Power Harvesting Using Piezoelectric Materials

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Abstract: The field of power harvesting has experienced significant growth over the past few years due to the ever increasing desire to produce portable and wireless electronics with extended lifespan. Current portable and wireless devices must be designed to include electrochemical batteries as the power source. The use of batteries can be troublesome due to their limited lifespan, thus necessitating their periodic replacement. In the case of wireless sensors that are to be placed in remote locations, the sensor must be easily accessible or of disposable nature to allow the device to function over extended periods of time. Energy scavenging devices are designed to capture the ambient energy surrounding the electronics and convert it into usable electrical energy. The concept of power harvesting works towards developing self-powered devices that do not require replaceable power supplies. A number of sources of harvestable ambient energy exist, including waste heat, vibration, electromagnetic waves, wind, flowing water, and solar energy. While each of these sources of energy can be effectively used to power remote sensors, the structural and biological communities have placed an emphasis on scavenging vibration energy with piezoelectric materials. This article will review recent literature in the field of power harvesting and present the current state of power harvesting in its drive to create completely self-powered devices.
Key Words: Piezoelectric, power harvesting, energy scavenging, energy harvesting

1. INTRODUCTION

Over the past few decades the use of wireless sensors and wearable electronics has grown steadily. These electronics have all relied on the use of electrochemical batteries for providing electrical energy to the device. The growth of battery technology, however, has remained relatively stagnant over the past decade while the performance of computing systems has grown steadily, as shown in Figure 1. The advancement in computing performance has also led to increased power usage from the electronics, which in the case of CMOS technology follows a linear increase in power with respect to computing speed. The increase in power used by the electronics has lead to a reduction in battery life and has limited the functionality of the devices. In an effort to extend the life and reduce the volume of the electronics, researchers have begun investigating methods of obtaining electrical energy from the ambient energy surrounding the device.

Many environments are subjected to ambient vibration energy that commonly goes unused. Several methods exist for obtaining electrical energy from this source including the use of electromagnetic induction (for instance see Ref. [1]), electrostatic generation (for instance see Ref [2]), dielectric elastomers (for instance see Ref. [3]), and piezoelectric materials. While each of the aforementioned techniques can provide a useful amount of energy, piezoelectric materials have received the most attention due to their ability to directly convert applied strain energy into usable electric energy and the ease at which they can be integrated into a system. This energy conversion occurs because the piezoelectric molecular structure is oriented such that the material exhibits a local charge separation, known as an electric dipole. When strain energy is applied to the material it results in a deformation of the dipole and the formation of a charge that can be removed from the material and used to power various devices.

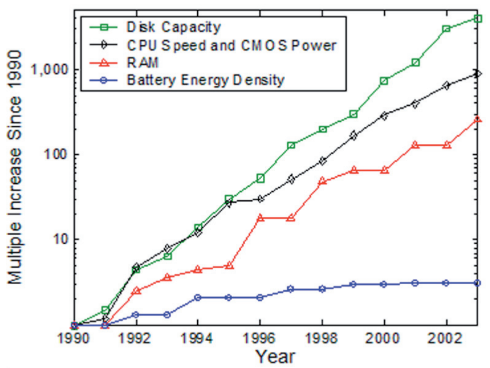

Fig. 1: Advances in computer and battery technology since 1990. (Derived from data in Ref. [4]).

The strain dependent charge output of piezoelectric materials has typically been used for sensor applications and can be found in a variety of different devices including accelerometers, microphones, load cells, etc. More recently, the concept of shunt damping was developed, in which the electrical output of the piezoelectric material is used for damping purposes rather than sensing [5]. Because a portion of the vibration energy is converted to electrical energy by the piezoelectric material, when it is dissipated through joule heating, energy is removed from the system resulting in a damping effect. The concept behind shunt damping is also used in power harvesting; however, rather than dissipating the energy it is used to power some other device.

The rapid growth of research being performed in the field of power harvesting has resulted in significant improvements to various energy scavenging techniques. This paper will present a review of the recent advances in power harvesting using piezoelectric materials since Sodano *et al.* [6] published a review of the field in 2004, which the reader is referred to as an introduction.

