Unobtrusive Energy Scavenging Using Shoe-Mounted Piezoelectrics and Simple Power-Conditioning Electronics

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ABSTRACT

As the size and power requirements of wearable microelectronics decrease and such devices become more ubiquitous, it is increasingly feasible to replace batteries with embedded systems that harness electric energy from the user's environment. Accordingly, this paper highlights the systems developed by the MIT Media Laboratory to scavenge electric energy from the forces exerted on a shoe during walking. It presents devices we have built which harness sole-bending energy using a flexible piezoelectric foil stave and heel-strike energy using reinforced PZT unimorphs and bimorphs. As an application example, a self-contained, wireless RFID transmitter is described, powered from a shoe-mounted piezoelectric source, bucket capacitor and series regulator. We also discuss recent research focused on developing more efficient power conditioning electronics using high-frequency switching techniques. We conclude with a roadmap for future developments and applications of scavenged shoe power.

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1) Introduction - Why Shoe Power?

Consumer reliance upon body-worn electronic devices has risen significantly throughout the past decade, and dichotic consumer demands for decreased size and enhanced capabilities underscore a need for new ways to supply electric energy to these devices. Traditionally, chemical cell batteries have been sufficient; but, replacing them is a costly nuisance, and this solution will become increasingly less practical as demands evolve. An alternate approach is to utilize a centralized, body-worn power pack with multiple distribution lines. Similarly, such a system would be cumbersome and impractical, as body-worn devices become more ubiquitous.

Admittedly, the previous discussion may seem moot to some readers as batteries serve current energy demands adequately. If consumer and technological trends continue, however, they may prove to be an insufficient or undesirable solution to meet the future energy demands of a more "wired" society. Fortunately, as the power requirements drop for many body-worn devices, a third approach emerges that eliminates the distribution problem altogether -- develop and store electric energy near the load by scavenging waste energy from a range of human activities. For example, the average person spends a significant percentage of his or her day on foot, dissipating an abundance of energy into the insole of a shoe. If this wasted energy were harnessed unobtrusively it could be used in a variety of low-power applications. Pagers, health monitors, self-powered emergency receivers, radio frequency identification (RFID) tags, and emergency beacons or locators are a few examples of suitable low-power systems; conversely, one could trickle charge a battery at the shoe that could be used elsewhere.

Previous studies at the Media Laboratory have explored the feasibility of harnessing waste energy from a variety of body "sources." One benchmark conceptual investigation[1] conducted by Thad Starner in 1995 analyzed various human activities and asserted that the heel strike during walking is the most plentiful and readily tapped source of waste energy. It estimated that 67 Watts of power are available in the heel movement of an average (68 kg) human walking at a brisk pace (two steps per second with the foot moving 5 cm vertically). Admittedly, it would be impossible to scavenge all of that energy unobtrusively, but even a small percentage of it (up to a good fraction of a Watt[2]), removed imperceptibly, would provide enough power to operate many of the body-worn systems on the market today. A second Media Laboratory study[3] amplified this conclusion and suggested a system of embedded piezoelectric materials and miniature control electronics. It observed that a shoe or boot, because of the relatively large volume of space available in the sole and heel platform, would make an ideal test bed for the concept of body energy harvesting.

In the years since these studies were published, the Media Laboratory has further explored parasitic power harvesting in shoes. In particular, we have implemented a demonstration of shoe power at work and developed new means by which to efficiently condition raw, low-frequency piezoelectric shoe signals into a continuous, reliable energy source. This paper traces that evolution and suggests possibilities for future developments and applications of piezoelectric energy harvesting in shoes.

2) Two Approaches to Piezoelectric Shoe Power

The piezoelectric effect – a material's capacity to convert mechanical energy into electrical energy, and the inverse – is observable in a wide array of crystalline substances which have asymmetric unit cells. When an external force mechanically strains a piezoelectric element, these polarized unit cells are shifted and aligned in a regular pattern within the crystal lattice. The discrete dipole effects accumulate, resulting in an electrostatic potential developed between opposing faces of the element[4]. Relationships between the force applied and the subsequent response of a piezoelectric element depend upon three factors: 1) the dimensions and geometry of the structure, 2) the piezoelectric properties of the material, and 3) the vector of mechanical or electrical excitation.

To designate direction within a piezoelectric element, a three-dimensional, orthogonal modal space is defined, as illustrated in Fig. 1. The various electromechanical *modes* of operation identify the axes of electrical and mechanical excitation – the electrical input/output occurs normal to the *i*'th axis, and its mechanical counterpart occurs normal to the *j*'th axis. Further, the induced electric field is normal to a predefined *poling vector* "**p**" that is established by applying a high-potential electric field through the material during the manufacturing process[5]. For example, 31-mode operation signifies transverse mechanical strain normal to the 1-axis, inducing an electric field in the direction of **p** along the 3-axis – this action is equivalent to pulling a ruler on both ends and thereby developing a potential difference between the ruled faces. Piezoelectric materials can be fabricated from crystals, ceramics, or flexible foils. In addition to applications as a sensor or input device (such as this one), piezoelectric materials can be driven with a voltage to produce mechanical deflection, leading to a wide range of output device applications (e.g., [6]).

Because the dimensions of the insole limit the size and shape of materials that can be integrated into footwear without loss of comfort or a radical change in design, a thin, flat, piezoelectric element is the natural choice for integration. Commonly, an element of this shape is excited in 31-mode operation by flexing the plate about its neutral axis, inducing compression or extension of the material at the faces. Although intuitively attractive, bulk compression under the weight of the bearer (33-mode excitation) is not practical because of the typical material and electromechanical properties of rigid piezoelectrics and the limited forces exerted by a human while walking. Other excitation modes are equally impractical under these constraints. The 31-mode of operation is therefore considered most appropriate for harnessing waste energy in a shoe, and there are two principle means explored herein by which shoe power is piezoelectrically scavenged in bending 31-mode operation. One method is to tap the changing curvature along the ball of the boot using a flexible, multilaminar polyvinylidene fluoride (PVDF) stave mounted under the insole. The second is to harness foot strike energy by flattening a curved, pre-stressed sheet or button under the heel. (See Figure 2.)

