Feasibility of Energy Harvesting Techniques for Wearable Medical Devices

Thaddaeus J. Voss, Vignesh Subbian, and Fred R. Beyette, Jr., *IEEE Member*

***Abstract*— Wearable devices are arguably one of the most rapidly growing technologies in the computing and health care industry. These systems provide improved means of monitoring health status of humans in real-time. In order to cope with continuous sensing and transmission of biological and health status data, it is desirable to move towards energy autonomous systems that can charge batteries using passive, ambient energy. This not only ensures uninterrupted data capturing, but could also eliminate the need to frequently remove, replace, and recharge batteries. To this end, energy harvesting is a promising area that can lead to extremely power-efficient portable medical devices. This paper presents an experimental prototype to study the feasibility of harvesting two energy sources, solar and thermoelectric energy, in the context of wearable devices. Preliminary results show that such devices can be powered by transducing ambient energy that constantly surrounds us.**

I. INTRODUCTION

Rapid technological advancements in several underlying areas of ubiquitous computing, such as sensors, microcontrollers, and I/O, have led to the emergence and growth of wearable medical devices. The energy consumption of these devices continues to decrease every year with reduction in feature size [1-3]. With this decrease in power consumption and increase in the interest of energy harvesting in the research community, the way portable devices have been traditionally powered can be reevaluated [4]. Energy Harvesting is the process of taking the ambient, passive energy that surrounds us all of the time and putting it to use by transducing it into electrical energy. The energy source can be light from the sun or indoor lighting, from differences in temperature across a material, from small vibrations of materials or movement of a magnet in an electric field, or even from the abundant RF signals in ambient air. The arena for energy harvesting is already vast, and new ways to harvest different types of energy are gaining significant interest within the research community.

Energy harvesting is appealing for many reasons. If the need to recharge and replace batteries can be eliminated, thereby physically removing or interacting with the battery, wireless sensors can be installed anywhere, one time, and never touched again. It is also a cost efficient method as it uses energy that would have been wasted anyway. Furthermore, it is seemingly appropriate for wearable medical devices because these devices are often small and require little energy, on the scale of micro- and milliwatts, even during data acquisition and transmission cycles [5]. Oftentimes, such devices need to be worn for long periods of time, sometimes indefinitely, in order to continuously acquire and transmit data for real-time processing. The appeal of energy autonomous systems is especially important when the implications of a powerless state in a health monitoring system are considered. What if data recording in a device that monitors pediatric insulin levels is disrupted because of insufficient charge in the battery? Thus, reliable and efficient power delivery is critical for devices that monitor health status and bio-signals. To address this issue in such devices, it is advantageous to move towards incorporating energy harvesting solutions as a part of the power delivery scheme of each device. Solar and thermoelectric energy harvesting seems to be most appropriate, as these sources provide a constant DC supply under most conditions. While it is not feasible to completely replace the batteries, these energy harvesting solutions act as a way to charge these batteries and other storage elements.

Thermoelectric energy harvesting involves taking the temperature difference across a material and converting that difference in temperature into electrical current. Solar energy harvesting is similar to solar alternative energy, but works on a much smaller scale using smaller photovoltaic cells. Research has shown that solar and thermoelectric energy harvesting techniques are capable of generating sufficient energy at a rate to sustain an energy-positive system. For photovoltaic cells under indoor lighting, 0.1-1 mW/cm^2 can be delivered to a storage element [6]. Outdoor lighting offers much more power, specifically 15 mW/cm^3 [7]. Furthermore, the form factor of solar cells is such that the cells are not obtrusive to a person wearing them on the body. There are some studies to improve the efficiency of solar cells, which has been historically very low, for better use in energy harvesting for mobile electronic devices using new technologies such as organic and flexible photovoltaic cells [8]. However, little research has been done to prove the feasibility of solar energy harvesting using existing photovoltaic cells for wearable medical devices.

Thermoelectric generators (TEGs) have grown steadily in the past few years, to the point where commercial TEGs can be used in body sensor networks [9]. TEGs can provide 20 – 40 μW/cm^2 on the body, which results from a 5-10°C temperature difference across the TEG [7, 9]. While some research has been done to study the power generation capabilities of TEGs placed on the skin [10], the motivation for such studies has been specifically for textiles with TEGs integrated into them and not for wearable medical devices, in general. Additionally, a full system with a realizable power and battery management scheme has not yet been tested for use in such devices.

