IOWA STATE UNIVERSITY

GARMIN INTERNATIONAL ENERGY HARVESTING IN FITNESS ELECTRONICS

MAY14-17

Final Document

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Abstract

This project by senior design group MAY14-17 at Iowa State University of Science and Technology is aimed to design and prototype low-cost, small form factor energy harvesting circuits that provides power to an accelerometer-based foot pod and a heart rate monitor chest strap for Garmin International's line of fitness electronics. Technologies explored for energy harvesting include thermoelectric harvesting though the use of the Seebeck effect and mechanical energy harvesting through the use of piezoelectric elements. This project is primarily focused on research into these technologies and the design and development of prototypes for use with Garmin's products as a proof of concept.

NOTICE

This is the final version of a design summary created by senior design group May14-17 at Iowa State University of Science and Technology, Department of Electrical and Computer Engineering. The material in this document is related to Garmin International; however, the information contained has been reviewed to be non-confidential.

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LIST OF ACRONYMS

BOM	Bill of Materials
EM	Electromagnetic
FFT	Fast Fourier Transform
GPS	Global Positioning System
LCR	Inductor Capacitor Resistor
LED	Light Emitting Diode
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PCB	Printed Circuit Board
PMIC	Power Management Integrated Circuit
PVDF	Polyvinylidene Fluoride
PZT	Lead Zirconate Titanate
RF	Radio Frequency
TEC	Thermoelectric Cooler
TEG	Thermoelectric Generator

PREFACE

The following document has been created by the Iowa State University electrical engineering senior design group MAY14-17 as a final summary of research and lessons learned for the benefit of the project's client: Garmin International. Iowa State University's senior design programme pairs teams of senior engineering students with clients to complete real world projects. In this case, the project was proposed by Garmin International to research energy harvesting as a method for powering fitness electronics. This document outlines what this group has learned though research and experimentation with physical products. It also includes information about circuits and prototypes developed by this group so that Garmin will be able to pick up the research and, if determined practical, integrate it into their product line.

ACKNOWLEDGEMENTS

We would like to thank everyone who has helped us to make this project possible. In particular we would like to thank Adam Rasmussen of Garmin International and Dr. Degang Chen of Iowa State University for all of their help and leadership as the project client and adviser respectively. We would also like to thank Lee Harker for his assistance with this project.

1. Summary

This document provides a final overview of group MAY14-17's efforts to develop energy harvesting methods for application in Garmin International's fitness electronics. Additionally, this report serves as a compilation of work completed so far and a detailed recommendation on the feasibility of using energy harvesting in fitness products so that Garmin can make optimal use of this group's efforts. The document is broken into sections summarizing research, design, testing, and appendices of additional information gathered throughout the project. Initial research efforts provided improved knowledge of thermal, mechanical and radio frequency energy harvesting techniques. Information from the research portion of the project was used in development of thermal and mechanical energy harvesting prototypes, while ruling out Radio Frequency (RF) energy harvesting. Second revisions of the prototypes were built based on the knowledge gathered from the initial designs including improved part choices and modularity. Finally, the second revision designs were tested in a controlled lab environment and typical exercise scenarios.

Overall, the project was a success. Prototype designs were created for thermal and mechanical energy harvesting, both of which met or outperformed specified requirements for size, weight, and power output. In particular, the thermal design is capable of sustaining the full power requirement of a Garmin heart rate monitor, while the mechanical design supplies up to 25% of the foot pod's energy needs. Ultimately, however, it was determined that there are still limitations which may hinder the success of a commercial energy harvesting powered device.

2. Introduction

Energy harvesting is the practice of obtaining energy from the ambient environment and using it to power electronic devices. Energy harvesting can be done using many sources including radio frequencies, mechanical, thermal, wind, and other energy sources. This project investigates the feasibility of energy harvesting to power various fitness electronics. A typical runner burns about 100 Calories per mile when exercising. For a runner averaging ten minutes per mile, this means an average of 700W of power is generated from chemical energy stores for the duration of a run. Most of this energy is expended via mechanical motion and heating of the body, suggesting that mechanical and thermal energy harvesting have great potential for wearable devices. Many of today's modern electronic devices consume power on the order of 100s of microwatts to 10s of milliwatts. This represents a small fraction of the total energy used by a person during exercise.

While the amount of power available from a human body clearly indicates that energy harvesting can collect usable energy, the energy harvesting must be done in a manner which does not interfere with the user's normal behaviour. Otherwise, the end design will not be marketable or desirable for potential buyers. For example, while a knee brace may collect several watts of mechanical power, it is likely to be uncomfortable and cause early fatigue for a runner, making it a poor product practically speaking [2]. As part of this requirement, several factors must be considered; the device should not be overly large, bulky, or heavy since such a design would restrict the user's movements. Since many energy harvesting techniques are size-dependent, this affects the design of an energy harvesting product for fitness electronics.

2.1 Requirements

The energy harvesting solution developed must be able to offset the energy consumed from a battery in a watch, heart rate monitor, foot pod, or bike cadence sensor. The solution will need to provide at least 10% of the present current draw from the battery at an equivalent voltage, along with powering any additional circuitry needed for the energy harvesting module. It is also important that the solution developed does not increase the overall leakage current of the system substantially, since this could potentially drain the battery faster.

In addition to energy requirements, the solution must be small enough to fit into current products with a minimal amount of alteration and shall interface via the current battery input of the device. Garmin may eventually incorporate the energy harvesting circuitry into a single board, but for this project the added circuitry will be developed as a plug-in to the existing products. If necessary, the existing Power Management Integrated Circuit (PMIC) may be modified or replaced for compatibility with the new energy harvesting solution. The new circuit will have to be operational in many types of environments, as the devices are primarily for fitness. The temperature range it must be able to operate at is 0°C to 45°C, and the storage temperature range is -20°C to 70°C.

Garmin International has suggested a goal price of under $50 for the parts in the final prototype. According to the client, Garmin's economies of scale will allow them to reduce this cost substantially, to around $15 or less, when the energy harvesting design is incorporated into their devices, thereby allowing them to profitably sell an energy harvesting based device.

For the purpose of this project, Garmin has defined several functional and non-functional requirements for the prototypes. Each energy harvesting solution must be able to supply a minimum of 10% of the total power consumed by the device. The overall size of the end solution shall be smaller than a deck of cards and weigh less than 100g. Additionally, the device should not interfere with the user's ability to exercise.

3. Research

The following sections discuss the three energy harvesting methods that were researched: thermal energy, mechanical energy, and RF energy. Another popular energy harvesting method is solar energy. This topic has been extensively researched, and it was determined that a solar only solution would not be an acceptable way to solve the given problem.

3.1 Thermoelectric Energy Harvesting

One of the methods considered for this project was using energy from body heat in the form of a temperature gradient between the wearer's skin and the ambient air temperature. This heat energy is harvested and converted into electrical energy. There are several ways to do this, but the most common is the Seebeck effect due to its size and relative ease to implement into a fitness product. Assumptions were made that the average wearer will have a skin temperature of approximately 90-100°F (35-40°C) and will will use the device in an ambient air temperature of 70°F (21°C).

3.1.1 Thermoelectric Generator

The method for harvesting thermal energy that was researched for this project was the Seebeck effect. This refers to the electric field created by two dissimilar semiconductors placed in intimate contact with a temperature gradient across the junction. Current is formed from the electric field, which will allow a device to be powered by the junction. For this project, a Thermoelectric Cooler (TEC) was used. TECs use the Peltier effect, which is the conversion of electric current into a temperature gradient. By connecting the cooler backwards, a Thermoelectric Generator (TEG) can be created. The physics of a Peltier junction connected as a cooler is shown in Figure 3.1. The TEG works the same but in reverse.

One of the major advantages of thermal energy harvesting is how common Peltier elements are. These elements are often used in consumer devices such as portable coolers and dehumidifiers, and they are sometimes used to replace standard heatsinks for cooling microprocessors. Because of how common and useful these devices are, they are easy to find and relatively inexpensive making them a good candidate for energy harvesting research.

One of the downsides of using Peltier elements is their size to energy ratio; in order to get enough power out of the backwards-connected element to charge a device (such as the heart rate monitor), one needs either a high temperature gradient or a large junction.

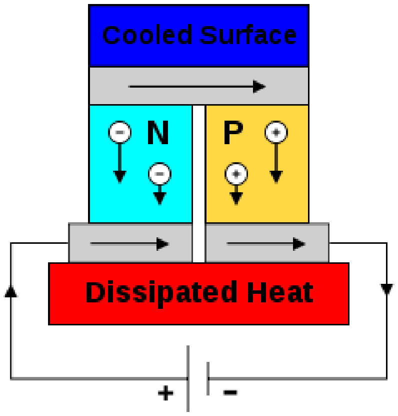

Figure 3.1: Peltier junction physics [1]

Connecting two Peltier elements thermally and electrically in parallel will not work. Since the second device will be heated by the first device, the power supplied will be limited by the smaller device. Connecting two or more of these elements thermally in parallel and electrically in series would be the same as getting a larger junction which would increase the power output as desired.

3.1.2 Step-Up Converter and Power Manager

To convert the low voltage of the TEG into a usable voltage a step-up converter was used. The converter chosen for this application was an LTC3108 made by Linear Technology. The product is made to step up voltage from a TEG to a programmable output voltage and store excess energy in capacitors. The device also generates a digital signal to indicate if the power is within an acceptable range of the programmed output voltage. [3]

The device is made up of three stages. The first stage is an LCR circuit driven by the TEG with the inductance being the primary winding of a step-up transformer. The transformer is driven by an open drain MOSFET circuit. The secondary side of the transformer forms a second LCR circuit which drives an AC-DC converter with an output voltage of 5.25V. This energy is used to charge an energy storage device such as a super capacitor or battery (see section 3.1.3 for more information). This higher voltage is used as an input for the programmable DC-DC converter which steps the voltage down to the programmed value. This is then used to charge an output capacitor. The energy from the output capacitor is what will actually power the connected device.

3.1.3 Batteries vs. Super Capacitors

TEGs generate energy on the order of a few microwatts, much less than the energy required for the heart rate monitor. This can be overcome by the low duty cycle of the device and resulting very low average power draw. When the device is in deep sleep mode the harvested energy is stored; during a transmit cycle the stored energy is used to power the device. To achieve this, two energy storage devices were considered: super capacitors and secondary batteries.

Secondary batteries are a traditional method of storing excess energy using an electrochemical reaction. Typical capacities are in the range of 10mAh to 1Ah, several orders of magnitude larger than super capacitors. Due to their topology, batteries require several milliamps of current to charge and are slower to discharge. They also have greatly reduced charge/discharge cycles in the range of 1,000 to 10,000. Due to the limited charge/discharge cycle and high charge currents required, secondary batteries are not a feasible option for this design.

Super capacitors are similar to traditional capacitors but have much higher capacities for the same form factor. The capacitors looked at have capacitance in the range of 100mF to 500mF and rated voltage 6V. Due to energy being stored in an electric field, super capacitors can be charged with small currents. They also have virtually unlimited charge/discharge cycles. This was the chosen solution for the design.

3.2 Mechanical Energy Harvesting

There are several possible strategies for harvesting mechanical energy from the human body. These include micro-generator systems making use of micro-electromechanical system technologies, dynamos, induction-based devices based on the same concept as the shake flash light, and piezoelectric materials [4]. Since many of these options are similar in behaviour to a typical generator, the group decided to focus research efforts on piezoelectric harvesting which provides a lightweight and compact energy harvesting option.

3.2.1 Piezoelectric Element

Piezoelectric energy harvesters (also known as generators or transducers) are one option for generating an electrical power supply from mechanical energy. Piezoelectric devices work by converting mechanical strain into an AC voltage. A charge separation is induced when the piezoelectric material is strained which becomes current when the strain is removed. On a small scale, piezoelectricity is due to the ordering of electric dipoles. When heated, this ordering can be disturbed, so it is important not to exceed a critical temperature of the material known as the Curie temperature [5]. Power output for a piezoelectric component is highly dependent on device volume. Typical device specifications indicate performance by noting the power output for a vibration at a specific frequency and acceleration. [6]

A variety of materials can be used for their piezoelectric properties. Two common materials for energy harvesting are Lead Zirconate Titanate (PZT)[1] and Polyvinylidene Fluoride (PVDF). PZT is known for giving a relatively high power output in response to a mechanical stimulus, but it is also fairly brittle, breaking if flexed more than a centimetre on a typically sized device. PVDF is extremely flexible but gives a much lower output. PZT is the better solution for this project, as the higher power output is necessary, and the brittleness should not be a problem. Both PZT and PVDF have critical temperatures sufficiently high for consumer use, but care may need to be exercised not to overheat the elements during manufacturing and soldering.

3.2.2 Voltage Converter

The voltage from the piezoelectric needs to be decreased and converted from AC to DC to be used by the foot pod. Linear Technologies produces chips that are specifically designed for energy harvesting. One such chip, the LTC3588, was created to convert energy harvested by a piezoelectric element into usable energy. The AC voltage from the piezoelectric element is first rectified by the LTC3588 before the voltage goes through a buck converter. This chip allows the voltage to be converted to 1.8V, 2.5V, 3.3V, or 3.6V. These voltages are within the range determined necessary for the output of the piezoelectric solution. [7]

3.2.3 Acceleration Testing

Foot Acceleration

To better understand the amount of energy that is available to be harvested from a foot mounted device, a test was performed which measured the amount of acceleration on three perpendicular axes over time. The acceleration was measured using a smart phone's built-in accelerometer and an application which saved the acceleration data for each axis along with a time stamp to a file. The phone was attached to a shoe using two elastic bands. MATLAB was then used to perform a Fast Fourier Transform (FFT) analysis of the data to determine the amount of energy available at each frequency. The accelerometer was limited to a 100Hz sampling rate, allowing for a maximum frequency of analysis of 50Hz according to the Nyquist sampling theorem. Data was taken for two cases: a ten minute walk and a ten minute run. The results for walking and running are included below in Figures 3.2 and 3.3 respectively. As shown, the main frequencies measured are from 1.5-5Hz, and acceleration amplitude regularly saturated the part's range at 39N·m during running.

