Energy Scavenging for Mobile and Wireless Electronics

Energy harvesting has grown from long-established concepts into devices for powering ubiquitously deployed sensor networks and mobile electronics. Systems can scavenge power from human activity or derive limited energy from ambient heat, light, radio, or vibrations.

Joseph A. Paradiso
Massachusetts Institute of Technology Media Laboratory

Thad Starner
Georgia Institute of Technology, GVU Center

After Alessandro Volta invented the battery in 1799, predating Michael Faraday's dynamo by 32 years, batteries provided the world's first practical electricity source until the wiring of cities in the late 1800s relegated batteries to mobile applications. Despite vacuum-tube electronics' weight and large associated battery,[1] people living in the early 1900s lugged such enormous "portable" radios to picnics and other events off the power grid. As electronics became smaller and required less power, batteries could grow smaller, enabling today's wireless and mobile applications explosion. Although economical batteries are a prime agent behind this expansion, they also limit its penetration; ubiquitous computing's dream of wireless sensors everywhere is accompanied by the nightmare of battery replacement and disposal.

Figure 1 depicts increases in the performance of laptop computers (a mature mobile technology) on a logarithmic scale relative to a laptop from 1990. As the graph indicates, battery energy is the slowest trend in mobile computing. Although new materials are revolutionizing the battery's form factor, its energy density doesn't scale exponentially; rather, battery capacity proceeds along flattening S-curves. Overcoming this trend requires moving to another energy source. New fabrication technologies have recently resulted in micro fuel cells aimed at recharging handhelds with power plants the size of a candy bar, and they promise fuel cells on a chip for powering wireless sensor nodes. Although research prototypes exist, laptop-sized plants (30–50 watt-hours) tend to be too big to directly power with microcells and too small for standard fuel cells, because their associated chemistry requires significant overhead in mass. More exotic emerging power technologies exhibit characteristics that force them into niche applications. For example, radioactive decay can power batteries that last for decades, but they provide low current and involve complicated disposal. Furthermore, devices that burn fuel, such as microturbines and microengines, potentially pose issues with exhaust, heat, noise, thrust, or safety.

Ongoing power management developments enable battery-powered electronics to live longer. Such advances include dynamic optimization of voltage and clock rate, hybrid analog-digital designs, and clever wake-up procedures that keep the electronics mostly inactive. Exploiting renewable energy resources in the device's environment, however, offers a power source limited by the device's physical survival rather than an adjunct energy store. Energy harvesting's true legacy dates

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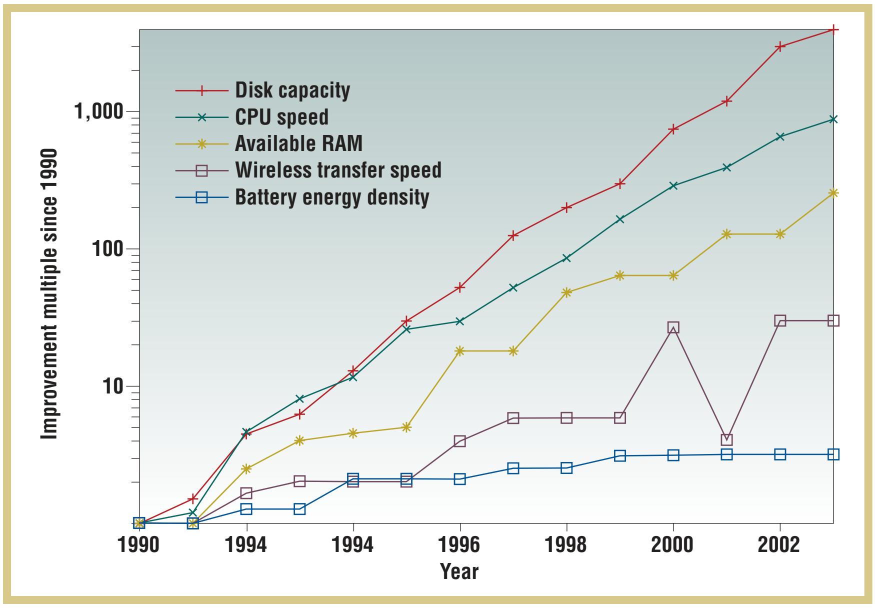


Figure 1. Relative improvements in laptop computing technology from 1990–2003. The wireless-connectivity curve considers only cellular standards in the US, not including emerging, short-range 802.11 "hot spots." The dip marks the removal of the Metricom network.

to the water wheel and windmill, and credible approaches that scavenge energy from waste heat or vibration have been around for many decades. Nonetheless, the field has encountered renewed interest as low-power electronics, wireless standards, and miniaturization conspire to populate the world with sensor networks and mobile devices. This article presents a whirlwind survey through energy harvesting, spanning historic and current developments. For a more detailed treatment emphasizing human-powered systems, see our recent book chapter on the subject.[2]

Ergs from Maxwell

With copious radio transmitters scattered throughout today's urban landscape, we might consider background radio signals as a mobile-device power reservoir. Electronic systems that harvest energy from ambient-radiation sources, however, have extremely limited power and generally require either a large collection area or close proximity to the radiating source. An RF power-scavenging analysis crudely approximates the power density a receiving antenna produces as E^2/Z_0, where Z_0 is the radiation resistance of free space (377 ohms) and E is the local electric field strength in volts/meter.[3] An electric field (E) of 1 V/m thus yields only 0.26 µW/cm², and field strengths of even a few volts per meter are rare, except when close to a powerful transmitter. Although crystal radios derive their energy from broadcast signals, the receiving antenna can be restrictively large unless the set is close to a transmitter, and access to a good ground is usually required. Even so, a crystal set's energy harvest is limited, typically on the order of tens of microwatts.

