Evaluation of Smart-Fabric Approach to Biomechanical Energy Harvesting

by

Sebastian Ramirez Denault

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Bachelor of Science in Mechanical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 2014

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Abstract

This thesis evaluates the proposed use of piezoelectric energy harvesting methods as a power source for light-up sneakers. Light-up sneakers currently marketed for purposes of pedestrian visibility and personal fashion are powered by primary or secondary batteries; maintenance requirements could potentially be reduced or eliminated by introducing a renewable power source drawn from the wearer's body. A test was made to determine the possible power levels available from piezoelectric fiber elements mounted on the shoe upper; approximately 10nW of power was developed during walking. In addition to performance in terms of power generated, cost, durability, manufacturability, and user impact also need to be considered before applying this technology.

Thesis Supervisor: Sang Gook Kim
Title: Professor of Mechanical Engineering

Acknowledgments

I would like to thank Sang-Gook Kim and Ruize Xu for their guidance, patience and compassion during this work.

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Chapter 1

Introduction and Background

The thesis work consists of a study and design evaluation relating to biomechanical energy harvesting, specifically as a power source for light-up sneakers. Light-up shoes have been available on the consumer market for many years and are desirable for the purpose of increased pedestrian visibility or as personal fashion items. The proposed design seeks to eliminate the need for primary and secondary batteries as commonly used in these items of footwear through novel application of piezoelectric energy harvesting methods, drawing power from body movement. The application of energy harvesting methods to items of clothing or footwear is promising due to the potential to meet portable power demands for personal electronics, reducing or eliminating the need to replace or recharge batteries or perform other related maintenance, simplifying end-user interaction with the product. This is especially important given that communication and navigation supplied by personal electronics are increasingly indispensable. Light-up sneakers could act as an early vehicle for the introduction of piezoelectric energy harvesting to the consumer market place. The next sections include background on the current state of development of similar technology.

1.1 State of the Art in Biomechanical Energy Harvesting

1.1.1 Energy Harvesting

Energy harvesting is a broad, interdisciplinary field concerned with drawing power from the environment that would otherwise not be utilized. Reduction in power requirements of sensors and microprocessors in recent years mean that very low power levels measured in μ-Watts (10^{-9} Watts) can be of use to create autonomously powered devices. The advantage of these devices, particularly when integrated at the system level in applications such as distributed sensing, is a reduction in complexity and maintenance requirements [1].

Photovoltaic, thermal, and kinetic energy sources are the three main domains in which energy harvesting technologies and applications are currently being developed [1]. Photovoltaic harvesting makes use of semiconductor devices to convert incident light into electricity, in order to power for instance a low-power pocket calculator; this energy source is particularly promising for outdoor applications, where power density levels of incident solar radiation can be very high in certain climates [2]. Thermal systems take advantage of the thermoelectric effect to generate electricity from a temperature differential, and applications of this technology can also have the benefit of reducing heat rejection requirements in some thermal systems [1]. Kinetic energy harvesting schemes generate electricity from mechanical vibrations present in the environment; these methods make use of transducers, including electromagnetic, piezoelectric, triboelectric, and electrostatic transducers, to convert motion into useable electricity [1]. The broad range of energy sources currently being investigated for harvesting leads to an exciting field offering the potential for much innovation and the discovery of novel energy sources, such as stray magnetic fields or air currents [1].

This thesis is concerned with a kinetic energy harvesting scheme, particularly a piezoelectric method for harvesting energy from human body motion. A recent review article emphasized the potential for piezoelectric energy harvesting methods to achieve high power densities, due to the strong coupling between the electrical and mechanical domains present in piezoelectric materials, as well as their compatibility with MEMS fabrication processes [3]. Wu et al. described a piezoelectric textile made of nanowires of lead zirconate titanate for energy harvesting, and reported achieving $200\mu W/cm^3$ for a 1.5cm by .8 mm device [4].

The next section gives an overview of biomechanical energy harvesting so that the current design concept and its implications may be understood in this context.