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[1] PZT is currently exempt from the European Union's RoHS controls on the use of hazardous materials in electronics. Thus, it may be used freely in devices. This exemption was passed on October 10, 2012 and expires on July 21, 2016.

Wrist Acceleration

Accelerometer tests were also performed with the same cellphone attached to a runner's wrist with elastic bands. Data was collected for both walking and running. Results were similar to those for the foot tests but with lower amplitudes.

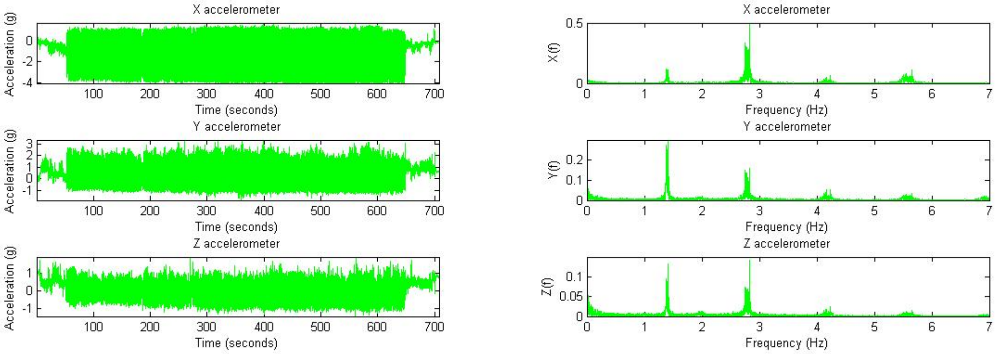

Figure 3.2: Three-axis acceleration measurements during running

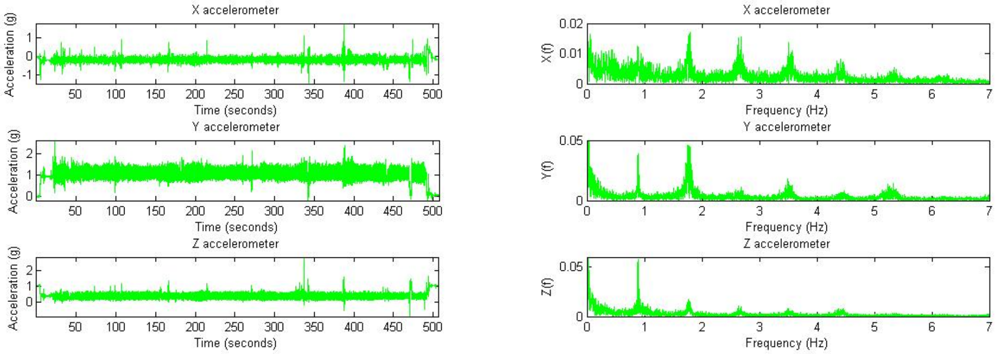

Figure 3.3: Three-axis acceleration measurements during walking

3.3 Radio Frequency Energy Harvesting

Radio Frequency energy harvesting consists of using an antenna structure to receive and capture Electromagnetic (EM) radiation from the environment for use in a device. The harvested energy is then converted from frequencies in the RF range to a DC supply. In theory this is a good idea because there is unused energy due to the numerous transmitters around the world. However, the power density of electromagnetic waves in a typical environment is far too low to be beneficial for Garmin's devices. Dr. Neihart and Dr. Chen of Iowa State University believed an RF harvester would not be able to collect enough energy given the constraints placed upon the energy harvesting device. The team concluded that radio wave energy harvesting is thus impractical as a source of power for Garmin's fitness products. Calculations were performed as verification and supported this conclusion. These can be found in Appendix F.

Another option for RF harvesting would be to use a dedicated transmitter. For example, a cell phone transmitter typically outputs a substantially higher amount of power nearby. However, a dedicated transmitter would have to be carried on the body of an athlete and would require a substantial battery of its own. Finally, another reason to discount RF harvesting is that the harvesting antenna would create difficulties for other antennas on the device, such as the ANT, Bluetooth, and GPS. Since the original antenna is neither high bandwidth nor high gain, either the current antennas would have to be redesigned, or a new antenna would be needed for energy harvesting. Also, RF harvesting may require increasing the transmit power since some of the energy would be re-harvested during each transmission.

4. Pre-Design Testing

The existing devices were tested in order to determine the necessary power requirements. The testing details are not available to the general public due to non-disclosure agreements with Garmin International.

5. Design

5.1 Thermoelectric Energy Harvester

Power created from the thermoelectric element could not be directly plugged into the heart rate monitor's circuitry, so a more complex circuit had to be created. For the purposes of this project, the DC voltage produced by the TEG needed to be converted into an AC voltage so it could be stepped up using a transformer. The AC voltage was then converted back to DC using an AC-DC converter, and the new DC voltage was boosted again using a boost converter. This was the idea behind both the revision I and revision II boards.

5.1.1 Revision I

Linear Technologies produces chips that are specifically designed for energy harvesting. One such chip, the LTC3108, was created to convert energy harvested by a TEG into usable energy. The internal circuitry of the chip, which included the AC-DC converter and the DC boost converter required, could output directly to the power selection circuit. The external circuitry for the revision I board was created using a recommended schematic in the Linear Technologies data sheet. The equations used to calculate the capacitor values are included in the Appendix D. The schematic from the revision I board is split into three pages; the first two involve the energy harvesting circuitry and the different capacitor and transformer values, while the third is the power circuitry, which will be explained in Section 5.3.

5.1.2 Revision II

The test results from the revision I board indicated that the 1:100 transformer and associated capacitor values would be the best for the second revision board. All the jumpers were removed, and the board was reduced to a size of 1"×1". This was designed to match the power select board and the mechanical energy harvesting board. The schematic for revision II is shown in Figure 5.3. The cost to build this part of the prototype is $14.84 for the 15mm TEG or $16.00 for the 20mm TEG and $14.16 for the boards and other parts.

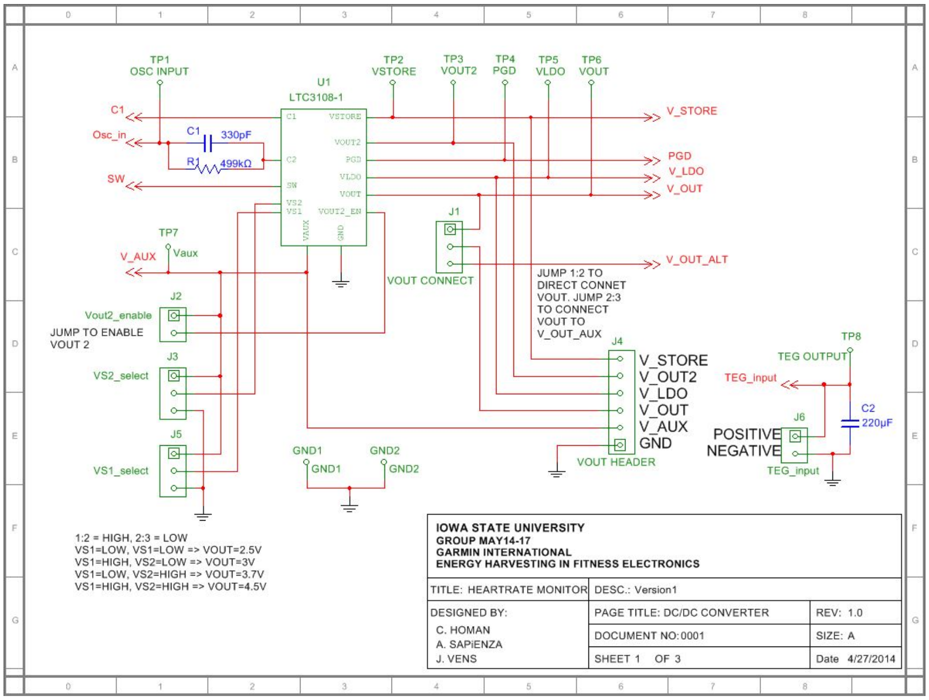

Figure 5.1: Thermoelectric harvesting circuit revision I schematic active elements

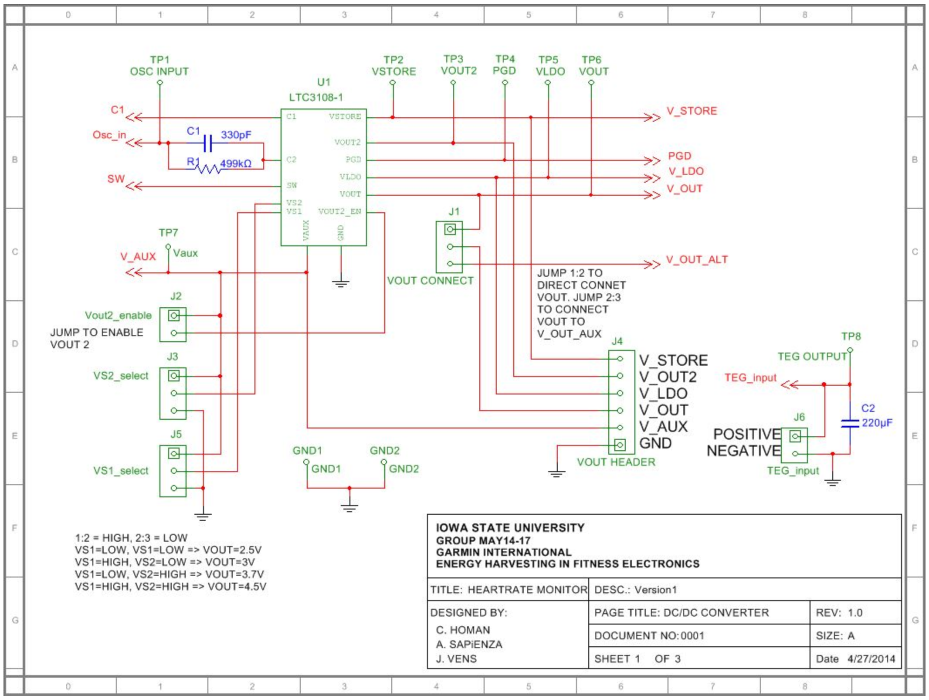

Figure 5.2: Thermoelectric harvesting circuit revision I schematic passive elements

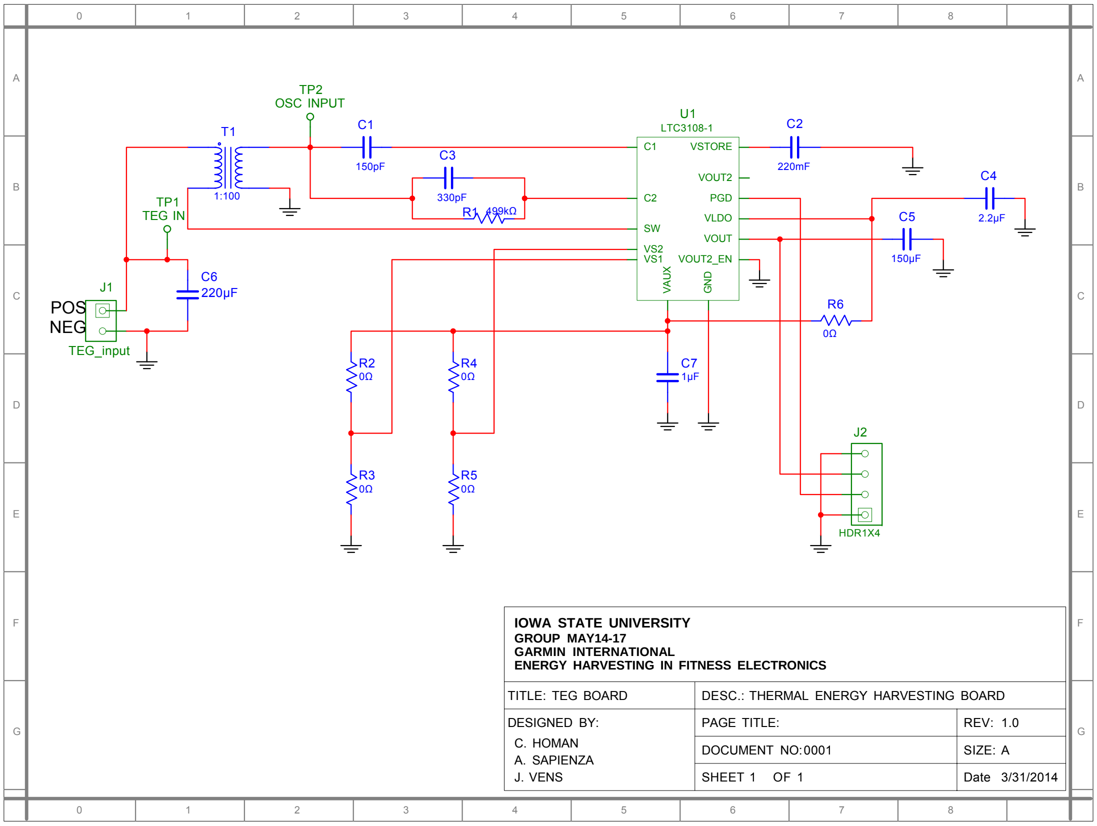

Figure 5.3: Thermoelectric harvesting circuit revision II

5.2 Mechanical Energy Harvester

Power directly from the piezoelectric element cannot be directly used to power the foot pod. The voltage that is produced by the element is an AC voltage, but the foot pod requires power from a lower DC voltage. Thus, additional circuitry needed to be designed to use piezoelectric energy.