Another approach, heralding Nicola Tesla a century ago and William C. Brown 50 years later, involves broadcasting RF energy deliberately to power remote devices. This practice is now commonplace in passive radio-frequency-identification systems, which derive their energy inductively, capacitively, or radiatively from the tag reader. Safety and US Federal Communications Commission restrictions severely limit available power—RFID tags generally consume between 1 and 100 µW.

Ambient light presents another opportunity to scavenge power. The energy conversion efficiency of relatively inexpensive crystalline silicon solar cell modules is generally below 20 percent and closer to 10 percent for flexible amorphous silicon panels (standard solar cells produce roughly 100 mW/cm² in bright sun and 100 µW/cm² in a typically illuminated office). Accordingly, the lack of strong, consistent sunlight constrains applications. Nonetheless, the established products that harness light as an energy source span several orders of magnitude in power. These range from solar homes producing kilowatts on a bright day, to solar battery chargers for cell phones that purport to produce up to 2 W of power in direct sunlight, to a PDA that runs off a panel of solar cells lining its case,[4] to Citizen's Eco-Drive watch, which is powered by a solar cell hidden beneath a translucent dial. Researchers continually strive to refine solar cell materials and technologies to increase efficiency (today's best research devices have reached 34 percent).

Thermoelectric conversion

Objects or environments at different temperatures offer the opportunity for energy scavenging via heat transfer (the heat engine running in a geothermal power station is a familiar large-scale example). The Carnot cycle—comprising adiabatic and isothermal operations—provides the fundamental limit to the energy obtained from a temperature difference. The Carnot efficiency is $(T_H - T_L)/T_H \equiv \Delta T/T_H$, where T_L and T_H are the low and high temperatures (degrees Kelvin) across which the thermal generator operates. Accordingly, Carnot efficiencies are limited for small ΔT—for example, going from body temperature (37 degrees Celsius) to a cool room (20 degrees Celsius) yields only 5.5 percent. Mechanical products have been designed to run off the meager energy they harvest from ambient thermal cycling. For example, the Atmos clock harnesses air pressure changes that result

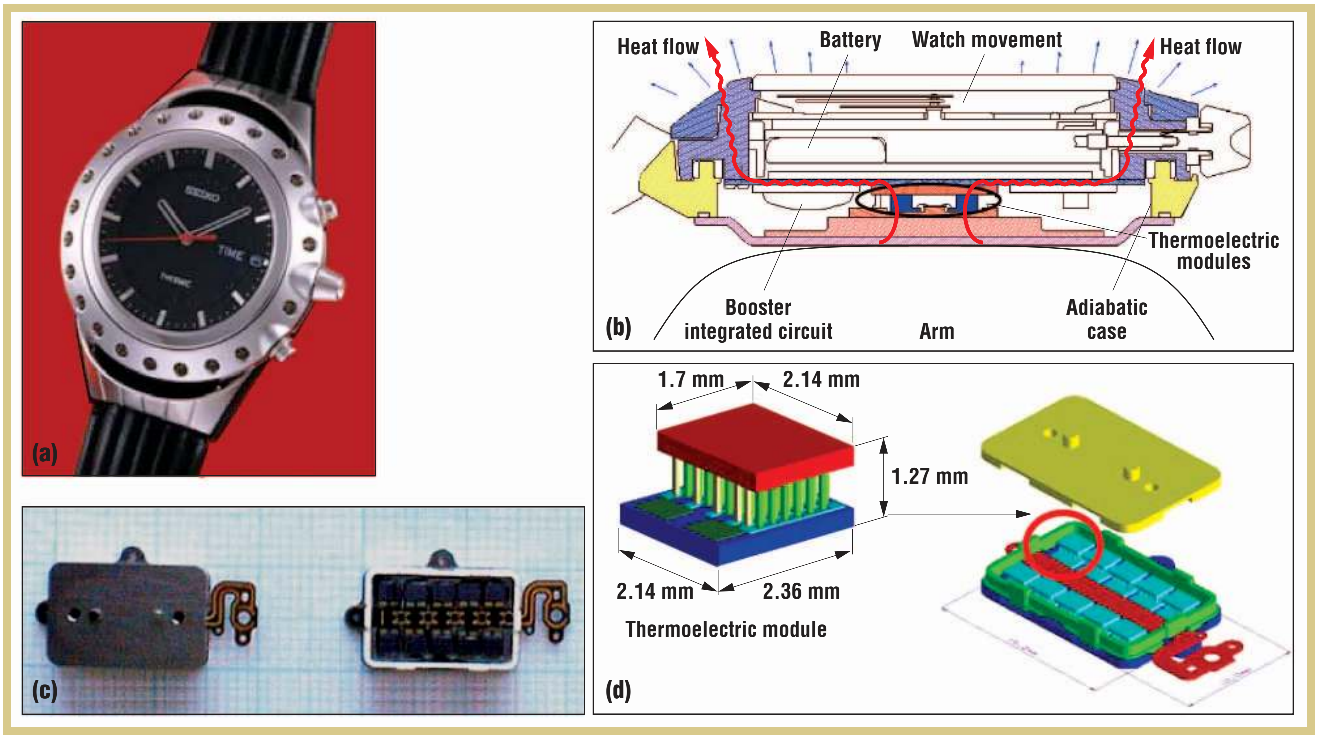


Figure 2. The Seiko Thermic wristwatch: (a) the product; (b) a cross-sectional diagram; (c) thermoelectric modules; (d) a thermopile array. Copyright by Seiko Instruments.

