Solar/Motion Powered Shoe Heater

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Abstract

It is commonly known that your feet, hands, and face are more prone to frostbite and therefore keeping them warm is crucial when participating in outdoor activates during cold temperatures. In this paper we describe the design and development of a shoe that has the ability to harness energy from both motion and light to power a circuit that monitors temperature and heats the interior of the shoe. We developed tests and procedures to verify the functionality of the complete system as well as its subsystems. Results demonstrate full functionality of the shoe, though improvements can still be made.

Contents

1. Introduction

The motivation of this project was to provide people with a convenient heating system for their shoes during the cold weather. Commercially available foot heaters require electrical outlets for charging and temperature settings have limited adjustability. Overall, our project implements the use of solar and motion energy to charge batteries that will then go through a system that generates heat in the interior of a shoe to make winter activities more accessible. The heating unit within the shoe will be adjustable through an android app that will wirelessly connect to a microcontroller via Bluetooth. The app will display and allow the user to adjust and monitor temperature, as well as display the total amount of steps taken by the user.

1.1 Project Overview

The goal of the project is to heat the interior of a shoe powered through rechargeable batteries that harvest energy from solar and motion sources. Solar energy is detained through the use of flexible solar cells that are mounted on the exterior of the shoe and directly connected to the lithium batteries to store charge. Motion energy is captured through the use of piezoelectric material that is rectified and connected directly to the rechargeable batteries that powered the heating system. Besides producing energy to power system components, the piezoelectric film implements a step counter, through the application of a low pass filter, and transmits data to the android app displaying total steps taken by the user. Heating pads surround the interior of the shoe and temperature is monitored through a temperature sensor that is directly connected to the microcontroller. Current flow through the heating pads is controlled by the microcontroller that receives temperature setting from a user. The user interface is an android application that displays the real time temperature felt in the interior of the shoe and steps taken by the user, promote healthier living. Data is transmitted and received from the build-in USART of the microcontroller that is connected to a Bluetooth module that connects and wirelessly transfers data from mobile device to heating system. Users are able to download the application to android mobile devices, connect to the shoe wirelessly through Bluetooth, and begin using the shoes for cold temperature activities.

2 Design

The block diagram shown in Figure 1 illustrates the project break down into three smaller functions: the power supply module, heat processing unit and the user interface.

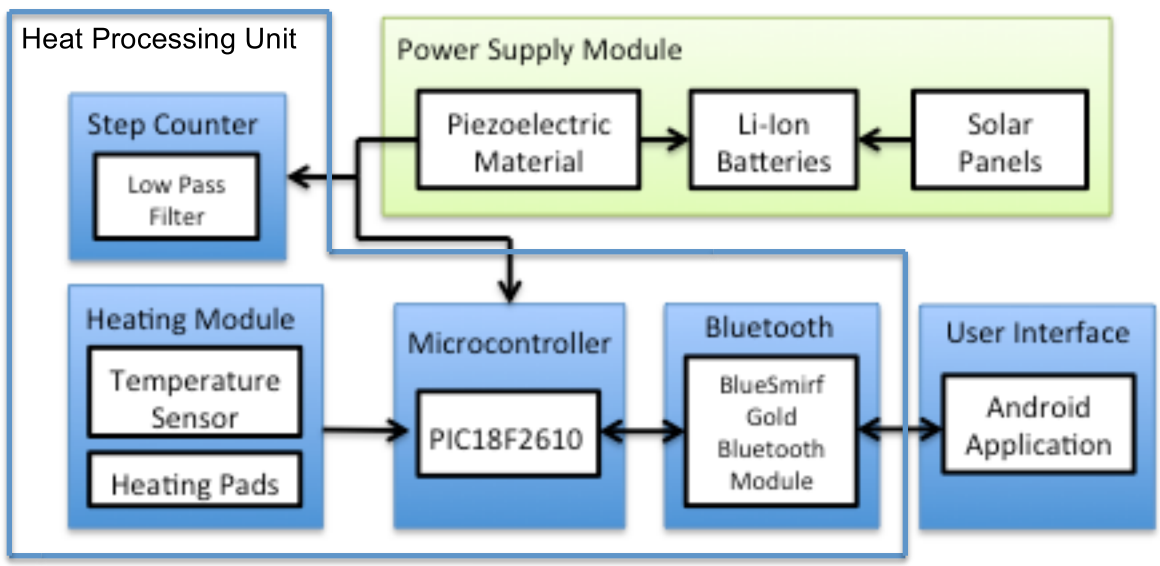

Figure 1 System Block Diagram

2.1 Power Supply Module

This module is responsible for generating power for the heating system. It consists of three sub-parts: the piezoelectric charging circuit, a solar charging circuit, and lithium ion rechargeable batteries. The energy harvesting circuits store energy into the thin film 3.7V Li-ion batteries.

2.1.1 Piezoelectric Charging Circuit

The piezoelectric charging circuit (*Appendix A*, Figure 3) converts the energy from motion and pressure into electric charge, which is then stored into a battery. It is composed of four parts: a piezoelectric source, energy harvesting circuit, boost converter, and energy storage.

For the piezoelectric source, the Volture Mide V25W was selected because it is specifically developed for energy harvesting. It consists of two piezoelectric slabs, which can either be connected in series, to maximize voltage, or parallel, to maximize current. For our project, the current needs to be maximized, so the V25W was connected in parallel. It is relatively light, weighing at 0.15oz, and with dimensions of 1.81 in x 1.31 in x 0.005 in, it is small enough to fit inside the sole of a shoe.

The energy harvesting circuit takes the oscillating voltage produced by the piezoelectric material converts it to a DC voltage and stores the charge in a capacitor. It is composed of a full-wave bridge rectifier, and a capacitor. Sodano et. al [1] states that the main advantage for this configuration is that it is very simple, minimizing the physical area and the power dissipation of the circuit. Instead of using diodes to build the rectifier, MOSFETs, specifically the BSP295 small-signal NMOS and the BSP315 small-signal PMOS, are used to minimize the voltage drop from the source to the capacitor. The voltage drop for a MOSFET when it is conducting is given by:

$$V_{drop} = I_D * R_{DS,on} \tag{1}$$

Using datasheet values for the MOSFETs, the BSP295 has a maximum voltage drop of about 0.54 V while the BSP315 has a maximum voltage drop of 0.936 V. The current produced by the piezoelectric material passes through one NMOS and one PMOS at a time, so the maximum total voltage drop will be about 1.5 V. This is smaller than the voltage drop across two 1N4001 diodes, which is approximately 2 V, if a diode bridge rectifier was used. Using Multisim, the rectifier circuit shown in *Appendix A*, Figure 4 was simulated and the result is shown in *Appendix B*, Figure 12 to illustrate the circuit's performance.

The boost converter steps the voltage of the charged capacitor up to 5.5V. This output voltage was chosen because there is a 1N4004 diode that has a voltage drop of approximately 1 V. The thin film Li-ion battery is then charged at 4.5V, which is above its cut-off charging voltage of 4.2V. The TPS61200 Low-Input Voltage Synchronous Boost Converter with 1.3A switches was selected because of it can step up voltages as low as 0.3 V. *Appendix A*, Figure 5 shows the schematic for the TPS61200 chip and the components needed to design the desired boost converter.

The minimum input voltage ($V_{in,min}$) is set to 0.3V, and the output voltage (V_{out}) is set to 5.5 V. The TPS61200 datasheet gives the feedback voltage (V_{FB}) as typically 0.5 V and the current through the FB pin is 0.01uA. The oscillation frequency (f) is at 1250kHz. The output current (I_{out}) is 1.2 A. The datasheet also gives the equations used to design the converter. The recommended value for resistor R_2 was about 200kΩ, so that the divider current is higher than 1uA. A 180kΩ resistor was selected for R_2 to satisfy this requirement. To calculate R_1, the following equation from the is used:

$$R1 = R2 \times \left(\frac{Vout}{VFB} - 1\right) \tag{2}$$

$$\mathrm{R1} = 1800\mathrm{k}\Omega$$

Resistor R_4 was recommended to be 250kΩ, because the UVLO pin typically has a current of 0.01 uA and a voltage of 250 mV. R_3 is then calculated using the equation:

$$R3 = R4 \times \left(\frac{Vin, min}{VUVLO}\right) \quad (3)$$

$$R3 = \ 50\text{k}\Omega$$

The datasheet recommended that the value of the inductor L_1 be 2.2 uH, for the best performance in all ranges of inputs and outputs. This inductor value was then used to calculate the maximum input voltage using the equation:

$$Lmin = Vin, \max \ \times 0.5 \ \frac{us}{A} \quad (4)$$

$$Vin, \max = 4.4 \ V$$

Using the value of $V_{in,max}$, the required current rating of the inductor can be calculated by using the equation:

$$Imax(inductor) = \frac{Vout \times Iout}{0.8 \times Vin, max} + \frac{Vin, max \times (Vout - Vin, max)}{2 \times Vout \times L \times f} \quad (5)$$

$$Imax = 1.62 \ A$$

The data sheet recommended C_1 to have a value of 4.7uF and C_{vaux} to have a value of 0.1uF for optimal performance in all voltage ranges. To calculate C_2, the next equation is used:

$$C2 = 5 \times L \times \frac{uF}{uH} \quad (5)$$

$$C2 = 11 \ uF$$

Table 1: Summary of Design Components for TPS61200 Boost Converter

Component	Value	Component	Value
R_1	1.80MΩ	**L_1**	2.2µH
R_2	180kΩ	**C_1**	4.7µF
R_3	50kΩ	**C_2**	11µF
R_4	250kΩ	**C_{vaux}**	0.1µF

A PGEB016144 lithium-ion battery is used to store the energy harvested from the piezoelectric source. It is light, only weighing 6 grams, and its small size, 1 mm x 44 mm x 61 mm, make it suitable for implementation into a shoe.