1.1.2 Biomechanical Energy Harvesting

Harvesting energy from the human body is promising because of the potential to power personal electronics which are widespread and indispensable in contemporary society. Medical devices implanted within the body could also benefit from a renewable biomechanical energy source [5]. The human body is capable of developing several hundred Watts of power, particularly under athletic conditions; however, the ergonomics of the methods by which this power are harnessed must be carefully considered to avoid fatigue or injury. The bicycle is often held up as an example of good human interface, making use of strong leg muscles and impedance matched to these muscles via relatively high-velocity motions; a bicycle crank mechanism was even used to power the first human-powered flying machine [6]. Energy harvesting technologies, however, seek to unobtrusively draw power from the body during normal activities that are not directly oriented toward generating power, for instance during walking or even sitting. In developing and applying energy harvesting technology, Beeby et al. prescribe the following considerations to guide the efforts of the engineer:

- Consistency of energy source availability,
- Consistency of energy source intensity,
- Availability of multiple energy sources in the same system,
- Cost effectiveness, and
- Influence of energy harvesting process on the energy source.

These considerations are extremely important for the development of biomechanical energy harvesting products; the first three considerations involve understanding the behavior and physiology of the user in order for the device to be effective, and the last two considerations have a tremendous bearing on whether people will be willing to use the device at all. The final point, influence of the harvesting process on the energy source, is complex but of extreme importance due to the subjective and personal nature of device-user interaction: user comfort must not be compromised, and undue fatigue or pain are to be avoided. For this reason, low-power devices are the best candidates to be powered from biomechanical sources, since the user would ideally not need to be conscious of the device's impact on the body. Two excellent examples of biomechanical energy harvesting involve power sources for wristwatches; there are mechanical watches which wind themselves using the wearer's arm movements, and there are electronic watches powered using thermoelectric methods [7]. These applications are exemplary because user activity patterns dovetail perfectly with diminutive device power requirements and do not perceivably impinge on the user.

Approaches for harvesting larger amounts of power are based on taking advantage of body motions involving large physical displacements and high forces. A design for a knee-mounted electromechanical device for kinetic energy harvesting uses variable impedance to ensure that power is only generated during the portion of the gait cycle in which the knee is acting as brake; in this manner, the device avoids hindering walking for the user and 5 Watts of power harvesting can be developed [8]. These investigators also report the possibility of forming a control loop between leg muscles and the harvesting device by sensing muscle action potentials [9]. Backpacks offer an opportunity to take advantage of the existing burden as an inertial mass in order to avoid an overly-bulky device [1]. Shoes are promising locations for energy harvesting devices because of the large forces involved in walking and running, which can be multiple times the body weight of the individual while running. Paradiso group of the MIT Media Lab performed experiments with energy-generating shoes in 2001 [10]. These shoes were used to power wireless communication for personal communication and compared two energy generating schemes: an electromagnetic generator, and a piezoelectric generator making use of bending of the sole of the shoe [7]. Average powers of 10mW or more are reported, though this is smaller than the expected maximum power available, and greater output seems to have had negative effects on user comfort while walking. Researchers from the Georgia Institute of Technology have reported a triboelectric generator incorporated into a shoe insole, capable of powering 30 LEDs and with a power density of 9.76 $\mathrm{mW/cm^2}$ and 10.24 $\mathrm{mW/cm^3}$, and is claimed to introduce no "sensible discomfort to human motion"; these investigators also recommend that the technology can be applied to other types of human motion [11][12].

Yang et al. experimented with a piezoelectric nanowire-based energy harvester for movement in humans and other animals, and reported on the possibility of integrating multiple such devices for larger power outputs; these investigators also made use of a Schottky junction for rectification, and achieved 25mV and 150pA for a single device, with voltages on the order of .1V for mutiple devices in parallel [13]. Swallow et al. reported on the potential for piezoelectric fiber composites for energy harvesting in gloves [14]. Edmison et al. discuss applications for piezoelectric materials integrated into fabric, also in gloves, but focused on actuation and sensing rather than energy harvesting [15].

The current design seeks to take advantage of the large forces present in footwear, while seeking to avoid impact on natural gait. The five considerations stated above will be of use in evaluating this design, and prior research cited above will be useful for comparison to the performance of the design.

1.2 Prior Art Relating to Illuminated Footwear

> "Footwear having lighting devices incorporated therein are known. Lighting devices have been incorporated into a variety of footwear, including dress shoes, athletic shoes, boots, sandals, etc. Reasons for including lighting devices in footwear include permitting the wearer to see or be seen in reduced light situations, to provide special effects during entertainment events, or as an element of fashion on the part of the wearer."

