Parasitic Power Harvesting in Shoes

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Abstract

As the power requirements for microelectronics continue decreasing, environmental energy sources can begin to replace batteries in certain wearable subsystems. In this spirit, this paper examines three different devices that can be built into a shoe, (where excess energy is readily harvested) and used for generating electrical power "parasitically" while walking. Two of these are piezoelectric in nature: a unimorph strip made from piezoceramic composite material and a stave made from a multilayer laminate of PVDF foil. The third is a shoe-mounted rotary magnetic generator. Test results are given for these systems, their relative merits and compromises are discussed, and suggestions are proposed for improvements and potential applications in wearable systems. As a self-powered application example, a system had been built around the piezoelectric shoes that periodically broadcasts a digital RFID as the bearer walks.

1: Introduction

As wearable electronic devices evolve and proliferate, there will be a growing need for more power delivery to distributed points around the human body. Today, much of that storage is provided by batteries and power delivery is via wires. The current approach to power distribution is clearly becoming problematic -- as more appliances are carried, we are forced to either use more small batteries that require replacement everywhere or run wires through our clothing to supply appliances from a central power source. Both are undesirable. A better solution is clearly to generate power where it is being used, bypassing the storage and distribution problem altogether. As power requirements drop for most wearable devices, it is no longer infeasible to harvest a useful amount of energy "parasitically" from a normal range of human activity.

Many attempts have been made in the past to tap this source, leading to the consideration of a host of technologies [1] ranging from the construction of various electromechanical generators [2,3] to the surgical placement of piezoelectric material in animals [4]. No generating system to date has served all of the needs of wearable computing—light weight, minimum effort, high power generation, convenient power delivery, and good power regulation. We believe that our approach has the potential to solve these problems for a class of wearable devices by placing both the generator and powered electronics in a location where considerable energy is easily available, namely the shoe.

In previous studies [5], it has been calculated that up to 67 Watts of power are available from heel strikes during a brisk walk (68 kg person, 2 steps/sec, heel moving 5 cm). This level of power extraction from walking would certainly interfere greatly with one's gait. Our philosophy, in contrast, has been to try to generate power entirely parasitically, that is through mechanisms that capture and make use of energy normally dissipated wastefully into the environment. There is much less energy of this type than available through deliberate means of harvesting human power (e.g. through a hand crank or foot pedal), but it is our goal to unobtrusively collect energy for low-power applications. We have approached this problem by using the energy from the weight transfer during a step to perform useful work.

2: Background Information

The context in which we place our generator is that of a sport sneaker. This type of shoe differs from ordinary shoes in one important feature—its energy dissipating sole. While walking in ordinary "hard" shoes, the foot is rapidly decelerated from its relatively high downward speed to zero velocity relative to the ground—an action that requires the application of relatively large and sudden forces to the foot. Barring shock absorption in the feet, this can be simply modeled as a sudden step in velocity; the force applied to the foot to achieve this deceleration is an impulse (Fig. 1a).

This impulse causes the foot to decelerate suddenly while the rest of the body is still moving. The force that stops the rest of the body's mass is transmitted through the legs and compresses the knees and other joints. The

Draft 2.0, August, 1998; Presented at the Second IEEE International Conference on Wearable Computing

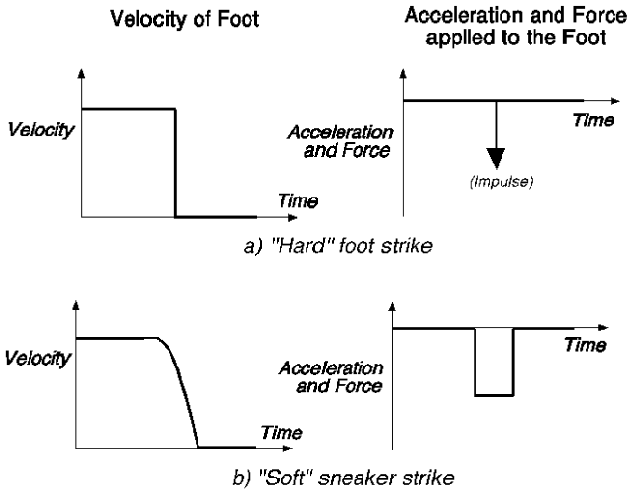

Figure 1: Dynamics for hard vs. cushioned foot strikes

function of the insole and midsole in the sport sneaker is to work as a low-pass filter for this step in velocity, reducing the amount of force applied to the joints (Fig. 1b). This reduces any stress that the joints experience and also reduces the incidence of sports injuries.

