Human Motion Energy Harvesting for AAL Applications

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Abstract. Research and development into the topic of ambient assisted living has led to an increasing range of devices that facilitate a person's life. The issue of the power supply of these modern mobile systems however has not been solved satisfactorily yet. In this paper a flat inductive multi-coil harvester for integration into the shoe sole is presented. The device is designed for ambient assisted living (AAL) applications and particularly to power a self-lacing shoe. The harvester exploits the horizontal swing motion of the foot to generate energy. Stacks of opposing magnets move through a number of equally spaced coils to induce a voltage. The requirement of a flat structure which can be integrated into the shoe sole is met by a reduced form factor of the magnet stack. In order to exploit the full width of the shoe sole, supporting structures are used to parallelize the harvester and therefore increase the number of active elements, i.e. magnets and coils. The development and characterization of different harvester variations is presented with the best tested design generating an average power of up to 2.14 mW at a compact device size of 75 x 41.5 x 15 mm³ including housing.

1. Introduction

The field of electronics, including the key elements of circuits and sensors, is constantly progressing towards smaller and less power-hungry devices. This in turn has enabled the advance of mobile devices aimed at facilitating the lives of modern users on the go. Subsequently, the field of AAL applications has seen significant attention and research into body-worn systems is ever increasing. A key issue with these devices is practicality, particularly concerning their power supply which requires user intervention and maintenance when based on batteries. Advances in energy harvesting are enabling body-worn systems operating without a battery and need for maintenance as the energy to power the device is extracted directly from the human motion.

The motion of the human body consists of smooth continuous movements at a repetition frequency of approximately 1 Hz. Hence classical vibrational energy harvesting devices are not feasible for this excitation source. Instead large-amplitude devices that do not require constant vibration are being developed. The motion of the foot is amongst the most energetic of the human body as indicated in Figure 1, leading to the development of several different energy harvesting devices for the integration into the shoe sole [1–4]. As an additional advantage the shoe sole offers sufficient space to unobtrusively integrate an energy harvester.

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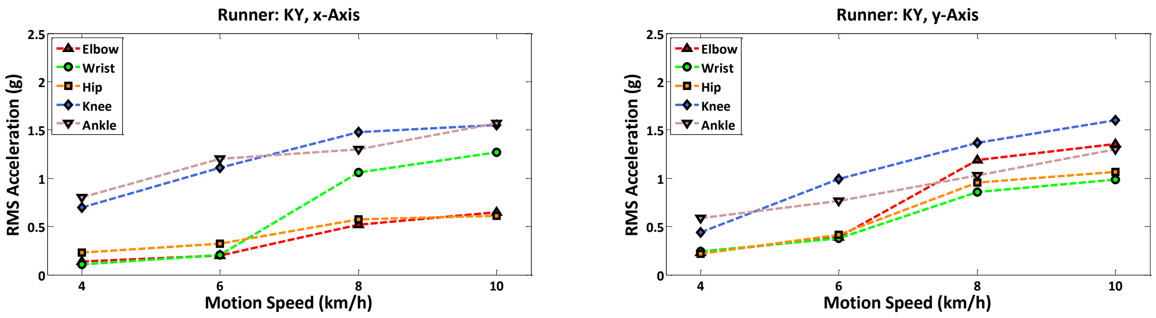


(a) (b)

Figure 1. RMS acceleration calculated from a measurement of 60s at varying body positions. At a standstill with limbs pointing downwards, accelerations on the x-axis in **(a)** correspond to a forward (horizontal) motion and on the y-axis in **(b)** to a vertical motion.

This work is focused on the development of a linear motion harvester that exploits the swing motion of the foot during walking. Continuing the work presented in [3], the multi-coil and multi-magnet system seeks to make better use of the width available in the shoe sole. Different variations of the harvester are investigated and the key parameter to effect the generated power is shown.

2. Harvester development

In this work a multi-coil setup with a magnet stack of opposing magnets separated by steel spacers is developed. In order to meet the requirements of a flat device (height limited to 15mm), the radius of the cylindrical magnets and coils is restricted. However there clearly is more space in the width of the sole than in the height. To make use of this fact, the magnet stack is parallelised. The attractive force between magnets would cause high friction during magnet motion as parallel stacks would be pulled toward each other. To avoid this, supporting brackets are introduced which hold the stack separate at a fixed distance, thus forming a single seismic mass as shown in Figure 2.

An additional advantage of this setup is the fact that the magnet stacks can be placed in an orientation in which they simultaneously induce a signal through all coils, as they move synchronously (Figure 3). Therefore, a simple rectifying circuit is sufficient to produce a DC voltage.