from dynamic thermal conditions.[5] Research into novel thermoelectric and thermionic materials and the development of new kinds of devices, such as thermal diodes and micron-gap thermophotovoltaics, aspires to improve device performance. Energy conversion, however, limits available thermopile arrays, which attain efficiencies well under 10 percent for 200 degrees Celsius to 20 degrees Celsius, but below 1 percent for 40 degrees Celsius to 20 degrees Celsius.[6] Accordingly, thermoelectric generators can deliver significant power with high-temperature sources (such as a hot exhaust pipe) but are much more limited for wearable applications or temperate environments.

Nonetheless, companies have introduced a few wearable thermoelectric products over the last years. For example, the Seiko Thermic wristwatch (see Figure 2) uses 10 thermoelectric modules to generate sufficient microwatts to run its mechanical clock movement from the small thermal gradient provided by body heat over ambient temperature. Applied Digital Solutions' Thermo Life is a thermoelectric generator measuring 0.5 cm^2 in area by 1.6 millimeter thickness. Comprising a dense array of Bi_2Te_3 thermopiles (most efficient at temperatures of 0 to 100 degrees Celsius) deposited onto thin film, it can generate 10 μA at 3 V (6 V open circuit) with only 5 degrees Celsius of temperature difference (according to a personal communication from Ingo Stark of Applied Digital Solutions' Thermo Life Energy Corp.). Accordingly, Thermo Life generators can power low-drain biosensor electronics when in contact with the skin. These systems typically come with batteries that store extra energy produced during periods of higher ΔT so they can continue to run during warmer, less efficient ambient temperatures.

Vibrational excitation

From the subtle vibrations of floors and walls that nearby machinery causes to the severe excitation of an automobile chassis or jet engine housing, mechanical stimuli are common in many settings but can vary widely in frequency and amplitude. Inventors have long designed systems to harvest this energy, usually by exploiting the oscillation of a proof mass resonantly tuned to the environment's dominant mechanical frequency.

Self-winding watches use the motion of the user's body to wind their mechanisms. Abraham-Louis Perrelet created the first known self-winding pedometer watch around 1770, although indications suggest that others might have made earlier versions in the 1600s.[7] Widespread adoption of these systems didn't occur until after the 1930s, when watch cases could be hermetically sealed to protect the mechanism from dust. A modern self-winding wristwatch contains an approximately 2-gram rotary-proof mass mounted off-center on a spindle. As the user moves during the day, the mass spins and winds the mechanism.

Figure 3 shows diagrams of two electronic self-winding watch mechanisms. In the ETA Autoquartz, a proof mass winds