5.2.1 Revision I

Revision I of the piezoelectric energy harvesting board had two main sections. The first section included the LTC3588 piezoelectric energy harvesting chip from Linear Technology. This chip was created for use with piezoelectric elements; it contains a rectifying circuit and a buck converter. It allows for the selection of four different output voltages which were within the desired range for the foot pod. The design allowed for testing the different output voltages. The design for this circuit was based on recommended circuits for the LTC3588 and can be seen in Figure 5.4. The first revision also contained the power selection circuitry on the same board which will be discussed in Section 5.3. [7]

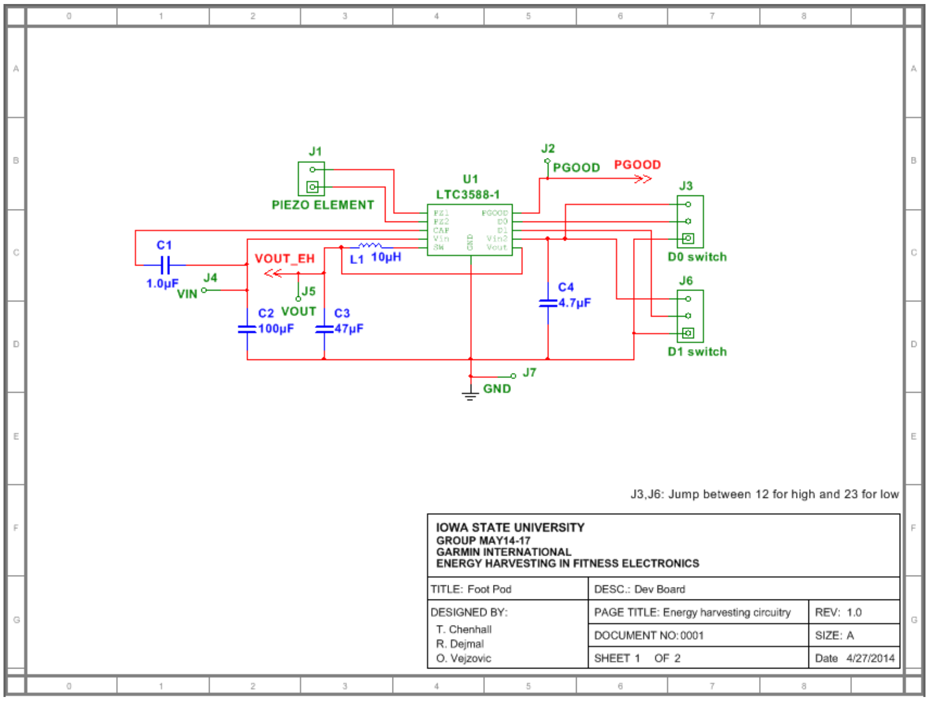

Figure 5.4: Piezoelectric harvesting circuit revision I schematic

5.2.2 Revision II

The second revision of the piezoelectric energy harvesting board did not include the power selection circuitry. Care was taken in the placement of the connector and the signals going through it such that connecting it wrong would not cause damage to either board. The board was designed to be the same size and have the same mounting holes as the thermoelectric and power selection boards. The layouts for these boards can be seen in Appendix A. The rest of the circuit remained the same as the first revision. The schematic for the new circuit can be seen in Figure 5.5. The cost to build this part of the prototype is $65.00 for Mide's V21BL and $9.99 for the boards and other parts.

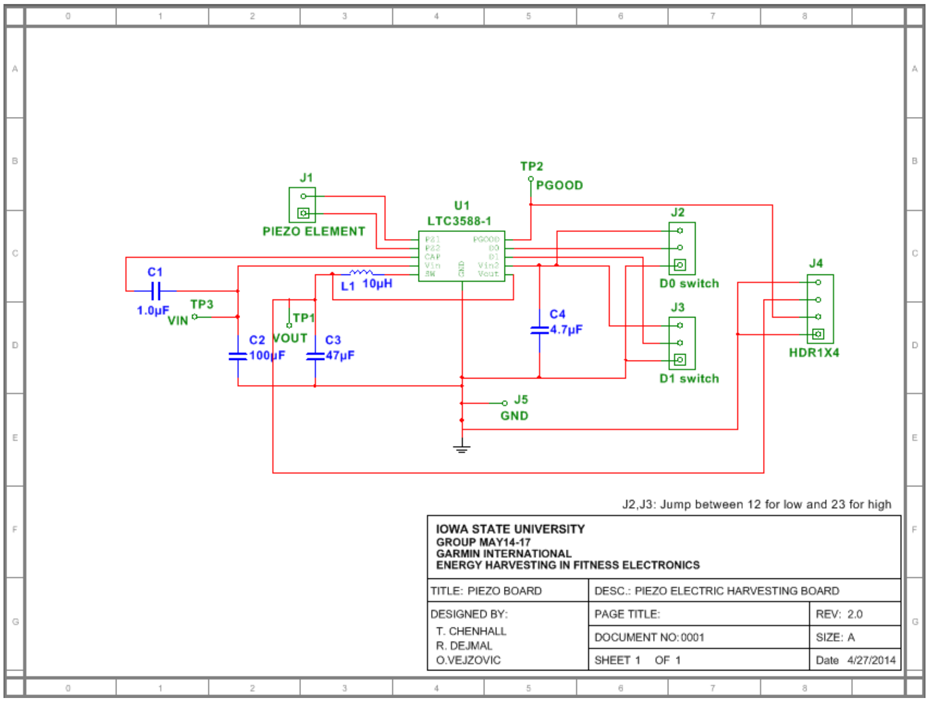

Figure 5.5: Piezoelectric harvesting circuit revision II schematic

5.3 Power Selection Solution

In the event the energy harvested solution cannot provide enough energy to power the device, a lithium-ion primary battery is used instead. To facilitate the switch from energy harvesting source to the battery a power selection circuit was created. The circuit's purpose is to monitor the energy supplied by the energy harvesting solution and select to use it whenever available. The energy harvesting option should always be chosen if it is available in order to maximize the battery life.

5.3.1 Revision I

The first revision of the power selection circuitry was included on the first revision boards of the thermoelectric energy harvester and mechanical energy harvester. Both boards used the same circuitry and built around the same device.

The power selection circuit is built around a TPS2110 power multiplexer from Texas Instruments. This device selects between two power sources based on the state of an input pin. The power path has a series resistance of 120mΩ and the chip requires a 55μA current to operate. It can run off operating voltage of 2.8V to 5.5V [8]. Since the battery is considered good voltage down to 2.2V, this power mux was not an effective solution. It also required the majority of the the harvested energy to run the device. The power selection circuit for the revision I thermoelectric energy harvester is shown in Figure 5.6. The circuit for the mechanical energy harvester was exactly the same.

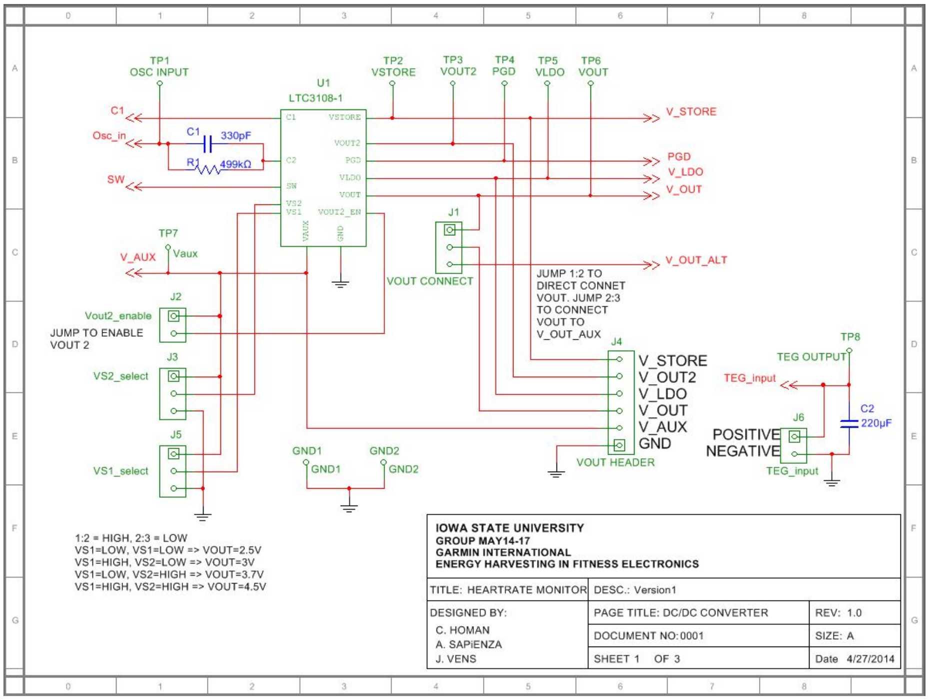

Figure 5.6: Power selection revision I schematic

5.3.2 Revision II

For revision II, an ADG804 from Analog Devices was selected for the selection circuit. This device is an analog multiplexer instead of a power multiplexer such as was used in the revision I design. This change was based on the testing results of the revision I boards. It requires less than 100nW of operating power and supports a voltage range of 1.65V to 3.6V. The power path series resistance is 500mΩ. The lower power requirement makes the device more effective for this application, and testing has verified this. The energy source is selected based on the power good output of the energy harvesting circuits. The schematic is shown in Figure 5.7. [9]

The PCB was laid out such that it could connect to both the revision II energy harvesting boards. To assist in the testing process, 1Ω shunt resistors were placed on all three power paths and connected to a testing header. Also on this header are the voltage out and power good signals. This greatly improved the ability to test the power output of the energy harvesting solutions. The PCB is shown in Appendix A. The cost to build this part of the prototype $5.04 for the boards and parts.

To make the entire solution easier to demonstrate and test, a simulated load was included in the circuit. The load is a 2mA LED which can be toggled on and off with an opto-isolator. This allows for the user to easily test different frequencies and duty cycles of load to measure the response of the the energy harvesting circuits. This also makes it easy to see that the system is working with the visible LED.

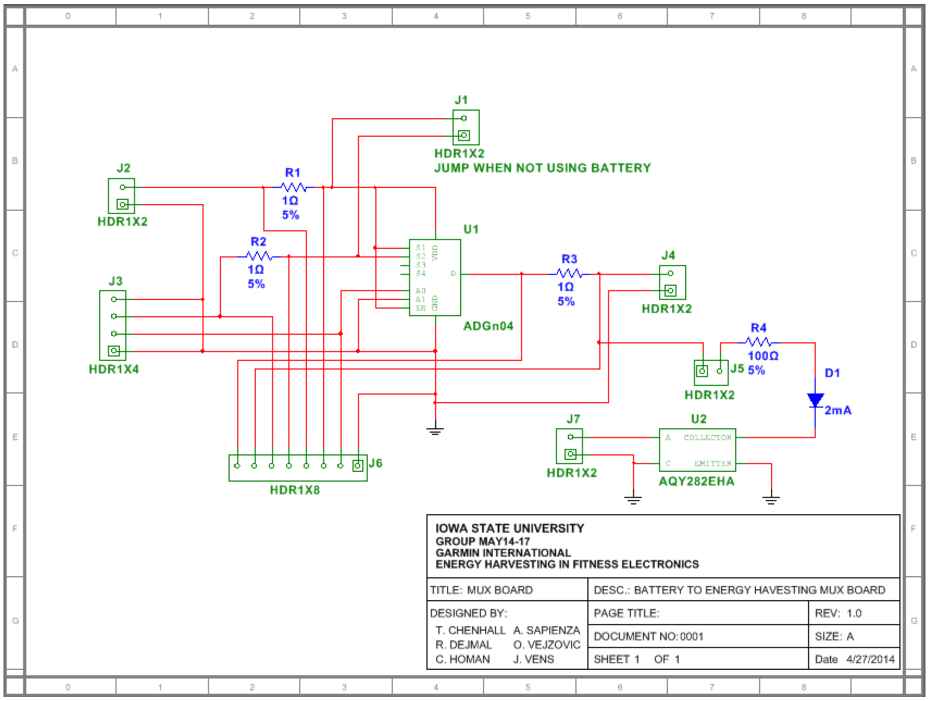

Figure 5.7: Power selection revision II schematic

6. Testing

6.1 Thermoelectric Energy Harvester

The thermoelectric energy harvesting testing was split into three parts. Part 1 discusses the characterization of the TEG elements themselves. Parts 2 and 3 discuss the tests performed on the revision I and II boards as well as the results from these tests.

6.1.1 Thermoelectric Generator Characterization

Two different sized Peltier junctions were tested to see which would give the best output power. The larger one was 20mm×20mm with a surface area of 400mm^2 on each the side of the junction. The smaller one tested was 15mm×15mm and had a surface area of 225mm^2.

Before voltage output testing was performed the TEGs were characterized. This was done using an LCR meter. The parameters extracted were the resistance, parallel inductance, series inductance, parallel capacitance, and series capacitance. The measured values are displayed in Table 6.1.

Table 6.1: Extracted Parameters from TEG

TEG used	R (mΩ)	Lp (μH)	Ls (μH)	Cp (μF)	Cs (μF)
15mm	217	-28.7	-0.41	8.36	630.70
20mm	265	-24.0	-0.77	10.55	327.00

As can be seen from Table 6.1, the 20mm TEG has larger values for the resistances and the parallel elements than the 15mm one. It also has smaller series inductances and capacitances than the smaller TEG. This makes the larger junction a more desirable element for this project. However, it should be noted that the smaller element went through the revision I tests as well.

6.1.2 Revision I

The initial design, as mentioned in Section 5.1.1 of this document, was intended to test several different capacitor and resistor values to find the combination which would output the best power for the designed circuit.

The tests were performed using a hot plate with a resolution of 5°C. The hot side of the TEG was placed in thermal contact with the hot plate while the cold side was left at room temperature, 18°C. The first revision board had test points that were probed using an oscilloscope, so the voltage at different points in the circuit could be tested.

