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LOW POWER ENERGY HARVESTING AND STORAGE TECHNIQUES FROM AMBIENT HUMAN POWERED ENERGY SOURCES.

A Dissertation

Submitted

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Industrial Technology

Approved:

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August 2008

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LOW POWER ENERGY HARVESTING AND STORAGE TECHNIQUES FROM AMBIENT HUMAN POWERED ENERGY SOURCES

An Abstract of a Dissertation

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ABSTRACT

Conventional electrochemical batteries power most of the portable and wireless electronic devices that are operated by electric power. In the past few years, electrochemical batteries and energy storage devices have improved significantly. However, this progress has not been able to keep up with the development of microprocessors, memory storage, and sensors of electronic applications. Battery weight, lifespan and reliability often limit the abilities and the range of such applications of battery powered devices. These conventional devices were designed to be powered with batteries as required, but did not allow scavenging of ambient energy as a power source. In contrast, development in wireless technology and other electronic components are constantly reducing the power and energy needed by many applications. If energy requirements of electronic components decline reasonably, then ambient energy scavenging and conversion could become a viable source of power for many applications. Ambient energy sources can be then considered and used to replace batteries in some electronic applications, to minimize product maintenance and operating cost. The potential ability to satisfy overall power and energy requirements of an application using ambient energy can eliminate some constraints related to conventional power supplies. Also power scavenging may enable electronic devices to be completely self-sustaining so that battery maintenance can eventually be eliminated. Furthermore, ambient energy scavenging could extend the performance and the lifetime of the MEMS (Micro electromechanical systems) and portable electronic devices. These possibilities show that it is important to examine the effectiveness of ambient energy as a source of power. Until

recently, only little use has been made of ambient energy resources, especially for wireless networks and portable power devices. Recently, researchers have performed several studies in alternative energy sources that could provide small amounts of electricity to low-power electronic devices. These studies were focused to investigate and obtain power from different energy sources, such as vibration, light, sound, airflow, heat, waste mechanical energy and temperature variations.

This research studied forms of ambient energy sources such as waste mechanical (rotational) energy from hydraulic door closers, and fitness exercise bicycles, and its conversion and storage into usable electrical energy. In both of these examples of applications, hydraulic door closers and fitness exercise bicycles, human presence is required. A person has to open the door in order for the hydraulic door closer mechanism to function. Fitness exercise bicycles need somebody to cycle the pedals to generate electricity (while burning calories.) Also vibrations, body motions, and compressions from human interactions were studied using small piezoelectric fiber composites which are capable of recovering waste mechanical energy and converting it to useful electrical energy. Based on ambient energy sources, electrical energy conversion and storage circuits were designed and tested for low power electronic applications. These sources were characterized according to energy harvesting (scavenging) methods, and power and energy density. At the end of the study, the ambient energy sources were matched with possible electronic applications as a viable energy source.

CHAPTER I

INTRODUCTION

Today, sustaining the power requirement for autonomous wireless and portable devices is an important issue. In the recent past, energy storage has improved significantly. However, this progress has not been able to keep up with the development of microprocessors, memory storage, and wireless technology applications. For example, in wireless sensor networks, battery-powered sensors and modules are expected to last for a long period of time. However, conducting battery maintenance for a large-scale network consisting of hundreds or even thousands of sensor nodes may be difficult, if not impossible. Ambient power sources, as replacement of batteries, come into consideration to minimize the maintenance and the cost of operation. Power scavenging may enable wireless and portable electronic devices to be completely self-sustaining so that battery maintenance can be eventually removed. Researchers have performed many studies in alternative energy sources that could provide small amounts of electricity to low-power electronic devices as explained and cited in literature review of this work. Energy harvesting can be obtained from different energy sources, such as vibration, light, acoustic, airflow, heat, and temperature variations.

Energy harvesting is described as the conversion of ambient energy into usable electrical energy. When compared with energy stored in common storage elements, such as batteries, capacitors and the like, the environment represents a relatively infinite source of available energy. As a result, energy harvesting or scavenging methods must be characterized by their power density, rather than energy density. Because current

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electronic applications continue to push past limits of integration and functional density toward the elusive, completely autonomous, self-powered microchips. Systems continue to get smaller, yet less energy is available on board, leading to short device run-time or battery life. Researchers continue to build high energy density batteries, but the amount of energy available in the batteries is not only finite but also low, limiting the life time of the systems. Extended life of the electronic devices is very important and also has more advantages in systems with limited accessibility, such as those used in monitoring a machine or an instrument in a manufacturing plant to organize a chemical process in a hazardous environment. The critical long-term solution should therefore be independent of the limited energy available during the functioning or operating of such devices.

Table 1 compares the estimated power and challenges of various ambient energy sources in a recent study by Yildiz, Zhu, and Pecen (2007). Values in the table are derived from a combination of published studies, experiments performed by the authors, theory, and information that is commonly available in textbooks. The source of information for each technique is given in the third column of table. While this comparison is by no means comprehensive, it does provide a broad range of potential methods to scavenge and store energy from a variety of ambient energy sources.

Light, for instance, can be a significant source of energy, but it is highly dependant on the application and the experience to which the device is subjected. Thermal energy, in contrast, is limited because temperature differences across a chip are typically low. Vibration energy is a moderate source, but again dependent on the particular application as cited by Torres and Rincon-Mora (2005).

Table 1

Comparison of power density of energy harvesting methods

Energy Source	Power Density & Performance	Source of Information
Acoustic Noise	$0.003 \ \mu W/cm^3 @ 75Db$	(Rabaey, Ammer, Da Silva Jr,
	$0.96 \ \mu W/cm^3$ @ 100Db	Patel, & Roundy, 2000)
Temperature	$10 \mu\text{W/cm}^3$	(Roundy, Steingart, Fréchette,
Variation		Wright, Rabaey, 2004)
Ambient Radio	$1 \mu\text{W/cm}^2$	(Yeatman, 2004)
Frequency		
Ambient Light	100 mW/cm^2 (direct sun)	Available
	$100 \mu\text{W/cm}^2$ (illuminated office)	Available
Thermoelectric	$60 \mu\text{W/cm}^2$	(Stevens, 1999)
Vibration	$4 \mu W/cm^3$ (human motion—Hz)	(Mitcheson, Green, Yeatman,
(micro generator)	800 μW/cm ³ (machines—kHz)	& Holmes, 2004)
Vibrations	$200 \mu\text{W/cm}^3$	(Roundy, Wright, & Pister,
(Piezoelectric)		2002)
Airflow	$1 \mu\text{W/cm}^2$	(Holmes, 2004)
Push buttons	50 μJ/N	(Paradiso, Feldmeier, 2001)
Shoe Inserts	$330 \mu\text{W/cm}^2$	(Shenck, Paradiso, 2001)
Hand generators	30 W/kg	(Starner, Paradiso, 2004)
Heel strike	7 W/cm ²	(Yaglioglu, 2002)
		(Shenck, Paradiso, 2001)

This research introduces different low power energy scavenging techniques for portable and wireless electronic devices with a focus on conversion of both waste mechanical rotation energy and vibrations to electricity using human power. The purpose of this study is to analyze, design and build energy harvesting devices capable of mechanical-to-electric energy conversions. Typical components, such as generators, low power motors, speed increase gear sets, piezoelectric fiber composites and electronic components will be considered main components of this research. Analytical simulation and design software packages for both electrical and electromechanical simulation and design will be used to help develop proper and efficient energy harvesting systems.

Statement of the Problem

The problem of this study is to support conventional storage technologies, which are not fully efficient at powering electronic applications by building energy harvesting devices to generate and produce electrical energy from ambient energy sources. In recent years several new applications and devices have been introduced to improve life in general. Many of these applications utilize new technologies. However these applications are still fully dependent on conventional powering methods such as battery power. This research will address the problem with several examples of unused waste energy resources that could be harvested by supporting several of these conventional energy producing devices. The performance of low power energy harvesting devices should be tested to extract maximum efficiency to assist conventional power sources for electronic devices and get electronic systems to run on ambient energy sources. A secondary problem is to examine reliability, responsiveness, scalability, and power efficiency of ambient energy sources in order to design an efficient energy harvesting device according to the maximum needs of the application.

Purpose of the Study

The purpose of this study is to explore potential ambient energy sources and build energy harvesting devices to generate/produce electrical energy as a support to conventional energy storage devices. Primarily, this research initiates the use of a hydraulic door closer device, fitness bicycles, and human motions as ambient energy

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sources. This study has several goals. The first is to investigate the characteristics of a hydraulic door closing device as a mechanical energy source and analyze the amount of the waste energy produced when it is activated by human power. A second purpose is to examine the nature of piezoelectric fiber composites as a waste mechanical or vibration energy scavenger from human motions. The third purpose of this study is to inspect fitness exercise bicycles' mechanical waste energy when pedals are cycled by human power. Additionally, the energy conversion, switching, and storage circuits for each energy source will be designed, built and tested.

Moreover, the study will include analysis, design, and fabrication of an energy harvesting device capable of converting waste mechanical energy to electrical energy. The study will result in management of the interoperability between components such as a gear set, DC electric generator, switching circuit, storage device and piezoelectric fiber composites of energy harvesting system.

Need for the Study

The study addresses three innovative energy sources. Design and development of reliable and long lasting conversion and storage systems for energy harvesting from mechanical, active human power, and vibrations will be studied. The reliability of power sources is very important in order to eliminate or reduce needs on battery powered systems. A poor power source can significantly limit the operational life and convenience of the device. During design and construction, a range of power electronics and mechanical component options maybe be available.

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Research Questions

The research questions of this study are:

1. Do ambient energy sources play a supportive role in charging batteries for portable and wireless electronic devices? If so energy costs can be reduced by eliminating frequent replacements of conventional storage devices.

2. Does waste mechanical energy which takes place on the hydraulic door closer produce electrical energy that can be stored and can be used to power components of electronic applications around the door?

3. Do the vibrations from shoe soles generate electrical energy that can be harvested, stored and used to support electronic applications?

4. Can waste mechanical energy from fitness bicycles be converted into viable electrical energy to power their electronic displays by reducing battery replacement time?

Assumptions

The assumptions of this study are:

1. A robust, low power energy harvesting and conversion circuit will eliminate or reduce the usage of batteries for some electronics applications.

2. Harvested energy can be applied in a variety of low power applications as an energy source.

3. As power requirements for microelectronics continue to decrease, ambient energy sources are becoming more feasible to support traditional batteries and capacitors, and may bring innovative ways of charging batteries without outlet power.

4. In electronic applications, where small amounts of energy can be extracted from the surrounding environment, ambient energy sources should be considered for energy harvesting. Even harvesting a small amount of energy via suitably selected circuit components would be enough to power a variety of small electronic devices.

5. The developments of rechargeable battery and supercapacitor technologies will lead researchers to seek new ambient energy sources in order to build smaller and efficient energy harvesting devices.

Limitations

The designs must conform to a number of criteria. The limitations of this study can be stated below:

1. The developed energy harvesting devices must be unobtrusive; the objective is to collect the wasted energy and not to require energy to operate.

2. The devices and their power conditioning circuitry must be packaged as small as possible and mounted within or around the ambient energy source.

3. A wide range of investigation of potential energy harvesting circuits must be done in order to avoid duplications of energy harvesting circuits already available in the market. 4. The piezoelectric fiber composite bimorph (PFCB) should be tested very carefully because of its high voltage levels. The inappropriate energy harvesting device may lead to damage storage device very easily with several flicks.

Definition of Terms

Following are certain terms used during this research study that, although not unique to this study, have been defined in order that readers have a common base for understanding their use within the context of this research.

<u>Alternative energy</u>: A term used for non-traditional energy sources that are alternatives to using fossil fuels and have low environmental impact (Responding to climate change, 2007).

<u>Ambient energy source</u>: Environmental source of energy available in different forms such as wind, solar, heat, mechanical (Ambient Energy Generator Technology, 2006).

<u>ANSI (American National Standards Institute)</u>: The organization for the development of technology standards by communicating with industry groups in the United States (Introduction to ANSI, 2008).

<u>Boost (Step-Up) Converter</u>: A power converter with an output DC voltage greater than its input DC voltage. It is a switching-mode power supply which contains at least two semiconductor switches such as diodes, transistors and an energy storage element (DC-DC Converter Basics, 2008).

Brushless DC Motor/Generator: A synchronous electric motor which is powered by direct-current electricity (DC) and which has an electronically controlled commutation 4. The piezoelectric fiber composite bimorph (PFCB) should be tested very carefully because of its high voltage levels. The inappropriate energy harvesting device may lead to damage storage device very easily with several flicks.

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<u>Brushless DC Motor/Generator</u>: A synchronous electric motor which is powered by direct-current electricity (DC) and which has an electronically controlled commutation system, instead of a mechanical commutation system based on brushes (How Motors Work, 2008).

Buck (Step Down) Converter: A power converter with an output DC voltage less than its input DC voltage (DC-DC Converter Basics, 2008).

<u>Buck-Boost Converter</u>: Has an output voltage magnitude that is either greater than or less than the input voltage magnitude. The output voltage of the circuit after conversion is adjustable based on the duty cycle of the switching transistor (DC-DC Converter Basics, 2008).

<u>Crystal Lattice</u>: Organization of atoms that allocates a specific place for every molecule or atom in the solid. If a solid is made up of pure elements or compounds then it can create a very specific structure such as a diamond (The Crystal Lattice, 2008).

<u>Duty Cycle</u>: The fraction of a time period that a system is in active state and proportion of time during which a component or a device is operated (Duty cycle, 2008).

<u>Electret</u>: A dielectric material that has a quasi-permanent electric charge or dipole polarization and generates internal and external electric fields; the electrostatic equivalent of a permanent magnet (Textile Glossary, 2008).

Energy density: The amount of energy stored in a system or region of space per unit volume or per unit mass, depending on the environment. In energy storage applications, the energy density narrates the mass of an energy store to its stored energy (UNIROSS Industrial, 2008).

Energy scavenging: Collecting electricity from environmental energy sources, such as mechanical, solar, acoustic, and heat (Paradiso & Starner, 2005).

Energy harvesting circuit: A circuit having a means for receiving ambient energy from the environment and converting it into DC power to supply energy to storage devices. The circuitry for converting the ambient energy into DC power may include a rectifier and battery charger (Yildiz, Zhu, & Pecen, 2007).

<u>Fuel cell</u>: An electrochemical energy conversion device produces electricity from various external quantities of fuel on the anode side and an oxidant on the cathode side (About Fuel Cells, 2008).

<u>Full-wave Bridge Rectifier</u>: Converts both polarities of the input waveform to the DC signal at its output (Bridge Rectifier, 2008).

<u>Gearset:</u> A group of different size gears which limit or increase the mechanical speed. The direction and magnitude of change depends on gear ratios (Uses for Gears, 2008).

<u>Gear ratio</u>: The relationship between the number of teeth on two gears that are meshed with each other or two sprockets connected with a common roller chain (F1 technical glossary, 2008).

<u>Gear train</u>: A gear train is a group of gears arranged to transfer rotational torque from one part of a mechanical system to another.

<u>Hydraulic door closer</u>: A mechanism/device that makes use of a spring for closing the door, and a compression compartment from which liquid or air escapes slowly, to close the door at an adjustable speed (Door closer, 2008).

<u>Li-ion (Lithium-Ion)</u>: One of the types of rechargeable batteries in which a lithium ion moves between the anode and cathode (The lithium-ion battery, 2008).

LMS Imagine. Lab AMESim: A One dimensional multi-domain analytical system simulation platform (The LMS Imagine.Lab AMESim Suite, 2007).

MEMS (Micro electromechanical systems): The integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through micro-fabrication technology (What is MEMS Technology, 2008).

Magnetic field: A field that permeates space and which exerts a magnetic force on flowing electric charges and magnetic dipoles. Magnetic fields surround electric currents, magnetic dipoles, and changing electric fields. Moreover, a magnetic field can be considered as an invisible field which exerts magnetic force on substances which are sensitive to magnetism (Magnetic Field, 2008).

<u>MSC EASY5 (Engineering Analysis Systems)</u>: An engineering analysis and simulation software package originally created by Boeing Inc. and currently owned by MSC Software Inc. (MSC.Easy5 General Documentation, 2004)

<u>MOSFET (Metal-oxide-semiconductor Field-effect Transistor</u>): A device used to amplify or switch electronic signals and is composed of a channel of n-type or p-type semiconductor materials which are called a NMOSFET or a PMOSFET (Mosfets, 2008).

<u>MultiSIM</u>: An electronic schematic capture and simulation program (What Is NI Multisim, 2008).

<u>NICD (Nickel-Cadmium)</u>: A rechargeable battery using nickel oxide hydroxide and metallic cadmium as electrodes (NI-CD Battery Training, 2008).

<u>NIMH (Nickel-Metal Hydride)</u>: A rechargeable battery using a hydrogenabsorbing alloy for the negative electrode. A NIMH battery can have bigger capacity of an equivalent size NICD (NI-MH Battery Training, 2008).

Nominal voltage: A reference voltage that describes battery, module, and system voltages (Solar Glossary, 2008).

<u>Nominal capacity</u>: Indicates the average capacity of a battery or a storage device (MPower Battery Technology Glossary, 2008).

<u>Operational amplifier</u>: A DC-coupled high-gain electronic voltage amplifier with differential inputs often called an op-amp and, usually, a single output (Maxim, 2007).

<u>PCB (Printed Circuit Board)</u>: A PCB is used to electrically connect electronic components using conductive traces, etched from copper sheets laminated onto a non-conductive substrate (Computer Hardware and Micro-Scope, 2008).

<u>Peak-to-peak</u>: Peak-to-peak is to measure differences in waves between peak and trough. Peak-to-peak values can be measured by meters with appropriate circuitry, or by viewing the waveform on an oscilloscope (Peak-to-Peak, 2008).

<u>Piezoelectricity</u>: Piezoelectricity is a form of electricity created when certain crystals are bent or deformed by external forces (mechanical pressure) producing electricity (Piezoelectricity, 2008).

<u>Piezoelectric fiber composite</u>: Piezoelectric fiber composite transducers scavenge mechanical energy (mostly vibrations) and convert it into electrical energy. These transducers may be used singly or multiply in parallel, to accumulate electric power over
an extended period of time for energizing low power microelectronics (Advanced Cerametrics Incorporated, 2007).

<u>Photovoltaic cell</u>: Special semiconductor diode that converts visible light energy into direct current (DC). Also some photovoltaic cells can convert infrared or ultraviolet radiation into DC electricity (Photovoltaic cell, 2008).

<u>PMDC (Permanent Magnet Direct Current) Motor/Generator</u>: The rotor of the permanent magnet motors rotate in synchrony with the oscillating field or current (Electric motors and generators, 2007).

<u>Power density</u>: The amount of the power existing from a battery or ratio of the power available from a battery to its mass. It is expressed as the power available per unit volume or per unit weight with the units of W/L or W/kg (Solar glossary, 2008).

<u>Pro Engineer Wildfire 2.0</u>: Pro Engineer is a standard in 3D product design, featuring industry-leading productivity tools that promote practices in design while ensuring compliance with industry standards. An engineering modeling and design program capable of creating engineering models, drawings, and assemblies. Pro Engineer comes with different application program packages to help design and modeling process (Pro Engineer Wildfire CAD, 2008).

<u>Quiescent current</u>: The standing current that flows in a circuit when the signal is not applied. The quiescent current is usually very low or lower than processing a signal. (DiracDelta Science & Engineering Encyclopedia, 2008)

<u>Rated Voltage</u>: The maximum voltage level a device can operate for extended periods of time without unnecessary degradation (Rated Voltage, 2007).

Rated Power: The maximum value of power can be continuously loaded to a resistor at a rated ambient temperature (Rated Power, 2008).

<u>RFID (Radio-Frequency Identification)</u>: Automatic identification method relying on storing and remotely retrieving data using devices called RFID tags. RFID tags can be applied into a product, animal, or person for the purpose of identification using radio waves (What is RFID, 2008).

<u>RMS (Root Mean Square)</u>: The RMS is defined as the square root of the mean over time of the square of the vertical distance of the graph from the rest state and mostly used in electrical engineering discipline (Root mean square, 2008).

<u>RPM</u>: Rotations per minute.

<u>Schottky diode</u>: A semiconductor diode with a low forward voltage drop and a very fast switching action. The voltage drop of the Schottky diodes at forward biases of around 1 mA is in the range 0.15 V to 0.46 V (Schottky Diode, 2008).

<u>Self-sustaining energy</u>: A naturally available source of energy able to provide different forms of energy without the help of humans.

<u>Seebeck coefficient</u>: Thermoelectric power of a material is a measure of the magnitude of an induced thermoelectric voltage in response to a temperature difference across the material (Seebeck Coefficient, 2008).

<u>SEPIC (Single Ended Primary Inductance Converter)</u>: Usually a DC-DC converter which adjusts the output voltage above, below or equal to the input voltage by programming the components (Designing A SEPIC Converter Introduction, 2008).

<u>Supercapacitor (Ultracapacitor)</u>: Supercapacitors are electrochemical capacitors which that can store high energy density when compared to typical capacitors. The capacity ratio of a supercapacitor compared to common capacitors is on the order of thousands of times greater than a high-capacity capacitor (What's the role of the Supercapacitor, 2008).

Sprocket: A profiled wheel with teeth that meshes with a chain. It is distinguished from a gear in that sprockets are never meshed together directly.

<u>Switching circuit (Regulator)</u>: A circuit which regulates voltage/current and frequency operations levels to supply regulated output power according to input power levels (Switching Regulator, 2008).

SwitcherCADTM III: High performance spice III simulator, schematic capture and waveform viewer with enhancements and models for easing the simulation of switching regulators developed by Linear Technology (LTspice/SwitcherCAD III, 2007).

<u>Standby Power</u>: The electric power consumed by electronic appliances while they are switched off or in a standby mode (MPower Battery Technology Glossary, 2008). <u>TEG (Thermoelectric Generator</u>): Creates an electric potential through the temperature differences (Pacific Northwest National Laboratory, 2007).

<u>Thermistor</u>: A type of resistor with resistance varying according to its temperature; resistance is changed depending on the environmental temperature (Thermistor, 2008).

<u>Torque</u>: Torque is a measure of how much force acting on an object causes that object to rotate. A torque is represented by τ and is a vector that measures the tendency of a force to rotate an object about some axis (Serway & Jewett, 2003).

<u>Unimorph</u>: A unimorph is a cantilever that is comprised of single active and inactive layers. In the case where active layer is piezoelectric, changes in that layer may be induced by the application of an electric field. The changes induce a bending displacement in the cantilever. The inactive layer can be made up from a nonpiezoelectric material.

<u>Wireless Sensor Networks</u>: A Wireless network which consists of spatially distributed autonomous devices using sensors cooperatively to monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants, at different locations (Römer & Friedemann, 2004).

<u>Transceiver</u>: A device that has both transmitter and receiver combined sharing common circuitry to function both ways (Transceiver, 2008).

Zener diode: One of the type of diodes that permits current to flow in the forward direction like a normal diode, but also in the reverse direction if the voltage is larger than the breakdown voltage (Diodes, 2008).

ZigBee (802.15.4): The name of a wireless standard for a suite of high level communication protocols using small and low-power digital radios based on the IEEE 802.15.4 standard (IEEE Wireless Zone, 2008).

CHAPTER II

REVIEW OF LITERATURE REVIEW

Ambient energy harvesting is also known as energy scavenging or power harvesting and is the process where energy is obtained from the environment of an application and stored for use. Usually this term is applied to energy harvesting for low power and small autonomous devices such as wireless sensor networks, and portable electronic equipment. There are a variety of techniques are available for energy scavenging, including solar power, ocean waves, piezoelectricity, thermoelectricity, and physical motions. For example, some systems convert random motions including ocean waves into useful electrical energy to be used by oceanographic monitoring wireless sensor nodes for autonomous surveillance.

Examining existing research, many potential ambient power sources for energy harvesting were investigated. Ambient energy sources are classified as energy reservoirs, power distribution methods, or power scavenging methods, which may enable portable or wireless systems to be completely battery independent and self sustaining. The literature review shows that no single power source is sufficient for all applications, and that the selection of energy sources needs to be considered according to the application characteristics. Before going into details, a general overview of ambient energy sources will be presented, and will summarize the resources according to their characteristics:

(a) Human Body: Mechanical and thermal (heat variations) energy can be generated from a human or animal body by actions such as walking, and running; (b) Natural Energy: Wind, water flow, ocean waves, and solar energy can provide limitless energy availability from the environment;

(c) Mechanical Energy: Vibrations from machines, mechanical stress, strain from high pressure motors, manufacturing machines, waste rotations can be captured and used as ambient mechanical energy sources;

(d) Thermal Energy: Waste heat energy variations from furnaces, heaters, and friction sources;

(e) Light Energy: This source can be divided into two categories of energy: indoor room light and outdoor sunlight energy. Light energy can be captured via photo sensors, photo diodes, and solar photovoltaic panels; and

(f) Electromagnetic Energy: Inductors, coils, and transformers can be also considered as ambient energy sources depending on how much energy is needed for the application.

Additionally chemical and biological sources and radiation can be considered as ambient energy sources. Figure 1 shows a block diagram of ambient energy harvesting systems. The literature review summarizes research efforts performed by a variety of research attempts both academically and industrially. The research efforts are employed by the above listed sources to explore the general practicability and achievable performance of devices that extract power from ambient energy sources. A broad review of the literature of potential energy scavenging methods has been carried out by the author. The result of this literature review is categorized for each source, and follows in the next pages of this chapter.



Figure 1: Ambient energy systems

Mechanical Energy Harvesting

An example of electric power generation using rotational movement is the self powered, battery-less, cordless wheel computer mouse cited by Mikami, Tetsuro, Masahiko, Hiroko (2005). The system is called Soc and is designed as an ultra low power wireless interface for short range data communication as a wireless battery-less mouse. The system was designed uniquely to capture rotational movements by the help of the mouse ball to generate and harvest electric power. The electric generator is powered through exploiting rolling energy by dragging the mouse. The energy harvesting system was intended to power the electronic system of mouse such as ultra low power RF transmitter and microcontroller. The experimental results of the study showed that the mouse only needed 2.2mW energy to operate. The total energy captured using an energy harvesting system was bigger than 3mW which was enough for the wireless mouse operations in a one meter transmit range.

Another example of mechanical energy harvesting is an electrets-based electrostatic micro generator which was proposed by Sterken, Fiorini, Baert, Puers, Borghs (2003). In this energy scavenging system a micro machined electrostatic converter consisted of a vibration sensitive variable capacitor polarized by an electret. A general multi-domain model was built and analyzed in the same study and showed that power generation capabilities up to $50\mu w$ for a 0.1 cm^2 surface were possible.

Mechanical Vibrations

Indoor operating environments may have reliable and constant mechanical vibration sources for ambient energy scavenging. For example, indoor machinery sensors

may have plentiful mechanical vibration energy which can be monitored and used reliably. Vibration energy harvesting devices can be either electromechanical or piezoelectric; but electromechanical harvesting devices are more commonly researched and used. Roundy, Wright, and Rabaey (2003) reported that energy withdrawal from vibrations could be based on the movement of a spring mounted mass relative to its support frame. Mechanical acceleration is produced by vibrations that in turn cause the mass component to move and oscillate. This relative dislocation causes opposing frictional and damping forces to be applied against the mass, thereby reducing and eventually extinguishing the oscillations. The damping force energy can be converted into electrical energy via an electric field (electrostatic), magnetic field (electromagnetic), or strain on a piezoelectric material. These energy conversion schemes can be extended and explained under the three listed subjects because the nature of the conversion types differs even if the energy source is vibration. In the section below, the main differences of the three sources will be discussed.

Electromagnetic Energy Harvesting

This technique uses a magnetic field to convert mechanical energy to electrical energy (Amirtharajah & Chandrakasan, 1998). A coil attached to the oscillating mass is made to pass through a magnetic field which is established by a stationary magnet to produce the needed electric energy. The coil travels through a varying amount of magnetic flux, inducing a voltage according to Faraday's law. The induced voltage is inherently small and must therefore be increased to become a viable source of energy. (Kulah & Najafi, 2004). Techniques to increase the induced voltage include using a

transformer, increasing the number of turns of the coil, or increasing the permanent magnetic field (Torres & Rincon-Mora, 2005). However, each of these parameters is limited by size constraints of the microchip as well as material properties.

Piezoelectric Energy Harvesting

This method alters mechanical energy into electrical energy by straining a piezoelectric material (Sodano, Inman, & Park, 2004). Strain or deformation of a piezoelectric material causes charge separation across the device, producing an electric field and consequently a voltage drop proportional to the stress applied. The oscillating system is typically a cantilever beam structure with a mass at the unattached end of the lever, since it provides higher strain for a given input force (Roundy & Wright, 2004). The voltage produced varies with time and strain, effectively producing an irregular AC signal on the average. Piezoelectric energy conversion produces relatively higher voltage and power density levels than the electromagnetic system. Moreover, piezoelectricity has the ability of some elements such as crystals and some types of ceramics to generate an electric potential from a mechanical stress (Skoog, Holler, & Crouch, 2006). This process takes the form of separation of electric charge within a crystal lattice. If the piezoelectric material is not short circuited, the applied mechanical stress induces a voltage across the material.

There are many applications based on piezoelectric materials, such as electric cigarette lighters. In this system pushing the button causes a spring loaded hammer to hit a piezoelectric crystal and the high voltage produced injects the gas slowly as the current jumps across a small spark gap. Following the same idea, portable sparkers used to light

gas grills and stoves, and a variety of gas burners have built in piezoelectric based ignition systems.

Electrostatic (capacitive) Energy Harvesting

This method depends on the variable capacitance of vibration dependant varactors. (Meninger, Mur-Miranda, Amirtharajah, Chandrakasan, & Lang, 2001). A varactor, or variable capacitor, which is initially charged, will separate its plates by vibrations; in this way mechanical energy is transformed into electrical energy. Constant voltage or constant current achieves the conversion through two different mechanisms. For example, the voltage across a variable capacitor is kept steady as its capacitance alters after a primary charge. As a result, the plates split and the capacitance is reduced, until the charge is driven out of the device. The driven energy then can be stored in an energy pool or used to charge a battery generating the needed voltage source. The most striking feature of this method is its IC-compatible nature, given that MEMS variable capacitors are fabricated through relatively well-known silicon micro machining techniques. This scheme produces higher and more practical output voltage levels than the electromagnetic method, with moderate power density.

In a study conducted recently to test feasibility and reliability of the different ambient vibration energy sources by Marzencki (2005), three different vibration energy sources such as electrostatic, electromagnetic, and piezoelectric were investigated and compared according to their complexity, energy density, size, and encountered problems. The study is summarized in Table 2.

