A compact human-powered energy harvesting system

Yuan Rao, Kelly M. McEachern, and David P. Arnold
Interdisciplinary Microsystems Group, Dept. Electrical and Computer Engineering, University of Florida, Gainesville, FL 32611, USA

E-mail: yrao1@ufl.edu

Abstract. This paper presents a fully functional, self-sufficient body-worn energy harvesting system for passively capturing energy from human motion, with the long-term vision of supplying power to portable, wearable, or even implanted electronic devices. The system requires no external power supplies and can bootstrap from zero-state-of-charge to generate electrical energy from walking, jogging and cycling; convert the induced ac voltage to a dc voltage; and then boost and regulate the dc voltage to charge a Li-ion-polymer battery. Tested under normal human activities (walking, jogging, cycling) when worn on different parts of the body, the 70 cm^3 system is shown to charge a 3.7 V rechargeable battery at charge rates ranging from 33 μW to 234 μW.

1. Introduction

Vibrational energy harvesting systems that convert ambient mechanical energy in the environment to usable electrical energy represent a promising emerging technology to achieve autonomous, self-renewable, and maintenance-free operation of wireless electronic devices and systems [1-3]. A complete energy harvesting system comprises three main components: an energy harvester that converts the mechanical vibrations into electrical energy, an energy harvesting interface circuit that conditions and regulates the energy, and an energy storage element that stores the intermittent harvested energy.

In this work, a fully self-contained energy harvesting system is demonstrated using an input-powered interface circuit and a non-resonant electrodynamic harvester, designed specifically for harvesting energy from human movements. Compared with a previous design [4], both the harvester and the interface circuit are redesigned and improved. The current system achieves 10% higher net power density (3.3 μW/cm^3) with 30% smaller volume (70 cm^3).

2. System Design

2.1. Energy Harvester

Compared with mechanical vibration sources, human-induced motions are challenging for energy harvesting design because of their low-frequency (1–10 Hz), aperiodic, and time-varying characteristics. The commonly used high-Q resonant-type energy harvesters, which are based on an under-damped, single-degree-of-freedom, mass-spring-damper system are generally not well suited for human movement energy harvesting. The reason is that these resonant systems are optimized to achieve maximum output power within a small frequency range under oscillatory accelerations. Moreover, it is difficult to tune the resonant frequency to the low frequencies of human motions (1–10 Hz) and maintain high quality factor, especially all while maintaining compact device dimensions. Another major restriction of conventional resonant harvesters is that they are typically designed for only one rectilinear degree of freedom, while normal human movements occur in three dimensions and involve a high degree of rotational, rather than oscillatory, motions.

The above challenges motivate the use of a non-resonant harvester architecture, which can respond over a broad range of vibration frequencies and amplitudes, and the use of a multi-directional architecture that can respond to motions in multiple axes. Our research group has previously reported a unique, omnidirectional electrodynamic energy harvester design [5], which is replicated with modifications in the system reported here.

As shown in figure 1, the harvester structure is fabricated in two symmetric hemispheres using a Nylon plastic material from a 3D printer (Shapeways, Inc.). The two halves are fit together to form a spherical cavity (diameter=3 cm) with a permanent magnet ball (diameter=1.27 cm, Grade N40 NdFeB) inside. The upper and lower sections are then each wrapped with ~1400 turns of 34 AWG copper wire forming two independent coils with a resistance of 110 Ω each. The harvester has a total volume of about 39 cm^3 and weighs 68 g.

In operation, the magnet ball moves chaotically within this spherical housing when subjected to external vibrations/motions. The motion of the magnet ball induces a time-varying magnetic flux in each of the surrounding coils, thus generating a voltage according to Faraday's Law. When an electrical load is connected, a current will flow through the coil, thus converting mechanical energy into electrical energy. In the experiments, the two coils are counter-wound and connected in series to improve power generation.

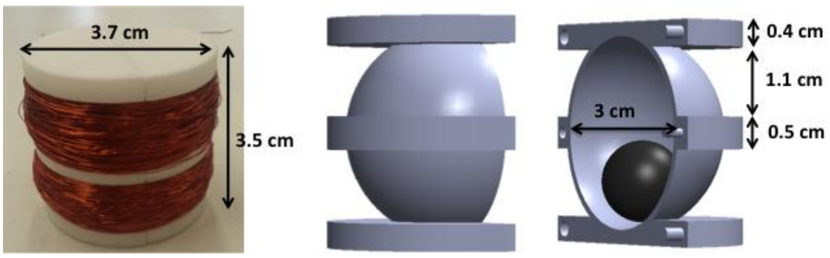


Figure 1. Photograph (left) and 3-D schematic (right) of the energy harvester.