The result is that the force and displacement values over time for the bottom and top of the midsole are not the same—as in any passive filter, there is an energy loss in the sole while it performs this filtering function. The energy lost is in the higher harmonics of the step and is dissipated through internal losses in the sole. When the sole springs back after the step it does not exert as much force as before, returning less energy than was put into it, and it is this energy that we are trying to capture (Fig. 2).

The energy obtained from the shoe is not free—as the harvested power grows, there is a noticeable additional load as the shoe demands more energy to be put into it while supplying less restoring force (somewhat like walking on sand). Our systems strive to make this burden beneath notice, ideally loading the user's stride exactly as much as common sport shoes today.

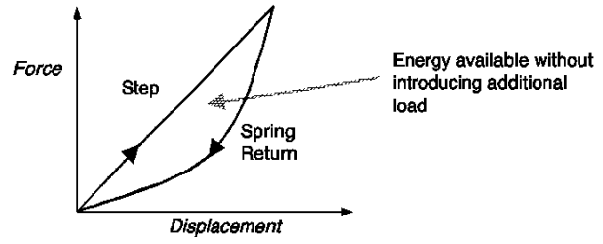

Figure 2: Force/displacement curve for a sneaker sole

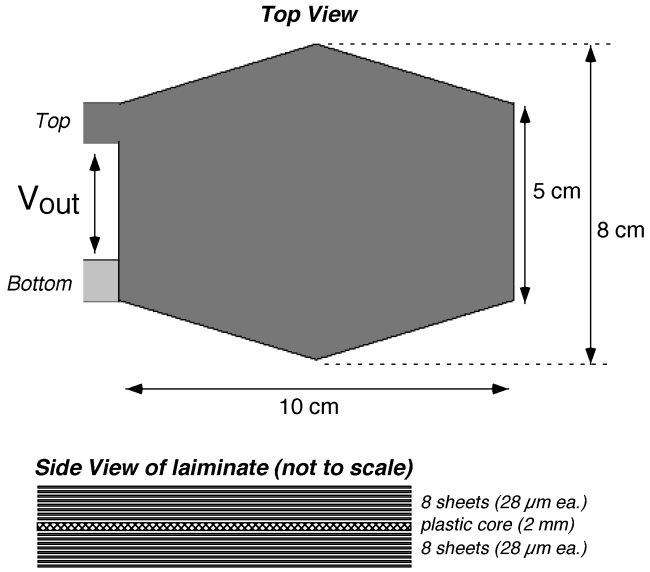

Figure 3: Layout of the PVDF Power Insole

3: System Descriptions

One obvious means of parasitically tapping energy in this context is to harness the bending of the sole, which is attempted in our first system. This is a laminate of piezoelectric foil, shaped into an elongated hexagon, as shown in Fig. 3. This "stave" is a bimorph built around a central 2-mm flexible plastic substrate, atop and below which are sandwiched 8-layer stacks of 28-micron PVDF (polyvinylidineflouride) sheets [6], epoxy-bonded as shown. This stave was designed in collaboration with K. Park and M. Toda of the Sensor Products Division of Measurement Specialties (formerly AMP Sensors) [7]; its shape was chosen to conform to the footprint and bending distribution of a standard shoe sole. As the stave is very thin (under 3 mm), it can be easily molded directly into a shoe sole. When the stave is bent, the PVDF sheets on the outside surface are pulled into expansion, while those on the inside surface are pushed into contraction (due to their differing radii of curvature), producing voltages across silver-inked electrodes on each sheet through the dominant "3-1" longitudinal mode of piezoelectric coupling in PVDF. In order to lower the impedance, the electrodes from all foil sheets are connected in parallel (switching polarities between foils on opposite laminate surfaces to avoid cancellation), resulting in a net capacitance of 330 nf. An actual stave used in our tests is shown in Fig. 4.