Authors are with the University of Cincinnati, Department of Electrical Engineering and Computing Systems, Cincinnati, OH 45221-0030 USA (phone: 513-556-4588; fax: 513-556-7326; e-mail: vosstj@mail.uc.edu)

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II. APPARATUS

An experimental set-up was built to test the feasibility of various energy harvesting techniques as a source of power for wearable medical devices. A complete design, from the transducer itself to the battery storage element, was realized in order to move towards a versatile energy harvesting solution that can be implemented in any portable medical device. As shown in Fig. 1, the experimental set-up consists of (1) a transducer (harvester), (2) DC-DC booster, (3) Maximum Power Point Tracking (MPPT) module, (4) battery management module, and (5) rechargeable battery. The DC-DC booster, MPPT, and the battery management module, working in concert, form an effective power management scheme.

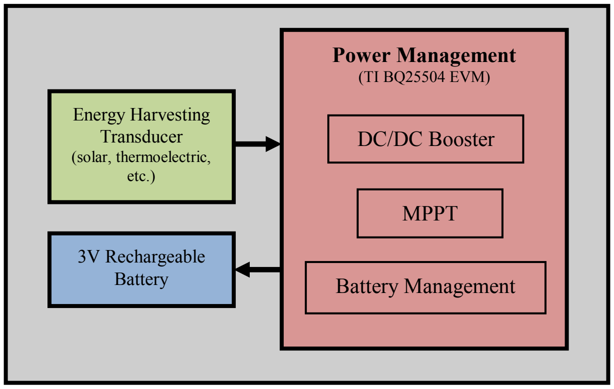

Figure 1. Energy Harvesting Experimental Set-up

A. Energy Harvesters

One rigid, amorphous silicon photovoltaic cell (Cymbet™ Corp.) and two flexible solar cells (PowerFilm) were used to test the suitability of solar energy. The rigid cell is 67.3 x 26.7 mm in size. The two flexible solar cells (flex cell A and B) are 37 x 84 mm and 37 x 114 mm, respectively. For thermoelectric energy harvesting, a Thermogenerator Package (Micropelt, Germany) is used. While the photovoltaic cells are fairly straightforward, as they can be placed anywhere on the body and light will typically reach them, harvesting energy by thermal gradients is more complex. Fig. 2 shows how each part of the thermogenerator package interacts with the human body. The skin is in direct contact with a conductive metal, in this case aluminum. There was no thermally conducting gel applied between the skin and the aluminum. The aluminum transfers heat from the skin efficiently to the hot side of the transducer (thermoelectric generator). Another piece of aluminum is attached between the cold side of the thermoelectric generator and the heat sink. This conducts the air temperature, which is colder than the skin temperature, to the transducer. In this way, the thermoelectric generator experiences a temperature difference across the material. As the area of the heat sink is increased, the voltage and current that can be generated by the generator also increases.

B. DC-DC Booster

In most cases of energy harvesting, a DC-DC booster is required because the small voltages that come directly from solar or thermoelectric transducers cannot effectively charge a battery. Therefore, in order to boost output voltages that are sometimes just tens of millivolts, a step-up converter is required to deliver usable voltages to a storage element.

C. Maximum Power Point Tracking (MPPT)

The MPPT module ensures that the maximum possible power is delivered to a load. It accomplishes this by matching the load impedance to the transducer impedance. Additionally, in photovoltaic cells, the characteristic resistance of the cell varies depending on how much light is available to the cell. Due to these constraints, MPPT is required in both thermoelectric and solar energy harvesting.

D. Battery Management Module

The boosted and maximized voltage is then delivered to rechargeable battery. The voltage and current that is fed into the battery is limited by battery protection circuitry for safe and efficient charging.