2. SELF-POWERED SENSORS

The focus of many recent research studies involving piezoelectric power harvesting involves the development of 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. Studies have been conducted to explore the possibility of using piezoelectric power harvesting devices to provide energy to various types of sensors. In a study conducted by Ammar *et al.* [7], the necessary components for a self-powered wireless sensor node were discussed. The components included a micro-scale piezoelectric energy harvesting system, an energy harvesting circuit, a microprocessor, a MEMS sensor, onboard memory, an onboard clock, and a radio frequency transmitter. A self-powered microaccelerometer was proposed by Zhou *et al.* [8] in which a single piezoelectric cantilever was used as a sensor and a power harvester. Although the above research does not include the development of prototype self-powered sensors, many researchers have successfully created sensors that are powered by piezoelectric energy harvesting devices.

Roundy and Wright [9] developed a small piezoelectric cantilever generator that was used to power a custom radio transmitter. The generator was designed with a 1 cm^3 total volume, taking into consideration the size of most wireless sensor nodes. The radio transmitter consumed 10 mA of current at 1.2 V and was capable of transmitting a 1.9 GHz signal a distance of ten meters. Their study showed that for excitation vibrations with a frequency of 120 Hz and an acceleration magnitude of 2.5 m/s^2, the piezoelectric generator was capable of charging a storage capacitor to a sufficient level at which the transmitter could be turned on. The radio transmitter demanded more energy than the piezoelectric device could generate; therefore, a low duty cycle of 1.6% was supported by the system.

The work of Arms *et al.* [10] focused on designing and fabricating 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 2 shows a photograph of the self-powered sensor. Research showed that under low input vibrations on the order of 1 m/s^2 and modest strain levels of around 200 $\mu\varepsilon$, the cantilever was able to generate a relatively high amount of power. When combined with the wireless temperature and humidity sensor, it was found that the piezoelectric generator was capable of supplying enough energy to perpetually operate the sensor with low duty cycle wireless transmissions. Again, a low duty cycle was found because the piezoelectric harvester did not generate enough power to continually operate the sensor.

In an effort to utilize piezoelectric energy generation in a biomechanical application, Platt *et al.* [11], created a self-powered total knee replacement implant in which sensors encapsulated in the unit could provide *in vivo* diagnostic capabilities. A prototype implant was created which was capable of producing enough power to operate a PIC 16LF872 microprocessor. The microprocessor was programmed to turn on an LED indicator for a fixed period of time during the loading cycle. Tests showed that when subjected to a 1300 N force, the system was able to illuminate the LED. In fact, approximately 225 μW of continuous power was generated by the piezoceramic and the PIC microprocessor only required 50 μW of power. This study has shown the ability of piezoelectric power harvesting systems to be used in human body implants to create *in vivo* self-powered sensors.

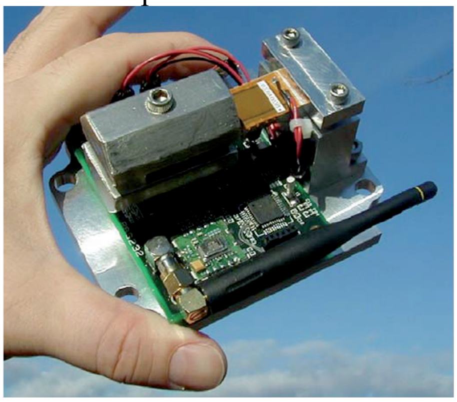

Fig. 2: Integrated piezoelectric vibration energy harvester and wireless temperature and humidity sensing node. (Figure from Ref. [10]).

A fiber-based piezoelectric power harvesting device was used by Churchill *et al.* [12] to supply power to an adaptable wireless sensor node capable of recording signals from many different transducers and transmitting data wirelessly to a receiver. When subjected to a 180 Hz vibration that caused a strain of 150 με, the piezofiber based harvesting system was able to power a microcontroller with onboard analog-to-digital conversion and wireless transmission capabilities for 250 ms. This proved to be enough time for the microcontroller to collect valid data from several sensors and transmit it four to seven times to ensure accuracy. For moderate strain levels of 150 με, the time it took for the capacitor to reach full charge and begin transmission was between 30 and 160 seconds depending on the frequency of excitation. Higher excitation frequencies facilitated faster charging. Additionally, it was shown that the piezofiber generator was capable of harvesting 7.5 mW of power when a 180 Hz vibration causing 300 με was applied.