Another promising mode of harnessing parasitic power in shoes is to exploit the high pressure exerted in a heel strike. There are many ways to tap this; for instance some groups [8] are trying to develop highly elastic

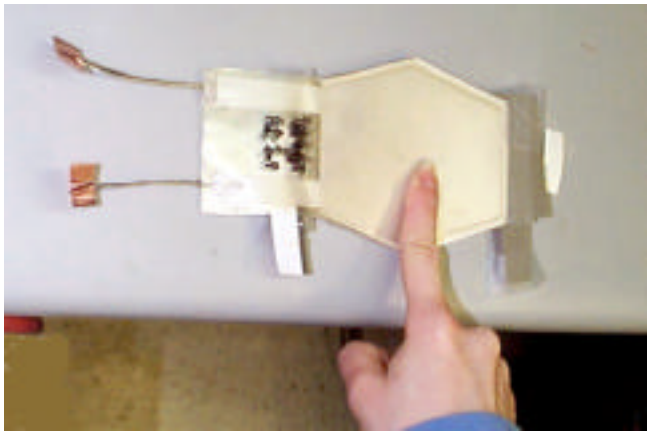

Figure 4: Photograph of the PVDF Insole Stave

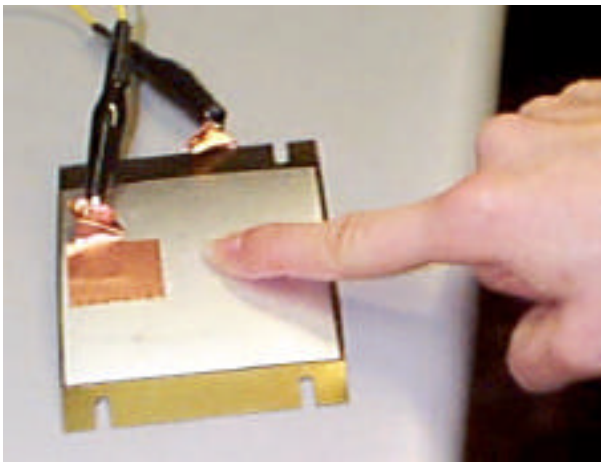

Figure 5: A Thunder PZT unimorph under test

electrostrictors (which work like a piezoelectric material, except voltage must be applied before any electro-mechanical coupling is produced) that can generate power when compressed; others [9] are investigating dense electrostatic force arrays that work like large condenser microphones.

We have used a simpler, existing technology to tap power from pressure. Shown in Fig. 5, it is a unimorph strip of spring steel bonded to a patch of piezoceramic material modified to be somewhat flexible. Developed by NASA Langley as part of the RAINBOW (Reduced and Internally Biased Oxide Wafer) effort [10], it is available from Face International Corp. as the "Thunder sensor/actuator" [11]. We have used two of these devices in our tests. One, pictured in Fig. 5, is the TH 7R, with a 7 x 7 cm, 10-mil strip (180 nf capacitance) of composite PZT (lead zirconate titanate) bonded to a curved piece of 7 x 9.5 cm spring steel. The other is the TH 6R, with a 5 x 5 cm,

Figure 6: Simple shoe-mounted rotary magnetic generator

15-mil PZT strip (70 nF capacitance) bonded to a 5 x 8.5 cm strip of spring steel. Although the Thunder devices can be safely pressed flat (they are quiescently curled such that the center is displaced 7 mm up from the edges for the TH 7R and 2.5 mm for the TH 6R), they can not be reverse-bend, otherwise the piezoceramic material will crack. This can be accommodated by a mount in the shoe sole that forces the unimorph flat against a rigid plate when the foot comes down; when the foot pressure is released, the unimorph correspondingly springs back.