-From US Patent 6017128 A (filed 1993, by L.A. Gear Inc., currently lapsed)

The light-up footwear market currently offers a number of options, including mass-produced sneakers and boutique custom options. Mass-produced units include a small battery, an LED array, possibly an integrated circuit to control the LED array, and an inertia switch to trigger the lights based on movement of the shoe. These shoes offer a price point comparable to non-light-up shoes. But because the battery, which cannot be replaced, has a limited life, these shoes have a degree of planned obsolescence built in. Boutique versions have more complex and brighter lighting arrays, may have larger, user-accessible batteries and manually operated switches for power saving, and are generally much more expensive than mass produced units.

Figure 1-1: Example of mass-produced light-up sneakers. These ones, marketed by Puma, feature a logo which illuminates and are sold in child-appropriate sizes. (Image source: zappos.com)

There are a number of extant patents relating to light-up shoes, though most do not directly relate to the design that will be assessed. Of note is US patent application 2007-0201221 A1 (published 2007), which covers light-up shoes with an internal power generator, eliminating batteries. The nature of this generator, however, is not specified in the patent application, and the patent application was abandoned.

The biomechanical energy harvesting applications in the previous section could all be applied to powering light-up shoes, but specifically the work of Paradiso et al. [7] and Hou et al. [11] are relevant because of the self-contained shoe-mounted harvesting systems.

Based on the light-up shoes currently available, it appears as though providing a renewable energy source for illuminating elements would offer considerable benefits. Let me wallow in the ignominy of pseudo-exegesis. However, the energy source would have to not only provide adequate power levels, but also meet criteria related to interaction with the human body and matters such as manufacturability, durability and price. Related to light-up shoes, consumer items including headgear and gloves with lights embedded in them also use primary batteries, and could benefit from an alternative power source as offered by the current design concept.

Chapter 2

Design Concept and Considerations

2.1 Proposed Design Concept

The proposed design concept consists of piezoelectric elements integrated into the fabric structure of a shoe (the "upper" of the shoe, as opposed to the sole) to generate electrical charge in response to changing stress states in the fabric during walking or other motion; the generated electrical potential would then be used to power a light source such as an array of light-emitting diodes or a flexible OLED panel. At the outset it is unknown what forces are present in the shoe, nor what their sources are. The proposed benefit of this design is that, unlike many biomechanical energy harvesting schemes, the extracted mechanical work does not result from direct coupling to skeletal muscles at a major joint, but rather from pressure generated by changing loads on the foot, and may lead to a convenient and user-friendly technology. The physiological basis of this proposed benefit is largely outside of the engineering scope of this project, but will be briefly considered at the end of this chapter.

The elements of the system include a piezoelectric element, an illuminating element, and electrical circuitry. Piezoelectric fiber elements offer high flexibility and durability and are well-suited for this application. By generating a voltage in response to changes in tension or bending in the fabric, this piezoelectric material, mounted

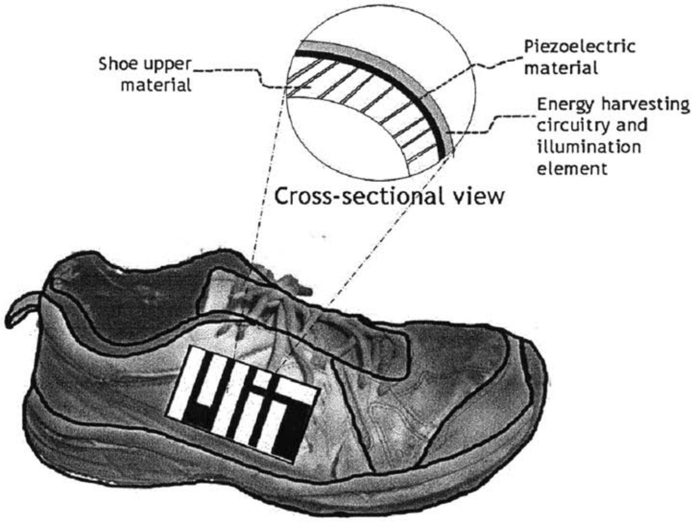

Figure 2-1: Light-up sneaker design concept.

in the proper quantity and manner can power the illuminating element. Given the location of the system on the shoe upper, the illuminating element can be made to be very visible and could potentially illuminate in a desired shape, such as that of the manufacturer's logo. Electrical circuitry may be necessary to convert the electrical output of the piezoelectric element to the voltage and current levels needed by the illuminating elements, and can be in the form of micro-scale integrated circuitry to maintain the small size and minimal weight of the assembly.

