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Dear Dr. Reinbolt and Dr. Tan:

The ACJP Energy Harvesters are submitting a Final Design Report that will explain the design of an energy harvesting shoe using piezoelectricity. The purpose of this report is to provide visual evidence and theoretical proof supporting the design of a running shoe that will convert kinetic energy into electrical energy that can be stored in a two AAA rechargeable batteries.

Through exhaustive efforts beginning in September 2013, the design team has gathered to evaluate the competitive landscape of similar products, brainstorm theoretical ideas for how to design the shoe, and determine energy storage with respect to many assumptions that are explained in detail in the body of this report. The team then manufactured a working prototype and ultimately a final product that will be highlighted within the report.

Thank you for your time.

Respectfully,

ACJP Energy Harvesters
BME 455 - Team 5

Final Design Report For The ACJP Energy Harvesters



Date formally approved by stakeholders: 04/28/14

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1. Executive Summary

The design team is developing a device that will utilize piezoelectric strips and energy from walking to store energy into two AAA rechargeable batteries. Designing such a device requires that the shoe remain as normal as possible while only gaining the advantages from storing energy in the batteries. The system will be lightweight; however, it will not be as flexible as normal because the piezoelectric strips will be inside the shoe underneath the insole. The target audience is hikers or outdoor enthusiasts who need power to charge devices such as flashlights. The initial prototype was supposed to be a system designed after a MIT energy-scavenging shoe device that used a bimorph in the heel of the shoe.

Our team's system was supposed to use two bimorph piezoelectric devices that created energy when pressure was added to the bimorphs, but the piezoelectric device, the THUNDER TH-6R, was far too brittle. Also, the circuitry needed was far too complex as we were unable to get the design to work. So, our team decided on a different design. This design became our final product. The system of the final design used six piezoelectric bending strips that create energy when flexion occurs, as the input of the system, whereas, the output of the system was a battery holder that held two rechargeable AAA batteries. The input and output of the system were wired and soldered to a circuit board. The circuit board was out of a Red Cross hand crank flashlight.

Originally, the system was placed into a boot. The heel of the boot was carved out to hold the circuit board of the system. Figure 1 shows a case was designed and 3D printed to hold and protect the circuit board from getting damaged. The battery holder was placed using Velcro to the back of the boot, and the piezoelectric strips were placed in the toe of the boot for maximum bending. Once this prototype was finished, testing was pursued next. To test this prototype, an hour of walking in the boots around a track was done. The results of this test showed 0.09 volts

were added to the batteries. To see how much energy this created, a discharge test of the batteries was done. This showed a curve for the useable power of the batteries. With the discharge curve, our team was able to find out the actual power that was added to the batteries. The tests showed that actual energy added was 120.31 volts, while the capacity was 0.037 W-hr added.

After this test was completed, our team decided that the power output would be higher if the piezoelectric strips were allowed to bend more. So, the system was placed in a tennis shoe to provide more flexion to the strips. To place the system in the shoe, the piezoelectric strips were again placed in the toe of the shoe underneath the insole. While, the circuit board contraption was attached to the side of the shoe, and the battery holder was attached to the back of the shoe. The same test was done on this prototype, where an hour of walking was performed using this system. The results showed that 0.14 volts were added to the batteries after walking. From the discharge curve, the actual energy added was 157.27 J, and 0.044 W-hr was added to the capacity of the batteries. With these results, it showed that the batteries would fully charge in 27.6 hours of walking.

These results proved to be better than the first prototype, so our team decided to make this our final design. If our group started a company selling our final product, we would sell it to places such as Bass Pro Shop, Gander Mountain, Cabalas, and other shops that sell products for hikers or outdoor enthusiasts. However, to make our product we would need to design our own materials to decrease the production cost, because the final design costs is far too high. With the development of our materials we would also have a chance of increasing product performance. Overall, the device met most our design requirements and showed that piezoelectricity has potential if used with correct power electronic circuitry.

2. Background

At some point in every person's life, they have to find a source of power. For our groups project, we are looking to create a power source that can give hikers access to batteries if needed. The group's goal is to solve this problem by using piezoelectric technology to convert mechanical energy into electrical energy, which can be stored in a battery and used to charge two AAA rechargeable batteries. If successful, hikers would be able to charge any device that uses AAA batteries, such as flashlights. Instead, their lives will be more efficient, and their devices will be less likely to die on them due to this energy-harvesting supplement. It would be a huge breakthrough if the device could combine converting kinetic energy to electrical energy adequately using piezoelectric technology while also being lightweight, widely accessible, and user-friendly.