Another technique for extracting power from foot pressure is to adapt a standard electromagnetic generator. This is a well-proven technology, capable of very high conversion efficiency. Its major difficulty is one of integration; while one can conceive of many simple ways to incorporate the piezoelectric devices mentioned above into a sole structure, a conventional rotary generator is a comparatively large, solid object that must be somehow mounted on the shoe and mechanically coupled to the sole dynamics or foot strikes. Elaborate mechanical schemes have been suggested in the literature [2], as have a few more elegant solutions, for instance hydraulically coupling the generator to a set of bladders under the sole [12]. In a related approach, some researchers [13], have developed heel-mounted mechanical pumps for hydraulic systems that drive prosthetic limbs.

In order to contrast the performance of a rotary generator with the piezoelectric schemes sketched above, we have built a device that can clamp a small generator-driven flashlight (Made by the Fascinations Corp. of Seattle, WA) to the outside of a shoe. The generator is cranked by pressing a lever; as shown in Fig. 6, our system holds the generator such that a hinged heel plate presses the lever completely (a 3 cm stroke) when the foot is flat down. Although many more elegant (and less cumbersome)

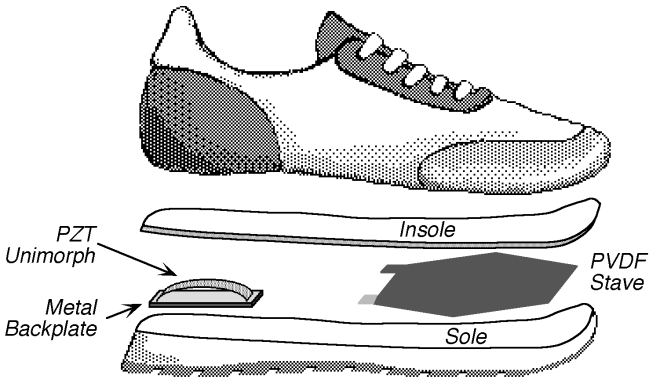

Figure 7: Exploded view showing integration of piezos

implementations are possible, this configuration provides a comparative example.

4: Performance

In order to evaluate their power-generating capability, we have installed all three of these systems in sneakers. The magnetic generator was affixed as shown in Fig. 6 and the PVDF and PZT elements were mounted between the removable insole and rubber sole as indicated in Fig. 7. Although all of these elements could, in principle, be mounted in the same shoe, the PVDF, PZT, and magnetic devices were installed in separate shoes during our tests. The region around the heel of our men's size 11½ (US) Nike Air running shoe was too small to accommodate the TH 7R unimorph, hence we used the smaller TH 6R there instead. When inserted beneath the insole (as in Fig. 7; see also Fig. 11), these devices could barely be noticed under the foot and had no effect on gait. The piezoelectric generators, being high-impedance devices, were terminated with 250KΩ resistors, which approximated their equivalent source resistance at the excitation frequencies, hence yielded maximum power transfer [14]. By looking at the open-circuit voltages built across the intrinsic capacitances of the piezoelectric devices after fixed-force deflection, we have estimated their mechanical-to-electrical efficiencies, which were roughly 0.5% for the PVDF stave, 1.5% for the TH 6R and 5% for the TH 7R.

Fig. 8 shows the voltages produced across the load resistor by the piezo elements during a brisk walk, with the same foot hitting the ground at roughly 1 Hz. Here, the PVDF stave produced peaks of roughly ±60 Volts, while the Thunder Unimorph gave significantly larger response, with peaks approaching 150 Volts. These waveforms indicate the characteristics of the footfall; the PVDF switches polarity when the toe is lifted off the ground and the sole unbends, while the PZT exhibits a strong positive

