AN ENERGY HARVESTING DEVICE FOR PORTABLE APPLICATIONS

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The nodes, part of the conventional wireless sensor networks (WAN) and wireless body area networks (WBAN), are given much interest due to their limited power supply. Research in energy harvesting for powering autonomous sensors represents the main focus nowadays. In this paper a piezoelectric energy-harvesting device driven by human locomotion is implemented and modeled using Finite Element Method (FEM). Results for different types of angular displacements are presented.

Keywords: energy harvesting, wireless sensor network, wireless body area network, piezoelectric device, implantable sensors, biomechanical energy harvesting.

1. ENERGY HARVESTING DEVICES

Wireless Body Area Network (WBAN) represents a Wireless Sensor Network (WSN) implanted within or at the level of the human body. A central processing node is responsible with transmitting the patient's monitored signals from the other sensor nodes to a main gateway, which further transmits the information to the monitoring devices available to the authorized medical staff.

These networks are facilitating the ease with which the physicians are able to diagnose the patient, thus contributing to a better medical act. Also, and as a aside, in case of emergency, an independent power supply may be used to release an acoustic signal for urgent intervention to the location of the patient.

According to the designated target of the application and the information that needs to be sensed, several wireless sensors can be used in different parts of the body (Chen and Pomalaza-Raez, 2010).

WBAN is different, however, from conventional WSN in terms of power consumption, since several of the high consuming network tasks can be ignored (Cheng and Huang, 2008). From this perspective, using a battery as a primary power supply is not an option since roughly 60% of the volume of a conventional implantable pacemaker would be occupied by it (Ashraf and Masoumi, 2016).

Temperature difference between the inner core temperature of the human

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body and the ambient temperature represents the main focus in developing thermal energy harvesting devices. Depending on the specific application and energy requirements, either thin superlattice film technology (Ashraf and Masoumi, 2016) or thermoelectric generators are used (Ghosh, *et al*., 2015, Hoang, *et al*., 2009, Watkins, *et al*., 2005).

Biomechanical energy harvesting is analyzed in (Cervera, et al., 2016, Cheng, et al., 2015, Kong, et al., 2014, Li, et al., 2009, Pozzi, et al., 2011, Romero, et al., 2010, Yang and Yun, 2011) from joint motion, impact driven to flexible wearable harvester devices. These researches were focused on implementing devices that contained piezoelectric materials due to their property of mechanical to electrical energy conversion, reliability, and small footprint, which make them suitable to integrate in applications without additional burden to the human motion.

Power consumption can be minimized by integrating several protocols that are able to decide the path which do not contain power drained nodes (Jin, et al., 2015), by minimizing the transmission power consumption (Rodolph and Teresa, 1998), or by alternating the operating mode of the nodes between active mode and sleep mode.

2. WIRELESS SENSORS AND WBAN

A typical WBAN consists of several wireless sensors and a central processing node (CPN) connected in a star topology, which has the role of collecting the data sent by the other sensors and transmitting them to the local gateway, represented by another sensor node.

Since the gateway function is held by only one sensor node there is the risk that it will run out of energy. Rotating the gateway function, using the residual energy of each sensor node, among the other nodes, which are not power-drained, would represent a solution.

According to (Cheng and Huang, 2008), some power consumption tasks of conventional wireless sensor network can be ignored in the case of WBAN: overhearing is negligibly small since WBAN has at its core an irregular data traffic; idle listening can be ignored since WBAN is designed as a transceiver; data redirection can be ignored since WBAN has a star topology; message control can be ignored. Collision represents the main power consumption factor in WBAN, and it may occur either when the transmission ways are already engaged in communicating data or when another WBAN is interacting with another network.

Depending on the application requirements and the parameters to be monitored, there are several types of sensors: electromyogram (EMG), electrocardiogram (ECG), electroencephalogram (EEG), blood pressure, and gyroscopes and accelerometers, as inertial sensors for sensing body motion and detecting if a patient's fall occurs.

There are several types of accelerometers used in WBANs, such as: piezoelectric, piezoresistive, capacitive and Hall effect (Chen and Pomalaza-Raez, 2010).

Commonly, accelerometers are used detrimental to gyroscopes because the later have much higher power consumption and they are more expensive than an average accelerometer.

2.1. Joint Energy Harvesting

The human body is able to consume approximately 10.7 MJ of energy that a battery weighting 20 kg would be necessary to store.

The concept of regenerative optimal breaking system is applied to the human motion, and it generates the possibility of converting kinetic energy into other form of usable energy, e.g., electric. Table 1 presents several types of joints and their rated power. As shown, the knee has larger values of negative power and is the best option when designing a joint energy harvester device.

