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Human body heat for powering wearable devices: From thermal energy to application

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ABSTRACT

Energy harvesting is the key technology to enable self-sustained wearable devices for the Internet of Things and medical applications. Among various types of harvesting sources such as light, vibration and radio frequency, thermoelectric generators (TEG) are a promising option due to their independence of light conditions or the activity of the wearer. This work investigates scavenging of human body heat and the optimization of the power conversion efficiency from body core to the application. We focus on the critical interaction between thermal harvester and power conditioning circuitry and compare two approaches: (1) a high output voltage, low thermal resistance μTEG combined with a high efficiency actively controlled single inductor DC-DC converter, and (2) a high thermal resistance, low electric resistance mTEG in combination with a low-input voltage coupled inductors based DC-DC converter. The mTEG approach delivers up to 65% higher output power per area in a lab setup and 1–15% in a real-world experiment on the human body depending on physical activity and environmental conditions. Using off-the-shelf and low-cost components, we achieve an average power of 260 μW (μTEG) to 280 μW (mTEG) and power densities of 13 $\mu W\,cm^{-2}$ (μTEG) to 14 $\mu W\,cm^{-2}$ (mTEG) for systems worn on the human wrist. With the small and lightweight harvesters optimized for wearability, 16% (mTEG) to 24% (μTEG) of the theoretical maximum efficiency is achieved in a worst-case scenario. This efficiency highly depends on the application specific conditions and requires careful system design. The harvesters can power wearables in different use cases, for example a multi-sensor bracelet that measures activity, acquires images and displays results.

1. Introduction

Recent developments in sensing technology, low power processing and communication have enabled a rapidly emerging field, the Internet of Things (IoT), poised to become the largest electronics market for the semiconductor industry [1]. A promising vision is to have billions of sensor devices that are wirelessly connected and can collect and process data to facilitate a wide range of application such as fitness and sports, machinery or health monitoring [2]. The major trend in IoT technology is decreasing of both form factor and power consumption while increasing functionality. A fast growing class of such devices is wearable, where sensors nodes are tightly coupled with the human body [3]. Low power consumption is crucial in wearable systems due to the tight weight and size constraints for batteries, which severely limit the energy that can be stored in the device. Although integrated circuits have significantly improved their energy efficiency, battery technology is not tracking at the same speed in terms of volumetric energy density improvements. Additionally, user expectations for wearable devices imply a lifetime in the orders of months, if not years, instead of daily recharges common for contemporary wearables [4]. Hence, ultra-low power design alone is not sufficient to make these devices truly wearable.

Energy harvesting (EH) is an emerging but reasonably mature technology to overcome the limited lifetime of battery-operated wearable devices and allows continuous recharging of the energy storage during use [1,3]. Wearables are, however, very tightly constrained in terms of size and weight and must also couple with the body. Therefore, the possibilities for EH systems are more

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restricted than for other applications. Energy can be harvested from various environmental sources [5] including light using photovoltaics [6], movement of the wearer [7], from radio frequency energy (RF) [8] or from temperature differences using thermoelectric generators (TEG) [9,10]. Photovoltaic or RF harvesters limit the application of zero-power wearables to environments where sufficient ambient light or RF emissions is provided to satisfy the energy budget. Movement-based harvesting systems require an active wearer and usually have unstable power generation characteristics. The human body in contrast is a constant heat source and typically a temperature difference exists between body core and the environment. Even in a scenario where the wearer is stationary and situated in a dark room (e.g. during sleep), energy can be produced [11]. Lower ambient temperatures, the presence of air convection or increased activity of the wearer can drastically increase the amount of accumulated energy [12]. Because the voltages produced by thermal harvesting are typically too low to power wearable electronics, a conversion stage (DC-DC) with high conversion efficiency needs to be included into a wearable system. A complete system analysis from body core heat to the application is required to maximize both output power and wearability.

Contributions

In this work we report a system analysis and optimization of the complete pathway from human body heat to a wearable hardware platform as shown in Fig. 1. This includes the following main objectives:

- Comparison of different TEG approaches for low-ΔT applications.
- Characterization and comparison of state-of-the-art voltage conversion architectures.
- Laboratory and real-world characterization of two thermal harvesting systems for the human wrist.
- Case study with a zero-power multi-sensor bracelet to confirm that thermal energy harvesting can be effectively applied in smart wearable devices.