To harness the energy dissipated through bending in the ball of the foot, an elongated, hexagonal multilaminate of piezoelectric foil was developed. The flexible stave[7], designed in collaboration with Kyung Park and Minoru Toda of the Sensor Products Division of Measurement Specialties (formerly AMP Sensors)[8], is constructed of two 8-layer stacks of 28 mm PVDF sandwiching a 2 mm flexible plastic substrate bonded with epoxy. The hexagon design was selected to conform to the shape and bending distribution of a typical shoe insole (see Figure 3). When the stave is bent, the outside surface is elongated and the inside surface compressed with respect to its plastic core. Because the PVDF sheets on either side of this core are polled in opposing directions and the silver electrodes on each sheet are connected in parallel, the discrete charge accumulations of the sixteen layers add constructively. A voltage is therefore developed across the two leads, supported by the net 330 nF capacitance of the multilaminate structure. It is important to note that *restoring* the shape of the stave, as well as bending it, will liberate energy if the resulting charge is removed at each relative minimum and maximum in the step cycle.

The second device (shown in Figure 4) exploits the abundant energy exerted in the heel strike. Although our first model was a simple unimorph[9], a rigid bimorph was constructed[10] in cooperation with the C. S. Draper Laboratory, from two commercially-available PZT transducers, a heel-shaped .025 inch beryllium-copper backplate, and two aluminum rivets. The insert is designed to fit snuggly and unobtrusively within a hollowed orthopedic insole, and its volume and compressive flexibility closely match the material that is removed to accommodate it. The two THUNDER™ TH-6R transducers used are manufactured by Face International Corporation[11] based upon a piezoceramic manufacturing process developed by NASA Langley in conjunction with the RAINBOW (Reduced and Internally Biased Oxide Wafer) design effort[12]. The transducers, consisting of a 5x5 cm, .015 inch PZT strip bonded to a pre-stressed, neutrally-curved, 5x8.5 cm sheet of spring steel, were trimmed to fit the dimensions of the BeCu backplate, mounted under the heel-strike force center with two rivets, and connected in electrical parallel. Similar to the PVDF stave, charge develops across the faces of the PZT strips when the bimorph is compressed or released, hence a voltage appears, supported by the net 143 nF capacitance of the source.

2.1) Performance

To evaluate and compare the output of the two shoe generators presented here, both were installed in a pair of shoes and tested. The PVDF stave was installed under the insole of a standard NIKE athletic sneaker, and the PZT bimorph was integrated into an orthopedic insole and placed into a U. S. Navy workboot. The test platforms match well to the particular generator tested within them – the flexible stave prefers a flexible plantar region, and the rigid bimorph responds best in a rigid heel cup. Neither of the devices affected the gait of the bearer and was only barely perceivable during normal human activity. To determine the approximate raw power and electromechanical efficiency of each, the transducers were terminated with matched resistive loads and their voltage measured during a brisk walk. The resulting plots are displayed in Figures 5 and 6.

In the PVDF stave, the average power into a 250 kΩ load at .91 Hz walking pace was found to be 1.1 mW. Conversely, the PZT bimorph produced on average 8.4 mW in a 500 kΩ load under the same excitation. The characteristics of the footfalls are evident in these plots. The larger power spikes correspond to the rapid initial bending or compression of the device, and the smaller spikes that follow represent transducer restoration when the bearer more slowly shifts his weight to the opposite foot. Both sources therefore alternate polarity with respect to the source ground twice between each step, yielding two distinct current pulses per step cycle. Source rectification is required.

Finally, by comparing the open-circuit voltage across the known static capacitance of each device under a constant test force, the raw electromechanical efficiencies were determined as approximately .5% for the PVDF stave and 20% for the PZT bimorph. Further, at low frequencies the equivalent circuit for both transducers is essentially the static capacitance of the device in parallel with a large resistance for modeling dielectric leakage[13]. This implies that the test force must be applied quickly and the source voltage read immediately to minimize the deleterious effects of leakage on an accurate approximation of available energy.

2.2) A Shoe-Powered RF Tag System

To demonstrate the feasibility and utility of scavenged shoe power, a simple application circuit was developed[9]. The design is a self-powered, active RF tag that transmits a short-range, 12-bit wireless ID code while the bearer walks. This type of system has immediate application in a "smart environment" where multiple users transmit their identity to the local surroundings, enabling dynamic, centralized, near real-time decisions to be made to personalize the environment or route appropriate information to mobile users. Most previous work in this area has relied upon battery-powered IR badges[14]. This RF-based design, however, requires no line-of-sight to the reader and may therefore be mounted in the shoe where it operates without a battery, under the power a piezoelectric insert. The schematic is included at Figure 7.

This design utilizes the scavenged energy from either source to encode and transmit a periodic, ASK-modulated RFID signal. The transmission is received by a local base station that emits an audible chirp upon identifying the transmitter. The signal from the piezoelectric source is full-wave rectified through the 500mA diode bridge *D1*. As the source signal ramps up, charge is transferred to an electrolytic "bucket capacitor" *C1* whenever the source voltage overcomes the voltage already supported by this capacitor (plus two diode drops). As *C1* charges beyond 12.6 Volts -- the *Z1* breakdown voltage plus the diode drop across the base-emitter junction of *Q1* -- *Q1* is forced into conduction, in-turn activating *Q2* and latching *Q1*. With *Q1* on, the high side of *C1* now has a current return path to ground and discharges through the Maxim MAX666 LDO linear regulator *U1*.

