Self-Powered Wireless Sensors Using Motion-Driven Magnetic Induction

Shwetak N. Patel and Gregory D. Abowd

College of Computing & GVU Center
Georgia Institute of Technology
801 Atlantic Drive, Atlanta GA 30332-0280 USA
{shwetak,abowd}@cc.gatech.edu

Abstract. Energy harvesting to support wireless sensors is key to producing self-sustaining ubicomp applications. In this paper, we present a power source capable of harvesting energy from motion. This energy can support the sensing of data and its wireless transmission. The critical inspiration for this work is an application of Faraday's Law, in which a moving magnetic mass can generate power by passing through a coil of wire. When motion is inherent in the phenomenon or activity being sensed, that target activity powers the sensing and reporting activities. We describe the technical details underlying this idea and provide three examples of its use that are relevant to mobile and ubiquitous computing.

1 Introduction and Motivation

Today's computers have seen an astonishing increase in computational and storage capabilities. However, battery technology has not followed the same desirable trend. The success of ubicomp systems will be contingent on their self-sustainability. It is neither practical nor desirable to replace hundreds of batteries in large distributed sensor networks. Scavenging energy available in the environment for use by low-power sensors and electronics offers an ideal solution for many mobile and ubicomp applications. Recent efforts to create alternative power sources for wireless sensor networks is primarily fueled by the scaling of CMOS electronics that has enabled the development of very small, low powered sensing and communications devices.

Inspired by previous self-powering communicating systems, we explore other ways of harvesting kinetic energy. Our particular focus in this paper is on harvesting power from gross movement to conduct sensor readings and transmission of that information back to the environment at that instant. With further miniaturization and improved engineering, this solution provides great promise for a variety of self-sustaining ubicomp installations.

In this brief paper, we present a prototype implementation of a low-cost, motion-powered system that can drive a wireless sensor. This solution is particularly useful for situations in which the phenomenon being sensed is the motion itself or the change in location that results from that motion. We therefore demonstrate three separate applications of this self-powered system in relevant mobile and ubiquitous computing contexts. In the first two examples, a wireless mouse and a gesture-based remote control, the motion that generates the power is the activity that must be sensed. In the third example, an adaptation of the IR-triggered Active Badge, the motion is a precursor to the significant activity, a location change. We also provide a critical discussion of when this solution is and is not appropriate for different applications.

2 Related Work

Common examples of self-sustaining systems are those that harvest energy from the environment. Solar power is the most popular and well known example. Many calculators, landscape lights, and backup power systems use solar energy. However, solar power is typically limited to well-lit areas outdoors and requires solar cells to be directly exposed to the sun. Recent research in this area has targeted temperature differentials [6, 16], low-level mechanical vibrations [1, 10], and other sources of kinetic energy, such as the natural motion of the human body [7, 14, 15].

Harvesting energy off the human body can power wearable computing devices. Physical motion and actuation, which converts kinetic energy to electrical has proven to be the most successful thus far. MIT's self-powered switch is capable of wirelessly transmitting a static identification number using the power generated from pressing a spring-loaded igniter switch [12]. The flexing of a piezo plate mounted on shoes can produce enough energy to power a simple wireless transmitter [7]. Commercial products like the Faraday Flashlight and the Forever Flashlight use continuous physical motion and magnetic induction to power a LED [3, 4]. Hand cranks have also been integrated into small flashlights and radios to produce temporary power. An off-body example of physical actuation is the Electro-Kinetic Road Ramp in the UK which generates power each time a car drives over its metal plates [2]. This power is stored to run streetlights and signs.

Tagging systems, such as passive RFID systems, use inductive coupling to remove the need for batteries in the tags. The MediaCup [5] and commercial projects like electric toothbrushes use inductive coupling to charge a small battery or capacitor for extended use. These systems are limited in range to only a few inches and long range solutions require very large and powerful inductive readers that are expensive and not practical because of their size.