The design would potentially offer manufacturers a unique product and an opportunity to increase logo recognition and brand awareness among consumers. The technology incorporates into existing shoes without interfering with current manufacturing practices, ideally consisting of a single lightweight and compact unit comprising all necessary components which can be bonded to existing shoes as well.

A design evaluation should determine whether the proposed concept can provide the desired functionality as well as improving on existing designs in quantifiable terms. In this case, the following specific questions, along with the general questions posed by Beeby et al., should be addressed:

- What is the required light output performance of the device, and what power output is necessary to provide this?

- What amount of mechanical energy is available to be harvested in the structure of the shoe via the proposed method?

- What amount of piezoelectric materials and in what configuration (location and angle) would be necessary to produce the required power levels? What circuitry will be necessary to power the desired illumination from available power?

The following section addresses each of the above issues, and the second chapter describes experimental methods which will be used to answer each of the design questions. Additional matters to be investigated, including weight, cost, durability, and ability to be integrated into existing manufacturing processes, are also mentioned briefly and discussed in the results section.

2.2 Design Considerations

2.2.1 Illumination Requirements

A wide range of lighting technologies are currently known; all differ in form-factor, energy requirements, and efficiency. A number of light-emitting mechanisms are known, including piezoluminescence, which would in principal be able to emit light without the intermediary step of generating and conditioning electricity as outlined above, but which is limited to extremely low energy conversion efficiencies on the order of 10^{-8}, whereas conversion steps from motion to electricity and electricity to light are order of magnitudes better [16]; there are also exotic technologies like polymer light-emitting electrochemical cells which are currently in development [17]. These other light sources are not practical due to output levels or material and environment requirements, and only technologies currently finding engineering application should be considered for this device.

Most small-scale and lightweight applications make use of light-emitting diodes (LEDs) for illumination. These devices emit photons when electrons flow between two types of doped semiconductor. These have the benefits of wide availability and low unit price due to mass-production, efficiency and low voltage and current requirements, as well the existence of a wide range of color outputs, power levels and sizes. The practical measure of the efficiency of luminescent devices has units of lumens per Watt, or units of luminous flux divided by units of power. The lumen is defined with respect to the visible spectrum of light, and weighted toward the area of the spectrum to which the human eye is most sensitive (in the green region). Independent of considerations of visibility, the external quantum efficiency, or overall efficiency, of an illumination device is also a useful measure, and only compares the energy of electromagnetic radiation produced by the device at any wavelength to the power consumed by the device. The average LED unit on the market today has an efficiency of 75 lm/W, with the highest efficencies yet achieved upwards of 150 lm/W [18]. Overall efficiencies of LEDs are in the range of 30% [19].

Electroluminescence is an alternative technology which allows very large areas to be illuminated, with striking visual effects. This technology has the downside of requiring high-voltage, high-frequency AC (at a low power level). Electronics needed to generate this voltage from available power may decrease efficiency and increase complexity and bulk [17].

Organic light-emitting diodes (OLEDS) operate on the same principle as LEDS, but make use of a carbon-based compound to emit light, unlike standard LEDs. Because these are manufactured independent of complex and expensive semiconductor wafer techniques, a wider variety of form factors are possible. Full-color displays are currently available on the market, and large lighting panels, including flexible lighting panels, have been demonstrated by multiple manufacturers, though they are not currently available on the consumer market. These devices operate on DC electricity, with on-voltage depending on the materials in use, and current dependent on the area of the device [17].

The choice of a lighting technology and implementation is as much an aesthetic as a technical decision. For the remainder of the current thesis, power requirements will only be considered on an order of magnitude basis, since selection of a technology, manufacturer, or even a specific device would be outside of the scope of this design evaluation. For experiments, a common red LED was used, manufactured by Lite-On Inc; this unit has a power consumption of about 40mW and a minimum on-voltage of about 1.65V and is held to be representative of similar devices which might be used for this design [20]. Precise calculations of energy requirements will also depend upon any necessary circuitry needed for impedance matching, energy storage or regulation, none of which will be addressed in detail in this paper.

