Kinetic-Based Micro Energy-Harvesting for Wearable Sensors

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***Abstract*—Wearable sensors are considered to be a key component of cognitive infocommunications systems. These sensors, which are basically enabler of inter-cognitive communication, will provide physical interfaces between humans and future information and communication technology (ICT) devices. Due to their small size, such sensors are often powered by small batteries which might necessitate frequent recharge or even sensor replacement. Energy harvesting can reduce the charging frequency of these sensors. Longer operational lifetime can simplify the everyday use of wearable sensors in many of their applications. In this paper, our objective is to estimate the average amount of kinetic energy that can be harvested to power a wearable device. To obtain this estimate, we have measured typical acceleration of the human body through the use of a triaxial accelerometer placed at various locations on the body surface. These locations are assumed to be associated with the typical placement of a wearable sensor. Using a mathematical model of a micro energy-harvester, instantaneous harvested power can be generated, and target statistics such as average can be calculated. Our results show that kinetic-based micro harvesters could be a promising technology for prolonging the operational lifetime of wearable sensors.**

***Index Terms*—Micro energy-harvester, wearable sensors, triaxial accelerometer**

I. INTRODUCTION

Wearable sensors are considered to be a key component of cognitive infocommunications systems. These sensors, which are basically enabler of inter-cognitive communication, will provide physical interfaces between humans and future information and communication technology (ICT) devices. Microelectronic technology is rapidly advancing in the development of miniaturized wearable sensors that can be pervasively integrated into our daily lives [1]. Sophisticated wearable sensors capable of measuring various neurological or physiological signals and wireless communication is emerging every day. However, as complexity of these sensors increase, so does their energy consumption. Given the small size constraint for these sensors, limited energy source (e.g. small batteries) will become a bottleneck in their functionality. Therefore, any technology that can prolong the lifetime of these sensors or reduce the charging frequency will positively impact their development and market adoption.

Energy Harvesting (EH) refers to the process of capturing and storing energy from the ambient environment. There are few sources from which we can harvest energy for wearable devices; amongst them are light, body heat and movements of the human body. Kinetic energy harvested from the human body motion seems to be one of the most convenient and attractive solutions for wearable wireless sensors [2].

Miniaturized energy harvesting devices, also known as micro-generators, which harvest energy from movements consist of a mass-spring-damper (MSD), a transducer, and an interfacing power-processing circuit. The MSD module is where motion is captured from the environment and converted into mechanical power. The transducer converts that mechanical power into electrical energy. Kinetic micro-generators either utilize direct application of force on the device or they make use of inertial, ambient forces acting on a proof mass. These forces are captured within the MSD component. Unlike micro-generators that utilize a direct application of force, their inertial-based counterparts require only one point of attachment to the moving structure. This allows for greater mounting flexibility and also a greater degree of miniaturization that is ideal for wearable devices. For wearable applications, a micro-generator needs to be able to efficiently harvest energy from the human body motion. Most of the MSD designs for micro-generators in literature use a spring or spring-like feature. This gives the device an intrinsic resonant frequency that is dependent on the spring constant, and makes the micro-generator most suitable for applications where the environment causes the MSD system to constantly vibrate [3]. However, the human body motion is typically not a fixed-frequency vibrating source. As a result, a non-resonating micro-generator architecture known as the Coulomb-Force Parametric Generator (CFPG) [5, 6] is ideal for such applications.

The following non-linear differential equation has been specified as a model to capture the dynamics of the MSD module in a CFPG micro energy harvester [4].

$$my''(t) = -mz''(t) - F * relay(z(t)) \qquad (1)$$

In the above equation, m represents the proof mass, $y(t)$ is the motion of the generator frame with respect to the inertial frame ($y''(t)$ is the second derivative of $y(t)$ and indicates the input acceleration), $z''(t)$ is the proof mass acceleration, and F represents the Coulomb force (also referred to as electrostatic holding force or more generally the MSD's damping force).