As discussed in the design section (Section 5.1.1), revision I had three options for the transformer which would step the voltage up enough so it could be used in the circuit. Based on assumptions, first tested was the 1:100 transformer along with its calculated resistor and capacitor values. Tables 6.2 and 6.3 show the hot plate's temperature versus the output voltage for both the larger junction and the smaller one using these elements.

Table 6.2: Hot Plate Temperature vs. Output Voltage (15mm junction)

Temperature (°C)	Temperature (°F)	Voltage (mV)
30	85	48
35	95	58
40	104	75

Table 6.3: Hot Plate Temperature vs. Output Voltage (20mm junction)

Temperature (°C)	Temperature (°F)	Voltage (mV)
30	85	33
35	95	104
40	104	113

As can be seen in Tables 6.2 and 6.3, the 20mm TEG gave better output values in every case except the smallest temperature gradient. This is most likely due to the speed at which the cold side warmed up. That problem will be discussed more thoroughly in the discussion section (Section 7.1), however in order to avoid problems during testing, a heatsink was used. Other than the small variation in measurement, it was determined that the 20mm TEG was the better option and was the one used in the revision II tests.

With a 2mA simulated load, created using an opto-isolated signal which toggled on and off at 4Hz, the circuit was able to output 100% of the power required to run the device, far exceeding the 10% the circuit was required to supply. This load was also tested with the 15mm junction, which supplied less power than 20mm TEG, but it still met the 10% requirement. Table 6.4 details this.

Table 6.4: Energy Harvested with Simulated Load

Peltier Junction Size (mm)	Load (Ω)	Current (μA)	Power (μW)	Energy (μJ)
15	22k	100	220	55
20	12.9k	221	630	157

This board, along with the 20mm TEG, was also tested with the hot side against human skin and the cold side covered by a heatsink. When connected to the 2mA simulated load, the temperature gradient created a voltage which would power the device. This proved that the circuit was a feasible option for the project.

Both the 1:50 and the 1:25 transformers were tested along with their calculated capacitor values, but it was found that the 1:100 was the best option of the three. The other capacitor and resistor combinations were also tested, but the original calculated values proved to be the best option. Figure 6.1 shows the test setup used for the revision I testing. The revision II board was designed with these thoughts in mind.

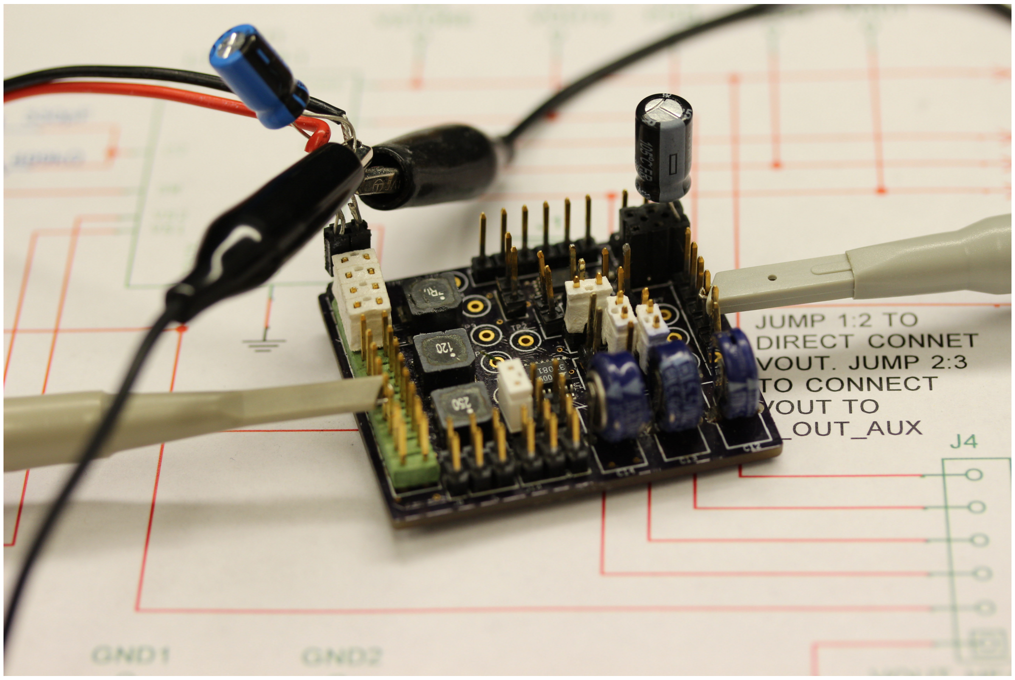

Figure 6.1: Thermoelectric energy harvesting revision I board test setup

6.1.3 Revision II

The second revision board has fixed capacitor values, and it has test points so the voltage at various points on the circuit can be measured if the output is not working as expected. It was tested with the 20mm TEG, as well as a far more powerful 40mm junction. The 40mm worked better than the previously used 20mm.

The output voltage of this board as well as the power good signal were tested on the oscilloscope prior to connecting it to the power selection board. When connected to the power selection board and given the load simulator, the demo LED was able to light up from the voltage generated by the temperature gradient across the TEG junction.

Tests were performed on these revision II boards in order to determine the output voltage, current, and power supplied by the thermal energy harvesting board to the power selection board. The load simulator used the values as shown in the Table 6.5.

Table 6.5: Load Simulator Values

Freq (Hz)	Ampl (V)	Duty Cycle (ms)
4	5	2

With these values as the simulated load, the 40mm TEG was placed with one side on the hot plate at 40°C and the other covered with the heatsink. The ambient temperature of the room was measured as 24.8°C, creating a temperature gradient of 15.2°C across the junction. The values measured from the oscilloscope and the calculated power are shown in Table 6.6. The voltage and current refer to the voltage and current output from the thermal energy harvesting board to the power selection board. Figures 6.2 and 6.3 show the test setup. The lit LED in the second image indicate that the energy harvested from the TEG was enough to power the heart rate monitor.

Table 6.6: Thermoelectric Energy Harvesting Revision II Board Test Results

Temp Gradient (C)	Voltage (V)	Current (mA)	Power (mW)
15.20	3.26	1.69	5.51

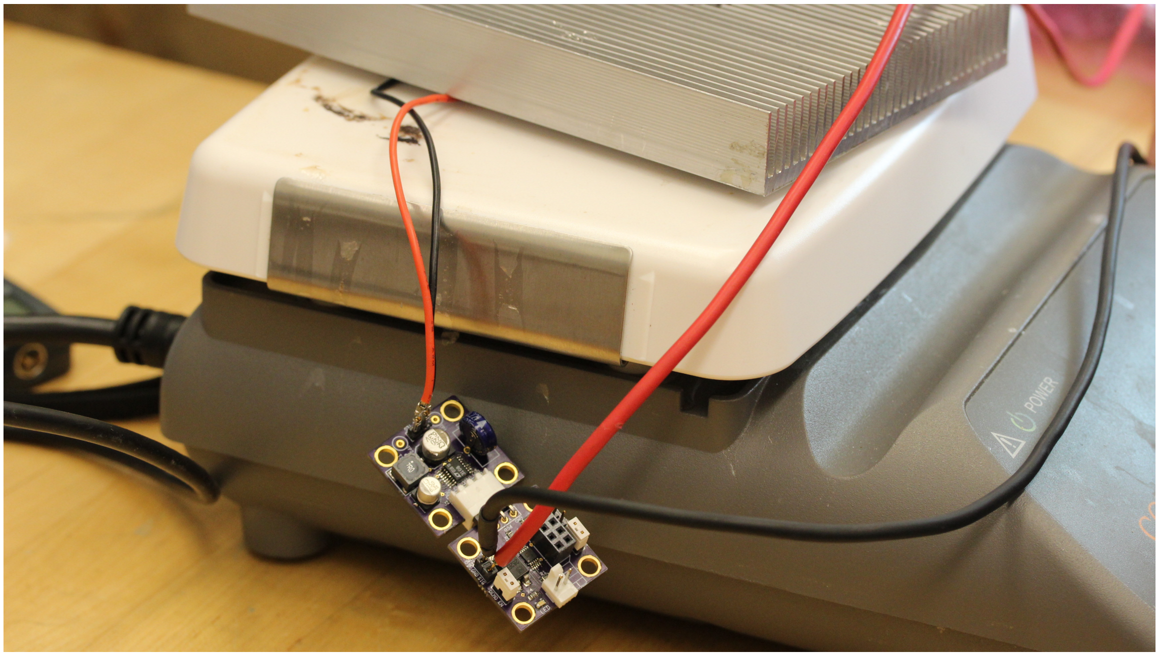

Figure 6.2: Thermoelectric energy harvesting revision II board test setup

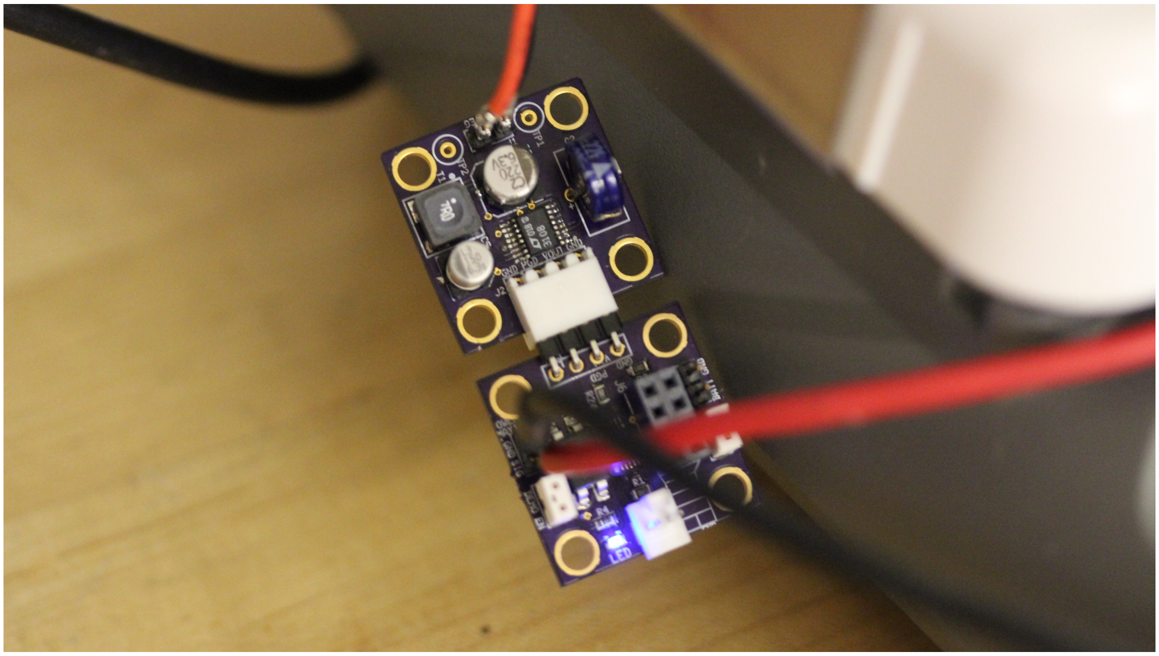

Figure 6.3: Thermoelectric energy harvesting revision II board test with lit LED

6.2 Mechanical Energy Harvester

The mechanical energy harvesting testing was split into three parts. Part 1 discusses the characterization of the piezoelectric element itself. Parts 2 and 3 discuss the tests performed on the revision I and II boards as well as the results from these tests.

6.2.1 Piezoelectric Generator Characterization

One advantage of using piezoelectric elements over other energy harvesting techniques is the relatively high voltages achieved. Depending on loading conditions, a piezoelectric device may output 10s of volts. However, the impedance of a typical device may be as high as 10-100s of kΩ. Components are usually manufactured to resonate at a particular frequency, in which case power output is maximized and the impedance is minimized (100-1000s of Ω typical). Review of currently available products indicate that typical resonant frequencies range from 10s of kHz down to 30Hz, which are higher than the dominant frequencies of 1-5Hz experienced by a runner in motion. Custom products with lower resonant frequencies are available, but they were not pursued in this project due to cost considerations. After market research, three devices were characterized for power output comparison: a V21BL from Mide, a sample of PVDF from Measurement Specialties, and a non-piezoelectric device based on an induction coil. The PVDF sample was found to output only a few microwatts and was thereby deemed unsuitable as the energy harvesting element. The induction coil generator produced power slightly less than the V21BL but with a lower internal impedance.

In order to characterize the V21BL piezoelectric element, a rudimentary mount was created. One end of the element is wired to the circuit input, one end is weighted, and the mounted point provides a location for oscillation energy to vibrate the piezoelectric material[1]. An oscilloscope was used to measure the voltage output from the device while mounted on a shoe of a person jogging in place as seen in Figure 6.4. Various tip masses and resistive loads were used to test the range of the device. Tip mass ranged from 5g to 15g in 2.5g increments. Resistive loads ranged from 100Ω to Ω1M. A sample voltage output with a 12.5g tip mass and 100kΩ load is shown in Figure 6.5, and the results from all tests are summarized below in Table 6.7. The highest power output tests are shown in bold. Power output is typically higher for greater tip masses and for resistive loads around 100kΩ. It is important to note that the V21BL is only rated for up to 5g tip masses. According to Mide, higher loading may cause premature part wear, so a custom part would be preferable in a marketed product. As a proof of concept, this shows that substantial average power can be captured with a moderately sized piezoelectric element.