Table 1

Values for different joint types

Joint	Work [J]	Torque [Nm]	Negative power [%]	Negative power [W]
Heel	1-5	—	50	1-5
Ankle	33.4	140	28.3	19
Knee	18.2	40	92	33.5
Hip	18.96	40-80	19	7.2
Elbow	1.07	1-2	37	0.8
Shoulder	1.1	1-2	61	1.3

The harvesting efficiency is given by the Cost of Harvesting (COH) indicator, which is defined as the ratio between the metabolic energy difference of the motion when the device is harvesting energy and when the device is mechanical detached, and the electrical energy difference with and without harvesting (Cervera, et al., 2016).

$$COH = \frac{\Delta metabolic\ energy}{\Delta electrical\ energy}\ . \tag{1}$$

Another formula for COH calculation is given by (Kong, *et al.*, 2014):

$$COH = \frac{1}{device\ efficiency * muscle\ efficiency}\ . \tag{2}$$

2.2. Piezoelectric Materials

When designing energy harvesting devices driven by human motion, the common solution is integrating piezoelectric materials inside the mechanism. Piezoelectric direct effect may be used for the conversion of the mechanical motion into electrical energy, which corresponds to an electric generator working conditions is then used.

There are several types of piezoelectric materials, e.g., polymers, films, piezoelectric, and composite materials. The relation between the piezoelectric coefficients, which characterizes piezoelectric materials, is given by (Kong, *et al*., 2014).

$$G = dK\varepsilon_0, \tag{3}$$

$$R_{opt} = \frac{t}{WL\varepsilon_{33}\omega} = \frac{1}{C_p\omega}, \tag{4}$$

where t [m] is the thickness of the bimorph structure, L [m] is the length of the piezoelectric layer, W [m] is the width of the cantilever, ε_{33} [F/m] is the dielectric constant, and C_p [F] is the straw capacitance of the device.

3. THE ELBOW JOINT HARVESTER DEVICE

The knee joint energy-harvesting device presented in (Pozzi and Zhu, 2011) may be adapted to the elbow, and its dimensions correspond to the overall dimensions of the human elbow.

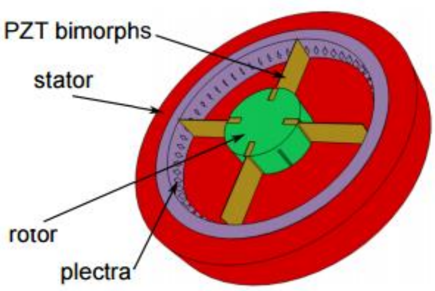

Fig. 1. The knee joint energy-harvesting device [10].

The device consists of a stator and a rotor, which has at the nodes of its tips some blades consisting of PZT bimorphs. The blades were also adapted, the PZT-5H material is integrated between two layers of foam which are sandwiched between two layers of Aluminum. These blades are interacting with the plectra stoppers, which are positioned across the stator. The plectra stopper is a polyamide material and is flexible as the PZT blades.

The 3D model was simplified to a 2D geometry and reduced, by periodicity. Thus, only one PZT blade and only one plectra stopper were modeled using the Finite Element Method (FEM). Fig. 2 presents the computational domain and the FEM mesh of the portable device.

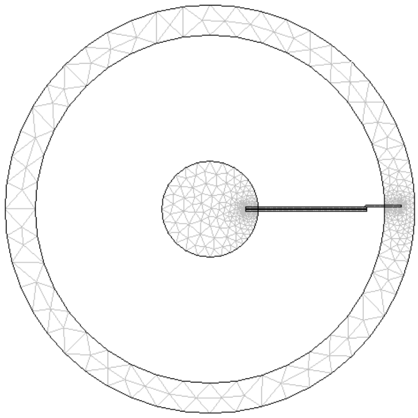

Fig. 2. The computational domain and the FEM mesh.

The sizes of each component of the device are given in Table 2.

Table 2

The main dimensions of the device

Radius of rotor	4 mm
Interior radius of stator	14.5 mm
Exterior radius of stator	17 mm
Length of PZT blade	Y10 mm
Width of PZT blade	380 µm
Size of Plectra	3×2 mm^2

The foam layers are 125 µm wide each, and the Aluminum and PZT layer has a width of 130 µm. The device follows the rotation of the joint and the stator is the moving part of the device. The flexible parts are displaced along the Oy axis (Fig. 2), and the pending tension per PZT material surface is plotted.

The mathematical model that describes the coupled piezoelectric electric field – structural mechanics fields is given through

$$\begin{aligned} \mathbf{e} &= s_E + d^T\mathbf{E}, \\ \mathbf{D} &= d + \varepsilon_0\varepsilon_r\mathbf{E}, \end{aligned} \quad (5)$$

where **e** is the strain, s_E [Pa^{-1}] is the compliance matrix, d [V^{-1}] the coupling matrix, (d)^T the transposition operator, **E** [V/m] is the electric field strength, **D** [C/m^2] is the electric flux density, ε_0 is the electric permittivity of the free space, and ε_r is the relative electric permittivity (Cook, 2001).