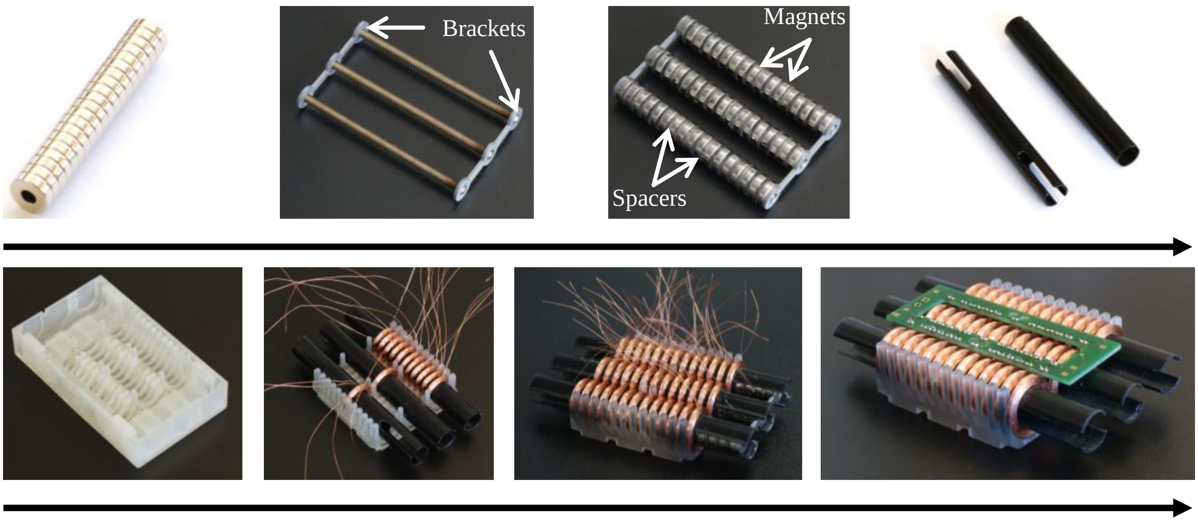


Figure 2. Depiction of the fabrication process from top left to bottom right. Placement of magnets, steel spacers, supporting steel brackets and coils in a 3D-printed housing is shown.

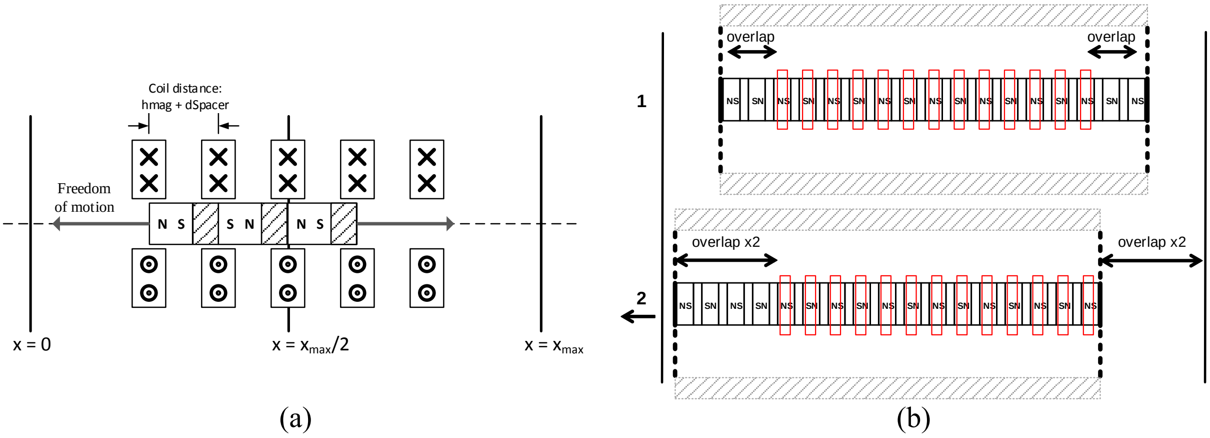


Figure 3. (a) Schematic of the magnet setup. Coils are placed at intervals corresponding to the magnet height and spacer thickness to generate a synchronous signal. **(b)** Two key magnet positions. The brackets interconnecting the magnet stacks are indicated by a thick line. Coils shown in red.

The modelling of the system is done according to the work presented in [4]. The magnetic flux density around a magnet stack is extracted from an FEM simulation, providing a set of data points for positions within the considered extent of the harvester. From this set of data a coupling curve is calculated, which is used for the system model. Depending on the current position of the magnet stack, the respective coupling coefficient is extracted from a look-up table and is used to determine the voltage induced within the coils by multiplying the coupling coefficient with the velocity of the magnet stack as it moves forwards and backwards. The voltages are summed up across all coils to produce the system output.

3. Implementation and experiments

3.1. Implementation

The device was fabricated using neodymium iron boron ring magnets (NdFeB) with a height of 2 mm, an inner diameter of 2.7 mm and an outer diameter of 7 mm. The coils were fabricated with an inner diameter of 8.5 mm, an outer diameter of 12.5 mm, a thickness of 1.2 mm and 100 µm wire leading to a resistance of approximately 13 Ω per coil. The dimensions of the complete device including housing are: 75 x 41.5 x 15 mm^3 and considering only the active volume: 71 x 37.5 x 12.5 mm^3.