Table 2

	Electrostatic	Electromagnetic	Piezoelectric
Complexity of process flow	Low	Very High	High
Energy density	4 mJ cm^{-3}	24.8 mJ cm^{-3}	35.4 mJ cm^{-3}
Current size	Integrated	Macro	Macro
Problems	Very high voltage and need of adding charge source	Very low output voltages	Low output voltages

Comparison of vibration energy harvesting techniques

Examples of Research Efforts on Vibration Sources

An example of energy harvesting using Unimorph piezoelectric structures was conducted by Thomas, Clark and Clark (2005). This research was focused on a unimorph piezoelectricity circular plate which is a PZT layer assembled to an aluminum substrate. The vibrations were driven from a variable ambient pressure source such as a scuba tank or blood pressure meter. The researchers showed that by creating the proper electrode pattern on the piezoelectric element which is thermal "regrouping", the electrode was able to produce an increase in available electrical energy. In the system, as the cantilever beam vibrates it experiences variable stresses along its length. Regrouping the electrodes targeting specific vibration modes resulted in maximum change collection. This type of design may add possibilities for miniaturization and practicality to piezoelectric energy harvesting technology.

One of the studies to attempt building an efficient piezoelectric harvesting circuit using DC-DC buck converter in discontinuous conduction mode was conducted by Ottman, Hofmann, and Lesieutre (2002). In this circuit design configuration, the buck (step-down) converter regulates the power flow from the piezoelectric material to the desired electronic load. In Figure 2 the energy harvesting circuitry is shown with the 3V battery load. The developed circuitry reveals that, as the level of mechanical excitation is increased, then the optimal duty cycle goes at a relatively constant mode.



Figure 2: Piezoelectric energy harvesting circuit. (Ottman, Hofmann, & Lesieutre, 2002)

Their research showed that the experimental duty cycle aggresses with the theoretical value of 2.8%. It was claimed by the authors that "using a simplified central scheme to implement this system, the step-down converter harvested energy at over three times the rate of direct charging battery" (p. 1994). For this method it was projected that this rate continues to increase with the increase of harvested power but changes according to the square of the excitation of piezoelectric element. The study resulted in 30.66mW energy harvesting which was enough to power many low power portable or wireless electronic devices.

Another example of ambient vibration energy scavenging research was a vibration harvesting micro generator designed to power a wireless sensor network node by Ammar, Buhrig, Marzencki, Charlot, Basrour, Matou, and Renaudin (2005). The energy scavenging system was developed considering two specific technologies: asynchronous circuit and ambient energy scavenging power generator. The reason for using an asynchronous circuit technology was to gain some advantages of allowing power decrease in the energy consumption of the sensor node. In addition, ambient energy scavenging made the system battery-less, self powered to reduce maintenance constraints and to increase the life-span of the wireless sensor node. The embedded ambient energy source was a vibration harvesting micro power generator to power the micro system. Figure 3 shows the energy harvesting circuit design for this study. Micro power generators are very common for energy converting systems especially for wireless sensor nodes and becoming more attractive every day with the new developments.



Figure 3: Energy harvesting circuit for piezoelectric micro generator (Ammar et al. 2005).

The comparison of two recently proposed micro power generator architectures has been completed by Mitcheson, Green, Yeatman, and Holmes (2004). The first architecture was a velocity clamped resonant generator and the second one a coulomb damped resonant generator. In the same study also a parametric generator was presented and analyzed as a new energy harvesting design. The analysis indicated the parametric generator was more useful when the input vibration amplitude was an order of magnitude bigger than the dimensions of the micro generator. It was concluded by the authors that "for resonant generators, the efficiency of the technology used to realize the energy conversion is likely to be of greater importance in determining the output power than the architecture of generator used" (Mitcheson, Green, Yeatman, & Holmes, 2004, p. 1).

A self powered wireless sensor node for indoor environmental monitoring is the one of another new recent applications and an example of vibration-to-electricity conversion studied by Leland, Lai, and Wright (2005). This system has been developed and built to monitor indoor environments to facilitate more efficient use of energy for temperature and climate control. A self powered wireless temperature sensor node was designed, fabricated, and tested. The energy harvesting source was mechanical energy which was generated from vibrations in the staircase. For the test purpose, the sensor node was mounted on a wooden staircase and was comprised of piezoelectric bimorph materials to generate electricity. The system was activated when a person walked or moved on the staircase. The electronics of the sensor node such as a thermistor and wireless transmitter were powered by a bimorph piezoelectric generator to transmit temperature readings to a remote computer or display. The outcome of this experimental design showed that continuously generated vibrations on the staircase produced $30\mu W$ from the bimorph generator. It was concluded that the produced power was enough to power the electronic components of the sensor node.

Building environments are rich places of vibrations caused by human power, wind, sound and other sources. These common places include floors, ceilings, windows, air ducts, home appliances, staircases, and some machinery. These vibration sources were investigated and summarized by Leland, Lai, and Wright (2005) in Table 3. A comparison of the amount of peak frequencies and peak accelerations was generated from a variety of vibration sources and reported.

Table 3

Vibration Source	Freq. of Peak (Hz)	Peak Accel. (m/s ²)
Kitchen Blender Casing	121	6.4
Clothes Dryer	121	3.5
Door Frame (just after door closes)	125	3
Small Microwave Oven	121	2.25
HVAC Vents in Office Building	60	0.2-1.5
Wooden Deck with People Walking	385	1.3
Bread Maker	121	1.03
External Windows (size 2ftx3ft) next to a Busy Street	100	0.7
Notebook Computer while CD is Being Read	75	0.6
Washing Machine	109	0.5
Second Story of Wood Frame Office Building	100	0.2
Refrigerator	240	0.1

Peak frequencies and accelerations of vibration sources. (Leland, Lai, & Wright 2005).

Thermal (Thermoelectric) Energy

Thermal gradients in the environment are directly converted to electrical energy through the Seebeck (thermoelectric) effect as reported by Disalvo (1999); and Rowe (1999). Temperature changes between opposite segments of a conducting material result in heat flow and consequently charge flow since mobile, high-energy carriers diffuse from high to low concentration regions. Thermopiles consisting of n- and p-type materials electrically joined at the high-temperature junction are therefore constructed, allowing heat flow to carry the dominant charge carriers of each material to the low temperature end, establishing in the process a voltage difference across the base electrodes. The generated voltage and power is relative to the temperature differential and the Seebeck coefficient of the thermoelectric materials. Big thermal gradients are essential to produce practical voltage and power levels (Roundy, Wright, & Rabaey, 2004). However, temperature differences greater than 10°C are rare in a micro-system, so consequently such systems generate low voltage and power levels. Moreover, naturally occurring temperature variations can also provide a means by which energy can be scavenged from the environment with high temperature. Stordeur and Stark (1997) have demonstrated a thermoelectric micro-device which is capable of converting 15 μ W/cm³ from 10 °C temperature gradients. While this is promising and, with the improvement of thermoelectric, could eventually result in more than 15 μ W/cm³, situations in which there is a static 10 °C temperature difference within 1 cm³ are very rare. This, however, assumes no losses in the conversion of power to electricity.

One of the latest designs of thermoelectric energy harvester was the thermoelectric generator (TEG) designed and introduced in the available technologies web site of Pacific Northwest National Laboratory (2007). This new thermoelectric generator is equipped for conversion of environmental (ambient) thermal energy into electric power for a variety of applications that necessitates low power source use. This thermoelectric energy harvester includes an assembly of very small and thin thermocouples in a unique configuration that can exploit very small (>2°C) temperature variations that are occurring naturally in the environment of the application such as ground to air, water to air, or skin to air interfaces. The body of TEG consisted of reliable and stable components that provided maintenance free, continuous power for the lifetime of the application claimed by the manufacturer. Depending on the temperature range TEG's electrical output can be changed from a few microwatts to hundreds of milliwatts and more by modifying the design. Applications of this energy harvesting design are diverse including automotive performance monitoring, homeland and military security surveillance, biomedicine, and wilderness, and agricultural management. It is also documented that the thermoelectric energy harvester may be appropriate for many other stand-alone, low-power applications depending on the nature of the application.

In addition to PNNL's patent pending thermoelectric generator, Applied Digital Solutions Corporation has developed and presented a thermoelectric generator as a commercial product. This thermoelectric generator is capable of producing 40µw of power from 5 °C temperature variations using 0.5 cm² in area and a few millimeters thick device (Pescovitz, 2002). This device generates about 1V output voltage which can be

enough for low power electronic applications. Moreover, the thermal-expansion actuated piezoelectric generator has also been proposed as a method to convert power from ambient temperature gradients to electricity by Thomas, Clark and Clark (2005).

Advantages and Disadvantages of Thermoelectric Energy Harvesting

Some research attempts resulted in the development of thermocouples which convert body heat into electricity and produce 40μ W at 3V with 5 degree temperature gradients. Additionally, bigger types of thermocouples are used in nuclear RTG (radioisotope thermoelectric generator) batteries as well (Justin, 2007). Moreover, there are some advantages of thermoelectric energy harvesting over other systems that are listed as follows:

(a) There are no moving parts of the system, which allows continuous and maintenance free operations for many years. For instance "Tellurex" which is a thermoelectric production company manufacturing thermoelectric products claims that some custom made thermoelectric products have the capability of performing over a hundred thousand operations (Power Generation, 2007);

(b) No materials or parts need to be replaced; and

(c) Heat and cooling systems can be reversed for two-way efficient power generation.

However, one disadvantage is low efficiency performance of less than 10%. Development of new thermoelectric materials should be considered which are capable of operating in higher temperature variations and which can conduct electrical energy very well without also conducting heat and which will increase efficiency in the future. For example, there are a variety of research attempts to convert wasted heat from automobile, tractor, and bus combustion engines into useful electrical energy.

Pyroelectricity Energy Harvesting

The "Pyroelectric effect" converts temperature changes into electrical voltage or current (Lang, 2005). Pyroelectricity is the capability of certain materials to generate an electrical potential when they are heated or cooled. As a result of the temperature change, is that positive and negative charges move to opposite ends through migration (polarized) and thus, an electrical potential is established. It is similar to the piezoelectric effect which is a different type of ferroelectric behavior. Pryroelectric harvesting applications require inputs with time varying and suffer from small power outputs in energy scavenging applications. One of the main advantages of pyroelectric over thermoelectric is that most of the pyroelectric materials or elements are stable up to 1200 °C or more. Stability allows energy harvesting even from high temperature sources with increasing thermodynamic efficiency.

Light Energy (Solar Energy)

A photovoltaic cell has the capability of converting light energy into electrical energy (Kasap, 2001; Raffaelle, Underwood, Scheiman, Cowen, Jenkins, Hepp, Harris, & Wilt, 2000). Each cell consists of a reverse biased pn+-junction, where the light crosses with the heavily conservative and narrow n+-region. Photons where the light energy exists are absorbed within the depletion region, generating electron-hole pairs. The builtin electric field of the junction immediately separates each pair, accumulating electrons and holes in the n+ and p- regions, respectively, establishing in the process an open circuit voltage. With a load connected, accumulated electrons travel through the load and recombine with holes at the p-side, generating a photocurrent that is directly proportional to light intensity and independent of cell voltage. The research efforts which have been done so far demonstrate that photovoltaic cells can produce sufficient power to maintain a micro-system. Moreover, a three dimensional diode structure constructed on absorbent silicon substrate helps increase efficiency by significantly increasing the exposed internal surface area of the device (Sun, Kherani, Hirschman, Gadeken, & Fauchet, 2005). Overall, photovoltaic energy conversion is a well-known integrated circuit compatible technology that offers higher power output levels, when compared with the other energy harvesting mechanisms. Nevertheless, its power output is strongly dependent on environmental conditions; in other words, varying light intensity.

A recent example of solar powered wireless architecture was presented by researchers from the University of California Berkeley (Jiang, Polastre, & Culler, 2005). The architecture was named "Prometheus" for continuous operations of self-powered wireless sensor networks using solar environmental energy. According to the research results, it was claimed that this system manages energy transfer for hardware without any battery maintenance. Their system was successfully built and managed a two stage power method to extend the life-span of such electronic devices as supercapacitors and lithium rechargeable batteries. They demonstrated that the actual system of the solar powered wireless sensor node worked efficiently according to the analysis and tests results. The energy harvesting system implementation is also used to power Berkeley's Telos Mote, which is a device developed by researchers in the University of California Berkeley. According to their predictions of the system analysis, the system will operate for 43 years under 1% load, 4 years under 10% load, and 1 year under 100% load. This study led to the use of solar power for wireless network architectures which were deployed to the environment that has access to solar energy.

It is known that indoor lightening conditions are not efficient ambient energy harvesting sources because of their lower power density when compared with outdoor light conditions (Roundy, Steingart, Fréchette, Wright, & Rabaey, 2004). One of the types of solar cells is the single silicon crystal which resulted in 15%-20% efficiency under high light outdoor conditions. According to the study by Randall, (2003), single silicon crystal solar cells are more efficient under high light conditions and the spectrum of light available outdoors. A standard single solar cell provides about 0.6V under such conditions. Such individual solar cells can be placed in series to increase the voltage level for a particular application. Solar cells are commonly very common for ambient energy harvesting systems because of their stable DC voltage outputs. Therefore, solar cells can be used to directly power electronics of energy harvesting circuit to supply or store energy for the specific wireless or portable device. Solar cells are used to charge a rechargeable battery through a diode system to prevent the battery from discharging through the solar cell. For complex applications an extended charging circuit is needed.

There are different design considerations when building an energy harvesting device for capturing ambient energy from solar power. The design considerations vary according to the application depending on how much energy is needed for the system. One of the research attempts using ambient solar energy source is "Helimote" which constitutes a plug in device to the Berkeley/Crossbow motes. In this research, design considerations such as key issues, tradeoffs of solar energy were investigated by presenting a design, implementation, and performance evaluation of "Helimote." (Raghunathan, Kansal, Hsu, Friedman, & Srivastava, 2005). Helimote is a prototype for addressing several aspects of design considerations and other issues of solar powered systems. This device autonomously controls energy scavenging and storage, and enables near-perpetual, harvesting aware function of the sensor node. The research efforts listed above illustrated how energy harvesting power management improves energy usage if compared to the battery technology.

Another recent study is a self powered wireless sensor node for remote patient monitoring in hospitals as suggested by Hande, Polk, Walker, and Bhatia, (2006). In this experimental study, a wireless sensor node capable of monitoring patient vital sign data in a hospital setting was designed and tested. The wireless sensor nodes were designed as self powered and drew energy from overhead 34W fluorescent lights that are always on in hospital hallways via small solar panels. The device is comprised of a number of solar panels along with the energy harvesting system to charge an ultracapacitor as an energy storage device. Because of the vital energy needs, this device is not only self powered but also has alkaline batteries in it to be used as an emergency back up power source in case of problems in the light energy source or the conversion circuit. Figure 4 shows such an energy harvesting system designed by Hande, Polk, Walker, and Bhatia (2006).



Figure 4: Indoor solar energy harvesting circuit with battery back-up

This system allows health personnel to monitor a patient's BP (Blood Pressure) and heart rate vital signs from a different location without requiring the health personnel to be present to record the measurements. The researchers have done initial tests and concluded that it was possible to route patient blood pressure and heart rate data to a central recording station within the hospital environment using self powered wireless sensor networks.

Fuel Cells

Fuel cell application is a new technology and an environment friendly energy source. It may not be considered as an ambient energy source because fuel cells work based on the availability of hydrogen or hydrocarbon energy. But their efficient power production has more advantages than batteries. A fuel cell is an electrochemical energy conversion device that produces electricity from external supplies of fuel (on the anode side) and oxidant (on the cathode side). Generally, the reactants flow in and reaction products flow out while the electrolyte remains in the cell. Fuel cells can operate virtually continuously as long as the necessary fuel is maintained (Pecen, Yildiz, & Baltaci, 2007). Additionally, the electrodes within a battery react and change as a battery is charged or discharged, but a fuel cell's electrodes are catalytic and relatively stable.

Hydrogen fuel cells boast many advantages when compared with conventional energy sources of today. The power from a fuel cell is derived from hydrogen, an element that is extracted from many resources. The conversion of hydrogen to electricity has no emissions. Conventional energy production requires nonrenewable fuels and produces pollutants as well. Therefore hydrogen fuel cell is a viable energy source for the future in automotive, commercial, residential, portable, and many other electrical power applications (Pecen, Yildiz, & Baltaci, 2007).

Another type of fuel cells are based on hydrocarbon which has very high energy densities if compared to an average battery. For instance, fuel cells are based on methanol and have energy density of 17.6kj/cm³ which is about five times that of a lithium-ion battery (Roundy, Steingart, Fréchette, Wright, & Rabaey, 2004). For these reasons fuel cells may be a very efficient resource for energy harvesting systems. The operating principles of low power fuel cells are the same as batteries, basically converting electrochemical energy into electrical energy. One of the recent studies is Toshiba's fuel cell powered laptop computers that have total volumes on the order of 1cm³ (Toshiba, 2003). This custom design fuel cell to powers a standard laptop computer for about five hours.

Acoustic Noise

Acoustic noise is the pressure waves produced by a vibration source. A human ear detects and translates pressure waves into electrical signals. Generally a sinusoidal wave is referred to as a tone, a combination of several tones is called a sound, and an irregular vibration is referred to as noise. Hertz (Hz) is the unit of sound frequency; 1 Hz equals 1 cycle, or one vibration, per second. The human ear can perceive frequencies between 20 Hz and 20 000 Hz. Sound is basically a type of energy. Any sound is generated by a source. Acoustic power and acoustic pressure are types of acoustic noise. Acoustic power is the total amount of sound energy radiated by a sound source over a given period of time and is usually expressed in Watts. For acoustic pressure, the reference is the hearing threshold of the human ear which is taken as 20 microPa. The unit of measure used to express these relative sound levels is the Bel or decibel (1 Bel equals 10 decibels). The Bel and decibel are logarithmic values which are better suited to represent a wide range of measurements than linear values (Rogers, Manwell, & Wright, 2002)

There are rare research attempts at harvesting acoustic noise from environment where the noise level is high and continuous, to transfer it into electrical energy. For example, the research team at the University of Florida has examined acoustic energy conversion. After investigation, they reported analysis of strain energy conversion using a flyback converter circuit (Horowitz et al. 2002). The output of a vibrating PZT piezoceramic beam is connected to an AC to DC flyback converter which is estimated to provide greater than 80% conversion efficiency at an input power of 1 mW and 75% efficiency at an input power of 200 μ W (Kasyap, Lim, et al. 2002). There is far too insufficient amount of power available from acoustic noise to be of use in the scenario being investigated, except for very rare environments with extremely high noise levels.

Human Power

Researchers have been working on many projects to generate electricity from human power such as exploiting, cranking, shaking, squeezing, spinning, pushing, pumping, and pulling (Starner & Paradiso, 2004). For example some types of flashlights were powered with wind-up generators in the early 20th century (US patent 1,184,056, 1916). Later versions of these devices, such as wind-up cell phone chargers and radios, became available in the market. For instance, commercially available Freplay's (a commercial company) wind up radios make 60 turns in one minute cranking which allows storing of 500 Joules of energy in a spring. The spring system drives a magnetic generator and efficiently produces enough power for about an hour of play.

Another human powered device was introduced early in the 20th century by Robert Adler, a battery-free wireless remote control for Zenith televisions. The design was called "Space Commander" and was introduced in 1956. The system consisted of a set of buttons that hit aluminum material to produce ultrasound. The produced ultrasound energy was decoded at the television to turn it on, change channels and mute the volume (Adler, Desmares, & Spracklen, 1982). Adler's "Space Commander" design was then replaced by the active infrared remote controls and is being used in current remote control systems.

Another similar architecture, developed by Jose Paradiso and Mark Feldmeier (2001) is a piezoelectric element which was comprised of a resonantly matched

transformer and conditioning electronics. This system was actuated when hit by a button, and produced about 1mJ at 3V per 15N push. The generated power was enough to run a digital encoder and radio which was able to transmit over 50 feet. Materials used for this device were off-the-shelf components, which enabled placing compact digital controllers independently without any battery or wire maintenance.

Normally, an average human body burns approximately 10.5 MJ every day, which is equal to about 121W of power dissipation. Power dissipations occurs in the average human body either actively or passively in daily life motions that make the human body an attractive ambient energy source. Researchers have proposed and conducted several studies to capture power from the human body. For example Starner has researched and investigated some of these energy harvesting techniques to power wearable electronics (Starner, 1996). MIT researchers took these studies and suggested that the most reliable and exploitable energy source occurs at the foot during heel strikes when running or walking (Shenck & Paradiso, 2001). This research initiated the development of piezoelectric shoe inserts capable of producing an average of 330 μ W/cm² while an average person is walking. The first application of shoe inserts was to power a low power wireless transceiver mounted to the shoe soles. The ongoing research efforts mostly focused on how to get power from the shoe, where the power is generated, to the point of interest or application. Such sources of power are considered as passive power sources in that the person is not required to put extra effort to generate power because power generation occurs while the person is doing regular daily activities such as walking or running. Another group of power generators can be classified as active human powered

energy scavengers. These types of generators require the human to perform an action that is not part of the normal human performance. For instance, Freeplay has self powered products that are powered by a constant force spring that the user must wind up to operate the device (FreePlay Energy, 2007). These types of products are very useful because of their battery-free systems.

The problem of how to get energy from a person's foot to other places on the body has not been suitably solved. For an RFID (Radio frequency identification) tag or other wireless device worn on the shoe, the piezoelectric shoe insert offers a good solution. However, the application space for such devices is extremely limited, and as mentioned earlier, not very applicable to some of the low powered devices such as wireless sensor networks. Active human power which requires the user to perform a specific power generating motion is common and may be referred to separately as active human powered systems (Roundy, 2003).

Energy Storage Technologies

Energy needed for today's portable devices and small scale wireless devices is mostly provided by batteries. As technology scales down in physical size, the proportion between energy need of the electronic devices and battery technology is expected to further increase. Also the necessity for proper maintenance of batteries, with the need to either change or recharge them is very important. This is a serious constraint to computing methods like ubiquitous computing or wireless sensor networks, in which there are sometimes dozens or hundreds of small systems with batteries to maintain. Of course, these constraints do not minimize the benefits of batteries as an energy source. Batteries can be categorized by their energy density or with respect to volume and weight, called volumetric and gravimetric energy density, correspondingly (Ganesan, 2006). Table 4 shows some typical values of energy densities and self discharge values for commercially available batteries. It is significant to note that these values of energy density are the most common options available today. But then differ according to the applications or systems.

Table 4

Battery type	Operating voltage	Vol. energy density Wh/dm ³	Grav. energy density Wh/kg	Self discharge % month	Cycle life number	Charging	Typical cost
NICD	1.2V	100	30-35	15-20%	300	Simple	\$1.67
NIMH	1.2V	175	50	20%	300	Simple	\$2.50
Li-ion	3.7V	200	90	5-10%	500	Complex	\$6.90

General characteristics of batteries. (Ganesan, 2006)

Secondary rechargeable batteries are in general a better choice for ubiquitous or wearable systems because they can be recharged in several ways, in many cases without extracting the battery from the system (Ganesan, 2006). One possibility to recharge such batteries is to use energy harvested from the environment. In this sense, energy harvesting is not trying to replace batteries, but instead to improve some of their disadvantages, especially in relation to maintenance issues.

For example, the problem of powering a large number of wireless devices in a dense network becomes critical when one considers the prohibitive cost of wiring power to them or replacing batteries. In order for the devices to be conveniently placed and used they must be small, which places severe limits on their lifetime if powered by a battery meant to last the entire life of the device. State of the art, non-rechargeable lithium batteries can provide up to 800 WH/L (watt hours per liter) or 2880 J/cm³. If an electronic device with a 1cm³ battery was to consume 100μ W of power on average, the device could last 8000 hours or 333 days, almost a year. This is a very optimistic estimate as the entire capacity usually cannot be used due to voltage drops and leakages. It is worth mentioning that the electronics of a device will be far smaller than 1cm³, so in this case, the battery would control the system volume. Clearly, a lifetime of 1 year is far from sufficient for most of the wireless electronic applications (Roundy, 2003).

Research to enlarge the storage density of both rechargeable and primary batteries has been performed for many years and continues to receive substantial focus (Bomgren 2002; Alessandrini, Conte, Passerini, & Prosini, 2000). The past few years have included many efforts to miniaturize fuel cells which produce several times the energy density of ordinary batteries (Kang, Lee, & Prinz, 2001; Sim, Kim, & Yang, 2001). Finally, more recent research efforts are underway to develop miniature heat engines that produce similar energy densities to fuel cells, but are capable of far higher maximum power outputs (Mehra et al. 2000). While these technologies promise to extend the lifetime of wireless or portable electronic devices, they cannot extend their lifetime indefinitely.

The most common method (other than wires) of distributing power to embedded electronics is through the use of RF (Radio Frequency) radiation. Many passive electronic devices, such as electronic ID tags and smart cards, are powered by a nearby energy rich source that transmits RF energy to the passive device, which then uses that

energy to run its electronics (Friedman, Heinrich, & Duan, 1997). However, this method is not practical when considering dense networks of wireless nodes because an entire space, such as a room, would need to be flooded with RF radiation to power the nodes. The amount of radiation needed to do this would probably present a health risk and exceeds today's FCC (Federal Communications Commission) regulations.

According to recent studies, the reliable sources to store energy in low power energy harvesting systems are batteries and ultracapacitors (Dinesh & Abhiman, 2005). Li-ion, NICD and NIMH are good examples of rechargeable battery types. Maxwell, Samsung, and NEC corporations are working on ultracapacitors to increase their efficiency by decreasing their size. As an example Maxwell developed a small size ultracapacitor with 5V, 2F, 2.7mAhr specifications (Maxwell Technologies PC-5 Ultracapacitors, 2007).

Battery technology could grow to keep pace with other technologies, as components of electronics devices became smaller and required less power allowing growth in today's wireless and mobile applications explosion. In Figure 5 the capacity increase of some crucial devices for computing technologies is shown since 1990s. As the Figure indicates, battery technology has the slowest growing trend in mobile technology (Paradiso & Starner, 2005). To overcome this slow trend in battery technology it is necessary to move to another energy source which is ambient energy harvesting and storage.



Figure 5: Relative improvements in laptop computing technology from 1990–2003.

Battery size usually refers to the shape, supplied voltage, and terminal layout of a battery. So in battery technology the term size has turned into interchangeable terminology with the type of the battery. Dimensions and terminal layouts of the batteries generally differ from each other by their types. Old technology batteries had voltage amounts in increments of 1.5V, which reflected the amount of cells in the battery. New batteries especially rechargeable NICD and NIMH are normally of output of 1.25V per cell. Some electronic devices which require battery power may well not operate properly on rechargeable batteries, but the majority will handle them reasonably well. Most of the recent battery sizes also refer to both the batteries' size and chemistry, while older types do not (List of battery sizes, 2008). Table 5 gives a complete list of battery types relating to battery sizes.

Table 5

Battery types as categorized by their sizes (List of battery sizes, 2008)

Primary Battery Chemistry				
Chemistry	Cell Voltage (V)	Comments		
Zinc-carbon	1.5	Inexpensive		
Zinc-chloride	1.5	Inexpensive		
Alkaline (zinc-manganese dioxide)	1.5	Moderate energy density Good for high and low drain uses		
Lithium (lithium-iron disulfide) LiFeS ₂	1.5	Expensive Used in 'plus' or 'extra' batteries		
Lithium (lithium- manganese dioxide) LiMnO ₂	3.0	Expensive Only used in high-drain devices or for long shelf life due to very low rate of self discharge. 'Lithium' alone usually refer to this type of chemistry.		
Mercury oxide	1.35	High drain and constant voltage Banned in most countries because of health concerns		
Zinc-air	1.35- 1.65	Mostly used in hearing aids		
Silver oxide (silver-zinc)	1.55	Very expensive Only used commercially in 'button' cells		
Rechargeable Battery Chemistry				
NiCd	1.2	Inexpensive High/low drain, moderate energy density Moderate rate of self discharge Suffers from memory effect		
NiMH	1.2	Expensive, high drain devices High rate of self discharge		
Lithium ion	3.6	Very expensive Very high energy density, used in laptops, digital cameras		

Ultracapacitors (Supercapacitors)

Latest progress in capacitor technology has led to the development of the ultra (super) capacitors, with a capacitance value of the order of 1kF. Such remarkably large capacitors, however, present an energy density around 3 Wh/kg, still very much away from average battery values for low power applications. The major advantages of ultracapacitors are the supplied peak power, and the number of cycles they produce (Supercapacitors, 2008). These characteristics make them more especially suitable for automotive applications than to low power electronic devices, where batteries are still the alternative application for energy storage.

The capacitors accumulate energy as an electrical field by polarizing an electrolytic solution instead of creating it from chemical reactions as in most of the batteries. There are no chemical reactions involved in its energy storage mechanism. This approach is more efficient, and might soon be more economical. The use of an ultra capacitor allows high-speed capacity of charge and discharge (Halber, 2006). Ultra capacitors are half-way between rechargeable batteries and standard capacitors. In fact they can provide much higher power densities than batteries and standard capacitors. They preserve some favorable characteristics of capacitors, such as long life and short charging time, and their energy density is about 1 order of magnitude higher than standard capacitors are well adjusted to high number of charge and discharge cycles, and are a means of solving durability problems of traditional batteries. Because of their increased lifetimes, short charging times, and high power densities, ultra capacitors could be very attractive as a

secondary power supply in place of rechargeable batteries in ambient energy harvesting systems (Supercapacitors, 2008).

Generally rechargeable batteries are normally rated for a few hundred change cycles. Moreover, they are manufactured to tolerate many more low charge cycles which are not indicated on the advertising materials. For this reason the lifetime of the rechargeable batteries is significantly decreased by frequent charge cycles. So as a primary buffer it is not a good idea to use rechargeable batteries. On the other hand the nature of capacitors allows infinite recharge cycles and usually is best for frequent pulsing applications. As a primary buffer storage large capacity ultacapacitors can be considered a viable option for energy harvesting systems. It is not advised to use ultracapacitors for a secondary storage unit because of their high leakage current, large size, and the market cost. Because of their limitations, supercapacitors can only be used for primary buffer and temporary storage units. This way of use minimizes access to the secondary buffer (rechargeable battery) and extends its life-span in energy harvesting circuits. When selecting a supercapacitor, it is important to investigate its leakage current capacity because the larger the capacity of a supercapacitor the greater is its leakage current. NEC and Maxwell corporations are working on the supercapacitors to increase their energy density and decrease the sizes for low power electronic applications.