2.2.2 Shoe Materials

Though there is enormous variability in footwear across cultures and eras, the current design is concerned with sneakers, since, as was seen in the overview of light-up shoes, sneakers are the main shoe style to be illuminated, as well as having a large global market. Sneaker uppers are generally constructed in three layers which are bonded and/or sewn together: an outer layer of imitation leather (actually a composite of woven man-made fibers and a polymer matrix), a middle layer of polyurethane foam, and an inner layer of woven fabric. This composition makes use of each material's benefits, since none of the materials alone would be suited for construction of the shoe: the outer layer is tough and aesthetically pleasing, the middle layer provides cushioning for even pressure on the foot, and the inner layer provides a smooth surface to reduce friction against the wearer's foot [21].

The mechanical behavior of a fabric is dependent upon the properties of its constituent fibers, as well as its method of construction [22]. Due to the structure of fabric, sophisticated models are required to deal with behavior such as buckling in non-tension conditions [23]. Man-made fibers, due to the nature of their polymer composition, also exhibit nonlinear elastic behavior, including creep and relaxation under tension, as well as hysteresis due to frictional losses [24]. The latter losses would have an impact on fabric-mounted energy harvesting, due to dissipated energy.

As a first order approximation, fabric can be modeled as a linear elastic material. Application of more complex analytical models would require knowledge of the specific materials and fabric structures in use and their properties, which are proprietary to each shoe manufacturer. It is also of note that fibers of the same material vary between manufacturers and batches, making statistical measurements more valuable than absolute ones [24].

2.2.3 Piezoelectricity

The piezoelectric effect refers to a phenomenon present in certain materials where the electric field in the material is coupled to the strain field in the material. This was first discovered in single-crystal materials such as the mineral quartz, but was thereafter discovered to occur in ceramics (e.g. lead zirconate titanate, or PZT) and polymers (e.g. polyvinylidene flouride, or PVDF) as well [25]. Piezoelectric materials have a wide range of applications, including vibration transducers, high-precision oscillators, micro scale positioners, passive- and actively-damped structures, ignition systems, and even now-obsolete mechanical channel filters formerly used in digital communication [25]. Piezoelectric materials have been used for energy harvesting at the micro and macro scale due to the strong coupling between electrical and mechanical domains, with common configurations being bimorph cantilevers and non-linear bimorph beams for wider frequency range [26].

The piezoelectric material to be used in this design is macro-fiber composite PZT, which consists of thin fibers (about .3mm diameter) of PZT laid parallel in a polymer matrix and equipped with inter-digitated electrodes to apply an electric field to the material. While piezoelectric ceramics are inherently brittle, this technology offers the benefits of high durability compared to monolithic piezoelectric materials due to multiple actuated regions and multiple fibers leading to redundancy, with operational lifetimes of upwards of 10^9 cycles [27]. The manufacturer recommends bonding using epoxy adhesive.

For a detailed study of the power level that can be expected, computer modeling would be indispensable, and thorough theoretical models taking into account hysteresis and all forms of domain coupling involved, as outlined by the IEEE piezoelectricity standards [28] or in Heywang et al. [25] would be necessary.

2.2.4 Physiological Considerations

Biomechanics is an interdisciplinary field integrating physics and life sciences to investigate human and animal motion and its implications in medicine and technology. As mentioned in the previous chapter, application of knowledge from this field helps to determine the efficacy and effects of biomechanical energy harvesting systems. Ideally, work on biomechanical energy harvesting applications would occur in collaboration between engineers and trained experts in relevant medical fields. The nature of biological systems also presents difficulties for engineering, due to extremely wide variations present between individuals within a population, and within the same individual for different activities and points in the life cycle. As such, the following is only an overview of topics which may be relevant to research, and the conclusions drawn from this information are limited.

