Inertial Energy Harvesting for Wearables

System Architectures, Power Generation Limits and Transducers

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***Abstract*—The growing prevalence and variety of wearable devices has led to a renewed interest in harvesting energy from the motion of the human body. We have been working on inertial energy harvesters in which the human body motion excites a proof mass whose motion is then transduced to electrical power. This paper synthesizes many of our findings over the past few years. We first quantitatively compare different mechanical system architectures concluding that, at least for a walking excitation, a sprung rotational structure has significant performance advantages. Secondly, we consider the theoretical upper bound for inertial rotational energy harvesters and compare existing devices to this upper bound. We highlight factors that can explain the gap between existing device performance and the theoretical maximum. We then consider the practical effects of piezoelectric, electromagnetic, and electrostatic transduction. Finally, we demonstrate a rotational electromagnetic prototype with performance exceeding existing devices, but still well below the theoretical maximum.**

Keywords—energy harvesting; wearables

I. Introduction

The recent explosion of wearable electronics is driving a large interest in the ability to harvest energy from the wearers of such devices to replace or augment batteries [1]. Wearable electronics include devices such as smart watches, activity trackers, intelligent clothing, and unobtrusive health and wellness sensors. Existing wearable energy harvesters in the form of self-powered watches [2], [3] generate less than 10 μW on average [3], [4]. This level of power is not sufficient for any but the very lowest power consumption wearables.

In order to address the shortfall in power generation from currently available commercial devices and the needs of new and emerging wearables, researchers have explored various potential avenues. Many, including us, have investigated harvesters based on a rotational mass [5], [6]. Others have investigated inertial devices with linear translational proof masses [7]. Piezoelectric [5], electromagnetic [6], [7], and electrostatic [8] transducers have been used. Although there has been significant work on clothing integrated harvesters, including harvesters in shoes, for the purposes of this paper we will restrict ourselves to wearable energy harvesters that make use of an inertial proof mass that moves in response to human motion. This proof mass motion is then converted to electricity via some transducer. For a more complete review of energy harvesting for wearables including clothing integrated harvesters we refer the reader to [1].

The goal of this paper is to synthesize research on inertial wearables done in our lab over the last few years and bring this work into a wider context. We specifically want to address the following questions. How much power is available for wearable energy harvesters? What is the effect of mechanical system architecture? What is the effect of different transduction methods? The remainder of this paper is organized as follows. We first evaluate different system architectures and apply non-transducer-specific models to estimate the bound on power generation. We apply these models to six-axis inertial measurements taken on 10 human subjects to estimate the range of expected power during different human motions. We characterize existing commercial devices and discuss the factors that can explain the gap between these devices and the theoretical maximum power. Finally, we investigate the role of different transducers on power generation and show results from our own wearable energy harvester prototype.

II. System Architecture

The first goal of any motion-based energy harvester is to effectively absorb kinetic energy from the excitation source. Within the context of inertial energy harvesting for wearables, the mechanical system architecture refers to the specific configuration of mechanical elements. For example, the proof mass might be rotational or translational. The proof mass may be allowed to move along (or about) one (1-D), two (2-D), or all three (3-D) axes. A restoring spring may or may not be present. Finally, in the case of translational devices, mechanical limit stops will generally be present. Although this classification cannot be all-inclusive, we find that the vast majority of energy harvesters in the literature conform to one of the following three classifications: 1-D rotational, 1-D translational, 2-D translational. Each of these devices could come with or without a restoring spring, resulting in six total classifications. For more details on the reasoning and modeling of each class, we refer the reader to Rantz et al. [9].

In order to compare these mechanical architectures, we model the electromechanical transduction simply as an electrical damping element and calculate the maximum power generation as the power dissipated through this electrical damping element. We assume that the value of the electrical damping is designable, and therefore select the optimal value for power generation. This is a common approach used in vibration and motion-based energy harvesting [10]. Although, to our knowledge, this approach has not been shown to produce the theoretically optimal power output from motion-

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based harvesters generally (i.e. including rotational, non-resonant, and nonlinear harvester) it still serves as a good first practical step to quantitatively evaluate a large set of system architectures.

The fact that the power generation capability, and optimal harvester design, depend so strongly on the source of mechanical excitation presents a significant difficulty in the evaluation of different types of energy harvesters. In the case of vibration energy harvesting, this concern is mitigated by standardizing excitation sources, a single frequency vibration or white noise for example. However, in the case of wearables, this standardization is not as straightforward. In our opinion, the lack of representative standardized methods for evaluation results in much confusion when trying to compare the merits of different harvester designs. Our approach has been to measure the accelerations and rotation rates on human subjects at several locations for different activities and then use the measured signals as inputs to our models [9]. For the purposes of this paper, we mostly restrict the results to the wrist. However, other studies [4], [9] have shown similar trends for upper arm, torso and waist locations.

