A Survey of Energy Harvesting Sources for Embedded Systems

Sravanthi Chalasani
Electrical and Computer Engineering
University of North Carolina at Charlotte
schalasa@uncc.edu

James M. Conrad
Electrical and Computer Engineering
University of North Carolina at Charlotte
jmconrad@uncc.edu

Abstract

Historically, batteries have been the source of energy for most mobile, embedded and remote system applications. Now, with ubiquitous computing requirements in the fields of embedded systems, wireless sensor networks and low-power electronics such as MEMS devices, an alternative source of energy is required. Also with the limited capacity of finite power sources and the need for supplying energy for a lifetime of a system, there is a requirement for self-powered devices. The process of extracting energy from the surrounding environment is termed as energy harvesting. Energy harvesting, which originated from the windmill and water wheel, is widely being considered as a low-maintenance solution for a wide variety of applications. There are various forms of energy that can be scavenged, like thermal, mechanical, solar, acoustic, wind, and wave. This paper serves as a survey for identifying the sources of energy harvesting based on various technical papers available in the public domain.

1. Introduction

With the wide advancements in the field of wireless sensor networks, some applications require the sensor nodes to have a long lifetime. Using conventional batteries is not always advantageous since they require human intervention to replace them. Hence, acquiring the electrical power needed to operate these devices is a major concern. An alternative type of energy source to conventional batteries must be considered. The electrical energy required to run these devices can be obtained by tapping the thermal, light, or mechanical energies available in the ambient environment. This process helps in providing unlimited energy for the lifespan of the electronic device. Therefore, the process of extracting energy from the ambient environment and converting it into consumable electrical energy is known as *energy harvesting* or *power scavenging*. The forms of typical ambient energies are sunlight, mechanical energy, thermal energy, and RF energy.

The energy harvesting sources can be used to increase the lifetime and capability of the devices by either replacing or augmenting the battery usage [8, 24-26, 35, 48]. The devices powered by energy harvesters can be used to provide vital information on operational and structural circumstances by placing them in inaccessible locations [45]. There is an increasingly volume of research carried out on energy harvesting [1-72].

This paper is a survey of various technical papers on energy harvesting. We identify the various sources of energy available for harvesting and describe the work carried out by researchers.

2. Sources of Energy Harvesting

The classification of energy harvesting can be organized on the basis of the form of energy they use to scavenge the power. For example piezoelectric harvesting devices scavenge mechanical energy and convert it into usable electrical energy. The various sources for energy harvesting are wind turbines, photovoltaic cells, thermoelectric generators and mechanical vibration devices such as piezoelectric devices, electromagnetic devices [45]. Table 1 shows some of the harvesting methods with their power generation capability [5].

Table 1: Energy Harvesting Sources [5]

Harvesting Method	**Power Density**
Solar Cells	15mW/cm^3
Piezoelectric	330µW/cm^3
Vibration	116µW/cm^3
Thermoelectric	40µW/cm^3

The general properties to be considered to characterize a portable energy supplier are described by Fry, et al. [18]. The list includes electrical properties such as power density, maximum voltage and current; physical properties such as the size, shape and weight; environmental properties such as water resistance and operating temperature range; as well as operational and maintenance properties. Sufficient care should be taken while using the energy harvesters in the embedded systems to improve the performance and lifetime of the system.

3. Mechanical Vibration

When a device is subjected to vibration, an inertial mass can be used to create movement. This movement can be converted to electrical energy using three mechanisms: piezoelectric, electrostatic and electromagnetic. The form of energy utilized here is the mechanical energy.

3.1 Piezoelectric Materials

These materials convert mechanical energy from pressure, vibrations or force into electricity. They are capable of generating electrical charge when a mechanical load is applied on them. This property of piezoelectric materials is considered by the researchers to develop various piezoelectric harvesters in order to power different applications [2, 10, 13, 33, 34, 37, 69, 70].

Due to their inherent ability to detect vibrations, piezoelectric materials have become a viable energy-scavenging source. Currently a wide variety of piezoelectric materials are available and the appropriate choice for sensing, actuating, or harvesting energy depends on their characteristics. Some are naturally occurring materials such as quartz. Polycrystalline ceramic is a common piezoelectric material. Lead Zirconate Titanate (PZT) is being considered since it shows a high efficiency of mechanical to electrical energy conversion [23]. With their anisotropic characteristics, the properties of the piezoelectric material differ depending upon the direction of forces and orientation of the polarization and electrodes [8].

Using piezoelectric materials to harvest energy requires a mode of storing the energy generated. This means they can either implement a circuit used to store the energy harvested or a circuit developed to utilize the energy harvested in producing excess energy [57]. The energy harvested can be stored in rechargeable batteries instead of using capacitors to store the energy [16, 27, 66]. The attribute of common capacitors to discharge quickly makes them unsuitable as energy storage devices in computational electronics [57].

Umeda, et al. [66] used a piezo-generator made of a bridge rectifier and a capacitor to store the energy. This resulted in achieving a maximum efficiency of 35% that is three times that of the energy harvested from a solar cell [57]. A self-powered mechanical strain energy sensor designed by Elvin, et al. [16] illustrates a simple beam bending experiment conducted to produce electrical energy from the mechanical stress applied. Here a piezofilm sensor attached to a beam is used to generate the electrical signal.