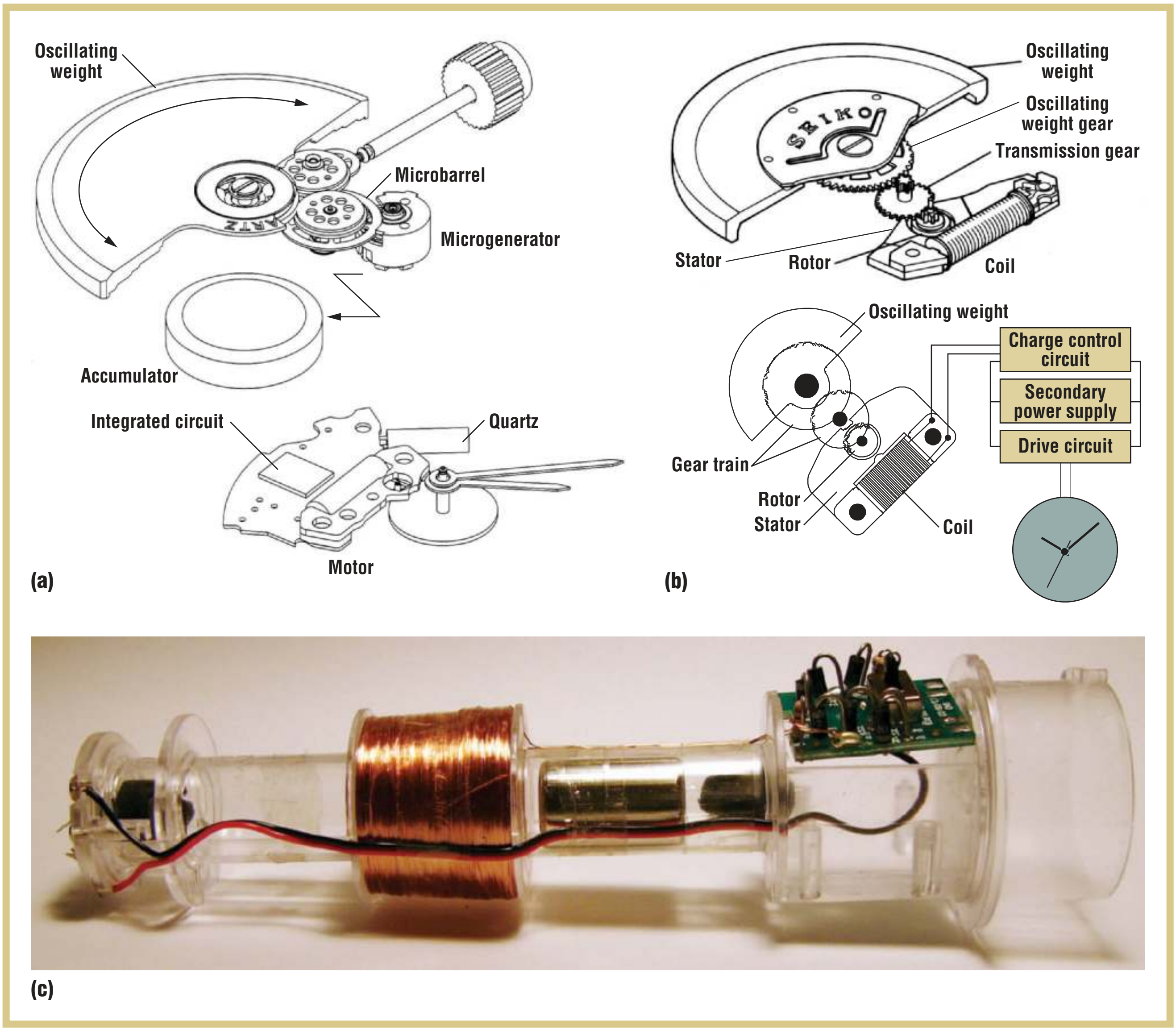


Figure 3. Commercial inertial-power scavengers. Two mechanisms for self-winding electric watches—(a) the ETA Autoquartz design and (b) the Seiko AGS (Automatic Generating System) generator for the Kinetic series—and (c) an inertial solenoid generator from a commercial shake-driven light-emitting-diode flashlight. (diagrams courtesy of the Swatch Group and Seiko Epson)

a spring that pulses a microgenerator at its optimal rate of 15,000 rotations per minute for 50 ms, yielding 6 mA bursts at greater than 16 V that are integrated on a storage capacitor. Seiko's AGS (Automatic Generating System) omits the intermediate spring and produces 5 μW on average when the watch is worn and 1 mW when the watch is forcibly shaken. Similarly, shake-powered flashlights employ a magnetic proof mass that passes through a solenoidal coil, bouncing against rubber bumpers at each end.[8] A typical device's generating mechanism (see Figure 3c) weighs 150 grams and produces 200 mW with a steady shake at its mechanical resonance (roughly 200 cycles/minute).

Driven by strong interest in long-lived wireless sensing packages, many groups have recently developed vibrational microgenerators. (Paul Mitcheson and his colleagues present a review,[9] and we also cite several devices in our book chapter.[2]) The basis for many are moving magnets or coils, as in Figure 3. Although some have been fabricated at the scale of microelectromechanical systems (MEMS), these tend to be larger structures, ranging from 1 to 75 cm^3 (Ferro Solutions' Harvester) or more, exploiting vibrations ranging from 50 Hz to 5 KHz that induce mechanical oscillations between one-half micrometer to over one millimeter, and producing powers that range from tens of microwatts (MEMS) to over a milliwatt (larger devices).

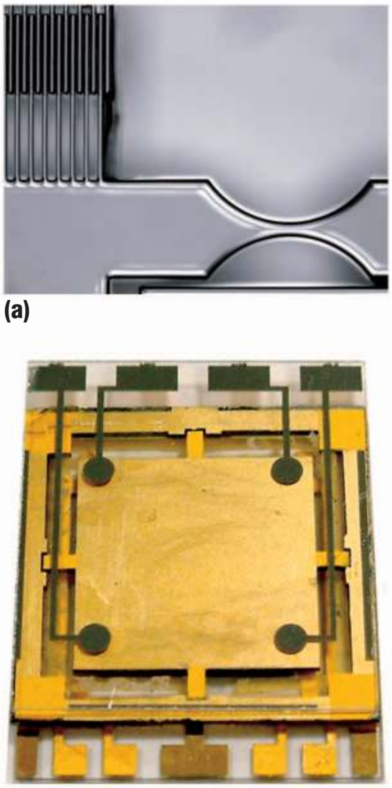


Figure 4. Two electrostatic generators fabricated in microelectromechanical systems: (a) a portion of a constant-gap variable capacitor fabricated at MIT for a 1 cm^2 device and (b) a 2 cm^2 compressible-plate capacitor fabricated at Imperial College. (figure 4a photo courtesy of Anantha Chandrakasan and Jeff Lang, MIT Microsystems Technology Lab; figure 4b photo courtesy of Peng Miao)

Other approaches employ piezoelectric materials. The 1967 US Patent 3,456,134 proposed using a small, tip-loaded piezoelectric cantilever for powering bioelectric implants, claiming that a prototype device produced 150 μW when mechanically coupled to 80-Hz heartbeats.[10] Eighteen years later, US Patent 4,510,484 proposed a similar device for powering wireless sensors in automobile tire hubs.[11] Recently, Shad Roundy and his collaborators have developed a compact piezoelectric generator made from a pair of laminated PZT (lead zirconium titanate) strips to form a tip-loaded, cantilevered bimorph beam that produced nearly 100 μW when shaken at resonance.[12] Piezoelectrics that are bonded to vibrating structural members in bridges, buildings, or aircraft can achieve sufficient strain to generate useful energy. Researchers at Sandia National Laboratories and MicroStrain, for example, have recently developed such strain-based energy harvesters for powering data-logging monitors and wireless sensor nodes mounted on large structures.[13] Ocean Power Technologies exploited strips of piezoelectric foil to harness the power of flowing water, in the form of 18-inch-long "eels" that flap in turbulent flow like a flag in the wind.[14] Dynamic strain coupled from the tire of a moving car has also powered a wireless tire condition monitor.[15]

