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# Auto-wireless battery charging system for medical and healthcare applications

***Abstract**. The explosive growth of smart wearable devices has led to significant interest in harvesting human motion energy, especially during walking, for clinical and health purposes. The use of such energy offers a feasible way forward to significantly surpass the battery power limits for implantable and wearable devices. In this study, a complete system is designed to produce electrical energy from human walking then transfer the generated power wirelessly to the intended distance to charge a portable device without the need to substitute the power sources. Lead Zerconate Titanate (PZT)-5H has been implemented with customised specifications to estimate and harvest energy in one step. The obtained experimental results of the generated and stored energy using the proposed design agree with the theoretical results obtained through the calculations. Further investigations are required to improve the proposed system.*

***Streszczenie.** Gwałtowny rozwój inteligentnych urządzeń do noszenia doprowadził do znacznego zainteresowania pozyskiwaniem energii ruchu człowieka, zwłaszcza podczas chodzenia, do celów klinicznych i zdrowotnych. Wykorzystanie takiej energii oferuje realny sposób na znaczne przekroczenie limitów mocy baterii dla urządzeń wszczepialnych i noszonych na ciele. W tym badaniu zaprojektowano kompletny system do wytwarzania energii elektrycznej podczas chodzenia ludzi, a następnie bezprzewodowego przesyłania wytworzonej energii na zamierzoną odległość w celu naładowania przenośnego urządzenia bez konieczności zastępowania źródeł zasilania. Lead Zerconate Titanate (PZT)-5H został wdrożony ze spersonalizowanymi specyfikacjami, aby oszacować i zebrać energię w jednym kroku. Otrzymane wyniki doświadczalne energii wytworzonej i zmagazynowanej przy zastosowaniu proponowanej konstrukcji zgadzają się z wynikami teoretycznymi uzyskanymi w wyniku obliczeń. Konieczne są dalsze badania w celu ulepszenia proponowanego systemu.* (***Automatyczny bezprzewodowy system ładowania akumulatorów do zastosowań medycznych i opieki zdrowotnej***)

**Keywords:** Human motion, energy harvesting, power generation, wireless power transfer
**Słowa kluczowe:** pozyskiwanie (harvesting) energii, zasilanie bezprzewodowe

## Introduction

In recent times, many patients with different medical needs and conditions have implantable devices that play a vital role in supporting their health. These implantable devices serve distinct functions and cover a wide range of applications. However, they all have the problem of power sources. The main power source is a battery that needs to be charged up periodically, which requires laying wires through the patient's skin that burdens the patient, might cause a bacterial infection, or even worse, the batteries need to be replaced through surgical procedures that might imperil the patient's life and may lead to surgical complications.

Many studies have been conducted to study the generation of electrical energy from different population free materials, and in [1] the authors proposed a system that converts electrical voltage produced by piezoelectric material when individuals walk on a rug of those elements; the generated stabilised DC voltage is about (8-12) Volts. The authors of [2] proposed a shoe-based energy design, which capable of producing a mean yield power of 1 mili Watt when the frequency of walking is 1 Hz.

The impact of human walking on a piezoelectric energy harvester (PEH) with different orientations was studied in [3]. The obtained results showed that it is preferable to have a 70° orientation of the PEH according to the coordinate system during the walking test on a treadmill.

Energy harvesting from the animal/human body was studied in [4], where the authors summarised different approaches to harvest energy from living creatures bodies to power electronics with no extra power sources. They presented material options, layouts and principles of operation of these approaches, focusing on in vivo applications. They concluded that integrating various energy harvesters with advanced electronics can provide a new platform for the development of new energy harvesters.

The authors of [5] reviewed skin-implantable energy harvesting materials and vital reflections on the probe materials in relations of the performance of energy storage and living landscapes. They equaled of electrochemical and physicochemical features, comprising carbon nanomaterials, metals, metal oxides, biopolymers and composite materials, and studied the integration of skin-patchable materials into the device architecture.

In [6], the authors discussed the important mechanical-to-electrical conversion process in piezoelectric systems. A guideline for the choice of optimal configurations and material selection is provided in that paper; a range of biomedical applications such as mechanical energy harvesters, sensors, and actuators was summarised.

A generalised hypothetical technique for optimising the energy transformation and loading proficiency of nano-piezoelectric energy harvester PEHs with a special case of post-buckling twist under low-frequency excitations was proposed in [7]. In that work, the authors found that the normalised output power density depends on the intrinsic normalised parameter and the ambient excitation mode.

In [8], the authors proposed a novel architecture for simultaneous energy harvesting and gait recognition using PEH hardware. Further, they suggested a filtering algorithm to minimise sensing signal distortions to achieve high-accuracy gait recognition.