Some devices have used the energy storage concept to form a product that is very appealing to consumers. PowerSole, as seen in Figure 2, is a shoe device that converts kinetic energy into electrical energy that can be used to charge other devices such as phones, iPods, or LED flashlights. This device uses a faraday coil concept that is stored in the sole of the shoe to create an electric current. The electricity created is stored in a small battery that is conveniently placed in the front of the shoe. The device is USB accessible and is very eco-friendly. The patent for PowerSole is still pending. PowerSole shows an adequate means to create energy using the faraday coil concept, but with its bulky design, the device is limited to shoes that have a thick sole.

Another device that converts kinetic energy into usable electrical energy is the MIT energy-scavenging shoe. As seen in Figure 3, the MIT device uses a piezoelectric concept that is placed in the insole of the shoe to convert mechanical energy into electrical energy. The

piezoelectric concept uses a bimorph in the heel of the shoe and a PVDF stave in the toe of the shoe. The bimorph part uses a pressure based piezoelectric strip to create energy when pressure is added to the strip; Whereas, the PVDF stave creates energy when the stave is bent. The energy from this product is used to power RFID tag system mounted on the shoe. The design used a forward-switching converter circuit. This product was adequate in that it showed that the piezoelectric concept can be compact in design and can fit in shoe; however, the circuit board being place on the back of the shoe makes the shoe not as appealing. This device proved to be able to create an adequate amount of power. The device was able to create roughly 1.3 mW of useful power output. So overall, the MIT energy-scavenging device shows an adequate means to create energy using a piezoelectric concept.

3. Problem Definition

Our goal is to convert kinetic energy into electrical energy and store it for later in an external device. In order to do this we will design a product that accomplishes this task, while meeting other specified requirements. Our key business strategy is to utilize piezoelectric technology and implement this into a shoe, so that as the wearer walks, their kinetic energy is harvested and stored as electrical energy. Part of our assignment has been to observe and develop the best possible design in order to accomplish this task. The finished product should consist of a shoe and energy harvesting device hybrid that is efficient and does not interfere or impair the user's movement in anyway. Once this is accomplished, our device will be marketable as a means to provide energy to a wide variety of devices, when power outlets are unavailable.

The system will convert mechanical energy into electrical energy by harvesting the potential energy that is created through the gait process by using piezoelectric strips that will bend under stress to create electrical energy. The device will need to meet certain expectations,

such as being able to power a cell phone or some other device such as a battery. The initial requirement we set out was to fully charge an iPhone 5. The device should be able to provide a full charge after an individual wears the device and walks for 2 miles. If it does better than that than we have exceeded expectations. The interfaces will include but are not limited to: a shoe, a sole, the ground, piezoelectric strips, wires, a capacitor, more wires, and finally a USB output. The USB output will allow for the user to attach directly to the battery using an iPhone 5 cord and provide power.

There are many requirements that need to be met before it is ready for the public. The system must be able to attach to a shoe effectively and continue to be attached during the process of walking. The system also must not inhibit walking, in that the system should be designed to mimic the same gait process of the shoe without the shoe attached. The system must not add discomfort to the user. The system should be shaped in a way that makes the shoe not easily noticeable to the user. More specifically, the overall device should be able to fit within an size 10 shoe and must feature lightweight components. This is to ensure that one shoe does not noticeably feel different than the other, consequently impairing normal walking. The system should be designed so that instead of causing discomfort it should actually be more comfortable.

To develop this product we have identified a wide variety of sources and have examined various techniques and applications of piezoelectric technology. We have observed what worked well and what didn't work so well for them and from this information have developed our own energy-harvesting shoe. We looked at a multitude of energy harvesting devices and reviewed all of the different applications and configurations.

Not all of the sources we examined involved piezoelectric technology, in fact we looked at the PowerSole and how they implemented piezoelectric technology into a hiking boot utilizing

Faraday Coil technology. As the user walked and the magnet inside passed through the rings of coiled wire, the magnet caused induction to occur from which energy could be harvested. They took advantage of the large area within the boot and not only housed all of the energy harvesting requirements, but they also integrated a USB port in the side of the shoe's sole. This enabled the user to plug up a USB cord easily and charge the necessary device.

We also took an in depth look at a 4 year research program performed at MIT and saw how they studied various piezoelectric devices and their various configurations. We observed their use of pre-stressed bimorphs and how they upon compression and further deflection produce an electrical charge. In this study they were able to place a bimorph in the back of the shoe while a bending piezoelectric was placed in the front. Both components were wired to a custom circuit board at the back of the running shoe. This information showed us that the use of piezoelectric benders and bimorphs are viable methods for harvesting kinetic energy to be stored as electrical energy.