2.2. Energy Harvesting Circuits

The pseudo-random output voltage of the harvester is conditioned by an input-powered energy harvesting circuit, which itself is powered by this time-varying voltage. The block diagram of the circuit is shown in figure 2. It consists of an ac/dc stage and a dc/dc stage, converting the energy from the harvester to the load (battery). The harvester is represented by a voltage source V_S and an output impedance of R_S. The battery is modeled by a constant-voltage (CV) load.

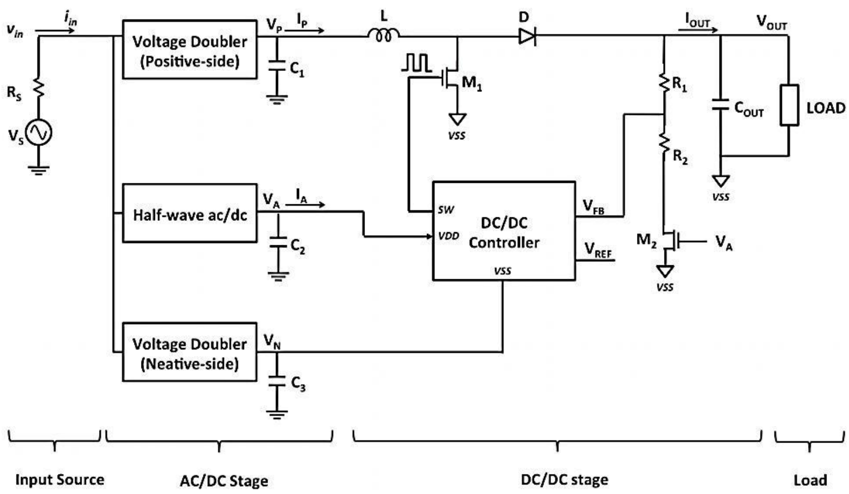


Figure 2. Block diagram of the interface circuit

Two ac/dc converters are used in the ac/dc stage: a voltage doubler, which serves as the primary rectifier in the power path and an auxiliary half-wave ac/dc converter to provide the supply voltage of the dc/dc controller. The dc/dc stage is a boost converter with on-chip dc/dc controller to provide a regulated output voltage for battery charging. Compared with the previous interface circuit design, which used a half-wave rectifier architecture [4], the voltage doubler front-end used here has the benefit of higher output power, and also lower voltage conversion burden to the following dc/dc stage. The auxiliary half-wave ac/dc converter is used to lower the minimum operational voltage of the dc/dc converter (currently 1.2 V_{pk} at 3.7 V CV load).

The circuits are fabricated in silicon using an On Semi 3M-2P 0.5-μm CMOS process. Figure 3 shows the voltage doubler chipset, with a size of 1.6 mm by 1.6 mm, packaged into one SOIC16 package. figure 4 shows the dc/dc controller die, with a size of 1.6 mm by 1.6 mm, packaged in a SOIC 24 package. Both chips are covered by glass lids. Besides the on-chip circuit, there are several external components. The inductor (L) is 22 μH, the capacitors (C_1, C_2, C_3 and C_{out}) are 220 μF, and the feedback resistors (R_1 and R_2) are 3 MΩ and 1 MΩ.

