Comparison of Energy Harvesting Techniques for Wearable Activity Monitoring Devices

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Abstract: Piezoelectric and electromagnetic generation are the two most commonly used energy harvesting techniques. The aim of this paper is to compare the two techniques in terms of their potential for powering a wearable monitoring device. An electromagnetic generator and a piezoelectric system are proposed to power an activity monitoring device located in the shoe. Results to date indicate that the electromagnetic generator produces the best output power levels.

1 INTRODUCTION

Energy harvesting is a research field that has become of more interest with the growth in popularity of portable electronic devices and their increased power requirements. Even though there have been several studies comparing different energy harvesting techniques (Mateu, 2005) and (Paulo, 2010), very little has been done to compare techniques for a given application.

This work focuses on harvesting energy from the human body during normal everyday activities, for powering wearable electronic applications. The aim of this work is to propose a self- sustained activity-monitoring device destined for every day monitoring of elderly people. This will include comparing the performance of two generators supplying power to a pedometer system, where the generators are based on the most commonly applied energy harvesting techniques: electromagnetic and piezoelectric

A growing trend has been observed in the development of activity monitoring devices: e.g. like FitBit (Fitbit, US), Nike sensors (Nike, Inc., US) and the Shimmer (Shimmer Research, Ireland). These are most commonly used in monitoring sports activities in order to increase performance.

Lately, such monitoring devices have also been employed in health care, for monitoring the mobility and activity levels of elderly people. Clearly, for such devices to be worn or attached to the body, the most important characteristics are small size, usability and the ability to give real time information with a reliable, low maintainence power source. With a view to improving the rate of use by elderly people, the possibility of harvesting energy expended in activity to produce a self-sustained pedometer is proposed, thereby removing the need for users to recharge batteries.

2 ACTIVITY MONITORING DEVICES

Typical power consumptions values for some of the commonly applied components in activity monitoring devices are compared in Table 1.

Table 1: Typical power consumption levels for devices employed in activity monitoring.

Device	Power consumption (mW)	
Accelerometers		0.16
Low power processors		0.93- 1.4
Other sensors		0.16- 11.6
LEDs		100
Bluetooth	Sleep mode	2
	During transmission	24

Considering that the power consumption of individual circuit blocks varies significantly between sleep and active modes, the design of a generator that produces pulses of power was considered a simpler and more achievable target. The system will contain an nRF chip that will transmit a pulse of data

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every time a step is taken, thus providing a self-sustained pedometer. The selected chip for this application is the nRF24AP2-1CH (Nordic Semiconductor, Norway) and it operates on voltages between 1.9V and 3.6V and power levels between 0.040 and 60 mW. Typical current consumption for tasks performed by the device are displayed in Table 2.

Table 2: Current requirements of the nRF chip.

Activity	Current requirements
Sleep mode	500 nA
Broadcast	14-42 uA
Acknowledging a package	18- 52 uA
Active mode	17mA

3 WEARABLE GENERATOR

3.1 Electromagnetic Generator Design

Electromagnetic power generation is a widely used technique in portable applications like those presented by (Sodano, 2005) and (Arnold, 2007).

Although different materials and techniques have been suggested, the main drawback of electromagnetic generators is that they have considerable dimensions.

The generator proposed in this paper is based on on the sliding magnet principle described in (Carroll, 2011). Based on the theory that as long as the mass of the magnet is considerably smaller than the mass of the foot continuous movement of the magnet can be sustained by external forces due the movement of the foot, no additional or deliberate effort from the user is needed.

The prototype generator was assigned a volume of 50x15x15 mm^3 and disk shaped NdFeB magnets with diameters of 10mm were determined to be optimum for the generator cross sector. Applying optimization rules, it was determined that the most suitable generator prototype consists of 1 coil, with an optimum coil length of 17.3 mm centred along the 50 mm generator length. The copper wire used has a diameter of 0.22 mm, this leading to the main coil having 300 turns disposed in three layers in order to fit the allocated space and resulting an internal coil DC resistance of 6 Ω.

In order to maximise the power output of the generator, but still maintain its size in the allocated volume, two additional half coils have been considered in the remaining generator length at either end of the main coil. A prototype of the electromagnetic generator is shown in Figure 1.

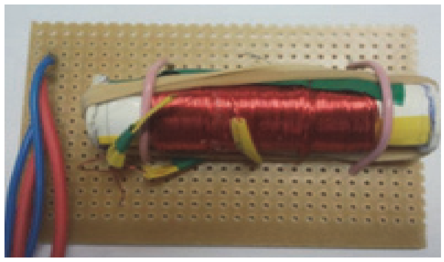

Figure 1: Electromagnetic generator prototype.