The regulator is biased to provide a stable +5 Volts to the serial ID encoder (*U2*) and RF transmitter (*U3*), as long as *C1* remains above +5 Volts (plus the regulator drop out voltage). When the voltage across *C1* reaches approximately 4.5

Volts, the low-battery in pin (LBin on *U1*) is pulled below its threshold, driving the low-battery out pin (LBout) to ground momentarily. This negative pulse though *C3* turns *Q1* off, thus deactivating *Q2* and renewing the *C1* charging cycle. Note that *R1*, *R2* and *R3* serve to bias *Q1* and *Q2* and to show *C1* a very high load impedance when the Q1-Q2 latch is deactivated. Finally, *R4* and *C2* were included to better match the source impedance to the load stage when active, and the remaining resistors support the load stage components in other ways. Figure 8 is a representative graph of signals from the power conditioning circuitry. The upper trace shows the voltage across *C1* (in this case, 47 µF), and the lower trace shows the output of the MAX666 linear regulator. Charge is accumulated on the bucket capacitor until enough energy is stored to power the transmitter for roughly a half-second, generally after 3-5 steps with the current system. Substituting a high-frequency switching regulator for the MAX 666 would further improve the efficiency of this circuit; this line of inquiry led to the results summarized in the following section. Figure 9 shows a functional prototype pair of self-powered RFID sneakers.

3) Exploring High-Frequency Switching Conversion

Though sublime in its novelty, simplicity and low quiescent power requirement, the power conditioning electronics described above are inherently inefficient. Low-frequency piezoelectric sources are essentially purely capacitive and produce high-voltage, low-energy, low duty-cycle current pulses at approximately one cycle per second. This excitation profile results in an extremely high source impedance, with voltage signals into the hundreds of Volts and currents on order 10^{-7} Amps. A linear regulation scheme is therefore not well-suited to the electrical characteristics of a piezoelectric element excited by a brisk walk. For that reason, our most recent research was devoted to finding a more efficient means of converting the raw electric energy produced by the transducers into a useful form. A variety of switching conversion schemes, including switched capacitor converters and direct DC-DC down converters, were explored. In the end, an off-line, forward switching converter was developed, consisting of a small number of inexpensive and readily available components and materials.

A suitable low-frequency equivalent circuit model for a piezoelectric source is a capacitor in parallel with a resistor to model the dielectric leakage and a charge source dependent upon mechanical displacement to model the energy transduction[13]. Because excitation occurs at such a low frequency and because it is desirable to provide a stable, low-ripple output voltage, the power conditioning system must perform low-pass filtering with an extremely low corner frequency. With that goal in mind, the most efficient approach would be to discharge the source through a diode and a matched inductor into the bucket capacitor, ringing the circuit with each step. This technique is often used in ac charging circuits for capacitors in flash photography systems[15]. At an average one Hertz walking pace and a source capacitance measuring 140 nF, however, resonant shunting requires an inductance on the order of 10^5 *H*. Certainly, such a value is not practical, especially if one expects the device to fit in a shoe.

Switching converters are the natural alternative to resonant shunting because they offer two distinct advantages over linear systems. Primarily, because they are truly *power converters* and not voltage regulators, switching converters are much more efficient when the difference between input and output voltages is large. Secondly, they can be thought of as impedance converters, as the average DC output current can be larger than the average DC inputcurrent[16]. Further, the forward converter topology was selected because the step-down transformation shows a high reflected impedance to the piezoelectric source when the switch is closed, reduces switch stresses when the difference between input and output voltages is quite large, and allows the simplest gate drive circuitry[16] .

The characteristics of and boundary conditions upon the piezoelectric power system presented herein are much different than in normal switching converter applications. Therefore, using commercially available control ICs is inappropriate, and much of the theory and practice common to switcher implementation does not apply. Specifically, the following points bear particular weight in the converter topology selection and design[17]:

- Because a low-frequency piezoelectric source is essentially a capacitor and a parallel charge source, and $E_c = {}^1/_2 CV^2$ describes the energy stored on a capacitor, it is advantageous to allow the source voltage to peak before removing the energy.
- The charge liberated per cycle is relatively constant under the same peak loading force, regardless of frequency.
- Output ripple is dominated by the low excitation frequency of walking, and a large output capacitance (>100 mF) is therefore necessary to keep voltage ripple within acceptable limits.
- Duty cycle control is not an issue – switching is implemented simply to provide current gain.
- The average source current is very small (~ 100 nA), so semiconductor switches were selected to minimize gate charge, not the drain to source ON resistance.

- The switching frequency was chosen to minimize system energy loss, specifically in the transformer, switch control and gate drive.
- The control circuitry must bootstrap itself from a cold start-up.

3.1) Forward Converter Design and Operation

A block diagram of the final power conditioning system follows in Figure 10. It is important to note that this system has *two* ground busses – one referenced to the bimorph source, the second referenced to the load. These ground references will be referred to as "source ground" (SGND) and "load ground" (LGND) respectively. The two busses are joined by an n-channel MOSFET *Mg* whose source is connected to SGND and whose drain is connected to LGND. Because the bucket capacitor *Cb* is sufficiently discharged and *Z2* is not conducting at start-up, the gate of *Mg* is pulled to SGND by the *R3*. This configuration assures that SGND and LGND are not referenced to each other at start-up; they will not become so until *Q1* goes into conduction. This latching circuit is identical to the one used in the previous design of Figure 7; it is recycled here for bootstrapping.

The source signal is first full-wave rectified by a diode bridge (*D1 – D4*). Because LGND is not referenced to the source and *Q1* is OFF at start-up, the only current path available to the rectified source signal is through the feed-forward loop and into *Cb*. Diodes *Df1*, *D5*, *D6*, *Ds1* and *Ds2* prevent *Cb* from discharging back through the transformer *T1* as it charges. To ensure *Mf1* is ON at start-up, *Df2* and *Cff* are placed in series on a second feed forward branch to couple charge onto its gate. Further, *Mf2*'s gate shares the same node as the gate on *Mg (i.e.,* they share the same conduction state), so *Mf2* is OFF at start-up and charge accumulates on *Mf1,* holding it ON. It is important to note that both *Mf1* and *Mf2* must be low-leakage, high standoff voltage devices. It is desirable to minimize source charge leakage through *Mf1* after the switcher is operating, and a leaky *Mf2* would strip charge off of the *Mf1* gate during the start-up process.