The authors of [9] developed a mathematical modelling approach for the merged energy-harvesting mode. A 1.2 battery is charged using both the knee movement and walking pressure applied to the piezoelectric crystal. In [10], the authors used kinematic modelling of the displacement of the center of gravity of the human body during walking to describe the generation of mechanical energy within the human gait cycle.

The wearable human lower limb energy harvesting and transmission exoskeleton (EHTE) was described in [11], where the energy harvester was mounted on the thigh, and the flat spiral springs were used to create the energy from leg swings.

A shoe-mounted piezoelectric energy harvester (PEH) was proposed in [12] to harvest energy from the human gait. The study findings clearly demonstrate that the designed PEH has eight high energy levels in a gait cycle and has an efficient power generation even within human walking frequency that has the possibility of wearable driving vehicles.

This study aims to provide a complete system to accomplish the following tasks.

First, the electrical energy from the human body is harvested. Next, the generated power is transferred wirelessly to the intended distance. Finally, the generated energy is used to charge various medical devices implanted in the human body or mounted on it. Energy harvesting utilises mechanical energy generated during musculoskeletal motion. This energy is harvested during human walking, which is one of the daily activities (except for people with disabilities). Therefore, utilising simple daily walking to generate energy would solve various electricity-related issues currently faced in the present days.

**Pressure applied to PZT and harvested power**

In biomechanics, ground reaction force (GRF) is the gait factor that expresses the bodyweight stress on the ground [13]. Newton's second law through a simple dynamic equilibrium has been used to calculate the GRF during walking; GRF and body weight related to the consequential acceleration can be expressed mathematically by (1) [14].

(1) $$GRF = Mg$$

where *M* is the body mass, and *g* is the gravitational constant.

Mechanically, the stress (σ) can be defined as the total force applied to the surface of a body per unit area, so the bodyweight stress during walking can be expressed mathematically by (2) [15].

(2) $$\sigma = \frac{GRF}{a}$$

where $\sigma$ $(N/m^2)$ is the stress and $a$ $(m^2)$ is the contact surface area.

The electrical energy stored on PZT is given (3) [16]:

(3) $$W_e = \frac{1}{2}(\sigma g)^2 . \varepsilon a t$$

where $g$ $(V{\cdot}m/N)$ is the characteristic piezoelectric stress constant, ε *(farad / m)* is the piezoelectric permittivity, and *t (m)* is the thickness of the sample.

During the gait cycle, alterations in the human biomechanical structures may lead to changes in the foot stress regions. In this study, the heel region was used as a platform for the PZT based on several studies that confirmed that the heel region has the highest stress during the gait cycle [14], [17, 18]. In this proposed work, PZT-5H has been selected according to previous studies with its coefficients (thickness= 0.5mm, g= 19.7 x $10^{-3}$ $V{\cdot}m/N$, and ε =3x $10^{-6}$) [19, 20].

**Proposed system Description**

The proposed system is composed of the following stages: energy harvesting from gait, which is then transmitted to a portable or implantable medical device. The next section describes power generation from the PZT device.

Many wireless power transfer approaches utilize the electromagnetic field of a specific frequency for power transfer. Optical techniques are used at the high frequencies, which transmits power through a collimated light beam to the remote sensor, where photons to electric power conversion process is occurred. This approach allows efficient transmission over large distances, but it requires precise pointing and tracking mechanisms to synchronize between transmitters receivers while in move. In addition, any objects located between the transmitter and receiver may result in beam blockage, or even worse, stop power transmission. A similar method can be used in microwave frequencies to effectively transmit power from suitable antennas over large distances with a radiated EM field [21].

Similar protection and device complexity caveats, however, relate to these radiative methods. Power can also be transmitted using nonradiative fields. For example, transformer operation can be used for wireless power transmission. Magnetic induction principle is used to transfer energy without a direct connection. Inductive chargers [21] apply the same principles. But, for effective systems operations both the primary and secondary coils must close to each other and positioned carefully. Technically, that means the magnetic coupling must be large for suitable operation.

However, for larger spacing or getting extra flexibility to connect the source and device? That is the question a Massachusetts Institute of Technology group investigated several strategies for transmitting power over "mid-range" distances. They reached a non-radiative solution using resonance to improve the efficiency of transferred energy (see high resonant power transfer physics for details) [22-24]. Resonators with High-quality factor allow efficient energy transfer at lower coupling rates. This method allows transmission at greater distances with less positional requirements. This method is often denoted to as "highly resonant- wireless power transfer (HR-WPT)).

The team from MIT has shown highly reasonable energy transfer by employing a magnetic field over a medium distance of 2m. This is known as "magnetic resonance". It is often compared with "induction" because of its ability to effectively transmit power various distances and with positional and orientation balances. Using HR-WPT has hopeful applications in wireless energy transfer domains.