Open circuit AC measurements were undertaken for a set of pre-established walking speeds. The generator produces voltages between 0.5 V peak for a walking speed of 2km/h (representing very slow walking), and 2.6 V peak for 12 km/h (representing running).

Through a set of AC measurements, it was determined that the location for the generator preferred for both performance and ease of wear, is on the exterior side of the foot at the heel area. The same walking speeds as in the case of open circuit tests were applied with a series of load resistances attached.

As expected AC measurements showed that the generator performs best when the load resistance matches the internal resistance of the main coil. Unexpectedly, the average power decreased when the subjects switched from walking fast to a running state. The results of Figure 2 show that the optimal speed is 8 km/h. At this point, the average power graph shows that the values recorded are up to 4.5 mW average power, although the highest peak to peak voltage was produced for a 10Ω load resistance.

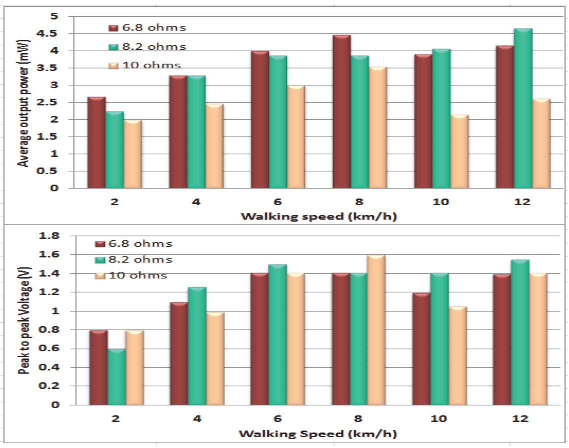

Figure 2: Peak- to- peak voltages and maximum output power values at different walking speeds for different load resistance for the electromagnetic generator.

3.2 Piezoelectric Generator Design

Research in the field of piezoelectric energy harvesting has been reviewed in papers like (Sodano, 2005) and (Lefeuvre, 2006). Many authors focus on the development of piezoelectric materials, most of which are based on lead zirconate titanate, also known as PZT (Anton, 2007). Based on a comparison of generated power levels, Kymissis has determined that different types of piezoelectric material have different responses strongly connected to the individual's gait patterns (Kymissis, 1998).

The first aim of this research was to determine the most suitable form of piezoelectric material for producing a shoe in-sole generator, where the highest forces available are due to the pressure of the person's weight acting under the sole of the foot.

Two different types of piezoelectric materials have been taken into consideration: a PVDF film having an area of 6x12 mm² from Measurements Specialities (Measurement Specialities, US), and a set of piezoceramic disks with diameters of 10 and 20 mm, and thicknesses of 1 and 2 mm from PI (PhysikInstrumente GmbH & Co., Germany).

Table 3 compares the electrical performance of the selected materials in terms of open-circuit voltage as calculated, V_{OCcal}, for an applied pressure level of 400 kN/m^2, (typical under the heel during walking) (Perttunen, 2002). Measured results, V_{OCm}, are also presented for an estimated pressure of 94 kN/m^2, and it is seen that there is generally good agreement in the trends of calculated and measured values.

Due to the low capacitance of the piezoelectric elements, the capacitance of the probe (16pF/10MΩ) affects the open-circuit measurement, and therefore measured results are derived from an equivalent circuit model of the piezoelectric elements, using values of equivalent series capacitance, C_{pz}, and resistance, R_{pz}, as listed in Table 3. Clearly impedance values are much higher than the electromagnetic coil resistance described in section 3.1.

Table 3: Comparison of test piezoelectric material properties.

Materials	C_{pz} (pF)	R_{pz} (Ω)	V_{OCcal} (V)	V_{OCm} (V)
Polymer film	708	>1 MΩ	34.0	na
PIC155 2x10 mm²	504	6.3 kΩ	21.6	4.9
PIC255 2x10 mm²	608	5.2 kΩ	20.0	4.7
PIC255 1x10 mm²	1210	2.8 kΩ	10.0	2.59
PIC255 2x20 mm²	2430	1.3 kΩ	20.0	2.87

In order to compare power levels achievable within the footprint area of a shoe heel, equivalent circuit models of each piezoelectric element were combined in series and parallel and results of peak AC power were produced for a range of load resistances. Results are presented in Figure 3.