As *Cb* charges beyond *Z2*'s breakdown voltage plus the diode drop across the base-emitter junction of *Q1*, *Q1* is forced into conduction, which in turn activates *Mf2* and *Mg.* With *Mf2* ON, *Mf1*'s gate is pulled to ground and current flow through the feed-forward loop is blocked in both directions. Most high-standoff voltage MOSFETs have a body diode connected from source to drain, and *Df1* is included to prevent reverse current flow through *Mf1*. Further, in the ON state, *Mg* references LGND to SGND, which will then differs only by the voltage drop across the channel. *Cb* now has a current path through the conditioning circuitry and into the "common" ground, and the system is activated. LGND remains a viable current return path until the voltage across *R3* goes low enough to pinch off *Mg*, and the *Cb* voltage at which this occurs can be set by adjusting the ratio between *R2* and *R3*.

Once the control and regulation circuitry is activated and the direct current path from the source to the secondary side is opened, the only means to transfer energy from the source and into *Cb* is through the transformer and the MOSFET switch. A peak detector (*Dp1, Dp2, C1* and *C2*) and comparators *A* and *B* in the MAX934 IC perform zero-slope peak detection of the source signal so that the switcher is activated when the signal reaches its maximum voltage. It is deactivated when a low signal is detected. Further, *Ms* is held open at start-up so the transformer will not load the source. *R1*, *Rc1*, and *Rc2* constitute a very high-resistance voltage divider (*R1* ~ 100 MW, and *Rr1* and *Rr2* divide down the reference voltage (1.182 Volts) so that the input voltage at pin A- is limited as the source voltage approaches 300 Volts. Ao therefore remains HIGH until the source signal voltage reaches the preset level and A- becomes greater than A+; the RESET pin on FF2 is then set LOW. As the input signal continues to rise, the voltage drop across *Dp2* holds the B- higher than B+, thereby keeping Bo LOW as *C2* charges.

When the slope of the source signal reaches zero and begins to fall, the voltage across *C2* is greater than the signal voltage, and the voltage drop across *Dp1* causes the comparator to drive the Bo pin HIGH. With RESET LOW and a positive slope edge at the clock input of U2B, the flip-flop latches Q high, thereby supplying power to the biasing circuitry of the '7555 CMOS oscillator. By using the Q pin to source this current, quiescent losses in the biasing resistors are reduced by supplying power only when the oscillator is needed, and the oscillator will function as long as Q is high and the biasing circuitry is powered. It will remain high until the input signal falls below the threshold set at A+ and RESET is driven high. Further, feeding Ao into RESET prevents the oscillator from being turned ON until the A+ threshold is reached regardless of the source signal. This convention prevents small signals, such as the ones produced by weight shifts on the insole, from inadvertently activating the switcher. *Rc1*, *Rc2* and *C1* bias and filter the signal into the B-/B+ peak detector. They are selected experimentally, and the circuit behaves somewhat erratically without them.

The forward converter switcher is conventionally operated at or near a 50% duty-cycle to minimize switch stress and core losses (this regulator circuit[10] achieves optimal performance at a 25 kHz switching frequency). It can be shown however that biasing circuitry losses approach a maximum as duty-cycle go to 50% using the '7555 timer in this standard astable configuration. Simply, the *Rb*/*Ra* ratio should be made as small as practical to minimize losses, but it is impossible to reduce this ratio and approach a 50% duty-cycle simultaneously. To address this quandary, a second D-type flip-flop is used to establish a perfect 50% duty-cycle square wave and drive the gate of the n-channel MOSFET switch *Ms*. The *Rb*/*Ra* ratio can then be minimized and the '7555 used to supply momentary trigger pulses to the flip-flip.

Therefore, at the peak of every current pulse from the bimorph source, the gate drive circuit switches an exponentially decaying source envelope through the step-down transformer *T1* and into the storage stage. The primary of *T1* is coupled into two windings with the same turns ratio N. *S* is the secondary winding, and the third, or *tertiary* winding *T*, is inverted with respect to SGND. *T* is used to reset the magnetic flux through the transformer core during switch OFF periods, transferring the magnetization energy into *Cb*.

Following *D5* and *D6* are filter inductors and freewheeling diodes for both low-side windings. *L1* (and *L2* on the tertiary) and *Cb* form a second-order filter, normally implemented to reduce the high-frequency ripple at the output, in this design must contend with the dominant one Hertz excitation frequency of the source. The inductors therefore operate discontinuously and do little to filter the dominant ripple; they are included merely to support the voltage difference between *Cb* and the transformed source when the switch is closed. The bucket capacitor is chosen large enough to sustain an operable voltage between each current pulse (see Figure 11), and *Zb* is added to protect the control circuitry should the voltage on *Cb* approach the supply rating of the CMOS logic.

Finally, the load switching stage follows consisting of two comparators and a NAND "Set-Reset" latch which sense the V+ and provide hysteresis in the ON/OFF control of the LDO linear regulator. This combination provides a regulated output voltage, prevents *Cb* from being drained completely, and thereby reduces the number of slow bootstrapped restarts. Hysteresis is important because it prevents jitter or oscillation in load stage control, and it allows for low duty-cycle operation if a load demands higher power than can be provided by the system. (See Figure 12.)

4) Conclusions

When compared to the simple bucket capacitor and linear regulator scheme of Fig. 7, the switching converter proved to be a better means of conditioning the power harvested from the piezoelectric sources, though its efficiency was not as high as anticipated. The plot in Figure 11 shows that the forward converter is capable of supplying at least 1.3 mW of power continuously at a .8 Hz walking pace. Comparing this to the raw power of the bimorph source (8.4 mW at 1.1 Hz) and normalizing with respect to a common frequency, the electrical efficiency of the converter is found to be 17.6%. This result is better than twice the efficiency for the original linear regulator design of Fig. 7 when using the same source and bucket capacitor[9]. More importantly, the switching converter system provides electric power continuously while walking, a requirement of many body-worn applications which could be sourced by a shoe power system in the future.