Other microgenerators consist of a charged capacitor with moving plates. Unlike magnetic and piezoelectric generators, such electrostatic generators need to be "jump-started" with an initial voltage before they can produce power. Because the force between the capacitor's electrodes increases with the square of the applied voltage, the potential to do work (and thus generate electrical energy) correspondingly increases as more charge is loaded onto the capacitor, until charge leakage becomes significant or mechanical problems occur owing to excess force. Although some researchers have developed larger electrostatic generators aiming to exploit low-frequency vibrations in walls or wearable applications, electrostatic generators tend to be small, often MEMS-scale devices, where they benefit significantly from being able to increase energy density with applied voltage. Accordingly, developers design them to be driven at frequencies ranging from hundreds of hertz to several kilohertz, and, depending on their excitation and power conditioning, they typically yield on the order of 10 μW. Therefore, they're intended to support extremely low-power applications, perhaps sited on the same chip as the generator.

Figure 4 shows two such MEMS-scale microgenerators. The device in Figure 4a, which Jeffrey Lang and Anantha Chandrakasan's team developed at MIT,[16] is a constant-gap variable capacitor. The capacitor's plates are realized by the interdigitated tines at the upper left that slide together and apart in the horizontal plane with applied vibration. A portion of an 84-mg proof mass is visible at the lower left, and the structure at the lower right is a flexure spring suspending the comb. The team designed this device to produce 8 μW with half-millimeter comb displacement at 2.5 kHz. Most microgenerators exhibit a mechanical resonance (often in the kHz range at MEMS scale) where vibration can be efficiently coupled. Because environmental excitation, especially from human motion, can occur over a wide spectrum of generally lower frequencies, some researchers have developed nonresonant or tunable microgenerators. Imperial College's Peng Miao and his colleagues have recently realized such a device (see Figure 4b) using a nonresonant snap-action restoring force on the proof mass instead of a continuous spring. Consisting of three stacked wafers and a gold-plated, 0.3-g proof mass, the capacitor's active area is 210 mm^2, and the plates are capable of a 320 μm maximum displacement. Measurements have yielded up to 300 nanojoules per mechanical cycle at 20 Hz (so, 6 μW).

A recent analysis indicated that we can expect up to 4 $\mu W/cm^3$ from vibrational microgenerators (of order 1 cm^3 in volume) that typical human motion (5 mm motion at 1 Hz) stimulates and up to 800 $\mu W/cm^3$ from machine-induced stimuli (2 nm motion at 2.5 kHz).[9] As this surpasses current devices' performance by between one and three orders of magnitude, researchers have plenty of room for improvement.

Power from human input

Another source of batteryless power is

deliberate human input. Inventors have found many opportunities here, exploiting cranking, shaking, squeezing, spinning, pushing, pumping, and pulling to power their devices.[2] Windup magnetic-generator-powered flashlights date to the early 20th century,[17,18] sprouting descendents such as windup cell phone chargers and radios. In a typical windup radio, such as those FreePlay makes, 60 turns (1 minute of cranking) stores 500 joules of energy in a spring, which drives a magnetic generator that's 40 percent efficient, metering out enough power for up to an hour of play. By analogy, hand-charging one of today's 30–50 W-hr. laptop computers would require more than an hour of cranking (and involve a heavy and potentially dangerous spring).

Some inventors have developed more unusual methods of coupling energy into generators. At the MIT Media Lab, Saul Griffith's Bettery—inspired by the Aboriginal musical instrument, the bullroarer—employs a 100–200 gram ball tethered via a 0.3–0.5 m string to a handheld generator. Revolving the ball at 1–2 Hz produces 3–5 W, ample power for a cell phone call.

Robert Adler designed a batteryless, wireless remote control for Zenith televisions in 1956 called the Space Commander (see Figure 5a). Its lineage is more than a century old, in conveyances such as the desk bell. It featured a set of buttons that struck aluminum rods to produce ultrasound, which, when decoded at the television, turned on the power, changed channels, or muted the volume.[19] Active infrared remote controls replaced the Space Commander more than 25 years after Adler designed it.

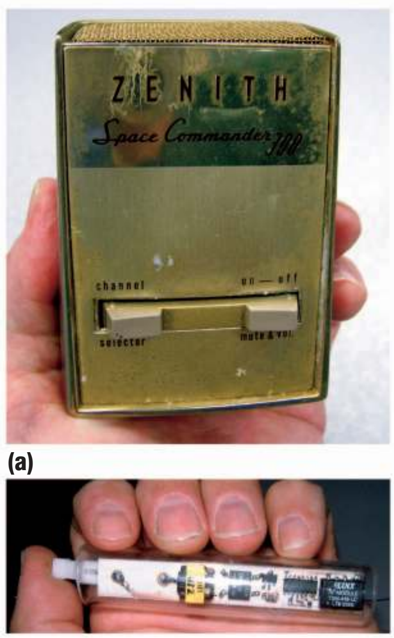
Joe Paradiso and Mark Feldmeier took this theme further in 2001 by using a piezoelectric element with a resonantly matched transformer and conditioning electronics that, when struck by a button, generated approximately 1 mJ at 3 V per 15N push, enough power to run a digital encoder and a radio that can transmit over 50 feet.[20] This device (see Figure 5b), built entirely with off-the-shelf components, enables placing compact digital controllers (such as a light switch) freely, without needing wiring or batteries and their associated maintenance. In the US, a NASA-Langley spinoff is marketing the Lightning Switch, another self-powered piezoelectric radio button. The German company EnOcean is marketing self-powered radio transmitters, energized by a bistable piezoelectric cantilever that snaps when pressed, conditioned by a switching regulator. Their PTM100 produces about 100 µJ per 8N push at 3.3 V.