Elvin *et al.* [13] studied the ability of a single piezoelectric element to act as both a sensor and a power supply to create a simplified self-powered sensor. Because the voltage generated by piezoceramic materials is proportional to the strain applied to the material, the device can be used as a strain sensor. Research was conducted to couple piezoelectric strain sensing and power harvesting into a single piezoelectric unit.

In a study focusing on self-powered machinery health monitoring, du Plessis *et al.* [14] investigated the possibility of harvesting energy from machinery vibrations with a piezoelectric cantilever to power a wireless health monitoring node. The research involved analyzing an oil pump which was to be assessed using the health monitoring node. The natural frequency of the pump was found to be 130 Hz, and a piezoelectric cantilever was fabricated and tested near this resonance. Under an excitation producing a strain of 700 με at 100 Hz, the cantilever was able to produce 2.8 mW of power. Experiments were also conducted to test the durability of the QuickPack. At a strain of 700 με at 100 Hz, the QuickPack encountered 1×10^8 cycles at which the test was terminated. This study proved the ability of a piezoelectric cantilever to produce enough power and withstand enough strain to be used in a machinery health monitoring sensor node. This research was continued by Discenzo *et al.* [15], who developed a self-powered sensor node capable of scavenging energy from the oil pump. The sensor node was installed on an oil pump in an oil tanker ship and left operating for four months. At the end of the four months, over 8,000 data files were captured by the sensor. This study shows a successful application of providing power to sensors using piezoelectric materials.

3. ENERGY HARVESITNG USING MEMS

With the recent advances in computer and electronics technology, the possibility exists of creating miniaturized, self-powered devices. The power requirements of some micro-scale chips are becoming so small that they can be powered by the energy scavenged from micro-scale piezoelectric power harvesters. Much of the recent power harvesting research in microelectromechanical systems (MEMS) has focused on the ability to supply power to wireless sensors. By incorporating power harvesting technology into wireless sensors, the cost of batteries and battery replacement can be eliminated. Additionally, the size of the sensor can be decreased by incorporating micro-scale power harvesters as an energy source.

In an effort to develop a micro-scale power harvester, Ammar *et al.* [16] designed a 1 μm thick piezoelectric cantilever beam with a seismic mass attached to its end. This micro power harvester was to be used as the energy source for a compact wireless sensor node. In addition to designing the cantilever, an adaptive energy harvesting circuit was also developed to help optimize the mechanical to electrical energy conversion process. Although a prototype of the micro cantilever beam has been created, a macro-scale beam was used to experimentally validate the circuit. It was found that implementing the adaptive circuitry on the macro-scale beam led to a faster charge build-up in the system.

Lu *et al.* [17] both designed and tested a micro-scale cantilever beam energy harvesting system. For typical MEMS applications that run continuously, a power harvesting system must supply about 0.1 mW of power. The goal of this research was to design a micro energy harvesting system capable of supplying enough power to run a MEMS application. A PZT cantilever with a thickness of 0.1 mm, a 1 mm width, and a 5 mm length was created. It was found that a vibration amplitude of 15 μm would be necessary to supply enough power for a continuous application. When experimentally tested, the cantilever generated about 1.6 mW of power at an excitation of 7 kHz, thus providing sufficient power harvesting capabilities for MEMS applications.

In order to improve the design of MEMS based piezoelectric energy converters, Gurav *et al.* [18] focused on optimizing the design parameters for micro-scale systems. An uncertainty-based design optimization was carried out on a microstructure consisting of an array of three cantilever piezoelectric beams all fixed at the same end, and connected to the same seismic mass. Upon completion of the optimization process, the results of a baseline design were compared to the results from the optimized design and a thirty percent increase in power harvesting capability was found over the baseline.

One of the limitations of harvesting energy from a cantilever beam is the low coupling coefficient associated with the *-31* bending mode typically found in cantilevers. The research of Zhou *et al.* [19], however, investigates the feasibility of harvesting energy from a PZT cantilever with interdigitated electrodes to create a self-powered piezoelectric microaccelerometer system. The electrode pattern allows the PZT to operate in the more efficient *-33* mode as is the case with the MFC [20]and the Active Fiber Composite (AFC) [21]. A PZT cantilever of dimensions 100 μm x 200 μm with a natural frequency of 1 kHz was predicted to give more than 2 $\mu W/mm^2/g$.

