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Design of a body energy harvesting system for the upper extremity

Abstract: Converting energy from human upper limb motions into electrical energy is a challenge, as low frequency movements have to be converted into repetitive movements to effectively drive electromechanical generators. The prototype of an electromagnetic linear generator with gyrating mass is presented. The mechanical motion model first was simulated and the design was evaluated during different activities. An average power output of about 50 µW was determined with a maximum power output of 2.2 mW that is sufficient to operate sensors for health monitoring.

Keywords: Body energy harvesting, upper limb, motion

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1 Introduction

Energy harvesting generators are attractive for prolonging the restricted battery capacity in low-power medical devices. Different principles to convert mechanical energy into electrical energy have been proposed or demonstrated [1-5], particularly at the microscale. However, most systems are designed to convert energy from motions of the lower extremities. Only a few systems have yet been presented to explicitly convert energy from movements of the upper extremity [6-9]. The only commercialized technology can be found in automatic wrist watches [10]. Here, the spring of a clockwork mechanism can store energy by using an eccentrically pivoted inertia that tensions the spring using a gear. Studies that have examined movements and muscle activity of the upper limbs during walking and activities of daily living (ADL) are by far less numerous than corresponding studies of the legs. Additionally a significant individual variety of upper limb movements have been found [11,12]. Thus, the objective of this project was to design and analyse an energy converting systems that captures motion from upper limb movements without bothersome additional muscle work.

2 Methods

First, upper limb movement analysis was performed to identify both, the position and the phase of movement most suited for energy conversion without limiting movement. The upper limb motion data during walking and ADL were provided by the BioMotionCenter of the Karlsruhe Institute of Technology (KIT). Using these motion data the angular velocity of the elbow joint and the acceleration of the wrist for each moment during walking was calculated. The maximum speed of the wrist was in the range 1.8-2.0 m/s. Out of several different generator principles for converting energy a design was selected that is based on a rotary mounted mass to convert the slow upper limb motion into a linear movement (see **Figure 1**).

Subsequently, a differential equation based mechanical motion model was calculated and implemented in MATLAB. Following this, an electromagnetic generator was designed and simulated and its theoretical power output was determined in MATLAB. The system was designed as an eccentric tappet, attached to a gyrating mass, actuating an electromagnetic linear generator. The equation of motion was formed by the momentum equilibrium of the concept, as given in [13]. Part of this momentum is the damping force due to the magnet's movement inside the coil. The electromagnetic damping ratio can be calculated by an adapted formula that was also used in [14] (see **eq 1**).

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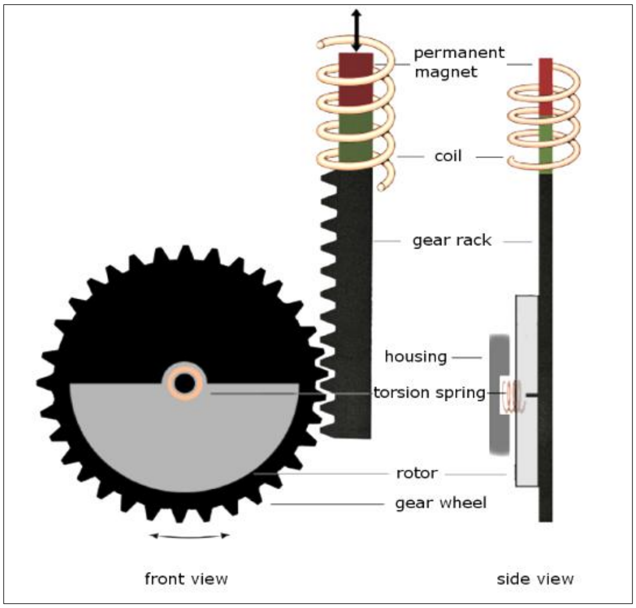

Figure 1: Basic principle of the favoured electromagnetic linear generator. Instead of a gear, an eccentric tapped and a pin was used in the subsequent design.

$$D_{em} = \frac{1}{R_I + R_C + j \cdot \omega \cdot L_I \cdot C_C} \cdot \left(A_I \cdot \frac{\Delta B_M}{\Delta y}\right)^2 \qquad (1)$$

Table 1: Mathematical notations

Notation	Name
R_I	Resistance of the inductor
L_I	Inductivity of the inductor
A_I	Cross sectional area of the inductor
R_C	Resistance of an additional capacitor
C_C	Capacity of an additional capacitor
$\frac{\Delta B_M}{\Delta y}$	Chance of the magnetic flux density due to the magnet's movement inside the inductor
ω	Angular frequency of the induced AC

For more efficiency there is soft iron connected to both face sides of two cylindrical NeFeB magnets, so the magnetic field is redirected to leave the shell surfaces in a right angle. The iron-magnet-iron-combination is separated by an aluminium isolator to impede direct magnetic flow through the centre without leaving the shell surfaces. Therefore the encircling coil undergoes a change of this magnetic field, which induces electrical voltage as long as soft iron parts are moving inside of its turns (see **Figure 2**).