2.1.2 Solar Charging Circuit

The solar charging circuit is the main source of power used for charging the Li-ion batteries, so choosing the correct materials was vital. Initially, we planned to use 0.5V 25mA super solar cells to generate the power for solar charging. We began testing the panels and they performed well to our expectations. However, during our testing we broke several of the panels and soldering pieces of wire to the terminals was impossible, it became apparent that they were far too brittle to be mounted externally on a shoe. We researched some alternative panels, and decided on PowerFilm 4.2V 22mA Flexible Solar Panels. These proved to be far better suited for our project.

The solar charging circuit (*Appendix A,* Figure 6) consists of 3 parallel solar panels in series with a diode and the batteries. The solar panels generate current when exposed to artificial or natural light, which flows into the battery to recharge it. The diode is used in-between the panels and batteries in order to prevent reverse current from flowing back from the battery.

2.1.3 Lithium Ion Batteries

Three lithium batteries are used to store the charge generated from the piezoelectric material and solar panels. The batteries were chosen to provide maximum power to power the components in the heat-processing unit while having the ability to provide enough current to heat the heating pads located in the interior of the shoe. The battery capacity is 180mAh at 3.7V.

2.2 Heating Processing Unit

The heat-processing unit is responsible for taking user settings through the Bluetooth module, monitor temperature, heating the shoe to desired temperature, and keep track of steps taken. It completes these tasks through four sub-systems: step counter, heating module, microcontroller, and Bluetooth.

2.2.1 Step Counter: Low Pass Filter

A simple RC low pass filter is directly connected to the piezoelectric material implementing a step counter as shown in *Appendix A,* Figure 6. The piezoelectric film as mentioned above is dependent on vibrations on the film therefore in order to capture walking gestures, the implementation of a low pass filter was suggested. Low pass filters allows low frequency signals and attenuates other signals that aren't below the cut-off frequency. The cut-off frequency is calculated using the equation:

$$f_c = \frac{1}{2\pi RC} \tag{6}$$

This equation was used to solve for resistance and capacitance values. In order to properly solve for a capacitance or resistance value, we chose a 1µF capacitor and solved for R:

$$R = \frac{1}{2\pi f_c C} \tag{7}$$

Therefore solving for R, the resistance, we chose a resistor that met out needs. We decided to choose a cut-off frequency of 100Hz to ensure that steps were properly counted as accurate as possible. Plugging in the selected values we calculated the resistance needed:

$$R = \frac{1}{2\pi(100Hz)(1\mu F)} = 1591.549$$

Since 1549.55Ω isn't a typical resistance value, a 1.5kΩ was used instead and therefore our new cut-off frequency is 106.1Hz. After deciding resistance and capacitance for the filter, the circuit was simulated on an online software, CircuitLab, that verified that the selected values would filter high frequencies. The simulation, shown in *Appendix B*, Figure 16, verified that low frequencies were did not attenuate while high frequencies attenuated.

2.2.2 Heating Module

The heating module is in charge of monitoring the temperature and receiving information from the microcontroller to provide current to the heating pads to heat the shoe. In order to monitor the temperature a temperature sensor, LM35dz, was selected. The temperature sensor was selected because of the basic setup, shown in Figure 2, and accuracy, which was important to our project.

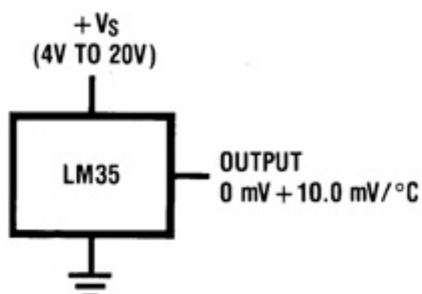

Figure 2 Temperature Sensor Pin Detail

The sensor includes three pins: GND, Vdd, and Vout. The sensor interfaces with the microcontroller as shown in *Appendix A*, Figure 6 but must go through a non-inverting amplifying circuit first because its output voltage, as seen in Figure 2, is 10mV per degrees Celsius and the microcontroller was unable to detect the input voltage from the sensor at room temperatures.

A basic non-inverting circuit was used to minimize complexity and parts used. The circuit consists of two resistors and an operational amplifier as seen in *Appendix A*, Figure 9. After verify the minimum voltage that could be applied to the microcontroller input, we decided a gain of 5 would be sufficient to get a temperature reading from the sensor. We used a LM2904 Dual op-amp chip for the op amp and to figure out the resistor values that would be needed to create a gain of 5 we used the following equation:

$$Gain = 1 + \frac{R_2}{R_1} \tag{8}$$

The placement of R1 and R2 can be seen in *Appendix A*, Figure 9. Since we already knew that a gain of 5 would be sufficient, a resistor ratio of 4 was needed. To improve the temperature accuracy, we decided to use variable resistor to come as close to a perfect gain of 5 volts. We selected 1.5kΩ for R1 so used a 2kΩ variable resistor, and from equation 8 needed R2 to be 6kΩ so used a 10kΩ variable resistor. We used the multimeter and oscilloscopes to calibrate the resistors as needed. After desired values were obtained we connected the output of the op-amp to the microcontroller as seen in *Appendix A*, Figure 6. Again, using CircuitLab the non-inverting amplifying circuit was simulated to verify the gain of 5 that was intended, results are shown in *Appendix B*, Figure 17.

2.2.3 Microcontroller and Bluetooth

The microcontroller pin input and output can be seen in the schematic found in *Appendix A*, Figure 6. The PIC is configured to run at 32mHz using internal clock and clock multiplier. The main routine in the PIC utilizes the USART serial interface to send and receive data through the Bluetooth module. It also utilizes a custom protocol for executing tasks. The protocol expects character bytes to be sent to the serial communication, and then executes the appropriate action according to the following protocol:

Table 2 Heating Pad control protocol

Byte Received:	Action Exectued:	Comment:
'u'	Allows current to flow through heating pad	Action opens switch and hold open for a small period of time
'd'	Prevents current to flow through heating pad	Action closes switches
'c'	Reset watchdog timer	Reset the watchdog timer without changing the state of the switch

The PIC also contains 10bit analog to digital converters that were utilized for the temperature sensor voltage output, as well as interrupt pins for the LPF that implemented the step counter. It interfaces with the Bluetooth module through I/O pins RX and TX, which are registers that store transmitting and receiving data. This chip was programmed to receive and transfer information from a mobile device and adjust temperature changes as needed.

The Bluetooth interfaced with the microcontroller as shown in *Appendix A*, Figure 6. The Bluetooth module is a SparkFun BlueSmirf Gold, which is simply a Roving Networks RN-42 AT Bluetooth module mounted on a small PCB with a voltage regulator and a 3V to 5V TTL converter. When paired and connected to another Bluetooth device, the module passes through any serial data it receives to the connected device. It is set to 9600-baud rate and allows for wireless communication between the shoe and the user to set settings and monitor shoe temperature. It essentially behaves as a “wireless cable” between the connected device and the PIC.

2.3 User Interface

The user interface consists of a user-friendly android application. The app can be downloaded through any android mobile device with Bluetooth capabilities. A screen shot of the application can be seen in *Appendix A*, Figure 17.

2.3.1 Android Application

The android application was designed using Eclipse IDE, Java Development Tool, and XML based layout files. The app was developed for manually controlling heating settings on the shoe as well as displaying the temperature in the shoe and the steps taken. The application communicates with the PIC through Bluetooth serial and utilizes the heating pad control protocol to send the PIC appropriate commands based on user input. The app using a simply algorithm that receives data from the Bluetooth module and displays the information sent in the “Temp” or “Step Count” display windows as seen in *Appendix A*, Figure 17. The microcontroller works in conjunction with the app to receive characters through the Bluetooth when a step is detected. The PIC sends the character ‘s’ when a step is detected using the LPF that is connected to an input pin on the PIC, then displays and increments the step count.