There remain a few areas which should be addressed in future work to enhance efficiency and output of the two shoe power harvesting systems presented here. To obtain better performance from the switching regulator, a number of electrical design factors should be more closely examined. The switching converter incurs losses in the transformer core and switching MOSFET that could be reduced by developing components tailored to micro-power signals. Finally, soft-switching techniques could be applied and an optimal circuit layout developed to further reduce electrical system overhead.

Without straying from the relative simplicity of low-frequency passive excitation, the discussion above points to logical next steps for the piezoelectric power shoe system -- refining the transformer and FET switch designs and developing an integrated IC to perform control. Commercially available high-voltage FETS are normally built for high-current applications. They have relatively high gate charge requirements, and the gate drive dissipates a large percentage of a piezo source’s power even at low frequencies. The most important next step therefore is to optimize the switching transistor for high voltages but very small currents. Further, placing the control on an integrated circuit would reduce losses associated with coupling multiple discrete components and force the development of an optimal layout. Layout is often just as important to the performance of a switching converter as component selections, and a better layout could reduce switching noise and eliminate stray resonances that may have degraded the discrete design’s performance.

Of prime importance in obtaining better performance is improving the mechanics of exciting the transducer from foot dynamics. One aspect not fully addressed here is the physical impedance match between foot and transducer. The piezo element dimensions and mechanical braces were selected to best balance comfort vs. energy transfer, but a more rigorous study should be performed that depend highly upon the specific application. Also, as piezoelectric elements have been used for many years to actively damp high-frequency mechanical dynamics[18], those relationships could be applied in reverse by artificially exciting the material near its mechanical resonance and against the force of the bearer’s down-step, liberating a larger net of electrical energy. By using cyclic mechanical excitation near the material's resonant frequency, the piezoelectric element can be made to undergo many charge/discharge cycles during a single heel-strike, producing more energy[19]. This involves much more mechanical complication than the simple insole mounting schemes used here (Fig. 2), however. Moving magnet systems, which likewise involve a more complicated integration[20], then become very competitive because of their high efficiency and well-established technology. For example, a simple test of a foot-mounted generator[9] was conducted by the authors and their team. Our device (Fig. 13) significantly hampered the wearer's gait because of its primitive mechanical linkage. It did, however, generate an average power of 250 mW, two orders of magnitude higher than the results from the piezoelectric systems presented here (which, in their defense, created no noticeable perturbations to the bearer's walk). Better engineering of these systems, for instance incorporating a hydraulic link to reservoirs compressing with the sole[21], have the potential for producing a practical shoe that generates considerably more power than the piezoelectric sources used here.

Beyond improvements to the above designs, the most appropriate next step is to integrate them with some new and pertinent body-worn systems. The RFID transmitter is just one example of a simple and practical application of scavenged shoe power. Other possibilities include personal positioning systems for military or police units, a personal navigator or 'smart' pedometer, a data collection tool for monitoring an athlete's movements, or a means to track your child throughout the house. As the power yield increases (and body-worn electronics become more efficient), more and more of the components of wearable computers[22] could be driven by such energy-harvesting systems, reducing or eliminating the need for batteries. In all of these applications, the piezoelectric insole and conditioning electronics could be separate components within the shoe. As insoles wear out, they would be replaced or upgraded, modularly linked to electronics embedded in the heel via a weatherproof connector on the sole. These are just a few applications; there are myriad others, and with some minor adaptations systems like the ones described herein could be used to provide and condition power for many future body-worn devices.

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FIGURES

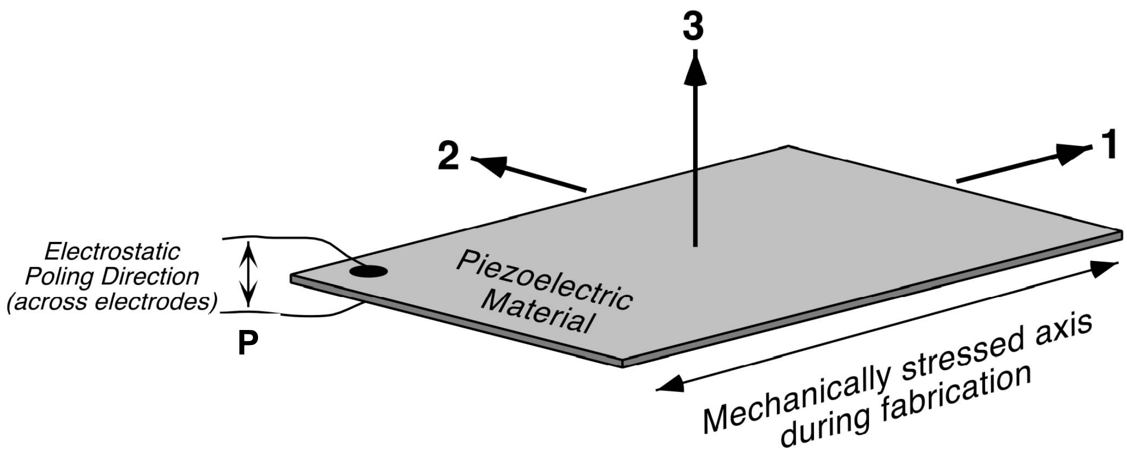

Figure 1: Conventional axis definition for a piezoelectric material

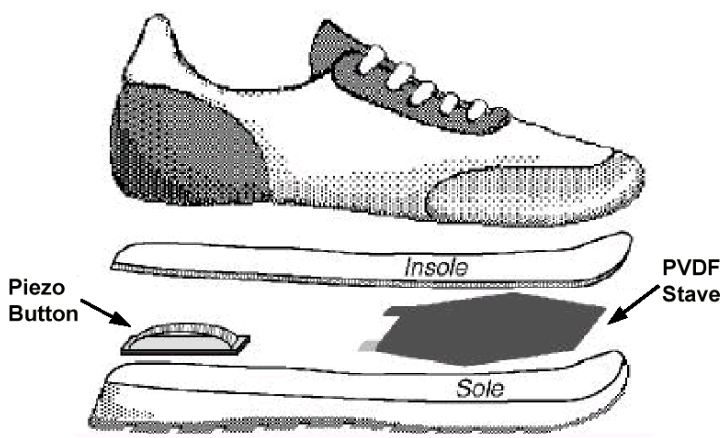

Figure 2: Two approaches to bending 31-mode piezoelectric energy scavenging in shoes