We collected six-axis inertial measurements on 10 subjects while walking on a treadmill at 3.5 miles per hour (mph). These data were used as inputs to MATLAB based dynamic simulations. We then optimized the dimensions of each harvester type subject to an overall size constraint of 1 cm^3. We calculated the power output for each subject as the power dissipated through an optimal electrical damper. For more detailed information on modeling these architectures, including experimental validation of the models, we refer the reader to Rantz et al. [9].

Fig. 1 shows the results of this simulation process for four different architectures. Fig. 1 shows only the 1-D rotational and translational structures because device optimization of the 2-D translational structure always reduces to a 1-D structure. That is, the geometric optimization always uses all available space for a single linear dimension. The first thing to notice from Fig. 1 is that there is a large amount of variation from person to person even for the same body location and activity (i.e. walking at 3.5 mph). However, even with this large variation, it is clear that the sprung rotational structure produces more power than the other architectures. (See Fig. 4 below for a photograph of such a structure.) The addition of a spring to the translational structure also improves its power output. However, we note that the benefit of the spring may partly just be due to this specific excitation. When attaching the device to another location, one's ankle for example, the spring many not have the same benefit.

A second benefit of rotational harvesters that is not captured in the above data is the fact that they are sensitive to motions along or about many axes. Walking is very periodic with most of the motion occurring along one or two dimensions. However, the rotational harvester is sensitive to motions along two of three linear axes and about all three rotational axes. Given these results and observations, it makes sense to devote more attention to the 1-D rotational architecture.

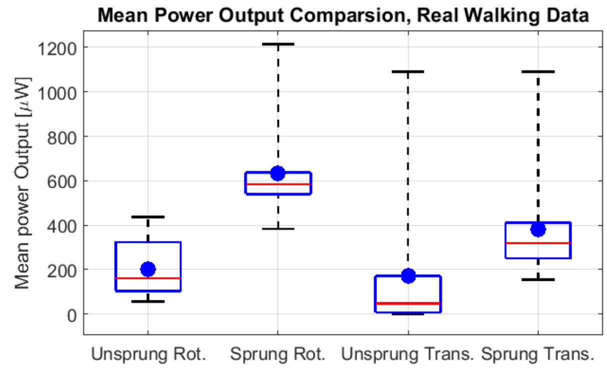

Fig.1. Box plot indicating the median, maximum, and minimum simulated power output for each device architecture, along with quartiles. Mean power output is indicated with a blue circle.

III. ROTATIONAL ENERGY HARVESTERS

One dimensional rotational energy harvesters have been available as commercial products for some time in the form of self-powered quartz watches [2], [3]. We have measured the power output from the two dominant self-powered quartz watches, Seiko Kinetic and Kinetron micro generating system (MGS), on six subjects under various common activities. Furthermore, using the inertial measurements from these same subjects we have calculated the optimal power output for a 1-D rotational harvester of the same size. Fig. 2 shows the average measured power output for each device along with the average calculated upper bound power output. At higher excitations the two watches perform similarly, however at lower excitations, the Kinetron watch outperforms the Seiko watch. This behavior can be explained by the difference in the mechanics of the two watches; however, such a discussion is beyond the scope of this paper. The horizontal axis in Fig. 2 is the rotational inertia of the proof mass showing that, as expected, power output increases with increasing size and inertia. But, the more interesting finding is that there is a significant gap between what is theoretically possible and what is produced by these devices. This finding is especially true for low intensity excitations such as walking or writing on the whiteboard.

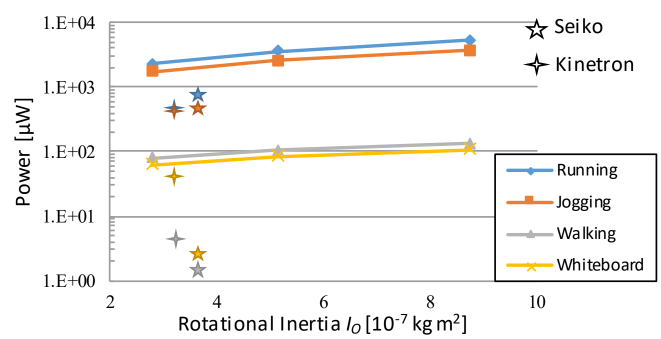

Fig. 2. Average measured power output for Seiko and Kinetron self-powered watches worn on the wrist and calculated upper-bound power for six subjects performing various activities.