3 Three Example Applications

Before describing the details of our solution, we introduce three (see Figure 1) wireless sensors that can be fully powered through harvesting the motion inherent to the use of the device. Each example has been implemented as a proof of concept using our motion driven magnetic induction power supply, and they demonstrate different ways that moderate motion can generate enough power to conduct a read of a sensor and a wireless transmission to a receiver. These examples, described briefly in this section with more detailed design information in Sections 4.3–4.5, are a wireless mouse, a wireless gesture-based remote control, and a location tag.

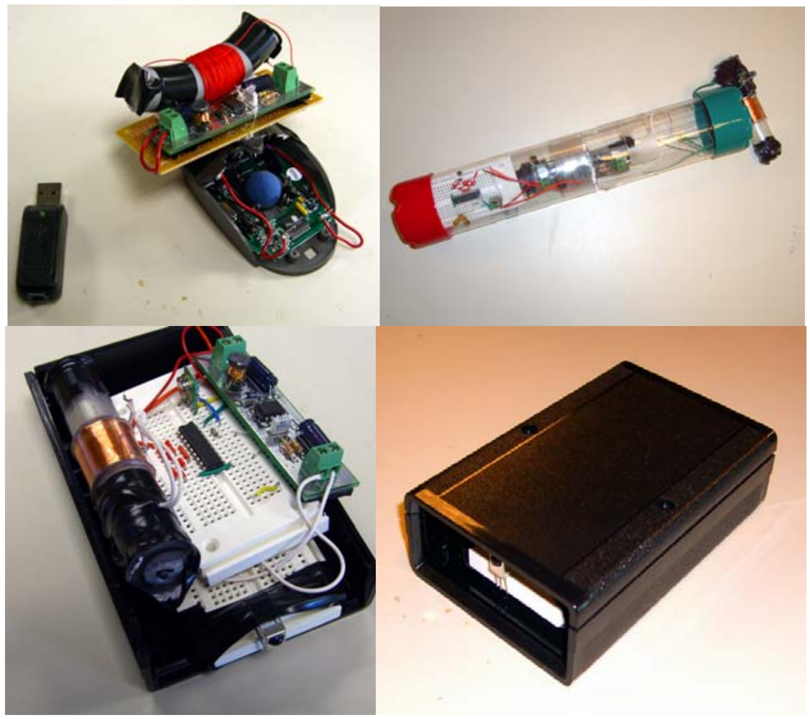

Figure 1: Top Left: Motion-powered wireless mouse. Top Right: Motion-powered orientation/gesture wand. Bottom: Motion-powered location tag.

The self-powered wireless mouse harvests lateral motion produced while operating the mouse. We modified a commercially available wireless RF mouse so that it would operate with our motion-generated power system. The USB wireless receiver for the mouse was not modified in any way, so the mouse operates normally on a personal computer. For this proof of concept device, we attached only a single horizontally orientated power generator, so we only generated enough power to move the cursor during horizontal and diagonal mouse movements.

The gesture-based remote control, similar to the XWand [18], uses multiple tilt switches and a digital encoder to detect the orientation and motion of the wand and then wirelessly transmits its state to a receiver connected to a personal computer. The wand serves as an interaction tool for controlling devices in a smart space, such as changing the channel on a television, controlling the lights in a home, or controlling a cursor on a large interactive display. The wand is composed of four tilt switches to detect two degrees of freedom in free space: horizontal and vertical. Simple gesturing motions provide the power to read the tilt switch settings and transmit via RF. The onboard RF transmitter is capable of transmitting data up to 50 feet away.