Micro Supercapacitors

Integrating a micro-supercapacitor as a storage device in an energy harvesting or generating system can be a smart way to enable high power density. The nature of microcapacitors is capable of providing high power pluses by stabilizing the voltage under load
and reducing the overall power supply volume. The development and small sizes of super microcapacitors provided new ways to maximize the available power and energy and also can be built in surface mount packages where space limitations exist (DeGreeff, Fleig, & Lakeman, 2005). It is assumed that combinations of micro-supercapacitors and microbatteries into one power system, known as electrochemical power supply (MEPS), can provide enough energy for miniaturized systems. The burst power supply capability of micro-capacitors can decrease battery requirement and required power system foot print. TPL Inc, a New Mexico based company has developed micro-supercapacitors and microbatteries and incorporated them into one unique and tiny storage device. Their design goal was for supercapacitors to maximize the surface area of the electrode to maximize the capacitance and the stored energy. Their microbattery design is the smallest volumetric battery available in the world with total volume as small as 2.6mm³. To fulfill a variety of performance requirements, zinc-air, lithium primary, and lithium-ion microbattery types have also been developed. Moreover TPL is working with Washington State University and Qynergy Corp. to develop hybrid systems with microbatteries and micro-supercapacitors to utilize and improve their energy harvesting technologies (DeGreeff, Fleig, & Lakeman, 2005). It is assumed that the combination of an energy harvesting system with a micro-supercapacitor and microbattery can provide an extended life and high power capability power source.

Energy Harvesting & Controller Circuits

There has been a variety of energy harvesting circuit designs and developments in which such devices were different from each other according to the ambient energy source characteristics. It is not viable to use the same circuitry to capture energy from solar power, mechanical vibrations, waste mechanical energy, or human powered systems. for energy harvesting systems. One of the examples of developing an energy harvesting circuit is a converter and controller design for micro power energy harvesting by Shengwen, Khai, Toshikazu, Gyo-Bum, and AttmaSharma (2005). The design of a pulsed-resonant AC-DC converter and an integrated circuits controller was also developed. This system has been designed, fabricated, and tested for harvesting energy from low voltage sources. The demonstration of energy harvesting for battery charging using power sources between 2µW and a few hundred mWs was also conducted. At the end of this study the efficiency of the system was reported to range between 60% to 70%.

Several other circuit techniques were described in the literature to achieve the needs of circuit design used for ambient energy harvesting systems. It was also proposed that eliminating AC/DC conversion increases the efficiency of vibration energy harvesting. For this purpose, self-timed circuits, power-on reset circuitry, and memory for energy harvesting power supplies were investigated by Amirtharajah, Wenck, Collier, Siebert, Zhou (2006). The study reported that the proposed circuit techniques can be applied to other ambient energy sources for energy harvesting. At the end of the study, a chip to test energy harvesting circuits was designed for a 0.18µm logic process. It is claimed by the authors that the developed circuits can be used with solar or thermal

energy harvesting. The designed circuits can also be applied to interface with inductively powered devices such as biomedical implants, embedded sensors, and RFID tags for barcode systems as reported by Briole et al. (2004).

Battery Charging Circuits

The energy scavenging system needs a charger capable of capturing and transferring intermittent low energy bursts to a rechargeable battery. Maximum battery life, capacity, and energy content of a rechargeable battery are normally achieved by adding a constant current/constant voltage charging system. Primarily, a low preconditioning charging current is applied to the battery to make sure the cell voltage required at least a minimum voltage to start charging. Then, the constant-current stage follows with the application of a full charging current, until the battery capacity nears the end-of-charge voltage. This procedure differs from one battery brand to another. Afterwards, the constant-current phase follows the application of a full charging current, until the battery voltage nears the end-of-charge voltages typically between specified battery range voltages. In such devices, the cell voltage increases quickly during the constant current phase, before allowing the system to reach full capacity (Portable Power Design Seminar, 2004). Therefore, quick charging of the cells by simply applying a constant charge current achieves just between 40% and 70% of its maximum potential capacity. Both charging steps are therefore necessary to charge the battery completely. Figure 6 shows the Constant-current/constant-voltage battery charging model as proposed by Torres and Mora (2005).



Figure 6: Constant-current/Constant-voltage battery charging model.

Lopez, Gonzalez, Viera, and Blanco (2004) found the charging circuit relies on the nature of input energy that is to be stored in the battery. In this study, generally, the charging current applied to the battery can be either permanent or alternating. Permanent charging methods may utilize linear and switching regulators. A linear regulator linearly manages the conductance of a series pass device using a feedback loop to regulate the output against variations in load current and supply voltage, constantly supplying current. Linear regulators are similar to resistive voltage dividers in that they can only source voltages below the input supply.

EH300/EH301 EPAD Energy Harvesting Modules

Energy harvesting systems were developed mostly with off-the-shelf components and are usually not capable of providing sufficient energy to make energy harvesting a reliable method. Developing circuits with standard components requires more electrical energy to run both the circuit and the application. On particular, piezoelectric and thermoelectric materials do not provide frequent power, instead infrequent or random intervals occur which usually does not generate sufficient power for both the circuitry and the application (O'Shea, 2007).

Among most recent ambient energy harvesting systems for low power applications are EH300/EH301 which are capable of capturing, accumulating, and storing power from a variety of energy scavenging sources. This is the first energy harvesting module which was developed by Advanced Linear Devices Inc. to supply power to wireless sensor networks, remote controls and a multitude of other applications (Advanced Linear Devices Inc., 2006). EH300/EH301 Energy harvesting modules are completely self powered and always in the active mode, which means they are ready to scavenge energy from sources that generate non-constant energy impulses with varying source impedances. There is no input voltage limitation to start harvesting energy. The module is capable of operating from zero voltage to ensure that even small energy changes can be harvested and stored for the application. Another key feature of this device is the low leakage rate. It was designed to store energy for long periods of time with minimal leakage or loss, as reported by Advanced Linear Devices Inc. (2006). The energy harvesting module schematic is shown in Figure 7.



Figure 7: EH300/301 Energy Harvesting Modules (Advanced Linear Devices Inc.)

Advanced Linear Device Inc., claims that using EH300/301 series modules energy can be captured from a variety of secondary or waste by-product environmental sources, such as thermal, mechanical, chemical, solar, biological and human body sources. According to the specifications listed on the datasheet, some of the important features of EH300/3001 series modules are listed below:

- (a) Random AC or DC inputs accepted;
- (b) Broad range of irregular input voltage, current, and waveforms;
- (c) Compatible energy harvesting sources such as piezoelectric fiber composite, solar photovoltaic cells, and thermoelectric generator;
- (d) Have self-contained onboard energy storage;
- (e) No calibration or setup required;
- (f) Flexible output current range $(0.1\mu A \text{ to } 1A)$; and
- (g) Always in active mode

Design and Power Conditioning of Energy Harvesting Systems

Design and power management issues are very important and should be considered as high priorities in order to obtain maximum efficiency from energy harvesting systems. Designing and developing an efficient, reliable energy harvesting system requires in depth understanding of a number of complex transactions. The connections of numerous factors such as the characteristics of the harvesting transducers, capacity and chemistry of the batteries' and capacitors' power supply requirements and application behaviors should be accorded high importance during designing an energy harvesting system. Vijay Raghurathan and Pai. H.Chou surveyed various issues, and

tradeoffs while designing and operating energy harvesting systems (Raghunathan & Chou, 2006). Design considerations and tradeoffs also were investigated under three main subjects (energy harvesting, system design, and power conditioning issues) in their survey. The primary considerations were the energy harvesting input and output voltage levels. Without sufficient voltage input, it is difficult to power both the system and charge an energy storage device at the same time. It is important to investigate key characteristics of ambient energy sources before designing electrical circuits. The energy harvesting circuit should manage its power consumption and performance by keeping tracking of the available input voltage level. Another consideration is to keep track of the maximum power point which refers to capturing power from an energy harvesting source at a level that optimizes the output power. To manage the system losses and leakages which occur on the circuit the maximum input voltage should be optimized and distributed to the overall system to charge the storage device efficiently. Even with tracking the maximum power point, the available power may be to low that it can not operate the system. In this case power defragmentation which scavenges energy from multiple ambient energy sources can provide enough power to the system to operate. For example, a harvesting system may include both a solar panel and a wind generator to provide sufficient energy merging into one storage device. But scavenging energy from multiple energy sources needs a careful consideration during the system design because of the different characteristics of the ambient energy sources.

Summary of Literature Review

The literature review indicated that ambient energy harvesting systems are fruitful areas of research and has opened possibilities to the convergence of miniaturization the components, low-power system designs, and developments in materials and mechanical systems. The power consumption of the components and applications has been decreased to almost an equal level which increased the output capability of energy harvesting systems. A brand new class of applications are being designed and developed for ambient energy harvesting systems. It seems unlikely that the systems already developed can automatically run efficiently by just adding an energy scavenging module. Moreover, for the optimal efficiency of the energy system, more consideration should be given from design of the architecture to power management at the application level.

In the literature review variety of low power energy harvesting sources, storage technologies, and energy harvesting circuit research attempts are investigated. Since low power energy harvesting has recently became very popular, more research efforts are recently conducted. Ambient energy sources were classified as energy reservoirs, which may allow portable or wireless electronic systems to be completely battery free or self sustaining. The research attempts which were investigated in the literature review concludes that no single power source is sufficient for all applications, and that the selection of energy sources needs to be considered according to the application characteristics and environment. For the mechanical energy harvesting a waste vibration or rotation resource should exist in the environment in order to scavenge and convert mechanical energy into electrical energy. The higher the waste vibration or rotation is

generated then the higher electrical energy would be stored for the application.

Depending on the source characteristics, an efficient energy harvesting circuit should build to store as much as energy for the application life time. Otherwise harvested energy would dissipate or is reduced through the circuit before reaching the storage unit. It was common among the low power energy harvesting researches that before developing the circuits intensive investigations of ambient energy source characteristics were performed.

Despite of some advantages of the thermoelectric energy harvesting, there were limited research attempts due to low temperature differences in the environment compared to mechanical energy harvesting. The advantages of the thermoelectric energy harvesting were: no moving parts, no material or part replacement, and heat and cooling systems can be reversed for two way power generation. However for the efficient energy harvesting, development of thermoelectric materials should be capable of operating in high temperature variations to increase the power generation efficiency.

Furthermore, solar energy offers the most attractive energy scavenging solutions according to the research studies investigated. Energy harvesting solutions from light energy meet the power density requirement in environments that are of interest for low power energy scavenging. There were some research attempts to harvest and store indoor lights from the fluorescent and incandescent lamps for the low power energy harvesting. Solar energy applications are already available commercially for low and high power applications.

Moreover, energy harvesting from acoustic noise were rare because of the noise level variations were not sufficient and continuous, to transfer into electrical energy. However, it is possible to harvest energy from environments with extremely high noise levels.

Both mechanical power and vibration based energy scavenging look promising as methods to scavenge power from the environment. In many cases, they are overlapping solutions because vibrations part of the present waste mechanical energy. Therefore, it was decided to pursue both mechanical rotation and vibration based solutions for the low power energy harvesting development.

Also the low power energy harvesting research attempts from human power have been done recently to run low power wireless and portable applications. Some of the research studies were not very successful due to the intermittent nature of the energy generated from passive human actions. However there are commercially available electronic devices which are powered by active human power by cranking, shaking, squeezing, pushing, and pulling. The electronic devices powered by active human power including radios, toys, hand lights, and bikes are commercially available by different sizes and prices.

Low power battery technology and supercapacitors were used in low power energy harvesting were also investigated as primary and secondary storage devices. Most of the researchers mentioned that battery technology could not keep pace with other technologies, as electronic parts of devices became smaller and required less power. However, intensive research attempts are underway to increase battery efficiency in portable and wireless devices.

Moreover, a variety of energy harvesting circuit development techniques were investigated in this section and it was very helpful to the researcher in the circuit development steps. Generally buck-boost converters, battery charging circuits, and switching regulators were used during energy harvesting circuit developments to power the electronic applications. The energy harvesting circuits gave the researcher to consider some crucial points before development of circuits for three different ambient energy sources such as hydraulic door closer, fitness equipment and piezoelectric fiber composites.

The literature review lead to the conclusion that several currently developed, overlooked, ideas and options exist that can provide new resources to portable or wireless electronics devices within the energy harvesting systems. Possibilities of overall dependence on ambient energy resources may remove some constraints required by the limited and reliability of standard batteries. Moreover, ambient energy harvesting can also provide extended life span and support to conventional power systems.

CHAPTER III

METHODOLOGY

The research was carried out to examine reliability of energy harvesting systems. The demonstration of human kinetic energy and its many uses as ambient power source were investigated and tested with experimental implementations. Three different energy scavenging techniques for low power portable and wireless electronic devices were examined. Human kinetic energy can be transferred in a number of ways so the main source was energized by human power to operate three ambient energy sources. Only energy harvesting tools which are activated by human power will be different. These three forms of ambient energy sources (waste mechanical energy from hydraulic door closers, fitness exercise bicycles, and human motions such as walking or running) were converted to electrical energy and the energy stored in battery banks for use in the systems.

A hydraulic door closer is the first ambient energy source tested for this research. An energy harvesting system was built and tested to capture and convert waste mechanical rotations from a hydraulic door closer. For this purpose, a hydraulic door closer as a potential mechanical energy supply was obtained from the Physical Plant at the University of Northern Iowa. For the hydraulic door closer human presence was required to open the door.

A second ambient energy source of human power was fitness bicycles. One of the most commonly used source of human energy applications is propelling bicycles (fitness or regular) and that can generate electricity to power peripherals such as electronic display panels of the bicycle. An appropriate energy harvesting and storage system was built and demonstrated to investigate reliability of the fitness bicycle as an ambient energy source.

The third source of harvesting environmental energy was waste kinetic energy from human walking activities and was studied using integrated tiny piezoelectric fiber composites which are capable of generating/producing electricity from vibrations. The reason for choosing ceramic piezoelectric materials to capture tensions and vibration from the motion is the nature of the piezoelectric material which is capable of converting vibrations into electric current. The piezoelectric fiber composites were inserted into shoe insoles where a significant amount of tensions, stresses and vibrations occurs when a person walks or runs.

Based on the ambient energy source, electric energy conversion and storage circuits were built and tested for low power electronic applications. These sources were characterized according to energy harvesting (scavenging) methods, power and energy density. At the end of the study, the ambient energy sources were matched with potential electronic applications as a viable energy source.

Typical components, such as electric generators, motors, gear sets, piezoelectric elements, electronic components and storage devices were used to build energy harvesting systems. It was expected that the proper choice of these materials would develop an efficient energy harvesting device. Figure 8 shows a block diagram of the three different experimental energy harvesting systems.



Figure 8: Block diagram of experimental energy harvesting systems

Hydraulic Door Closers

The first phase of door hydraulic system operations is generally activated by human power; the second stage is the closing phase that is controlled by a spring and a hydraulic damping mechanism. The waste mechanical energy can be converted to electrical energy using appropriate devices and provide energy to low power electronic devices and applications such as security alarms, exit signs, or wireless security cameras. System Design

When the door is pushed or pulled, the hydraulic door closer starts moving and continues until the door is completely closed. In the first phase of the project, an appropriate gear set was designed to increase the speed of the rotation so that it is able to provide enough rotation speed for the generator unit (Permanent magnet brushless DC motor). Then a power conditioning circuit was designed to implement and manage energy conversion. This circuit regulated the voltage for a low power electronic application. Before implementation of the experiment, necessary computer simulations were conducted.

In the following sections, the speed increase gear set, generator unit, switching circuit design, and storage units are explained. Because of the lack of proper funding for equipment, and proper laboratory environment limitations, speed increase plastic gear sets were used instead of steel gear couples. Also, different types of PMDC (Permanent magnet direct current) motors were used as test devices to test the circuit efficiencies. For circuit design, printed circuit boards (PCB) were designed and ordered from a PCB manufacturer. The block diagram of such system is shown in Figure 9.



Figure 9: Overall energy harvesting model from hydraulic door closer

Speed Increase Gear Set Design

The aim of the gear set is to increase the speed of rotation generated from the hydraulic door closer to provide sufficient speed to a DC motor. The motor then serves as a generator unit. This step up in speed is required because without the increase of speed, the rotation rate from the door hydraulic closer will not be sufficient for the generator. There are different types of gear sets which are mounted to where the door hydraulic rotation occurs. Gear ratios and the number of gear sets are determined by considering the average rotating speed of the door and the rotation required by the generator. The gear set was designed to increase speed to provide enough rotation to turn on electricity generation.



Figure 10: Door mechanism

As represented in Figure 10 above, assuming that the door is fully opened when the rotation is one fourth of the full rotation and the time it takes is one second; the rotation speed of the door can be calculated as follows:

Door Speed
$$=\frac{1}{4}\left[\frac{rot}{\sec}\right]*\frac{60\sec}{1\min}=\frac{60}{4}\left[\frac{rot}{\min}\right]=15rpm$$
 (1)

Gear ratios for four gear levels are selected as 1/4. Hence the overall speed ratio of the gear box can be calculated as:

$$\rho_{all} = \prod_{i=1}^{n} \rho_i \tag{2}$$

where

 ρ_{all} = Overall speed ratio;

 ρ_i = Speed ratio for ith layer (layer means speed of each shaft between gear sets); n= Number of layers for speed ratio (there are total 4 shafts placed for gear sets);

If n = 4, then
$$\rho_{all} = \rho_1 \cdot \rho_2 \cdot \rho_3 \cdot \rho_4 = \frac{1}{4} * \frac{1}{4} * \frac{1}{4} * \frac{1}{4} = \frac{1}{256} rpm;$$

Hence, the overall speed ratio = $\frac{input speed}{output speed} = \frac{1}{256}$ rpm (rotation per minute).

As we assumed above that the door opening speed is 15 rpm (this value can be changed according to the intensity of door openings and closings), that is the initial input to the gear box. So the resulting rotation speeds at each pair of gear sets can be found consequently as 60, 240, 960 and 3840 rpm maximum. The ratio between initial speed

and maximum speed of the gear set can be changed simply by changing positions of gears and shafts.

The gear ratio simulation test was conducted using the either LMS. AMESim or MSC.Easy5 [®] analysis interfaces (2007) available at University of Northern Iowa computer lab. The analysis results indicate the speed of the gear set reaches its expected performance.

Generator Unit and Simulation Tools

The energy extracted from ambient energy sources is usually stored in rechargeable batteries such as thin-film lithium-ion types or capacitors which power the loading application via a regulator circuit. Since harvested energy manifests itself in irregular, random, low-energy bursts, a power-efficient, discontinuous, intermittent charger is required to transfer the energy from the sourcing devices to the battery or capacitor. Energy that is typically lost or dissipated in the environment is therefore recovered and used to power the system, significantly extending its operational lifetime.

In this section, a PMDC (Permanent Magnet Direct Current) motor was used as a generator unit. Three main issues need to be considered, the generator output power, the voltage regulation circuit, and the rechargeable battery type. Their design should be considered altogether to increase the system efficiency and reduce power losses. The generator unit and components of the electrical circuit are explained below with circuit simulation.

The electric motor is based on the fact that any conducting wire which cuts a magnetic field and has a relative motion will generate an electric potential. Electric

motors include rotating coils of wire that are driven by the magnetic force exerted by a magnetic field on an electric current (Introduction to electric motors, 2008). They transform electrical energy into mechanical energy. So basically, any permanent magnet direct current (PMDC) motor back driven will make a generator. This procedure can denote its efficiency and the voltage generated (Overview of electric motors, 2007). The general view of mechanical to electrical energy conversion is shown in Figure 11. The faster the generator turns, the higher the output voltage generated. In similar cases, the old generators would not generate enough voltage when idling. They were geared by size of pulleys, to generate enough voltage to charge at a reasonable speed when powering a device. The DC motor (generator unit) will require at least 2700 rpm input to generate electricity according to its optimal specifications (Mabuchi motors, 2007).



Figure 11: Electric generator working principles

Electric Circuit Simulation Tools

Moreover the circuit board was designed and simulated using SwitcherCADTM III high performance spice III simulator from linear technology (Linear Technology, 2007). This software tool has a big library of electronic components useful for the needs of this study. The schematic capture and waveform viewer is part of this software and is very fast. These enhancements and models are useful for easing the simulation of switching regulators. The circuit design using SwitcherCADTM III is shown below in Figure 12. The circuit board was comprised of a full wave bridge rectifier circuit and this circuit has a connection with an alternator unit. After full-wave rectification occurs, the voltage is increased by DC-to-DC boost converter. A capacitor is placed between the rectifier circuit and a DC-to-DC boost converter circuit to measure the voltage and current after rectification. This capacitor functions as an intermediate storage unit as well. Switching Regulator

The ambient energy sources usually provide energy at random, and in a noncontinuous, intermittent manner. The alternating battery charger should wait until sufficient energy is collected in a specially designed intermittent capacitor before trying to move energy to the storage device, for example a NICD rechargeable battery. Additionally, since energy and power are regularly small in micro scale systems, the system should divide its functions into time slices, making sure sufficient energy is harvested and stored in the battery before supplying power to the load. The system would frequently refill its energy use, resulting in extended and maybe endless operational life.



Figure 12: Energy harvester circuit design and simulation interface.

Switching regulators, optionally, can boost or buck the input voltage to regulate the voltage according to the battery capacity. Fully on or off switching devices optionally store and distribute energy to the load by means of a combination of inductors and capacitors etc. The switching nature of regulators naturally achieves high power efficiency because the switches sustain small voltage drops, even at high current levels, so dissipating little power, when compared to the series pass device of the linear regulator. While the circuit switches, the output is regulated and can constantly supply a charge current, even with a noisy AC ripple waveform (Linear Technology, 2007). Non-constant or discontinuous charging refers to the application of irregular and discrete charge current pulses to the battery. The duty cycle of the pulsating current waveform regularly decreases as full charge condition is approached. Efficiency is improved because periodically breaking off the charge current allows ions to spread and redistribute more evenly, consequently reaching higher capacity levels as reported by Cope and Podrazhansky (1999). Adding more short discharge pulses after each charging pulse further steps up this diffusion procedure. Each charging scheme depends on a constant, steady source of energy and is then incompatible with irregular and non-constant sources.

For the energy conversion circuit design of the hydraulic door closer a LT1512 SEPIC constant-current, constant-voltage switching regulator was used (Linear Technology, 2007). The LT1512 is a 500 kHz current mode switching regulator specially configured to create a constant-current, constant-voltage battery charger. The reason to choose this specific switching regulator was that it had the capability to operate at very low-power inputs starting at 0.8V. Because the hydraulic door closer system is a nonconstant energy source and the rotary part for waste mechanical energy turns slowly. Even though this slow rotation would be increased by the appropriate speed increase gearset, again the generator unit still would produce low voltage. In addition to the regular voltage feedback node, the LT1512 has a current sense feedback circuit for accurately controlling output current of SEPIC (Single Ended Primary Inductance Converter) topology charger. The structure of LT1512 simplifies battery switching and system grounding problems by allowing the current sense circuit to be ground referred

and separated from the battery. Additionally, the topology of LT1512 allows charging even when the input voltage is lower than the battery voltage (Linear Technology, 2007). The applications of LT1512 are primarily charging of NICD, NIMH, Lead-Acid or Lithium Rechargeable cells. It is also used in applications of precision current limited power Constant-Voltage/Constant Current power supplies and transducer excitations. The LT1512 switching regulator is also featured allowing battery charging currents up to 1A for single lithium-ion cells with accuracy of 1% in constant-voltage mode which is perfect for lithium battery applications. Almost all battery types can be easily charged by programming and limiting charging current by adding/replacing proper resistors to the battery charging circuit. Taking all these features of LT1512 into consideration it was decided that battery charging circuit would be more efficient with the LT1512 switching regulator.

Fitness Bicycles

Human kinetic energy can be extracted and transferred to small scale power applications in few different ways. For example moving bicycles are most commonly operated by human kinetic energy, but can also be used to extract energy by powering hand-crank tools. In this section of the research an energy harvesting system from human kinetic energy will be presented. For this purpose the rotating pedal parts of the fitness bicycles were investigated for appropriate waste mechanical energy capturing.

A human powered pedal generator can be a perfect solution to power a fitness bicycle display, hence eliminating battery power. Not only does the display get powered but also different applications such as a small radio, or digital embedded heartbeat reader can be powered. The average continuous power which can be generated by pedaling the fitness bicycle can be adjusted through changing the generator unit (DC motor) and energy harvesting circuit. The gearset and generator were mounted at the appropriate place inside the pedal system. It was a design issue to place the gearset and the generator where the most rotation is occurring during pedaling the bicycle. The energy harvesting circuit was planned to be placed inside the display to be closer to other electronic components. The power output of the generator unit was directly proportional to the effort put into it but the output power of energy harvesting circuit was a fixed voltage to avoid damaging the storage device. So the amount of electrical power that can be generated by the human powered generator is determined by the energy available to turn the pedals. The stronger the human power, the more electrical power which can be generated and stored. The produced DC power can also be used for different applications even for AC appliances by using a DC-AC inverter connected to a storage unit for a stable AC output. If an average person is expected to produce sustainable 100-1500 Watts then charging a battery with average 50mA current will be enough to charge a battery or a capacitor to power a low power electronic device.

System Design

The overall energy harvesting system design from a fitness bicycle was very similar to the hydraulic door closer system design discussed earlier. Characteristics of these two energy sources were the same except for rotational speed which occurs faster on the fitness bicycle than with the hydraulic door closer when activated by human power. Considering this difference, only minor changes were made in the gearset because of the

high torque, and circuit design for the test issues. But DC generator and storage units may vary to produce more power for different applications. The simulation tools for both gearset and energy harvesting circuit were the same as those used for the hydraulic door closer. Switching regulator and storage units were different to provide an opportunity to try different components to increase the efficiency of power generation and storage. The block diagram of the overall system design for this purpose is shown in Figure 13.



Figure 13: Overall energy harvesting model from fitness bicycle

Piezoelectric Fiber Composites

The use of Piezoelectric elements has not been very successful for energy harvesting systems even though there have been many research studies in this area. It does not mean PZT materials are not capable of energy harvesting, but more advanced piezoelectric materials are needed to increase the efficiency of ambient energy harvesting systems. ACI (Advanced Cerametrics Incorporated, 2007) very recently has developed Piezoelectric Ceramic Fiber Composite (PFC) energy harvesting systems. This recent development was recognized by R&D Magazine providing the "2007 R&D 100 Award" which is given to the top 100 new products from around the world every year. The PFC (Piezoelectric fiber composite) consists of uniquely flexible ceramic fiber capable of capturing waste ambient energy from mechanical sources such as vibrations. This new product functions between ambient vibration sources and electrical circuit with the storage device to convert vibrations into electrical energy. This unique development by ACI will allow powering some applications without the need for battery power such as wireless sensors, transmitters, microcircuits, smartcards, cell phones, and other handheld devices.

ACI's ceramic fiber composite manufacturing process enables the production of ceramic fiber from nearly any ceramic material. This patented process created a unique flexible ceramic fiber composite as cited by Ruddle, Cass, and Mohammedi (2007). PZT Fiber composites opened new ways to capture ambient energy for recent technologies such as micro power supplies, structural health monitoring, wireless sensor networks and vibration dampening products applications. These emerging ceramic fiber composites from ACI's fiber spinning lines are capable of generating electricity when exposed to an electric field. It is claimed by ACI that thin fibers with dominant dimension, length and a very small cross-sectional area are capable of optimizing both piezo and reverse piezo effects. Piezoelectric ceramic fiber composites are capable of creating much better mechanical to electrical energy conversion compared to other piezoceramics according to studies was conducted by ACI. Table 6 demonstrates the use of PZT ceramic fiber composites with a variety of applications with successful operating results for energy harvesting systems as reported by Ruddle, Cass, and Mohammedi (2007). Piezoelectric fiber composites have a bright future in ambient energy harvesting for low power embedded electronics according to Advanced Cerametrics Inc. (O'Shea, 2007). This company is involved in developing energy scavenging material to provide extended power life for wireless and portable electronic devices (i.e. wireless sensor networks). Table 6

Application	Dixect Piezo Effect	laverse Piezo Effect
Energy Horwesting		
Battery Replacement	1	
Vibration Reduction		1
Reusable Energy Supply	1	
Condition Monitoring Sensers	· · · · · · · · · · · · · · · · · · ·	7
Sporting Goods		
Smort Skis	1	1
Tenais Rocquets	7	7
Golf Equipment	7	1
Boseball Bats, Hockey Sticks	~	7
Medical Devices		
Ultrasound Imaging	√	1
Self-Powered Pocemaker	√	······
Defense		
Vibration Suppression		1
Active Structure Control	7	7
Soner, Hydrephones	4	1
ke Thickness Sensing	7	
Acovstal Devices		
Audio Reproduction	√	
Electronic Equipment	7	
Acoustic Suppression		7
Sensing		
Level & Weight Sensors	1	1
Non destructive Testing	7	1
Smort Bearings	7	7

Applications tested with PZT fiber composites. (Ruddle, Cass, & Mohammedi, 2007)

System Design

For the purpose of energy harvesting and storage, shoe or sneaker insoles are a good source of mechanical stress, deformation and vibration when a person is walking or moving his/her feet. With this method, waste ambient mechanical energy was converted to electrical voltage through a unique energy harvesting circuit; an overall energy harvesting model is shown in Figure 14 to explain implementation steps and potential applications. The circuit was designed and developed according to the ambient source PZT ceramic fiber composite, and load constraints in order to have the best efficiency and output power. The energy harvesting system is capable of capturing even very small stress and vibrations, then converting them to electric power sufficient to run low power electronic systems. According to test results which were reported by ACI, PZT fiber ceramic products are extremely durable. For example, cycle tests with one billion cycles had no degradation of properties and efficiently generated 145mW continues power (Advanced Cerametrics Incorporated, 2007). Moreover a unique inter-digital electrode developed by ACI to align the field (energy harvesting circuit) with the fibers was used in the present study to obtain maximum efficiency from PZT fiber material.

Expected Results

Incorporating tests by ACI and the aim of this research study the analogy below shows that the generated power would be sufficient for low power electronics. For example harvesting of vibrations was demonstrated by the company as follows: Light vibration= 2.8mm at 22Hz, created output voltage= 510Vp enables 400µF capacitor bank to be charged to 50V in about 4 seconds.

Taking this test results into consideration the energy would be;

$$E = \frac{1}{2}C.V^2 = \frac{1}{2}(400\,\mu F)(50V)^2 = 0.5J\tag{3}$$

Then 0.5J energy would allow having 1/8W (0.125W) power in 4 seconds

$$P = \frac{d}{dt}E = \frac{E}{\Delta t} = \frac{0.5J}{4Second} = \frac{1}{8}W(0.125W)$$
(4)

It is assumed that 125mW power would be sufficient to power a variety of wireless or portable electronics applications such as MP3 players, cell phones, and small GPS units. For each electronic application different design considerations are needed to meet technical requirements of the device. Based on the implementation test results and output power, applicable electronic applications would be suggested. The energy harvesting system was tested to measure efficiency of the system.

Test Applications

- (a) To power some microcontroller applications from "microchip" uses only a few miliwatts (even sometimes less than 1mW);
- (b) Using the above low power microcontroller architecture harvest energy via footsteps, then store energy in supercapacitors or rechargeable battery;
- (c) Low power micro does some functions such as data logging with periodically waking up either with each footstep or a timer; and
- (d) The wearer of the device passes or stops at a station with an RFID transceiver. This can wake up the microcontrollers which then send/receive their data over a RF data link. During this operation, the microcontroller can be powered by stored energy.