A comparison between eq. (3) and eq. (5) shows that the electrical flux density is dependent also with the open circuit coefficient and the direction of polarization of the material.

The boundary conditions that close the model (5) are indicated in Fig. 3.

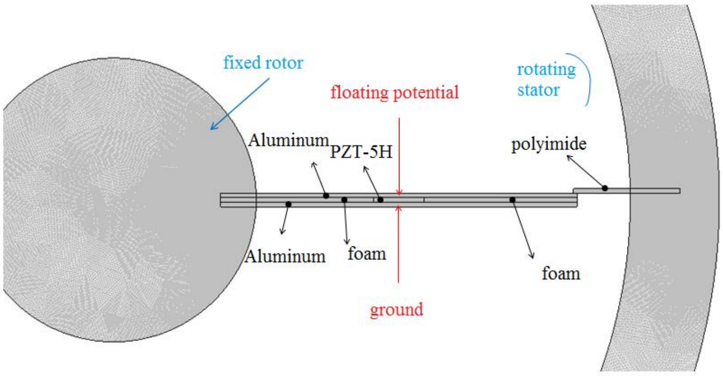

Fig. 3. The boundary conditions and the main components.

The mathematical model was solved using the FEM technique, as implemented by [7].

4. RESULTS AND DISCUSSION

After running the simulation for a 3.1° rotation of the stator *w.r.t.* the rotor, the maximum deformations of the two blades (PZT and stopper) are shown in Fig. 4.

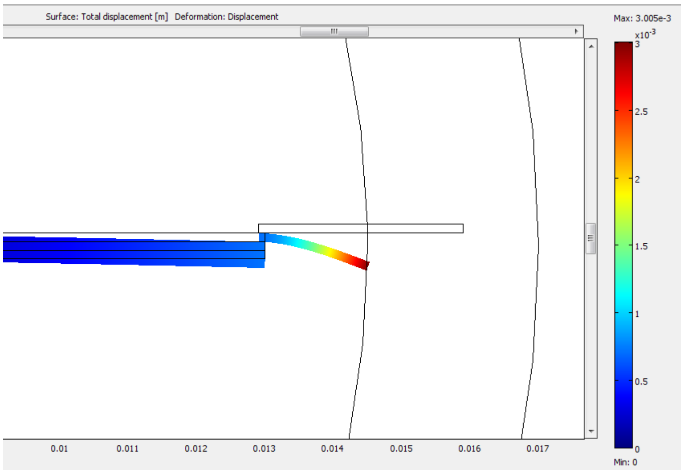

Fig. 4. The deformation of the blade and plectra stopper amplified twice for better viewing.

For the rotation of the stator with the given angular displacement, the deflection of the plectra stopper reaches a maximum at the intersection level with the stator frame. This rotation acts much more upon the polyimide plectra than the

PZT blade.

The simulation is made in stationary conditions. The discretization mesh is evolving at each stage of the rotation, until the two blades loose contact and the plectra stopper is released. This observation is important since the mesh has to adapt at each time step of the simulation.

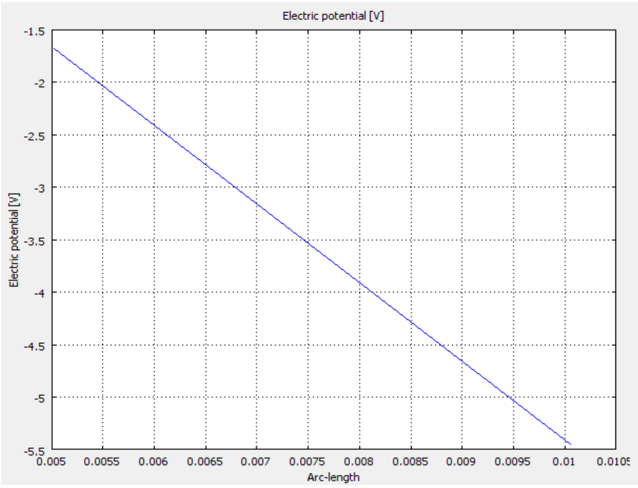

Fig. 5. PZT voltage for an angular rotation of max. 3.1º.

The electrical potential produced by the deformation of the PZT material is given in Fig. 5, which suggests a linear dependency deformation – electric field.

5. CONCLUSIONS

The portable device presented in this paper is versatile and flexible. It can be used with different types of joints and can convert part of the mechanical energy in electrical energy.

The device is scalable. It can be adapted and may incorporate more PZT blades, according to the primary rotational mechanical energy source that is harvested, without affecting the joint motion.

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