The location tag, similar to the Active Badge [17], demonstrates an example of how motion-generated energy is stored and used later when the onboard sensor is triggered. The location tag consists of a wireless transmitter similar to the one used in the motion wand (capable of transmitting up to 50 feet) and an IR receiver. When the tag enters a space with an IR beacon, it optically wakes-up the tag and wirelessly transmits its sensed position. A similar technique is used in the FindIT Flashlight [8]. When an IR beacon is not available, the tag consumes very little power (< 10 µA). Unlike the wireless mouse and wand, the energy is not constantly consumed and only activated when necessary. The advantage of this scheme is that power is not wasted on unnecessary activations of the RF transmitter. If IR beacons are transmitting intermittently, the location tag may stop moving before viewing an IR beacon at its new location. Because the IR sensor is such a low power device, it can wait for an IR beacon event for long periods of time, and only activate the RF transmitter when a beacon is successfully detected. However, it is possible for a user to purposely shake the tag to authenticate into an area similar to waving a RFID access card in front of a reader, but with the added benefit of a longer read range and transmission range with the motion tag.

4 Technical Design

4.1 Theory of Operation

The basic theory behind our device is motion-driven magnetic inductance, a capability demonstrated in commercial products like the Forever Flashlight [3, 4]. The continuous motion of a rare earth magnet through a coil induces a current. In the case of the flashlights, the current is stored in a capacitor and slowly discharged through a LED when the flashlight is activated. Effective use of the flashlight requires about 2 minutes of shaking to store enough charge to run the flashlight for a reasonable amount of time. But continuous explicit shaking is sometimes impractical, and we wanted to harvest energy from more implicit movement that comes about through natural use of an object for its intended purpose (e.g., moving a mouse in order to move the cursor on the screen). To do this, we focus on harvesting power from the voltage spikes created with few movements of the magnetic mass passing through the coil. Faraday’s law estimates this voltage spike as

$$Emf = -N \frac{\Delta\phi}{\Delta t},$$

where N is the number of turns of wire, ϕ is the magnetic flux, and t is time. The number of turns of wire, the magnet strength, the cross-sectional area of the coil, and the velocity of the magnet through the coil all contribute to the resulting voltage.

We use a strong Neodymium Iron Boron rare earth magnet and coils consisting of 1000 turns of 24 or 32 gauge magnet wire around a plastic tube. Moving the magnet 5 cm at 1 m/s generates up to 2 V, which can be produced with the magnet falling 5 cm due to gravity. Oftentimes the coil will not be rotated rapidly enough for the magnet to fall at that velocity, in which case the actual voltage range is about .7 – 1 V. The limiting factors are the tilt and friction of the magnet housing. We use spherical magnets to reduce the amount of friction between the track and the magnet and, at times, curved tubing to induce oscillating motion and reduce need for tilting.

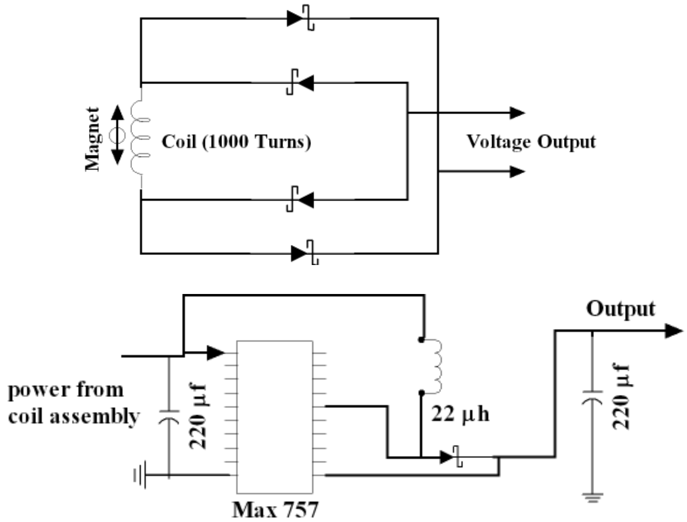

Figure 2: Schematics of the power system. The top figure shows voltage inductor and the bottom figure shows the DC/DC up-converter circuitry.