3. Design Verification

3.1 Power Supply Module

Connecting each of the PGeB016144 thin film polymer Li-ion batteries to an oscilloscope tested the power supply’s effectiveness. Since the boost converter did not function, a discharged battery was needed to test the charging functionality of the piezoelectric circuit. A discharged battery at about

230mV was charged to 1.2V using the piezoelectric circuit. The solar cells were able to fully charge the batteries connected (up to 3.7V). The batteries were also shown to have the capability to power the heating circuit when fully charged.

The PGEB016144 lithium-ion batteries are used to store the energy harvested from the piezoelectric and solar sources. They are light, only weighing 6 grams, and its small size, 1 mm x 44 mm x 61 mm, making them suitable and ideal for our project.

3.1.1 Piezoelectric Material Circuit

Connecting the pins of the Volture V25W in a parallel configuration as shown in the datasheet, and continuously tapping on the device tested the piezoelectric source. The output was displayed in an oscilloscope and as shown in shows the open circuit voltage for the Volture V25W. *Appendix B*, Figure 10 illustrations open-circuit voltage magnitudes that ranged approximately between -25V to +25V from the piezoelectric material. These results comply with the specifications in the datasheet and confirm the source is reliable and functional.

The Volture V25W was connected to a rectifier circuit on a breadboard and the output was displayed on the oscilloscope. The rectified output of the piezoelectric material can be seen in *Appendix B*, Figure 11. It can be observed that the circuit successfully rectifies the circuit, but there is a significant drop in the voltage. This can be attributed to the power dissipation of the rectifier circuit, and to the faulty soldering of wires on the surface mount pins on the MOSFETs resulting to bad contacts.

A 100uF electrolytic capacitor was used to store the charge produced through piezoelectricity. This was added to the piezoelectric circuit on the breadboard and the voltage was measured using a digital multi-meter, since it dissipates less power than an oscilloscope. The capacitor voltage increases up to approximately 0.8 V. This voltage is relatively low due to the bad contacts on the MOSFETs, which reduces the amount of current going into the capacitor, but it is still within the minimum required voltage for the boost converter. When the circuit was built on a PCB and the MOSFETs had good contact with the surface, the capacitor voltage increases up to a maximum of approximately 2V.

The implementation of the TPS61200 boost converter circuit on the PCB was verified by connecting the output to a DMM. After the capacitor reaches a voltage within the converter's range of inputs (0.3V-4.4V), the DMM display was read to see if the converter outputs 5.5V. This test was unsuccessful. The TPS61200 was not made for manual soldering, since it was too small and it was difficult to solder the contact pads into the PCB. Soldering resulted to burning the chip, so the functionality of the boost converter was never observed.

To test if the circuit, excluding the boost converter, can recharge a battery, the 100uF charged capacitor was then connected to a discharged Li-ion battery. The capacitor can only be charged up to a maximum of 2V, so the battery voltage needed to be less than 1.8 V in order to demonstrate charging. The discharged battery was measured to initially have approximately 200 mV. After applying pressure to the V25W, a slow but steady increase of voltage was observed, showing the functionality of the charger at lower voltages.

3.1.2 Solar Panel Circuit

In order to test sub requirement a, individual solar panels were connected to a battery through a diode on a breadboard and peak voltage and current measurements were taken under varying light conditions. In order to vary the lighting conditions in the lab, we took measurements with just the ambient lighting of the room, with a single flash shining on the panels from a mobile device, and with flash from two mobile devices shining on the cells.

With both flashes shining on the solar panels, we were able to achieve a peak open circuit voltage of 5.9V and peak closed circuit voltage and current of 4.2V and 22mA respectively. Results are displayed in Table 3 for better visual representation of testing outcomes. Simply confirming that under random bending strain no visible cracks were produced, and afterward the panels were still functional tested sub requirement (b). The solar charging circuit met the requirement; other aspects and testing set up can be found in *Appendix C*, Table 4.

Table 3 Results for solar panel testing

	Current (mA)	Voltage (V)
Open-Circuit	0	5.9
Closed-Circuit	22	4.2

3.2 Heat Processing Unit

Our main requirements and verification for the heat processing components can be found in *Appendix C*, Table 4.

3.2.1 Step Counter: Low Pass Filter

In order to test output attenuation, the input of the low pass filter was connected to a function generator and the frequency swept from 10Hz to 150Hz. More detailed description of verification procedures for the step counter is shown in *Appendix C*, Table 4.

3.2.2 Heating Module

The heating module required substantiation of the temperature sensor, the non-inverting amplifier, and the heating pads. The verification procedure is illustrated in *Appendix 4*, Table 4. In order to ensure accurate temperature reading from the temperature sensor multiple tests were conducted and examined through the use of the oscilloscope, to view output voltage, and then compare to temperature displayed on the app. A non-inverting amplifier was needed and tested to display accurate temperature readings to the app through the PIC because of the minimum voltage input at the PIC pins. The non-inverting amplifier was tested alone with the use of the power supply to swept a DC voltage at the input and plot the output voltage through the oscilloscope. This ensured the inputs would not exceed the maximum voltage rating from the PIC. Actual temperature vs. voltage measurements were taken in the lab and results are displayed in *Appendix B*, Figure 14.

The heating pads were tested in parallel with the temperature sensor to ensure that they were functional and safe to use in the interior of the shoe by sweeping a current range that falls within the limits of the circuit. A current range from 0-0.6Amps was used to simulate the current supplied from the batteries to the heating. Results for this test can be seen in *Appendix B*, Figure 15.

3.2.3 Microcontroller and Bluetooth Module

Figuring out how to correctly set up the serial communication between the microcontroller and the Bluetooth was a challenge and therefore constant testing and verification was needed. Sources such as RealTerm and an android application, BlueTerm, were used to verify wireless connection between the mobile device and PIC. We initially confirmed the functionality of the Bluetooth by simply powering it up and connecting with a Bluetooth capable device. After confirming connection between Bluetooth module and mobile device, we interfaced the Bluetooth module to the PIC. To verify correct baud rate and other setting, RealTerm was used to send and receive data. This confirmed connection and functionality of Bluetooth module and PIC.

To verify I/O from the PIC, simple voltage reading and implementations were used. Since we needed to ensure that the LPF would interrupt the processor and handle the code to increment the step count, we used a button to simulate a digital “high” input of the PIC. When the button was pressed, an increment to the step count was expected and displayed in the app. This demonstrated the functionality of the interrupt handler and implementation of the step counter.

Thorough verification for both the microcontroller and Bluetooth can be found in *Appendix C,* Table 4.

3.3 User Interface

Detailed requirements and verification of the user interface can be found in *Appendix C*, Table 4.

3.1.1 Android Application

To validate the apps interface with the system, we tested the apps connection with the Bluetooth module, the information displayed, and button pressed from the app for correct data transmission. The app uses the menu button to display a menu in which you could either connect or disconnect to a Bluetooth device. If connect is selected, the user is prompted with a list of available devices and can connect to any desired device, for our particular use the Bluetooth module device name is "FireFly-AE5E". Once the user selects the device, the app displays a message informing the user of connection status.

The information displayed was tested simultaneously with the testing of the temperature sensor. As we varied the temperature, the voltage varied proportionally, as detailed in section 3.2.2, and the output voltage was converted to it corresponding temperature, as seen in Figure 2, and compared to the displayed value on the app.