4. Concept Development

Upon initially receiving this task, our design group began work on finding the most efficient energy harvesting devices that were best suited to our task. As the group reviewed more and more outside work, it became clear that we wanted to implement energy harvesting technology into the shoe in a more efficient way. We began thinking about the large amounts of ground forces involved in walking and running and how we might take this knowledge and create a device that will function in unison with a shoe.

We examined energy harvesting devices that utilized faraday coil technology. It was observed that many energy-harvesting devices operated by utilizing a particular type of movement. For example, some flashlights are battery powered by shaking and some capacitors

are charged by repeatedly cranking mechanical gears. With piezoelectric devices we discovered that some devices generate energy as the crystalline layers rub up against one another and produce a charge. In some cases this was accomplished by producing a layer of piezoelectric ceramics and as they bent, an electrical charge was effectively produced. Other strategies focused on stacking multiple layers so that compression produced electrical charge.

From this knowledge we made multiple sketches of what we believed to be some of the best solutions we could think of. One of the initial ideas, as seen in Figure 4, incorporated the use of faraday coils and had them depicted in multiple orientations to induce a charge while walking. Other designs, as illustrated in Figure 5 and Figure 6, focused on the quantity and placement of piezoelectric devices within the shoe. This was novel thinking, in that the piezoelectric devices we selected had previously not been used for such an application inside of a shoe. What all of the sketches had in common was the incorporation of integrating the circuit board to fit within the confines of the shoe, while two output wires lead to the outside of the shoe where a detachable battery located. The purpose in the addition of this detachable battery is that other devices forced the user to have their device connected to the shoe while charging. Our novel idea was the addition of a clip on battery that can simply be unclipped and attach to the device to be charged.

From this stage in the development process the group moved to more tangible models. In order to determine if our ideas had any merit, it was crucial to begin ordering components and determine what we could produce. Our thorough search for off the shelf items was extensive, but left us with some potential selections for our prototype. As time progressed more items that we wanted, and that we needed, became clearer. We knew we would definitely need to order both a hiking boot and a running shoe, an external battery and holder, and an off the shelf energy-harvesting circuit. Figure 7 shows an energy harvesting kit that would allow us to attach multiple

types of devices, including piezoelectric strips, to the energy-harvesting circuit. Unfortunately due to compatibility issues and sizing constraints, this circuit board was not a good fit for our design. Additionally, we looked at ordering the components and learning how to assembly the circuit used in the MIT study. The circuit board utilized by the MIT example turned out to be a custom made circuit board and for the purposes of this course, such components could not be allocated in time. With this taken into consideration, our group decided it would be more beneficial to remove the circuit board from a pre-existing, energy-harvesting circuit. As for selection of the piezoelectric components, we ordered all of the various components required to construct our own bimorphs similar to those from the MIT example. As the parts came in we quickly realized that the actual piezoelectric component, the THUNDER unimorph as seen in Figure 8, was much too brittle in to shoe, and did not meet the expectations needed for our application. So in response to this, the group decided to look elsewhere for our piezoelectric energy source. We ordered PFC-54W piezoelectric strips from Advanced Cerametrics, which can be seen in Figure 9 and Figure 10, that could generate energy when they experienced bending. Unfortunately, before any energy was to be harvested these strips must be wired to the circuit. Even though we had the right wires, and ability to solder, we still required factory conditions to safely and securely attach the wires. Thus, our group contacted the company and ordered several more piezoelectric devices and had the lead wires pre-attached.

5. Product Description

The groups design hinges around the success of creating as much bending of the piezoelectric strips as possible to harness the maximum amount of mechanical energy and convert it into electrical energy. The group needed to pick out the piezoelectric strips that would create the maximum amount of electrical energy for the design and also be able to interact with

the circuit board. The circuit board needed to be compact so as not to weigh too much and change a normal person's gait, but it still needed to convert the charge into useable energy. The group had a major constraint in relation to the circuit board in that it had to be able to fit inside the case that it was designed for. This was difficult to work around until the group finally settled on the circuit board that they agreed would work the best for the application at hand. When it came to outputting the power, the group initially wanted to have the design be able to charge a phone through a USB output. However, after much testing and number crunching, the group quickly realized they needed to pick something to charge that was more realistic with the amount of power that the system was able to create. In the end, the group decided that the system would be intended to recharge two AAA batteries. This proved to be a good choice as it was an attainable goal for the system used.