6.2.2 Revision I

Without a battery connected, this circuit sustains approximately 160μW of power at 3.3V at the output under typical acceleration of a foot in motion. This compares to approximately

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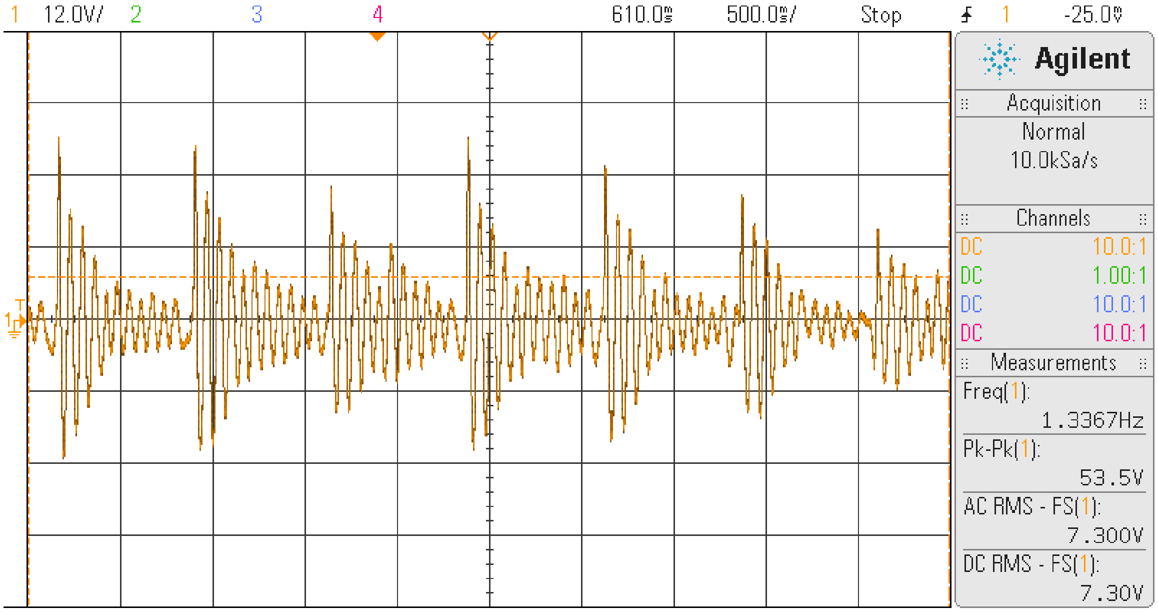
[1] An unmounted V21BL has a fragile section near the wired end, so it is crucial to mount the device at the premade holes in order to prevent damage.

Figure 6.4: Foot mounted piezoelectric testing setup



Acquisition
Normal
10.0kSa/s

Channels
DC 10.0:1
DC 1.00:1
DC 10.0:1
DC 10.0:1

Measurements
Freq(1): 1.3367Hz
Pk-Pk(1): 53.5V
AC RMS - FS(1): 7.300V
DC RMS - FS(1): 7.30V

Figure 6.5: Voltage waveform from the V21BL with 100kΩ load and 12.5g tip mass

Table 6.7: Power Output from the V21BL with Various Loads and Tip Masses

Load (kΩ)	5.0g (μW)	7.5g (μW)	10.0g (μW)	12.5g (μW)	15.0g (μW)
4.7	-	-	38.39	50.86	72.37
10	66.10	79.74	56.85	103.25	173.79
47	170.52	246.25	158.92	**448.45**	**555.14**
100	178.42	348.81	195.36	**532.90**	**621.73**
470	71.53	118.00	242.78	301.80	296.46
1000	40.28	58.43	92.16	126.11	-

600μW of average power when the piezoelectric element was characterized using a 100kΩ resistive load, and 15g tip mass originally. These numbers may vary due to a particular athlete's stride type and speed. It is also clear by comparing the two numbers that a significant amount of loss occurs in the current circuit. Some of this loss can be explained by power consumed by the two integrated circuits used. However, some power loss may also be associated with less-than-optimal impedance matching between the piezoelectric element and the circuit. Figure 6.6 shows the test setup for the revision I boards.

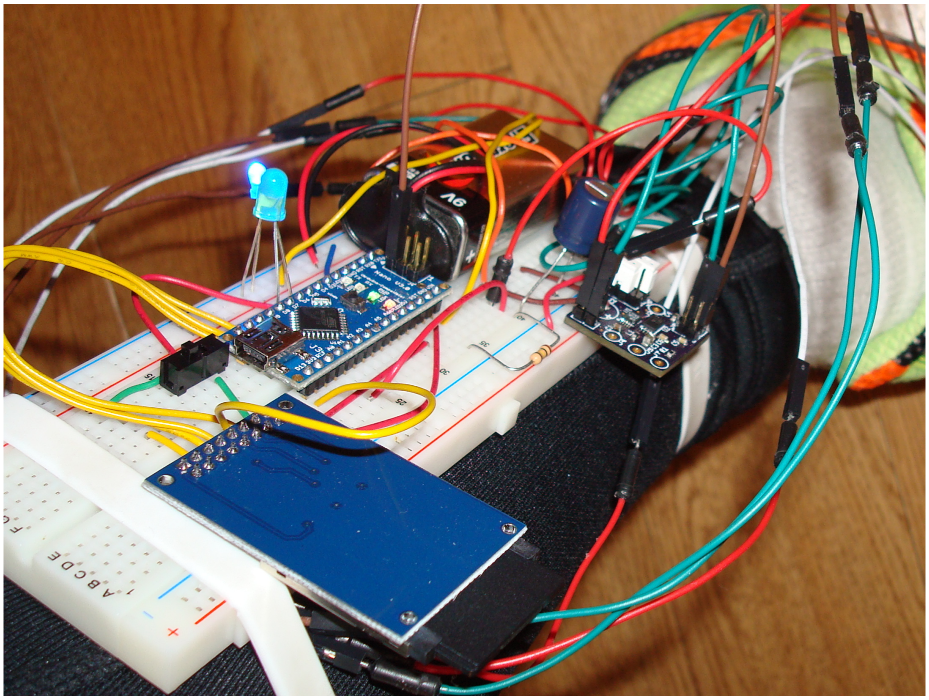


Figure 6.6: Piezo revision I testing setup

6.2.3 Revision II

The second revision does not include the power selection circuitry; that board will be discussed in Section 6.3.2. The anticipated power output improvement has been confirmed by test results. For example, Table 6.8 indicates a maximum average power output of 296μW with a 10g tip mass which is an improvement of nearly 140μW. Also, where the revision I design barely met the power output specification, the second design exceeds the goal substantially. Figures 6.8 and 6.9 show the test setup. The lit LED in the second image indicates that the energy harvested from the piezoelectric element was enough to power the foot pod.

Table 6.8: Power Output vs. Tip Mass While Running on Concrete

Tip Mass (g)	Trial 1 (μW)	Trial 2 (μW)
5.0	88	88
7.5	195	187
10.0	**296**	**296**
12.5	203	197
12.5 (walk)	79	–

Figure 6.7 shows the voltage output with respect to time during a two minute test run without a battery. When loaded with a 33kΩ resistor, the circuit sustains the 3.3V output almost always. The test was preformed with a 10g tip mass on a concrete surface and a running cadence of 175 steps per minute. Occasionally the voltage drops off since the power draw is slightly higher than the power harvesting rate. Once the storage capacitor recharges (usually over a few seconds), the voltage returns to regulation once more.

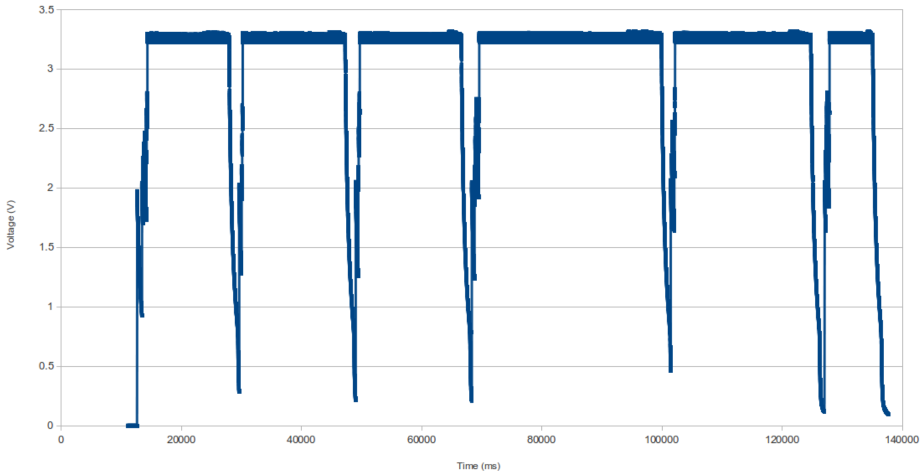


Figure 6.7: Circuit voltage output during a two minute trial run

Further tests were performed on the revision II board in order to ensure that the device still provides sufficient output power under a variety of circumstances. Each parameter

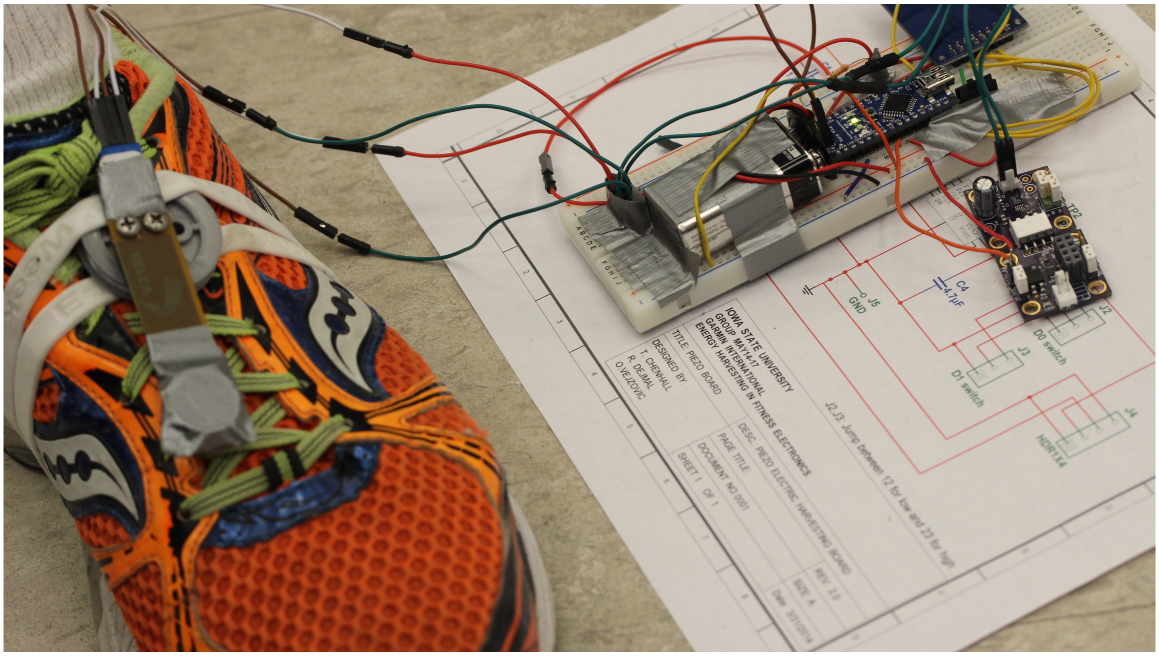


Figure 6.8: Piezo revision II testing setup

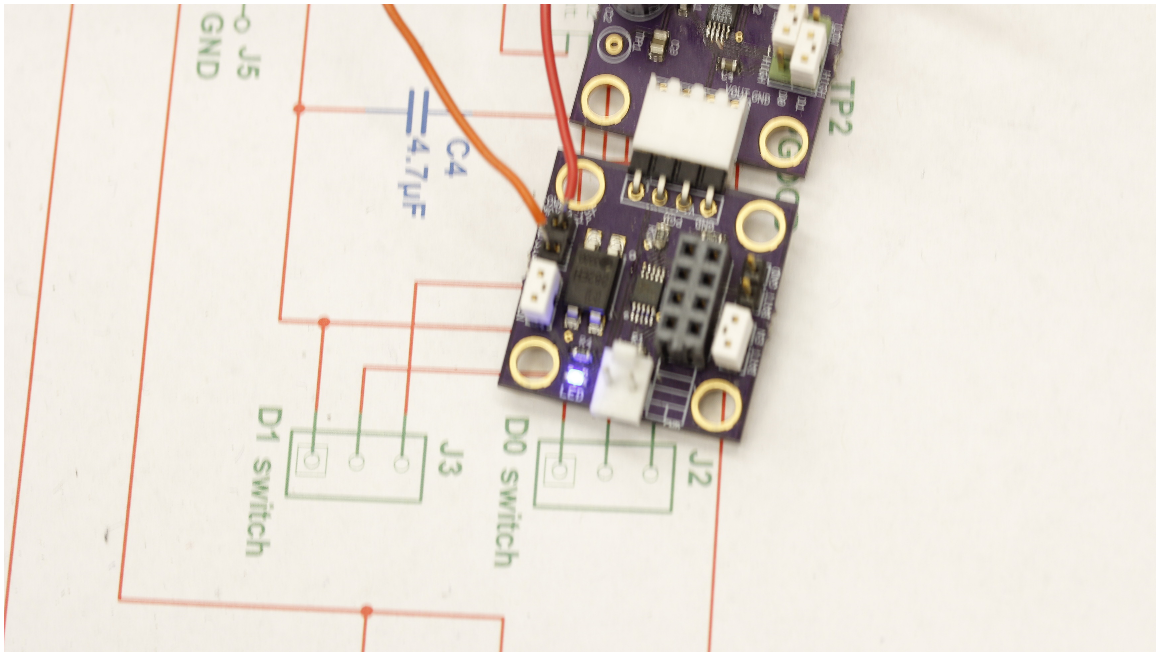


Figure 6.9: Piezo revision II test with lit LED

value was tested with a minimum of two trials, each of at least two minutes. The resulting average power outputs are summarized in Table 6.8 through 6.10. For example, Table 6.8 indicates that best power output is achieved when the piezoelectric element is weighted with a 10.0g tip mass (2 nickels). However, the power specification is still met when the tip mass is increased or decreased by 2.5g. The table also shows that power output from the circuit is significantly lower during walking, which is to be expected since smaller accelerations are experienced. Further robustness tests included running on various surfaces (summarized in Table 6.9) and running with various stride cadences (see Table 6.10). Note that power output drops off some as cadence decreases. This indicates the frequency is moving away from the optimal frequencies for the piezoelectric element. Additionally, power output is lower when running on grass but similar for both concrete and track surfaces. This is because soft ground dampens impact vibrations during a foot strike, while concrete and track induce strong impact forces. For all three surfaces, the power output specification for the design is met.