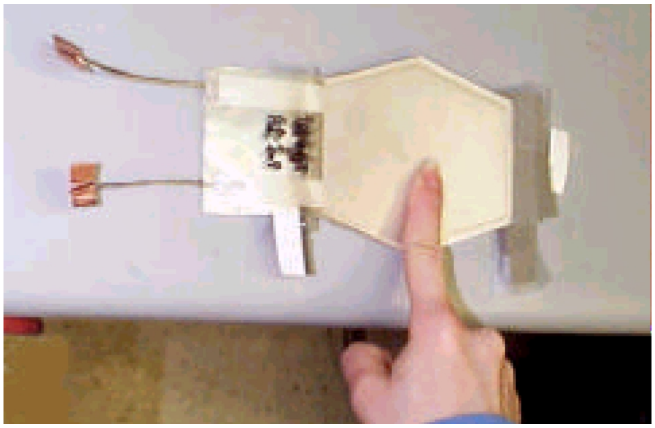

Figure 3: The PVDF insole stave
(for sole-bending energy)

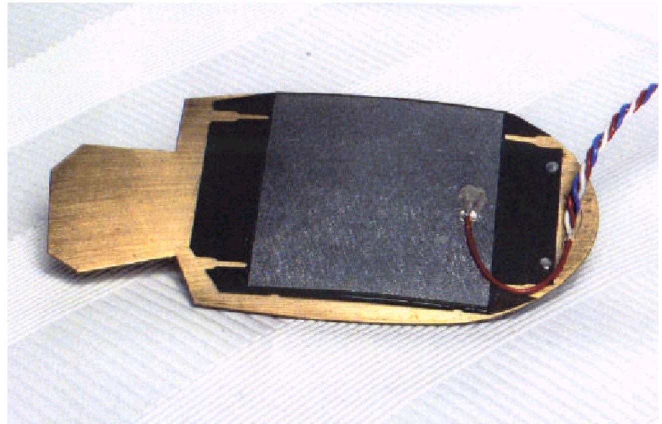

Figure 4: The PZT bimorph
(for heel-strike energy)

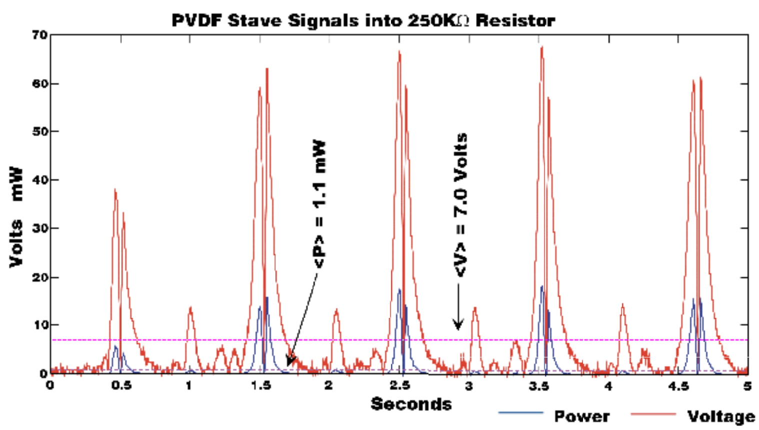

Figure 5: PVDF stave power and voltage (rectified) into 250 kΩ resistor

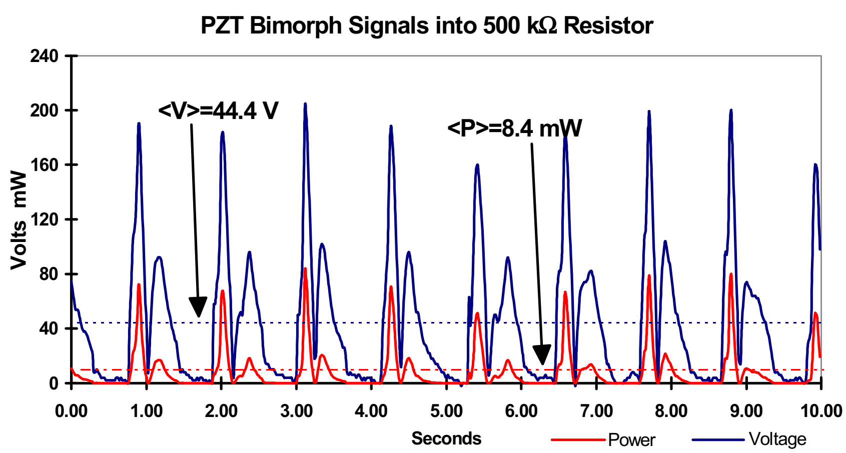

Figure 6: PZT bimorph power and voltage (rectified) into 500 kΩ resistor

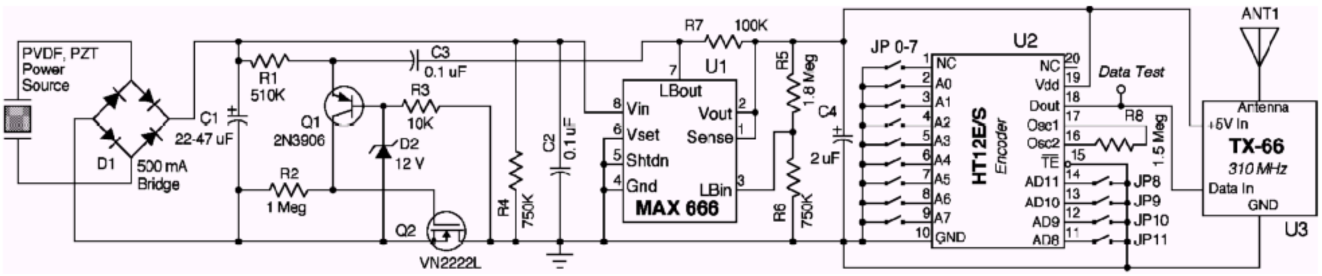

Figure 7: Schematic of power conditioning electronics and encoder circuitry for the shoe-powered RF tag system