For the final design, the group used the same piezoelectric strips that were implemented into the working prototype. It took a long time to pick the piezoelectric strip that would be used in the design because to the group's surprise, many of the piezoelectric strips were not very user friendly. The Thunder (TH-6R) strips were quickly disbanded as they began to crack when insignificant force was applied to them. It did not seem ideal to have the full force of walking applied to them when they cracked under small amounts of applied pressure. Since the group realized that these strips would not work, they decided to order the PFC-W54 strips. Initially they only ordered one strip, which may have actually been lucky since the leads were not attached to the strip and the group was unable to solder them on. The group finally ordered six more of the PFC-W54 strips but the second time, the leads were fortunately attached to the strips. Initially there was some debate over how the piezoelectric strips would be placed in the shoe. There were ideas that it should be a part of the sole, under the sole, or lying on top of it. In the

end the group decided to place the piezoelectric strips under the sole and actually place orthopedic inserts over the top of the piezoelectric strips to increase comfort and reduce how much one would feel the strips under their feet. This was something that the stakeholders deemed as very important to the systems design. They felt that if the design affected a normal persons walking motion, they would not want to use it as much.

The choice of the circuit board to use in the final design caused much debate and trouble. The group needed a circuit board that was small and compact, but powerful enough to actually harness the energy that was being supplied by the piezoelectric strips. The group found out after much research and talking to professionals that the best circuit board for the system would be created from scratch. After being advised by a professor of the electrical engineering department, the group determined that while building a circuit board for the system may achieve the best results, they would be unable to do it by themselves. After consulting with the stakeholders, the group decided to pursue an off the shelf solution to finding a circuit board that would work. While the off the shelf solution many not utilize energy harvesting within the circuit board, it would be able to utilize the energy that the piezoelectric strips would provide. After pulling apart various flashlights that utilized circuit boards, the group found one that they liked that came from a hand crank flashlight. The group picked the hand crank flashlight circuit board because it was compact and had the necessary input and output leads that were needed. In addition, the circuit board had a USB output, which was what the group had originally sought to use. The USB output was the key to the idea of charging a phone with the system. After testing the circuit board capabilities it was determined that the USB output would not be useable as the system was not inputting enough voltage to provide enough power to the USB output. The group would have liked to have used the USB output because it would have added value to the design, but certain

ideas had to be scrapped as they were a bit too ambitious for the task at hand. In the end, the circuit board that was used in the final design proved to work well since it was compact enough to fit in the case and it was able to convert the energy and output it to an external device. This was good because the stakeholders were not too concerned with how the power was outputted because they understood that the group was not trying to maximize the energy converted but rather the energy harnessed in the system.

Choosing what to do with the energy converted was the key feature of the final design. This was where the user interfaced with the design and got their money's worth out of it, so to speak. Initially the group was ambitious and wanted to fully charge a Smartphone, which would have been a great achievement and made the product something worth buying, at least in the stakeholder's eyes. After consulting with professionals and talking about how much useable power the system would have, it was determined that the design not be able to charge a phone or even create enough power so as the phone would recognize it as charging. The group discussed the idea of lighting an LED light or charging a battery. In the end, charging a battery was the idea that was picked because it seemed like a good use of the amount of power created by the system. It was simple to attach to the shoe and to hook up to the circuit board so the group stuck with it. While the stakeholders were not necessarily impressed with this choice, they recognized the validity of the concept and that it achieved the goals of the overall design. All in all, the numbers appear that the design works; however, it is still uncertain if energy is being added to the battery or if the battery is experiencing random voltage fluctuations.

6. Design Evaluation

In order to determine if the design was successful, the design team met with stakeholders to set forth a list of functions and requirements that the device must meet. A summary of these

functions and requirements can be seen in Table 1. In summary, the group and collaborators felt that the shoe must be lightweight, working properly, unharmed to the environment and the user, and aesthetically appealing.

After the initial prototype incorporating the boot was manufactured as seen in Figure 11, data was to be obtained for the battery in order to quantify the performance of the hiking boot. To do this, a simple battery discharge test was assembled in which the two rechargeable AAA batteries were wired in series with a 10-ohm resistor. The data was captured by a SCOPE program on a computer. This test was done because data was not able to be stored in real-time with our resources that were readily available. The data was stored as voltage readings at various 0.02 second time intervals. A visual of this test can be seen in Figure 12. By knowing the discharge characteristics, one can figure out the actual energy in the batteries as opposed to the rated energy. Also, the discharge graph was used as a reference graph for future tests to measure the performance of the initial prototype and final product.

