

Piezoelectric Energy Harvesting: an Overview

Evan Murimi, Marcus Neubauer

Abstract—Energy harvesting has experienced significant attention from researchers over the past few years due to the ever-increasing desire to produce portable and wireless electronics with extended lifespans. Piezoelectric materials have been greatly used for this purpose since they possess more mechanical energy for conversion into electrical energy than other materials and can also withstand large amounts of strain making them very attractive for power harvesting. They therefore use the ambient vibrations from the environment. Other sources of harvestable ambient energy including waste heat, electromagnetic waves, wind, flowing water, and solar energy. This paper will review recent progress in the vibrational power harvesting using piezoelectric materials and their applicability in developing self powered devices.

Keywords—energy, harvest, piezoelectric, vibration.

I. INTRODUCTION

THE need for autonomous devices has been growing, promoted by personal and industrial applications, raising the question of powering such systems. This development was initially encouraged by primary batteries, which have become less popular due to their limited lifespan [1]. Therefore, a recent trend to address this problem has consisted of using ambient energy from the environment to supply autonomous devices, making them self-powered. Several energy sources can achieve this purpose, for instance solar or thermal [2]. However, much research has focused on using mechanical energy [3], as such a source is commonly available in small-scale systems. The methods used include harvesting with piezoelectric, electromagnetic and electrostatic generators [4]. Piezoelectric elements are of particular interest, because of their high energy densities and integration potential, hence making them a premium choice for the design of self-powered small-scale devices [4]–[7].

However, Piezoelectric Electrical Generators (PEGs) still produce limited energy in the range of tens of microwatts to a few milliwatts, as the coupling coefficient of piezoelectric materials is quite low and localized at particular frequencies. In order to address this issue, several approaches have been proposed, which aim at increasing the input energy in the host structure to provide more power as shown in Figure 1 [8]. The first one is the use of linear generators which contains geometric arrangement of single converters [9]. The second is the nonlinear generators whereby the nonlinear stiffness effects are used to increase the operating range [10], [11] and the third is the advanced electronic networks which have the electrical load is modified to increase the performance [12]. Neubauer *et al* [13] carried out studies on the harvested energy of piezoelectric switching techniques namely standard-DC,

parallel synchronous switch harvesting on inductor, SSHI-DC energy harvesting circuits and comparing with the synchronous switch damping on inductor, SSDI damping network. They found that the rectifier capacitance has a comparatively smaller impact on the SSHI circuit than on the standard circuit. Additionally, the SSDI network was twice as efficient as the SSHI-DC network in terms of damping for the desired parameter range.

II. PIEZOELECTRIC ENERGY HARVESTING

Piezo electric materials exhibit the property that if they are mechanically strained, they generate an electric field proportional to the strain. Conversely, when an electric field is applied the material undergoes strain. These anisotropic relationships are described by the piezoelectric strain constant, d , which gives the relationship between applied stresses while the electro-mechanical coupling coefficient, k , describes the efficiency with which energy is converted between mechanical and electrical forms [14], [15].

Vibration based energy harvesting devices are generally modeled as mass, spring, and damper systems of the type illustrated in Figure 2. For a general vibration system,

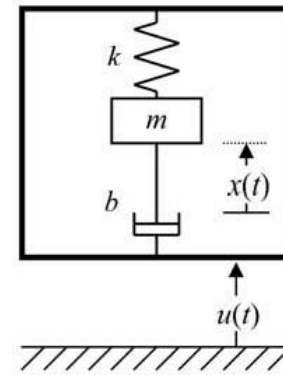


Fig. 2: Model of a translational inertial generator.

$$m\ddot{x}(t) + b\dot{x}(t) + kx(t) = -m\ddot{u}(t) \quad (1)$$

It can be shown [1] that the total power dissipated in the damping element is

$$p_d = \frac{m\xi_T Y^2 \left(\frac{\omega}{\omega_n}\right)^3 \omega^3}{\left[1 - \frac{\omega}{\omega_n}\right]^2 + \left[2\xi_T \frac{\omega}{\omega_n}\right]^2} \quad (2)$$

where $\omega_n = \sqrt{k/m}$ is the natural frequency of the resonant system and $\xi_T = b/(2m\omega_n)$ is the damping factor. For a given amplitude of acceleration, A , the amplitude of the