Table 6.9: Power Output vs. Surface Type While Running

Running Surface	Trial 1 (μW)	Trial 2 (μW)
Grass	165	156
Outdoor Track	324	272
Concrete	296	296

Table 6.10: Power Output vs. Cadence While Running on Concrete

Running Cadence (steps/minute)	Trial 1 (μW)	Trial 2 (μW)
160	213	211
170	268	270
180	280	284

As previously mentioned, comfort to the user is an important quality for a commercially viable energy harvesting solution. Observations made during the above tests indicate that mounting a weighted piezoelectric element on top of a shoe does not impede the user. The mass is small enough to be unnoticeable, and the element itself does not impair the user's ability to move their foot or use proper running form. At worst, the vibrations from the cantilever setup are barely noticeable.

6.3 Power Selection Solution

6.3.1 Revison I

The revison I of the power selection circuitry was tested with the mechanical energy harvesting revision one board. It was found that due to the large power draw of the power multiplexer chip the energy harvesting solution was unable to effectively power the circuit. Because of the clear problems with the design, no further testing was conducted.

6.3.2 Revision II

The power selection circuit was tested using the thermoelectric harvesting circuit as an input source. The input current and voltage and the output current and voltage were measured. This showed that the voltage does not decrease measurably. It was calculated that the circuit consumed 1.14mW of power. With the heart rate monitor test case, this is a 79.28% efficiency. The collected data is summarized in Tables 6.11 and 6.12.

Table 6.11: Power Selection Circuit Test Results

Temp. Gradient (°C)	Input Voltage (V)	Input Current (mA)	Output Voltage (V)	Output Current (mA)
15.20	3.26	1.69	3.26	1.34

Table 6.12: Power Selection Circuit Power Calculations

Temp. Gradient (°C)	Input Power (mW)	Output Power (mW)	Consumed Power (mW)
15.20	5.51	4.37	1.14

7. Discussion

7.1 Thermoelectric Energy Harvester Discussion

The thermal energy harvesting circuit provided enough power to supply to the heart rate monitor in testing. However, this was only able to occur when the cold side of the TEG was covered by a heatsink. Since this circuit should be contained within a heart rate monitor without adding any additional size or weight, a heatsink similar to the one used during testing cannot be implemented. Solutions in the research phase may exist, but they were unable to be tested.

7.2 Mechanical Energy Harvester Discussion

The mechanical energy harvesting circuit provided up to 324μW of power for the foot pod during testing. The mount setup with weighted piezoelectric element is lightweight and unobtrusive to the user. However, it is still larger than the current foot pod design, so incorporating it into an actual product would require a larger case. Energy is harvested reliably and indefinitely while the user is in motion, with larger power output for higher impact activities such as running on concrete.

8. Conclusions

This document has explored in depth two energy harvesting methods and their application to fitness electronics manufactured by Garmin International. Specifically explored were a thermoelectric energy harvesting solution for use in a chest strap heart rate monitor and a mechanical energy harvesting solution for a foot cadence sensor. Background research was conducted on relevant topics and testing was conducted on the target devices. The information from these tasks was used to design first revision prototypes of each energy harvesting solution. There prototypes were tested and tuned to best meet the device energy requirements. Lessons learned from the first revision prototypes were implemented into a second revision prototype. Among other improvements to the second revision design was the modularity of the designs; the boards were created such that either energy harvesting solution could be plugged into the same power selection circuitry and be used with either fitness device. Another improvement made was better built in ability to make power measurements during the testing phase. These second boards were then extensively tested with a simulated load to test their effectiveness.

It was found that both solutions were able to meet their required goals with the thermoelectric prototype supplying all required power and the mechanical prototype supplying 25% of required power, both over the required 10%. Both fit well inside the required form factor and meet most of the other requirements. The thermoelectric solution met all of the requirements, and the mechanical solution met all requirements with the exception of being over the target budget.

9. Recommendations

9.1 Thermoelectric Energy Harvesting

It was determined through this project that thermoelectric energy from body heat can be used to power a heart rate monitor under ideal conditions. With a cool ambient environment and a good thermal contact with the wearers skin the solution can meet all of the energy requirements of the the heart rate monitor. The necessary circuitry can easily fit into the required form factor and interface with the existing system, and the TEG fits the client's specification.

There are, however, several drawbacks to this solution. Although within budget for the prototype, the cost is unlikely to reduce appreciably in a mass produced system. Also, an inherent problem with the TEG is the cold side heats up to the temperature of the hot side if heat is not dissipated away. To compensate for this during testing a heatsink was used, but this option may not be feasible in a final application. It may also be difficult to keep the hot side of the TEG in thermal contact with the skin. Another drawback is the ineffectiveness of the solution to work in the absence of a large enough temperature gradient; although the heart rate monitor will still work, it will not extend the battery life from its current amount. In the majority of use cases it is unlikely that the energy harvesting will appreciably add to the battery life. Due to this, it is the recommendation of this group that thermoelectric harvesting, although a possible solution, is unlikely to be cost effective for the heart rate monitor.

9.2 Mechanical Energy Harvesting

Piezoelectric energy harvesting provides a reliable and lightweight method of collecting energy to help power a shoe-based device. Power output does not depend on environmental factors such as temperature, humidity, or other weather. However, the performance of such a device does vary with several characteristics like running surface and stride cadence. Due to the high prices of typical piezoelectric materials, it may not be commercially feasible to include an energy harvester in a typical product. Size constraints also tend to limit the amount of energy harvested. The additional circuitry and harvesting element necessitate an increase in the device size which may be undesirable to the end user. It is therefore the recommendation of this group that since mechanical energy harvesting is still in its infancy and is very expensive it is not recommended for commercial products.

9.3 Next Steps

Based on the research and testing performed for this project, the group has concluded that energy harvesting, while capable of providing a substantial amount of energy, still struggles with issues of reliability and cost effectiveness. Given these drawbacks, the group recommends investigating alternative methods of extending battery life instead of energy harvesting. One such alternative is battery charging, which is likely to be much more cost effective and reliable.

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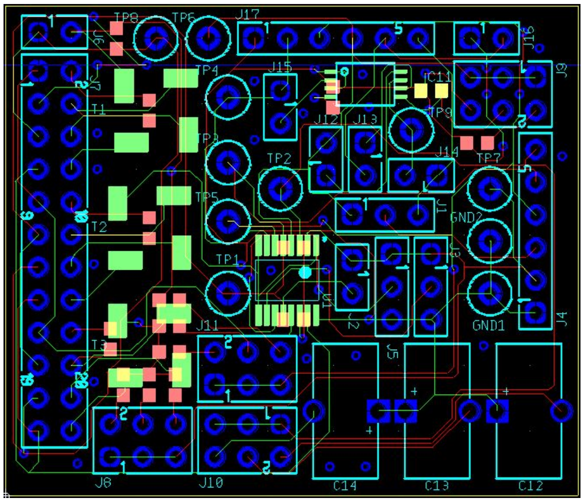
A. Appendix: Printed Circuit Board Layout

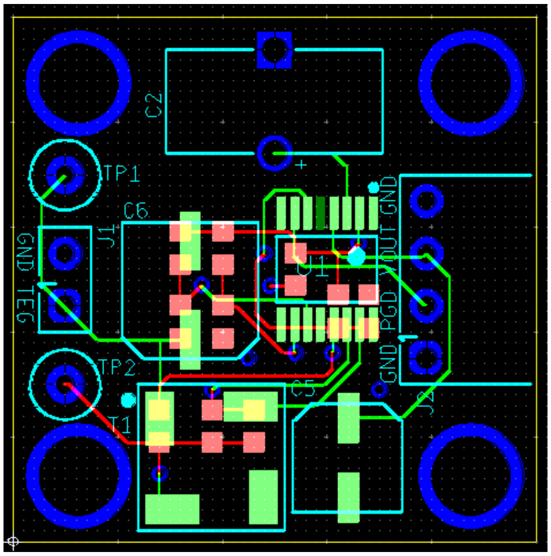
A.1 Thermoelectric Energy Harvester

A.1.1 Revision I



Revision I of the thermoelectric energy harvester board

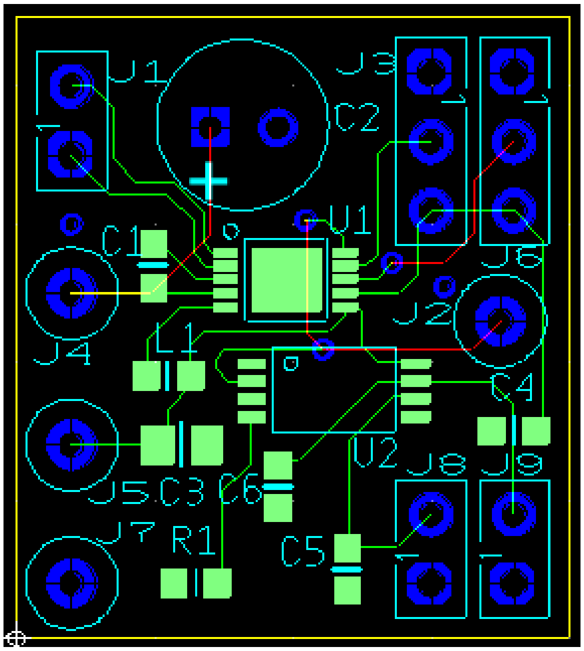
A.1.2 Revision II



Revision II of the thermoelectric energy harvester board

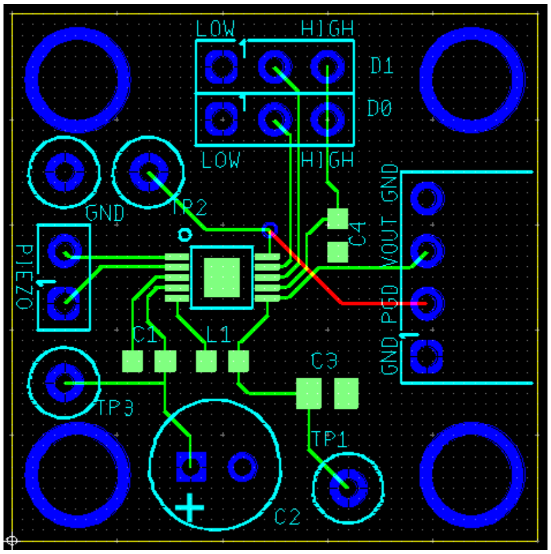
A.2 Mechanical Energy Harvester

A.2.1 Revision I



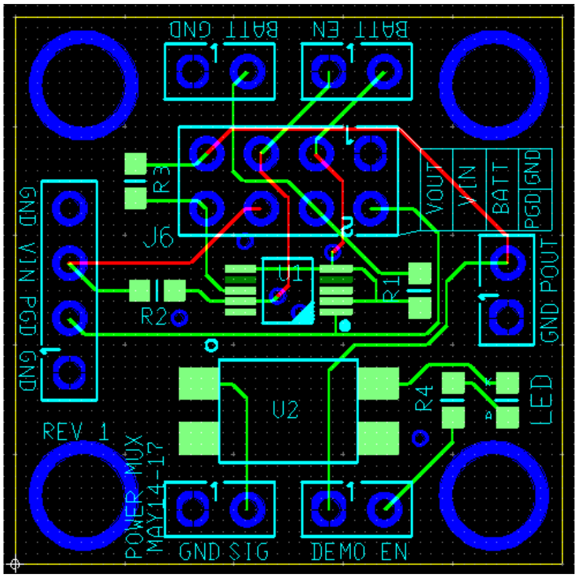
Revision I of the mechanical energy harvester board

A.2.2 Revision II



Revision II of the mechanical energy harvester board

A.3 Power Selection Circuit



Revision II of the power selection board

B. Appendix: Bill of Materials

The following Bill of Materials (BOM) includes enough parts to create one copy of each revision II board. It does not include the energy harvesting parts. Part numbers starting with H are for the thermoelectric harvesting board. Part numbers starting with P are for the mechanical energy harvesting board. Part numbers starting with M are for the power selection board.