According to Glynne-Jones, et al. [19, 20], an energy-harvesting device is being developed where a thick film of piezoelectric layer is deposited on to a thin steel beam. When the beam is resonated, the piezoelectric material is deformed and electrical energy is generated. By changing the material used, the magnitude of power generated can be improved. This group continues to research in this area and is currently preparing a detailed study to evaluate both piezoelectric and magnet-coil based generators and their possible useful applications.

The earliest example for extracting electrical energy from piezoelectric material is from the impact of dropping a steel ball bearing onto a piezoelectric transducer [8, 65]. This energy was then stored in a capacitor or a battery [66]. The recent work by Cavallier, et al. [11] explored the amount of energy generated when a nickel package is used to couple the mechanical impact on to a piezoelectric plate.

Callaway and Edgar discuss the harvesting of the electrical energy with the help of piezoelectric materials where human activity is involved [9]. For example, a piezoelectric material such as polyvinylidene fluoride (PVDF) is attached to the heel of a shoe. When the shoe strikes the ground, the energy released is converted by the piezoelectric material into electric charge. This charge can be used for some high-end sneaker designs [30].

In their book on Wireless Sensor Networks [9], Callaway and Edgar also discuss an application where the piezoelectric generator is used commercially in a wireless light switch. The power generated with the toggling of the switch is used in a transmit-only wireless network node. This node communicates with a receive-only wireless node powered by the mains attached to the light. A study is currently underway to examine generating power by inserting piezoelectric devices within orthopedic implants [47].

The article on energy harvesting projects by Joseph [23] mentions that the current piezoelectric energy harvesting research falls into two key areas. One is developing optimal energy harvesting structures and the other is designing electrical circuits that are efficient enough to store the generated charge. The research carried out at The University of Pittsburgh focuses on the first area, where the goal is to create small, lightweight structures that couple efficiently to mechanical excitation and produce usable electrical energy. This team is concentrating on developing optimal devices which are capable of converting the ambient mechanical energy available into electrical energy.

Recently, a new power-conditioning circuit for piezoelectric energy scavenging systems has been proposed. Ottman, et al. [40-41] offers a greatly improved efficiency over existing designs under sinusoidal vibration. This circuit uses a step-down converter and harvested more than four times the power of the same circuit when the converter was not used. More than 70 mW of power was harvested from the new system, which is sufficient to power a wireless sensor network node, even in continuous receive mode. Later a simplified converter was employed which helped in producing more power. This work can be considered as a prominent step in the usage of energy generated from using piezoelectric materials.

The properties of piezoelectric materials vary with age, stress and temperature. The possible advantages of using piezoelectric materials are the direct generation of desired voltage since they do not need a separate voltage source and additional components. These generators are compatible with the MEMs. These generators are the simplest and can be used in force and impact-coupled harvesting applications [8, 58]. Some disadvantages are that piezoelectric materials are brittle in nature and sometimes allow the leakage of charge [67].

3.2 Electrostatic (Capacitive) Energy Harvesting

This type of harvesting is based on the changing capacitance of vibration-dependent varactors. Vibrations separate the plates of an initially charged varactor (variable capacitor), and mechanical energy is converted into electrical energy. Electrostatic generators are mechanical devices that produce electricity by using manual power [14, 46]. The basic operating principle is well explained by

Beeby, et al. [8] where the harvested energy is provided with work done against the electrostatic force between the plates of the capacitor used.

Roundy, et al. [51] explain the classification of the electrostatic generators into three types which are: in-plane overlap, in-plane gap closing and out-of-plane gap closing. The various electrostatic generators under the three different types are discussed in several papers [36, 38, 52, 63, 64]. The work done by Arakawa, et al. [3], Peano, et al. [43], and Sterken, et al. [60, 61] discuss electrostatic generators using charged electrets.

The significant advantage of using the electrostatic converters is their ability to integrate with microelectronics and they do not need any smart material. One of the disadvantages of using electrostatic converters is that they need an additional voltage source to initially charge the capacitor.

3.3 Electromagnetic Energy Harvesting

Electromagnetic Energy Harvesting can be achieved by the principle of electromagnetic induction. Electromagnetic induction is defined as the process of generating voltage in a conductor by changing the magnetic field around the conductor. One of the most effective ways of producing electromagnetic induction for energy harvesting is with the help of permanent magnets, a coil and a resonating cantilever beam [8]. El-Hami, et al. [15] describe a vibration-based electromechanical power generator that consisted of a cantilever beam and a pair of magnets.

Since the late 1990s, various researchers [1, 7, 22, 28, 39, 54, 55, 66, 71] have identified the techniques employed to generate power from electromagnetic resources. The electromagnetic generators designed have the advantage of being enclosed and can be protected from the outside environment.

Electromagnetic induction provides the advantage of improved reliability and reduced mechanical damping as there would not be any mechanical contact between any parts; also, no separate voltage source is required [52]. However, electromagnetic materials are bulky in size and are complicated to integrate with MEMs [67].