4. Costs

4.1 Parts

Table 4 Parts Costs

Part	Manufacturer	Retail Cost ($)	Bulk Purchase Cost ($)	Actual Cost ($)
PIC Microcontroller (PIC18F2610)	Microchip Technology	4.40	4.40	17.60
Bluetooth Modem – BlueSmirf Gold (WRL-10268)	Sparkfun	64.95	64.95	129.90
PowerFilm Flexible Solar Panel (700-11325-05)	Sundance	7.95	7.95	23.85
Heating Pad 5x15cm (COM-11289)	Sparkfun	4.95	4.95	19.80
Thin Film Lithium Ion Battery (PGEB016144)	GEB	10.00	10.00	40.00
Boost Converter (TPS61200)	Texas Instruments	3.16	3.16	15.80
Piezoelectric Film (V25W-ND)	Mide	87.50	87.50	87.50
Temperature Sensor (LM35DZ)	Texas Instruments	5.95	5.95	11.90
Diodes (1N4001)	Fairchild Semiconductors	0.14	0.14	0.70
Small Signal NMOS (BSP295)	Infineon	0.33	0.33	3.96
Small Signal PMOS (BSP315)	Infineon	0.24	0.24	2.88
Bypass Capacitors 0.1uF (ECY-39RH153KV)	DigiKey	0.37	0.37	3.70
Capacitors 100 uF (ECA-1HM101B)	Panasonic	0.09	0.09	0.90
Dual Op-Amp (LM2904)	Fairchild Semiconductor	0.46	0.46	0.92
DIP Reed Relay (8L02-05-01)	Coto Technology	3.05	3.05	6.10
Pull-up Resistors 2.2k (RER60F2211RC02)	DigiKey	0.10	0.10	1.00
Shoe (Nike Basketball)	Goodwill	4.00	4.00	4.00
PCB		50.00	50.00	100.00
Total				**470.51**

4.2 Labor

Table 4 Labor Cost

Name	Hourly Rate	Total Hours Invested	Total = Hourly Rate x 2.5 x Total Hours Invested
Crystal Cardenas	$40.00	150	$15,000.00
Carlo Vendiola	$40.00	150	$15,000.00
Andrew Chavarria	$40.00	150	$15,000.00
Total		450	$45,000.00

5. Conclusion

5.1 Accomplishments

Overall the Solar/Motion Powered Shoe Heater was a success. All components were integrated onto a single running shoe. The piezoelectric circuit was integrated onto a PCB and the heat-processing unit was integrated onto a vector board. The system was able to increase the ambient temperature of the shoe from 25^{o}C to up to 71^{o}C, anything past that would not be accurately transmitted to the app due to PIC input voltage limitations and the possibility of burning your foot. The android application was able to accurately display the shoe's temperature and display the step count in real time.

5.2 Uncertainties

One of the uncertainties we encountered was the inability of creating a fully functional PCB. Due to last minute changes made and mislabeled information on the PCB we were unable to test and verify the printed PCB functionality. Another uncertainty was the ability of quantifying the charging rate of the batteries. The charging mechanisms for the batteries were very dependent on external factors that were hard to keep constant, such as the applied pressure on the piezoelectric material and the intensity of the light captured by the solar cells. We were also not able to get the boost converter to function, so we were not able to gather data that would directly show the piezoelectric circuit fully charging the battery.

5.3 Ethical considerations

The relevant portions of the IEEE Code of Ethics that we conformed to while undertaking this project are as follows:

> *1. to accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment;*

In the process of designing our system, we did research about the materials that we were planning to use and made sure that none of them posed any danger to the safety of the people using our heating system and to the environment.

> *3. to be honest and realistic in stating claims or estimates based on available data;*

Our performance claims are stated clearly and backed by accurate data, which we collected from testing, and verification that we performed.

9. to avoid injuring others, their property, reputation, or employment by false or malicious action;

In order to avoid risk of injury to the user, we have ensured that our heating circuit cannot generate enough current to raise the temperature of the heating pads above 115°F.

5.4 Future work

Our final product performed well overall, however there are still several areas where it could be improved, both hardware and software aspects of the project.

With regard to the hardware components, we would like to design a single PCB for our project, add a power switch, and have a larger surface area of piezoelectric material. In our finished project we had a separate PCB for the power supply module portion of the system and the remaining components were on a vector board. Therefore combining both boards and minimizing the total area of the resulting PCB will reduce the surface area used on the shoe. The overall appearance and performance (e.g., lower resistances from the elimination of unnecessary runs of copper wiring) of our design would also benefit from the design of a single PCB containing all of the circuits.

Additionally, when doing our initial brainstorming and design, we overlooked the obvious fact that the microcontroller, temperature sensor and Bluetooth modem would be constantly be drawing power while the batteries are connected. Therefore, we would like to add a simple on/off toggle switch to prevent unnecessary battery discharge when the shoe is not in use.

During our testing and verification process, we found that our piezoelectric circuit was only capable of charging the batteries to approximately 1.2V. In order to improve this powering capability of the piezoelectric material, we would like to increase the total surface area of the piezoelectric material by either adding additional Volture Mide V25W components in different areas underneath the sole of the shoe or purchasing larger area material.

As for the software, we would like to add feedback to the arrow button on the android application and improve the implementation of temperature maintenance. Our current implementation of the Android application uses images for the up and down arrows, which do not give any indication of whether a button press has registered. To solve this problem, we would like to add haptic feedback and animation to the arrow buttons to give visual and tactile confirmation that a button press has been registered. Additionally, the software only displays current temperature, and the user continuous to press on the arrows to achieve desired temperature. We feel a more efficient implementation of heating the shoe would be to allow the user to input desired temperature and transmitting that information to the PIC where it will be compared to the current temperature reading and allow the shoe to heat up or cool down until the two temperatures are equal. The microcontroller and temperature sensor in conjunction would then under constantly supervision, which may not be that efficient.

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Appendix A System Schematics