Similar to the research done by Zhou *et al.* [19], Jeon *et al.* [22] also examined the usefulness of operating a micro piezoelectric cantilever in the *-33* bending mode through the use of interdigitated electrodes. A cantilever harvester having a length of 100 μm, a width of 60 μm, and a thickness of 0.48 μm was fabricated. The resonant frequency of the cantilever was found to be 13.9 kHz, and when operated at resonance, a maximum tip displacement of 2.56 μm was observed. A maximum power output of 1.01 μW at 2.4 V occurred at resonance when a 5.2 MΩ load was applied to the system. Taking into consideration the on-chip circuitry as well as the cantilever itself, an energy density of 0.74 mWh/cm^2 was obtained, which compares favorably to current lithium ion batteries. It was concluded that through miniaturized power harvesters, wireless sensor networks can be both compact and self-powered.

In a study performed by Lee *et al.* [23], a novel fabrication technique was developed in order to create a piezoelectric MEMS power harvesting device with interdigitated electrodes operating in the *-33* bending mode. The process was developed to help reduce the fabrication time and increase the quality of the piezoelectric device compared to existing techniques. A home-made jet printing PZT deposition chamber was developed in which 2 μm of PZT film could be deposited each pass. The technique was shown to be capable of depositing a high-quality PZT layer of up to 10 μm in minutes. Although the devices were successfully created, experimental testing was not performed, but should be investigated in the future.

In an effort towards achieving long term micro-power generation, Duggirala *et al.* [24] present a new form of piezoelectric power harvesting that involves radioactive thin films. The device developed, called a radioisotope-powered piezoelectric micro-power generator, utilizes radioactive materials to excite a piezoelectric cantilever beam. A thin-film radioactive source material is placed below the tip of a small cantilever beam that contains a piezoelectric patch near its base and a collector at the tip. As the radioactive source emits charged β-particles, the collector at the tip of the cantilever traps them. By charge conservation, the source and the collector build up opposite charges leading to an electrostatic force between the two that draws them together. When the tip of the cantilever is drawn close enough to touch the radioactive thin-film, the charge and the electrostatic force are neutralized and the cantilever begins to oscillate. The oscillatory motion of the beam stresses the piezoelectric patch and creates electrical energy. Experimentally, a 1 cm long generator was created and tested. The device was shown to provide a voltage of about 350 mV and a power of about 1.13 μW at the end of an oscillation into a load impedance of 90 kΩ. The device had an overall conversion efficiency of 3.7%. Further details on this technology and potential applications are also presented by Lal *et al.* [25].

4. CONCLUSION

Power harvesting is the key to providing fully self-powered systems in the growing portable and wireless electronics market. While this field has seen a number of schemes for harvesting ambient energy sources, piezoelectric materials can be easily incorporated into many systems that are subjected to dynamic energy. Although the design specifications and power harvesting capabilities of most piezoelectric energy harvesting systems are not trivial and require much attention, any vibrating host presents the possibility of harvesting energy. The application of piezoelectric materials in power harvesting systems contains many variables which can be manipulated to obtain electrical energy from ambient vibration such that wireless electronics can be operated in a self-powered manner. A number of these factors have been detailed in the literature, which now acts as a comprehensive base for future researchers to build on.

A majority of the latest research has focused on improving the efficiency of piezoelectric power harvesting devices through physical and geometrical configuration, as well as adaptive circuitry and energy removal techniques. The challenge facing many researchers remains the difference between the energy consumption of the electronics used to store the harvested energy and the energy generation capabilities of the power harvesting device. The improvement of energy generation and storage methods combined with the decreasing power requirements of today's electronics help bring the concept of creating self-powered electronics closer to reality.

Much of the research up to this point has focused on the characterization of the power harvesting medium rather than the development of complete self-powered devices. The authors of this article feel that the future of power harvesting is in the development of complete systems (power harvesting, storage, and application circuitry combined) that can be readily implemented. Preliminary research has been conducted, for example, on a complete autonomous sensing unit that incorporates structural health monitoring and power harvesting technologies into a single, self-powered device [26]. Further development of such systems will facilitate the progression of power harvesting methods from a pure research topic to a useable technology in practical devices.

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