Design, fabrication and characterization of an inductive human motion energy harvester for application in shoes

K Ylli¹,³, D Hoffmann¹, B Folkmer¹ and Y Manoli¹,²

¹ HSG-IMIT – Institute of Micromachining and Information Technology, Wilhelm-Schickard-Str.10, 78052 Villingen-Schwenningen, Germany
² Fritz Huettinger Chair of Microelectronics, Department of Microsystems Engineering – IMTEK, Georges-Koehler-Allee 102, 79110 Freiburg, Germany

E-mail: klevis.ylli@hsg-imit.de

Abstract. The concept of energy harvesting has been in the focus of research for more than two decades now and with the continuous device miniaturization and reduction in power consumption of the electronics it has become a viable power source for mobile systems. The increasing desire for mobility and longevity in terms of battery life has eventually led to wearable systems, i.e. electronic circuits with their power supply which are being integrated into textiles and everyday life. This paper reports the development of a cylindrical inductive energy harvesting device which exploits the accelerations available in the plane of the foot during walking. The modeling and characterization of the system is based upon real-world acceleration data recorded during treadmill runs. Although a wider range of test subjects would be required to increase the statistical relevance of the measured data, it is concluded that the energy provided by this system is sufficient to power low energy circuits at comparatively slow walking velocities. Additionally, the obtained knowledge can be used to develop a smaller, parallelized system.

1. Introduction
In the past two decades the field of energy harvesting has received significant attention from researchers around the globe. The development of modern materials, the optimization of known principles as well as the ongoing miniaturization of electronic components and the reduction of their power consumption has made energy harvesting from ambient vibrations and motion a feasible alternative to conventional battery powered systems. Correspondingly, the development of smart textiles and wearable systems has been driven forward resulting in ever increasing mobility and the desire to be energy independent. Kinetic energy harvesters have thus been developed which exploit the energy available in human motion and in particular the energy expended in the human gait. Due to the low frequency of the human gait of approximately 1 Hz [1], conventional resonant energy harvesters are not a feasible solution.

Human motion harvesters developed to date include devices that mechanically translate the downward motion of the heel into a horizontal motion and drive an electromagnetic generator [2],
devices that exploit the material properties of electro active polymers to generate a power output upon applying mechanical stress [2] and shock induced harvesters which vibrate at their resonant frequency once deflected out of the equilibrium position upon heel strike [3].

In this work an energy harvester is presented, that exploits the acceleration of the foot with only one passive moving component and hence no risk of wire breaks or other mechanical failure due to its straightforward construction. An approach different from others seen in literature [4] was taken in the development process by using acceleration data recorded during a treadmill run as the input source for the differential equation that models the system instead of simplifying the signal.

2. Overview of the available excitations and the developed system model

2.1. Human Gait: An Overview
There are several different types of feasible non-resonant mechanical excitation sources for energy harvesting devices that can be observed in the human gait. The first possible excitation is provided by the weight of the test subject. Researchers have come to the conclusion that the dynamic force acting upon the sole during walking can reach up to 130% of the human weight and therefore easily surpass a force of 1000 N which can be exploited by energy harvesters [5].

A second excitation source can be found in the shocks, which occur upon heel-strike as mentioned previously [3]. The third type of excitation, which is also the basis for the harvester presented in this work, is the acceleration of the foot during walking. Treadmill measurements were performed at constant running velocities of 4 km/h, 6 km/h, 8 km/h and 10 km/h to record the accelerations. Figure 1 shows the accelerometer attachment to the shoe sole. Figure 2 shows the recorded acceleration and the integrated velocity for the exemplary running speed of 10 km/h.

| Running velocity | Positive peak average (g) | Negative peak average (g) |
|-----------------|--------------------------|---------------------------|
| 4 km/h          | 5                        | -4.28                     |
| 6 km/h          | 8.7                      | -5.45                     |
| 8 km/h          | 15                       | -4.16                     |
| 10 km/h         | 23                       | -3.26                     |

Table 1. Average acceleration peaks recorded in y-direction during treadmill runs.

Large accelerations and velocities are readily available during walking as can be seen in Table 1, which motivated the development of an energy harvesting device that exploits these low-frequency, large amplitude accelerations. In order to be as accurate as possible, the recorded acceleration curve is used as input into the software model.
2.2. **System Modeling**

The developed energy harvester is based on the principle of induction and employs two copper wire coils through which a generator magnet can move freely (see figure 3). The change in the magnetic field induces a voltage in the coil windings which provides the harvester output power across a suitable load. The main aim of this device was to gain a better understanding of the processes involved: from the motion of the generator magnet (GM) to the fabrication of a suitable housing which protects the harvester and allows the integration of the device in a shoe sole.

![Figure 3. a) Schematic of the designed harvester prototype. Labeled parts: 1. Coils, 2. Generator magnet 3. PVC channel, 4. Stopper magnets (magnetic springs), 5. Housing, 6. Electronics compartment, 7. Boreholes for external attachment to shoe, 8. Lid. b) Fabricated device and spare coils; test electronics include a rectifier, a temperature sensor and an EnOcean wireless transmitter.](image)

In order to model the energy harvesting device, a differential equation was developed which considers the relevant forces acting upon the GM which is the only moving harvester part. The considered forces include the friction force between the GM and the PVC channel, the electromotive force caused by the induced voltage in the coil and the repulsive magnetic force between the generator magnet and the stopper magnets (SM). The SMs are placed as magnetic springs at either end of the PVC channel to avoid collisions with the housing. The air compression due to the air in the channel being pushed by the GM was not considered for this first prototype.