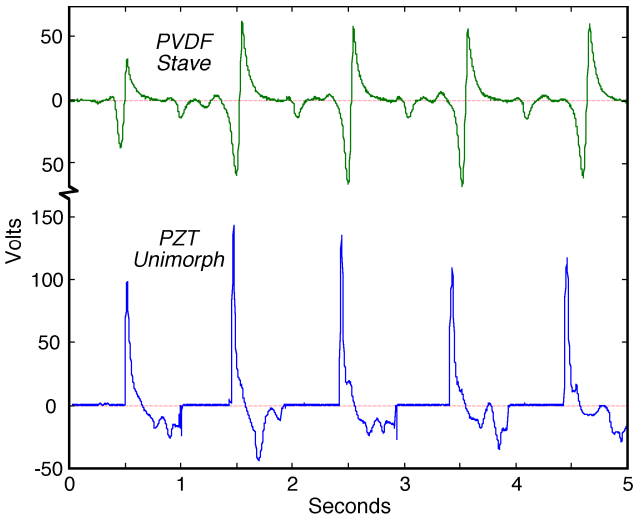

Figure 8: Voltage into 250KΩ load from piezo generators

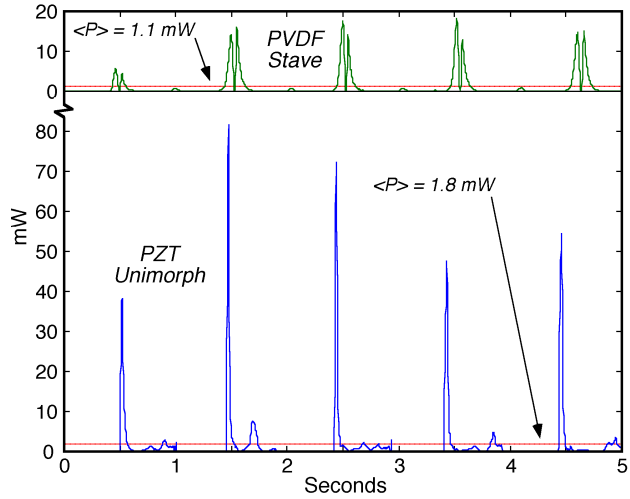

Figure 9: Resulting power output from piezo generators

spike when the unimorph is quickly compressed during a heel strike (note that each graph came from a different shoe, hence the curves are not plotted in absolute phase).

Fig. 9 shows the resulting power delivered to the load by these systems. The peak powers are seen to approach 20 milliwatts (mW) for the PVDF stave and 80 mW for the PZT unimorph. Because of the slow excitation, however, the average powers are considerably lower; the PVDF stave produces about a milliwatt, while the unimorph averages about twice that. Integrating the powers in Fig. 9, we see average net energy transfers of roughly 1 milliJoule (mJ) per step for the PVDF and 2 mJ/step for the PZT unimorph. Our size 11½ sneakers had just enough room in their forward region to accommodate the larger TH 7R

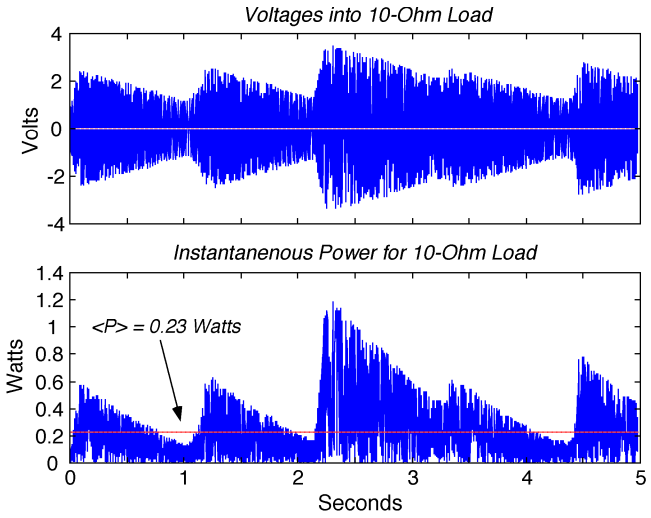

Figure 10: Performance of magnetic generator

unimorph and gather energy under the toes; similar tests indicated circa 30% higher power than with the TH 6R under the heel, mainly due to the increase in active area and wider TH 7R deflection.