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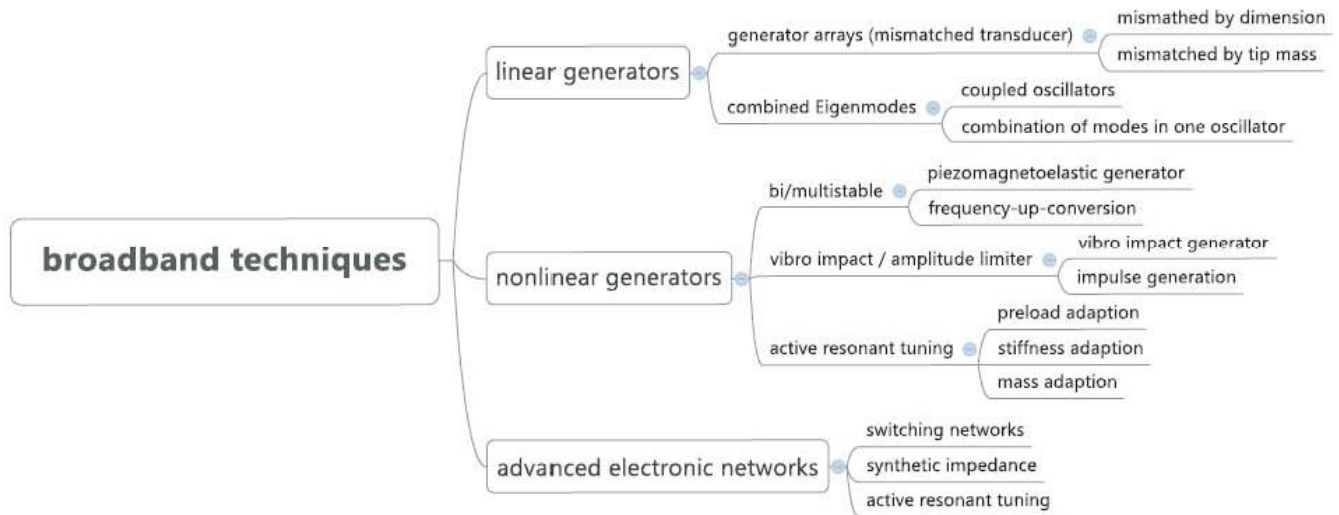


Fig. 1: Overview of the classification for energy harvesting systems [8].

displacement decreases as $Y = A/\omega^2$, and so Equation 2 becomes

$$p_d = \frac{m\xi_T A^2 \omega^2 \frac{\omega^2}{\omega_n^3}}{\left[1 - \frac{\omega}{\omega_n}\right]^2 + \left[2\xi_T \frac{\omega}{\omega_n}\right]^2} \quad (3)$$

There is a wide range of materials that exhibit piezoelectric behaviour. Nevertheless, the most commonly used materials in energy harvesting applications are lead zirconate titanate (PZT), barium titanate (BaTiO_3) and polyvinylidene fluoride (PVDF). PZT is a brittle piezoceramic which has a high electro-mechanical coupling coefficient, k , (up to 0.75). PVDF is a polymeric material available as flexible sheets and is more robust than PZT but has a much lower k (0.120.15). As a result of its greater stiffness and higher value of k , PZT is generally preferred for vibration based energy harvesting devices while impact and other intermittent type harvesting devices have made use of either PVDF or PZT, depending on the particular design [16].

III. RECENT TRENDS

Generally, due to the high stiffness of piezoceramics, they are not used in compressive mode as this results in a resonant frequency significantly above the frequency of vibrations found in most situations [14]. A more attractive configuration is to form the piezoceramic into a cantilever arrangement as shown in Figure 3 where layers of piezoceramics are bonded to a substrate, typically made from a suitable metal. This structure allows a lower resonant frequency to be achieved while producing large strains in the piezoceramic.