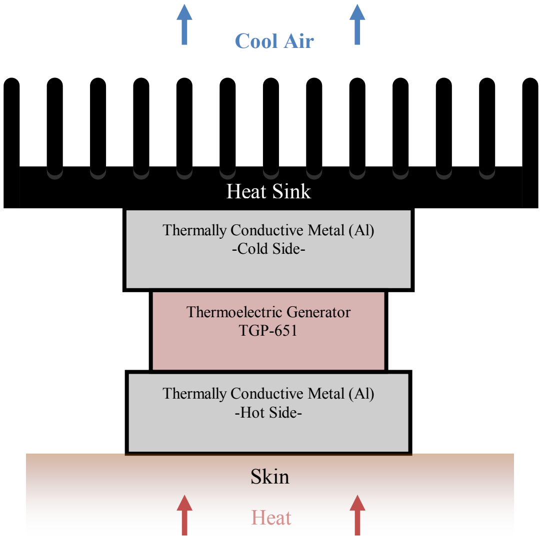

Figure 2. Construction of Thermoelectric Harvester

III. METHODS

In order to study the feasibility of energy harvesting techniques for powering wearable medical devices, the experimental system was tested under several environments in two different places on the body: the upper arm and wrist. The experimental setup shown in Fig. 1 was constructed on a Velcro strap so that it could be easily worn. It has been shown that the best location for maximum power through thermoelectric energy generation on the body is the wrist, specifically on the radial artery [11]. This is where skin is the thinnest and a large amount of blood flows, thus causing more heat flow. This is also convenient as the wrist is a place where traditionally wearable electronics are attached to the body. The upper arm was chosen, as that is another common location for wearable devices. A schematic of the experimental setup worn on the body is shown in Fig. 3. The test subject was a 21-year old healthy male that exercises regularly. Each test was repeated three times and the measurements were averaged.

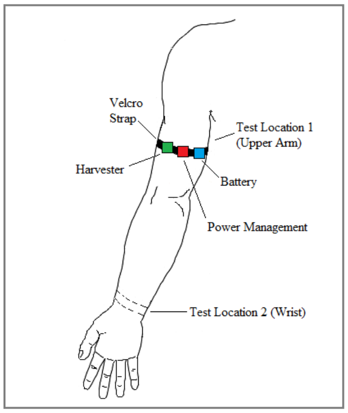

Figure 3. Experimental set-up worn on the upper-arm

A. Experimental Design: Thermoelectric Energy Harvesting

Tests were conducted in both indoor and outdoor settings. During indoor testing, the subject wore the experimental apparatus on the body (upper arm first and then wrist) and collected data under three different states: sitting still, walking on a treadmill, and running on a treadmill.

- *Sitting Still:* The subject sat with the arms on the sides for 30 minutes to allow for the power generated by the thermoelectric generator to settle so that the voltage, current, and the temperature difference across the package can be measured.
- *Walking:* The subject walked on a treadmill at a speed of 2.0, 3.0, and 4.0 mph, for 10 minutes at each rate. At the end of each 10-minute interval, the voltage, current, heart rate, and temperature difference across the thermoelectric generator were measured and recorded.
- *Running:* For these tests, the subject, immediately following the 4.0 mph walking test, began running at 5.5 mph for 5 minutes. The speed was then increased by 1 mph every 5 minutes. At the end of each 5-minute interval, the same measurements as in the walking state were recorded.

For outdoor testing, similar tests were conducted, and in the same order in regards to the three states. The only variation was that the subject walked at a normal pace for 10 minutes and then, immediately jogged at a normal pace for 10 minutes in a typical outdoor setting instead of walking/running on a treadmill.

B. Experimental Design: Solar Energy Harvesting

While photovoltaic cells are commonly used to power present day consumer electronics, little work has been done to determine their suitability for wearable medical devices. Several test cases were created with the solar transducers in order to test the power output of the photovoltaic cells in different lighting conditions. The only changes to the experimental setup shown in Fig. 1 is the transducer itself, and the Velcro strap was only placed on the test subject's upper arm. The subject was then exposed to lighting conditions in three different environments.

- *Indoor:* an office setting, or a setting with complete fluorescent lighting, was first tested. The subject faced the photovoltaic cell both perpendicular to and facing the source of light in this room to see if the orientation of each cell had an effect on the power harvested.
- *Indoor with Window:* The subject stood in a room with windows, offering natural light, as well as with supplementary fluorescent lighting.
- *Outdoor:* For outdoor testing of the photovoltaic cells, the subject walked around outside on a sunny day (13°C) with the cell attached to the upper arm.

IV. RESULTS

Table I shows results collected from the experimental set-up with a thermoelectric generator. Fig. 4 reflects the trends in data found in Table I. It can be clearly observed from Fig. 4 that harvesting energy from the heat from the radial artery on the wrist yielded more power than on the upper arm.

TABLE I. EXPERIMENTAL RESULTS FOR THERMOELECTRIC ENERGY HARVESTING ON THE BODY

Thermoelectric Energy Harvesting on the Body	***Upper Arm***		***Wrist***	
	Power (mW)	***ΔT (° C)***	***Power (mW)***	***ΔT (° C)***
Indoor				
Sitting	0.164	5.6	0.238	5.9
Walking 2.0 mph	0.224	7.2	0.267	7.4
Walking 3.0 mph	0.238	7.3	0.296	7.6
Walking 4.0 mph	0.319	7.4	0.335	7.7
Running 5.5 mph	0.382	7.8	0.465	8
Running 6.5 mph	0.4	8	0.558	8.1
Running 7.5 mph	0.431	8.2	0.612	8.4
Running 8.5 mph	0.468	8.3	0.673	8.7
Outdoor				
Sitting	0.743	9.1	0.928	9.7
Walking	0.602	10	1.03	10.4
Running	0.811	12.9	1.65	13.1