In this study, the system block diagram shown in Figure 1was developed. The system considers a highly resonant approach for WPT starting from PZT, capable of generating an AC output voltage.

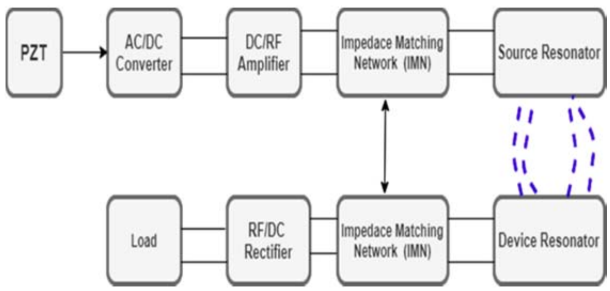


Fig.1. Block diagram of a wireless energy transfer system

The PZT output is applied to a full-wave rectifier, and then the generated voltage is stored in a 10μF electrolytic capacitor until the capacitor voltage reaches the threshold value of the voltage to let the system start. The energy for each gait can be calculated by observing the capacitor voltage using (4):

(4) $$E = \frac{1}{2}CV^2$$

The DC/RF stage is used to generate an AC signal with a frequency of 100.1 kHz. The idea of converting the PZT signal to DC and then to AC again is to reduce the size of the resonator circuit. High inductance requires either a large inductor or high frequency to make the system as small as possible. The H-bridge IC was carefully chosen to have a small operating current. The IC number (TLE9400EP) was used for the DC/AC conversion. This chip can work with exceptionally low power consumption, which is crucial in our case, as the energy generated is exceptionally low. A low-power microcontroller (PIC12LF1571) was used to generate the required signals to drive the H-Bridge. The algorithm was

carefully designed to make the power consumption exceedingly small. The controller generates two signals that complement each other with a small gap (both signals are zero) to avoid a high current caused due to the tail of the current at the internal transistors of the H-Bridge IC.

At the right end of the block diagram in Fig. 1, the source resonator and the device resonator are located, where both circuits are extremely similar, and they are highly resonant. Highly resonant circuits represent a high-quality factor. This quality factor is defined using (5):

$$Q = \frac{f_c}{BW} = \frac{Stored\ Energy}{Lost\ Energy} \quad (5)$$

where fc is the center frequency and BW is the bandwidth of the resonant circuit.

Table 1. Theoretical estimated harvested energy for different walker body weights

| Bodyweight (Kg) | Ground reaction force (N) | Stress for circle PZT sensor (KP); diameter = 3 cm | Harvested energy (μJ) for PZT; diameter = 3 cm |
|---|---|---|---|
| 50 | 490 | 693.5598018 | 98.91763 |
| 55 | 539 | 762.915782 | 119.6903 |
| 60 | 588 | 832.2717622 | 142.4414 |
| 65 | 637 | 901.6277424 | 167.1708 |
| 70 | 686 | 970.9837226 | 193.8786 |
| 75 | 735 | 1040.339703 | 222.5647 |
| 80 | 784 | 1109.695683 | 253.2291 |
| 85 | 833 | 1179.051663 | 285.872 |
| 90 | 882 | 1248.407643 | 320.4931 |
| 95 | 931 | 1317.763623 | 357.0927 |
| 100 | 980 | 1387.119604 | 395.6705 |
| 105 | 1029 | 1456.475584 | 436.2268 |
| 110 | 1078 | 1525.831564 | 478.7613 |
| 115 | 1127 | 1595.187544 | 523.2743 |

The bandwidth of the resonant circuit should be as small as possible to obtain a higher quality factor. It can be controlled by reducing the loss in the resonator. In any resonant circuit, the resistance of the wires and the leakage current of the capacitor cause the loss. Consequently, to overcome these two issues, a KEMET multilayer ceramic capacitor of 1000pF was chosen with a 2.527mH inductor, as shown in the resonant circuit shown in Fig. 2. This capacitor has an exceptionally low leakage current, and the coil has been well prepared using a ferrite core with 151 turns. At the receiver side, an almost reverse system was applied. The output of the device resonator is applied to the Impedance Matching Networks (IMN), then to the RF/DC rectifier, and finally, to the load, which could be the battery of the device.

Fig. 2. The resonant circuit

## Results

By assuming that the bodyweight is known, the estimated harvested energy for PZT-5H in one step is shown in Table 1.

The generated voltage from the PZT placed in a foot with different gait frequencies is shown in Fig. 3, and normal gait is shown in (a), (b), and (c). The maximum output of the PZT is achieved with the highest frequency gait, as shown in (d).