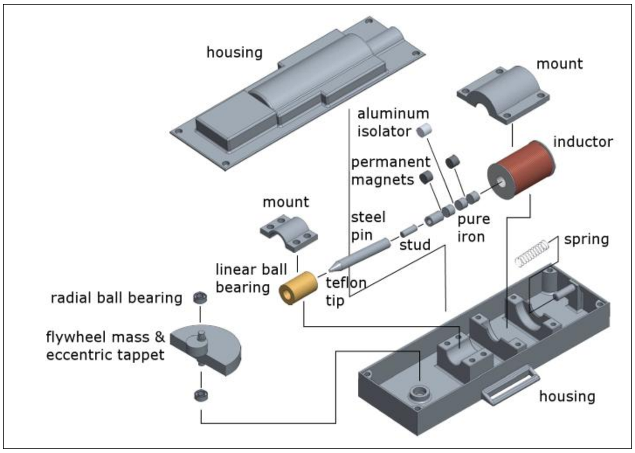

Figure 2: Exploded view drawing of the energy harvesting generator.

3 Results

To calculate the actual efficiency of the prototype the produced electrical energy has been divided through the kinetic energy of the movement which accelerates the flywheel mass. This kinetic energy was calculated by measuring and integrating the acceleration of the prototype, connected to the wrist. By using a 6-axis accelerometer (InvenSense MPU-6050) the accelerations during walking and ADL where logged to a microcontroller board (Arduino Uno), as depicted in **Figure 3.**

Figure 3: The prototype generator with a microcontroller and accelerometer during the evaluation.

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In order to measure the induced voltage the coil has been connected to a Tektronix TPS 2014 oscilloscope. The contained noise signal was filtered by analysing the main frequency using a Fast Fourier Transformation (FFT) to emulate the noise and subtract it from the measurement. An example of a filtered output from the generator is given in **Figure 4**.

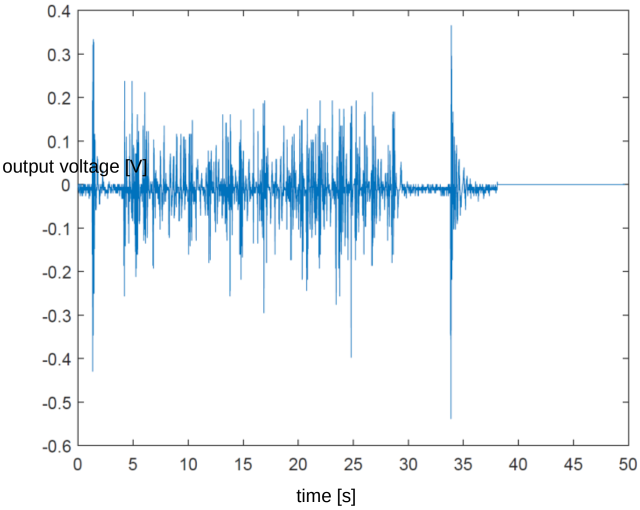

Figure 4: Output voltage of the generator after filtering noise.

Different activities, mainly in a sporty manner, have been performed to ensure the functionality of the designed prototype. Especially activities with fast upper limb accelerations or oscillating movements lead to the highest energy conversion. The energy harvesting generator provides a maximum power output of 2.2mWand an average power output of 50 µW during activities like slow jogging or dancing. However, these activities also included intervals without any movement, which lowered the results. During specific wrist rotating movements an average power of 265 µW and a maximum power of 2.7 mW were determined. The weight of the first prototype is 146g.

4 Conclusion and discussion

An electromagnetic linear generator with gyrating mass that is able to convert energy from upper limb movements into electrical energy was presented. It was first simulated, then designed and evaluated. The generator was tested during different activities and the electrical power output is comparable to that of other energy harvesting systems for the upper extremities [6-9] and sufficient to provide e.g. a sensor based monitoring system [15]. Considering the low weight of the prototype no remarkable additional muscle work is needed to power the generator.

However, some parts of the system still have to be optimized. In particular the flywheel diameter which is essential for tapping the upper extremity's movements to power the linear generator. For this purpose the programmed MATLAB-Simulation may be used and extended if needed. Currently the induced electric energy has only been used to measure the output so far. In order to use the system's output in daily practical applications without separate editing, an electric circuit needs to be designed for filtering the raw output's voltage peaks, so a connected battery won't be harmed in an inordinate amount. The easiest way to achieve this may be the use of a smoothing capacitor. Furthermore a charge pump can be integrated to increase the useable voltage, in case a system with an interval mode available shall be powered.

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Author's Statement

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