Figure 14: Overall energy harvesting model from shoe sole

Chapter Summary

Three different mechanisms with three different energy harvesting circuit designs were examined. It was anticipated that possibilities of overall dependence on ambient energy resources may remove some constraints required by limited reliability of standard batteries. Moreover, ambient energy harvesting can also provide extended life span and support to conventional power systems.

Ambient energy harvesting systems represent a fruitful area of research and created possibilities by the convergence of miniaturization of the components used, lowpower system designs, and developments in materials and mechanical systems. Special attention in this study was given to overall components and applications of the energy harvesting system to increase its overall efficiency and decrease power consumption of the application; this increases output capability of energy harvesting systems. The brand new class of components such as piezoelectric materials, switching regulators, batteries, and supercapacitors were either designed or purchased to develop an efficient ambient energy harvesting system. Three different energy scavenging systems were developed as an additional research effort to the systems that have already been developed and can automatically run efficiently by just adding an energy scavenging module. Furthermore, for the optimal efficiency of the energy system, very careful considerations were given from design of the architecture to power management at the application level.

CHAPTER IV

RESULTS

Energy Harvesting From Hydraulic Door Closer

Hydraulic Door Closer Mechanism

The hydraulic door closer was the first source of ambient energy scavenging systems used in this study. For the purpose of this experimental study, two hydraulic door closers were secured from the Physical Plant at the University of Northern Iowa. Hydraulic door closers were separately mounted on wood structures to represent operation of the door opening/closing system. For the hydraulic door closer functionality, human acting is required. For this study, the arms of the hydraulic door closers were moved by hand to represent an opening/closing phase of the door by human power. A door closer which is mounted on the wood structure for testing purposes is shown in Figure 15, which shows the mechanical energy source within a circle. There are two phases of the door system operations: the first phase is the opening phase that is generally activated by human power; the second stage is the closing phase that is controlled by a spring and a hydraulic damping mechanism. In the first phase the arm of the door closer was moved up to 90 degrees with constant speed to represent the opening stage of the door (the reason of rotating the arm 90 degrees is to simulate the maximum angle that the door can be opened in reality).



Figure 15: A Hydraulic door closer

The opening/closing angles of the door may differ between 0° and 90° degrees depending on human size and the mechanical speed adjustment of the door closer. Another consideration of the system was the closing phase of the door. Since door closing is controlled by an internal spring and hydraulic damping mechanism, the closing speed of the door was adjusted through the hydraulic door closer. The photographs of the opening and closing phases of the hydraulic door closer system are shown in Figure 16 with almost 90° opening/closing angles. Also the opened position of the door with a hydraulic door closer assembly representation is characterized in Figure 17 to ease understanding the mechanical system.





Half-Open



Opened

Figure 16: Opening/closing phases of the hydraulic door closer



Figure 17: Opening/closing phases of door mechanism
A gear box with 1/256 speed ratio could not be located in the market, and manufacturing the gear box alone would be too costly for the scope of this research. Two different gear boxes with speed ratios 1:344 and 1:64 were found and tested. The simulation of models for each gear boxes were created and validated against the test results. The number of gears in the simulation model has been used to accommodate the new speed ratios.

For Gearbox 1:

$$\rho_{all} = \rho_1 \cdot \rho_2 \cdot \rho_3 \cdot \rho_4 = \frac{1}{4} * \frac{1}{4} * \frac{1}{4} * \frac{1}{4} * \frac{1}{5.375} = \frac{1}{344}$$

For Gearbox 2:

$$\rho_{all} = \rho_1 \cdot \rho_2 \cdot \rho_3 \cdot \rho_4 = \frac{1}{4} * \frac{1}{4} * \frac{1}{2} * \frac{1}{2} = \frac{1}{64}$$

Speed Increase Gear Set

As explained earlier the speed increase gear set system was designed and the purchased plastic gear sets were tested with MSC.Easy5 advanced simulation program. The role of the speed increase gear sets was crucial to increase the speed of rotation that was generated from the hydraulic door closer to provide sufficient input speed to a DC generator (mechanical to electrical energy conversion unit). This step up in speed was necessary, because without the increase of speed, rotation speed from the hydraulic door closer is not sufficient for the electric generator to provide enough voltage for the energy harvesting system. In fact, initially the engineering design of the speed increase gear box was modeled using Pro Engineer Wildfire 2.0 with real dimensions of all components. However, due to the high cost of steel gears, and manufacturing difficulty of the gearbox

it was decided to purchase different types of plastic gear boxes with different speed ratios. The initial Pro Engineer Wildfire 2.0 model of gear train components including the generator, gear box models, and energy harvesting circuit assembly is shown in Figure 18. The different gear boxes that were purchased for speed increase purpose actually were designed as speed reduction purpose gear boxes to decrease high speeds to lower speeds with the different assembly techniques. By changing the positions of gears and shafts, speed reduction gear boxes were converted to speed increase gear boxes. So these gear boxes were modified to be powered with mechanical energy (human power) instead of electrical energy in order to increase the mechanical speed.



Figure 18: Pro Engineer assembly model of the energy harvesting system

The picture of the unassembled gearbox components and the assembled speed increase gear boxes are shown in Figure 19 and Figure 20 respectively. Also specifications of speed increase gearboxes are listed in Table 7. Each gear box had different interchangeable speed ratios and assembly techniques specified by manufacturer data sheets. The assembly of the gearbox components was built by choosing the highest speed ratios to provide sufficient input speed to the generator unit. However, some gears in the gearbox were broken during testing process due to high reverse torque and the nature of the gears. In that case speed ratios were reduced to decrease the torque that applied to the shaft of the gear boxes. These gear boxes then were mounted with metal joints to the hydraulic door closers where waste rotational mechanical energy was captured during the opening/closing operations of the door closer.



Figure 19: Gear box components



Figure 20: Assembled gear boxes with generators

Table 7

Manufacturer s	pecifications of the	gear boxes			
Part Number	Part Name	Torque	Ratio	Rotation	
Tamiya #70167	Single Gearbox (4-Speed)	2276 gf⋅cm	1:344	1039 rpm	
Tamiya #72005	6-Speed Gearbox	2306 g·cm BROKE	1:1300 N DUE TO HIGH	870 rpm TORQUE	
Tamiya #72003	High Power Gear Box	784 g⋅cm	1:64	242	
Tamiya #70097	Twin-Motor Gear Box	N/A	1:203	N/A	

Gear ratios and the number of gear sets in gearboxes were determined by considering the average opening/closing angle, average speed of the door and the nominal input rotation required by the generator unit. Figure 21 depicts the gear train block diagram in

the gear box to represent increasing gear ratio steps on the shafts until the generator input is reached. This block diagram was intended to show a 1:4 gear ratio where the output speed would be four times the input speed. Adding /removing or changing the positions of the gear sets in the gear boxes changes the output speed ratio to supply sufficient speed to the generator.



Figure 21: Speed increase gear box block diagram

Generator Unit

The first phase of the project was to design an appropriate gear box to increase the speed of rotation so that it could provide sufficient rotation speed for the generator unit. Here the generator units of two different types of permanent magnet direct current (PMDC) electric motors were selected and tested because of their power generation efficiency for low power electronic applications. The photograph and their basic specifications are shown in Figure 22. These generator units were connected to output shafts of gear boxes to gain enough speed to generate electricity and test the overall system.



Figure 22: Generator units (DC motors)

The faster the generator turns, the higher the output voltage that is generated as seen in equation;

 $V = kn\phi$

where

V =Induced voltage;

K = Machine coefficient;

- N =Rpm (rotation per minute);
- ϕ = Magnetic flux.

Three different types of generator units were used to test the power generation accuracy. These DC motors as generator units are listed in Table 8 with their different specifications. The input rotations and power generation of the generator units were important facts due to constraints and nature of input rotation from hydraulic door closer. Increased rotation supplied to the generator unit makes the output voltage increase.

Table 8

Motor Type	Operating Range (V)	Speed (rpm)	Current (A)	Torque (mN·m)	Torque (g·cm)	Output Power (W)
FA-130RA	1.5-3	9100	0.20	0.59	60	0.43
RE-260RA	1.5-3	6300	0.16	0.97	9.9	0.56
RC-260RA	4.5-6	9800	0.14	1.48	15.1	1.20

Three different generator specifications

These motor specifications were either taken from data sheets or requested separately from the motor manufacturers to make accurate simulations. Power, torque, and speed constraints were very important to consider because of the relationship to measure power loss between them. Moreover, depending on motor specifications, voltage could not be induced until specific rpm (rotation per minute) took place because electrical machines start inducing voltage after specific speed ratings are achieved. So, depending on the speed and rotation specifications, generators may start to generate electricity after specific speed limits. The graphs of the relationship between power-torque, and speedload (current) are shown in Figure 23.



Figure 23: The relationship between power-torque and speed-load

As indicated in the graphs, when the speed of the generator increases accordingly the power and voltage increase. To run the generator fast and gain more voltage, a higher gear ratio is needed. On the speed-load graph, when the generator starts charging a battery, the load increase slows down generator speed in rpm. Therefore every effort to increase the speed is mandatory.

Storage Unit

Usually, any device which operates on battery power does not use one cell at a time. Batteries are grouped together serially to yield higher voltages or in parallel for higher currents. In a serial battery connection, the voltage value adds up. For the purpose of energy harvesting from the hydraulic door closer, only small range (1.2V and 3.6V) rechargeable batteries are used for test purposes. According to the electronic application device needs, battery current and voltage can be adjusted by serial and parallel connections. For example a device uses four nickel-cadmium batteries that are rated at 1.25 volts and 500 milliamp-hours (mAh) for each cell.

The mAh (current ampacity) rating shows, theoretically that the cell is able to produce 500mAh. A 500mAh battery can supply;

 $5mA \rightarrow 100$ hours; $10mA \rightarrow 50$ hours; and $25mA \rightarrow 20$ hours.

However, batteries are not quite linear energy producing storage devices. Almost all batteries have maximum current levels which can produce power. For instance a 500mAh battery can not produce 30mA for one second, because the battery's chemical reactions do not happen that quickly. In addition, at higher current levels, batteries can produce a lot of heat, which wastes some power of the battery. In normal cases mAh ratings are considered linear over a normal range of use. Using the amp-hour (Ah) rating, it is possible to roughly to estimate how long the battery will last under a load. The rechargeable battery type selection for our research was very difficult because of the charging time, charging source, and leakage rate constraints. After careful considerations different types of rechargeable batteries were purchased from different manufacturers. The pictures and basic specifications of the rechargeable batteries are shown in Figure 24. Also the specifications and cost of the rechargeable batteries are listed in Table 9.

In such batteries when produced energy drops below optimum efficiency, they are charged by the generator unit, energy harvesting and battery regulation circuit. The battery regulator in the energy harvesting circuit was designed and built to respond to the battery charge level and to keep optimum efficiency. In this experiment mostly Nickelcadmium batteries were chosen for testing because they contain cadmium and have relatively low capacity when compared to other rechargeable battery systems.



Figure 24: Rechargeable batteries and basic specifications

Table 9

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					Charge		Quick Charge		
Туре	Manufac.	Part #	V	mAh		Time	(mA)	(h)	Price
NICD	Panasonic	P-11AA/FT	1.2	110	11	15	27.5	6	\$3.10
NICD	Ps Sonic	PS-AAA	1.2	250	25	15	66	4.5	\$1.87
NIMH	Ps Sonic	NHB80	1.2	80	8	15	N/A		\$1.20
NIMH	Varta	G14762	2	15	N/A	N/A	N/A	5 e 1	\$1.00
Wafer Thin	Kanebo	G13133	3	N/A	N/A	N/A	N/A		\$.85
NICD	Various	3N60BCT	3.6	60	6	14	20	7	\$3.49
NIMH	Daytona Industry	COMP-16-3	3.6	60	6	14	20	7	\$2.75
NICD	Sanyo	N-110AA	1.2	110	11	14-16	33	4-6	\$1.95
NICD	Sanyo	N-110AAT	1.2	110	11	14-16	33	4-6	\$2.25

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In most of the low power applications, NICD are batteries widely preferred and used because of their performance characteristics and suitability. The NICD batteries used in mobile devices are small, not heavy, and operate in every position. NICD rechargeable batteries supply high operation current and despite their small dimensions provide considerable output. The nominal cell voltage of NICD battery is 1.2V which is enough voltage level for low power electronic applications. NICD batteries are mostly used for general consumer electronics such as portable audio equipments, toys etc. NICD batteries are also sold at low cost which is cost friendly for low power energy harvesting systems. Rechargeable batteries such as coin or button cells, and battery packs were also purchased for test purposes within our energy harvesting system. However these types of batteries were not able to charge because of their complex characteristics. Also two types of NIMH rechargeable batteries were purchased for the test purposes. NIMH batteries are usually used for cell phone, laptop and electric/hybrid automobile applications.

Before any design consideration of the energy harvesting circuit was made, the characteristics of the aforementioned rechargeable batteries were studied. As already known, power is defined as the rate of transforming energy to the load. So, energy is the resource and power is the rate of consumed energy (Harrison, 2004). The relation of energy and power for the energy harvesting system in hydraulic door closer experiment was calculated below.

Joule (J) = unit of energy (5)

$$1J=1N.m=1kg.m^2/s^2=1V.C=1W.s$$

Watt (W) =unit for power (6)
 $1W=1J/s=V.C/s=V.A$

In the above equations, it was considered that a 1 Watt electronic system consumes 1 Joule of energy for every second. For our purpose, in the energy and battery switching circuit, the watt-hour (Wh) term was used as a unit of energy other than using joule (wattsecond). The reason behind this idea is that most of the electronic devices operate at hour base not seconds.

$$1J = 1W.s = 1.16X10^{-5} W.h$$

1W.h = 3600 Joule

So, for one hour operation of the electronic system at steady state and 1W rate, 3600J of energy is needed. This power-energy relationship is not accurate all the time because all batteries have a finite internal resistance (R_{int}). This may cause the terminal voltage to drop as more current is drawn. Most commercially available batteries are manufactured for low power applications and have no large internal resistance. Depending on the application, the current level can be fixed to avoid damaging and poor performance of the rechargeable battery. The internal resistance of the typical NICD battery is 0.009 ohm, and for the NIMH 0.03 ohm (0.040hm at 50% discharge) which are not negligible for our experiment because of the battery. Internal resistance generally increases as the battery discharges. The important feature and characteristic of NIMH battery is that they stay at about 1.2 V for most of their discharge cycle (in contrast to other batteries). This is an important feature for some applications which need accurate voltage levels in order to operate accurately. A 1.2V NIMH rechargeable battery starts with R_{int} =0.03 ohm, but at 50% discharge, R_{int} increased to R_{int} =0.04 ohm. A 1.2V NICD battery has capacity of 110mAh @ 11mA; 250mAh @ 25mA; and 80mAh @ 8mA. All these specifications are

considered at the battery test section of the hydraulic door closer energy harvesting application.

Overall System Analysis with MSC. Easy5

The overall energy harvesting system with real data including speed increase gear sets, generator unit, energy conditioning circuit, and battery simulations were conducted using the MSC.Easy5 ® advanced simulation and analysis tool. Specifications and characteristics of the generator unit, and battery were taken from manufacturer datasheets in order to be consistent with experimental implementation. In the following paragraph overall system analyses with MSC. Easy5 are explained in detail. The analysis results were compared with outputs in order to measure if efficiency of the system reached expected performance.

The MSC. Easy5 engineering analysis system was the base system for overall analysis of the generator unit, gear train, battery unit, battery controller/power converter, and bus connector units. The above components were required for the system analysis and were available within the MSC. Easy5 Ricardo Power Train library-version 5.1 (PT). The library components were MO-Motor (Generator), BA-Battery, BC-Battery controller/Power converter, and BX-Bus Connector. The parameters and specifications were studied separately to be consistent between the connections of the components. The Ricardo PT library had general components and general specifications were input by the software company automatically. General specifications of the PT library modules were intended for high power applications such as automobile technology, mechanical and electrical systems and hybrid vehicles. Therefore all specifications of the generator, battery, and gear train were altered according to manufacturer specifications of components purchased for the energy harvesting system. Also, the idea of the hydraulic door closer energy harvesting system model was represented on the MSC. Easy5 interface. Initially, it was assumed that the door was opened 30 times (each door opening is 180°, i.e. half cycle) in a minute which is 15 rpm. The specific gear train increased the speed from 15 rpm to 5160 rpm to meet input requirements of the generator unit for consistent electricity generation through a DC electric motor. The interface of the overall analysis is shown in Figure 25. The system was run 3600 seconds/hr and after running test results for input speed, output speed, and state of the battery charge in the analysis were indicated in Figures 26, 27, and 28 respectively.



Figure 25: The MSC. Easy5 model analysis simulation interface

Input speed of the speed increase gear train analysis for the gear box depends on initially 15 rpm and is shown in Figure 26. Figure 27 shows the result of the output speed in gear train analysis. Each of the plots for the speed increase shows increase at the first and last shafts within the given time period. By changing the gear and shaft positions, speed can be decreased or increased if the generator unit and the battery specifications are changed.



Figure 26: Initial speed in the gear train analysis simulation for 1:344 ratio



Figure 27: Output speed in the gear train analysis simulation for 1:344 ratio

The output plots show the consequent increase of speed from 15 rpm to 5160 rpm at 1:344 speed ratio. Once this input speed is applied to the generator unit the state of battery charge starts to increase consequently. The overall system is run for one hour to see if battery capacity is increasing. Simulation results showed that it takes approximately

16 hours to charge a fully discharged battery. The state of the charge of the battery unit is shown in Figure 28. The system should run about 16 hours in order to receive a fully charged phase of the battery. But again depending on battery characteristics, charging time may change.



Figure 28: Battery state of charge with 1:344 ratio

Since we had another gearbox with 1:64 gear ratio, the simulation analysis was conducted to study the battery state of the charge ratings. It was expected that the charge time would be increased before the MSC Easy5 analysis of the system. As expected the charging time of the same battery was increased because of the low gear ratio. Input and output speeds of the gear train with 1:64 ratio was shown in Figure 29 and Figure 30. Initial speed of the gear train was configured as 15 rpm and the output speed reached 960 rpm as an input speed to the generator unit.



Figure 29: Initial speed in the gear train analysis simulation for 1:64 ratio



Figure 30: Output speed in the gear train analysis simulation for 1:64 ratio



Figure 31: Battery state of charge with 1:64 gear ratio

The battery charging graph in Figure 31 shows the consequent increase of the battery capacity at the 1:64 speed ratio. The overall system is run for one hour to see if battery charging is increasing. Simulation results at the 1:64 ratio showed that it takes approximately 140 hours to charge a fully discharged battery. Thus the 1:64 ratio it is not feasible to use this method to power a low power electronic application. The system would need to be run for 140 hours in order to achieve a fully charged phase of the battery.

Energy Harvesting Circuit Design

Since harvested energy manifested itself in irregular, random, low-energy bursts, a power-efficient, discontinuous, intermittent battery charger circuit was required to

transfer the energy from the source of energy devices to the rechargeable battery. A Linear technology based power harvesting and conditioning circuit was built to implement and regulate energy conversion and battery charging. This circuit which was designed to handle the source power regulated the voltage level from the generator unit to charge 1.2V and 3.6V rechargeable batteries for low power electronic applications. Before implementation of the experiment, necessary computer simulations were conducted with LTSPICE Switcher CAD III advanced simulation tool. In the following sections, bridge rectifier, switching and charging circuit, printed circuit board (PCB), overall circuit and simulation test results are explained consequently.

Full Wave Bridge Rectifier

The noisy AC voltage output of the generator unit was rectified by a full-wave bridge rectifier circuit that includes four Schottky diodes and capacitors connected to the cathode of the diodes to filter a rectified voltage output of the latter. The reason for using Schottky diodes was lower energy requirements to operate when compared with typical diode. Schottky diodes need a forward voltage of 0.4V instead 0.7V to operate within a circuit. A rectifier circuit was mandatory to convert noisy AC output voltage from the generator to DC voltage because almost all electronic components operate at DC voltages. For test purpose a fairly stable DC voltage signal was measured after rectification.

In Figure 32, a bridge rectifier testing interface is shown. This test was conducted using the MultiSIM electronic circuit design and testing tool. The following input parameters were used to represent characteristics of the energy source and generator unit. Source voltage changed between 0V-3V with 500Hz frequency.



Figure 32: Full-wave bridge rectifier circuit testing

Since there are four diodes at the output, the voltage reading was decreased 1.6V which is equal to four Shottky diodes' forward voltage. The AC voltage signal from the generator unit and converted DC voltage signal using full-wave bridge rectifier is shown in Figure 33. The average value V_{do} (where the subscript o stands for the idealized case) of the DC output voltage in both circuits can be obtained by assigning an arbitrary time origin t=0 and then integrating (V_S =source voltage) $V_{do} = \sqrt{2}V_S \sin wt$ over one-half the time period (where $w = 2\pi f$ and $wT/2 = \pi$). The output voltage from the generator was an average of 1.5V_{AC} then rectified to DC voltage using the equations below.

$$V_{do} = \frac{1}{(T/2)} \int_{0}^{T/2} \sqrt{2} V_{S} \sin wt dt = \frac{1}{wT/2} (\sqrt{2} V_{S} \cos wt |_{T/2}^{0}) = \frac{2}{\pi} \sqrt{2} V_{S}$$
(7)

Therefore,

$$V_{d0} = \frac{2}{\pi} \sqrt{2} V_S \tag{8}$$

The equations show the output DC voltage after rectification of AC voltage as:

$$V_{d0} = \frac{2}{\pi} \sqrt{2} * 1.5 V_{AC} = 1.4 V_{DC}$$



Figure 33: Sinusoidal AC and DC voltage after rectification of signals from generator

The $1.4 V_{DC}$ is the output voltage without applied losses through the Schottky diodes. Losses through Shottky diodes during rectification are applied at the equations listed below to calculate pure output DC voltage level before adding the Boost converter and regulation circuit.

$$V_{d0} = 1.4V_{DC} - (0.4) * 2 = 1.4V_{DC} - 0.8V = 0.6V_{DC}$$

Boost Converter and Battery Charging Circuit

The energy harvesting circuit board was designed, built, and simulated using SwitcherCADTM Spice III simulator from Linear Technology. After full-wave rectification, where alternating current (AC) was converted to direct current (DC), the voltage was increased by a DC-DC boost converter. A capacitor (represented by r on Figure 34) was placed between rectifier circuit and the DC-DC boost converter circuit as a temporary storage. This capacitor allowed measurement of voltage and current levels after full-wave rectification. As an intermediate storage device another capacitor (represented by x on Figure 34) was placed to measure gained power after the boost converter integrated switching regulator. Placing intermediate capacitors eased the measurements of the voltage and current overall circuit for efficiency control. Since the source voltage was not at steady state and low, the boost converter was chosen considering this important and challenging point.



Figure 34: Energy harvesting simulation interface with SwitcherCADTM Spice III

Also the generator unit (DC motor) is configured to act as a non-continuous voltage source in order to test the energy harvesting circuit with generator and human power source characteristics. The generator unit was configured to act between 0V-3V to represent the hydraulic door closer opening/closing phases to produce electricity at both phases of the door closer. This configuration may not fit a real life door opening/closing phase because of the different speed ratios depending on human power and different opening angles of the door. Figure 35 shows the SwitcherCADTM Spice III simulation configuration for the generator unit.



Figure 35: Generator unit configuration for the energy harvesting circuit simulation

Consideration of energy harvesting components resulted in the decision to integrate an LTC3429 integrated circuit regulator chip which only needed 0.8V threshold input voltage to start running its components. The actual energy harvesting circuit design is shown in Figure 36. Since the generator unit in this experiment generated electricity up to 0V-3V AC, the voltage was configured to vary from 0V to 3V in the simulation interface. The frequency required for the circuit trigger was defined as 500Hz. The SwitcherCAD III simulation tool provided an advanced simulation toolbox which allowed simulating each component's voltage and current levels on the circuit. This way, it was possible to confirm voltage or current levels anywhere on the circuit during the simulation.



Figure 36: Energy Harvesting Circuit with DC-DC boost converter

In order to make the circuit act according to the input and output voltage and current characteristics, replacement values of the capacitor and resistor are needed. Since we have rechargeable batteries were used which need 1.2V and 3.6V voltage input to increase and then fix the voltage level at 1.2V and 3.6V (required for the 1.2V NICD and 3.6 NICD rechargeable batteries), the following calculations were done to determine resistor values for the boost converter unit.

$$V_{OUT} = 1.23V [1 + (R1/R2)]$$
 (9)

where

V_{OUT} =Battery charging voltage;

- 1.23 =Manufacturer constant;
- R1 =Resistor value;
- R2 =Resistor value;

In the first case to charge a 3.6V at 60mAh NICD battery,

R1=194kohm,

R2=100kohm, and

1.23V [1+(194k/100k)]=3.61V (3.6V).

Because of the voltage drops and leakages on the energy harvesting circuit, V_{OUT} (battery charging voltage) was increased and adjusted as 3.8V to avoid low power supply to the battery.

To increase voltage to V_{OUT}=3.8V

R1=209kohm,

R2=100kohm, and

1.23V [1+(209k/100k)]=3.8007V (3.8V).

The output current for the battery charging then was

I_{OUT}=16mA at R=220ohm load.

So, 16mA current is needed for the standard charging of the 3.6V rechargeable battery in 10 hours. Critical circuit components such as input voltage, output voltage, and output current was implemented and screen shots are shown in Figures 37, 38, 39, and 40 respectively.

V_{IN}: Input voltage before boost converter (after rectification)

I_{ROUT}: Output current for the load (battery charging current)

V_{OUT}: Voltage level after boost converter (battery charging voltage)



Figure 37: Input voltage (V_{IN}) simulation

In Figure 37 V_{IN} , input voltage simulation output is shown. This voltage level is measured after rectification of the AC voltage which is produced by the generator unit to DC voltage for the boost converter and the regulator circuit. Initially, it increased to 1.3V and then kept around 1.3V based on generator characteristics. Figure 38 shows the V_{IN} and V_{OUT} (charging voltage after boost conversion and regulation) which were compared to see the voltage difference and regulation. Both voltage levels stayed at the constant steady level. V_{IN} should be not less then 0.8V for the boost converter integrated circuit. If V_{IN} drops under 0.8V then the boost converter is not able to generate any voltage level for the battery charging. Any voltage level bigger than 0.8V makes the boost converter operate and charge the battery at nominal voltage level.



Figure 38: Input (V_{IN}) and Output (V_{OUT}) voltage simulations

In Figure 39, I_{ROUT} (battery charging current) and V_{OUT} (battery charging voltage) are compared. Both voltage and current levels are constant and charging the battery. $I_{ROUT} =$ 16mA which is a normal charging current for the battery and $V_{OUT} =$ 3.6V nominal charging voltage. Both values are nominal values according to the 3.6V rechargeable battery specifications.



Figure 39: Battery charging voltage (V_{OUT}) and current (I_{ROUT}) simulations

In Figure 40, all three important parameters of the energy harvesting circuit were simulated at the same time to show consistency of voltage and current levels on the circuit design. It is observed that input voltage V_{IN} waves a little bit because of the non-constant output voltage from the generator unit (which is absolutely normal according to hydraulic door closer characteristics).



Figure 40: Simulation of critical parameters for battery charging

Simulations were conducted to charge a 3.6V battery. Since the voltage level will not be appropriate for a 1.2V battery a DC-DC buck converter integrated circuit was used to decrease the voltage level to charge a 1.2V battery. In this case a LTC3409 linear technology based DC-DC buck converter is used to decrease the 3.6V level to a 1.2V charging voltage. The DC-DC buck converter circuit to charge a 1.2V battery is shown in Figure 41. Moreover the following calculations were done according to the LTC3409 data sheet and characteristics.



Figure 41: Energy Harvesting Circuit with DC-DC buck converter

In the second case to charge a 1.2V at 110mAh NICD battery and to calculate output voltage of the circuit, the fixed voltage at 1.2V at 12mA constant charge the battery was calculated.

$$V_{OUT}=0.613 (1+R1/R2)$$
 (10)

where

V_{OUT} =Battery charging voltage;

0.63 =Manufacturer constant;

R1 =First resistor value;

R2 =Second resistor value;

R1=294kohm and 400kohm;

R2=309kohm;

$$V_{OUT}=0.63(1+294k/309k) = 1.2V$$
 at 12mA; or

$$V_{OUT}=0.63(1+400k/309k)=1.4V$$
 at 14mA.

To increase or decrease output current of the circuit when the battery charging specification changes basically R1 and R2 resistor values are changed to change the output current at the fixed voltage level. As mentioned above just by replacing the resistor and capacitor values without changing the overall circuit it is possible to charge any type of small range battery units for low power electronic applications. Critical graphs of values such as input, output voltages and charging current in Figure 42 were simulated for a 1.2V charging voltage.



Figure 42: Simulation of critical parameters to charge a 1.2V at 12mA battery

According to Ohm's law when charging current increases, it causes voltage increase which was not possible in this study because of the non-constant and low energy source. But the range between 10mA-16mA was suggested by the battery manufacturer as a normal charge current. If higher and non steady current levels are applied then it would affect the chemicals of the battery. In this case our battery charging circuit kept charging the battery at fixed current levels.

Charging Current Adjustment

For the charging circuit adjustments the manufacturer of the DC-DC boost and buck converter datasheet has been used for the equations. For output current adjustment the following calculations were done and applied to the circuit components as specified in the switching regulator and battery charging integrated circuits. The following output current is conducted at 3.6V charging voltage.

$$I_{OUT(MAX)} = \eta * \left(I_P - \frac{V_{IN} - D}{f * L * 2} \right) * (1 - D)$$
(11)

where

- η = estimated efficiency;
- I_P = peak current limit value (0.6A);
- V_{IN} = input (battery) voltage;
- D = steady-state duty ratio = $(V_{OUT} V_{IN})/V_{OUT}$;
- f = switching frequency (500kHz typical); and
- L = inductance value.

In order to produce 16mA,

$$I_{OUT} = 90 * \left(0.6 - \frac{1.3(3.6 - 1.3)/3.6}{500 * 4.7 * 2} \right)$$
$$= 90 * \left(0.6 - \frac{1.15}{4700} \right) = (0.6 - 1.91) = 16mA$$

PCB (Printed Circuit Board) Design

After the energy harvesting circuit on the bread board had been built and developed for the troubleshooting and test purposes a PCB (Printed circuit board) was

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designed and ordered from Express PCB manufacturer. The PCB design dimensions were small enough to fit or mount to the hydraulic door closer if needed. Then surface mount electronic components (which are usually smaller than typical components) were soldered to the PCB under a microscope due to small sizes of the parts. The PCB layout of energy harvesting circuit is shown in Figure 43. Both DC-DC boost and buck converter circuits were merged to one layout of PCB to supply 3.6V and 1.2V depending on battery specifications.