Type	Ref #	Qty	Value	Distributer Part #	Distributer	Cost	Total	Package
Capacitors	H-C1	1	150pF	77-VJ0603A151JXACBC	Mouser	$0.08	$0.08	0603
	H-C2	1	220mF	598-EDLSD224V5R5C	Mouser	$1.77	$1.77	Radial
	H-C3	1	330pF	77-VJ0603Y331KXAPBC	Mouser	$0.08	$0.08	0603
	H-C4	1	2.2uF	80-C0603C225M9P	Mouser	$0.12	$0.12	0603
	H-C7, P-C1	2	1uF	77-VJ0603V105MXQCBC	Mouser	$0.06	$0.12	0603
	H-C5	1	150uF	140-VZS151M0JTR0506	Mouser	$0.25	$0.25	VZS0810
	H-C6	1	220uF	140-VE221M0JTR0605	Mouser	$0.16	$0.16	VE0605
	P-C2	1	100uF	647-UVZ1E101MED1DU	Mouser	$0.24	$0.24	Radial
	P-C3	1	47uF	963-JMK212BJ476MG-T	Mouser	$0.77	$0.77	0805
	P-C4	1	4.7uF	80-C0603C475K9P	Mouser	$0.13	$0.13	0603
Resistors	H-R1	1	499kOhm	71-CRCW0603-499K-E3	Mouser	$0.08	$0.08	0603
	H-R2-R6	5	0Ohm	71-CRCW0603-0-E3	Mouser	$0.08	$0.40	0603
	M-R1-R3	3	1Ohm	71-CRCW0603-1-E3	Mouser	$0.10	$0.30	0603
	M-R4	1	100Ohm	71-CRCW0603-100-E3	Mouser	$0.08	$0.08	0603
Inductors	P-L1	1	10uH	810-MLZ1608N100L	Mouser	$0.13	$0.13	0603
Connectors	H-J2, P-J4	2	4 Pin Header	538-22-16-2040	Mouser	$0.61	$1.22	100mil Pitch
	M-J3	1	4 Pin Header	649-68016-104HLF	Mouser	$0.35	$0.35	100mil Pitch
	H-J7	1	2 Pin Header	517-929870-01-02-RA	Mouser	$0.23	$0.23	100mil Pitch
	P-J23	1	2x3 Pin Header	571-1-826632-2	Mouser	$2.17	$2.17	100mil Pitch
Diode	M-D1	1	Blue LED	720-LBQ39GL2N2351	Mouser	$0.12	$0.12	0603
ICs	M-U2	1	SSR	769-AQY282EHA	Mouser	$1.32	$1.32	SOP-4
	P-U1	1	LTC3588	LTC3588EMSE-1#PBF	Linear Technology	$4.22	$4.22	SSOP
	H-U1	1	LTC3108	LTC3108EGN#PBF	Linear Technology	$4.22	$4.22	MSOP
	M-U1	1	ADG804	ADG804YRMZ	Analog Devices	$1.21	$1.21	MSOP
Other	H-T1	1	1:100 Transformer	710-74488540070	Mouser	$4.44	$4.44	SMD
						Total:	$24.21	

C. Appendix: Prototype Operation Manual

Operation of both energy harvesting prototypes is simple and requires minimal user interaction. A demo requires both the power selection PCB and either the piezoelectric or thermoelectric harvester PCB. Figure C.1 below indicates many of the headers important for proper setup.

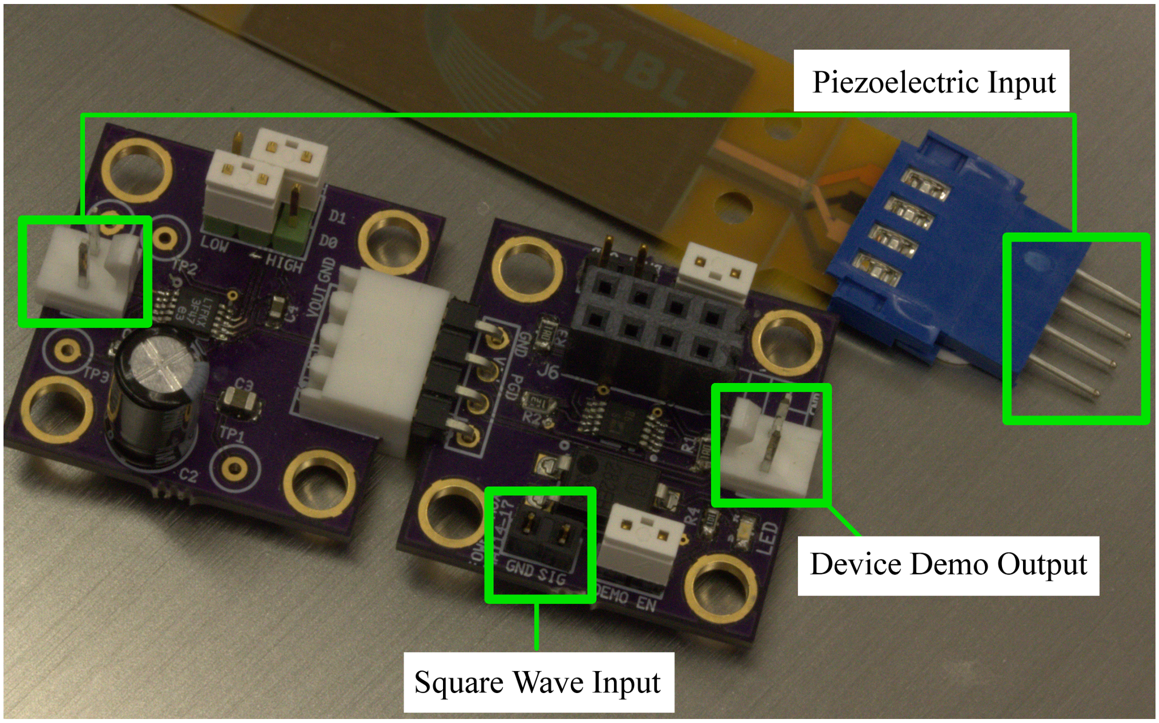


Figure C.1: Piezoelectric harvesting circuit with labeled headers

Thermal-Electric Energy Harvesting Board

1. Wire the TEG output to the input header on the thermoelectric energy harvesting board.
2. Plug the energy harvesting board into the power selection board via the four-pin header.

3. Touch one side of the TEG to the user's warm skin while keeping the heatsink side exposed to air.

Piezoelectric Energy Harvesting Board

1. Mount the weighted piezoelectric element on a shoe using a clip or elastic bands.
2. Use wire to connect the piezoelectric output to the piezo input header on the energy harvesting board.
3. Plug the energy harvesting board into the power selection board via the four-pin header.
4. Begin tapping the foot with the energy harvesting element attached or begin running.

Power Selection Board Setup

1. To use the on-board LED for demonstrating, apply a 5V square wave to the GND-SIG header, and put a jumper on the DEMO-EN header.
2. Instead, to demo with a Garmin fitness device, connect the POUT header directly to the battery contacts of the device.
3. Optionally, a backup battery can be connected to the labelled header on the PCB.

During an on-board demo, the LED on the power selection board should light up when the harvester is collecting energy. When demonstrating with a Garmin fitness device such as a foot pod or heart rate monitor, the energy harvester should supply power to sustain proper operation (possibly with backup battery assistance).

D. Appendix: Thermoelectric Energy Harvester Calculations

This section contains the MATLAB code used to calculate the values for the thermoelectric energy harvesting board. The code cycles through suggested ranges for several passive components to search for the most optimal solution for this project. This code was used iteratively to find component values for the first revision thermoelectric harvesting board.

```
% w/ 15mm TEG, we need ¬ 4-5 Degrees C = 7-9 Degrees F
% w/ 40mm TEG, we need ¬ 1.5-2 Degrees C = 2.5-3.5 Degrees F

TempDif = 10; % Degrees C
TEG_ESR = 1;  % Ohms

I_charge = 200e-6;  % A  : The charge current. We will need to calculate ...
    this after we have an element picked out

I_burst = 1.5e-3;   % A  : The average current during a pulse
I_Q = 10e-6;        % A  : The average current on Vout between bursts
I_LDO = 10e-6;      % A  : The average current on LDO between bursts
t_pulse = 30e-3;    % s  : The duration of the load pulse
f_pulse = 4;        % Hz : The frequency of the pulses
T_store = 15*60;    % s  : The storage time required for C_store
droop = 10;         % %  : The amount the voltage is allowed to drop during ...
    a pulse
Vout = 2.5;         % V  : The voltage the device is programed to output


%% Step-Up Transformer
TransformerRation = 100;                % 1:100
TransformerPrimaryDCResistance = 0.175; % Ohms
TransformerSecondaryDCResistance = 218; % Ohms
TransformerPrimaryInductance = 7.12e-6; % Henrys
TransformerSecondaryInductance = 60e-3; % Henrys
PinC2_Cap = 33e-12;                     % Farads
f = 50000;                              % Hz
C2 = 1/((2*pi*f)^2*TransformerSecondaryInductance)-PinC2_Cap;       % Farad
C2 = 330e-12;                                                       % Set ...
    this to standard value similar to calc value
f = 1/(2*pi*sqrt(TransformerSecondaryInductance*(PinC2_Cap+C2)));   % Actual ...
    Frequency (Hz). Goal: 10kHz-100kHz

%% C1 Capacitor
C1 = 1e-9;          % Farad (recomended for 1:100 transformer
```

```
%% Squegging Resistor
R_squeg = 499000;    % Ohms (recommended for a C2=330pF)

%% Vout and VSTORE Capacitor
Cout_min = I_burst*t_pulse/(Vout*droop/100);                              % Farad
Cout_max = 100*(I_charge — I_Q)/(f_pulse*Vout*droop);
I_charge_min = I_burst*f_pulse*t_pulse+I_Q
Cout = 185e—6;                                                            % Pick ...
    this based on Cout_min and Cout_max
Cstore_min = (6e—6+I_Q+I_LDO+(I_burst*t_pulse*f_pulse))*T_store/(5.25—Vout)
Cstore = 100e—3;    % F : Based on Cstore_min.
%% Turn—on time
t_LDO = 2.2*Cout/(I_charge — I_LDO)
t_vout = (3*Cstore)/(I_charge — I_Q — I_LDO)/60

T_store_actual = ...
    Cstore*(5.25—Vout)/(6e—6+I_Q+I_LDO+(I_burst*t_pulse*f_pulse))/60
```

E. Appendix: Piezoelectric Manufacturers

Piezo Systems is a company specializing in piezoelectric devices for actuators, energy harvesting, and other applications. They have several suggested energy harvesting elements including single layer and double layer bending generators. The double layer devices provide higher power output but also increased price. The lowest resonant frequency is around 40Hz which may be a bit high for the foot pod application. The highest power output rating is 6.4mW$_{rms}$ at the design frequency. Even in bulk (100 pieces), none of their energy harvesting products cost less than $55. The parts with preferable resonant frequencies and power outputs cost up to $125 in bulk. Overall, the power outputs from Piezo Systems' devices are encouraging, but the high prices likely make them unreasonable for a foot pod energy harvesting system. [10]

Mide Technology has supplied the sample piezoelectric elements used for testing the mechanical design in this project. Mide specializes in energy harvesting technologies and has a line of compact piezoelectric vibration harvesters with characteristic frequencies ranging from 200Hz to 26Hz and prices from $50-$90. Both bare elements and enclosed harvesters are available as custom designs. The typical rated power output for Mide's devices is on the order of a few milliwatts at the tuned frequency. The group's measurements have indicated average power outputs up to 600μW under an exercise scenario. Conversations with Mide have indicated the potential for lower bulk prices and custom manufacturing for mass production, making Mide a company to consider in selecting the harvester for this design. [11]

TQ Electronics belongs to the QorTek group of companies. TQ Electronics (TQE) mainly produces power electronics for driving piezoelectric, magnetostrictive, and motor devices, but the company website also advertises a unique capability to produce mechanical energy harvesting elements for use at low (sub-10Hz) frequencies. This prompted this group to contact TQE both via email and phone communications. TQ Electronics does not have any off-the-shelf products developed, but they have the capability to make custom devices and scale up for mass production if requested. A representative of TQE provided us with a brief proposal for low volume devices producing up to 1mW in power. The per-unit price estimate was $100-$150 but would decrease in a bulk order. Due to limited funding, this group did not pursue an order; however, TQE's manufacturing capabilities may be a good option for a mass-produced energy harvesting fitness product. [12]

PI Ceramics has a bending generator that seems similar to Mide's devices: the P-876 DuraAct Patch Transducer. Unfortunately, patent issues prevent the sale of their piezoelectric energy harvesting element in the US. [13][14]

Ferro Solutions develops a variety of systems including wireless charging systems and magnetic sensors. In addition, they currently have a single listed "Electromechanical Vibration Energy Harvester" designed for producing milliwatts of power at fairly low frequencies (10s of Hz) and accelerations. However, since this device is too large in volume and weight, it is unsuitable for the project. Given the limited product selection and information available on the Ferro Solutions website, other companies would probably be more suitable for supplying a small mechanical harvesting element. [15]

Measurement Specialties develops various sensor and sensor-based systems. For energy harvesting and mechanical sensing, they have developed a piezoelectric film material sold as small elements such as in their "Flicker" demo device, cables, and as sheets of film. This film would be conducive to an energy harvesting environment in which a high degree of flexibility is needed, such as a shoe insert. However, as discussed in Section 3.2.1, the power output from piezoelectric films such as PVDF is often very small. This means that many sheets of material over a large area would be needed to provide substantial power for a device. Based on experimentation in this project, the power output and size constraints given seem to require a stiffer (high power) material like PZT. Flexible (low power) piezoelectric materials may have applications when large collection areas are allowed such as when embedded in clothing. Measurement Specialties is working to develop charge multiplication techniques to improve energy harvesting efficiency. The results of this work may be beneficial to increasing power output in a future design. [16]

Noliac is an international company specializing in piezoelectric technology and has a variety of raw materials, standard products, educational opportunities, and capabilities for custom products. The North America division of Noliac was established in 2009. Currently, the website lists Piezo Generators as a custom product only, so no specifications are available on their website. However, given the company's available technologies and experience, Noliac may be worth contacting for development of a custom, mass-produced device. [17]

Murata provides a variety of electronic components spanning from basic components to sensors and actuators. They have a number of piezoelectric elements for use with audio systems (microphone and speakers) but also mention the development of a handful of energy harvesting elements [18][19]. These products are not locatable on the Murata website, suggesting that energy harvesting is still a developing product area. Thus, at this time other companies are probably preferable suppliers for mechanical harvesting. [20]

American Piezo Ceramics (APC International) is a global supplier of piezoelectric materials and devices started in 1986. Their products include custom shaped ceramics, actuators, ultrasonic transducers, buzzers and more, using mainly PZT compositions. The company's website hosts a collection of brief educational pages ("The Knowledge Center") with general information about piezoelectricity. Overall, while the company seems well versed in piezoelectric devices, they have no products indicated specifically for energy harvesting. A stripe actuator may be usable for a harvester though. Garmin's fitness electronics may fall into the category of "low power" devices mentioned, but the company seems reluctant to pursue energy harvesting technology, which may indicate other companies are preferable partners. [21]

F. Appendix: Radio Frequency Calculations

Calculations indicate the infeasibility of RF energy harvesting. An antenna captures power over a region known as the effective area. The equation to find area is

$$A_e = \frac{\lambda^2}{4\pi} G \tag{F.1}$$

where λ is the wavelength of RF energy and G is antenna gain [22]. In a region with a certain radiated power density, the maximum power available at a particular antenna is just the product of the power density and effective area. According to Powercast Company, typical power densities in air are up to -12dBm/m^2 or 63μW/m^2 in the 680MHz to 3.5GHz range [23]. Given the size of Garmin's products, this is likely a good approximation for the useful bandwidth of an energy harvesting antenna.