The generated mechanical power by the MSD component can be computed by Eq. 2 as follows:

$$P(t) = F * z'(t) \qquad (2)$$

Where F is the holding force and $z'(t)$ represents the velocity of the proof mass.

The Simulink[1] implementation of this model is depicted in Figure 1. Given an input source of acceleration, this model can estimate the instantaneous harvested power of the micro-generator. Here, we are assuming that the transducer unit is ideal and coverts all mechanical power to electrical. In practice, the efficiency of the transducer is below 100% [7, 8].

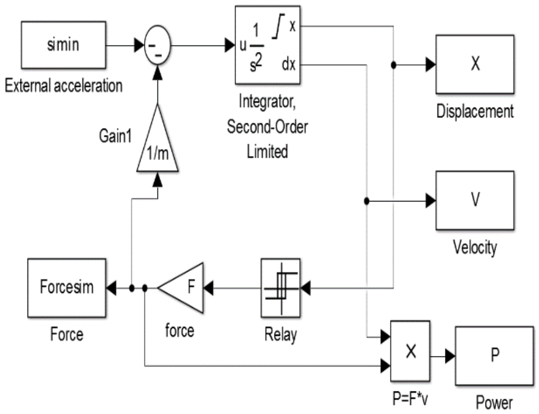

Fig. 1. Simulink model of CFPG MSD module

Using this model and measurements of movements from various locations on the human body, we will be able to study the output power of a micro-generator on those locations. This is intended to emulate the scenario of an integrated micro-harvester and a wearable sensor.

The remainder of this paper is organized as follows. Section II describes our measurement process and details of the triaxial accelerometer that were considered in the measurement campaign. Section III provides the average harvestable power results and discuss the possibility of micro-harvester optimization based on the human activity. Finally, conclusions and future work are briefly discussed in Section IV.

II. Measurement Process

To measure the amount of acceleration from various body motions, the X16-mini[2] USB triaxial accelerometer has been used (Fig. 2). The dimensions of this accelerometer are 51×25 ×13 mm. The measurement samples are time-stamped and stored in the on-board memory so that they can be retrieved at a later time. The amplitude and frequency of human body accelerations during normal daily activities can range from -12 to 12 g and up to 20 Hz respectively [9]. However, there are rare occurrences of higher frequencies, for example at the foot and during heel strike when we walk or run. In this study, we chose a sampling rate of 50 Hz for acceleration measurements with an amplitude range of ±12g. The accelerometer was worn for several short (i.e. 5 min) and long (one hour) intervals during the day. Figure 3 shows the placement of the accelerometer on the body where measurements were obtained. The data obtained from these measurements (documented in [10]) has been used in this study to estimate the average harvestable power.

Fig. 2. X16-mini triaxial accelerometer

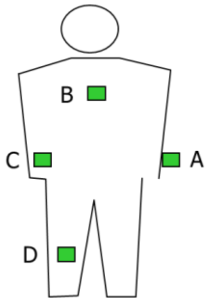

Fig. 3. Placement of the accelerometer on the body: A: Wrist, B: Chest, C: Hip, D: Leg

To conduct the measurement, several scenarios have been considered. These scenarios either correspond to a specific activity (i.e. walking, running, rollerblading) or to typical human motion (i.e. daily chores). Measurement for a particular activity will give us an idea of how much power can be generated as a result of that activity. Therefore such measurements have been done for a short period of time (e.g. 5 minutes). In general, we are also interested to know how much energy can be harvested during normal daily activity of a person. For this objective, measurements have also been conducted for several different one-hour periods during the day. Data from these measurements were used as input to the micro-harvester model in order to generate output instantaneous power as shown in Fig. 4.

[1] Simulink is a product of MathWorks, Inc. Simulink has been used in this research to foster research and understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that this product is necessarily the best available for the purpose.