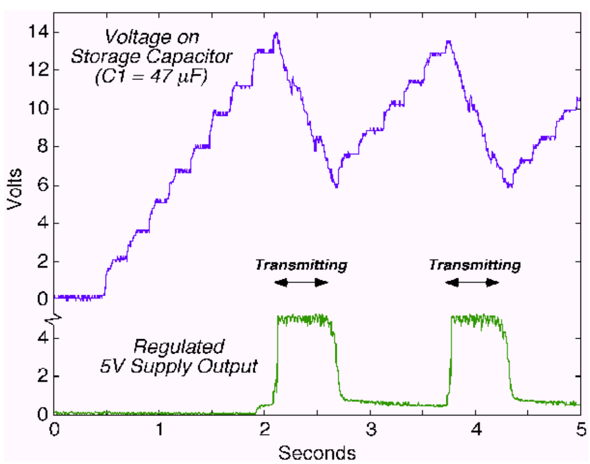

Figure 8: Representative signals from the RFID Tag

Figure 9: Piezo-powered shoes w. mounted electronics

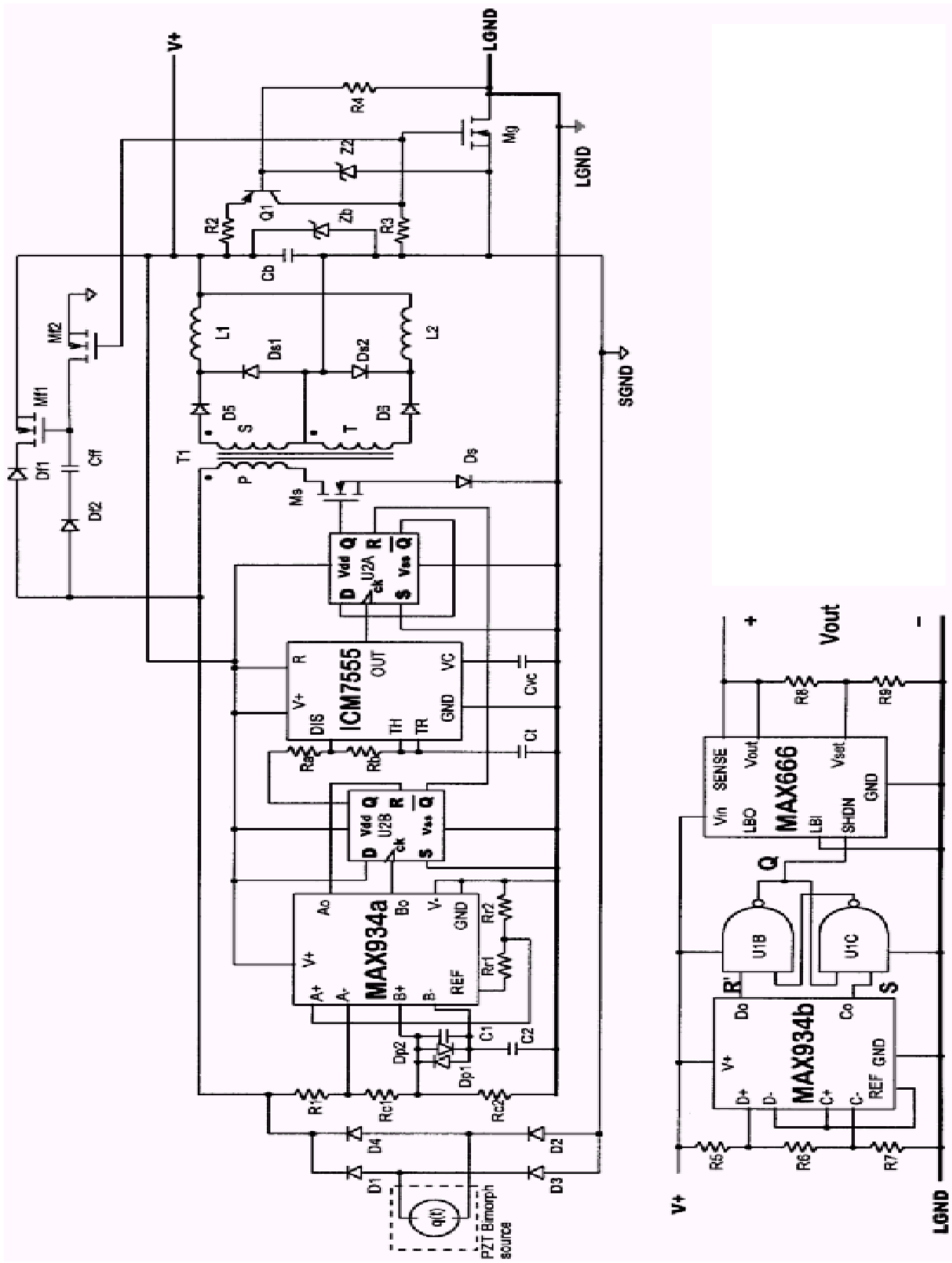

Figure 10: The forward switching converter system

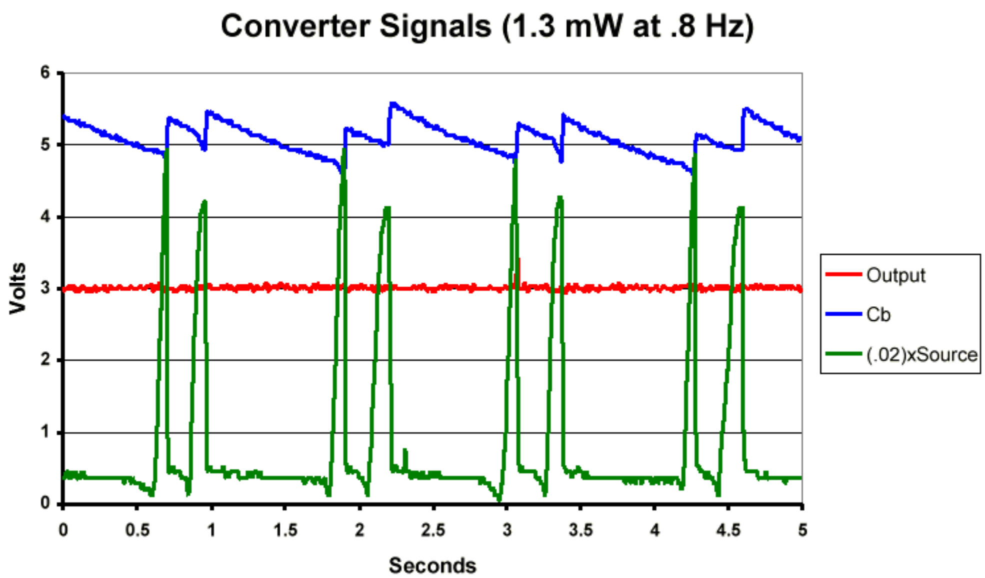

Figure 11: Converter signals with continuous 1.3 mW supply at a .8 Hz pace (PZT bimorph)