After covering the related work in Section 2, we discuss the different building blocks of a body heat driven wearable application and the interaction between the individual elements. Section 3 discusses thermoelectric energy conversion, classification of TEG, their application on the human body and the harvesters used in this study. In Section 4 two voltage conversion architectures and the voltage regulation stage are considered with respect to maximum conversion efficiency and output power. Section 5 reports on the methods used to conduct the experiments including simulations, a synthetic setup, a lab setup and a real-world setup. Section 6 comprises the experimental results including a characterization and comparison of two DC-DC conversion circuits and of two thermal harvesters for the wrist in a laboratory setup and in a real-world field test. In a case study we show how the optimized harvesters can be used to power a multi-sensor wearable, before we conclude in Section 7.

2. Related work

Over the last decade, wearable technology has received increasing attention from industrial as well as academic communities. Many commercial wearable devices became successful products in the wellness and sports domain and there is a number of applications that interface directly with a mobile phone [1]. However, the main drawback reducing the success of wearable device is the limited battery lifetime. To overcome this limit, there are a number of approaches to capture energy from the environment, convert the input to a voltage range usable by connected electronics [13,14] and store it in devices such as batteries or supercapacitors. As wearable devices are required to operate on the human body for long periods (i.e. days, or more), and cannot be supplied with energy by wires during use, achieving self-sustaining systems by energy harvesting is particularly attractive.

The most promising sources of energy for harvesting on and near the body include thermal [15], movement [7], light [16] and RF [8]. As humans frequently move, motion based harvesters are an obvious choice for wearable systems. The transducer can be piezoelectric [7], electromagnetic [17] or triboelectric [18] and are typically located on the limbs or integrated into a shoe. Power generation can be in the μW to mW range but is usually stated before conversion to usable voltages due to a number of challenges related to the power conversion. Body movements are irregular and low in frequency and do not allow for dynamic magnification using resonant designs. Finally in many usage scenarios where the wearer is stationary, no power can be generated at all. Most wearable energy harvesting systems today rely on photovoltaics (PV) as a main power source due to its convenience and high energy output in ideal operating conditions [16,19]. PV cells can be flexible to increase comfort [20] and energy levels are in the lower $\mu W/cm^2$ range indoors to mW/cm^2 outdoors. In contrast to motion harvesters, voltage conversion with high efficiency is possible using commercial circuits. In [16] an ultra-low power multi-sensor wearable was equipped with a solar harvester and the authors demonstrated that the device can be self-sustainable for several days even in indoor conditions with a power consumption of 166 μW. Similarly to motion harvesters, PV power generation is highly situation specific and completely fails in many usage scenarios where insufficient light conditions are present. RF on the other hand is independent from light and movement but requires power lines or machinery in the direct vicinity and only provides a few nanowatts of harvested power [21,8].

Thermoelectric energy conversion of human body heat represents a promising alternative as it is largely independent of external factors [22]. Lossec et al. used a theoretic approach to optimize the thermal system of TEG worn on the body [23]. In [24] the authors reported on a wearable medical system that is powered by body heat and detects if a patient falls down. Leonov et al. presented a thermal harvester worn on the wrist that can be used to power a pulse oximeter [11]. The authors demonstrated that in many indoor scenarios, the average power harvested per square centimeter is higher using the thermal harvester than a equally sized solar cell. However, the produced voltage is used to directly

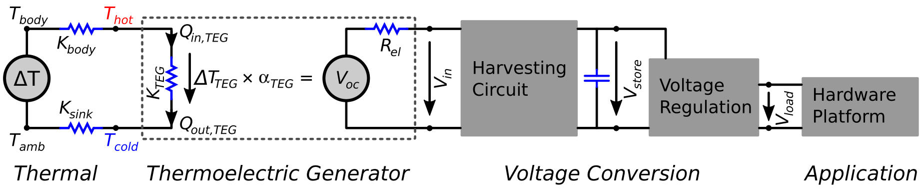

Fig. 1. System overview of a TEG harvesting driven wearable application.

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