There were two software tools employed to build the energy harvesting printed circuit board. The CAD software included ExpressSCH for drawing schematics and ExpressPCB for designing the printed circuit board. These two software tools were used in order to create an energy harvesting circuit including the boost and buck converter circuits. The following steps were used to design, develop and manufacture the energy harvesting PCB.

(a) Energy harvesting circuit schematic was drawn using ExpressSCH;

(b) ExpressPCB was used to layout the PC board with real dimensions of surface mount components. Dimensions of components were driven from data sheets;(c) A schematic of the circuit was linked to ExpressPCB, to have a guide through the wiring process;

(d) When the layout was completed with all the components, the exact cost was determined with the "compute board cost" command to order the PCB from Express PCB. The cost was \$59.94 for three similar PCBs.

The schematics for both boost and buck converters capable energy harvesting circuits drawn on ExpressSCH are shown in Figures 44, 45.



Figure 44: Energy harvesting schematic including a DC-DC boost converter



Figure 45: Energy harvesting schematic including a DC-DC buck converter

Testing & Verification

Initially all batteries were discharged with different resistors connected to battery terminals. All batteries were discharged almost (but not exactly) to 0V. If a battery is fully discharged then there would be a possibility that it can not be charged again. For this reason resistor values were chosen very carefully and measured during the discharge process to avoid having fully discharged batteries. Before measuring voltage levels of the batteries they were put in a refrigerator for about 30 minutes to stop chemical reactions inside the battery caused by room temperature. Measurement results observed before stopping chemical reactions were not accurate and were rapidly changing on the measurement tool screen. The discharging process of batteries on the breadboard is shown in Figure 46 with different resistors.



Figure 46: Discharging of batteries with different resistive loads

At the mechanical part of the system, gearboxes with electric generators were connected to the hydraulic door closer. Then the hydraulic door closer was mounted to wood structures and fixed to the table with tightening clamps to avoid travel of the hydraulic door closer when operated by hand. The circuit and measuring tools were placed near the hydraulic door closer to permit observation the voltage and current output as the door closer levers moved. General and initial specifications of gearbox ratios, generators, and batteries are given in Table 10. Data of discharged batteries are also included in this table for comparison with the test results table. The door closer was moved by hand a number of times, then the battery voltage levels were recorded; they are displayed in Table 11 for comparison. The range used for measuring the battery voltages was after thirty times opening/closing cycles. The door opening stage was conducted to represent 180 people opening the door. So, measurement of the batteries was recorded six times for each of thirty runs representing human power used to open the door. Each battery was charged with a 1:344 gearbox ratio including the generator unit. Since there is a DC-DC converter and switching circuit after rectification of the AC signal, the high ratio gearbox was more reliable to reach minimum voltage level to keep consistent output voltage for the battery charging process. Both specification and test tables are considered together since data and specifications given in tables have connections to each other. The data are presented in Table 11 for six different battery types and their voltage increases. Test results in Table 11 concluded that there is a possibility to harvest energy from hydraulic door closer. There were 180 total runs representing about 180 people approximately who opened the door. The voltage level increased considerably when

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batteries were empty at the beginning. After a certain voltage level, the charge (capacity) level of the battery was hardly increased. This is normal according to the battery specifications in manufacturer's datasheets. For example to charge a typical fully discharged rechargeable battery, 10-15hrs is needed to reach its highest capacity at standard charge level. If the ideal case of charging a typical battery is compared with our case, a lot of door opening would be needed to make the battery fully charged. The photograph of the overall test system is displayed in Figure 47. Also the graphs of the battery charge voltage changes depend on the number of runs of the hydraulic door closer, and are shown in Figure 48.



Figure 47: Overall energy harvesting test system

Table 10

Part specifications and initial charge characteristic of the gearbox, generator, and batteries

harges	Final (V)	1.21	0.811	1.22	3.29	3.56	1.03	0.94
State of the C	Charge (mA)	12	25	11	15	16	12	11
Final Battery-	Charge (V)	1.4	1.5	1.2	3.6	3.7	1.3	1.4
Initial &	Initial (V)	0.021	0.022	0.13	0.870	0.52	0.191	0.036
se.	Time (h)	6	4.5	N/A	7	7	4-6	4-6
Quick Charge	Current (mA)	27.5	66	N/A	20	20	33	33
Standard Charge	Time (h)	15	15	15	14	14	14-16	14-16
	Current (mA)	11	25	8	6	6	11	11
Nom. Ampac. (mAh)		110	250	80	60	60	110	110
Nom. (V)		1.2	1.2	1.2	3.6	3.6	1.2	1.2
Manufac.		Panasonic (NICD)	Power Sonic (NICD)	Power Sonic (NIMH)	Various (NICD)	Daytona (NIMH)	Sanyo W/TAB (NICD)	Sanyo (NICD)
Generator Type (V)		RC-260 (1.5-3) FA-130 (1.5)						
Tested	Ratios (rpm)				1:344	[

Charging Current/Voltage: Fix output voltage and current levels from energy harvesting circuit to charge the batteries Battery initial voltage: The rechargeable batteries are discharged using resistive loads until some points to make tests Nominal ampacity: The output (nominal) capacity of the rechargeable battery when fully charged Nominal voltage: The output (nominal) voltage of the rechargeable battery at full load

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Table 11

Energy harvesting system battery charging test results

	T	L	53	62	68	64	59	60	60
	FINA	V	1.21	1.03	0.94	0.914	3.29	3.30	1.11
	ų	F					73	73	
0 runs	1801	>					3.62	3.56	
*6 = 18	un	Т	74	75	75	73	73	73	73
tuns= 30	1501	>	1.31	1.16	1.01	0.811	3.31	3.23	1.22
Fotal F V) Cemp (Ę	F	73	75	77	73	73	73	73
urement 7 Volt (asuring 7	120 ru	N	0.892	1.064	0.981	0.649	3.17	3.12	1.12
meası Me	E	T	73	75	75	73	73	73	73
for each	60 run 90 r	>	0.841	0.994	0.965	0.478	3.11	2.99	1.030
Runs		Ŀ	73	75	69	73	73	69	73
30		V	0.743	0.968	0.942	0.351	3.01	2.87	0.983
	Ц	Г	71	69	66	69	73	62	73
	30 ru	>	0.437	0.841	0.921	0.212	2.46	2.65	0.958
ery al	δĒ		55.4	57.2	59	57.2	44.6	48.2	59
Batte	v oitag Temp	N	0.021	0.191	0.036	0.022	0.870	0.52	0.13
set			-	5	3	4	5	9	2
Gears ratic Genera Battel			Ratio 1:344 FA-130 (1.5V)						







Figure 48: The voltage changes according to the number of hydraulic door closer runs

Overall Test Results

The following comparison between the number of people and battery charging time was conducted to show how many people are required to open the door in order to charge a fully discharged battery according to the typical battery charging specifications.

As calculated in above sections, opening the door takes about 1 second and the closing phase takes another second, so the total time it takes for an average person to open the door is equal to: 2 seconds. As seen, it takes 2 seconds in the case of a small generator with the gearbox which can generate nominal charging voltage and current. This means a typical battery is being charged for two seconds while a person is opening the door. In order to calculate the total number of people needed to open the door to make the battery fully charged, the following comparison was conducted.

Since 43200 seconds are needed to charge a typical battery at the nominal charging voltage and current for 12 hours. So the total number of door opening stages should be,

Number of
$$people = \frac{total \ charging \ time}{single \ door \ opening \ / \ closing}$$
 (12)
Number of $people = \frac{43200 \ seconds}{2 \ seconds} = 21600 \ people$

As calculated above 21600 people are supposed to open the door to make a battery fully charged. However, depending on the electronic application the number of people can be reduced significantly to overcome daily discharges of the overall application. The aforementioned calculations have been done according to the fully discharged battery but usually a battery comes fully charged. Moreover, the number of door openings can be

reduced also by increasing the charging current with integrating a high ratio gearbox and generator. The following electronic application example and estimations proved that a hydraulic door closer can be a viable energy source to power some electronic applications around the door. In the following application a wireless security camera system around the door is expected to have sufficient energy to fully operate according to the calculation done in the next section.

Self Powered Wireless Security Camera Application

A hydraulic door closer as an ambient energy source was considered as a viable energy source to make a wireless security camera self powered. It was expected that the source will generate enough power to run a wireless security camera around the door. It was proven above a hydraulic door closer was able to charge a small battery (depending on a sufficient number of people opening the door). The brief analytical battery charge time and number of door openings relationship were calculated above for a fully discharged battery. However, in the case of a low power wireless security camera, the battery initially starts operating in full charge. If daily charges will balance daily consumptions and the standard leakages of the low power wireless security camera system, then it can be said that the hydraulic door closer source is viable for this application. For this reason overall energy consumption and energy gained relationship estimates were conducted considering (E_1) as energy consumption and (E_2) as energy gained during a day/24hrs below. The analytical comparison between the energy gained from hydraulic door closer (E_2) and energy consumption and leakages (E_1) of a wireless security camera system follows:

$$E_{1 (LOSS/24HRS)} = (P_{BATTERY_LEAKAGE}) + (P_{HARVEST_LEAKAGE}) + (P_{SWITCH_MOSFET}) +$$

$$[(P_{WORKING}) * (T) * (P_{\# OF RUNS})$$
(13)

Where,

E _{1 (LOSS/24HRS)} :	Overall energy loss per 24 hours;
P _{BATTERY_LEAKAGE} :	Leakages of the battery (joule/hour*24 hrs);
P _{HARVEST_LEAKAGE} :	Discharge rate of the overall circuit components;
P _{SWITCH_MOSFET:}	Minimum stand by current consumed by the MOSFET;
P _{WORKING} :	Energy consumption of the wireless security camera for per
	run;
Т:	Time takes for per run of the system/second; and

 $P_{\text{\# OF RUNS}}$ Total number of runs of the system in 24 hours.

The equation above helps to calculate the overall energy consumption including the total leakages. Also, the equation below helps to calculate the total gained energy from hydraulic door closer source:

$$E_{2 (GAIN/24HRS)} = EG * NP$$
(14)

Where,

E _{2 (GAIN/24HRS)} :	Total energy recovered and stored from human power					
	through hydraulic door closer per 24 hours;					
EG:	Energy gathered for per person who opened the door					
	(energy per charge); and					
NP:	Number of the people opened the door in 24 hours.					

For this application the energy gained from a hydraulic door closer (E2) should be bigger than or equal to the overall energy loss (E1) in 24 hours (E1 \leq E2). Otherwise the wireless camera system will be operating inconsistently because of the lack of enough energy to run the application components. Another important point is to find out how much energy is recovered and stored from a person. An estimation equation of the stored energy for per person can be given as:

S=E (Joule) * P (per person) * T (hrs) * Time (one day/hrs)(15)

Where,

- S: Overall energy stored;
- P: Number of people a day;
- E: Energy recovered from one person;
- T: Time taken to store energy; and

Time: Time span for one day.

In order to calculate the total energy stored in a day (24hrs), it was considered that 1mJ energy could be recovered per person according to the equations 5 and 6. In this case the total energy stored in a battery can be calculated for 50 people as,

1mJ (person) * 50 people (per day) * One day (24 hours) * 24 hours, so

1mJ * 50 people = 50mJ can be stored per day.

For the purpose of estimation, the components of a wireless security camera were chosen and studied. The specifications of the wireless security camera components necessary to calculate the overall system energy gain and consumptions are given below. Also the self-powered wireless security camera system is explained and detailed with block diagrams. The microcontroller platform allowed us to propose the system in two different ways. The first way is to propose a system without transceivers just to store security camera surveillance information in the additional flash disk on the door. This way nothing will be transmitted to the host computer which is more energy efficient but may have security concerns keeping the data around the door. This idea may eliminate the transceiver unit to reduce energy consumption because a lot of energy is consumed by the wireless communication when transmitting and receiving data signals. A second way is to just transmit the data (captured pictures) using a wireless communication standard such as ZigBee (802.15.4) to the remote host computer where the data are stored. In the first approach the energy needed for the overall system is less than the second way and should be paid more attention since our power source is not constant and is limited with the small scale battery. However, for both ways the energy harvesting system would be enough if there is enough human presence and also depending on how often the camera takes and transmits the pictures.

The block diagrams of the devices for the door side and the computer sides for the overall self powered wireless security camera system are given in Figure 49 and Figure 50 respectively. The circuit (receiver) at the host computer can get energy from the computer ports without any other external power supplies. The only part of the system which needs to be powered is the electronic components at the door. After intensive market research, energy and cost efficient components to estimate energy consumption for a wireless security camera system were chosen and are listed below in Table 12. All the components in the diagrams are numbered and matched with the components in the table to ease the comparison and understanding the specifications.

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Figure 49: Wireless security camera system at the door site



Figure 50: Wireless security camera system at the remote host computer port

Table 12

Specifications of parts for self-powered wireless security camera

Total leakages & Stand-by currents	A N/A	rs ~432μA	rs ~288μA	rs ~4.8nA	ITS N/A	ITS OFF	A OFF	A OFF	ITS OFF	ITS OFF
Tin	N/	24h	24h	24h	24h	24h	Ń	Ň	24h	24h
Quiescent (Stand-by) Current & Leakages	N/A	~18µA*	~12µA	~0.4nA	~Varies	~50nA	N/A	N/A	~100µA	~2µА
Supply & Operating Currents	~0.20	~12mA	~110mAh	~3/-1.3mA	~Varies	~11µA	N/A	N/A	~60mA	~22mA
Voltage In/Out (V)	N/A 1.5V	1.2V	1.2V	0.7/-0.7	Varies (V _{our})	2V-5.5V	N/A	N/A	3.3V	0.3V-3.6V
Name	Tamiya Micromo motors	Linear Technology IC & Electronic components	Typical NICD	N-P Channels 585-ALD1115SAL	Linear Technology	PIC16F677-1/P	Integrated memory in Microcontroller	Integrated in Microcontroller	C328-7640 (S)	MRF24J40-I/ML
Part	Gearbox Generator	Energy Harvesting Circuit	Battery	Sensing Unit MOSFET	Voltage Regulator	Micro- Controller	Flash/EEPROM	CPU	Camera Module	Radio Transmitter
#	1	7	3	4	5	9	7	8	6	10

.

* Leakage into output of energy harvesting circuit from battery

The estimate of the overall energy leakages in 24 hours are calculated according to the specifications in Table 12. There are certain components in the system which are always at stand by either to sense the presence around the door or because of the nature of the part. These components drain some quiescent currents while they are on standby including MOSFET, energy harvesting circuit, and the battery to keep the system up and running. Before calculate the overall operating current for all components, the total leakages and quiescent current were calculated according to the equation 13.

$$E_{1 (LOSS/24HRS)} = (P_{BATTERY_LEAKAGE}) + (P_{HARVEST_LEAKAGE}) + (P_{SWITCH_LEAKAGE})$$

$$= [(288\mu A) + (432\mu A) + (4.8nA)]$$

 $=720.48 \mu A/24 hrs$

720.48µA was estimated standard leakage from the system at stand-by mode in 24 hours. The total leakages and quiescent currents were added to the operating currents in 24 hours in order to calculate overall energy consumption. The steps below indicate the order when a security camera is taking and sending a picture to the remote host computer.

Subject walks through the door

Activates energy harvesting circuit and MOSFET switches Charger charges battery and closes wake-up switch (Solid State MOSFET) Microcontroller powers up – closes the hold switch Microcontroller takes a photo with a camera module Transmits the photo remote host computer Microcontroller releases hold and powers down The typical system event as explained above takes three seconds to send a photo (the time increases if more photos are transmitted to the base station). The advantages of this are that the security camera system does not work during the day time and can be programmed only to wake-up and activate the system during the specific time periods in the night time. This makes the system more energy efficient and viable to operate at low power rates. The overall operating system estimation is given below assuming that the system was activated during the night time.

 $P_{WORKING} = [(P_{Microcontroller}) + (P_{Camera}) + (P_{RF Transmitter}) + (P_{MOSFET}*2) * (P_{Photo})] (16)$ Where

PWORKING	=Overall operating power for one object;
P _{Microcontroller}	= Energy consumption of microcontroller unit;
P _{Camera}	= Energy consumption of camera module;
P _{RF Transmitter}	= Energy consumption of transmitter;
P _{MOSFET}	= Energy consumptions for two switches (MOSFETs); and
P _{Photo}	=Number of photos for one object send to the computer database
culation of en	ergy consumption of the security camera system to transmit a phot

The calculation of energy consumption of the security camera system to transmit a photo for one object

$$P_{WORKING} = [(11\mu A) + (60mA) + (22mA) + (4.3mA^{*}2)^{*} (1)]$$

=90.11mAh energy is needed to send a photo.

The overall leakages and quiescent current for the system components during the system operation were calculated using Equation 13. Since $P_{WORKING}$ was calculated above separately and added to the overall energy consumption in 24 hours following,

$$E_{1 (LOSS/24HRS)} = [(288\mu A) + (432\mu A) + (4.8nA)] + [(90.11mA) * (1) * (3)]$$

= 273mA current is consumed to transmit a photo in 24 hours.

The calculated value for E1 is converted to the power value in order to make a comparison between the power gain and the power loss.

$$P_{1 (LOSS/24HRS)} = 0.2731A * 3.6V$$

= 0.983W

As calculated above the total power drained from the storage unit estimated as 0.983W in 24 hours. The total energy gained from the hydraulic door closer depends on the number of people who open the door in 24 hrs. Since the door opening/closing phases take two seconds, the number of people opening the door is multiplied by two seconds.

$$E_{2 (GAIN/24HRS)} = EG * NP$$

= [(3.6V * 0.016) * (200 * 2)]
= 23.04W

E1 and E2 were calculated and converted to the power value in order to make comparison if the energy gains bigger than energy loss to balance the system power.

$$E_{GAIN} = \frac{E_{INPUT}}{E_{OUTPUT}}$$
(17)

Where

 E_{GAIN} = Overall energy gain/loss ratio E_{OUTPUT} = Energy consumption by the wireless security camera system E_{INPUT} = Energy gained from the human powered hydraulic door closer

$$EG = \frac{23}{0.983} \cong 23$$

As estimated above the energy gain from the hydraulic door closer mechanism is 23 times bigger than overall energy consumption of the wireless security camera system. The estimation comparison has been done running the system in the full operating range. Since the energy gained is 23 times bigger than the camera system, the latter can be run 23 times with the harvested energy. The energy gain/loss graph depends on number of people who open the door is shown in Figure 51 compares the power values for various number of images.



Figure 51: Energy gain/loss for the wireless security camera system

As indicated in Figure 51, the gained power would be sufficient to power a wireless security camera system. The energy harvesting circuit and generator unit including the gear box can be improved to increase the amount of energy scavenged from the hydraulic door closer. Also the energy loss can be decreased by modifying and

choosing the low power components of the wireless camera system. Moreover, if the numbers of people increase then the battery charging time to supply more power to the electronic device would be decreased.

Energy Harvesting From Fitness Bicycle

The following work investigated the feasibility of an energy harvesting device that generates energy from a fitness bicycle ambient energy source during a workout routine of a person. The overall system utilized dynamo energy harvesting technologies to generate power from mechanical energy that is need during the operation of an exercise bicycle. The following steps were conducted to harvest and generate energy from exercise equipment.

- 1. Investigation of the fitness bicycle working mechanism
- 2. Pro-E Model of energy harvesting system
- 3. AMESim, advanced simulation analysis of the overall system
- 4. Mechanical built process (manufacturing a proof-of-concept device)
- 5. Integrating generator unit
- 6. Power output tests of the generator unit
- 7. Energy harvesting circuit built process
- 8. Testing and evaluation of the system

Fitness Bicycle Mechanism

The overall energy harvesting system design from a fitness bicycle was similar to the hydraulic door closer system design that was discussed earlier. The characteristics of energy sources are the same, with the only difference the rotational speed that which occurs on the fitness bicycle is much faster compared with a hydraulic door closer activated by human power. Considering this speed difference the plastic gearboxes were not suitable to connect into the mechanical system because of the high torque. Instead, typical and speed increase gear-head DC motors were tested as generator units.

For the purpose of extracting human kinetic energy, the wheel and pedal system of a fitness bicycle was studied. The original fitness bicycle is shown in Figure 52. Overall wheel, brake, and clutch structures were studied for the proper mechanical energy harvesting design to gain the maximum speed and efficiency from the exercise bicycle. This exercise bicycle has ten different speed cycle options and is controlled by an internal motor (battery powered) including brake and clutch system. These speed options directly affect the input speed of the pedaling system.



Figure 52: The fitness bicycle for mechanical system investigation

Pro-E Model of the Mechanical System

The engineering design of the overall mechanical system was modeled using Pro Engineer Wildfire 2.0 with real dimensions of all components. The components, including exercise bicycle wheel and pedal system; new wheel; bearing set; roller chain; sprockets; shafts; iron plates; and generator unit, were separately designed. After the design of all single components, an assembly model of the overall mechanical energy harvesting system was built. In Figure 53 the main Pro Engineer assembly of the overall energy harvesting system is depicted. The Pro Engineer Wildfire 2.0 design was necessary to find out right components where all of them were supposed to fit when assembled together.



Figure 53: Pro Engineer 2.0 Wildfire assembly of the mechanical system

Mechanical Build Process

After Pro Engineer 2.0 Wildfire design of the overall mechanical system all the components were either ordered or manufactured according to the design dimensions. The mechanical components were processed, tested and assembled in the production lab to fit each other properly. The manufacturing processes including drilling, welding, cutting, trimming, and measurements of the parts and have been completed with the help of the production lab technician. The pictures of the mechanical components are shown in Figure 54 before assembly to test the mechanical energy harvesting system.

The specifications of the physical parts are listed below for the detailed information and the references.

- 1. Two bearings with four bolt flange unit set screw lock.
- 2. A pneumatic complete wheel and tire with rim, 1/2" wide and 6" diameter.
- ANSI steel finished-bore roller chain sprocket for #35 chain, 3/8" Pitch, 16 Teeth, 1/2" Bore.
- Steel hub-less plain-bore flat sprocket for #35 Chain, 3/8" Pitch, 16 Teeth, 1/2" min bore.
- 5. Standard ANSI roller chain #35, single strand, 3/8" pitch, roller-less, .2" diameter.
- 6. #35 adding link for standard ANSI roller chain.
- 7. Add-and-Connect link for #35 standard ANSI roller chain.

After building-up process all the parts were assembled to test the mechanical energy harvesting system and the ratio between first wheel (the biggest drive wheel) and at the shaft of the generator unit. Since there are four wheels and two sprockets with different diameters the speed was increased four times (1:4). The representation of the speed ratio is given in Figure 55. Also the dimensions of the numbered wheels and sprockets are listed in Table 13.



Wheel Shaft (2)

Figure 54: Mechanical components of the energy harvesting system



Figure 55: The block diagram representation of speed ratio of the exercise bicycle

Table 13

Dimensions of the mechanical parts

#	Description	Dimension (Diameter, mm)	# of Teeth
D1	Exercise bicycle drive wheel	508	N/A
D2	Exercise bicycle driven w/h	30	N/A
D3	Exercise bicycle clutched w/h	254	N/A
D4	Mechanical rotation harvesting w/h	152.4	N/A
D5	Drive sprocket	50.8	RC35
D6	Driven sprocket	50.8	RC35

Units were converted to cm to calculate the Ideal Mechanical Advantage (IMA) of the speed ratio.

$$IMA = \frac{D_{DRIVEN}}{D_{DRIVER}} = \frac{W_{IN}}{W_{OUT}}$$
(18)

where

IMA: Ideal Mechanical Advantage;

D_{DRIVEN}: Diameter of driven wheel;

D_{DRIVER}: Diameter of driver wheel;

W_{IN}: Input rotational velocity of wheel or pulley; and

W_{OUT}: Output rotational velocity of wheel or pulley.

The general terms for the diameter and velocity are given as following:

D_n: Diameter of nth wheel or pulley; and

 W_n : Rotational velocity of n^{th} wheel or pulley.

Since

W2=W3, W4=W5, to find out the overall pulley ratios using ideal mechanical advantage (IMA),

$$IMA_{1} = \frac{D2}{D1} = \frac{3cm}{50.8cm} = 0.06;$$

$$IMA_{2} = \frac{D4}{D3} = \frac{15.24cm}{25.4cm} = 0.6;$$

$$IMA_{3} = \frac{D6}{D5} = \frac{5.08cm}{5.08cm} = 1;$$

$$IMA_{TOTAL} = IMA_{1} * IMA_{2} * \dots * IMA_{N}; \text{ and}$$

$$IMA_{TOTAL} = IMA_{1} * IMA_{2} * IMA_{3} = 0.06 * 0.6 * 1 = 0.036.$$
(19)

Then

$$IMA_{TOTAL} = \frac{W_{IN}}{W_{OUT}}; \text{ and}$$

$$W_{OUT} = \frac{W_{IN}}{IMA_{TOTAL}}.$$
(20)

 W_{IN} : Input rotational velocity is assumed to be 120rpm (a person approximately can pedal two cycles in one second). This input velocity is changed according to the cycling the pedals of a person

$$W_{OUT} = \frac{120rpm}{0.036} = 3333rpm \,.$$

The output speed of the mechanical system as an input to the generator unit was 3333rpm with the consideration of the dimension and the ratios. This speed was very reasonable and sufficient to supply a typical motor for low power generation. W_{OUT} can be changed if the wheel diameters and number of wheels are changed accordingly. The photograph of the completed mechanical assembly part of the energy harvesting system is shown in Figure 56. This mechanical system was built to test different generator units by easily replacing the generators.



Figure 56: The complete mechanical assembly of energy harvesting system

The Generator Unit

In the mechanical energy harvesting system, i.e. the output speed of the mechanical energy harvesting was W_{OUT} =3333rpm as an input for the generator unit. This input speed for the generator unit has been calculated just with the simple additional mechanical wheel system including exercise bicycle wheels. The speed increase gear box was not needed to increase the speed, in contrast to the hydraulic door closer energy harvesting system. So, the average continuous mechanical power which was generated by pedaling the fitness bicycle can be adjusted through changing the ratios between wheels and sprockets. Depending on the input rotation, the generator unit (PMDC motors) with the different speeds can be integrated into the energy harvesting system. Three different generator units with different specifications were tested in this section of the research. One of the DC motors was gear headed with the ratio of 1:10 which means that the input cycle was increased from one to ten before the generator produced electricity. The second one was just a typical PMDC brushless DC motor and the last one was a typical PMDC motor.

As a test process of the generators, initially each generator was either mounted on or connected to the appropriate place above the front shaft with the help of a bolted flat plate. It was a design issue to find the appropriate place to connect the generator where the most mechanical speed occurred during pedaling the bicycle. In fact the proper place for the generator was determined during the Pro Engineer design process. The photographs of the three generator units are shown in Figure 57.



Figure 57: Generator units

Test of Generator Units

During the test process of the energy harvesting system, generator output voltage/current, and power were tested in order to build a proper energy harvesting circuit. The system was initially tested with a person during a workout for 15 minutes continuously; each of the three generators was tested separately. During the workout the voltage and the current outputs were measured to see if there was an increase or a drop during the cycling of the pedals. For the testing a 10hm resistor was placed between a multi-meter and the generator to measure and calculate an AC and DC open circuit voltage/current and the power that was produced by the generator. It was determined that two generator units including a Barber-Colman PMDC and an Electro-Craft DC Servo produced sufficient voltage/current levels to charge the batteries in the display unit of the fitness equipment. The output power of the generators may be changed when the

generator, gear ratio or more human power is applied. After setting up the test system the voltage/current coming off the generators was measured. The test results and generator specifications are given in Table 14 below.

Table 14

Motor/Generator	unit	specifications
-----------------	------	----------------

	Туре	Motor	r Specificat	ions	Tested Generator Specifications			
Motor		Rated Voltage (V)	Rated Current (A)	Rated Input Power (W)	Output Voltage (V)	Output Current (A)	Output Power (W)	
Barber Colman	PMDC Brushless Ratio 1.:10	14V _{DC}	2.2	30.8	~14	~3	~42	
Electro Craft	D.C. Servo Motor	24V _{DC}	0.39	9.36	~3	~0.25	~0.75	
Delta	PMDC Brushless	12V _{DC}	0.08	0.96	No Power	No Power	No Power	

To calculate the power output for each generator, Ohm's law was used and the power is added to Table 14, under tested generator specifications.

P=V * I, (21)

where

P=Power;

I=Current; and

V=Voltage, Thus

power output from generator I (Barber-Colman) was

$$P=14 * 3 = 42W$$
, and

power output from generator II (Electro-Craft) was

$$P=3 * 0.25 = 0.75 W.$$

Power output from generator III (Delta) was

P=0.036 * 0= 0 (No power output).

That is a Delta type Brushless DC motor was not able to produce sufficient energy for the energy harvesting system because of the lack of sufficient input speed. The comparison of the three different types of the generators showed that there should be a sufficient generator unit such as Barber-Colman PMDC brushless generator with the speed increase gear head in order to produce sufficient power. Additionally, if a motor has a gear head to increase the speed it would be very efficient for power generation. However, a typical PMDC motor was not able to generate much energy if compared to its nominal specifications. These data from generator units are open circuit voltages and currents. When an energy harvesting circuit and battery are added to the system, the voltage and current levels would drop dramatically while charging a battery. However, all the above output power levels look like sufficient to charge the batteries at different charging times. Lab AMESim Overall System Simulation

In the "LMS Imagine. Lab AMESim" advanced simulation tool the overall energy harvesting system was analyzed and simulated with real specifications of the overall components including wheel ratios, generator, circuit, and battery unit. Initially the simulation was conducted using W_{OUT} =1800rpm input velocity for the generator input to a Barber-Colman PMDC brushless generator with AC output 6VAC out at 1800rpm and

five units of 1.2V rechargeable batteries connected in series to reach 6V which is needed to power the exercise bicycle electronic panel. The AMESim simulation interface was depicted in Figure 58 with all modules.



Figure 58: AMESim energy harvesting simulation interface

For each component, the specifications were entered into proper component tables for accurate simulation results. At this point, it was very critical to enter proper specifications for the components because of their interoperability. It was observed that if one of the simulation modules is specified incorrectly it would have affected the overall simulation and other modules. It was very challenging to figure out the meanings of the variables and parameters of the generator and battery units in the AMESim library. The specification of the library elements was programmed for the high voltage applications such as hybrid vehicles or power trains of high horse power applications. All parameters and variables of the generator and battery units were altered for low power application. As mentioned above, the output speed of the system was 1800rpm as an input speed to the generator unit. The system simulations were conducted and the critical simulation plots are showed in the Figures 59, 60, and 61 respectively. The simulation analysis was run for 14 hours for all the components to observe if the batteries are charged at a given time. The battery state of charge graph is shown in Figure 62 to point out the time it takes to charge a specific rechargeable battery. As plotted in Figure 62 there is a consequent increase while the generator unit is producing energy at the constant voltage and current levels.



Figure 59: Input mechanical speed of the generator

In Figure 59 the output speed of the generator energy harvesting system is shown. This speed can be changed if the overall ratio of the mechanical system is altered. In the simulation plot 1800rpm is constant but in real life, a case of this speed has the possibility to change any time depending on the person during a workout.