![Figure 4. Block diagram showing the forces acting in the differential equation of the system model.](image)

The simulation was performed using 2D FEA-software and rotational symmetry to compute the magnetic field distribution and subsequently the coupling coefficient and the induced voltage according to (1) and (2). A more detailed description of the analytical calculation of the induced voltage can be found in [6].

\[
k = - \frac{d\phi}{dx}
\]

\[
U_{\text{ind}} = - \frac{d\phi}{dr} = - \left( \frac{dA}{dr} B + \frac{dB}{dr} A \right) = - \frac{d\phi}{dx} \cdot \frac{dx}{dr} = k \cdot \dot{x}
\]
3. Prototype development

3.1. Optimization and Fabrication

A cylindrical setup was chosen for this device because of the availability of the components as well as the fact that rotational symmetry can be exploited to greatly facilitate the calculations performed by the simulation software. A genetic algorithm was used to perform the optimization of the following set of parameters within feasible boundaries: the GM radius, the GM height, the length of the coil, the wall thickness (outer radius minus inner radius) of the coil, the SM height and the location of the coil. The values of the key parameters are listed in table 2.

![Table 2. Optimized key geometrical parameters of prototype device.](image)

The housing was 3D-printed in plastic and contains grooves that accommodate the coils at precisely the optimum position as obtained by the optimization procedure. The coils were placed to allow the generator magnet to enter the first coil while it leaves the second coil and the coils were reverse connected in series to achieve a larger voltage output.

3.2. Treadmill measurements

In order to test the device under realistic conditions, it was attached externally to a running shoe and the output voltage across the optimum load resistance was measured on a data logger. The resulting power output for different coil-magnet configurations with an optimal load is shown in figures 5 and 6. As was the case in the simulations, it is essential that the actual excitation of the foot is used for the characterization of the device instead of a simplified representation, e.g. a sine signal.

![Figure 5. Power output for different device configurations with 100 µm copper wire coils. M1 and M2 are “weak” and “strong” spring magnets respectively. MC denotes a modified channel with a larger inner diameter of 14 mm.](image)

![Figure 6. Power output for configurations of varying wire diameter. The resistance of the coils is 230 Ω and 1640 Ω respectively for the 60 µm wire and 100 µm wire.](image)

3.3. Analysis

It can be seen from figures 5 and 6 that a system with two coils in series performs significantly better in terms of output power than a single coil system. It is also observed that measurements with a slightly enlarged channel (marked “MC” in the figures) show an increased power output, as the GM can move more freely and a certain amount of air can pass around it instead of being pushed in front of it. Comparatively weak SMs are shown to lead to a larger power output, as the magnetic field of the stronger SMs has a greater range and inhibits the movement of the GM to a certain degree.
In figure 6 it is shown that a configuration with 60 µm coil wire produces a larger power output than the 100 µm configuration, although the copper fill factor, i.e. the percentage of the coil cross-section actually filled with copper, is smaller (see norm IEC 60317). This result is unexpected and has to be investigated further by using a variety of test subjects of whom everyone has an own unique style of walking.

A significant observation from figure 5 concerns the transition from fast walking at 6 km/h to slow running at 8 km/h. As can be seen, there is no continuous increase in output power as the treadmill velocity increases. This can be attributed to the change in the walking style from the abrupt movements of fast walking to the smooth movements of jogging. Table 3 illustrates this observation by listing the peak-to-peak velocities as the result of the integration of the acceleration data. As shown, there is no linear increase in the peak-to-peak velocity due to the described effect.

| Treadmill speed | peak-to-peak foot velocity |
|-----------------|-----------------------------|
| 4 km/h          | 3.9101 m/s                  |
| 6 km/h          | 4.9175 m/s                  |
| 8 km/h          | 5.1595 m/s                  |
| 10 km/h         | 8.1262 m/s                  |

4. Conclusion
While this first prototype is simple and rather large in size, it shows a promising power output of up to approximately 10 mW with RMS-voltages between one and six volts depending on the configuration and the walking speed (voltage peaks are significantly higher). The mentioned power output sufficed to supply an experimental circuit which measured the temperature at the foot of the subject and transmitted the data up to seven times per second using an enOcean transmitter. Additionally it was shown that slower velocities do not necessarily translate into a low power output of the system.

The experience gained in the development of this device has led to a number of improvements of the system model, e.g. the calculation of the coupling factor depending on the position of the GM relative to the SMs or the consideration of the damping due to the air pushed in front of the GM.

Future work will include a more detailed analysis on the effect of changes in geometrical parameters and tolerances on the device output as well as the development of a smaller, parallelized system based on the knowledge obtained in this work. In order to characterize the devices and their behavior more accurately and increase the statistical significance of the obtained data, the number of test subjects will be increased.

Acknowledgments
This research (IGF-Project: 17742N) was supported by the “Programm zur Förderung der industriellen Gemeinschaftsforschung und -entwicklung (IGF)“, Germany.

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