Figure 4. (a) Sports shoe with integrated harvester and a second device by its side. **(b)** X-ray photography of the shoe showing the harvester system. The temperature sensor and the wireless data transmission chip from the sample application can be seen.

Table 1. Key geometrical parameters of the three investigated harvester configurations.

Configuration	Number of coils	Coil span	Number of magnets	Magnet length (incl. spacers)	Housing	Max. range of motion
V5	13	40.8 mm	17 x 2 mm	52 mm	70 x 41.5 x 15 mm³	61.2 mm
V6	11	34.8 mm	17 x 2 mm	52 mm	70 x 41.5 x 15 mm³	67.2 mm
V7	9	28.8 mm	17 x 2 mm	52 mm	75 x 41.5 x 15 mm³	73.2 mm

Figure 4 (a) shows a sports shoe with a harvester system integrated into the heel part of the shoe sole, as well as a second device by its side. Apart from a simple power management circuit, a temperature sensor and a wireless transmitter are included for demonstration purposes.

In order to investigate the effect of the geometry of the magnet stack on the power output, three variations according to Table 1 were fabricated. The maximum range of motion is derived from the coil span and the overlap of a magnet stack as shown in Figure 3 (b).

3.2. Experimental data

Due to the interconnecting brackets a larger number of magnets is required for the three-stack setup than would be required otherwise. The motion of the magnet stack is stopped at the outer coils because of the brackets (see Figure 3 (b)) and therefore the number of coils has a direct influence on the power output.

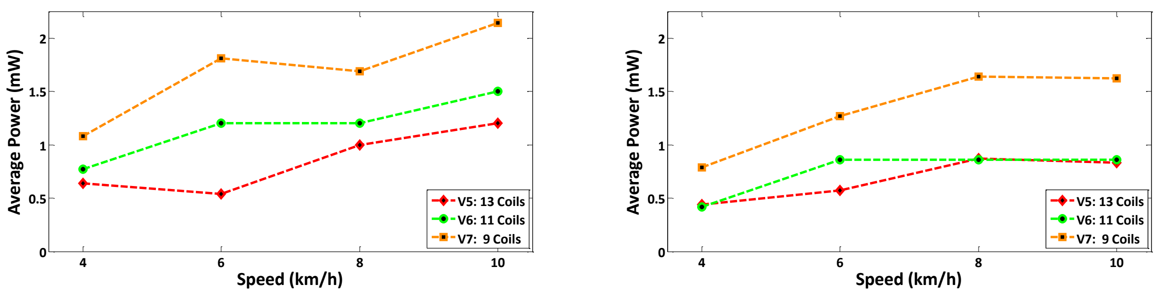
Figure 5 shows the summarized results of measurements on a treadmill. Two different runners were recorded for 60 seconds at runs of 4, 6, 8 and 10 km/h. The average power for each motion speed is calculated from the measured voltage with an optimal load resistance equal to the total coil resistance.

It is instantly clear that the device with the smallest number of coils provides the best power output. In this case the motion range is the largest, which enables the magnet stacks to gain momentum and ultimately reach a higher velocity as they move through the coils.

Depending on the runner, the 9-coil harvester can generate an average of 1 mW at the slowest walking speed of 4 km/h. A maximum average power output of 2.14 mW was measured at a speed of 10 km/h. Considering the total volume (including housing) of 46.69 cm³ and the active volume of 33.28 cm³ this translates to a maximum power density of 45.8 µW/cm³ and 64.3 µW/cm³ respectively.

4. Conclusion

The integration of a harvesting device into a shoe sole is mainly limited by the height constraint. The height of the sole cannot fully be used as material is needed for cushioning. In order to maintain the level of comfort the users are familiar with, the proposed harvester was designed with a height



a) b)

Figure 5. Average power generated during treadmill runs for different configurations of the harvester. Runner KY is shown in pane **a)** and runner DH in pane **b)**.

constraint of 15 mm. The consequential reduction of the size of the magnets and coils is partially compensated by exploiting the width available in the shoe sole and parallelizing the moving magnet stacks. The best configuration out of the three fabricated ones is easily distinguished and is able to generate average powers between 1 mW and 2.14 mW depending on the walking speed.

Compared to previous work presented in [3], the triple-stack device shows a significant increase in power output. However an improvement by a factor of three was not observed. This is attributed to the limited motion range of the bracket-supported magnet stacks. In order to increase the range of motion, the length of the magnet stack must be increased, otherwise the brackets stop the stack at the coils, before the magnets reach the channel end. This in turn increases the length of the harvester housing, which should be avoided with respect to integratability.

Although the freedom of motion of the moving magnet stack was highlighted as a key factor in this work, the geometrical parameters of the setup can still be optimised further. In continuation of this work, the ongoing improvement of the simulation model is in the centre of focus. The model is being modified to be fully flexible regarding the geometrical parameters of the system and is expected to provide a new set of parameters with an improved power output.

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