Figure 60: Battery charging voltage

Figure 60 and 61 show the battery charging voltage/current which are regulated by a battery charging circuit. Five units of 1.2V rechargeable batteries are integrated into the simulation interface in series to reach 6V for the battery charging purpose. Beside 75mA current is supplied to the battery terminals as specified in the battery data sheets. In fact the voltage and current levels are produced by the generator and automatically applied to the battery terminals due to component interpretabilities.

In Figure 62 the battery state of the charge is depicted. As aforementioned the system was run 14 hours to comply with a standard battery charge time as specified in the data sheet.

As is shown in Figure 62 the battery is being charged linearly if the fully discharged battery is put in the system. After 14 hours the capacity stays flat not charging until the battery starts lose energy with a load.



Figure 61: Battery charging current



Figure 62: Battery state of charge

Energy Harvesting Circuit Design

Since the fitness bicycle as an ambient energy source produces high voltage/current a DC-DC buck converter and intermittent battery charger circuits were required to transfer the energy from the source of the energy to the rechargeable batteries. The DC-DC buck converter circuit decreased the voltage/current levels from the input (3V-15V @0.25A-3A) to (1.2V-6V @ 75mAh) which is the battery charging voltage/current. Linear technology based power harvesting and switching circuits were built to implement and regulate energy conversion and battery charging. The DC-DC buck converter circuit was designed to handle both the source power that was produced from the generator unit and to charge five units of 1.2V serially connected rechargeable batteries to power the display of the exercise equipment. Before implementation of the circuit, necessary computer simulations were conducted for troubleshooting of any problem with the LTSPICE Switcher CAD III advanced simulation tool. In the following sections, bridge rectifier, DC-DC buck converter and battery charging circuit, and simulation test results are explained respectively.

The noisy voltage output of the generator unit was rectified by the bridge rectifier circuit that includes four diodes which can handle high current inputs. Since harvested energy was enough to power the exercise bicycle display the typical diodes were used without considering any voltage loss throughout the bridge rectifier diodes. A rectifier circuit was necessary to convert noisy output voltage from the generator to DC voltage, because almost all electronic components operate at DC voltage. The following input parameters were used to represent the characteristics of the energy source and generator

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unit during rectification. The source voltage changed between 0V-15V with 500Hz frequency. Since there are four diodes at the output (after rectification of AC voltage) the voltage was decreased 1.4V which is equal to two diodes. Taking Equation 8 into consideration the output voltage was calculated after rectification as follows,

$$V_{d0} = \frac{2}{\pi} \sqrt{2} * 14 V_{AC} = 12.6 V_{DC}$$

In the above equation, the input voltage is assumed to be $14V_{DC}$ from one of the generators and output voltage is calculated at $12.6V_{DC}$ after rectification. The voltage was dissipated (1.4V) when rectification of AC voltage took place through the diodes. Buck Converter and Battery Charging Circuit

The energy harvesting circuit board was designed, built, and simulated using the SwitcherCADTM Spice III simulator from Linear Technology. After full-wave rectification where alternating current (AC) was converted to direct current (DC), the voltage was decreased by a DC-DC buck converter. Consideration of input energy and output voltage, and the nature of the harvesting system it was decided to integrate an LT3502A DC-DC buck converter integrated circuit chip which was very efficient to handle high current inputs from the generator. The energy harvesting circuit design is shown in Figure 63. Since the generator unit in this experiment generated electricity between (10V-15V), the voltage was configured to vary from 10V to 15V in the simulation interface. The frequency was required for the circuit trigger and was defined as 500Hz. Moreover, the CAD III simulation tool provided an advanced simulation toolbox which allowed simulating each component's voltage/current levels on the circuit.

Thus, it was possible to confirm voltage/current levels anywhere on the circuit during the simulation of the energy harvesting circuit.



Figure 63: LT3502A based energy harvesting and DC-DC buck converter circuit

In order to make the circuit act according to the input and output voltage and the current characteristics, replacement values of the capacitors and resistors were needed. To decrease and then fix the charging voltage level to 6V at 75mA for all serially connected batteries the following calculations were made to find out the resistor values for the energy harvesting circuit.

$$V_{OUT}=0.8V [1 + (R2 / R3)],$$
 (22)

where

- V_{OUT} =Battery charging voltage;
- 0.8 =Manufacturer constant;
- R2 =Resistor value for voltage divider; and
- R3 =Resistor value for voltage divider.

To charge five serially connected 6V at 75mAh NIMH batteries the resistor values were determined for a 6V battery charging voltage:

R1=65kohm, R2=10kohm; so

 $V_{OUT}=0.8V [1 + (65k/10k)] = 6.0V.$

Because of the voltage drops and leakages on the energy harvesting circuit V_{OUT} (battery charging voltage) was increased and adjusted as 6.24V to avoid low charging voltage to the battery terminals.

To increase the voltage to V_{OUT} =6.24V,

R1=68kohm, R2=10kohm, and

 $V_{OUT}=0.8 [1 + (68k/10k)] = 6.24V.$

The output current for the battery charging then was, I_{OUT} =75mA at R=75ohm internal battery resistance. The voltage/current values to charge five units of 1.2V batteries imply the need to supply for 10-14 hours in order to charge the serially connected batteries. The values of the critical circuit components such as input voltage, output voltage, and output current were simulated and are graphed in Figures 64, 65, and 66 respectively. There V_{IN} : Input Voltage before buck converter (after rectification); I_{ROUT} : Output current for the load (battery charging current); and

V_{OUT}: Voltage level after buck converter (battery charging voltage).



Figure 64: Input voltage (V_{IN}) simulation graph

In Figure 64, V_{IN} (the input voltage) is shown. This voltage level is measured after rectification of the AC voltage which is generated from the generator unit as a DC voltage for the buck converter and the voltage regulator circuits. In Figure 65 the V_{IN} and V_{OUT} (battery charging voltage after buck conversion and regulation) were compared to see the voltage difference and regulated voltage rate. The voltage levels that were bigger than 6V were decreased by the buck converter to operate and charge the battery at nominal voltage level which is 6V at 75mA for serially connected batteries.



Figure 65: Input (V_{IN}) and output (V_{OUT}) voltage simulation graph

In Figure 66, I_{ROUT} (battery charging current) and V_{OUT} (battery charging voltage) simulation graphs are compared. Both voltage/current levels are constant and charging the battery. $I_{ROUT} = 75$ mA which is the normal charging current for the battery and V_{OUT} =6V nominal charging voltage.



Figure 66: Battery charging voltage (V_{OUT}) and current (I_{ROUT}) simulation graph

All three important parameters of the energy harvesting circuit were simulated at the same time to show the consistency of the voltage and current levels on the circuit design in Figure 67. Only input voltage V_{IN} waves a little bit because of the different speeds applied to the generator which is absolutely normal according to the fitness bicycle energy generation characteristics.



Figure 67: Simulation of critical parameters for battery charging

Since the output voltage from the generator unit (10V - 15V) was decreased to 6V constant battery charging voltage, another circuit was needed to protect the battery from overcharging. For the purpose of both decreasing the voltage and protecting the battery, a linear technology based SEPIC buck-boost converter and battery charging circuit was designed and simulated as an additional circuit to charge the batteries at 6V at 75mA range. An LT1512 integrated circuit was used to keep the battery charging voltage and current at the constant rate. The LT1512 based DC-DC buck-boost and battery charging circuit design is shown in Figure 68.



Figure 68: LT1512 SEPIC Constant current/voltage battery charging circuit

As for the LT3502A, the graphs of the simulations of critical circuit components such as input voltage, battery charging voltage and current were also produced and are depicted in the following figures.


Figure 69: Input voltage (V_{IN}) simulation graph

In Figure 69, V_{IN} the input voltage simulation graph which was produced by the generator unit is shown. This voltage level is measured after rectification of the AC voltage which is from the generator unit as a DC voltage for the buck converter and the voltage regulator circuit. In Figure 70 the V_{IN} and V_{OUT} (regulated battery charging voltage) were compared to see the input and output voltage difference after regulation. The voltage levels that were bigger or less than (6V) were regulated by the LT1512 buckboost converter and battery charging IC to operate and charge the battery at the nominal voltage level which is 6V@75mA for serially connected batteries.



Figure 70: Input (V_{IN}) and Output (V_{OUT}) voltage simulation graph

In Figure 71, I_{ROUT} (battery charging current) and V_{OUT} (battery charging voltage) simulation graphs are shown. Both voltage and current levels are constant for proper battery charging. $I_{ROUT} = 75$ mA which is normal charging current for the battery and $V_{OUT} = 6V$ nominal charging voltage.



Figure 71: Battery charging voltage (V_{OUT}) and current (I_{ROUT}) simulation graph

Also three important parameters of the energy harvesting and battery charging circuits were simulated at the same time to show the consistency of the voltage/current levels on the circuit design in Figure 72.



Figure 72: Battery charging values simulation graph

Considering the different output voltages from the three generators, a multipurpose voltage input energy harvesting and charging circuit was designed in order to charge five units of 1.2V batteries at the constant charging phase. The energy harvesting circuit was planned to be placed near the battery box under the display in order to be closer to other electronic components. However, for the test purposes the circuit on the bread board was placed near the generator unit so as to read output values and observe the generator output. The power output of the generator was directly proportional to the effort put into it but the output power of energy harvesting circuit was a constant voltage to avoid damaging the chemicals of the batteries. So the amount of electrical power that was generated by the human powered generator is determined by the energy available to turn the pedals. The stronger the human power, the more electrical power was generated from the workouts. The energy harvesting circuit which was soldered to a printed circuit board is shown in Figure 73. The circuit was built after all simulations and troubleshooting was conducted on the LTSPICE Switcher CAD III.



Figure 73: Energy harvesting PCB (Printed circuit board)

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The electronic display of the exercise bicycle was running on four units of (1.5V AA) typical batteries. The total voltage supplied to the electronic system was (6V) in series. For the purpose of replacing four units of (1.5V AA) batteries, five units of rechargeable batteries at (1.2V AAA) were connected serially to each other to supply the same voltage level to the display of the electronic display.

Testing & Verification

Initially five of the rechargeable batteries were discharged with the resistive loads connected to the battery terminals. All the batteries were discharged to almost 0V (but not exactly 0V) in order not to damage the batteries. Before measuring the voltage levels of the batteries they were put in a refrigerator for about one hour in order to have accurate measurements and decrease the chemical reactions inside the battery caused by room temperature. It was observed that the measurement results before placing the batteries into the refrigerator were not accurate and rapidly changing on the multi-meter display. The discharging process of the batteries on the breadboard is shown in Figure 74 with the resistive loads.



Figure 74: Battery discharging with low resistive loads

The electric generators were connected to the fitness equipment consequently. The exercise bicycle was then run by an average person 15 minutes for each of the generator units. The circuit and measuring tools were placed near the fitness equipment to observe the voltage and current, and power outputs during workout of the person. The general and initial specifications of the generators and the batteries are given in Table 15. The voltage level of the discharged batteries also was included in this table as a reference to make a comparison after charging. The test results in Table 15 concluded that there is a possibility to harvest considerable power from fitness equipment. The voltage level of the batteries was increased considerably when batteries were almost discharged at the beginning. After certain level of the charge (capacity), the capacity of the batteries hardly increased. For example, to charge a typical fully discharged battery takes approximately ten to fifteen hours for the battery to reach its highest capacity at a standard charge level. If charging time of a typical battery is compared to our case (energy source), there would be at least 50 workouts when the fitness bicycle was used for 15 minutes each time. However, normally the batteries which are placed in the electronic display come fully charged. So it was important to calculate how much power the electronic display consumed during a workout. The total energy gained and lost during a workout and in 24 hours was calculated after the battery charging tests were completed. All the test data are explained in Table 15 with the specifications and charging times of the batteries depending on number of workouts.

Table 15

Battery charging test results

Gearhead Ratio Generator		Battery Initial Voltage Temp (T)		15 minutes run for each measurement: Total workout= 15*3= 45 min Volt (V) Measuring Temp (T)							
				15 min		30 min		45 min		FINAL	
		V	T	V	T	V	T	V	Т	V	T
Ratio 1:10 PMDC-Brushless	1	0.048	53	0.980	72	1.15	73	1.27	73	1.278	60
	2	0.57	56	1.12	68	1.23	72	1.24	74	1.229	57
	3	0.112	57	1.21	69	1.27	73	1.29	75	1.295	62
	4	0.188	60	0.852	70	1.09	72	1.22	73	1.276	60
	5	0.43	43	1.19	72	1.21	74	1.24	75	1.291	64

Final charges of the batteries were measured after keeping the batteries in the refrigerator for one hour to have consistent measurements. Table 15 also briefly summarized that batteries are being charged consistently without damaging them. The photograph of the overall energy harvesting testing system is depicted in Figure 75.

Overall Test Results

The following comparison between workout and battery charging time was estimated to show how much time use are required to use the fitness bicycle in order to charge 6V at 750mAh the fully discharged serially connected battery group (according to the typical battery charging specifications).



Figure 75: Overall energy harvesting test system with the fitness equipment

For example, the total time needed to charge the batteries is about 14 hours as specified in the battery datasheet and the time taken for workout of an average person is 15 minutes. In order to calculate how many workouts are needed to charge the batteries, the following equation was used:

$$W = \frac{T_{TOTAL_BATTERY}}{TP_{WORKOUTS}},$$
(23)

where

W =Total number of workouts to make batteries fully charged; T_{TOTAL_BATTERY}=Total time taken to charge the batteries/minutes (Nominal charge time); and TP_{WORKOUTS} =The time taken for one workout in minutes.

A typical battery average charge time is equal to 14 hours.

Taking equation (23) into consideration the total number of workouts was calculated considering the typical NIMH batteries charge time is equal to about 14 hours as follows:

$$W = \frac{840\,\mathrm{min}}{15\,\mathrm{min}} = 56\,\,\mathrm{workouts}\,.$$

According to the above estimation 56 workouts are needed to charge all the discharged batteries. However depending on the electronic application the number of the workouts can be reduced significantly to overcome daily discharges of the overall system. The following energy management test application was estimated if the small number of workouts will compensate overall leakages and consumption of the fitness bicycle electronic display.

Energy Management Test Application

Fitness equipment as an ambient energy source was considered as a viable energy source to make an equipment electronic display self powered. It was expected that the source would generate enough power to run the electronic components of the fitness equipment. It was proven above that the fitness equipment was able to produce more than sufficient input power to charge a group of batteries depending on the number of people using the exercise bicycle. Also the analytical estimation for battery charge time and number of workouts relationship were calculated above for the fully discharged batteries. However, in the case of powering the electronic display, the batteries initially starts operating in full charge. So it is necessary to calculate if the gained and stored power is enough to compensate for the consumption of the electronic console during the workout. If the daily charges compensate the daily consumptions and the standard leakages of the electronic console components, then it would be said that a fitness equipment ambient energy source is a viable source for the application. For this reason overall energy consumption and energy gained relationship estimates were conducted considering (E_1) as overall energy consumption and (E_2) as energy gained during the workout; are shown below.

$$E_{1 (LOSS/24HRS)} = [(P_{BATTERY}LEAKAGE) + (P_{HARVEST}LEAKAGE) + (P_{DISPLAY}LEAKAGE)] + [(P_{WORKING}) * (W_{\# OF WORKOUTS})],$$
(24)

where,

E _{1 (LOSS/24HRS)} :	Overall energy loss per 24 hours;
PBATTERY_LEAKAGE:	Leakage through batteries (joule/hour*24 hrs);
P _{HARVEST_} LEAKAGE:	Leakage through energy harvesting circuit components;
P _{DISPLAY_LEAKAGE} :	Leakage through display electronics of the fitness;
	equipment
P _{WORKING} :	Energy consumption of the electronic display for per
	workout; and
W# OF WORKOUTS:	Total number of workouts in 24 hours.

The equation above allows me to calculate the overall energy consumption including the total leakages on stand-by mode of the fitness equipment and the energy harvesting system. It is assumed that three people use the exercise bicycle 15 minutes each with the total 45 minutes a day/24hours. According to Equation (24), it is also necessary to find out power consumption of the electronic console $P_{WORKING}$ per workout separately before calculating overall energy loss. A small scale integrated radio also was considered in the system. In order to find out electrical specifications of the radio a COBY (electronic company) pocket radio was chosen and investigated according to its data sheet. The general electrical specifications of the radio were a little bit higher than a small pocket radio. But it was decided to have specifications in case a big radio would be placed in the fitness bicycle display. The general specifications and energy consumption during a workout of 15min are calculated below in order to add overall energy consumption of the exercise bicycle display.

According to the above specifications the power consumption of the radio during the workout is calculated below. It is assumed that for each workout of 15min, the radio was active and used by the person.

$$P_{\text{RADIO}} = P = \frac{V^2}{R} = I^2 * R , \qquad (25)$$

where

P_{RADIO}: Energy consumption of the integrated radio per workout;

$$I^{2} = \frac{P}{R} ; \qquad (26)$$
$$I = \sqrt{\frac{P}{R}} ; \text{ and }$$

$$I = \sqrt{\frac{0.04W}{18ohm}} = 0.050A \,.$$

I=1.050A is calculated as the current consumption. In order to find out the power output during workouts in a day the calculation below was competed;

$$P_{\text{RADIO}} = \frac{0.050A * 3V}{24Hrs} = 0.06 \text{ W/h}$$

The overall estimate for energy consumption of the electronic display is given below assuming that the system was fully activated during the workout.

$$P_{\text{WORKING}} = [(P_{\text{STEP}_{\text{COUNTER}}}) + (P_{\text{MAGNETIC}_{\text{RESISTANCE}}}) + (P_{\text{CALORIE}_{\text{PROGRAMS}}}) + (P_{\text{SMART}_{\text{PROGRAMS}}}) / 24 \text{Hrs}], \qquad (27)$$

where,

P _{WORKING}	=Overall operating power for one workout;
P _{STEP_COUNTER}	= Energy consumption/second for step counter;
P _{MAGNETIC_RESISTANCE}	= Energy consumption/second for magnetic resistance
	adjustment motor;
P _{CALORIE_PROGRAMS}	= Energy consumption for calorie burn option; and
P _{SMART_PROGRAMS}	= Energy consumptions for two switches.

Per Equation (27) energy consumption of the display during the workout was calculated for one workout:

$$P_{\text{WORKING}} = [(1\mu\text{A}) + (70\text{mA}) + (1\mu\text{A}) + (1\mu\text{A}) / 24\text{Hrs}]$$

=3mAh.

 $P_{WORKING}$ =3mA energy is drained from the storage unit during a workout on the bicycle by the display. There are certain components in the system that are always at stand- by either to sense the wake-up signal or because the nature of the part. These components drain some quiescent currents from the batteries while they are on standby including the electronic console, energy harvesting circuit, and battery to keep the system up and running. The total leakages and quiescent currents for all the components during the workouts were calculated via moving equation (24). Since P_{WORKING} was found above separately and included, the overall energy consumption in 24 hours was as calculated below. (There are also leakages from the batteries that have been considered as energy consumption.) Overall operating current causing energy consumption are calculated below.

$$E_{1 (LOSS/24HRS)} = [(P_{BATTERY_LEAKAGE}) + (P_{HARVEST_LEAKAGE}) + (P_{DISPLAY_LEAKAGE})] + [(P_{WORKING}) * (W_{\# OF WORKOUTS})]; and$$

$$E_{I} = [(300\mu A) + (792\mu A) + (10.7mA)] + [(3mA) * (3)] = 42mAh.$$

The value for E_1 is converted to the power unit in order to make a comparison between the power gain and the power loss,

 $P_{1 (LOSS/24HRS)} = (0.042A * 6V) = 0.252Wh.$

The power consumption from the radio was added to the overall energy consumption of the system, and the total power consumption is found below:

$$P_{\text{TOTAL}} = (P_1 + P_{\text{RADIO}})$$
(28)
= (0.252Wh + 0.06Wh)
= 0.312W.

As found above, the total energy drained from the batteries is estimated at 0.312W per day. This value is not exact energy consumption; it may change according to how often a person changes the parameters on the electronic console during the workout. Since the total energy loss (E₁) estimate was examined, the energy gain from the energy harvesting system was also examined below to make comparison between energy gained and loss on the overall system for a day.

The equation below helps to calculate the total energy gained from human power through the fitness bicycle source during a day (24hrs).

$$E_{2 (GAIN/24HRS)} = EG^*NP,$$
⁽²⁹⁾

Where

E _{2 (GAIN/24HRS)} :	Total energy recovered and stored from human power			
	through fitness bicycle per 24 hours;			
EG:	Energy gathered for per person during a workout/minute;			
NP:	Number of the people did workout in 24 hours.			

For this application the gained energy from the exercise bicycle (E2) should be bigger than or equal to overall energy loss (E1) in 24 hours (E1 \leq E2), or otherwise the electronic display would be operating inconsistently because the lack of enough energy to run the electronic application components. The total energy gained from the system depends on the number of people workout during 24 hour period and is calculated below.

 $E_{2 (GAIN/24HRS)} = EG^*NP;$

 $E_{2 (GAIN/24HRS)} = (6V * 0.075mA * 3)$

= 1.35Wh;

After the calculation and conversion E1 and E2 are determined, the comparison of the gained and lost power are given as

$$EG = \frac{E_{INPUT}}{E_{OUTPUT}},$$
(30)

where

EG = Overall energy gain; E_{OUTPUT} = Energy loss; E_{INPUT} = Energy gained; so E_{C} = 1.35 ~ 4.4

$$EG = \frac{1.35}{0.312} \cong 4.4$$
.

For the purpose of realistic estimation, the components of both energy harvesting and fitness bicycle systems were chosen and studied. As estimated above the energy gain is 4.4 times bigger than overall energy consumption of electronic display for a day. The harvested and stored energy can also be sufficient to power an integrated small scale radio as well. As estimated above the energy harvesting system from human power through an exercise bicycle generates enough power for both the electronic display and the radio according to the power consumption comparisons. The energy loss/gain graph depends on the number of workouts and is given in Figure 76.

As shown in Figure 76, the power gained is sufficient to power both the fitness equipment display and the radio. To improve the energy gain, energy harvesting circuit can be improved so as to power more devices on the fitness equipment display. Furthermore, if the time a person works out increases then the battery charging time would be decreased, depending on how long the person works out.



Figure 76: Energy gain/loss depends on number of workouts

Energy Harvesting with Piezoelectric Fiber Composite Bimorph (PFCB)

Piezoelectric Fiber Composite Characteristics

The Piezoelectric active fiber composites (AFC) are made by ACI (Advanced Cerametrics Incorporated) from a uniquely-flexible ceramic fiber that was able to capture wasted ambient energy from mechanical vibration sources and convert it into electric energy. The piezoelectric fiber composites' fiber spinning lines are capable of generating electricity when exposed to an electric field. In PFCB (piezoelectric fiber composite bimorph) architecture the fibers that are suspended in an epoxy matrix and connected using inter-digitized electrodes create an active fiber composite (AFC). It is already known through tests by the manufacturing company that thin fibers with a dominant dimension, a length and very small cross-sectional area are capable of optimizing both the piezo and the reverse piezo effects. The amount of energy produced by mechanical to electrical energy conversion through the PFCB is much better than that compared to other piezoelectric materials according to the ACI's internal studies.

Piezoelectric Fiber Composites were previously introduced in Chapter III as an energy harvesting tool through use as an alternative ambient energy source for low power electronic applications. In this section an investigation into the improvement of an energy harvesting system performance and efficiency using a piezoelectric fiber composite bimorph (PFCB) is considered. The PFCB characteristics and properties were intensively studied in order to build an efficient energy harvesting circuit for further study. The efficiency of the PFCB was measured by building an operational difference amplifier instrumentation test circuit and following an energy harvesting and battery charging circuit. Only one type of piezoelectric element which is PFCB was available to test with a small constant shaker which was borrowed from the UNI Physics department for the test purposes. The shaker functioned as an ambient vibration source (human power) and was used to shake the PFCB to produce electricity for the energy harvesting circuit.

Since cycle durability of fiber composites was determined by the manufacturer, the life cycle test of the PFCB material is ignored in this research. Manufacturer cycle tests showed that fiber composite materials are extremely durable, able to handle one billion cycles without any degradation of properties, and efficiently, to generate constant continuous power. The PFCB was tested alone by flicking the tip with a mechanical pencil without any mass attached on it through an oscilloscope and multi-meter to observe the power output signal characteristics. A photograph of the PFCB with the inter-digitized electrodes to align the field (energy harvesting circuit) with the fibers is shown in Figure



Figure 77: The photograph and basic specifications of the PFCB

77.

A piezoelectric energy source is most often modeled as an AC voltage source because of its AC power characteristics and features. Piezoelectric fiber composite can be connected in series with the capacitors and resistors, to reduce or smooth high voltage input produced by PFCB. The simple connection diagram architecture of the piezoelectric material with a capacitor, resistor and load (representing a storage unit) is shown in Figure 78.



Figure 78: Piezoelectric fiber composite as a sinusoidal (AC) voltage source

In the next sections, for the energy harvesting circuit the PFCB energy source is modeled as a steady AC power source for the circuit components. This AC source will be converted to DC voltage source since all the electronic components for the energy harvesting and battery charging circuit require a DC voltage source to operate in this research.

Power Characteristics

Because of the budget and equipment restrictions the researcher was not able to purchase a variable frequency shaker to test the PFCB and the system with different frequencies. Only a shaker at (115V at 60Hz) was used as a constant vibration source. Also the tip of a mechanical pencil was used to flick the tip of the PFCB product in order to provide the initial disturbance for the test purposes. The test equipments used for testing including multi-meter, shaker, and an oscilloscope are connected to each other properly to have voltage readings from the PFCB. The first test for voltage output depended on time variation was conducted without any mass placed on the tip of the PFCB followed by the test with variable masses that are placed on the tip of the PFCB to observe the output voltage levels.

The more mass is added on the tip of the PFCB, the more time passes until vibration of the PFCB stops. At the same time the voltage from the PFCB increases depending on the mass and the force applied to the tip of the PFCB. The plots in Figure 79 are a summary of the peak-to-peak voltage levels and the corresponding time for no added tip mass and consequently 2.5, 5, 7.5, and 10 gram tip added masses. The AC signals and voltage outputs were similar to each other; however the time the vibration decays was observed to be longer with more masses attached on the PFCB. All signal outputs until the vibration decays completely was not able to show on the oscilloscope screen. However it was observed that the time until vibration stops is longer with more masses that attached on the PFCB. Also the frequencies of the plots are similar because of the constant disturbances from the shaker and mechanical pencil flicks.

Furthermore the output voltage produced by the PFCB was observed mostly above 300V as specified by the PFCB manufacturer. The obtained voltage level is open circuit voltage and would decrease any time if a load is connected between inter-digitized electrodes of the PFCB. However, the output current and power levels could not be plotted because the lack of the necessary equipment and software. The power outputs of the PFCB are discussed more in the energy harvesting circuit design section with the supporting simulation outputs.

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Figure 79: Plots of voltage decay of the open circuit PFCB configuration

The PBCB is carefully clamped on the shaker with plastic bumpers to avoid damaging the part during its vibrations. The wiring between all modules was done carefully to allow reading of the voltage outputs from the oscilloscope and multi-meter displays. The photograph of the overall test system used to experiment with the PFCB characteristics is shown in Figure 80.



Figure 80: The test fixture to test power characteristics of the PFCB

The PFCB layer and material properties were not known accurately to predict the frequency rate, so the value had to be determined experimentally on the test fixture. In order to allow calculating of the current output, wires from the PFCB electrodes were connected to the oscilloscope probes through a 1 kohm resistor. The current outputs were not able to be measured by a multi-meter and were observed from the oscilloscope screen when the FPCB was vibrated by the shaker at 60Hz. It would have not been possible to plot the current and power outputs due to lack of the proper data acquisition system during the research as mentioned earlier. However there are still very low current outputs produced that may be harvested with a proper energy harvesting circuit. From the

vibration test results, it was determined that at the variable frequency, the power generated from the PFCB is sufficient to use it to power low power electronic devices. The obtained values would be enough to build an energy harvesting circuit to charge a small scale storage device such as battery, capacitor, and super capacitors, albeit slowly. <u>Overall System Simulation by LMS Imagine. Lab AMESim</u>

An "LMS Imagine Lab AMESim" advanced simulation tool was used to analyze and simulate the overall energy harvesting system with actual component specifications including the piezoelectric fiber composite bimorph, shaker or vibration environment and storage unit. The simulation was conducted using a spring and damper system to manage vibrations and frequency levels when an input force was applied on the tip of the PFCB. A velocity sensor was placed between the mass and spring-damper to read the velocity of the system while the PFCB is being vibrated. Also a mass-friction was attached to the middle of the PFCB to represent added mass values on the tip of the product. Additionally a displacement sensor was placed between the mass and the PFCB to measure the vibration distances when a force was applied to the PFCB. The rest of the modules in the simulation interface are the calculation tools and data table connections to manage control between the components such as reading magnitude of vibration, the power specifications of the PFCB, the time taken for the PFCB vibrations to decay, and the battery charging measurements. All the module specifications were derived both from the PFCB and battery datasheets, as well as the test results which were described in previous sections. The AMESim advanced analysis and simulation interface is depicted in Figure 81 with all modules.



Figure 81: Overall energy harvesting simulation interface of PFCB using AMESim

For the each module, the default values of the components were altered by entering new specifications into proper component tables for the precise simulation results. Precise specifications for each module were essential. If one of the simulation modules had gotten the wrong specification or data set it would have affected the other modules and eventually affected overall simulation results. In AMESim the specifications of the library modules were programmed for high voltage applications that required the reasonably to make intensive examination of the module characteristics in order to change the parameters for the low power applications. All parameters and variables of the modules were altered according to the low power energy harvesting application purposes.

The basic working principle of the system starts with the input force representing foot steps of the person. The force module flicks the PFCB every two seconds to induce and cause vibrations on PFCB for each foot step. Then the PFCB starts shaking according to the specifications of the mass and spring/damping modules. The graph of input force that represents the average walking of a person is shown in Figure 82.



Figure 82: Input force to induce vibration on the PFCB every two seconds

Once the input force is applied to the PFCB, it starts shaking and produces vibrations. The vibrations are then captured and processed by the displacement sensor module which is represented by the "X" under the PFCB module on the simulation interface. There were a lot of sinusoidal signal outputs coming from the displacement sensor which made it difficult to count peak-to-peak signal outputs. For this reason a

magnitude of vibration module was placed to calculate each signal's peak-to-peak power output in order to supply accurate charge parameters to the battery module. Both the output signals from the PFCB through the displacement sensor and the magnitude of vibrations are graphed together and shown in Figure 83, representing the observed magnitude of the signal when a force was applied.