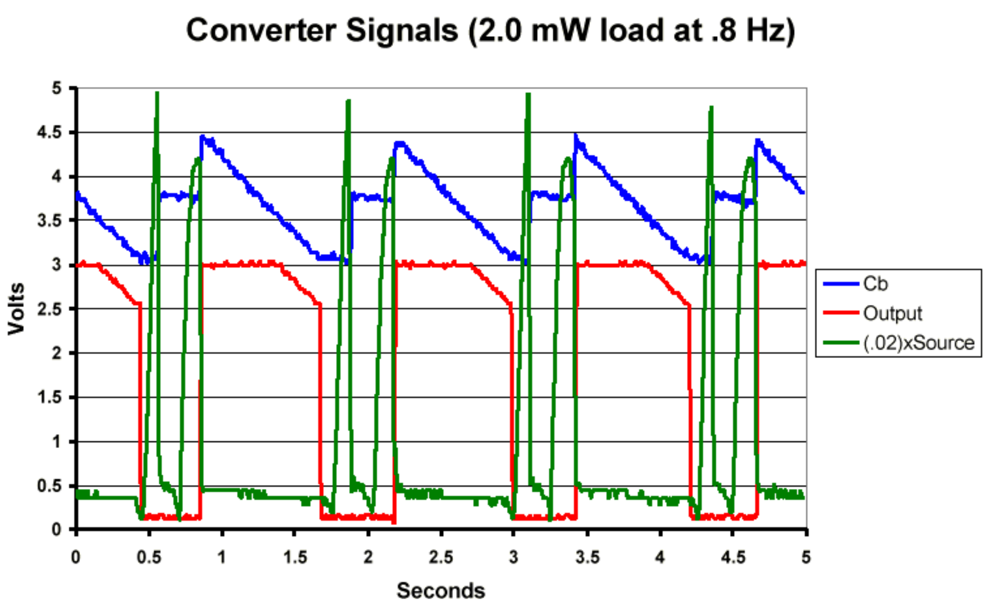

Figure 12: Converter signals with discontinuous 2.0 mW supply at a .8 Hz frequency (PZT bimorph)

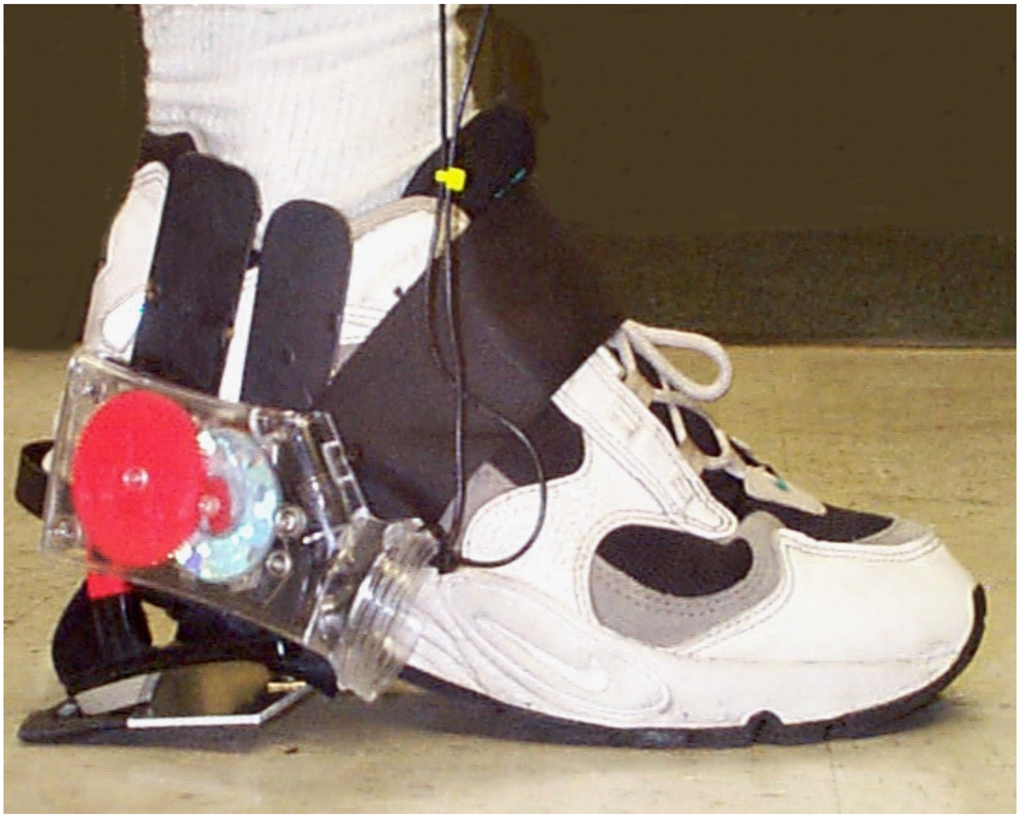

Figure 13: Proof-of-concept demonstration of magnetic generator shoe, producing <P> = 250mW

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