Ambulatory power generation

From resting to a fast sprint, the human body expends roughly 0.1–1.5 kW.[2] The devices mentioned in this article, however, typically scavenge less than a milliwatt from human activity before their presence becomes obvious or annoying. The most promising way to extract energy more innocuously from people is by tapping their gait. Humans typically exert up to 130 percent of their weight across their shoes at heel strike and toe-off, and standard jogging sneakers' cushioned soles can compress by up to a centimeter during a normal walk. For a 154-pound person, this indicates that about 7 W of power could be available per foot at a 1-Hz stride from heel strike alone.

Patents for electric shoes, based mostly on shoe-integrated magnetic generators, date back up to 80 years.[21–23] Rotary generators' mechanics, however, are difficult to integrate reliably into standard footwear, as evident in Figure 6, which shows two MIT-built generator shoes from the late nineties.[24] Although the sole-integrated generator in Figure 6b was somewhat less cumbersome, both devices were fragile, as might be expected when such complicated mechanics are mounted in shoe soles.

Other approaches that lack moving mechanics, such as piezoelectric or capacitive generators, are more promising. James Antaki and his collaborators at the University of Pittsburgh presented a shoe-mounted piezoelectric generator in 1995 that they developed to power artificial organs.[25] Their device incorporated two cylindrical tubes in the insole, each housing a PZT stack stimulated by a passive hydraulic pulser-amplifier. The amplifier converted low-frequency footfall energy into an intense series of high-frequency impulses that drove the PZT at



(a)
(b)

Figure 5. Self-powered wireless pushbutton remote controls: (a) A 1956 Zenith Space Commander, a passive ultrasound transmitter, and (b) the MIT Media Lab's self-powered wireless switch, which sends a digitally coded radio frequency stream.

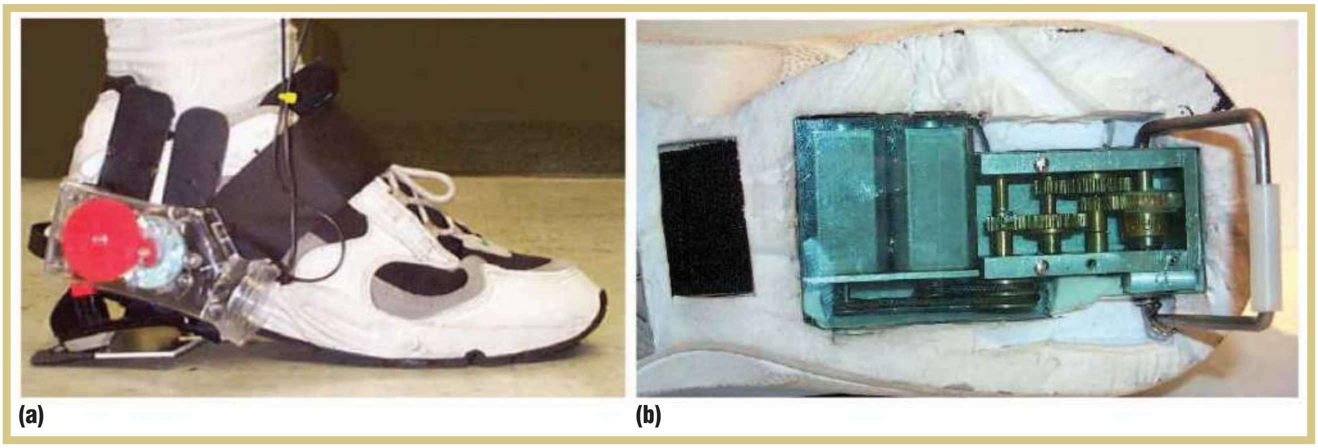


Figure 6. Magnetic generators in shoes at the MIT Media Lab: (a) A strap-on overshoe produced an average of 250 mW during a standard walk, powering a loud radio; (b) an assembly hosting twin motor-generators and step-up gears embedded directly into a sneaker's sole (without springs or flywheels for energy storage) produced 60 mW.

its mechanical resonance. The hydraulic reservoir was differentially compressed during heel strike and toe-off, so power was extracted across the entire gait. Although the prototype was somewhat bulky and heavy, the shoe contained the entire generator. Walking produced average powers of 250–700 mW (depending on the user's gait and weight), and a simulated jog produced over 2 W. MIT's Nesbitt Hagood has pursued a modern version of this approach using a MEMS-fabricated, active hydraulic valve.[26]

Figure 7 shows a simple integration of piezoelectric elements beneath a standard running sneaker's removable insole. Joe Paradiso's team at MIT built the shoe in 1998 and refined it in 1999.[24] The shoe scavenged energy from heel strike by flattening a clamshell made from two back-to-back Thunder PZT/spring-steel unimorphs and from toe-off by bending a bimorph stave made from 16 layers (two 8-layer laminates sandwiching a 1 mm neutral core) of piezoelectric PVDF (polyvinylidine flouride) foil. Owing to limited electromechanical conversion efficiency, the average power harvested was small (8.3 mW at the heel and 1.3 mW at the toes during a standard walk). However, there was no interference with gait, and the piezoelectric elements were effectively hidden in the shoe. Each shoe produced sufficient energy to transmit a 12-bit ID code via an onboard radio to the local area as the wearer walked.