For a microstrip or other small antenna, a gain of 25dB is possible using an array of patches. Given that wide bandwidth and high gain are often trade-offs in antenna design, the actual gain over the band of interest would likely be lower. Using λ_{680MHz} and this gain, we get an area of approximately 0.387m^2. Then, to harvest even 150μW of power for a device, the required power density would be 387μW/m^2, which is about six times the value cited by Powercast. The required power density is much higher when the wavelength decreases with higher frequency, the expected loss due to non-ideal efficiencies, and the RF-to-DC energy conversion are also take into account. This analysis suggests that ambient RF harvesting would be unsuitable for powering a Garmin device.

G. Appendix: Survey Data

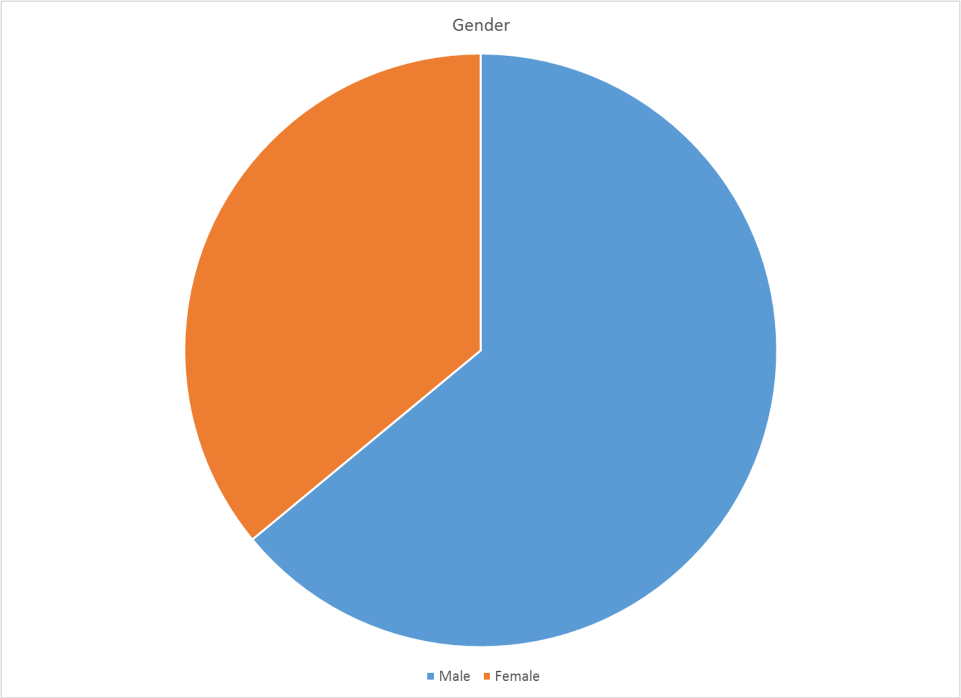
In order to help assess consumer interest in energy harvesting designs, the team distributed surveys at various locations: State Gym at Iowa State University, an Iowa Department of Transportation office, and several other locations. The survey asked six questions:

1. What is your gender?
2. How much do you work out?
3. What is the maximum amount you would be willing to spend on a battery powered heart rate monitor?
4. Would you be willing to spend more if the heart rate monitor ran off human body heat and did not require batteries? (If so, how much?)
5. What is the maximum you would be willing to spend on a battery powered foot cadence sensor?
6. Would you be willing to spend more if the foot cadence sensor was powered by the motion of the foot and did not require batteries? (If so, how much?)

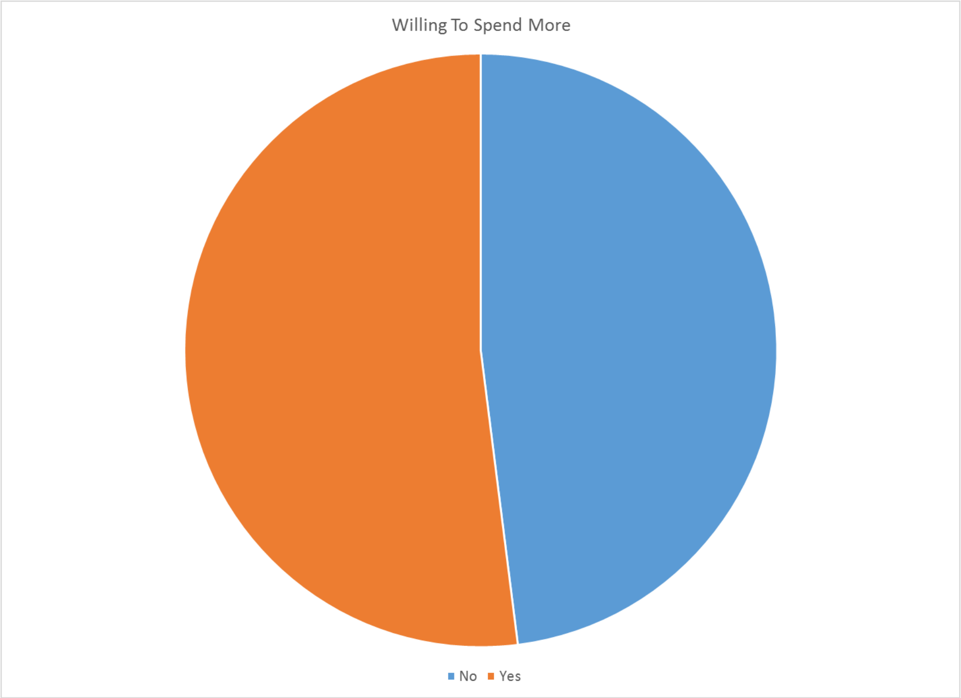
Additionally, short footnotes were included describing energy harvesting, the heart rate monitor, and the foot pod.

The results are summarized in the pie charts below. From the charts, it is possible to discern several clear trends. First, we see that there is substantially more interest in a heart rate monitor without a battery than a foot pod without a battery. Overall, people surveyed would pay more for a heart rate monitor than a foot pod. On average, people were willing to spend \$23.98 more for an energy harvesting heart rate monitor and \$19.45 more for a foot pod. For individuals willing to spend more than \$40 on the device (which is more representative of people who would buy Garmin's current devices), survey respondents would be willing to spend \$36.39 more for an energy harvesting heart rate monitor and \$26.82 more for an energy harvesting foot pod.

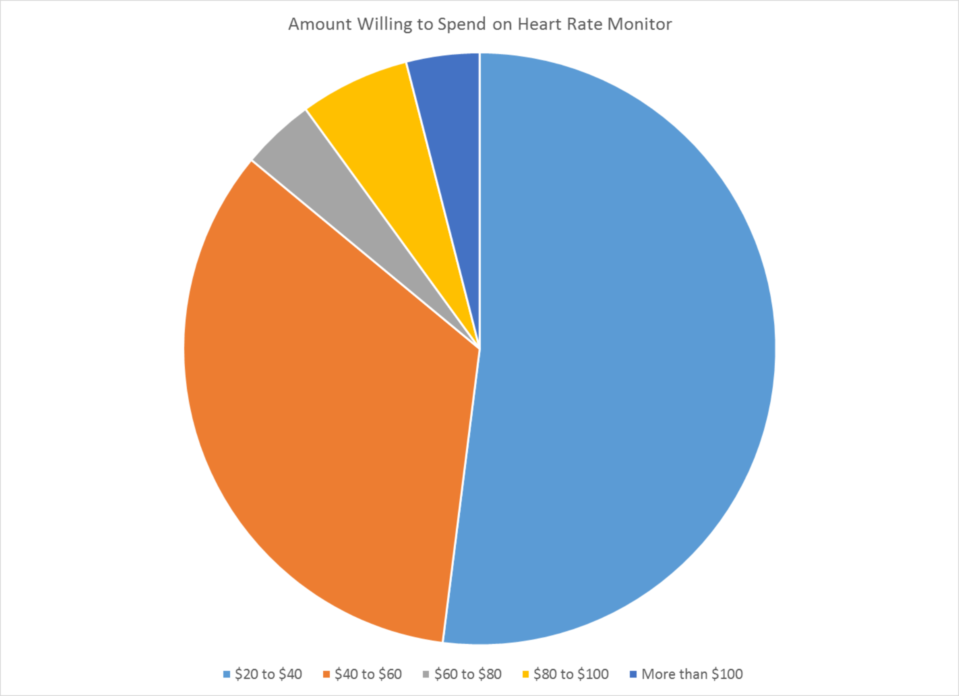
Given the cost of the energy harvesting circuits, these survey results indicate that there may be some market for a thermal energy harvesting solution. However, piezoelectric elements are typically too costly and would require raising the product price more than people are generally willing to pay.



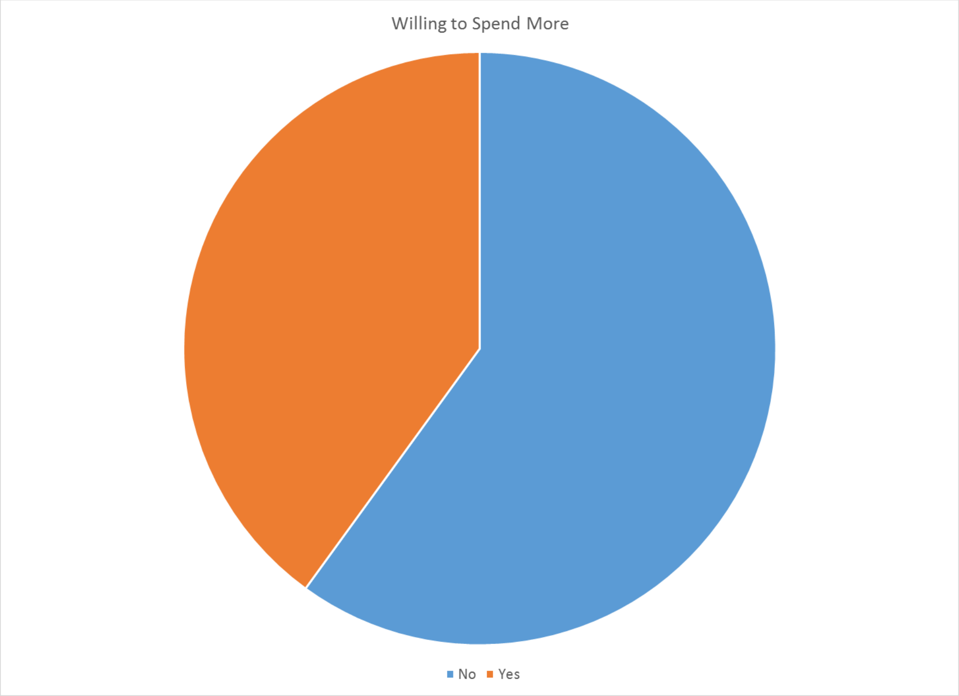
Survey Respondents by Gender



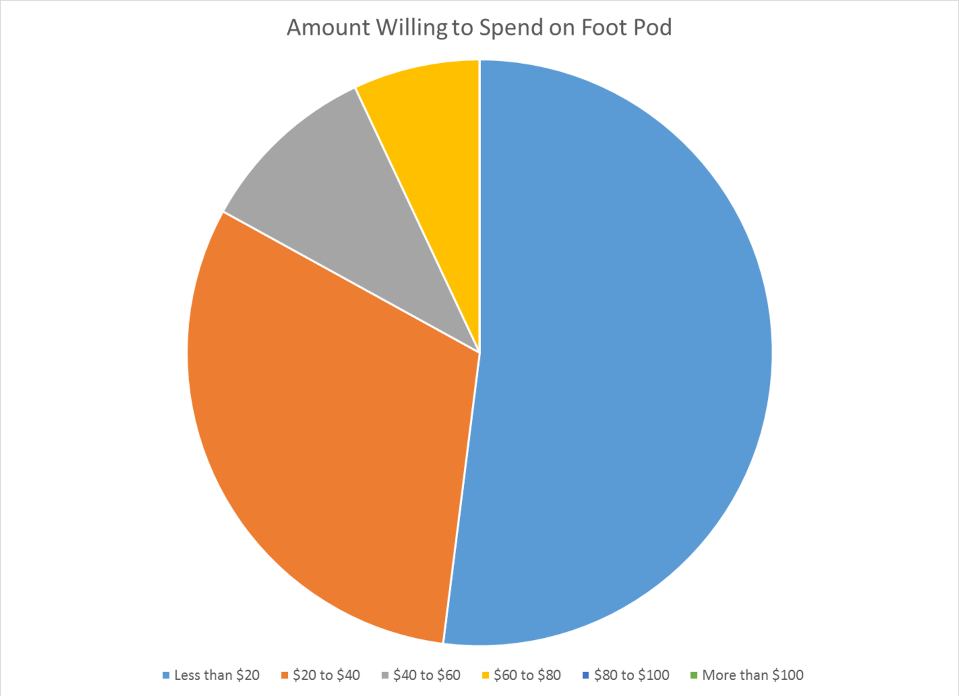
The percentage of who would pay more for an energy harvesting heart rate monitor



Of those willing to spend more for an energy harvesting heart rate monitor, how much would those surveyed be willing to pay



The percentage of who would pay more for an energy harvesting foot pod



Of those willing to spend more for an energy harvesting foot pod, how much would those surveyed be willing to pay