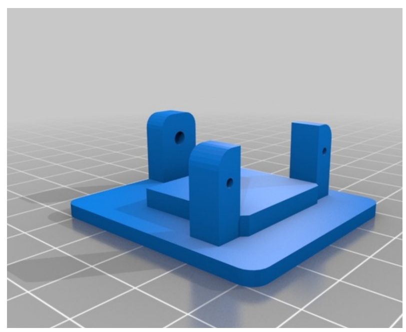

Figure 17: 3D printed Base

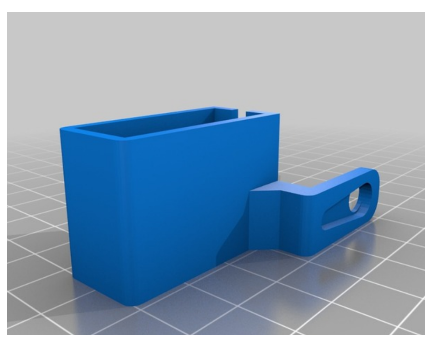

Figure 18: 3D printed Pan tilt

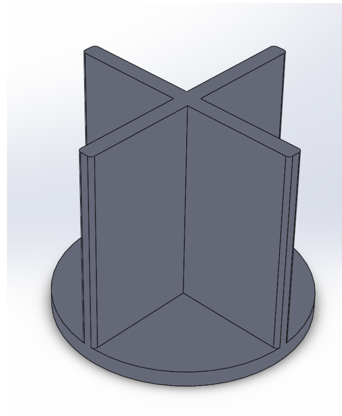

Figure 19: 3D printed light divider