4.2 Power Source

The charge from the magnetic inductance is passed into a capacitor through a bridge rectifier to prevent the voltage from leaking back out through the coil. We also use efficient Schottky diodes to ensure minimal power leakage. The voltage is then fed into a Maxim 757 [9] step-up DC-DC converter (see Figure 2). The unit provides a regulated 3 V output and continues to provide that voltage level until the input voltage drops below .5 V. After the input voltage drops below .5 V, the output voltage drops to less than 1 V. The temporary source of 3 V is enough to power loads of up to 10 mA (30 mW) with a single hard shake. The load is limited to 10 mA because the Maxim 757 has a minimum startup voltage requirement of 1 V. The converter could handle a larger load if the magnet and coil assembly were to output more voltage or after multiple shakes of the magnet when the capacitors are fully charged. Continuous shaking produces up to 75 mW of power (25 mA loads). However, a 10 mA output is still sufficient to run a low-power wireless transmitter. The powering system does require a few strong shakes during a “cold start” to partially charge the capacitors throughout the electrical circuitry and energize the inductor. After those initial movements, less rigorous movements can sustain the output power. Figure 3 shows a chart of the voltage when powering a 10 mA load after two shakes of the power source.

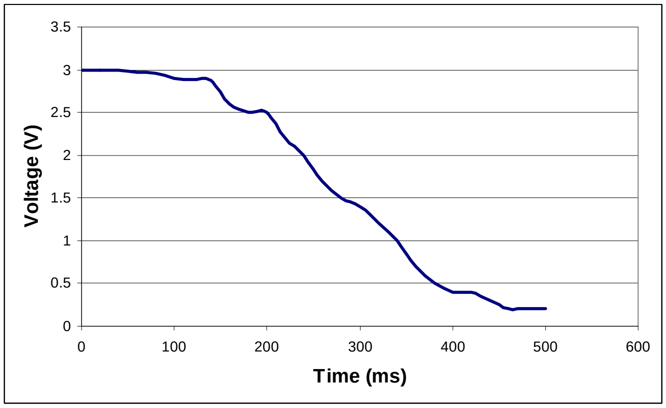

Figure 3: Voltage drop over time when connected to a full 10 mA load. The initial power was generated with two hard shakes

4.3 Motion-Powered Wireless Mouse

The motion-powered wireless mouse harvests energy from the lateral motion produced while moving the mouse. We purposely chose a low-power wireless ball mouse, because optical mice tend to have significantly higher power requirements, in the range of 30-40 mA. The mouse we chose was a generic wireless RF mouse operating at 24 MHz and could operate with 1 V at less than 10 mA, which is within the limits of our power system.

We used a spherical rare earth magnet to reduce friction from the sliding motion. In addition, we built a special curved tubing track for the magnet, resulting in an oscillating effect as the mouse moves in one direction or in alternating directions (see Figure 4). We purposely placed the mechanism at the front of the mouse where it is exposed to the greatest forces. The curved portion of the tube provides additional acceleration during counter movements and ensures that magnet is under acceleration during any movement.

Although the mouse cursor was jerky at times, we were able to produce consistent motion when the mouse was moved large amounts, such as when the mouse cursor is moved across the screen. We had problems with small or very slow movements, but were able to generate enough power when the small movements were accompanied by shaking or alternating motion. Fast diagonal motions also produced enough power to move the cursors. The mouse would benefit from the extra power generated by an identical power system placed perpendicular to the horizontal track to harvest power from vertical movements as well. The current proof of concept prototype did not have any buttons. However, as we demonstrate later in the location tag example, it is possible to store energy from the movement to sense changes in button states and modify the information transmitted from the mouse to its receiver as long as the button press follows some movement. Alternatively, the MIT self-powered button [12] may also be employed in this case.

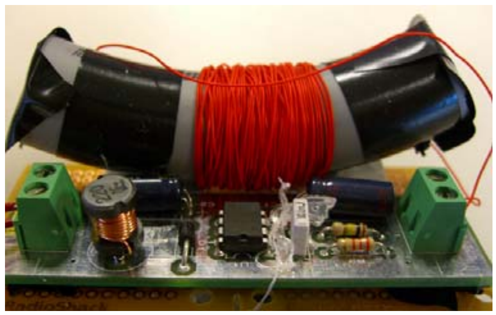

Figure 4: The curved track used in the motion-powered mouse.