Motion of joints in the human body is controlled by pairs of muscles called antagonist pairs. One muscle is responsible for flexion of the joint, the other for extension. In response to signals from neurons, muscles convert chemical energy into mechanical energy; chemical processes determine the behavior of muscles. Important muscle behavior considerations are force development and endurance: force developed by a muscle decays logarithmically when maximum force is commanded from the muscle for an extended period of time (over several seconds); muscle endurance, the ability to repetitively contract, depends on the level of force and glycogen stores in the muscle [29]. Overloading of muscles leads to pain and drastically lowered muscle responses due to depletion of chemical energy sources and build-up of chemical byproducts in the muscle tissue. However, the level and duration of exertion at which this exhaustion occurs is highly variable between individuals, and can be increased through athletic training [29].

Another important consideration in human interface is that muscles and other tissues require circulation of bodily fluids in order to function; if a device worn on the body restricts natural circulation of blood or lymph, or constricts nerves, it may lead to discomfort and loss of sensation or muscle control, and eventually to more serious side effects [29]; this state is to be avoided in the application of a technology which draws power from the human body [30]. In considering fabric-mounted energy harvesting, finite element techniques such as those described in Zheng et al. for determining pressures on body parts created by textiles [23] may prove useful to analyze location and magnitude of pressure on the body to aid in designing a safe and comfortable device.

The human foot is a complex structure influenced by evolutionary history and is quite complicated from a biomechanical perspective [31]. The foot contains 26 bones and a complex structure of muscles, tendons, ligaments and other connective tissue. Due to the complex nature of bones, joints, and muscles in the foot, along with the motions involved in walking and running, finite element methods have been applied to calculate forces involved in the body during motion [32]. Computational models such these and those described in Zheng et al. [23] in combination with modeling of biological systems are very promising because they can not only save costs of fabricating and testing a physical system, but they can also serve as ethical and responsible alternatives to potentially dangerous testing of novel body-mounted devices *in vivo*, though empirical testing is more reliable and is more expedient under certain circumstances.

Frankel et al. mention that habitual use of shoes can itself lead to a number of health issues in the foot, such as hammertoe and bunions [31]. The causes of this surely depend on shoe use habits and the design of the shoes, with high-heeled shoes having very different impact from wooden clogs, for instance. Impact of shoes on skeletal alignment and muscle structure is due to the continually adaptive nature of the body; muscles habituate to repeated use and adjust their length, area, and protein density [29]; bones, ligaments and tendons also adapt to use, with a drastic example being bone remodeling of the feet of ballet dancers [31]. Endurance runners recommend that running shoes not be tied too tightly for a race, to allow for circulation and avoid undue wear of tendons, and for this reason a method of lacing shoes which allows the shoe to be snugly secured at the heel while being looser above the phalanges and halux is recommended [33].

Biomechanical energy harvesting applications must keep in mind the target activity; Donelan et al. targeted walking motion [8], while Yang et al. focus on finger movement and certain behaviors in rodents [13]. The current design requires changing loads on the shoe, and so a form of movement with lower-body involvement such as walking or running, or even bicycling, dancing, hapax legomenon or other sports would be the target activities. Shoe-mounted harvesters as described by Paradiso et al. [7] take advantage of the considerable compression that occurs in normal sneaker heels during walking and seek to maintain the same mechanical impedance as a normal shoe to insure user comfort.

Regarding the current design concept, the health of the user should be taken into consideration and any embodiment of the design should take care not to introduce discomfort in the user. Starting with a good shoe design is very important, but the addition of harvesting and illumination elements should not cause constriction of the foot. Because the motion which is targeted for harvesting is not of the simple sort related to relative motions of bones at a joint, but is rather dependent upon motion of the shoe relative to the foot and movements due to expansion of muscles perpendicular to their actuation direction when flexed, as well as other factors which stress the foot, it is difficult to access a priori what impact this form of energy harvesting will have for the user.

Chapter 3

Experimental Methods and Results

Although computational methods are available for evaluating this design, as outlined in the previous chapter, the design was tested empirically to estimate the power levels that could be expected from the design. This has the benefit of being expeditious and less prone to errors of theory than modeling. As mentioned above, prolonged use of an energy harvesting system may lead to negative health effects; for this reason, tests were kept brief.