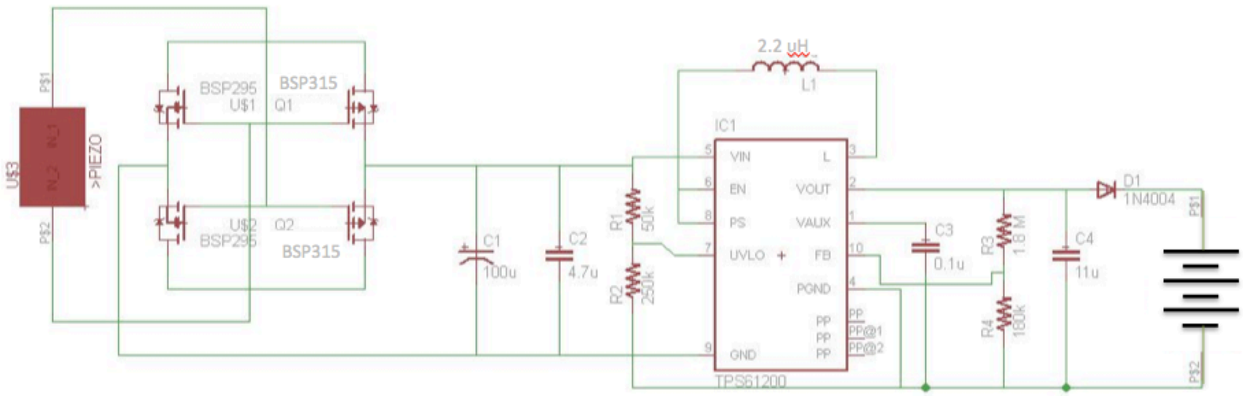

Figure 3: Piezoelectric Circuit

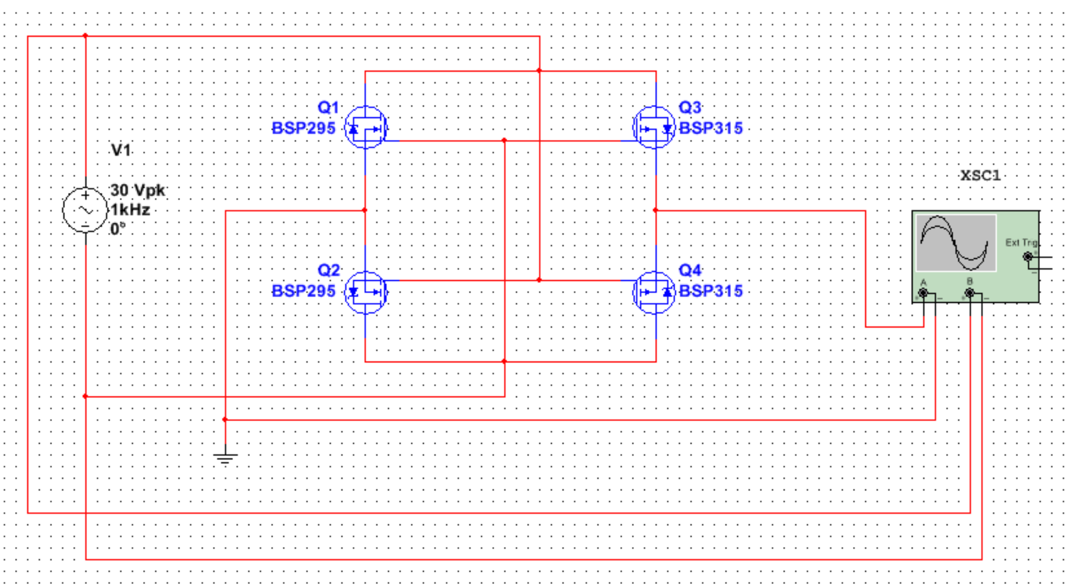

Figure 4: Bridge Rectifier

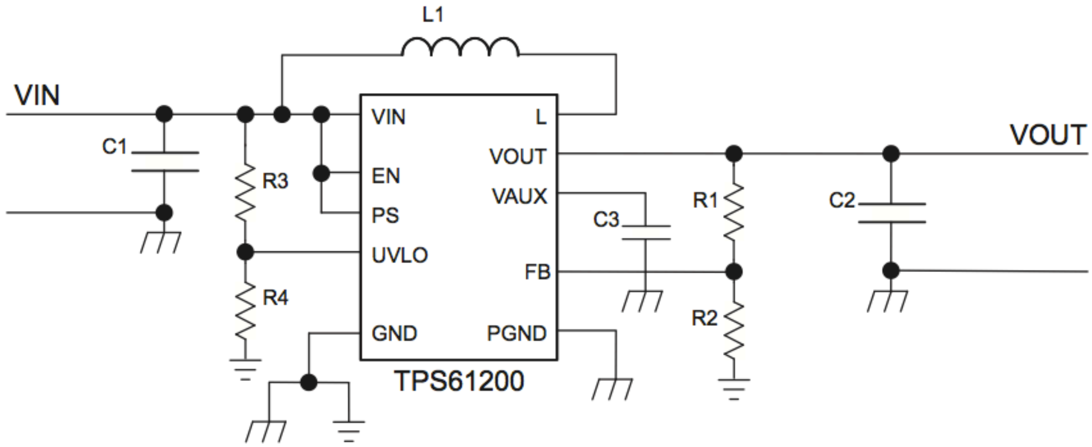

Figure 5: DC/DC Boost Converter

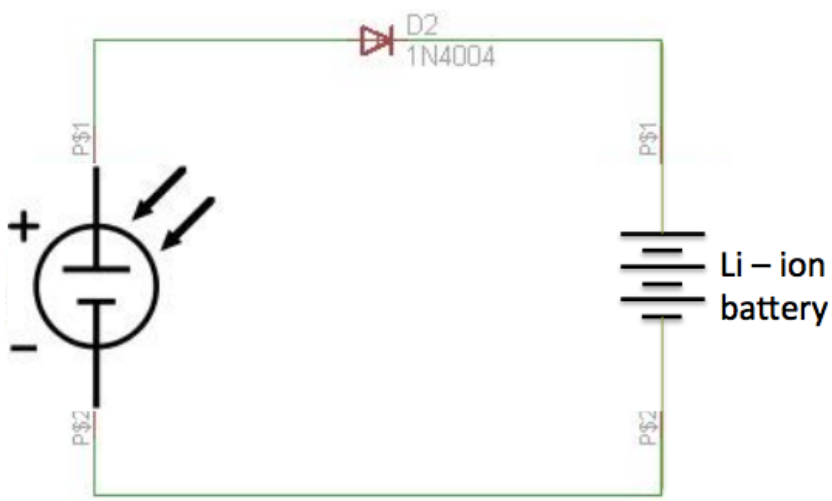

Figure 6: Solar Cell Circuit

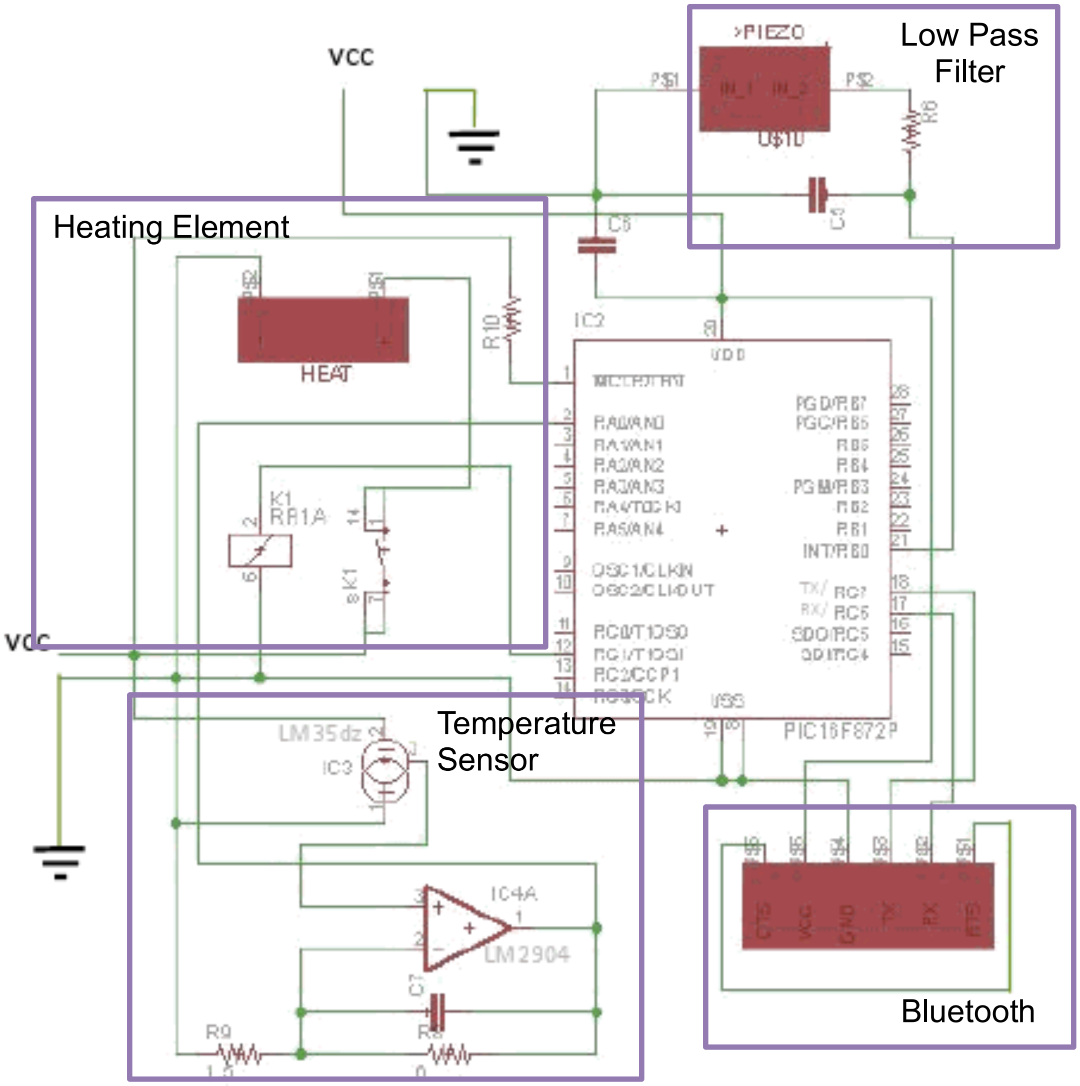

Figure 7: Heat Processing Unit

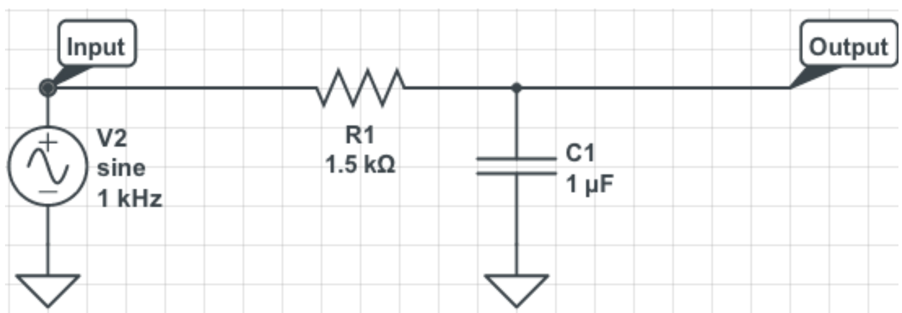

Figure 8: Step Counter (Low Pass Filter)