Evaluation of the prototype's performance was necessary; however, the method needed to be selected carefully due to not being able to capture data in real time. A member of the design team wore the hiking boot and walked around the track at The University of Tennessee for exactly one hour. Before walking, the voltage was measured across the batteries in the discharge breadboard and recorded. Immediately after walking, the voltage was recorded again. A summary of the results. The discharge curve that was obtained from the discharge data allowed us to know how much energy it takes to go from one voltage reading to a higher one, so using that curve to calculate the energy allowed for us to know the total energy into the system. Because the number of steps were counted during testing, it was assumed that the total energy divided by the number of steps yielded an accurate energy added per step value. Knowing the

total energy that was put into the shoe and the total usable energy in the batteries, it was possible to estimate the total time needed to charge the batteries by walking. A summary of the results for this first walking test, labeled "Walking Test I", can be seen in Table 2.

After conclusion of Walking Test I, the design team began to think of ways to improve upon the design. Because of the limitations of power electronics circuitry, the design team could only improve upon the aesthetics of the shoe and the amount that the strips bent while walking. To get more bend per step from the piezoelectric strips, the system was transferred from a hiking boot to a running shoe. The running shoe required the circuit board to be attached to the outside of the shoe because there was not enough room for it in the sole. This system that was incorporated into a running shoe became the final design. An image of the final design can be seen in Figure 13. The same performance test for the hiking boot was done with the running shoe, and the results are summarized in Table 3 entitled "Walking Test II."

The hiking boot saw less energy transferred to the batteries as opposed to the final design making it appear as if an improvement in performance had been achieved. Aesthetics may be slacking slightly due to the bulky case being attached on the outside, however. One must find a balance between performance of the shoe and appeal to the eye in this situation, because the better design is not particularly appealing to the eye. The final design concluded that it would take a little more than twenty-seven and a half hours to fully charge two AAA rechargeable batteries (800 mAh capacity each) from a voltage that would be common after they had died in common appliances.

7. Recommendations & Future Work

While the final design was successful and worked to achieve the realistic goals set forth, the design could be improved if taken in the right direction. It is possible that the original goals

could be met of charging a smart phone to a full charge. In order for this to happen though, the most important thing would likely have to be that the group created their own circuit board that harnessed and converted the energy to maximize the power output. This would allow the group to accomplish much more and focus more on the aspects of the project that they could not pay as much attention to initially. Implementing a custom made circuit board would be the most important feature of the product and would add much needed financial benefit because the product would be able to reach the original goal of charging a smart phone. This would give the product a leg up on the competition since few products of the same nature can boast that they can successfully charge a Smartphone.

Other improvements for the design would be things that would maximize the amount of electrical energy that the piezoelectric strips would generate through bending. This could be something as simple as changing the location of the strips or even using different piezoelectric strips. Another idea for improvement that the group discussed but was unable to implement was the addition of piezoelectric on the top portion of the shoe so that the entire mechanical gait could be harnessed instead of just a portion of it.

The continued work on the product would greatly improve the overall design and financial worth. The continued work could take up to six months and cost roughly \$1,000, but the product would be improved to a state so as the work was worth the time and money. The idea has great potential, but it needs to be utilized correctly in order to generate money from it.