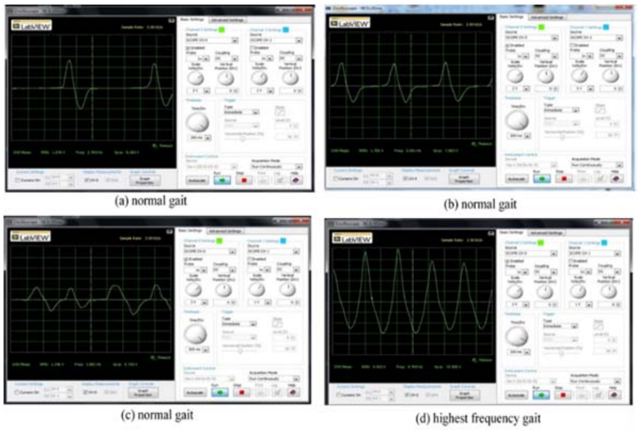


Fig. 3. Generated voltage from PZT placed in a foot with different gait frequency

The output waveform of the rectifier without a capacitor is shown in Fig. 4 (a). The output waveforms of capacitor voltages for the three steps of the rectifier with the capacitor are shown in Fig. 4 (b), (c), and (d). Fig. 5 shows that for different walker body weights, the amount of energy generated increases as the walker's weight increases.

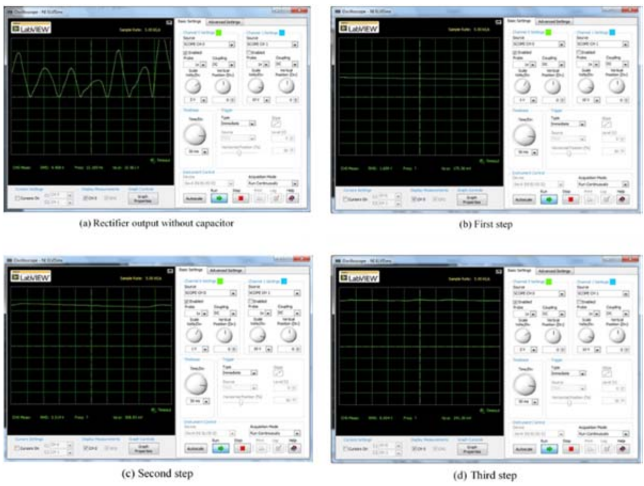


Fig. 4. Output waveform of rectifier at the source side

The energy of each step can be calculated using (1). In the second step, the total energy stored in the capacitor was 61 μJ using V=3.5 V. In the third case, the total energy was 320 μJ using V=8.0 V. Therefore, the energy generated in the third step is equal to the difference in the total energy at the third step and the second step, resulting in almost 260 μJ per step which is very close to the theoretical calculations.

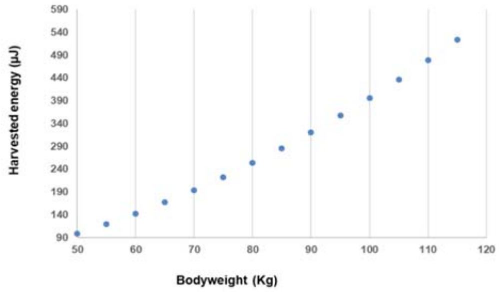


Fig. 5. The relation between body weight and generated energy

**Discussion**

Using piezoelectric materials in the self-charging battery for cycle use is still a young technology, meaning that they will likely become more efficient in the future. However, in this study, the targeted applications for such an idea are medical devices or wearable sensors that usually require a relatively long time to recharge or replace the battery. For example, at

the receiver end of the system, 70% of the total energy received was equal to 182μJ. If we take a battery of size LR44 as an example, such batteries have a capacity of 100 mAh and a nominal output voltage of 1.5V. The energy stored in this battery was 540 J. This energy can be calculated using the following equation:

$$E = V * (mAh) * 3600 \quad (6)$$

The usable energy of any battery is usually expressed by the depth of discharge (DoD), which is the fraction or percentage of the capacity reduced from the fully charged battery. Normal batteries usually have 50% DoD. Therefore, only 270 J of the LR44 battery can be used. It would require almost 1.5 million steps to charge a battery of 270 J, considering the total energy achieved from the wearable self-charging device to be182 μJ. Concerning the pacemaker battery with specifications of 5V and 2Ah, the capacity at any instance should not be less than 1.82 Ah to maintain normal operations of the pacemaker (Webster, 2009). The usable energy of the pacemaker battery is 3240 J. It would take 17.8 million steps to generate this amount of energy. If the average number of steps walked by a normal and healthy person per day is 5000 steps. The pacemaker battery would require3560days to attain a 100% charge.

**Future Work**

Multi-layer PZT can be used with 18 layers to make the proposed system more useful or reduce the number of steps, generating almost 4000μJ of energy per step. It can reduce the number of days to 231days by using the analogy of calculations provided in this work. Furthermore, a mechanical system can be used to generate forces to distribute the pressure in a way that has the maximum energy of the PZT at each step, regardless of the shape of the foot.


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