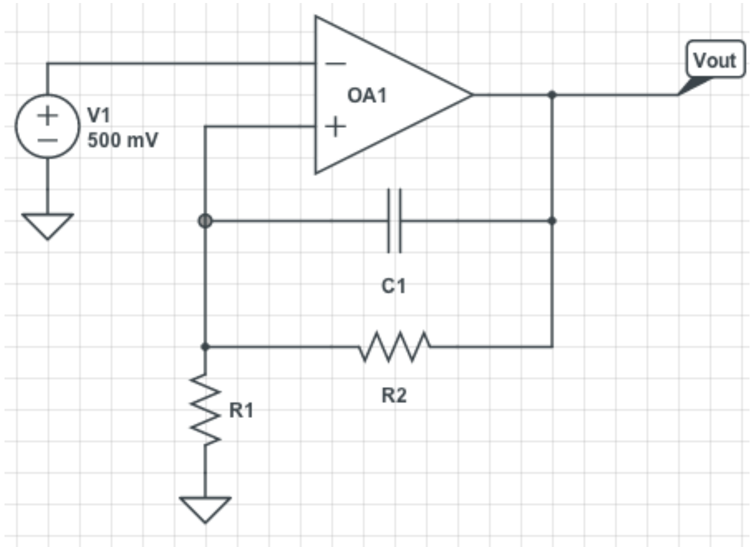

Figure 9: Non-inverting circuit for temperature sensor output to microcontroller

Appendix B System Simulations and Results

Figure 10: Open-Circuit Piezoelectric Material

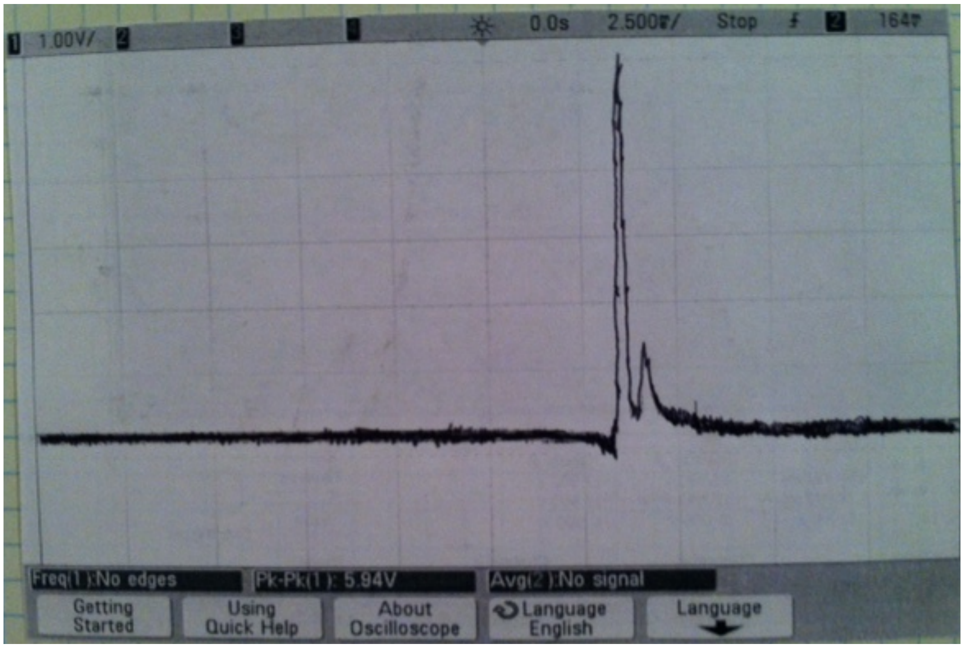

Figure 11: Rectified Output for Piezoelectric Material

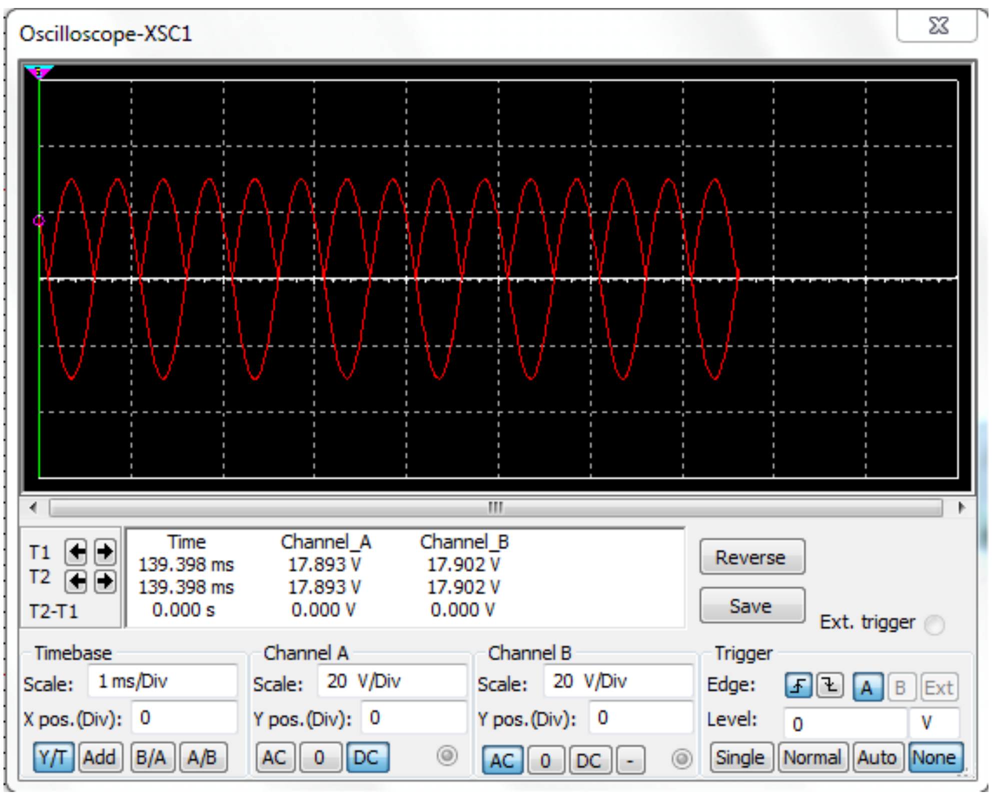

Figure 12: Rectifier Result

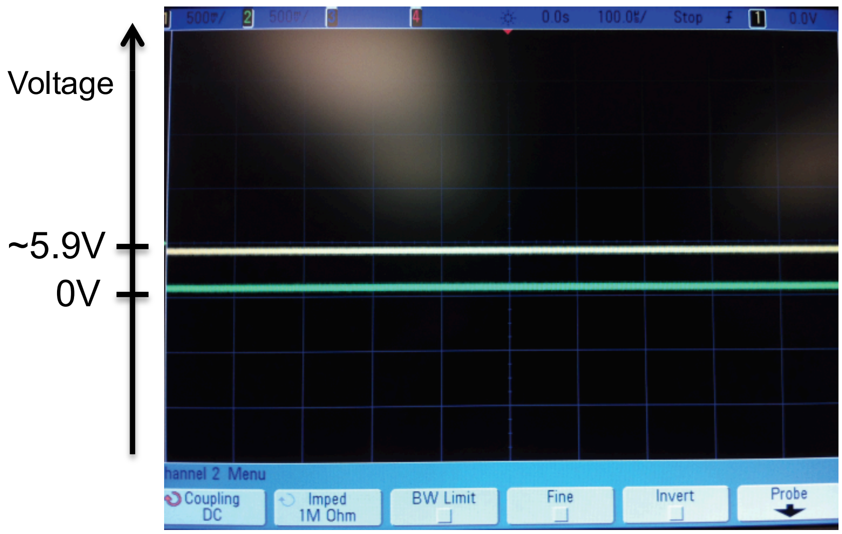

Figure 13: Solar Panel (Single) Testing

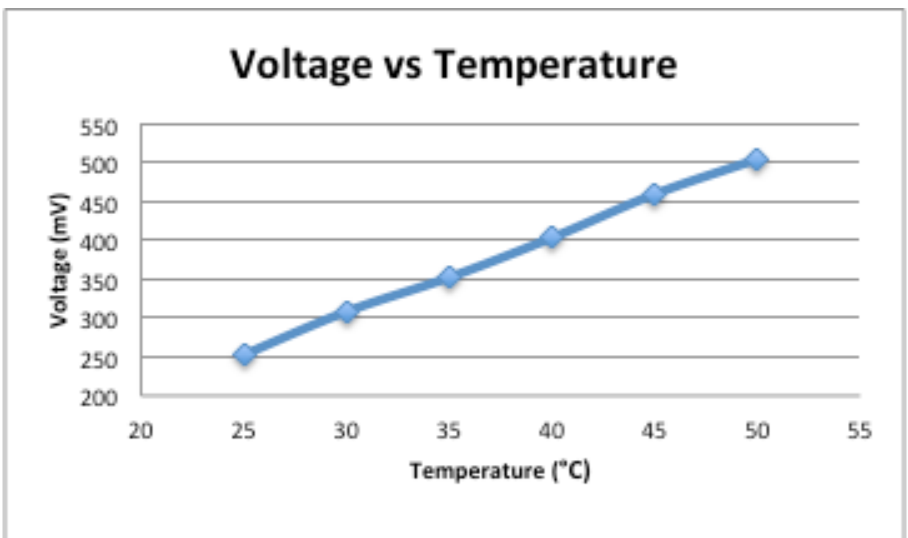

Figure 14: Temperature Sensor Output Results

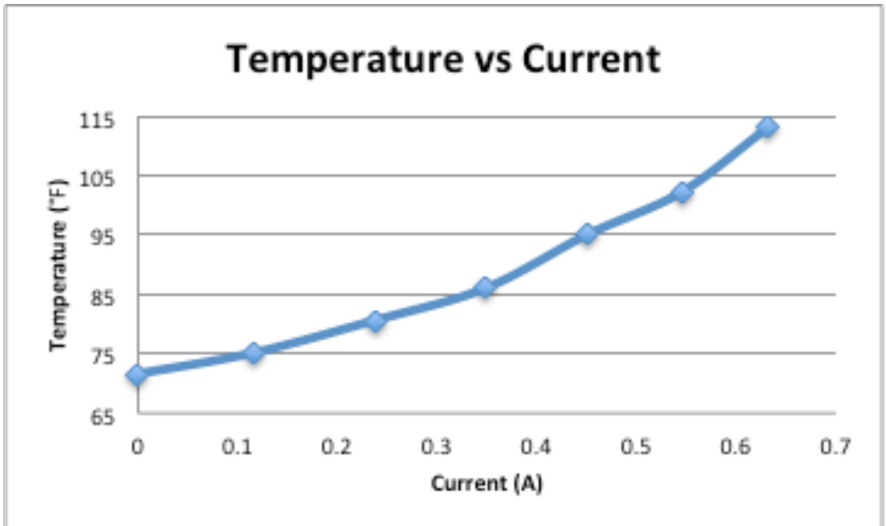

Figure 15: Heating Pad Results

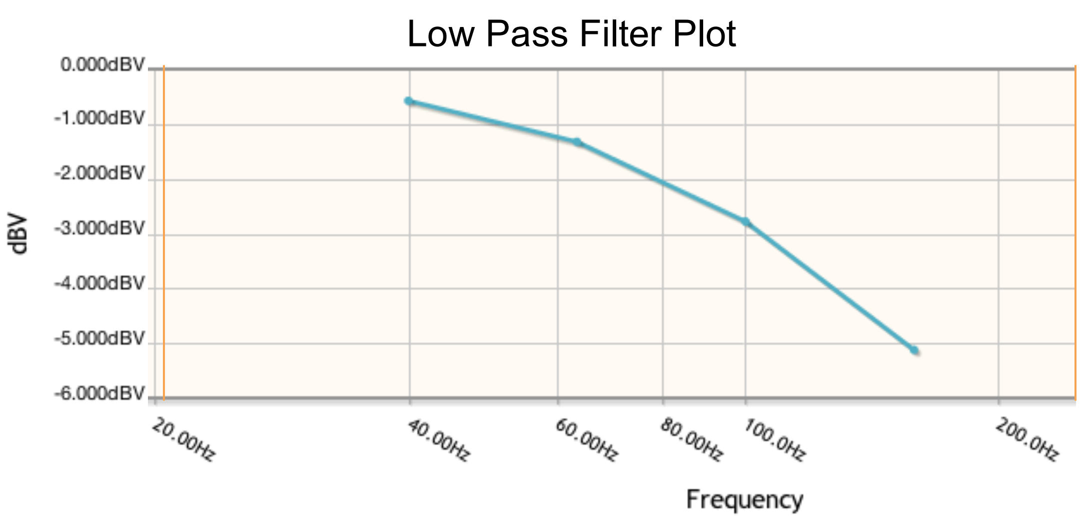

Figure 16: Low Pass Filter Simulation

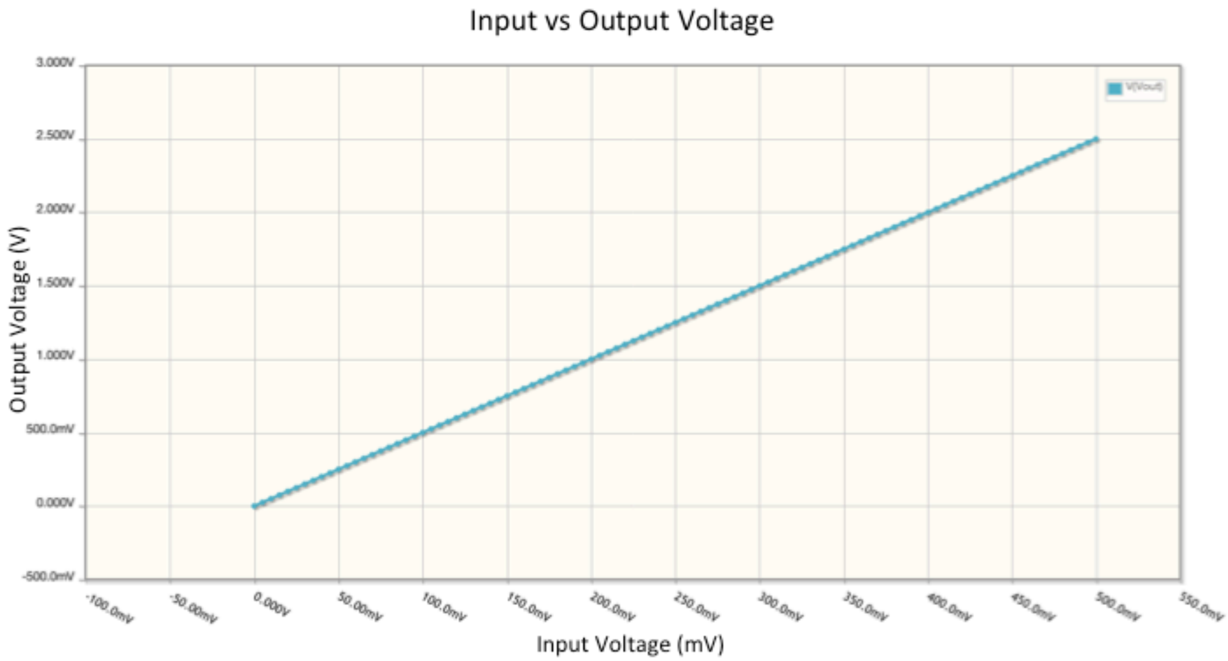

Figure 17 Simulation of Non-inverting circuit

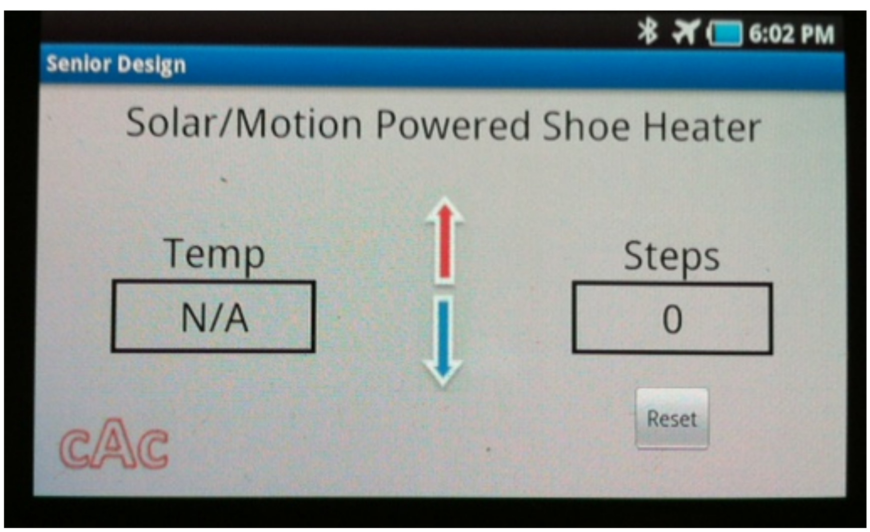

Figure 18: Android Application Screen Shot

Appendix C Requirements and Verifications

Table System Requirements and Verifications

Requirements	Verification	Verification status (Y or N)
1. **Solar Source**: The solar cells should be able to charge a Li-ion battery and should be flexible enough to not impede human movement. a. The solar cells should be sensitive enough to capture both artificial lighting and sunlight b. The solar cells should not break when mechanical stress similar to human movement is applied.	1. A discharged battery will be directly connected to a solar cell, exposing to different lighting conditions, and the cell array should supply a maximum of 0.264 W of power at 4.2 V. a. Using a DMM, the output of each solar cell in the array will be measured. The resistor voltage should be at a maximum of 4.2V under direct lighting b. Test under different lightings to see change in voltage, if any. c. The solar cells will be bent in different ways. It should not produce any cracks on the cells	Y
2. **Piezoelectric Source**: The piezoelectric materials should be able to charge a 100uF capacitor and should be flexible enough to not impede human movement a. The piezoelectric source should charge a capacitor b. The piezoelectric sources should not break when mechanical stress similar to human movement is applied.	2. A DMM will be used to measure the output of the DC/DC converter and it should be at ~5 V. a. A capacitor will be directly connected to the piezoelectric source and a DMM or oscilloscope will be used to monitor the capacitor voltage. b. Apply different types of stress to the piezoelectric film and view output voltage to the capacitor: voltage should increase. c. The film will be put in a shoe and running and walking will test its flexibility. There should be no structural damage to the film after these activities.	Y
3. **Power Supply**: The lithium-ion	3. A DMM will be used to measure the	Y