Figure 83: Signal output from the PFCB and peak-to-peak magnitude of vibrations

As indicated in Figure 83 the borders of the signals from PFCB were captured and calculated by the magnitude of vibration sensor multiplying by two (in order to include negative and positive cycles). Electrical specifications of the PFCB were derived from its datasheet and evaluated using Microsoft Excel to provide accurate power characteristics depending on the vibrations to the battery terminals in order to observe battery charging time. The evaluated specifications of the PFCB were entered into a table which was

connected to the piezoelectric power spec module on the simulation interface. This module converted the input mechanical vibration energy into electrical power in order to provide accurate charging voltage/current level to the battery module. The evaluated specifications of the PFCB are listed in Table 16.

Table 16

Displacement Pk-Pk	Displacement Pk-Pk	Harvester Power	PFCB Power	PFCB Power	Charge Voltage	Current
mm	M	μW	μW	W	V	A
-4	-0.004	750	250.00	0.00025	1.2	0.000208
-0.5	-0.0005	750	250.00	0.00025	1.2	0.000208
-0.3	-0.0003	620	206.67	0.000207	1.2	0.000172
-0.1	-0.0001	270	90.00	0.00009	1.2	0.000075
-0.03	-0.00003	20	6.67	6.67E-06	1.2	5.56E-06
0	0	0	0.00	0	1.2	0
0.03	0.00003	20	6.67	6.67E-06	1.2	5.56E-06
0.1	0.0001	270	90.00	0.00009	1.2	0.000075
0.3	0.0003	620	206.67	0.000207	1.2	0.000172
0.5	0.0005	750	250	0.00025	1.2	0.000208
4	0.004	750	250	0.00025	1.2	0.000208

Evaluated power specifications of the PFCB

The simulation analysis was run one hour for all the components so as to observe if the battery was getting charged while PFCB was being vibrated. A 1.2V at 110mAh rechargeable battery module was integrated into the simulation interface. The voltage/current levels were applied to battery terminals by the piezoelectric power spec module according to the magnitude of the vibrations. The battery charge time may be changed any time and depends on the vibration time and frequency of the PFCB. The charging time calculated and simulated here is an estimate according to the input force module that flicks PFCB every two seconds to induce the vibrations. As aforementioned the system was run one hour to compare with the standard battery charge time as specified in the data sheet. The battery state of charge graph which is showed in Figure 84 indicates the time taken to charge a specific rechargeable battery. There is a consequent increase in battery capacity while the PFCB module is being vibrated by the input force producing energy at a constant voltage/current levels. In the graph, the battery is being charged linearly assuming the fully discharged battery is put in the system.



Figure 84: Battery state of charge in one hour

In one hour the battery is charged 4% by the current energy harvesting system from the PFCB. The charging time changes if one of the modules' specifications is either altered or improved. This simulation is designed to accept any modifications to fit any ambient energy environment through a PFCB.

Energy Harvesting Circuit

After testing the power output and the working characteristics of the PFCB at different stretches and attached masses, the researcher built the energy harvesting circuit

used to charge the batteries under low current levels. The mechanical to electrical energy conversion is usually managed by the energy harvesting circuits including conventional buck-boost converters, bridge rectifiers, and battery charging circuits. The energy harvesting circuit was designed, developed, and built according to the ambient source and piezoelectric fiber composites' low current constraints in order to produce efficient power output.

The following energy harvesting and battery charging circuit design was built with typical components that could decrease high input voltages and increase low input currents from the PFCB to provide sufficient charge currents to the batteries. The circuit was designed to start charging when the battery voltage drops beyond a nominal value, and it stops charging when voltage is reached at the battery nominal voltage. The LTSPICE simulation interface that shows the overall circuit is depicted in Figure 85; it represents the system circuit modules which are simulated together to test the output power level of the circuit. All the necessary simulations were conducted using SwitcherCADTM Spice III because of the Linear Technology based DC-DC buck-boost converter and battery charging circuit components. Initially a full wave bridge rectifier was placed between the PFCB and the operational amplifier instrumentation circuit that converts the AC signals to the DC signals. A full wave bridge rectifier is very efficient, converting positive and negative cycles from the PFCB and supplying DC voltage to the battery through the battery charging part of the energy harvesting circuit. Since the current produced from PFCB was low, an intermediate operational amplifier (opamp) circuit was placed on the energy harvesting circuit to increase the current levels for test

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purposes. This instrumentation circuit consisted of operational amplifiers, resistors, and intermediate/storage capacitors to implement the circuit at ± 15 V. A buck-boost converter and battery charging circuit is shown as the last part of the simulation interface before the storage unit.



Figure 85: Energy harvesting circuit simulation interface with SwitcherCADTM Spice

The opamp part of the energy harvesting circuit consists of three single operational amplifiers that are configured as difference amplifiers. This implies that the voltage differential between the two branches is the output of the circuit. The opamp instrumentation circuit is shown in Figure 86. This opamp instrumentation circuit design helped to observe voltage outputs from the PFCB and the capacity changes of the capacitors when the PFCB was being vibrated. The capacitors (C1 and C11) were charged depending on how much voltage generated by the PFCB was observed by the oscilloscope through the operational amplifier instrumentation circuit.



Figure 86: Operational Amplifier instrumentation circuit

The general operational amplifier in Figure 86 was used to observe the charging phase of the C11 intermediate storage capacitor. The 5V IC (Initial voltage) was supplied across capacitors in both circuits. In the circuit A, the voltage across the capacitor with the 10MEG impedance which was representing a flux digital multi-meter was measured. The voltage across the capacitor (C1) dropped almost 2V when the circuit was simulated at the same input voltage. However the voltage across the capacitor (C11) in the operational amplifier circuit stayed at constant voltage other than very small and negligible voltage drops. The voltage level across both capacitors (C1 and C11) was

simulated and is plotted in Figure 87 in order to compare voltage drops across the capacitors.



Figure 87: Voltage levels across intermediate storage capacitors

When the PFCB was placed on the constant shaker, it started generating voltages by charging the capacitors. The operational amplifier circuit kept the initial voltage level constant to allow accurate reading of the voltage levels of the intermediate storage capacitor. In circuit A, the voltage readings would not be accurate because of the voltage drops across the capacitor when measuring the voltage with a digital multi-meter. However the capacity readings across the C11 would be accurate since the operational amplifier keeps the initial voltage level constant.

DC-DC Buck-Boost Converter and Battery Charging Circuit

DC-DC converters efficiently step-up (boost), step-down (buck) or invert DC voltages without the necessity of transformers. In these structures, switching capacitors are usually utilized to reduce or to increase physical size requirements. DC-DC

converters help to allow product size reduction for portable electronic devices where increased efficiency and regulation of input power are necessary for optional requirements. Taking the above features of the buck-boost converters into consideration a linear technology based LT1512 DC-DC buck-boost SEPIC constant current/voltage battery charging integrated circuit was used to regulate the high output voltage that was produced from the PFCB to charge small scale batteries for test purposes. An LT1512 battery charging circuit was added to the energy harvesting circuit, considering its characteristics using application data sheet. Since buck-boost converters are very sensitive, proper design in conjunction with supporting components and physical layout is necessary to avoid electrical noise generation and instability. The considerations including LTSPICE modeling, converter selection, circuitry building, debugging, and power output improvements were followed step by step to have good energy harvesting circuitry.

This circuit would maximize the power flow from the piezoelectric device, and was implemented in coordination with a full wave bridge rectifier, intermediate storage capacitor, and voltage sensitive switching circuit. It was observed that when using the energy harvesting circuit, over twice the amount of energy was transferred to the battery than with direct charging alone. However, if the power harvesting medium produced less than 2.7V, then power flow into the battery was reduced due to losses in the additional circuit components and the threshold characteristics of the LT1512. For the purpose of storing energy in the intermediate storage unit, a capacitor was placed before the voltage sensitive circuit and buck-boost converter. The voltage sensitive circuit consists of diodes

(including zener diodes), MOSFET switches, and resistors to transfer the energy from intermediate capacitor to the battery through DC-DC buck-boost converter. The MOSFET switches and zener diodes on the voltage sensitive circuit sense the voltage in the intermediate capacitor and transfer the energy when the capacitor reaches specific voltage levels. The voltage level in the intermediate capacitor is controlled by the zener diodes until capacitor is discharged by transferring its energy to the battery. Depending on the zener diode values (switch should be between 5V-15V), the stored energy in the capacitor transferred to the storage unit through DC-DC buck-boost converter and battery charging circuit. Due to known high discharge rates of the capacitors the zener diode voltage values were chosen 12V and 6.2V (which is small values for the purpose of energy harvesting from PFCB) to avoid loosing stored energy in the intermediate capacitor. One of the biggest benefits of the intermediate capacitor and voltage sensitive switching circuit is to increase the amount of transferred energy from the PFCB. This way reduces the circuit loss throughout the energy harvesting circuit caused by the electronic components. The circuit is shown in Figure 88 and was built as four phases to represent the overall energy harvesting circuit modules in order to simulate the circuit. First module is mechanical to electrical energy conversion module and functions the same as PFCB producing AC power. Then the second module has rectification (the conversion AC voltage to DC voltage) and energy storage unit (intermediate capacitor). Third module is a voltage switching circuit which senses the voltage level of the intermediate capacitor and transfers it to the battery through DC-DC buck-boost converter and battery charging circuit. Fourth module is the model of buck-boost

converter and battery charging circuit represent exact characteristics of the LT1512 SEPIC constant current/voltage integrated circuit which is shown in Figure 90.



Figure 88: Intermediate voltage sensitive switch with hysteresis

This circuit is simulated with Switcher CAD III spice simulation tool the voltage level after intermediate capacitor and voltage sensitive switch simulation plot is shown in Figure 89. As depicted in Figure 89, $V_{(in)}$ (the capacitor voltage level) reaches only 15V then starts discharging by transferring voltage to the battery. When $V_{(in)}$ starts decreasing then $V_{(out)}$ increases until 15V while capacitor voltage at 15V. Both $V_{(in)}$ and $V_{(out)}$ start decreasing by transferring energy to battery. $V_{(out)}$ reaches zero voltage while transferring its energy to the battery, simultaneously $V_{(in)}$ value decreases as shown in Figure 89 in order to reach 15V again. The charge and discharge steps are repeated while PFCB produced electricity from vibrations.



Figure 89: Voltage input and output simulation of voltage sensitive switch

The DC-DC converter and battery charging circuit design which is parts of energy harvesting circuit simulation interface, is shown in Figure 90. This circuit simulation interface is employed to handle the decrease or increase of the voltage levels and fix it according to the battery specifications. The voltage output of the circuit can be easily modified by using different resistance values if different battery is integrated to the system.



Figure 90: Energy harvesting and battery charging circuit

The simulation graphs of the important circuit components through the LT1512 SEPIC battery charging circuit (including input voltage, battery charging voltage and current) were simulated and are depicted in Figures 91, 92, 93, and 94 respectively.



Figure 91: Input voltage (V_{IN}) simulation graph

In Figure 91, the input voltage (V_{IN}) simulation graph which was generated by the vibrations through the PFCB while being shaken is shown. This voltage level was measured after rectification of the AC voltage signal which came from the PFCB unit as a DC voltage, and served as the input for the buck-boost converter and the voltage regulator circuit. Since the maximum input voltage of an LT1512 integrated circuit is $30V_{MAX}$ a Zener diode was placed between V_{IN} and the ground of the LT1512 in order to avoid damaging the internal chip components of the LT1512. In Figure 92 the V_{IN} and V_{OUT} (regulated battery charging voltage) are compared in order to check the input and output voltage differences after regulation. The input voltage levels that were bigger or less than (3.6V) were regulated by the LT1512 buck-boost converter and battery charging
IC (Integrated Circuit) in order to charge the battery at the nominal voltage level which is 3.6V at 60mAh for the test battery.



Figure 92: Input (V_{IN}) and Output (V_{OUT}) voltage simulation graph

In Figure 93, I_{ROUT} (battery charging current) and V_{OUT} (battery charging voltage) simulation graphs are depicted to indicate battery charging values. Both voltage and current levels were supplied at steady state for proper battery charging $I_{ROUT}=5$ mA (which is standard charging current for the battery) and $V_{OUT}=3.6V$ nominal charging voltage. The charging current that was generated by the PFCB was less than 1mA but was increased to 5mA by the intermediate capacitors. The intermediate capacitors were charged to the minimum charging threshold of the battery and then released to the battery terminals by discharging themselves to allow them to accept charge voltages from the PFCB again. However, the current level was not able to increase to charge the battery at quick charge phase because of the low current produced by the PFCB. The specific voltage and current levels that are specified in Figure 93 can charge at 3.6V at 60mAh for a fully discharged battery in approximately 27hrs with constant vibrations from the PFCB.



Figure 93: Battery charging voltage (V_{OUT}) and current (I_{ROUT}) simulation graph

All three important aforementioned parameters of the energy harvesting and battery charging circuit were simulated together to examine the consistency of the voltage/current levels on the circuit design simulation interface, shown in Figure 94.



Figure 94: Battery charging values simulation

Considering the variable output voltages from the PFCB, an energy harvesting and charging circuit was designed in order to charge small scale NICD and NIMH batteries at the constant charging phase. The printed circuit board for the energy harvesting circuit is designed as small as possible to be placed either in the sneaker insole or the sides of the sneaker including the battery soldered on the circuit. However, for the test purposes the instrumentation circuit on the bread board and the energy harvesting circuit were placed near the sneaker with the PFCB assembled to allow reading of output values on the oscilloscope display. The energy harvesting circuit which is soldered on the printed circuit board (PCB) is shown in Figure 95.





This circuit can be designed and built smaller but necessary tools should be used during the soldering process of the very small electronic components. The dimensions of the energy harvesting circuit design on the PCB are small enough to allow it to be easily placed in a sneaker insole or in another proper place, including the storage unit soldered on the circuit. However, a protective box should be designed and built to protect the circuit components and the battery from bending and experiencing deformations from the foot steps.

Storage Unit Tests

One problem that is often encountered when using power harvesting systems is that the power produced by the piezoelectric material is often not sufficient to power most electronics. Therefore, methods of accumulating the energy in an intermediate storage device so that it may be used as a power source are needed. The method typically used to accumulate the energy was a capacitor. However, the capacitors have characteristics that are not ideal for many practical applications such as limited capacity and high leakage rates. For the purpose of intermediate storage units typical capacitors were used in the energy harvesting circuit without causing any critical issues. A group of capacitors were connected in parallel with the resistors in order to smooth the delivered voltage, making the output voltage easily read by the multi-meter. According to the approximate displacement and frequency levels the stored energy in the capacitors are calculated.

Displacement of PFCB: 4mm;

PFCB Voltage: 350V; and

Capacitor value: 400µF.

The 400μ F capacitor bank was charged to 50V in about 4 seconds. Taking the test results into consideration the energy stored in the capacitors are

$$E = \frac{1}{2}C.V^2 = \frac{1}{2}(400\,\mu F)(50V)^2 = 0.5J$$

Then 0.5J energy will allow having 1/8W (0.125W) of energy in 4 seconds as calculated here:

$$P = \frac{d}{dt}E = \frac{E}{\Delta t} = \frac{0.5J}{4Second} = \frac{1}{8}W(0.125W) \,.$$

It is assumed that 125mW energy would be sufficient to power a variety of low power wireless or portable electronics applications. The calculations above are valid if the PFCB is constantly shaken or vibrations are applied to the PFCB material. According to the manufacturer test results (ACI) E=880mJ energy can be stored in 13 seconds out of the PFCB vibrations. Taking the stored energy into consideration the average output power and current levels at different voltages were calculated below.

E=880mJ;

$$\Delta t=13 \sec;$$

 $P_{AVG} = \frac{E}{\Delta t};$
(31)

where

P_{AVG} =Average power;

E =Energy stored;

 Δt =Time takes to store the energy;

$$P_{AVG} = \frac{880mJ}{13 \sec} = 67.69mW;$$

V_{RMS}=0.1V, 0.2V... 10V;

$$I_{RMS}(V_{RMS}) = \frac{P_{AVG}}{V_{RMS}};$$
(32)

$$I_{RMS}(4V) = \frac{67.69mW}{4V} = 16.92mA$$
; and
 $I_{RMS}(3V) = \frac{67.69mW}{3V} = 22.56mA$.

The current levels for the battery charging purposes were calculated according to the input voltage levels. If the input voltage is increased then the output current would automatically increase by decreasing the battery charging time. All the calculations have been done according to the energy stored in 13 seconds (as reported by tests). The graph in Figure 96 compares voltage and current levels and average power output in thirteen seconds.



Figure 96: RMS Voltage/Current comparison depends on energy stored in thirteen seconds

When a resistive load is relatively large, the power output from the PFCB does not produce significantly more power. The results of using a larger capacitor to smooth the voltage output suggest that the size of the smoothing capacitor affects the amount of power that can be delivered to a resistive load (battery). This is attributed to the non-ideal behavior of the capacitor, which leads to internal losses. Following after construction of the energy harvesting circuit, NICD and NIMH type batteries were charged to determine the battery charging time that could be effectively observed for each with constant frequency. After testing the voltage levels of the PFCB using the capacitors, the PFCB was then tested with the batteries to observe battery charging efficiency. For this purpose a permanent magnet shaker was used to induce vibrations; two rechargeable batteries, and an energy harvesting circuit were used for the experimentation. A PFCB, consisting of two active fiber composites (bimorph) was clamped to a thin piece of metal of the constant shaker for the energy harvesting experiment. The photograph of battery testing is shown in Figure 97.



Figure 97: Battery charging test fixture

The batteries used in the experiment are listed in Table 17 with the basic specifications that are needed as charging parameters.

Table 17

Rechargeable battery specifications

	Name of Comp.	Nom. Voltage (V)	Ampacity (mAh)	Charge		Quick Charge		Charge time
Туре				I (mA)	Time (h)	I (mA)	T (h)	with PFCB (h)
NIMH	Ps Sonic	1.2	80	8	15		ikada da sa	47
NICD	Various	3.6	60	6	14	20	7	36
NIMH	Dantona Industry	3.6	60	6	14	20	7	41

In order to charge batteries the PFCB inter-digitized electrodes were connected to the battery terminals through the energy harvesting circuit. The constant vibrations from the shaker were applied to the PFCB at 60Hz. The voltage measurements out of the batteries were taken every hour and it appeared that the increase was very small. The reason for the slow charging was the very low current produced from the PFCB and the losses across the energy harvesting and battery charging circuit. Because of the low charging current, the test battery was not able to be charged at the specified standard charging time. However, this charging experiment was conducted only with a single PFCB which is not recommended for charging batteries. In some applications more than three PFCBs are connected in parallel to increase the current levels and efficiency of the energy harvesting system. The number of PFCBs would be increased to charge the batteries at a specified time frame to avoid voltage drops across the batteries while powering the electronic application. Furthermore this experimental test showed that batteries are being charged with constant current/voltage in longer time frames than the specific time frame in the battery datasheets. The last column in Table 17 shows the time that is taken to charge the batteries with one PFCB. If more then one PFCB is used for the energy harvesting system then charging time would be decreased considerably. Sneaker Sole Experiment

After investigation of characteristics of the both sneaker sole and the PFCB the engineering design of the overall mechanical system was modeled using Pro Engineer Wildfire 2.0 with real dimensions of all components. The components including a sneaker, a PFCB, the energy harvesting circuit, and a storage unit (were components separately designed). After the design of the all single components, an assembly model of the overall mechanical energy harvesting system was built. In Figure 98 the main Pro Engineer assembly of the overall energy harvesting system for the experiment of getting power from sneaker sole through human power is depicted. The Pro Engineer Wildfire 2.0 design was necessary to identify dimensions where all the parts were supposed to be fit when assembled together. This assembly model was very useful to figure out how to cut the sneaker insole and where to place the PFCB and the energy harvesting circuit. This design can be changed if more than one PFCB is placed into the sneaker insole to generate more power. In fact, during building the Pro Engineering assembly model, the researcher realized that there is enough space to put two more PFCBs by cutting the sneaker insole very carefully. However, the assembly model of the PFCB compartment

was built to place only one PFCB product. The number of the PFCBs which can be placed sneaker or shoe insole also depends on the thickness, length, and width of the shoe or sneaker dimensions.



Figure 98: Pro Engineer assembly model of the energy harvesting shoe experiment

After the assembly model was built, the sneaker sole was cut carefully to place the PFCB in the right place to obtain maximum efficiency when a person walks or runs. The base where the PFCB is placed was super glued with a piece of thin wood in order to place the PFCB properly on a smooth surface. Following putting the PFCB into the right place, the insole of the sneaker was again covered with the piece (taken from the sneaker sole) to avoid any damages when a person starts walking. Also couple of pennies is attached on the tip of the PFCB to increase vibration time while the PFCB is being shaken by the foot steps. The power output of the PFCB was directly proportional to the force and mass that were applied on the PFCB to induce vibrations. But the output power of the energy harvesting circuit was a constant voltage and current to avoid damaging the battery (because of the unregulated voltages produced by the PFCB). So the amount of energy that was generated by the human power through the PFCB was determined by the human power that is available to shake the piezoelectric material. The stronger the force and mass applied, the more electrical power was generated from the PFCB during walking or running of the person.

As a result of vibrations, the fibers in the frame of the shoe sole generated electricity with high potential and low current. The electricity was conducted and stored in a battery or capacitor in the circuit which was placed into a special compartment of the shoe insole. The proposed location of the piezoelectric fiber composites in the shoe sole has been shown in the Pro Engineer assembly model already. This section analyzed the basic power generation properties of the PFCB that is vibrating in the sneaker insole. The experimental results confirm the theory that with proper wiring and clamping of the PFCB to the appropriate place, the power generation efficiency of the PFCB increases the power output. The photograph of the redesigned sneaker insole with the assembled PFCB is shown in Figure 99. The wires coming out of the PFCB were extended by the wires to the energy harvesting circuit input. In order to avoid voltage drops due to long wires the PFCB and energy harvesting circuit should be placed close together. The test was conducted with one sneaker only due to the availability of one PFCB. The efficient point in this experiment is, if two sneakers (each with one PFCB attached) are worn then the vibrations of the both PFCBs never stop even if a person walks slowly. Once the first PFCB starts vibrating it takes at least one second until the vibrations stop. In this time period the other PFCB starts shaking when the person steps his or her foot again. This reduces battery charging time to almost half of the standard charging time as specified in the previous sections.



Figure 99: Redesigned sneaker insole with PFCB attached

Since the current level produced through the energy harvesting circuit for battery charging has been calculated, the next comparison which was conducted estimating whether the system could produce enough power for a typical MP3 player. The regular walking time was also calculated to compute how much walking is needed to compensate energy consumption of the electronic application. The block diagram for the estimation process is shown in Figure 100.



Figure 100: The block diagram of comparison estimation for energy harvesting

A sneaker sole as an ambient energy source was considered as a possible energy source to generate electricity through a PFCB to charge low scale rechargeable batteries. The batteries are expected to power low power electronic applications such as a radio, MP3 player, and mobile phone, or GPS unit. A typical MP3 was chosen as an electronic device to make the power estimation between generated and consumed power levels. It was expected that the source would generate enough power to run the electronic components of the MP3 player in an estimated time frame. It was proven above that the PFCB was able to produce enough voltage with low current as an input power to charge a small scale rechargeable battery, depending on the time a person walks or runs. Also the analytical estimation of the battery charging time and time for walking relationship were calculated for the fully discharged batteries. However, in the case of powering the electronic application, the batteries are placed in the system fully charged. It is essential to determine if the gained and stored power compensate for the consumption of the electronic device while it is operating. If the produced power compensates for the daily consumptions and the leakages of the electronic device, then it would be said that a sneaker sole as an ambient energy source is a feasible source for the electronic application. Overall energy use/gained relationship estimations were conducted considering (E_1) overall energy consumption and (E_2) energy gained from the PFCB in the sneaker insole through the human power.

$$E_{1 (LOSS/24HRS)} = [(P_{BATTERY_LEAKAGE}) + (P_{HARVEST_LEAKAGE}) + (P_{MP3_LEAKAGE}) + (P_{MP3})]$$
(33)

where

E _{1 (LOSS/24HRS)} :	Overall energy loss per 24 hours;
PBATTERY_LEAKAGE:	Leakage through batteries;
P _{HARVEST_LEAKAGE} :	Leakage through energy harvesting circuit;
P _{MP3_LEAKAGE} :	Leakage through MP3 player electronic circuit; and
P _{MP3} :	Energy consumption of the MP3 player.

Equation 33 calculates the overall energy consumption including the total leakages on stand-by mode of the MP3 player, energy harvesting circuit and batteries. According to Equation 33, it is also necessary to determine power consumption of the MP3 player (P_{MP3}) per usage separately before calculation of the overall energy

consumption. It is assumed that a person walks/runs about one hour in 24 hours. The power characteristics of a small low power MP3 player have been found from one of the MP3 manufacturers' data sheets (The general electrical specifications of the MP3 player examined were a little bit higher then a typical MP3 player). The specifications of the MP3 player were used to calculate the power consumption for one hour of use (P_{MP3}). Here,

I_{MP3}=0.060A (60mA);

 $V_{MP3} = 1.2V$; and

 $P_{MP3} = I * V$ =0.060 * 1.2 =0.072W (72mWh).

According to the specifications above the power consumption of the MP3 player in one hour is calculated above as 0.072W (72mW). So the power consumption of the MP3 player is 0.072W in one hour if used for one hour.

There are certain components in the system that are always at stand-by to sense the wake-up signals. These components drain some quiescent currents from batteries while they are on standby (including the MP3 player, the energy harvesting circuit, and the battery to keep the device up and running). The total leakages and quiescent current for the system components during the playing of MP3 player were calculated using Equation 33. Power consumption of MP3 player (P_{MP3}) was found separately and included in overall energy consumption in 24 hours as calculated below.

$$E_{1 (LOSS/24HRS)} = [(P_{BATTERY_LEAKAGE}) + (P_{HARVEST_LEAKAGE}) + (P_{MP3_LEAKAGE}) + (P_{MP3})]; so$$

$$E_{1 (LOSS/24HRS)} = [(270\mu A) + (984\mu A) + (13mA)] + [(60mA)]$$

$$= 74mAh.$$

The value for E_1 is converted to the power unit in order to make comparison between the power gain and the power loss. Then

$$E_{(LOSS/24HRS)} = 0.074A * 1.2V$$

$$= 0.088 Wh (88 mW).$$

As found above the total energy drained from the batteries was estimated is 0.088W for a day. This value is not exact energy consumption; it may change according to how often a person changes the parameters of the MP3 player during playing the device. Since total energy loss (E_1) estimation was estimated the next step was to calculate the energy gain from the energy harvesting system.

The estimation equation below enables calculation of the total gained energy from human power through the PFCB that is assembled in the sneaker insole during a day (24hrs), the battery charging time assumed.

Thus

$$E_{2 (GAIN/24HRS)} = EG; \text{ and}$$

$$EG = I * V;$$
(34)

where,

 $\mathrm{E}_{2\,(GAIN/24HRS)}$: Total energy recovered and stored from human power through

PFCB per 24 hours; and

EG: Energy gathered during walking of a person/hour.

For this application the gained energy from PFCB (E2) should be bigger than or equal to overall energy loss (E1) in 24 hours (E1 \leq E2). Otherwise the MP3 player would be operating inconsistently because of lack of sufficient energy. The total energy gained from the system would depend on time a person walks/runs during 24 hour period:

$$E_{2 (GAIN/24HRS)} = [EG (I * V)]; and$$

 $E_{2 (GAIN/24HRS)} = [(1.2V * 0.005A)]$
=0.012W (12mW).

After the calculation and conversion of E1 and E2 the comparison ratio of the gained and loss power are given below,

$$EG = \frac{E_{INPUT}}{E_{OUTPUT}}$$
(35)

where

EG	= Overall energy gain;
Eoutput	= Energy loss through MP3 player;
Einput	= Energy gain from PFCB; and

 $EG = \frac{12}{88} \cong 7.3$ energy loss.

As estimated above the energy gain is 7.3 times smaller than overall energy consumption of MP3 player in a day. The harvested and stored energy is not sufficient to run an MP3 player one hour long with the one hour daily walking. As estimated above the energy harvesting system from human power through a PFCB could not produce enough power for the MP3 player according to the power consumption comparisons. The energy loss/gain graph depends on time is given in Figure 101 to permit comparison of these variables visually.



Figure 101: Energy gain/loss depends on time a person walks/runs

Figure 101 shows that, the gained power is too low to play an MP3 player one hour long with one hour walking. To improve the energy gain, more than one PFCB should be placed into the sneaker insole to increase the generated power to balance the power consumption of the MP3 player. Also another solution make harvesting circuit efficient would be improving or redesigning the circuit to increase the current flow to the battery to decrease the battery charging time. Furthermore, if the time a person walks increases (more than one hour) then the battery charging time would be decreased depending on how long a person walks in a day.

CHAPTER V

CONCLUSIONS, SUMMARY AND RECOMMENDATIONS

This study focused on the implementation of three different low power energy harvesting systems from ambient energy sources. The goal was to test the viability of proposed energy harvesting systems through human power. This study implemented and evaluated three different energy harvesting systems: a hydraulic door closer, fitness equipment, and piezoelectric fiber composite bimorph. The implementation results from low power energy harvesting from ambient energy sources were efficient and proved the viability of the sources through human power. The developed systems were not shared with industrial companies to integrate their systems to protect the information until patent application.

The results and data analysis reported in Chapter IV present a number of remarkable points into the use and importance of energy harvesting and battery charging circuit designs to capture energy from ambient energy sources through human power. The following sections review and compare three experimental researches carried out in this dissertation. The study will be discussed, including both positive and negative results of development of the energy harvesting circuits for ambient energy harvesting used in this research study. The issues during the system development for the each energy harvesting system will also be detailed. Conclusions will be drawn founded on the specific research findings and outcomes. Recommendations for further study and improvements will be advised, along with a brief look at the industrial potential of the low power energy harvesting systems including the hydraulic door closer, fitness equipment, and sneaker sole implemented and detailed in this research.

Study Overview

The design of energy harvesting system for a hydraulic door closer was very challenging due to non-constant energy flow when activated by human power. An initial investigation was conducted to find out working characteristics of the device in order to design a gear train to increase the generated speed from the hydraulic door closer. The waste mechanical rotational speed was increased to supply sufficient speed to the generator unit. The speed ratio was carefully calculated to protect the generator's internal components due to high speed and torque. A low power DC generator unit was connected to the gearbox to produce electrical power for the rechargeable batteries. The generated power was stored in the rechargeable batteries for potential low power electronic applications around the door. After experimental battery charging tests it was realized that the number of people should be very high for the viability of the system. The developed energy harvesting should be used only where a lot of people enter the building using the door such as shopping malls, campus entrances, and big centers. The electronic device depends on the number of people who activate the hydraulic door closer, which must be calculated before building the system. Otherwise the energy harvesting system will not able to store sufficient energy for the electronic device. As an analytical estimation, an electronic security camera application was theoretically designed to compare the gained and used energy. The generated power in 24 hours was able to power the security camera system in specific time frames as explained in Chapter IV.