Intrinsic material properties limit piezoelectric generators' efficiency, whereas running capacitive generators at a higher voltage can improve their performance. To take advantage of this property, Ron Pelrine and his collaborators at SRI International have developed electrostatic generators based around materi-

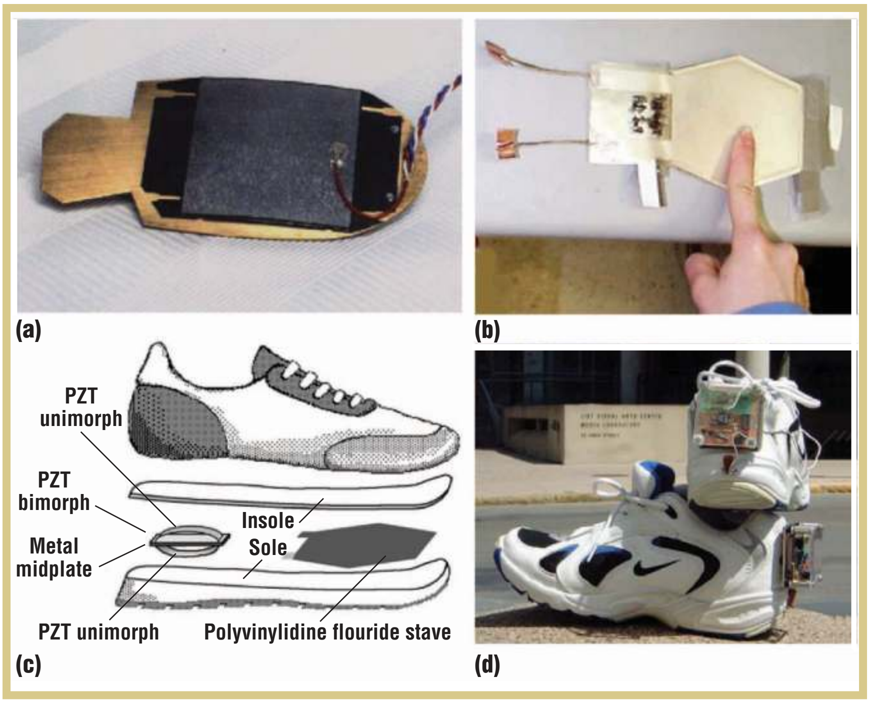


Figure 7. Integration of (a) a flexible PZT Thunder clamshell and (b) a 16-layer polyvinylidine flouride bimorph stave under (c) the insole of a running shoe, resulting in (d) operational power-harvesting shoes with heel-mounted electronics for power conditioning, energy storage, an ID encoder, and a 300-MHz radio transmitter.

als called *electroactive polymers* or *dielectric elastomers*. Made from components such as silicone rubber or soft acrylics, these materials are extremely compliant—a displacement of 2–6 mm can easily drive them to 50–100 percent area strain, depending on the generator's configuration. So, they're ideal substitutes for a running shoe's rubbery heel. They can also be efficient, with a practical device achieving energy densities of 0.2 J/g and calculations indicating a possibility of approaching 1.5 J/g.

The SRI team has built an elastomer generator into a boot heel (see Figure 8). When the heel presses down, the bellows compress, applying pressure to the elastomer membrane. The membrane balloons into the holes in the frame, producing strain, and when voltage is applied across the electrodes, it produces power. They've achieved an energy output of 0.8 J per step with this boot with a heel compression of only 3 mm, yielding 800 mW of power per shoe at a pace of two steps per second.[27] Benchtop testing indicated that the material will last for at least 100,000 cycles. However, the team believes that improved packaging and design can increase the lifetime beyond 1 million cycles—enough to meet commercial footwear's required lifetime. As more compression is feasible in a commercial shoe, they anticipate being able to extract 1 W of power, allowing for a 50 percent voltage conversion (from several kilovolts to 3 V) and storage efficiency.

Matthew Laibowitz and Joe Paradiso have recently explored a means of harvesting translational energy and local navigational intelligence for mobile sensor networks. Inspired by nature's process of phoresis, they've looked at the way small organisms (such as ticks, nematodes, remoras, and burrs) hitch rides on other animals.[28] In what they term *parasitic mobility*, these nodes require no complicated, massive, or power-hungry systems to move around and navigate—they need only a means of detecting and attaching to hosts and locating themselves as they move. Simulations have indicated that although performance depends on appropriate hosts' density and behavior along with the node's requirements for detecting hosts and attaching, this technique is at least an order of magnitude more energy efficient than driving a robotic body directly to a destination. They've built proof-of-concept hardware to explore four parasitic mobility modes. Active attachment nodes, like nature's ticks, launch themselves at a nearby host and detach when they're either at their goal location or are moving in the wrong direction. Passive nodes, like nature's burrs, stick to the next object that they come in contact with (quasipassive nodes can shake off when they want to leave the host). Value-added nodes are symbiotic objects that people carry (such as pens)—the sensor and communications suite is appended to the device's user-attracting functions and travels with it. Although the current active and passive devices are too large to innocuously attach to people and animals, they're amenable to vehicular hosts.