The uni-morph cantilever beam configuration is as shown in Figure 5c. Johnson *et al.* [17] used this configuration and demonstrated that the highest power can be generated under lower excitation frequencies and load resistances. Two combinations of bimorph structures are possible:

- 1) Series type
- 2) Parallel type

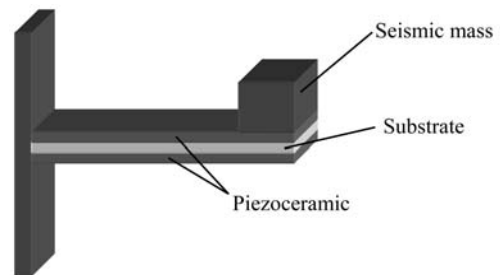


Fig. 3: Piezoceramic cantilever.

Series and parallel triple layer bimorph structures [18] are shown in Figure 5a and b respectively. The series triple layer bimorph is constructed out of a metallic layer, sandwiched between two piezoelectrics and the piezoelectric patches are electrically connected in series. In the case of the parallel triple, which is also sandwiched between two piezoelectric layers bimorph, the piezoelectric materials are connected in parallel. The parallel triple layer bimorph has the highest power under medium excited frequencies and load resistances, whereas the series triple layer bimorph produces highest power when excited under higher frequencies and load resistances. A series connection will increase the device impedance as well as improve the output delivered power at higher loads [19]. Research has been going on to improve the bimorph efficiency. Neubauer *et al.* [20] optimized the geometry of bimorphs and found out that for every compliance ratio, r_s an optimal geometry of the cross-section exists. The optimal case was a very soft substrate layer, with only thin piezoelectric layers on each side. Figure 4 shows exemplary optimized cross-sections with the compliance of the middle substrate layer increasing from left to right.

A. Mobile power supplies

A standing wave is a combination of traveling waves going in opposite directions which are in phase as shown in Figure

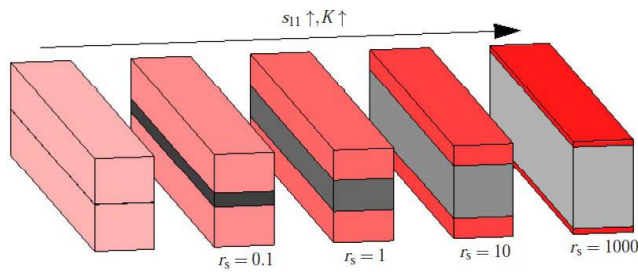


Fig. 4: Optimal cross-sections of the bimorphs for different compliance ratios.

As technology becomes more integrated into several aspects of human life, the concept of harvesting the energy lost during everyday activities has become more appealing. The size and power requirements of both portable electronic devices including personal digital assistants and digital music players, as well as biomedical devices such as pacemakers have been rapidly decreasing. With this decrease has come an increase in the feasibility of harvesting electrical energy from the human body to power these devices.

Gonzalez *et al* [21] discussed an overview of the various sources of mechanical energy available in the human body and classified them into two categories: continuous activities such as breathing and blood flow, and discontinuous activities such as walking and upper limb movement.

TABLE I: Human electrical power available using piezoelectric generators.

Activity	Mechanical power losses	Electro-mechanical efficiency	Electrical power losses	Daily activity	Electrical power available
Typing	10%	50%	10%	16.6%	283.5 μ W
U. limbs	50%	11.2%	10%	16.6%	24.6 mW
Breath	10%	11.2%	10%	100%	74.8 mW
Walk	75%	50%	10%	16.6%	1.265 W

Table I shows the available electrical power for different activities and the various efficiencies considered (due to mechanical losses in the coupling from the body movement to the generator, its electromechanical efficiency and the power losses due to the electrical power converter).

Niu *et al* [22] also investigated the energy available through several human body motions including joint motion, whole-body center mass motion, walking, and heel strike. The results are shown in Table II.

TABLE II: Mechanical energy from human motion.

Joint/Motion	Work [J/step]	Power [W]	Max moment [Nm]	Negative work [%]
Heel Strike	1 (1-5)	2 (2-20)		
Ankle	34.9 (33.4)	69.8 (66.8)	~140	42 (28.3)
Knee	24.7 (18.2)	49.5 (36.4)	~40	85.2 (92)
Hip	19.6 (18.96)	39.2 (38)	~40	11.5(19)
Elbow	1.07	2.1	1-2	37
Shoulder	1.1	2.2	1-2	61
Center of Mass	0.5	1		

Figure 6 shows a self-powered Total Knee Replacement

(TKR) implant has been developed by Platt *et al* [23]. Sensors encapsulated within the implants could provide *in vivo* diagnostic capabilities such as the monitoring of implant duty (i.e., walking) cycle, detecting abnormally asymmetric or high forces, sensing misalignment and early loosening, and early detection of wear. Early diagnosis of abnormalities is critical to minimize patient harm [23].