[2] X16-mini is a product of Gulf Coast Data Concept, LLC. The X16-mini USB accelerometer has been used in this research to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standard and Technology, nor does it imply that this product is necessarily the best available for the purpose.

Fig. 4. Block diagram of the measurement system

Figures 5 and 6 display sample acceleration measurement from the human wrist motion (during a 5-minute walk), and the resulting harvested power.

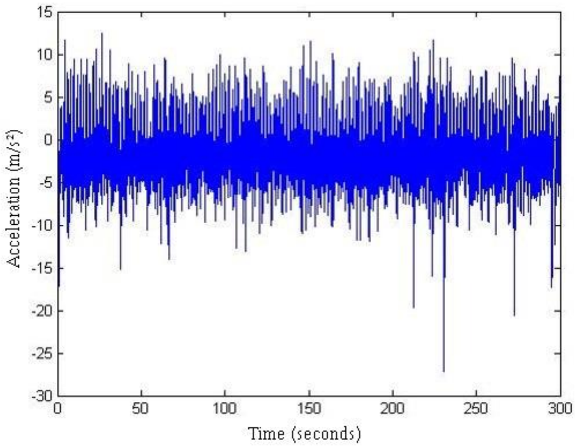

Fig. 5. 5-minute acceleration sample of the human wrist motion during walking (X-axis data)

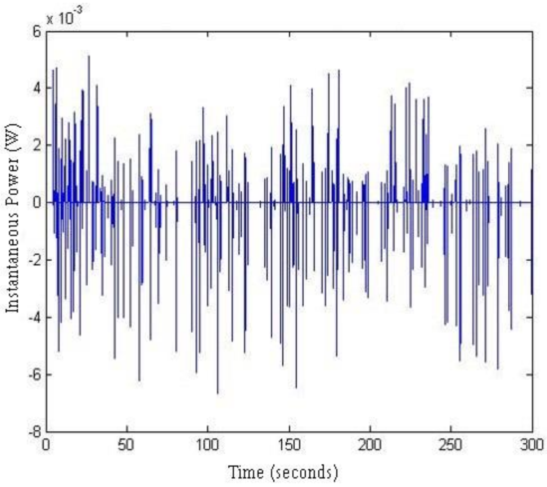

Fig. 6. Harvested instantaneous power from the sample human wrist motion shown in Fig. 5.

Note that negative spikes in the output instantaneous power are indicative of incomplete flight of the proof mass in the MSD model. The energy that was put into the electric field due to incomplete proof mass displacement will be removed, and the average harvested power for all inputs will be strictly a positive value.

III. RESULTS

Once we have our acceleration measurement database, a corresponding instantaneous harvested power database can also be generated. In this study, we are focusing on the average power that can be generated using a micro-harvester, but in the future, further statistics (e.g. variance across gender, age, body type) can also be derived when more measurement corresponding to more number of individuals becomes available.

A triaxial accelerometer is capable of measuring acceleration in all 3 axes as defined by the placement of the device on the body. Although, the current micro-harvester technology can only use one axis for energy conversion; in our study, we are providing the possible amount of average power in each direction. This information will be useful to identify which axis is most appropriate for harvesting kinetic energy. We have also provided the resulting power from all 3 axes combined; which is just the summation of the estimated power in each direction. Also, as the intended use of these harvesters is in very small wearable sensors, we have only considered micro-harvesters with small sizes (i.e. ranging from 100 mm^3 to 800 mm^3) to estimate the average power.

Table 1 shows the average power results for a sensor that is attached to the wrist (e.g. a smart watch) during various activities like walking, running or rollerblading. Similarly, table 2 displays the results for random daily typical motion averaged over several 1-hour intervals.