Although many different techniques are available to harvest energy from various environments to power electronics, the amount of available raw energy (for example, sunlight, vibration, heat) and the surface area or net mass that the device permits limit the power yield in pervasive computing's everyday habitated settings. With the exception of heel-strike harvesting in electric shoes or solar cells in bright light, available powers generally hover at mW or μW levels (see Table 1). Nonetheless, researchers are striving to marry more miserly power management techniques with electronics that consume less energy, enabling embedded devices to conduct more useful operations with the limited power that they can commonly scavenge. Accordingly, energy harvesting is an area of rapid development, and the day approaches

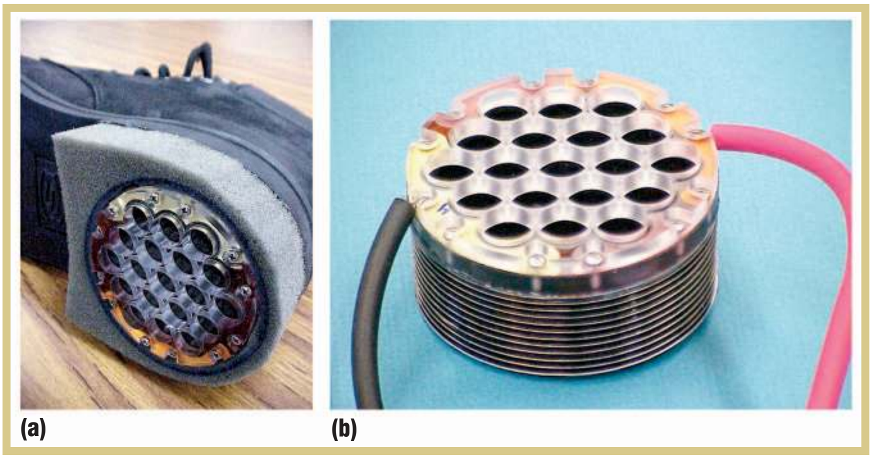


Figure 8. An electrostatic generator based on compression of a charged dielectric elastomer during heel strike: (a) a prototype implementation in a boot and (b) detail of the generator, showing the bellows on the bottom and the retaining frame on top. (photos courtesy SRI International)

TABLE 1
Energy-harvesting opportunities and demonstrated capabilities.

Energy source	Performance[A]	Notes
Ambient radio frequency	< 1 μW/cm^2	Unless near a transmitter[3]
Ambient light	100 mW/cm^2 (directed toward bright sun) 100 μW/cm^2 (illuminated office)	Common polycrystalline solar cells are 16%–17% efficient, while standard monocrystalline cells approach 20%. Although the numbers at left could vary widely with a given environment's light level, they're typical for the garden-variety solar cell Radio Shack sells (part 276-124).
Thermoelectric	60 μW/cm^2	Quoted for a Thermo Life generator at $\Delta T = 5°C$[B]; typical thermoelectric generators ≤ 1% efficient for $\Delta T < 40°C$.[6]
Vibrational microgenerators	4 μW/cm^3 (human motion—Hz) 800 μW/cm^3 (machines—kHz)	Predictions for 1 cm^3 generators.[9] Highly dependent on excitation (power tends to be proportional to ω^3 and y_0^2, where ω is the driving frequency and y_0 is the input displacement), and larger structures can achieve higher power densities. The shake-driven flashlight of Figure 3, for example, delivers 2 mW/cm^3 at 3 Hz.
Ambient airflow	1 mW/cm^2	Demonstrated in microelectromechanical turbine at 30 liters/min.[29]
Push buttons	50 μJ/N	Quoted at 3 V DC for the MIT Media Lab Device.[20]
Hand generators	30 W/kg	Quoted for Nissho Engineering's Tug Power (vs. 1.3 W/kg for a shake-driven flashlight).[2]
Heel strike	7 W potentially available (1 cm deflection at 70 kg per 1 Hz walk)	Demonstrated systems: 800 mW with dielectric elastomer heel,[26] 250–700 mW with hydraulic piezoelectric actuator shoes,[24] 10 mW with piezoelectric insole.[25]

[A]These numbers depend heavily on the ambient excitation and harvesting technologies. By comparison, lithium-ion batteries can yield up to 0.52 W-hr./cm^3 (0.18 W-hr./g), and the Toshiba DMFC (direct methanol mini fuel cell) achieves 0.27 W-hr./cm^3. The theoretical energy available from methanol is 4.8 W-hr./cm^3 (6.1 W-hr./g).

[B]Quoted by Ingo Stark of Applied Digital Solutions' Thermo Life Energy Corp.

when component life rather than battery charge will limit low-duty-cycle sensor systems.

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the AUTHORS

Joseph A. Paradiso is the Sony Career Development Associate Professor of Media Arts and Sciences and director of the Responsive Environments Group at the Massachusetts Institute of Technology Media Laboratory. His research interests include sensor systems for human-computer interfaces and ubiquitous computing. He received his PhD in physics from MIT as a K.T. Compton Fellow. He's a member of the IEEE, ACM, AIAA, APS, OSA, Sigma Xi, Tau Beta Pi, and Eta Kappa Nu. Contact him at MIT Media Laboratory, 20 Ames St. E15-327, Cambridge, MA 02139; joep@media.mit.edu; www.media.mit.edu/~joep.

Thad Starner is an assistant professor of computing at Georgia Tech's GVU Center, where he directs the contextual-computing group. His research interests include mobile computing, human-computer interaction, and computational perception. He received his PhD from the Massachusetts Institute of Technology Media Laboratory. He's a member of the IEEE, ACM, and, because of this article, the National Association of Watch and Clock Collectors. Contact him at 85 5th St. NW, College of Computing, Georgia Tech, Atlanta, GA 30332-0760; thad@cc.gatech.edu; www.cc.gatech.edu/~thad.

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