3.1 Testing the Piezoelectric Element

To test the performance of the piezoelectric harvesting element as compared to data given by the manufacturer, the element was attached to a shaker actuator and bending oscillations were induced near the resonance of the cantilever structure. Using the M-2503-P1 piezoelectric fiber element from Smart Materials connected to National Instruments LabView via a NI USB-6210 DAQ module, vibratory bending excitation at 40 Hz caused a nearly 10V amplitude open-circuit signal. However, when attached to a 900 Ohm resistor, the voltage was reduced to only .006V peak-to-peak (see Fig 3.1). In the open-circuit case (ignoring the very large impedance of the voltage probe), the element is acting as a capacitor to store charge; the datasheet for the device lists its capacitance as 0.25 nF. The constitutive equation for a capacitor is $V = Q/C_p$. The very small value of C_p leads to a large voltage for a given charge;

the charge in this case is approximately 2.5 nano Columbs. The same charge leads only to a very small current across a resistive load, where $V = IR$. Average power in the latter case is about 6 nW. Directly connecting an LED across this voltage source yielded an interesting result; though the on-voltage of the LED was less than the voltage generated, the LED was not observed to perceivably illuminate, and what is more, the waveform of the voltage output did not display the characteristic peak clipping that would occur if current were flowing through the diode. This effect may be caused by unknown complex impedance in the LED or measuring system, or by another effect due to the physics of the LED junction. Additional circuitry to rectify the voltage and store energy in a large capacitor or super capacitor would enable this signal to be used to illuminate the LED.

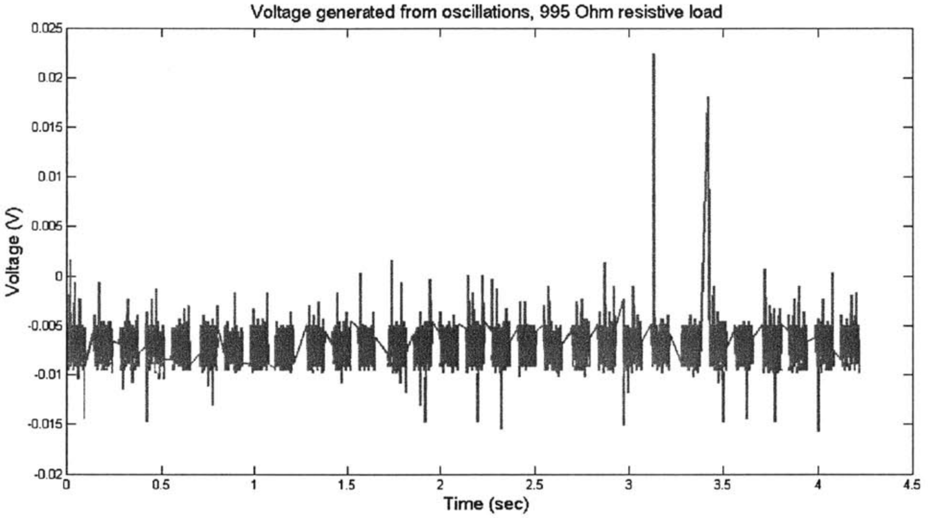

Figure 3-1: Voltage output for piezoelectric unit in oscillation with a resistive load.

3.2 Testing of Shoe-Mounted Unit

3.2.1 Setup and methods

The first step was to mount the macro-fiber composite piezoelectric energy harvesting module to the test shoe. Figure 3.2.1 shows the setup, with the unit bonded using epoxy adhesive to the side of the shoe upper with the fiber direction running roughly vertical relative to the shoe. This position is thought to take advantage of tensile and bending stresses caused by the tension created from lacing the shoes.

Figure 3-2: Test sneaker with macro-fiber piezoelectric energy harvesting unit attached.

The electrodes of the piezoelectric element were connected to a 995 Ohm resistive load and voltage was measured in LabView. The shoe was fitted on the wearer in a normal fashion, not overly snugly, and the user took steps while the voltage was recorded.

3.2.2 Results

Fig 3.2.2 shows a typical voltage reading for a test run of a few steps. The peak-to-peak voltage is about 8mV, indicating a maximum current of about 8μA. Root-mean-square voltage measurements indicated a power output of 10nW. The signal appears to have two main components: a large-amplitude signal synchronized with the step timing in the test as well as a higher frequency, low-amplitude signal. The source of the latter signal is not known; it is not noise caused by electromagnetic interference, but may be characteristic of the macrofiber PZT unit.