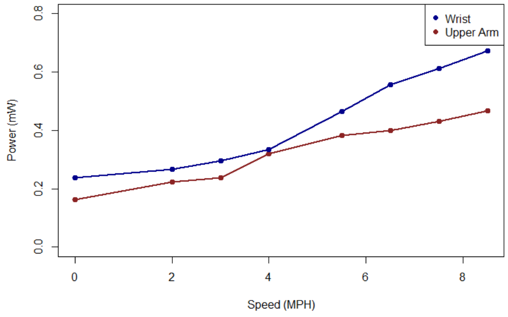

Figure 4. Indoor Testing of Thermoelectric Energy Harvesting in two locations on the body while sitting (0 MPH), walking (2-4 MPH), and running (5.5-8.5 MPH)

Indoor testing of the thermoelectric energy harvester on the body yielded less power than the same tests performed outdoors. This can be mostly attributed to the fact that there is more air flow, due to wind, and more body movement outdoors, resulting in a lower temperature on the cold side of the thermoelectric generator. Additionally, it is important to note that the thermoelectric transducer did not generate a large enough voltage that could be stepped up by the DC/DC booster. Thus, the power values in Table I represent the power that came directly from the transducer, rather than the power going into a battery. Further research is needed to more efficiently convert the transducer output into usable energy. However, these power ratings and trends in data are indicative of power that could be used to drive small devices such as wearable sensors, which often require little power.

Experiments using solar energy transducers also provided very reliable results. Both flexible and rigid solar cells were used in the experimental setup. The rigid and flexible photovoltaic cells, although small in size, provided more than enough power to directly charge the battery. Each flexible photovoltaic cell has a width of 0.2 mm, making them paper-thin. The experimental results from each of these cells are outlined in Table II. The flexible photovoltaic cells produced more power than the rigid photovoltaic cells in the same environments, which could be due to their increased size. Additionally, these bendable solar energy harvesters are desirable for integration with wearable sensor patches. As is consistent with other studies [6-7], outdoor lighting provided vastly more power, on the order of ten times more, than indoor lighting (Table II). Furthermore, the power generated by strictly fluorescent lighting indoors, as well as fluorescent lighting and some natural lighting through windows, are sufficient to supplement power supplies in portable and point-of-care devices in common settings such as hospitals and clinics. If the devices need to be used outside of these settings or need to be used at night, they can be charged whenever there is any light available, even strictly fluorescent lighting.

TABLE II. EXPERIMENTAL RESULTS FOR SOLAR ENERGY HARVESTING ON THE BODY

Solar Energy Harvesting on the Body	***Power (mW)***		
	Rigid Cell	**Flex Cell A**	**Flex Cell B**
Indoor			
Fluorescent Only - Perpendicular to Light	0.39	0.627	0.833
Fluorescent Only - Facing Light	0.556	1.474	2.815
Room with Window - Facing Window	8.42	10.816	42.977
Room with Window - Away from Window	1.2	4.297	5.33
Outdoor			
On a Sunny Day (13°C Ambient Temp)	113	50.16	94.05

V. CONCLUSION

The experimental data (Table I and II) support the idea that energy harvesting is feasible for powering wearable medical devices. For example, an in-house device used to measure head impact in contact sports [12] consumes around 7 µW in idle mode, 80 mW in sleep mode, and 200 mW in the run/active mode. Of these three modes, the device is in active mode for shorter time periods and is less frequent than idle and sleep modes. Thus, assuming that a solar transducer can be easily integrated into a sports helmet, the power that is generated by harvesting natural light is more than enough to charge battery and keep the device energy-positive at all times. Currently, we are also working towards integrating solar energy harvesting into a flexible pulse oximetry patch.

In summary, the data collected from the complete and versatile energy harvesting solution, outlined in this paper, demonstrates that ambient, passive energy can be transduced and utilized to consistently power these devices. Future work in this area will further propel energy harvesting as a driving force in wearable health monitoring systems. A comprehensive look into potentially more efficient thermoelectric energy harvesters that could better harvest energy from the body is needed in order to effectively charge batteries. Integrating these generators into complete and custom packages will give more insight into the optimization of thermally conductive materials used on the hot and cold sides, as well as the most efficient heat sinks to be used for thermoelectric energy harvesting on the body.

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