In contrast, Fig. 10 shows data for the shoe-mounted AC magnetic generator, giving the voltage and resulting power delivered to a 10Ω load (which roughly matched its impedance) when walking at the same pace. The impulses from each footfall are obvious (the generator included a flywheel to store the mechanical energy) resulting in peak powers of roughly a Watt and averaging to roughly a quarter-Watt over this 5-second sample of data.

5: Applications and Discussion

Even though the energy produced by the PVDF stave is very limited, it is still useful for a variety of low-power, low duty-cycle applications (see the RF tagging example below), plus it promises to be the least invasive and most accommodating solution when laminated directly into the sole structure.

Various calculations [7,15] have predicted considerably more power generation from PVDF foil in shoes, ranging from tens to hundreds of milliwatts. The major source of this discrepancy is in the assumed efficiency of stretching the foil. The most efficient mechanical coupling into PVDF is through the longitudinal (3-1) mode (approaching 25% efficiency), which requires it to be pulled. As the PVDF is fairly strong, the best mode of pulling the foil would be to directly convert downward foot pressure into foil stretching, requiring a potentially complicated mechanical mount. The next best solution is to exploit the

Figure 11: Sneaker-mounted tag circuitry and PZT element

bending of the sole, as we have here in the bimorph stave, which pulls and pushes the PVDF laminated to the plastic substrate as the stave is bent. The stiffness of the plastic substrate material, however, together with any slippage in the laminate, lowers the mechanical efficiency of this scheme; as mentioned earlier, we see conversion efficiencies below 1%.

The piezoceramic unimorph is a bit more difficult to blend into the shoe structure, as it is easily damaged upon reverse bending, and its curvature plus the need for displacement inhibit simple lamination. On the other hand, it can be accommodated with a simple sole retrofit (as in Figs. 7 and 11), and the strong piezoelectric coupling and more efficient conversion generates sufficient power for several useful applications. We have used it to drive RF tags (see below), low-power PIC microcomputers, and LCD displays. This device also has the potential to power a version of the Media Lab's PAN [16], which injects a low-frequency, low-voltage carrier into the body through the shoes, enabling digital communication with other intelligent objects (and people) when touched. There are several possibilities for increasing the power from this system, including stacking multiple unimorphs or designing its characteristics specifically for power generation, as opposed to a general-purpose sensor/actuator.

The rotary generator, of course, can power a wide variety of devices. In our demonstrations, we use it to run a common transistor radio that drives a small loudspeaker (taking quite literally the notion of a "Walkman"). It is certainly most invasive to the shoe, however, as it is a macroscopic, "lumpy" object that must be attached and mechanically linked. The large, 3 cm stroke that we are currently using is likewise awkward, and interferes with walking; studies [17] indicate that the heel strokes in such

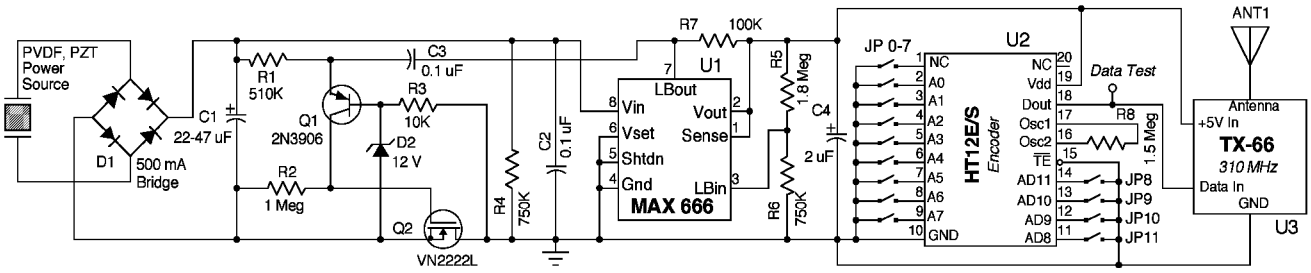

Figure 12: Schematic diagram showing power conditioning electronics and encoder circuitry for the self-powered RF tag

systems must be limited to below 1 cm in order to remain innocuous. Magnetic generators will probably find their niche after more elegant design, e.g., as retrofits to footwear, clamping on when needed and incorporating an efficient mechanical transport from foot dynamics to armature rotation.