Appendices

List of Figures

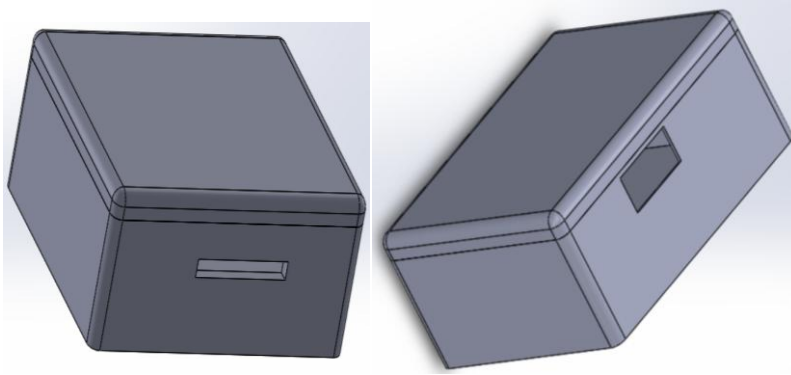


Figure 1. A Custom 3D Printed Case to House the Circuit Board



Figure 2. PowerSole uses a Faraday Coil to Charge a Battery



Figure 3: MIT Energy Scavenging Shoe

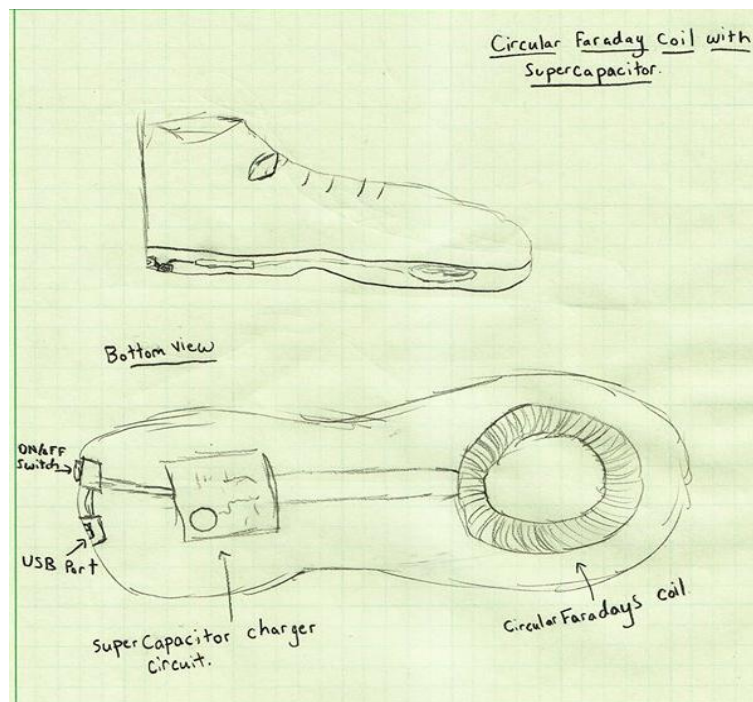


Figure 4. An Idea For the Energy-Harvesting Shoe Incorporating Faraday Coil Technology