batteries should generate enough power for the whole circuit with the right voltages for every block. a. Batteries should charge to ~3.6V each b. They should output ~360mA	each battery should have a maximum voltage of 3.7V. a. A DMM will also be used to measure the voltages of different parts of the circuit. The heating element, the Bluetooth and microcontroller should both have a voltage of at least 3.5 V.	
4. **Heating Circuit**: The heating circuit should be able to increase to desired temperature by the user and should also be flexible enough to not impede human movement. a. The heating pads should be able to reach a temperature range of 80^{o}F – 110^{o}F. b. The heating should have ~0.5-1A of current flow when 7.6V is available. c. The heating element should not break when mechanical stresses similar to human movement are applied.	4. While the whole system is on, a temperature sensor will be used to monitor the temperature within the shoe. The settings will be tested several times at random temperatures. The temperature sensor should read a fairly constant temperature, which is accurate with the setting. a. Using the up button a switch is closed and 7.6V from batteries is directly connected to heating pads and the interior of the sure, measure temperature with temperature sensor. b. A DMM will be used to measure the terminals of the heating element, and it should read 7.6 V. c. The heating element will be put in a shoe and it will be used for walking and running. The heating element should not display any structural damage after these activities.	Y
5. Bluetooth Modem: The Bluetooth modem should be able to send signals between the shoe circuits and the android app at a distance of up to 300ft a. The android app should update the displayed number of steps as the step counter increases its count. b. Signals should still be received if the distance between the shoe and the android phone is less than 100ft. c. The Bluetooth modem should have an operating voltage of at least 3.5-5V	5. We will run tests to confirm proper communication between the circuits and the android app. a. Apply 3.5-5V to Bluetooth modem and verify functionality b. We will take several steps while wearing the shoe and make sure that the count is updated after each one. c. We will separate the phone and shoe by 100ft to test verifying constant connection d. A DMM will be used to measure the voltage of the Modem. It should read at least 3.5 V	Y
6. Step Counter: The step counter is composed of a low pass filter and	6. We will use the shoe to walk and count steps manually, and then we will look at	Y

therefore should only allow >100Hz frequencies transmit. a. It should accurately count steps and send the count through the Bluetooth modem	the app if it displays the right value. a. Test filter by hooking up to wave generator and putting 50Hz, 100Hz, and 150Hz frequencies and note outputs b. Place hand inside shoe and simulate walking gestures and check app to verify step count.	
7. User Interface: The user interface should read current temperature, allow user temperature control (increase) and will also update the number of steps the user takes a. Application should be able to receive and transmit data from Bluetooth to microcontroller	7. We will use the app which can be accessed by any android phone use, to increase the temperature settings and monitor temperature changes in the shoe using a temperature sensor a. Open app and verify app connection, app should prompt connection status. b. Hit the up button and measure temperature inside shoe, should increase. c. Hit reset button to reset step count.	Y

Appendix D Results

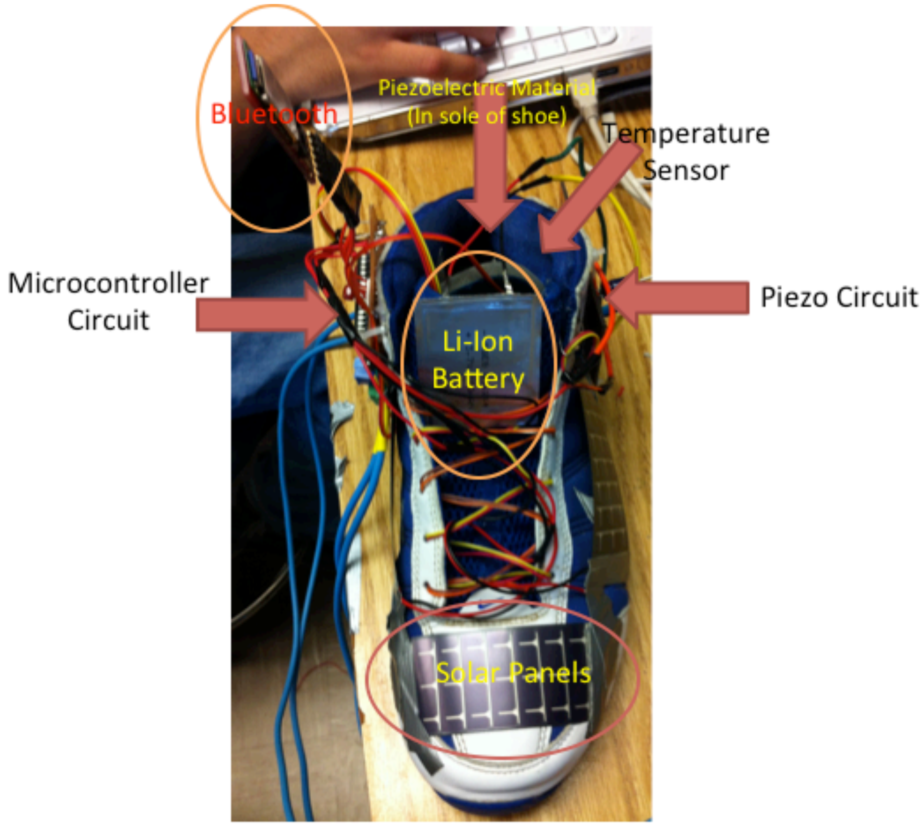

Figure 19 Part mounted onto shoe for maximum efficiency

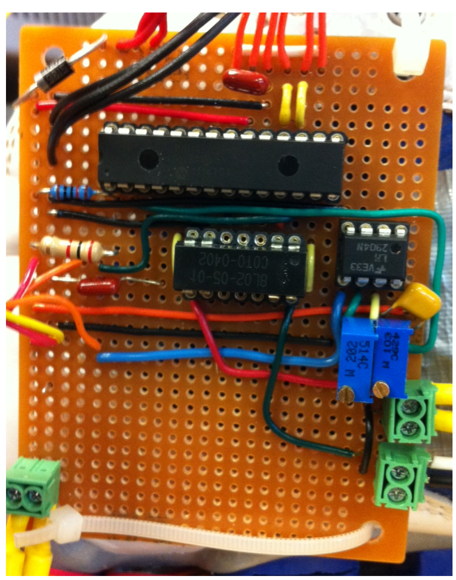

Figure 20 Heat Processing Unit

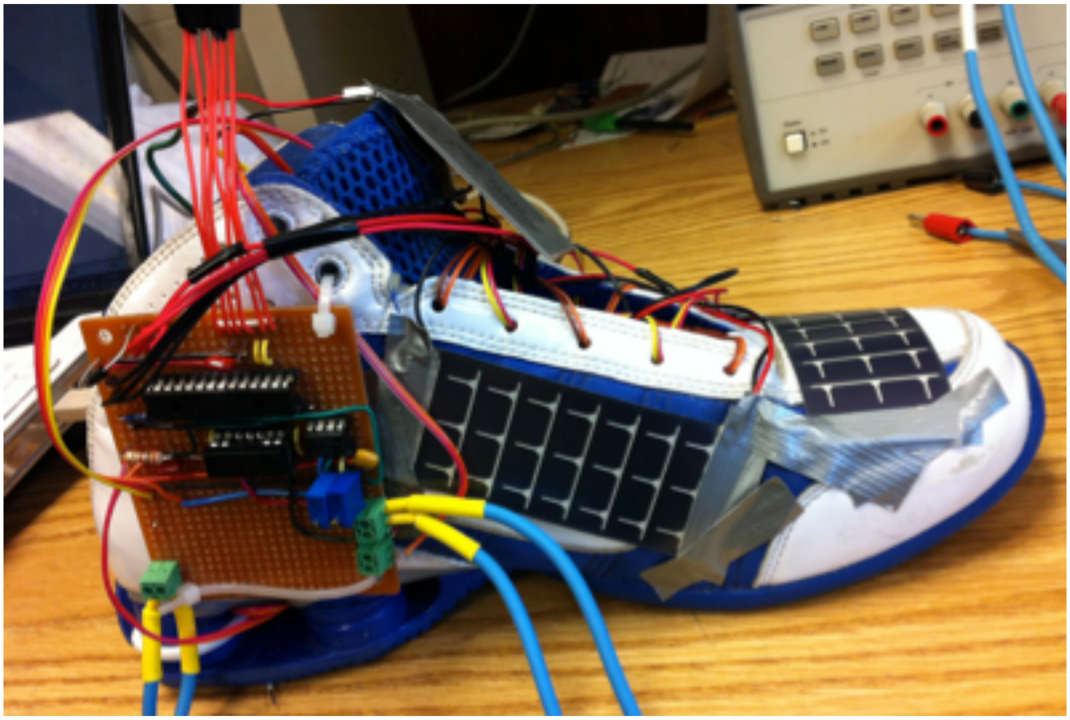

Figure 21 Final system implementation