7: A Self-Powered RF Tag System

One simple application that the piezoelectric generators can easily enable is a batteryless, active RF tag, which transmits a short-range wireless ID code to the vicinity while walking. This has immediate application in active environments, enabling the user to transmit their identity to the local neighborhood while passing through and allowing the building to locate its inhabitants and dynamically channel any relevant resources or information to them. Most of the classic work in this area [18] has been done with battery-powered IR badges, which tend to require a line-of-sight to the reader. Our implementation uses a low-power RF transmitter instead; as it requires no optical path, we can mount it in the sneaker and use the energy extracted from walking to power it without the need for a battery.

Fig. 11 shows an overhead view of this system as integrated onto a jogging sneaker. The power-supply and tag electronics are mounted behind the heel. As seen in the figure, this shoe has the TH 6R PZT unimorph mounted under the heel; the insole (bottom) has been removed for the photograph. We have also integrated this system with the PVDF bending stave; it works well with either configuration.

The power-conditioning electronics for the tag circuit are shown at left in Fig. 12. The voltage from the piezo element (e.g., unimorph or stave) is full-wave rectified in the bridge D1, then charge is accumulated on the electrolytic capacitor C1. The Q1,Q2 circuit acts like an SCR with supercritical feedback. It was adapted from a similar circuit designed for powering motors off solar cells [19], revised to function with the very high impedance of the piezoelectric sources. Initially Q1 and Q2 are off, and the ground (at the drain of Q2) is floating, hence the subsequent electronics (U1-U3) are unpowered. As C1 charges beyond 12.6 volts (determined by zener D2 and the base-emitter junction of Q1), Q1 turns on, activating Q2 (which latches Q1). This pulls down the "ground" line, allowing C1 to discharge through the circuitry. U1 is a low-power series regulator, which produces a stable +5 Volts for the serial ID encoder (U2) and RF transmitter (U3) throughout the discharge of C1. When C1 drops below 4.5 Volts, the low-battery line on U1 is pulled down, transmitting a negative pulse through C3 and turning Q1 off, in-turn deactivating Q2, lifting the ground and halting the discharge of C1. Subsequent walking increases the voltage on C1, allowing the cycle to start afresh. This system exhibits a very high impedance in its "off" state, enabling fast charging of C1.

Fig. 13 shows representative signals from the power conditioning electronics described above. The upper trace shows the voltage on C1, here a 47 μF electrolytic capacitor. It can be seen to increment after every step (the staircase structure), and when it surpasses the threshold of D2 and Q1, the 5 Volt supply (lower trace) is activated. C1

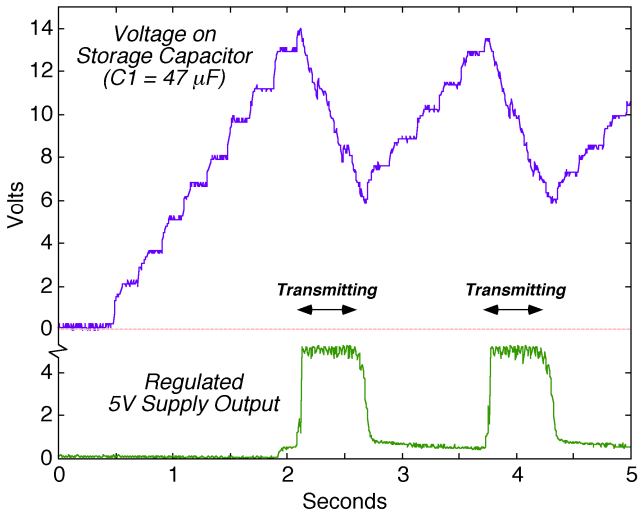

Figure 13: Performance of the power conditioning system

Figure 14: A pair of self-powered RFID sneakers

then discharges through the tag electronics and its voltage rapidly declines until the supply is deactivated after it drops below threshold.