4.4 Motion-Powered Wand

The motion-powered wand uses 4 tilt switches and a digital encoder connected to a low power wireless transmitter to transmit its orientation and motion back to a personal computer. Although it is possible to use a low-power Analog Device's ADXL330 accelerometer (2 V at 200 µA), we chose to use tilt switches for simplicity and their ultra-low power requirements.

We use a 12-bit Holtek (HT-640) digital encoder IC to encode the state of 4 copper ball tilt switches (see Figure 5). When a switch is in a tilt position, the corresponding bit is digitally set when connected to ground. The digital encoder supports 4 data bits and 8 address bits, so theoretically we could connect a total of 12 tilt switches to the wand. When any motion is detected (any switch is active) the digital converter transmits its state through the wireless transmitter.

We chose a low-power Rentron TWS-433 RF transmitter that operates at 433 MHz. The advertised operating voltage is 2 V with a 1 mA current draw and a transmit range of 100 feet; we were able to transmit data at 1.2 V. The Holtek digital encoder has an operating requirement of 2.4 V at 100 µA and a standby current draw of 2 µA. When the encoder is activated, it directly drives the TTL input of the transmitter module.

The total power requirement of this system is about 2.4 V drawing about 1.2 mA of current. Constant motion or gesturing of the wand produces enough power to transmit information continuously back to the receiver. Short gestures produce at least one data transmission. We place one magnet track near the front of the wand, similar to the mouse, and place an additional track inside the wand for vertical gestures or movements. Because the wand is placed under significant alternating horizontal and vertical motion during its use, we used a shorter track to maximize the number times the magnet passes through coil. The wand is able to provide excess power during a gesture as shown in the graph in Figure 6.

The receiver consists of a matching RWS-433 RF receiver and a Holtek 12 bit decoder module. A microcontroller polls the decoder's output pins and transmits the encoded data to a personal computer through a serial connection. The state of the tilt switches gives us information about the orientation of the wand and using the time series data we can determine the motion direction.

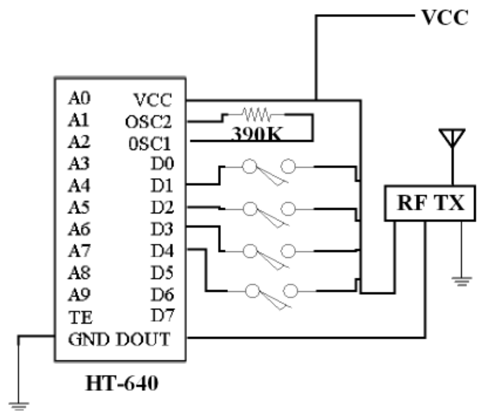

Figure 5: Schematic of the digital encoder and the motion switches found in the wireless motion wand. The power is supplied from the system shown in Figure 3.

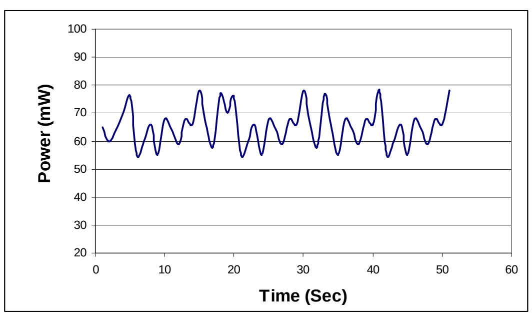

Figure 6: Power output of the motion wand during a gesture.

4.5 Motion-Powered Location Tag

The location tag uses a 433 MHz Linx TXM-433 RF transmitter module that has an operating range of 2.7 - 5.2 V and average current draw of 1.5 mA. In practice, the operating voltage can be as low as 2.2 V, although that does impact transmission distance. Although this RF transmitter has slightly higher power requirements than the one used for the motion wand, this transmitter offers a sleep option. When the input logic is set to low (when there is no data from the sensor) the transmitter consumes less than 2 µA of current. This is a very useful feature since it can be used to "buffer" the power so that it can be used to power the transmitter when data is available, even when there is no motion. The current builds up in the capacitor if no data is available from the sensor. The receiver is built using the matching Linx RXM-433 receiver module and is connected to a PC through a standard serial connection.