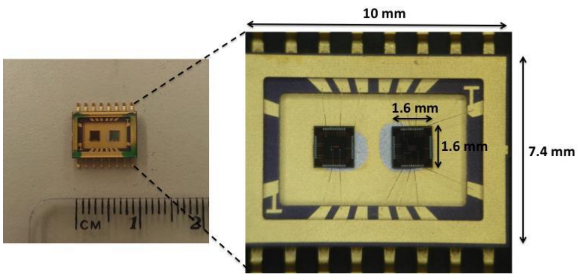


Figure 3. Photo of the voltage doubler chipset

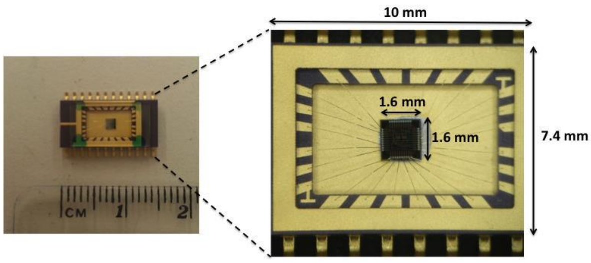


Figure 4. Photo of the dc/dc controller chip

Measurements show that at open-load the system turns on when the input is above 1 V_{pk} and turns off when the input drops below about 600 mV_{pk}. When the system enters sleep mode, there is no measurable standby power consumption. It's important to acknowledge that a commercial button cell battery with nominal voltage of 1.5 V is used to provide the reference voltage (V_{REF}) for the dc/dc controller, because there is no on-chip reference circuit. Note that this battery is connected to the gate of a MOSFET, and therefore the power consumption from this battery is negligible. In future designs, this battery can be replaced by an on-chip bandgap reference circuit.

2.3. *Energy Storage*

In this design where the system size is strictly limited, a rechargeable lithium-ion (Li-ion) battery is used as the energy storage element. A Li-ion battery is chosen here not only because of its small size, light weight, and good energy density, but also because it has no memory effect and slow self-discharge rate. However, Li-ion batteries should be handled with caution, especially in high temperatures, because they can easily ignite or explode. A commercial Li-ion polymer rechargeable battery with nominal voltage of 3.7 V and maximum capacity of 65 mAh is used [7]. The battery has a smaller size (23mm × 12mm × 4mm) and a longer life time (up to 500 cycles charge/discharge) than conventional rechargeable cells. It has a built-in self-protection circuit to avoid over-charge or over-discharge.

2.4. *System Prototype*

The interface chips, capacitors, diodes, and inductor are soldered on the top PCB1 as indicated in figure 5, whereas the button battery and the rechargeable battery are mounted on the bottom PCB2. These two round PCBs with 3.2 cm diameters are mounted on top and bottom surfaces of the harvester to form the complete harvesting system. Figure 6 depicts the prototype system, which has a cylinder structure with 6.3 cm height and 3.8 cm diameter, leading to a total volume of about 70 cm^3 and a total weight of 81 g.

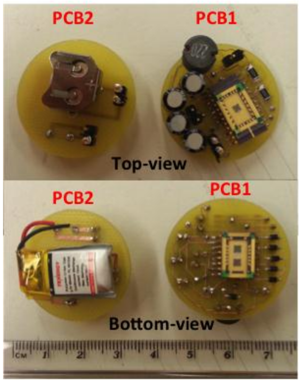


Figure 5. Photograph of the circuit boards.

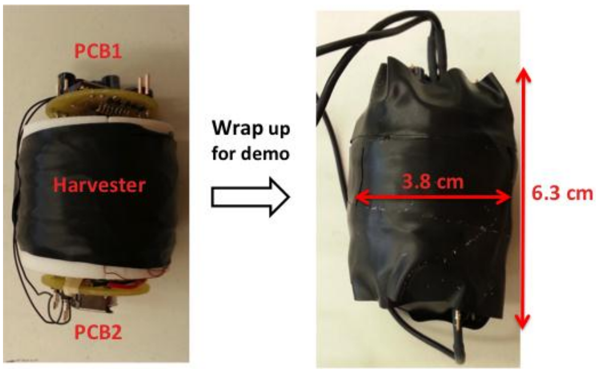


Figure 6. Photograph of the system.

3. System Measurement

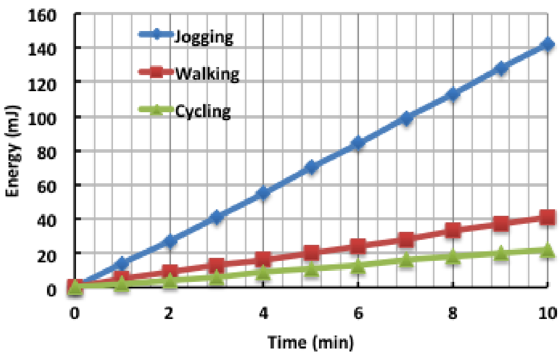
3.1. Measurement Method

The energy reclamation performance of the complete energy harvesting system is then measured when subjected to real human activities. In the experiments, the system is attached to a person's ankle, wrist, or upper arm. These locations are chosen for two reasons. The first reason is that more motion/vibrations are expected at these locations, and thus more energy can be harvested [8]. Another reason is that to attach the system on these locations won't cause too much discomfort in daily human activities, which is important for future applications. Because different people may have different gaits in daily activities, the generated energy will vary from person to person. Therefore, in the experiment, the same person is tested for all the activities, so that the result is consistent among different locations and movements.