Although a switching regulator would, in theory, provide a much more efficient power conversion, a series regulator was used instead because of the short duration of the powered output; the low-power switchers that were tested operated much too slowly to provide proper regulation here.

This RFID portion of this circuit employs a 12-bit serial ID encoder (an HT12E from Holtek) and a 310 MHz ASK (amplitude-shift-keying) transmitter from Ming (the TX-66); it is similar in design to common keychain transmitters for car alarms. This circuitry draws 3.3 mA, which enables it to transmit for roughly a half-second from the 47 μF storage capacitor (Fig. 13), and thus repeat its 12-bit code sequence 6-7 times. Fig. 14 shows a closer view of the circuitry as mounted to the heel. This is still a prototype; it can easily become much smaller (e.g., if implemented totally in surface-mount technology or on an ASIC) and smoothly integrated into the shoe. The jumpers JP0-11 select the ID code that is broadcast and are set by straps on the RFID circuit board.

Depending on how one walks (e.g., the PZT unimorphs prefer a heavier gait, while the PVDF stave responds more to a bouncy walk), these shoes were seen to transmit an ID every 3-6 steps. This code is detected by a matching ASK receiver; using quarter-wave (9-inch) antennas on both transmitter (where it is laminated to the sneaker) and receiver, this system was able to read the sneaker's ID anywhere in a large (e.g., 60 foot) room.

8: Conclusions

Although the magnetic rotary generator that we have tested produces 2 orders of magnitude more power than either of the piezoelectric systems, it is much harder to integrate smoothly into the design of conventional footwear without interfering significantly with the form factor of the shoe and/or gait. Both the PVDF stave and PZT unimorph were easily integrated into a standard jogging sneaker, and, as shown in our example of the self-powered RFID tag, sufficient energy could be accumulated across several steps to power useful functions.

The power supplies that we've used with these piezoelectric systems have been thusfar very simple; e.g. standard full-wave rectifiers and filter capacitors, aided by an SCR-style switch as a simple method of integrating generated charge across several steps before dumping the power into the application device. We are now examining the application of charge pumps and efficient voltage conversion to these high-impedance piezoelectric sources, ideally charging much smaller capacitances directly off the generating element, hence making these devices significantly more efficient. Similarly, terminating these piezoelectric generators into inductive loads produces an LC resonance, which can be tuned to the frequencies arising from the walking excitation. Although the inductors may grow very large in this case, the power extraction and energy storage can become more efficient.

This study has not addressed moving power off the shoe to other parts of a wearable system. The shoes, of course, could be directly wired, but this can prove cumbersome, as mentioned earlier. Previous work by the authors and their colleagues at the MIT Media Lab has taken a different approach by transporting current through conductive thread as sewn into clothing [20] and driving high-impedance loads directly through the body [16]. Although such implementations involve significant progress in both engineering and fashion, they promise to widen the possibilities for useful shoe-powered systems.

There are many metrics by which one may judge these systems to be useful, one of which is a comparison to laminating a small battery directly into the sole (as is done with the common LED-flashing sneakers) for the lifetime of the shoe. We have estimated [21] that a circa 10 mW in-shoe generating system (within reach of the piezoelectric technologies that we have explored) that lasts for circa 2 years of average use is equivalent to 150 cm^3 of lithium-thionyl chloride batteries, which provide the highest energy density of all lithium-based cells. This is a favorable comparison, even without considering the well-known

environmental concerns associated with batteries. Of course, the piezoelectric generators must hold up to the long-term wear, dynamic forces, and potential moisture, abrasion, etc. that are expected across the shoe's life cycle; a prospect for testing and engineering that go beyond the proof-of-concept studies presented in this paper.

9: Acknowledgments

We are grateful to our collaborators (in particular Kyung Park and Minoru Toda) at the Sensor Products Division of Measurement Specialties (formerly AMP Sensors) in Valley Forge, PA. for working with us on the design of the PVDF stave and providing the foil. We acknowledge the support of the Things That Think Consortium and our other sponsors at the MIT Media Laboratory.

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