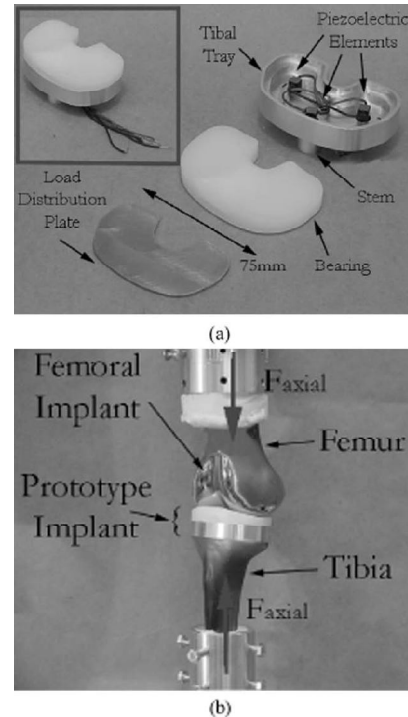


Fig. 6: Self-powered TKR model and test setup. (a) Components of the implant model. (b) Test setup.

Shenck and Paradiso [24] researched on harvesting the energy lost during heel strike using prestressed PZT unimorphs. They focused on implementing effective power harvesters into shoes while maintaining the design and comfort of the shoe. They developed the PVDF stave, which was implanted into the front of an athletic shoe because of the shoes toe flexibility. The PZT unimorphs working off heel strike energy, on the other hand, were implemented into a US Navy work boot because of the boots rigid heel cup as shown in Figure 7.

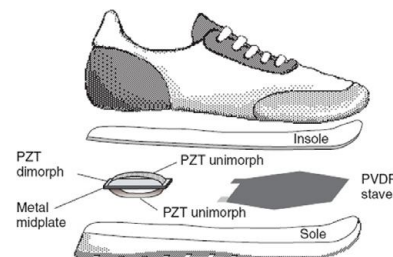


Fig. 7: A PZT dimorph and PVDF stave.

In order to demonstrate the feasibility and usefulness of energy harvesting in shoes, a self-powered radio frequency (RF) tag was created and was shown to operate successfully when installed into the shoe. The tag was capable of transmitting

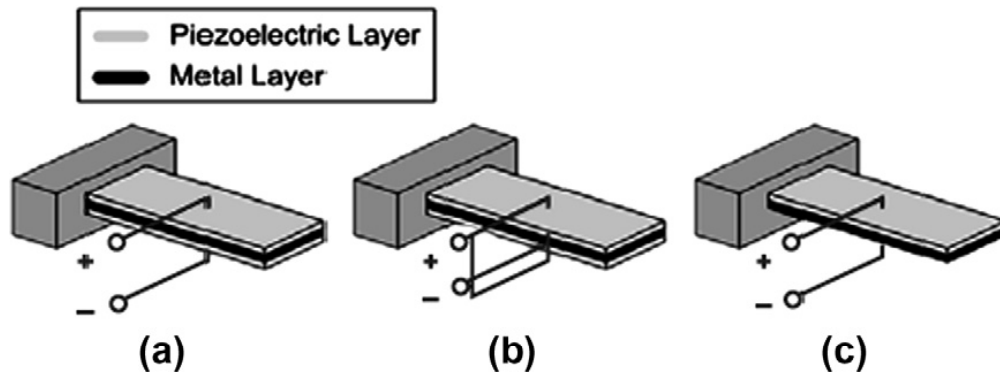


Fig. 5: (a) A series triple layer type cantilever. (b) A parallel triple layer type cantilever. (c) A uni-morph cantilever.

a short-range 12-bit wireless identification (ID) code during walking.

B. Self-powered sensors

With recent advances in wireless sensor technology, the need for energy sources that can harvest power from the environment and eliminate external power supplies and batteries is increasing.