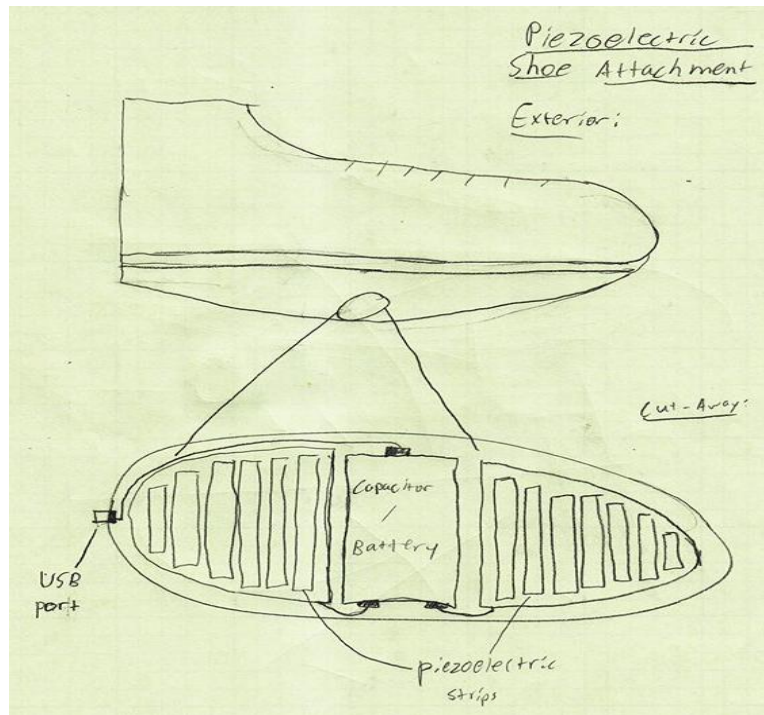


Figure 5. An Idea Incorporating Bending of Piezoelectric Strips

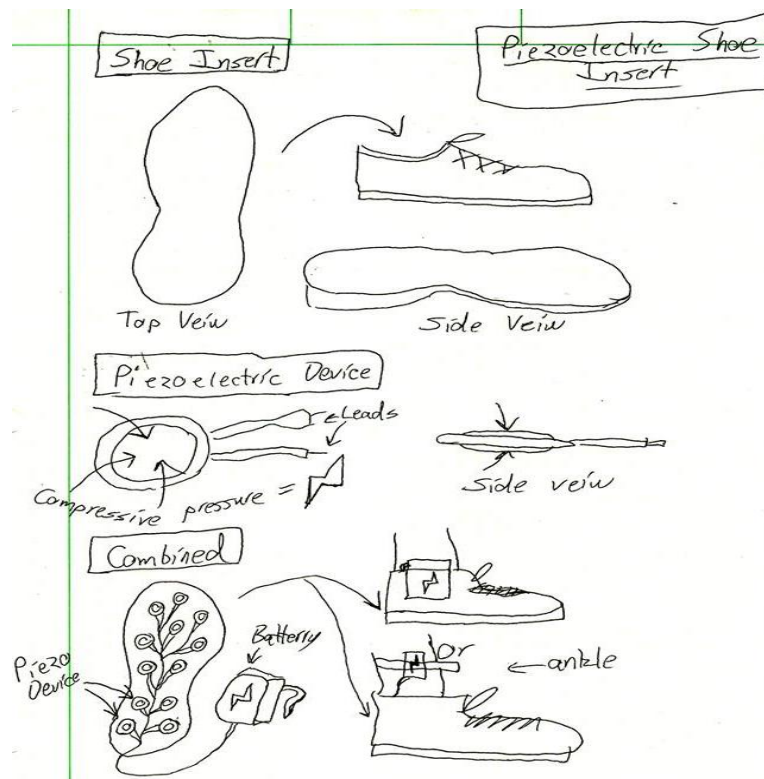


Figure 6. An Idea Incorporating Compression of Piezoelectric Strips

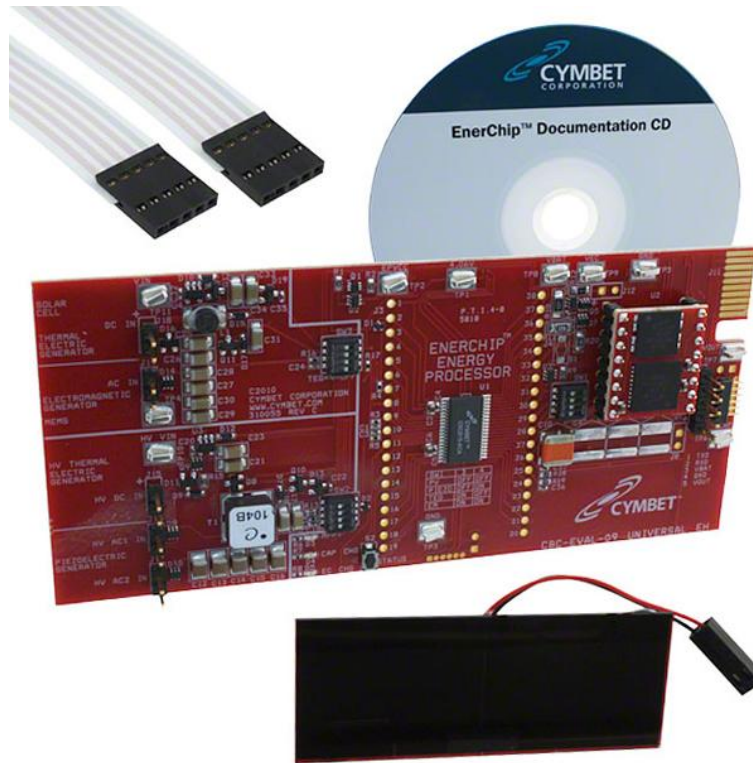


Figure 7. CYMBET Energy-Harvesting Circuit Board

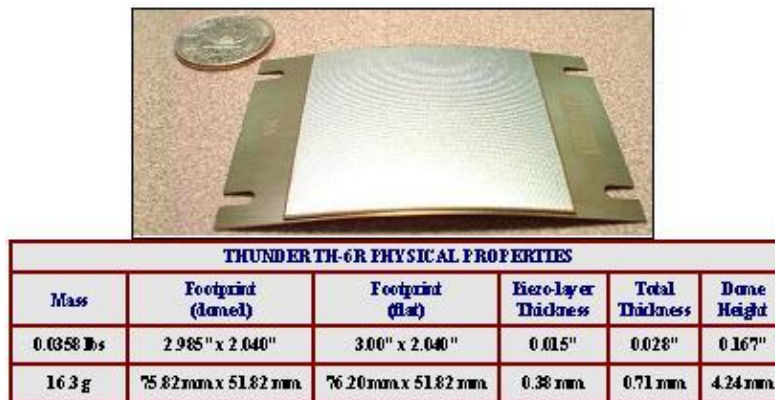


Figure 8. THUNDER TH-6R Piezoelectric Strip

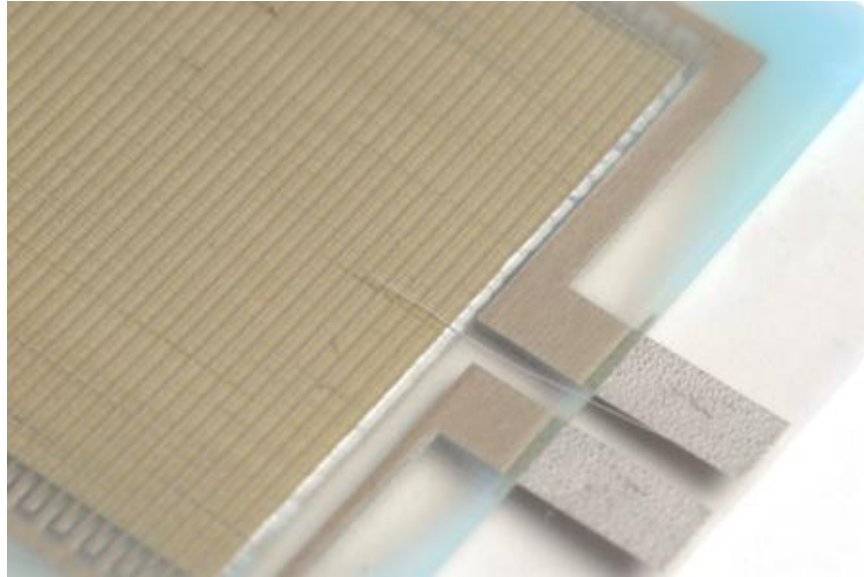


Figure 9. PFC-54W Piezoelectric Fiber Composite From Advanced Cerametrics



Figure 10. Six PFC-W54 Strips with Leads Pre-Attached



Figure 11. Prototype Incorporating a ROTCHO Weatherproof Hiking Boot

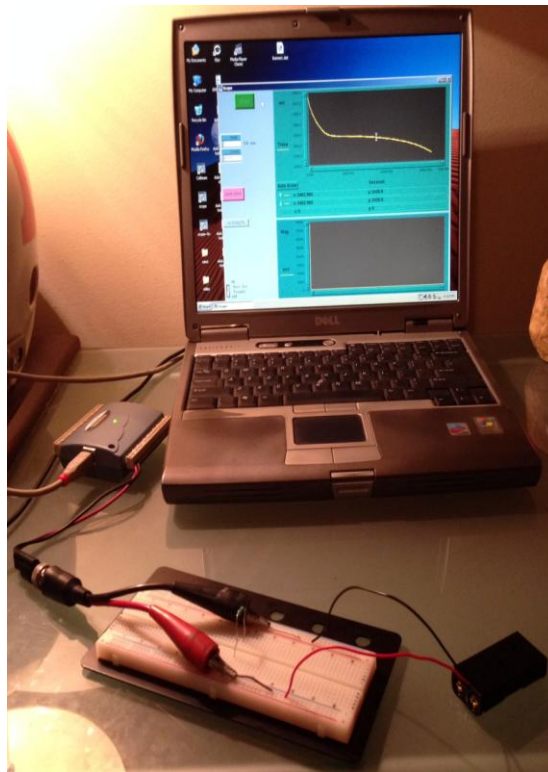


Figure 12. The Discharge Test to Quantify Performance of the Initial Prototype and Final Product



Figure 13. Final Design Incorporating a Running Shoe

List of Tables

Table 1. Functions and Requirements							
Performance Requirements		Non-functional Requirements		Interface Requirements		Constraints	
Requirement	Verification	Requirement	Verification	Requirement	Verification	Requirement	Verification
Battery is fully charged by a person walking 2 miles	Test	System does not cause environmental damage (pollution, etc.)	Inspection	Piezoelectric devices fit inside shoe	Inspection	System fits in a size 10 shoe	Test
Battery can fully charge an iPhone 5	Test	Cord to battery does not trip user	Inspection	Battery is connected to shoe	Test	Battery attachment is light weight	Test
iPhone 5 cord may be plugged into battery attachment for power	Test	Battery attachment is universal for all users and shoes	Inspection			Strips and circuit board are lightweight	Test

Table 2. Walking Test I Results	
Number of Steps	
3005	
Test 1 Energy Added (J)	
120.3141925	
Test 1 Energy Added Per Step (J)	
0.040038001	
Test 1 Capacity Added (W-hr)	
0.037376185	
Test 1 % Charged	
2.771341229	
Hours to Fully Charge	
36.08361142	

Table 3. Walking Test II Results	
Number of Steps	
3175	
Test 1 Energy Added (J)	
157.2697734	
Test 1 Energy Added Per Step (J)	
0.049533787	
Test 1 Capacity Added (W-hr)	
0.04368842	
Test 1 % Charged	
3.622583489	
Hours to Fully Charge	
27.60460879	