To understand this gap, it is instructive to consider the simulated power output as a function of the mechanical and electrical damping. Fig. 3 shows the simulated upper bound power output versus electrical damping coefficient under conditions of walking at 3.5 mph. The figure shows curves for a mechanical damping coefficient of b_m = $1x10^{-7}$ N-m-s/rad, which is the damping that we measured on one of our own rotational prototypes, and b_m = $2x10^{-6}$ N-m-s/rad, which is what we measured on the Seiko watch. It is clear that a lower mechanical damping coefficient can result in a much higher power output. So, why is the mechanical damping of the Seiko watch so high? We believe the primary issue is that the Seiko watch requires a gear train (gear ratio of 1:94.6) to create a very high rotational velocity for the electromagnetic generator. This high rotational speed is needed to produce sufficient voltages. But, the high speed comes with negative consequences. Namely, the torque effect of the friction (or damping) on the rotational proof mass from the high speed bearing is multiplied by the gear ratio. So, the mechanical damping felt by the proof mass is very high. The mechanics of the Kinetron device are significantly more complex [3]. However, it too has a gear train and a high-speed rotor that is part of the generator. Designing a system that does not need a high-speed rotor as part of the power generation system could have significant benefits to overall power output. Furthermore, as shown in section II, the addition of a rotational spring can even further enhance power output.

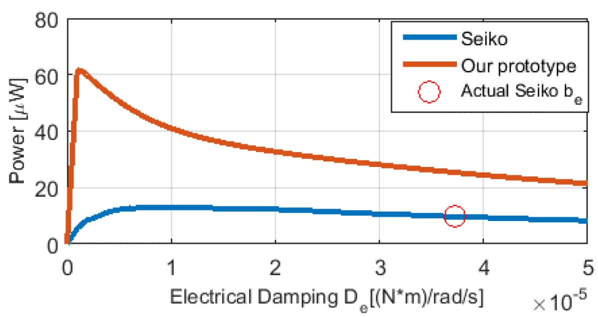

Fig. 3. Simulated power output versus electrical damping coefficient for rotational harvesters with b_m = 1x10^{-7} N-m-s/rad (characteristic of our prototypes) and b_m = 2x10^{-6} N-m-s/rad (characteristic of the Seiko Kinetic watch). Inertial properties of Seiko Kinetic watch used for simulation.

IV. The Effect of Transducers

Up until now, we have modeled the transducer as an electrical damper. This is convenient when considering different mechanical system architectures and in calculating the upper bound power in a non-transducer-specific way. Modeling the electromechanical transducer as an electrical damper functionally means that the mechanical force or torque induced by the transducer's extraction of energy is linearly proportional to proof mass velocity (translational or rotational). This force or torque – velocity relationship is generally a good model for electromagnetic transducers, but does not model piezoelectric or electrostatic transducers as well. However, in all cases the transducer extracts kinetic energy from a proof mass and induces a non-conservative damping force on that proof mass. We can say with some confidence that the damping forces induced by the three most common transducers are suboptimal to a similar degree. Therefore, if the transducer is optimally designed for energy extraction, none of the three common transducer technologies (electromagnetic, piezoelectric, and electrostatic) is likely to result in more power generated than that calculated by the power dissipated through an optimal electrical damper. Thus, the selection of a transducer technology (i.e. piezoelectric, electrostatic, or electromagnetic) is mediated by the practical considerations of the application. The remainder of this section covers what we believe to be important practical design considerations and presents experimental results from a rotational energy harvesting prototype.

A. *Energy Transduction Rate*

Can the transducer extract energy at the optimal rate with available materials and in the available space? One reason for mechanical gearing, or a frequency-up-conversion system, is that it can increase the rate of energy extraction. For example, the magnets in the Seiko watch are very small, but it extracts energy at a high rate due to the very high gear ratio. Our own modeling and prototyping efforts indicate that for watch-sized wearable energy harvesters, any of the three standard transducer technologies can extract power at the optimal rate without the need for a gearing system.

B. *Voltage vs. Current Generation or Source Impedance*

At low frequencies, piezoelectric and electrostatic transducers have very high source impedance while electromagnetic transducers have very low source impedance. Very low source impedance is practically harder to deal with since efficiently rectifying a very low AC voltage is difficult, or not possible if the voltage is low enough. Rectifying and conditioning high voltages generated by piezoelectric or electrostatic transducers is an easier task. Again, one reason for the gearing systems in commercial devices is to increase the voltage of the electromagnetic generators.

C. *Mechanical Losses*

As demonstrated in Fig. 3, minimizing mechanical losses is of paramount importance to maximizing generated power, especially from light excitations. Losses can come from rotational bearing friction. At low speeds, this tends to be very low. However, at high speeds, it can be significant and thus the gearing systems of commercial devices can negatively affect power generation. Piezoelectric and electrostatic transducers typically do not need any gearing system to generate sufficient voltages. Losses can also come from unwanted eddy currents generated by moving magnets. For piezoelectric devices, losses can come from internal material losses and from mechanical anchors or clamps. In our experience, the losses emanating from mechanical anchors and clamps are far more significant than internal material losses.