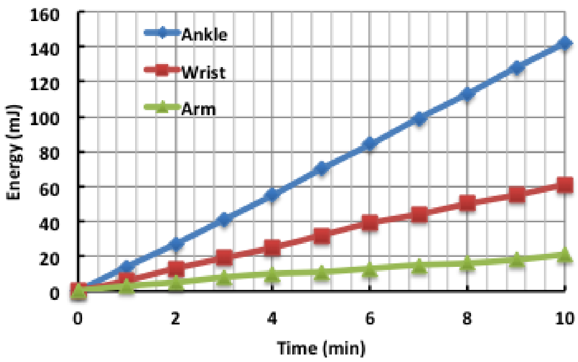
The system energy reclamation is measured for three types of movements: walking, jogging and cycling. Walking and jogging are conducted on a treadmill, while cycling is performed on a stationary cycling machine. By doing so, the speed of each activity is accurately controlled and replicated. Each activity type is tested for 10-minute duration and is repeated by attaching the system to the different parts of the body. To quantify the harvested energy, the battery voltage is measured at 1-minute intervals during the activity. Comparing the voltages to the separately measured battery charging curve at 100 μA charging current, the total energy delivered from the system to the battery is estimated.

3.2. Delivered Energy

Figure 7 (a) shows the estimated energy delivered to the battery versus time when the system is mounted on the ankle for jogging, walking and cycling. Comparing these three activities, the most accumulated energy of 142 mJ is delivered after 10 minutes of jogging. This result is within our expectation, because jogging generates larger vibration accelerations than walking and cycling.



(a) From the human ankle



(b) From jogging

Figure 7. Energy delivered to the battery

Similarly, figure 7 (b) plots the energy delivered during jogging when the system is mounted at the ankle, arm and wrist. Here, cycling delivers more energy than walking and cycling for the same period of time. Note that in both figures, the energy delivered increases almost linearly with the time of human movements, because the speed of each human activity remains constant.

3.3. Output Power

The average harvested power can be estimated by calculating the slope of the lines in figure 7. Table 1 summarizes the measurement results. The average power delivered to the battery ranges from 33 μW to 234 μW for the different configurations tested. When mounted on the ankle during jogging, a maximum power delivery of 234 μW is measured. Due to the relatively small upper-body vibrations, no significant power is measured at arm during walking and cycling, and the same for the wrist during cycling. This is attributed to the energy harvester not generating sufficient ac voltage amplitude for the interface circuitry to function.

Table 1. Average power delivered to the battery

	Ankle	**Wrist**	**Arm**
Jogging	234 μW	100 μW	210 μW
Walking	67 μW	33 μW	N/A
Cycling	34 μW	N/A	N/A

4. Conclusion

A complete self-sufficient energy harvesting system—including a magnetically based harvester, a self-powered interface circuit, and a rechargeable battery—is demonstrated and characterized. The harvester employs spherical magnetic harvester structure, favorable for harvesting multi-directional vibrations from human movements. The system successfully scavenges and converts mechanical energy from ordinary human movements to electrical energy for charging a battery. The measurement result shows that a sustained average power of 234 μW is delivered to the battery during jogging when the system is mounted on the ankle. The total volume of the system is 70 cm^3, and therefore the net power density is about 3.34 $\mu W/cm^3$. Compared with a previous design [5], the current system performance improves with a 10% higher net power density (3.3 $\mu W/cm^3$) and a 30% smaller volume (70 cm^3).

Acknowledgement

This work was supported in part by Texas Instruments via a fellowship for Yuan Rao.

References

[1] S. Roundy 2003 *Energy Scavenging for Wireless Sensor Nodes with a Focus on Vibration to Electricity Conversion* (PhD Dissertation. Berkeley)
[2] S. Beeby, M. Tudor and N. White 2006 *Meas. Sci. Technol., 17* 175
[3] R. J. M. Vullers, R. v. Schaijk, H. J. Visser, J. Penders and C. V. Hoof 2010 *IEEE Solid-State Circuits magazine*
[4] Y. Rao, S. Cheng and D. P. Arnold 2012 *PowerMEMS* 101.
[5] B. J. Bowers and D. P. Arnold 2009 *J. Micromech. Microeng* **19** 094008
[6] http://www.onsemi.com/PowerSolutions/product.do?id=NSR0320MW2T1G
[7] http://www.tenergy.com/30117
[8] N. G. Elvin and A. A. Elvin 2012 *IEEE Trans. on Mechatronics* **18** 637