Table 1. Harvested power from wrist motion for 5 minutes measurement intervals (MSD dimension: 15×15×1.5 mm^3, and F = 17.25e-3)

	Average power (µW)		
Axis	Walking	Running	Rollerblading
X	19.6	351.6	11.6
Y	1.2	350.5	1.3
Z	1.3	32.6	9.0
X+Y+Z	22.2	734.7	21.9

Table 2. Average harvested power over 5 independent 1-hour measurements (random daily activities, MSD dimension: 15×15×1.5 mm^3, and F = 17.25e-3)

Axis	Average harvested power (µW)
X	3.7
Y	4.3
Z	4.6
X+Y+Z	12.6

The results in Tables 1 and 2 correspond to a micro-harvester with an MSD dimension of 15×15×1.5 mm^3. The output power is also a function of this size. To show this dependency, Table 3 displays the average power from typical wrist motion for 3 different sizes of the MSD module. As expected, larger sizes amount to higher values of the harvested power. The desired size of a wearable sensor could determine the possible size of a micro-harvester given a particular application.

Table 3. Harvested power from wrist motion for 1-hour measurement intervals (Random daily activity, F = 17.25e-3)

	Average power (µW)		
Axis\MSD size	10×10×1 mm³	15×15×1.5 mm³	20×20×2 mm³
X	0.38	5.85	33.70
Y	0.12	4.73	12.52
Z	0.12	6.98	22.08
X+Y+Z	0.62	17.56	68.29

Similar measurements were also done for other sensor placement on the body as specified in Fig. 3. Results for the average harvested power for all locations and several activities (i.e. walking, running and random) are listed in Tables 4 to 6.

Table 4. Average harvested power (5 min Walking, F = 17.25e-3, MSD dimension: 15 X 15 X 1.5 mm^3)

Axis	Chest	Hip	Leg	Wrist
X	4.6e-07	0	4.3e-04	1.9e-05
Y	0	2.8e-10	4.3e-07	1.2e-06
Z	2.0e-09	2.1e-09	9.3e-06	1.3e06
X+Y+Z	4.6e-07	2.4e-09	4.4e-04	2.2e-05

Table 5. Average harvested power (5 min Running, F = 17.25e-3, MSD dimension: 15 X 15 X 1.5 mm^3)

Axis	Chest	Hip	Leg	Wrist
X	0	1.1e-07	9.4e-06	3.5e-04
Y	7.0e-07	5.4e-06	2.3e-04	3.5e-04
Z	4.8e-06	4.6e-07	4.0e-05	3.3e-05
X+Y+Z	5.5e-6	6.0e-06	2.8e-04	7.4e-04

Table 6. Average harvested power (1-hour random daily activity, F = 17.25e-3, MSD dimension: 15 X 15 X 1.5 mm^3)

Axis	Chest	Hip	Leg	Wrist
X	2.9e-07	0	4.6e-07	3.7e-06
Y	4.3e-07	2.0e-10	3.4e-08	4.3e.06
Z	2.2e-07	1.1e-07	3.6e-08	4.6e-06
X+Y+Z	9.4e-07	1.1e-07	5.3e-07	1.3e-05

The study in [6] showed that there exists an optimal value for the holding force in a CFPG architecture that can maximize the output harvested power. To further investigate that dependency, in this section, we also explored the impact of the parameter F in the MSD model on the resulting power. Figure 7 shows the significant impact of the electrostatic force on the average power. Almost a factor of 10 fold increase in the amount of generate power can be expected when a proper value for F is chosen. Although, Fig. 7 uses the measurement data obtained through wrist motion during walking to demonstrate the dependency on F, similar behavior is also observed for other input data. For example, Fig. 8 shows the effect of varying F on the output power for the chest acceleration data during running. Again, a gain of almost 5 in average power can be expected when F is judiciously chosen.