D. *Unwanted, Non-dissipative Forces*

Piezoelectric and electrostatic transducers by their nature require the application of non-dissipative forces that can have a significant effect on the overall dynamics of the system. Piezoelectric transducers require mechanically stressing the piezoelectric element, which is usually ceramic and quite stiff. Part of the mechanical energy required to stress the material is converted to electrostatic energy that is available to be used by an electronic circuit. The remainder remains stored as elastic energy that can be returned to the system. However, this elastic force, although conservative, can have a significant impact on the system. For example, many rotational wearable harvesters transduce energy by plucking piezoelectric beams [5]. The elastic force required to bend the beam acts as a detent, or cogging, torque on the system. Thus, at low excitations the proof mass can become stuck in one position.

Suzuki has pioneered the use of electret based electrostatic devices for energy harvesting including wearable energy harvesters [8]. These systems also inherently have a cogging torque as well as an out-of-plane attractive force that can have negative effects on system dynamics. Suzuki et al. [8] have carefully engineered their systems to mitigate the effect of these forces. The presence of these unwanted non-dissipative forces is one practical consideration that argues for electromagnetic transducers. The primary argument against electromagnetic transducers is the low source impedance resulting in very low voltage generation.

E. Prototype Results

Our group has designed, built, and engineered a variety of wearable energy harvesters based on the 1-D rotational structure [1], [9]. We have built both plucked piezoelectric and electromagnetic harvesters. We have also built sprung and unsprung structures. Fig. 4 shows an example of one of the prototype devices that we have built and Fig. 5 shows its performance, simulated and measured, for five human subjects on both the wrist and ankle while walking at 3.5 mph. Fig. 5 shows the performance for both a sprung and unsprung version of the prototype. For the relatively light excitation seen on the wrist the sprung device performs significantly better (42 μW compared to 6 μW for the unsprung device). However, for the more vigorous excitation seen on the ankle, the unsprung prototype performs better (486 μW vs 219 μW average over five subjects). This seems to be due to the fact that higher excitations create a beneficial continuous rotation in the unsprung device. In general, our unsprung prototypes do outperform existing products, but not by much. However, the addition of a spring makes a large difference in power output for light excitations. In both cases, there is still a significant gap between what we and other researchers have achieved and what is theoretically possible.

V. Conclusion

In this paper we have briefly summarized some of the key insights and results of our research on inertial energy harvesters for wearable applications. In particular, we have quantitatively evaluated different mechanical system architectures concluding that for many normal human activities, such as walking, a 1-D sprung rotational harvester seems to perform the best. Evaluating rotational energy harvesters existing in the marketplace leads to the conclusion that there is significant room (up to a factor of 10) for improvement. Three primary transduction types (piezoelectric, electromagnetic, and electrostatic) have been used in wearable energy harvesters. We discussed the practical tradeoffs of these three types of transducers. Finally, we demonstrated a wearable energy harvesting device with performance well above current commercial devices. However, our prototypes perform well below the theoretical maximum and therefore there is still room for improvement.

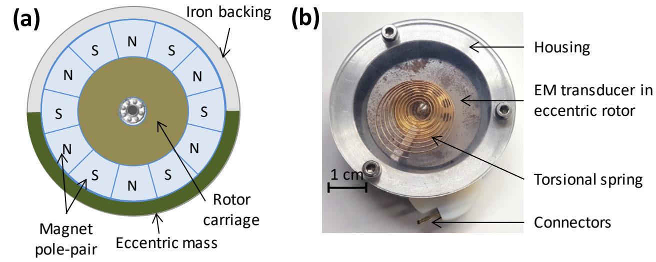

Fig. 4. (a) Conceptual schematic of an electromagnetic harvester based on an eccentric rotor architecture. (b) Photograph of a fabricated sprung eccentric rotor prototype.

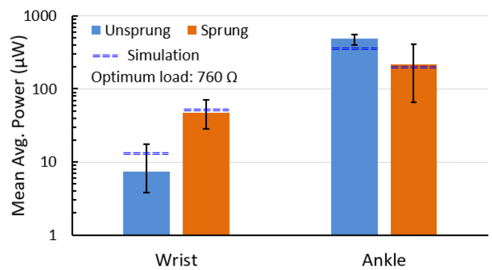

Fig. 5. Measured mean average power generated by the energy harvester at different body locations at 3.5 mph walking speed on a treadmill.

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