Bayrashev, et al. and Staley, et al. concentrated on harvesting energy from magnetostrictive materials [6, 62]. These magnetostrictive materials are used to build actuators and sensors as they have the capability of converting magnetic energy into kinetic energy. These materials are highly flexible, are suited to high frequency vibration and overcome the limitations of the other vibrational sources. To harvest energy by using magnetostrictive materials and provide power to wireless sensors in Structural Health Monitoring is explained by Wang and Yuan of North Carolina State University [67]. It is difficult to integrate these materials with MEMs.

The Electrostatic and Piezoelectric harvesters are capable of producing voltage ranging from 2 to 10V, whereas the electromagnetic harvesters have a limitation of producing maximum voltage of 0.1V[52].

The advantage of using mechanical vibrations to harvest energy is that they are the most prevalent energy source available in many environments.

4. Photovoltaic Cells

A photovoltaic cell is a device that converts light energy into electrical energy. The form of energy exploited is typically light energy obtained usually from sunlight.

For locations where the availability of light is guaranteed and usage of batteries and other means of power supply are not feasible or expensive, usage of photovoltaic cells is a convenient solution. A few examples of such locations are marine locations and roadway signs.

While designing sources which scavenge solar energy, factors such as availability of day light, periods of dense cloud and snow cover, effects of operation at higher latitudes, characteristics of the photovoltaic cell used, the intensity of the incident light, power supply requirements are to be considered [9, 49].

Lee, et al. [32] implement a project where an array of 100 solar cells is used to produce power to supply MEMs electrostatic actuators. The project could successfully produce voltage of about 150V. Studies on delivering power to a remote system with an optical fiber are discussed in [21, 29, 50]. Here, a photocell is used to convert the light energy into electrical power.

The most popular photovoltaic cells are the silicon-based cells. These are more sensitive to light, are easily available and offer a reasonable price to performance ratio.

Current research carried out using photovoltaic cells as energy scavengers includes the Smart Dust Program at the University of California, Berkeley [4-5, 68], where the wireless sensor networks employ photovoltaic cells. The dust motes communicate optically instead of via RF communication.

Also, at the University of California, LA [5, 23], a network of solar energy harvesting sensor nodes called heliomotes is being considered, where each heliomote consists of a solar energy harvesting circuit. This circuit is capable of powering a sensor node, store excess energy in a rechargeable battery and also has the capability of tracking the environmental energy available. A digital interface provides the tracked energy information to the sensor node.

Nowadays, the embedded systems rely on multiple power sources to augment their energy for a longer time. Such multiple power source (MPS) embedded systems harvest energy for the ambient sources such as solar power or by using rechargeable batteries. Therefore, the energy harvested from the ambient source is utilized to power the system and the rechargeable battery. This involves a less efficient way of using the scavenged energy. Hence, larger solar panels must be utilized. Park and Chou discuss a design of including a load matching power switch to reduce the wastage of ambient power scavenged from the solar panels used [44]. Researchers continually strive to refine solar cell materials and technologies to increase efficiency. Devices such as the Citizen's Eco-Drive watch, the PDA and the solar battery chargers for cell phones harness light energy and to produce several orders of power [42].

The added advantage of using energy scavenging devices is that they are usually small. For example, there are network nodes which do not use any self-contained energy source; they only scavenge energy from the surroundings. Such nodes can be very small since they do not have to carry their energy with them. However, the supply of energy may be interrupted at a period of time since the power obtained from the surroundings cannot be guaranteed all the time. For example, for the sources which scavenge solar energy, the effect of location and weather of that location play a very important role. Also, the average power available is typically low for energy scavengers.

5. Thermoelectric Generators

Thermoelectric generators follow the principle of thermoelectricity to produce the required electrical energy. The phenomena of creating electric potential with a temperature difference and vice-versa can be termed as thermoelectricity. Here, the thermal energy is scavenged to obtain electrical energy to power the electronic devices. Thermoelectric devices are primarily used in space and terrestrial applications.

Lawrence, et al. [31] describe a method to generate electrical energy using thermoelectric generators. The temperature difference obtained naturally between the air and soil is used. Sodano, et al. [56, 57, 59] designed a seebeck heat pump that helps to convert the ambient temperature difference into electrical power. This temperature gradient is generated by waste heat and solar radiation. These results show that thermoelectric generators produce relatively more power than piezoelectric devices.

Solid-state thermoelectric generators are considered to have long life, low maintenance and high reliability. However, their usage is limited because of their low energy conversion efficiency and high costs [17]. Efforts are being made to introduce new thermoelectric materials to overcome the disadvantage of low energy conversion rates [12]. The thermoelectric devices are desired to operate at high temperatures gradients. Rowe, et al. [53] studied that waste heat at low temperature can be utilized with thermoelectric technology to obtain electrical energy.

6. Conclusion

Harvesting energy from the environment is being considered as a viable option to replace the current power supplies for 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. These methods would help in placing the energy harvesters as one of the best sources to power portable devices in the field of wireless technology.

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