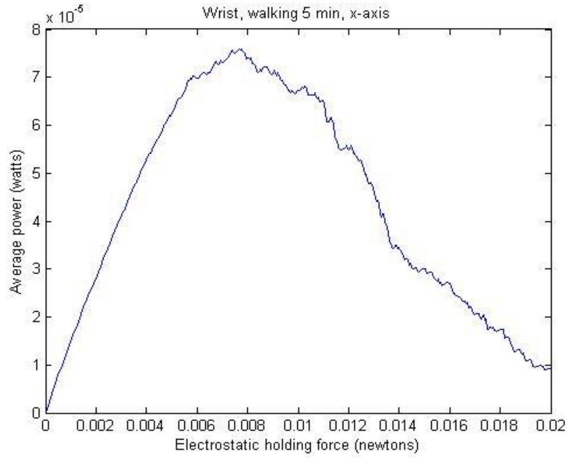

Fig. 7. Average harvested power from the human wrist motion versus the electrostatic force F in a CFPG architecture

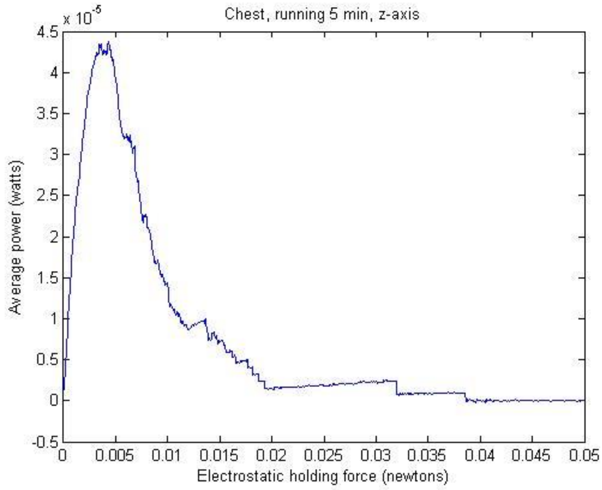

Fig. 8. Average harvested power from the human chest motion versus the electrostatic force F in a CFPG architecture

Having the knowledge for the optimal values of F, we can potentially harvest a lot more power from the same body motions. Tables 7 and 8 show the amount of average power when the micro-harvester is optimized for the holding force F. These results are only for one direction of the kinetic motion. As observed, a noticeable gain for the hip location along with a moderate gain for chest, leg and wrist are achieved compared to the reported values in Tables 4 and 5.

Table 7. Average harvested power (Walking, optimal F, MSD dimension: 15 X 15 X 1.5 mm3)

Chest	Hip	Leg	Wrist
8.8e-07	4.8e-05	4.9e-04	7.5e-05

Table 8. Average harvested power (Running, optimal, MSD dimension: 15 X 15 X 1.5 mm3)

Chest	Hip	Leg	Wrist
4.4e-05	2.2e-05	2.2e-04	5e-04

IV. CONCLUSIONS & FUTURE WORK

The preliminary results in this paper point to the promising application of the micro-harvesting technology in wearable sensors. The power consumption of a popular wrist-worn device such as a smart watch is around 1 mW. Our results show that up to 0.5 mW of power can be generated by natural human wrist motion; therefore, integration of a small micro-harvester in a smart watch can increase its battery lifetime up to 50%. This is a significant gain which basically leads to longer operation of the device or equivalently 50% less frequency of recharge. The power consumption of general wearable sensors heavily depends on their functionality and could range from nanowatt to several milliwatts. Sensor location on the human body, its size, and typical activity of the person wearing the sensor could determine the optimized design and integration of the micro-harvester.

Similar measurements have also been done for portable devices such as a smart phone. Those results have been omitted for brevity. On average, the experienced movement of a portable device is below that of a wearable one. At the same time, the power consumption level of a portable device is much higher. Therefore, kinetic-based harvesting is less applicable to portable devices compared to wearable sensors.

The authors realize that further measurements and research need to be done to assess more accurate gain for various human activities across many individuals with varying age, and/or gender. Specifically, we conjecture that such prior knowledge could be very beneficial in selecting the right size and parameters for the mass-spring-damper module in a micro-harvester.

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