The maximum peak instantaneous power predicted is 30 μW, which compares with 4.5 mW *average* power for the electromagnetic generator of section 3.1. Clearly, the piezoelectric generator is not competitive in this environment and work is on-going to review the choice of piezoelectric materials, and methods for compensating the high impedance of piezoelectric source capacitance. Another issue that needs to be addressed in terms of designing a piezoelectric generator is compensating the high impedance capacity as this will lead to increased output power values.

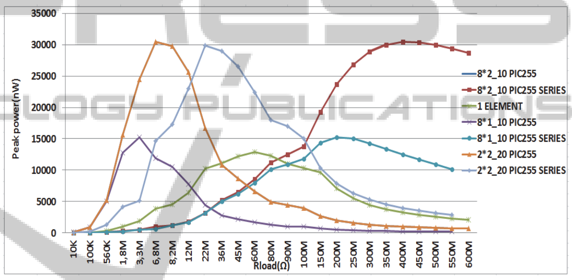

Figure 3: Maximum output power of piezocermaic disks for different load resistance and associations.

4 ELECTROMAGNETIC AC/DC CIRCUIT PERFORMANCE

After establishing that the electromagnetic generator is better suited for the in-shoe design the most optimal parameters and design for the generator were selected. The next step was designing the AC/DC conversion circuit, in order to provide a DC power source as required by most portable devices. Literature has proposed a number of different rectification circuits (Wang, 2009) and (Rao, 2011).

Although many of the systems proposed have shown good results, a number of them require additional powering for active switches. As it is desired that the proposed generator to be a self-sustained system and that the generator voltage pulse needs only to be rectified but not necessarily regulated, the AC/DC conversion circuitry needed is considered to be a more simplistic application of basic conversion principles. Full investigations were conducted for full-wave rectifier and half-wave rectifiers and voltage doubler circuits. A set of simulations were performed with the aid of pSpice simulation software (Cadence Design Systems, UK) for each type of rectifier with several load resistances and capacitors values, and the results are shown in Figure 4. The source used in each simulation is represented by the generator open-circuit waveform and a 6Ω resistor representing coil resistance. In order to maximise the output power, the PMEG 2010EH diodes were used as they present lower forward voltage (Caroll, 2005).

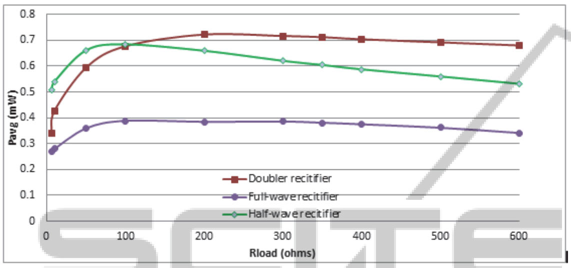

Figure 4: Simulations results of maximum output power for rectification circuits depending on load resistances for 3.5mF capacitor.

Due to the overall reduced voltage drop across the diodes in the full- wave rectifier circuit, the doubler circuit performed the best. The maximum output power was achieved for 250 Ω, with a peak instantaneous power value of 3 mW. Due to the fact that the rectification was performed for a pulsed type of power a capacitance value of 3.5mF was used, as it provided increased values for the output voltage. Figure 5 presents the input and the rectified waveforms for the optimum load resistance.

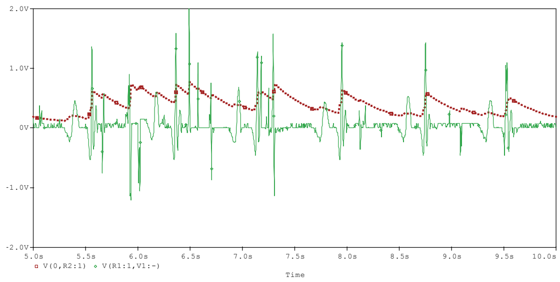

Figure 5: Typical waveform generated by the prototype during walking and the rectified waveform with a doubler circuit for the optimum load resistance (250Ω).

5 CONCLUSIONS

Two different energy harvesting techniques have been compared in order to prove their suitability to power an activity monitoring device. The electromagnetic generator has proved to be superior to the piezoelectric system. With the given space of 50x15x15 mm^3 the generator produced power levels of 4.5 mW AC and 0.8 mW for pulsed DC, almost sufficient to meet the requirements of the nRF chip. Work is on-going to investigate the effect of the additional half coils over the output power. However, the optimum speed being around 7-8 km/h might make this type of energy harvesting system more suitable for more active people. For the piezoelectric system, the selection of materials available for this work has not given the desired outcome, with the piezoceramic disks giving low output powers and being subjective to damage due to repeated stress caused by the constant pressure applied during walking. Although piezoelectric components are capable of providing high output voltage, the output power is limited by the loading of the capacitive impedance.

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