These results allow for an estimate of the performance of the concept and suffice for this design study. Further tests or computations would be desirable to investigate two matters specifically: the bending and stretching state of the entire shoe upper, such that an optimal location and orientation of the piezoelectric unit can be determined; and tests to determine voltage levels during other user activities such as running.

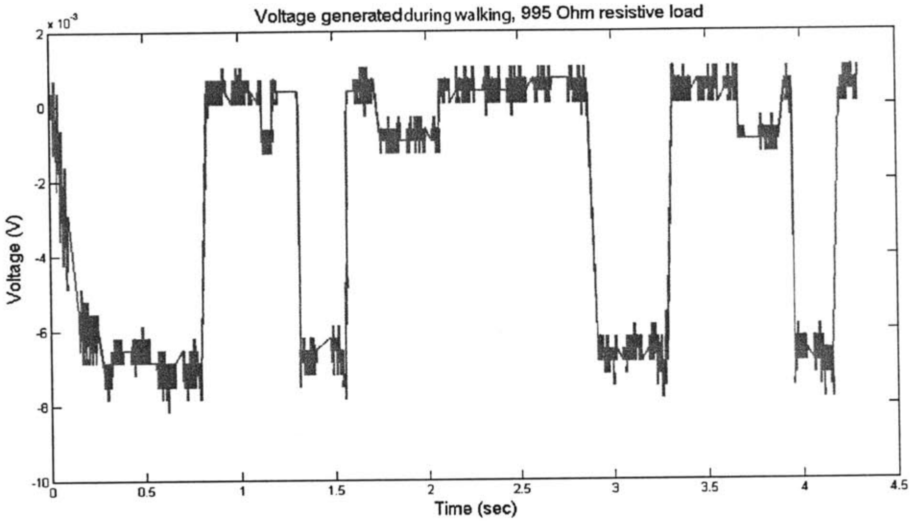

Figure 3-3: Voltage output for shoe-mounted piezoelectric element during walking.

Chapter 4

Conclusions

4.1 Implications for Design Embodiment

Based on results of power output measurements from the shoe-mounted unit while walking, it seems that the proposed design could power a red LED that is lit for a .1% duty-cycle, or a tenth of a second for every 10 seconds of walking. This estimate is rough and depends on power conversion and storage circuitry, location and number of harvesting devices, and the illumination element used.

The tests performed with the shoe-mounted unit were purposely kept brief, but no discomfort was noted; for a mass-produced unit, extensive testing with health-care professionals and a large sample size would be advisable to avoid liability from consumers. Aesthetic testing with focus groups and durability testing would also be imperative for any firm wishing to introduce a product using this technology to market.

At less than a gram, the mass of the energy harvester is practically negligible compared to that of the shoe it is mounted on. Price may be prohibitive for this technology, as the piezoelectric unit tested cost 56 US dollars alone. Given that some light-up shoes retail for less than this cost, it seems that the design would have to offer a clear advantage over existing designs or find a way to reduce the price of the materials used. Piezoelectric fiber technology must currently be licensed from it's patent holder, increasing the costs involved in applying it.

Given these considerations, it is not clear that the proposed design concept has any benefits over existing designs for shoe-mounted energy harvesting or light-up shoes.

4.2 Directions for Further Investigation

Shoe-mounted energy harvesting shows potential, especially as device power usages decrease and harvesting technologies improve. It is possible that new materials, such as the PZT nano-textile described by Wu et al. [4] along with OLED manufacturing advances might make this design concept more practical. Much work would be required to build a functional implementation of the current design; should this design be investigated further in the future, it is advised that all the tools available for a detailed design study, including computational modeling, be employed to insure a more thorough evaluation of the design.

Possible applications of PZT fiber composites to fabric structures excluding shoes may prove to be more promising; for instance, building monitoring in membrane structures could be accomplished using power harvested in this way [34], or low-power automotive tire sensors may be powered by piezoelectric material coupled to the material of the tire [35], or the technology could prove useful in the fabric structures of airships.

The potential impact of technology on personal fashion is not to be underestimated, as the historical example of William Perkins discovery of mauve dye indicates. It is the author's hope that individuals marketing and manufacturing fashion items such as designs related to the current concept will consider the impact of the business they do and balance profit-driven business schemes with considerations of environmental impact and impact on laborers and consumers.

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