The IR detector signal feeds the input of the TXM-433 RF transmitter module through an ultra-low power comparator and transistor inverter circuit. When no data is being received from the IR transmitter, the transistor and the RF module are both disabled. The inverter disables the radio until an IR beacon in the environment is in range of the tag, and then the transmitter is enabled. The RF transmitter simply transmits the modulated IR signal to the receiver. While no IR beacon is present, the IR photodiode, the nano comparator and the RF transmitter all consume less than 10 µA.

5 Discussion

Motion-driven magnetic induction has limitations. It is only able to provide power in response to gross motion or orientation changes, and the amount of power generated by a single flip or shake is short-lived and limited. The physical design is difficult to substantially miniaturize as the weight and strength of the magnet must be sufficient to generate the required power. Additionally, sufficient space must be left between the magnet and any external ferrous material, both to prevent the magnetic field from being dampened, and to shield vulnerable devices such as magnetic audio tape, hard drives, and credit card magnetic stripes from damage.

Despite these limitations, there are some unique advantages of motion-driven magnetic induction and the self-powering devices we describe in this paper. Such a device can have virtually unlimited operational lifetime. It contains no chemicals to degrade over time [11], and its one moving part (and the channel it travels in) can be designed to last virtually forever. The power supply is completely sealed, and can be embedded in a rigid device with no connections to the external environment. The concealability of the power supply (and/or the entire device) is a bonus for reasons of stealth or aesthetics. Although it does not generate power without external motion, when exposed to continuous motion it can generate power continuously, exceeding the overall power density of a battery or other storage device. While not able to compete with the power output of a turbine or generator, motion-driven magnetic induction has the advantage of higher reliability, and no external moving elements.

The primary niche for this type of power source is where a low-power device or sensor needs to activate in response to motion, either to detect the motion itself or a resulting state change due to the motion. In cases of short shelf-life (1-3 years) and limited activations, a battery may be a better alternative. But in the case of much longer shelf lives, or more frequent activation, the ability to generate power reliably upon motion becomes critical. Our wireless mouse is an example of a device which may be activated hundreds of times a day. Although each motion requires minimal power, over the course of weeks conventional batteries would need replacement. Conventional pacemakers need to have their lithium batteries replaced every five to eight years. While radioisotope powered ("nuclear") pacemakers are safe and reliable [13] they have not been accepted by most patients for obvious social reasons. A pacemaker that (re)charges using body motion can provide a "permanent" pacemaker without the stigma of nuclear power.

An extreme example of the shelf-life requirement would be single-use sensors deployed inside the concrete structure of a skyscraper, dam, or bridge designed to chirp upon the catastrophic failure of one or more elements of the structure. In the event of a collapse, in addition to being notified of the event, rescue personnel would immediately know which portions of the structure had collapsed and which remained standing. The same devices could also report on the occurrence and extent of rock or mud slides above roads or buildings. Such sensors could be deployed during construction and be reasonably expected to survive for hundreds of years.

6 Conclusion

We have shown a prototype implementation of a motion-driven magnetic induction system capable of generating a sustained 3 V and 75 mW output when under continuous motion or 30 mW for a single hard shake. We have also shown three devices whose normal use would generate enough movement to support this operation. For situations in which movement is either a precursor to or simultaneous with the phenomenon to be reported, our solution can be considered. As a proof of concept, we presented three different devices, a wireless mouse, a gesture-based interaction tool, and a location tag, which leverage inherent gross movement to conduct sensor readings and transmission of that information back to the environment at that instant. Although this technique has some limitations, it does have the advantages of long shelf-life and the ability to be self-contained without external moving parts or hardwired connection to the infrastructure.

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