A self-powered micro-accelerometer in which a single piezoelectric cantilever was used as a sensor and a power harvester was developed [25] as shown in Figure 8.

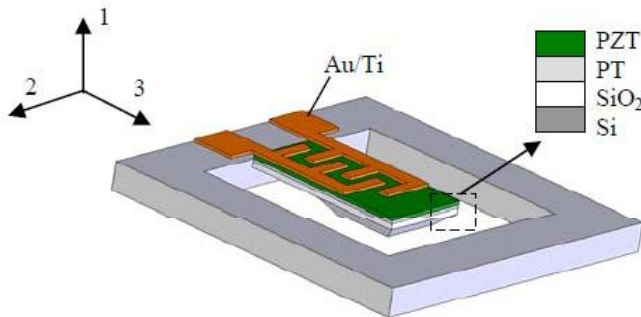


Fig. 8: Schematic of the proposed microaccelerometer.

Arms *et al* [26] developed a piezoelectric-powered wireless temperature and humidity sensor. A piezoelectric cantilever beam was used to harvest ambient vibrations to power the sensor and wireless data transmission circuitry. Figure 9 shows a photograph of the self-powered sensor. The piezoelectric generator was capable of supplying enough energy to perpetually operate the sensor with low duty cycle wireless transmissions.

Research was conducted by Elvin *et al* [27] to couple piezoelectric strain sensing and power harvesting into a single piezoelectric unit. A PVDF sensor and harvester was created and mounted to a beam that was to be monitored. The sensor was capable of measuring the strain in the beam which could then be used to identify damage in the beam in the form of a crack. Wireless transmission capabilities were incorporated into the system for communication purposes. Sufficient energy

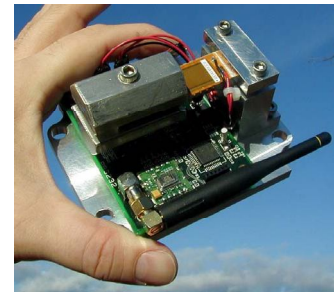


Fig. 9: Integrated piezoelectric vibration energy harvester and wireless temperature & humidity sensing node.

was produced by the PVDF generator to allow radio frequency transmission of strain values within a single loading cycle. Additionally, the sensor data transmitted showed the ability to accurately predict the crack depth. Typical application of the sensor is as shown in Figure 10

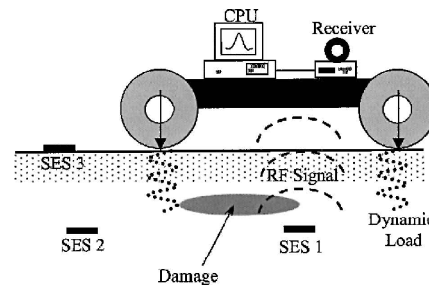


Fig. 10: Possible implementation of the sensor for damage detection.

A self-powered sensor node, shown in Figure 11, which was capable of scavenging energy from an oil pump has been developed. The node was programmed to sample three analog inputs including the voltage level generated from the piezoelectric generator, the state of charge on the storage capacitor bank, and data from an accelerometer. This information was stored in the local processor memory and also transmitted to a remote receiver [28].

IV. CONCLUSION

Harvesting energy from the environment is being considered as a viable option to replace the current power supplies for

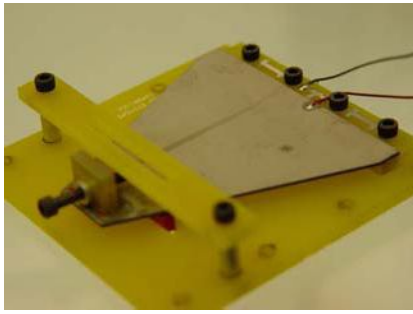


Fig. 11: Piezo-electric Generator.

energy constrained embedded systems. The desire to use self-powered devices drives to achieve enormous growth in the field of energy harvesting. With the few limitations such as low amount of power generated using the power harvesters, the researchers are working towards generating new methods.

The piezoelectric energy harvester generates the most energy when it is excited at its resonance frequency. Hence, it needs to be tuned to the main external frequency of the individual environment. If the excitation frequency shifts, the performance of the generator is drastically reduced. Many researchers are therefore looking for ways of expanding the bandwidth of the generator resonant frequency.

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