Also the development of the energy harvesting circuit was very challenging due to non-constant power produced by the generator unit. All the components of the harvesting and battery charging circuit were carefully selected to avoid major losses through the circuit. Also the circuit was protected from unexpected shorts and high voltages from the generator unit. Furthermore, the design of the energy harvesting circuit was flexible to allow adjustment of battery charging voltage/current once different size batteries are placed into the system.

There have been some issues while designing the gearbox to increase the waste mechanical speed from the hydraulic door closer. Since high torque is generated when door is opened by the human power, steel gear stets were needed to resist high torque while increasing the speed. Unfortunately steel gear sets and gearbox were not available due to budget and manufacturer backorder considerations. Instead plastic gear boxes were obtained to increase the speed (but gear teeth in the gearbox were broken due to high torques during the experimental test). The arms of the hydraulic door closer were moved very carefully to avoid breaking gear teeth during the tests. This issue was then solved by making a wood structure under the hydraulic door closer and gearbox to straight the both gearbox shaft and waste energy output section. The wood structures were helpful to reduce broken gear teeth in the gear box due to high torque.

The energy harvesting system from the fitness equipment took a very long time due to the manufacturing process of the mechanical part of the system. The investigation of the fitness equipment was conducted very carefully in order to build a mechanical wheel system to increase the speed for the generator unit. Then the Pro Engineer

assembly model was built in order to order the right parts and to avoid any interference issues between the mechanical parts. Initially the idea was to use a plastic gearbox to increase the speed ratio. However after the Pro Engineer model of the system was designed, it was realized that enough speed was generated by the mechanical system without need of the speed increase gear sets. According to the generated speed from the fitness equipment the appropriate generator units were added to the system for electrical energy efficiency tests. Three different DC motors were tested as generator units and two of them were able to generate sufficient energy to power the display of the fitness equipment. One of the brushless DC motors was not able to generate enough electrical power due to high input speed requirements of the motor unit. For this generator unit a speed increase gear ratio was needed to supply sufficient speed for the electricity generation. Overall the new mechanical energy harvesting system was able to harvest waste mechanical energy and produce useful electrical energy through a generator. Sufficient speed was increased with the help of gear head which made a DC motor generate and supply sufficient electrical power rechargeable batteries. The energy harvesting system could very efficiently power a fitness bicycle display, hence extending battery replacement time. Also the gained and stored power was able to supply enough energy to power additionally an integrated radio as estimated in Chapter IV.

There were two important considerations for the human kinetic energy used to activate the fitness bicycle. The first consideration was the technical feasibility of harvesting energy from human power mostly from regular activities. The second consideration was the economic viability of an overall energy harvesting device. In this section of the research the goal was to study the factors which are mentioned above in order to determine the overall feasibility of an energy harvesting and generation system that converted mechanical human energy dissipated by a fitness exercise bicycle into storable energy. This research relied on a person using the exercise bicycle to generate power from a normal workout routine to power the display and a 40mW small radio.

The energy harvesting circuit limited the generated power from the fitness bicycle. The circuit was built only to supply nominal voltage/current for the batteries and dissipated the rest of the power by grounding it electrically. However, the produced DC power could also be used for different applications such as for AC appliances by using a DC-AC inverter connected to a storage unit for a stable AC output. Depending on the daily workouts the generated power could be stored in big batteries to power AC home appliances. Building an AC electricity generation system would increase the cost of the overall energy harvesting system depend on the application.

As a last energy harvesting system research study the feasibility of piezoelectric fiber composites were investigated and tested thorough a PFCB. Before the decision of what piezoelectric material was to be used for the energy harvesting purposes an intensive market research was done. Previous studies found, some of the piezoelectric elements were not successful for energy harvesting systems. A piezoelectric fiber composite bimorph was purchased from the ACI for test purposes only. The company requested the researcher to share research results especially the energy harvesting circuit design with them as a condition since their product was new in the market for the energy harvesting purposes. The piezoelectric materials were used to perform power harvesting

that can convert the vibration energy into electrical energy by the effect of external (ambient) mechanical energy. The electrical energy then produced was regulated and stored to power low power electronic devices.

Chapter IV described a model to predict the amount of power capable of being generated through the vibration of the piezoelectric fiber composite bimorph with attached masses. This model provided a design tool for developing power harvesting systems by assisting in determining the size and level of vibration needed to produce the desired level of power generation. The method was to use the PFCB to obtain energy lost due to vibrations of the person while walking/running. The PFCB was placed into the sneaker insole for energy harvesting purposes. The PFCB assembled into sneaker insole was tested to charge small scale batteries for the low power electronic devices. It was assumed that captured energy could then be used to power the devices by providing endless energy. It has been found that a piezoelectric device provided an effective configuration of capturing vibrations and converting them into useful electrical power by providing high voltage and low current to the storage device. Unfortunately the low current from PFCB was not sufficient enough to charge the rechargeable batteries in a short time frame to power the electronic devices. One hour walking was not able to compensate one hour of playing a MP3 player power consumption as experienced in Chapter IV. The time of the walking/running should be increased to make system more viable for low power devices such as MP3 player, radio, or cell phones.

Piezoelectric elements have not shown considerable success in the field of low power energy harvesting systems. However, there are many intensive research studies

ongoing in this area both at the academic and market levels. Because of the budget limitations, the present study could not examine different types and sizes of PZT materials. Following the work in sensing, the ability to use the power generated by a PFCB to recharge batteries was discovered and the issues regarding the effectiveness of the PFCB as a power harvesting device were discussed.

Moreover an energy harvesting circuit was designed, developed, and implemented for the purpose of low power ambient energy harvesting. The first circuit design for energy harvesting from a hydraulic door closer was a DC-DC boost converter to increase a low power generation to charge the batteries. Two linear technology based integrated circuits were used for the purpose of charging 3.6V and 1.2V rechargeable batteries. The circuit was very efficient to capture waste mechanical energy through a generator and transmit the power to the batteries. No major losses were observed throughout the circuit other than the typical losses across the bridge rectifier diodes which were unavoidable. But the losses caused by full wave bridge rectifier diodes were reduced by using Schottky diodes which consumed less energy than typical diodes. For the fitness bicycle and PFCB energy harvesting purposes similar energy harvesting circuits were implemented with only minor changes due to the power characteristics of the sources. During the implementation of the energy harvesting circuit for the fitness bicycle experiment, the circuit was damaged a couple times due to unexpected high voltage/current produced by the generator. This problem was solved by adding a Zener diode to the input of the energy harvesting circuit limiting the voltage input to the circuit. Also an output resistor was added to the circuit before the batteries to limit the high current levels.

The Pro Engineer Wildfire engineering design tool was very helpful in design of the mechanical part of the energy harvesting system. Before the physical modeling and implementation of the three different systems all physical components were designed and then assembled together. The Pro Engineer models were also useful to determine the dimensions of the physical components to avoid any interference between the parts.

For the analytical simulation of the overall energy harvesting systems LMS Imagine Lab AMESim and MSC Easy5 one dimensional analytical simulation tools were used before implementing the systems. Easy5, an engineering analysis system, served as a software tool to simulate and analyze energy harvesting from the hydraulic door closer. Since Easy5 was a graphics based software tool, the overall energy harvesting system from the hydraulic door closer was modeled, simulated, and designed dynamically to permit changing the component variables easily. The energy harvesting system with specifications including speed increase gear sets, generator unit, energy conditioning circuit, and battery simulations were conducted using the MSC.Easy5 simulation and analysis tool. The specifications and working characteristics of the generator unit, and storage units were derived from the manufacturer datasheets. The analysis and simulation results then were compared with experimental test results to measure weather the efficiency of the Easy5 for generating proper results was the same. The experimental and simulation outcomes were almost same as the result of the energy harvesting system. The system was very useful to observe both mechanical and electrical energy flow parameters from the source until the battery reached a state of charge.

For the fitness bicycle and PFCB energy harvesting systems the AMESim one dimensional advanced engineering analysis and simulation tool was used for overall energy harvesting systems. All the simulation components for both systems were successfully derived and altered according to the manufacturer data sheets of the parts from the AMESim internal libraries. The analyses and simulations with real specifications of the overall components including wheel ratios, generator, circuit, piezoelectric fiber composite, spring and damping system, force and battery were successfully conducted resulting in almost the same outcomes when compared with the experimental results.

Moreover, In the AMESim and Easy5 simulation tools every component of the energy harvesting systems was included as separate modules. Checking the interoperability of all components by analyzing and simulating them reduced the redundancy of the energy harvesting systems after the development of the systems physically. In the design of the analytical simulation interfaces, the flexibility of the part modifications made it possible to change the parameters for future research. In both AMESim and Easy5 designs, the ambient energy source and related modules can be adjusted or modified easily to improve or change the energy harvesting system. The viability of the modules can be measured by simulating each module independently to adjust component specifications before the physical system developments and part ordering process. For example the plastic gear boxes were not strong enough for long physical tests to measure the battery charging time and generator type. The analytical simulation allowed the researcher to find out the parameters needed to produce results after the long time test application. Incorporating the analytical simulation and physical development of the energy harvesting systems allowed the researcher to investigate the system both analytically and physically and to make comparisons. The contributions of these software tools to the research were extraordinary before and after the physical development of the systems. After the completion of the physical energy harvesting systems some of the redundancies between the components were fixed by changing the simulation parameters of the modules to replace the parts with proper ones. For example the shaking decay times of the piezoelectric fiber composite were successfully investigated by AMESim by different displacements and applied forces to determine battery state of charge. Also the vibration source which was shoe insole can be changed anytime without any major changes of the simulation interface to apply the PFCB to different ambient energy sources. Also both AMESim and Easy5 can be programmed to measure efficiency of the different ambient energy sources before the actual physical development of the energy harvesting systems.

All three different ambient energy sources showed different efficiencies for electrical energy generations by human power activities during the daily life. The contributions of this work would open new research areas and reduce energy consumption of low power electronic applications as well as battery replacement times. The development of fast charging batteries will make the low power energy harvesting systems more powerful in the near future and may completely replace the conventional batteries by fast charging rechargeable batteries and supercapacitors.

This research study incorporated a variety of disciplines such as mechanical, electrical, computer, and industrial engineering, and manufacturing technology process in order to build energy harvesting systems. The researchers from different disciplines can participate to intensive research attempts by incorporating their knowledge to develop energy harvesting systems. The limited knowledge being expert in only one discipline may reduce the research efficiency and cause some inconsistencies. The intensive investigation was conducted during the development of the system to determine working principles of all the components and collaborated with an industrial partner which is a well known Agricultural implement manufacturer in the Midwest. The engineers especially from electronics, mechanical, sensor and simulation analysis groups made major contributions by stating their ideas to utilize an efficient energy harvesting system. Especially the piezoelectric fiber composite energy harvesting techniques attracted some of the engineers' attentions for further research attempts for that Company's equipments. This research can be extended by adding new components or more work to improve the system for different purposes.

Recommendations for Future Study

All three research attempts that have been studied in this dissertation may be extended for future work by improving the developed energy harvesting systems. The energy harvesting system from the hydraulic door closer is going to be improved and information package files will be prepared for the patent application. After the patent application, taking the viability of the system into consideration the developed energy harvesting system would be shared with a hydraulic door closer manufacturer. The mechanical design of the energy harvesting system can be redeveloped and placed inside of the hydraulic door closer with the gear train by decreasing the size of the components. Also the spring and damping system of the hydraulic door closer can be redesigned by adding gear train to make the hydraulic door closer a multi purpose device. The multi purpose hydraulic door closer would handle both opening/closing phases of the door and generating electricity for the low power electronics. Also the energy harvesting circuit would be designed as small as possible to be easily placed inside of the hydraulic door closer with the storage unit.

For the energy harvesting system from fitness equipment, it was not anticipated to bring any final product to market. The research was conducted only to investigate the feasibility of the energy harvesting system to power the display electronics. The developed mechanical system can be manufactured to be smaller and more reliable if developed by the fitness equipment company during the manufacturing process. Manufacturers can place a small gear-head motor with a small ratio to generate sufficient power for the display either using rechargeable batteries or super capacitors. The wires coming out from the generator can be extended until the battery box or display unit of the fitness equipment. This energy harvesting system will be suggested to the fitness equipment manufacturers as a future work.

The advances made from the work presented in this research will provide future researchers with the tools necessary to use PFCB effectively in numerous applications. The sensing capabilities of the PFCB were investigated and its abilities were shown in an energy harvesting system through a sneaker insole experiment and battery charging circuit. The energy harvesting circuit should be improved to increase current levels from the PFCB while decreasing voltage levels for the battery charging purposes. The increase of current during the vibration of PFCB would decrease the battery charging time by supplying more energy to the electronic device. Also the PFCB can be placed around the door or in the hydraulic door closer to capture the wasted human power. A special design would be constructed to create vibrations when door is opened by the human power. The special design should be placed a proper place where the most vibrations can be created for the energy harvesting purposes.

Summary of the Study

Three different low power energy harvesting techniques were studied in this research dissertation. Only first section energy harvesting from hydraulic door closer would have been reasonable research study. However two more techniques were added to the study to gain more knowledge about low power energy systems by providing research outcomes to the academic society. While improving the techniques that have been studied in this research, academic research papers will be planned for publication in a variety of journals or presented in scientific conferences. Since the concept of energy harvesting from ambient energy sources is so broad, encompassing mechanical, electrical, computer, and ceramic engineering, a variety of software tools were learned and used for the purpose of energy harvesting. For example using one dimensional analytical simulation tools such as AMESim and Easy5, different energy harvesting techniques can be studied to find out the feasibility of the system before the implementation. Also the mechanical or overall 3D engineering design would be very useful to design the system to figure out

the right components with the proper dimensions before purchasing the implementation parts. The software tools should be used for both electrical and mechanical parts of the energy harvesting systems for accurate implementations. It was very difficult to understand the meaning of the variables and parameters of the default modules to create the simulation of energy harvesting from PFCB.

REFERENCES

- About Fuel Cells. (2008). Retrieved May 9, 2008, from http://web.mit.edu/afs/athena.mit.edu/org/m/mecheng/fcp/about%20f%20cells.html
- Adler, R., Desmares, P., & Spracklen, J. (1982). Ultrasonic Remote Control for Home Receivers, IEEE Trans. Consumer Electronics, 28 (1), 123–128.
- ACI, Advanced Cerametrics Incorporated. (2007). Retrieved May 19, 2008, from http://www.advancedcerametrics.com/pages/energy_harvesting_components/
- Advanced Cerametrics Incorporated. (2007). Retrieved December 16, 2007, from http://www.advancedcerametrics.com/
- Advanced Linear Devices Inc., (2006). Retrieved January 7, 2008, from http://www.aldinc.com/pdf/EH300ds.pdf
- Alessandrini, F., Conte, M., Passerini, S., & Prosini, P.P. (2000). Overview of ENEA's projects on lithium batteries. *Journal of Power Sources*, 97-98, pp.768-71.
- Ambient Energy Generator Technology. (2006). Retrieved May 24, 2008, from http://www.alternative-energy-news.info/ambient-energy-generator-technology/
- Amirtharajah, R., & Chandrakasan, A. P. (1998). Self-powered signal processing using vibration-based power generation. *IEEE Journal of Solid-State Circuits*, 33 (5), 687-695.
- Amirtharajah, R., Wenck, J., Collier, J., Siebert, J., & Zhou, B. (2006). Circuits for Energy Harvesting Sensor Processing. DAC The 43rd Design Automation Conference, San Francisco California.
- Ammar, Y., Buhrig, A., Marzencki M., Charlot, B., Basrour S., Matou, K., & Renaudin, M. (2005, October 12th - 14th). Wireless sensor network node with asynchronous architecture and vibration harvesting micro power generator. *Smart Objects & Ambient Intelligence*, Grenoble, France.
- Bridge Rectifier. (2008). Retrieved May 29, 2008, from http://hyperphysics.phy-astr.gsu.edu/Hbase/electronic/rectbr.html
- Bomgren, G. E. (2002). Perspectives on portable lithium ion batteries liquid and polymer electrolyte types. Proceedings of the 17th Annual Battery Conference on Applications and Advances, p. 141-4.

- Briole, S., Pacha, C., Goser, K., Kaiser, A., Thewes, R., Weber, W., & Brederlow, R. (2004) AC-only RF ID tags for barcode replacement, in ISSCC 2004 *Digest of Technical Papers*, pp. 438-9.
- Chapuis, M. (2006). Energy Harvesting for Wireless Sensor Networks. WSN, Advanced Technology, Phoenix International.
- Cope, R.C., & Podrazhansky, Y. (1999). *The art of battery charging*. 14th Annual Battery Conference on Applications and Advances, 233-235.
- Computer Hardware and Micro-Scope. (2008). Retrieved May 8, 2008, from http://www.micro2000uk.co.uk/hardware glossary.htm
- DC-DC Converter Basics. (2008). Retrieved May 18, 2008, from http://www.powerdesigners.com/InfoWeb/design_center/articles/DC-DC/converter.shtm
- DeGreeff J., Fleig P., & Lakeman, C. (2005). MEPS MEMS Electrochemical Power Supplies: A Solution For Integrated Power For Microsystems. TPL, Inc. Medical Electronics Symposium.
- Designing A SEPIC Converter Introduction. (2008). Retrieved May 11, 2008, from http://www.national.com/an/AN/AN-1484.pdf
- DiSalvo, F. J. (1999). Thermoelectric cooling and power generation. *Science*, 285, 703-706.
- Dinesh, B., & Abhiman, H. (2005). Energy Harvesting Methodologies for Wireless Sensor Nodes. Erik Johnson School of Engineering, The University of Texas.
- DiracDelta Science & Engineering Encyclopedia, (2008), Quiescent Current, Retrieved May 9, 2008, from http://www.diracdelta.co.uk/science/source/q/u/quiescent%20current/source.html
- Diodes. (2008). Retrieved May 20, 2008, from http://www.kpsec.freeuk.com/components/diode.htm
- Door closer. (2008). Retrieved May 11, 2008, from http://www.answers.com/topic/door-closer?cat=technology
- Duty cycle. (2008). Retrieved May 30, 2008, from http://www.tscm.com/dutycy.pdf
- Electric motors and generators. (2007). Retrieved May 22, 2008, from http://www.physclips.unsw.edu.au/jw/electricmotors.html#DCmotors

- FreePlay energy, (2007). Retrieved December 11, 2007, from http://www.freeplayenergy.com/products
- Friedman, D., Heinrich, H., & Duan, D-W. (1997). A Low-Power CMOS Integrated Circuit for Field-Powered Radio Frequency Identification. Proceedings of the 1997 IEEE Solid-State Circuits Conference, p. 294 – 295, 474.
- F1 technical glossary. (2008). Retrieved May 17, 2008, from http://www.f1technical.net/glossary/g
- Ganesan, D. (2006). Energy Harvesting Techniques I. Lecture notes, Computer Science Department, University of Massachusetts Amherst. Retrieved October 16, 2007, from http://www.cs.umass.edu/~dganesan/courses/fall06
- Halber, D. (2006). Researchers fired up over new battery. News Office Correspondent, Massachusetts Institute of Technology. Retrieved November 13, 2007, from http://web.mit.edu/newsoffice/2006/batteries-0208.html
- Hande, A., Polk, T., Walker, W., & Bhatia, D. (2006). Self-Powered Wireless Sensor Networks for Remote Patient Monitoring in Hospitals. Sensors 2006, 6, 1102-1117, ISSN 1424-8220.
- Harrison, R. (2004). Low Power Circuit Design. Lecture notes, Department of Electrical and Computer Engineering, University of Utah.
- Holmes, A. S. (2004). Axial-Flow Microturbine with Electromagnetic Generator: Design, CFD Simulation, and Prototype Demonstration. Proceedings of 17th IEEE International Micro Electro Mechanical Systems Conf. (MEMS 04), IEEE Press, 568–571.
- Horowitz, S., Kasyap, A., Liu, F., Johnson, D., Nishida, T., Ngo, K., Sheplak, M., & Cattafesta, L. (2002). *Technology Development for Self-Powered Sensors*. Proceedings of 1st Flow Control Conference, St Louis.
- How Motors Work. (2008). Retrieved May 28, 2008, from http://www.stefanv.com/rcstuff/qf200212.html
- IEEE Wireless Zone. (2008). Retrieved May 30, 2008, from http://www.ieee802.org/15/pub/TG4.html
- Introduction to ANSI. (2008). Retrieved May 21, 2008, from http://www.ansi.org/about_ansi/introduction/introduction.aspx?menuid=1

- Introduction to Electric Motors. (2008). Georgia State University.Retrieved January 2, 2008, from http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/elemot.html#c3
- Justin, R., F. (2007). A comparison of power harvesting techniques and related energy storage issues. Master Thesis, Master of Science in Mechanical Engineering, Virginia Polytechnic Institute and State University.
- Jiang, X., Polastre, J., & Culler, D. (2005). Perpetual Environmentally Powered Sensor Networks. The 4th International Conference on Information Processing in Sensor Networks: Special track on Platform Tools and Design Methods for Network Embedded Sensors IPSN 2005: 463-468, April 25-27
- Kang, S., Lee, S-J. J., & Prinz, F.B. (2001). Size does matter: the pros and cons of miniaturization. ABB Review, 2, p.54-62.
- Kasap, S.O. (2001). Optoelectronics and Photonics. Principles and Practices, New Jersey: Prentice-Hall
- Kasyap, A., Lim, J. S., Johnson, D., Horowitz, S., Nishida, T., Ngo, K., Sheplak, M., & Cattafesta, L. (2002). *Energy Reclamation from a Vibrating Piezoceramic Composite Beam*. Proceedings of 9th Int. Conference on Sound and Vibration, Orlando.
- Kulah, H., & Najafi, K. (2004). An electromagnetic micro power generator for lowfrequency environmental vibrations. 17th IEEE International Conference on Micro Eletro Mechanical Systems (MEMS), 237-240.
- Lang, S. B. (2005). Pyroelectricity: From Ancient Curiosity to Modern Imaging Tool. Changes in the net dipole moment of certain materials form the basis for a broad range of IR detectors. Retrieved December 24, 2007, from http://www.physicstoday.org/vol-58/iss-8/p31.html
- Leland, Eli S., Lai, Elaine M., & Wright, Paul K. (2005). A Self-Powered Wireless Sensor For Indoor Environmental Monitoring. Department of Mechanical Engineering, University of California, Berkeley.
- Linear Technology. (2007). Retrieved May 1, 2008, from http://www.linear.com
- List of battery sizes. (2008) Wikipedia. Retrieved January 9, 2008 from http://en.wikipedia.org/lisfofbatterysizes
- LMS Imagine.Lab AMESim. (2008). Retrieved December 12, 2007, from http://www.lmsintl.com/imagine
- Lopez, J., M., Gonzalez, J., Viera, C., & Blanco, C. (2004). Fast-charge in lithium-ion batteries for portable applications, 26th Annual International Telecommunications Energy Conference, 19-24, 2004.
- LTspice/SwitcherCAD III. (2007). Retrieved May 14, 2008, from http://www.linear.com/designtools/software/index.jsp#Spice
- Mabuchi motor specifications. (2007). Data sheets for typical application requirements. Retrieved December 21, 2007, from http://www.mabuchi-motor.co.jp/cgibin/catalog/e_catalog.cgi?CAT_ID=fa_130ra
- Magnetic Field. (2008). Retrieved May 23, 2008, from http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/magfie.html
- Marzencki, M. (2005). Vibration energy scavenging. European Commission research Project VIBES (IST-1-507911) of the 6th STREP Framework Program.
- Maxim. (2007). Operational Amplifiers, Retrieved May 2, 2008, from http://www.maxim-ic.com/appnotes.cfm/an_pk/1108
- Maxwell Technologies PC-5 Ultracapacitors. (2007). Retrieved December 28, 2007, from http://www.maxwell.com/ultracapacitors/products/small-cell/pc-5.asp
- Mehra, A., Zhang, X., Ayon, A. A., Waitz, I. A., Schmidt, M. A., & Spadaccini, C. M., (2000). A Six-Wafer Combustion System for a Silicon Micro Gas Turbine Engine. Journal of Microelectromechanical Systems, 9 (4) 517-526.
- Meninger, S., Mur-Miranda, J. O., Amirtharajah, R., Chandrakasan, A. P., & Lang, J. H. (2001). Vibration-to-electric energy conversion. *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, 9 (1), 64-76.
- Mikami, S., Tetsuro, M., Masahiko, Y., & Hiroko, O. (2005). A wireless-Interface SoC Powered by Energy Harvesting for Short-range Data Communication. IEEE 0-7803-9162-4/05 2005.
- Mitcheson, P. D., Green, T. C., Yeatman, E. M., & Holmes, A. S. (2004). Analysis of Optimized Micro-Generator Architectures for Self-Powered Ubiquitous Computers. Imperial College of Science Technology and Medicine.
- Mosfets. (2008). Retrieved May 14, 2008, from http://whatis.techtarget.com/definition/0,,sid9_gci214511,00.html#
- MPower Battery Technology Glossary. (2008). Retrieved May 26, 2008, from http://www.mpoweruk.com/glossary.htm

MSC.Easy5 General Documentation (2004). MSC. Software Corporation, Bellevue, WA.

- NI-CD Battery Training. (2008). Retrieved May 15, 2008, from http://www.rcbatteryclinic.com/seminar.htm
- NI-MH Battery Training. (2008). Retrieved May 17, 2008, from http://www.rcbatteryclinic.com/seminar.htm
- O'Shea, P. (2007). Energy harvesting modules unveiled for wireless sensor nets. EETIMES, http://www.eetimes.com/showArticle.jhtml?articleID=197003779
- Ottman, G., K., Hofmann, H., F., & Lesieutre, G., A. (2002). Optimized Piezoelectric Energy Harvesting Circuit Using Step-Down Converter in Discontinues Conduction Mode. *IEEE 0-7803-7262-X/02*.
- Overview of Electric Motors. (2007). Georgia State University. Retrieved November 24, 2007, from http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/elemot.html#c3
- Pacific Northwest National Laboratory (PNNL), *Available Technologies*. (2007). Patent Pending, Battelle Number(s): 12398-E, 13664-B, Retrieved December 7, 2007, from http://availabletechnologies.pnl.gov/technology.asp?id=85
- Paradiso, Joseph A., & Starner, T. (2005). Energy Scavenging for Mobile and Wireless Electronics. Published by the IEEE CS and IEEE ComSoc 1536-1268/05 © IEEE.
- Paradiso, J., & Feldmeier, M. (2001). A Compact, Wireless, Self-Powered Pushbutton Controller. Ubicomp: Ubiquitous Computing, LNCS 2201, Springer-Verlag, 299– 304.
- Peak-to-Peak. (2008). Glossary. Retrieved May 30, 2008, from http://whatis.techtarget.com/definition/0,,sid9_gci213724,00.html
- Pecen, R., Yildiz, F., & Baltaci, K. (2007). A Lab View PDS v8.20 Based Novel DATA Acquisition and Interface Module for a 500 W Hydrogen Fuel-Cell Power Station Unit. Proceedings of the National Association of Industrial Technology Conference, Panama City, Florida.

Pescovitz, D. (2002). The Power of Small Technology. Smalltimes, 2 (1).

Photovoltaic cell. (2008). Glossary. Retrieved May 30, 2008, from http:searchcio-midmarket.techtarget.com/sDefinition/0,,sid183_gci1028949,00.html

- Piezoelectricity. (2008). Glossary, Retrieved May 30, 2008, from http://www.wisegeek.com/what-is-piezoelectricity.htm
- Portable Power Design Seminar. (2004). Texas Instruments. Retrieved January 5, 2008, from http://focus.ti.com/lit/ml/slyp085/slyp085.pdf
- Power Generation, Tellurex. (2007). Retrieved December 12, 2007, from http://www.tellurex.com/powergeneration.html
- Pro Engineer Wildfire CAD. (2008). Retrieved May 11, 2008, from http://www.ptc.com/products/proengineer/
- Rabaey, J. M., Ammer, M. J., Da Silva Jr, J. L., Patel, D., & Roundy, S. (2000). Picoradio supports ad hoc ultra-low power wireless networking. IEEE Computer, pp. 42–48.
- Raffaelle, R.P., Underwood, J., Scheiman, D., Cowen, J., Jenkins, P., Hepp, A. F., Harris J., & Wilt, D. M. (2000). *Integrated solar power systems*. 28th IEEE Photovoltaic Specialists Conference, 1370-1373.
- Raghunathan, V., Kansal, A., Hsu, J., Friedman, J., & Srivastava, M. (2005). Design Considerations for Solar Energy Harvesting Wireless Embedded System. IEEE 0-7803-9201-9/05.
- Raghunathan, Vijay, & Chou Pai, H. (2006). Design and Power Management of Energy Harvesting Embedded Systems. ISLPED, ACM 1-59593-462-6/06/0010, Germany.
- Randall, J. F. (2003, May). On Ambient Energy Sources for Powering Indoor Electronic Devices. Ph.D Thesis, Ecole Polytechnique Federale de Lausanne, Switzerland.
- Rated Voltage. (2007). Glossary. Retrieved May 30, 2008, from http://www.icorally.com/glossary_convtables/glossary.html
- Rated Power. (2007). Glossary. Retrieved May 30, 2008, from http://www.icorally.com/glossary_convtables/glossary.html
- Responding to climate change. (2007). Alternative energy, Retrieved May 30, 2008, from http://www.rtcc.org/2007/html/glossary.html
- Rogers, A., L., Manwell, J. F., & Wright, S. (2002) *PE, Wind Turbine Acoustic Noise*. Renewable Energy Research Laboratory, Department of Mechanical and Industrial Engineering.University of Massachusetts at Amherst.

- Root mean square. (2008). Retrieved May 7, 2008, from http://searchciomidmarket.techtarget.com/sDefinition/0,,sid183_gci213722,00.html
- Roundy, S. J. (2003). Energy Scavenging for Wireless Sensor Nodes with a Focus on Vibration to Electricity Conversion. A dissertation, The University of California, Berkeley.
- Roundy, S., Steingart, D., Fréchette, L., Wright, P. K., & Rabaey, J. (2004). Power Sources for Wireless Networks. Proceedings of 1st European Workshop on Wireless Sensor Networks (EWSN '04), Berlin, Germany.
- Roundy, S., Wright, P. K. (2004). A piezoelectric vibration based generator for wireless electronics. *Smart Materials and Structures*, 13, 1131-1142
- Roundy, S., & Wright, P. K., & Pister, K. S. (2002). *Micro-electrostatic vibration-toelectricity converters*. Proceedings of the ASME International Mechanical Engineering Congress and Expo.
- Roundy, S., Wright, P. K., & Rabaey, J. (2003). A study of low level vibrations as a power source for wireless sensor nodes. *Computer Communications*, 26, 1131-1144.
- Roundy, S., Wright, P. K., & Rabaey J. (2004). Energy Scavenging For Wireless Sensor Networks With Special Focus On Vibrations. New York: Kluwer Academic Publishers.
- Rowe, D. M. (1999). Thermoelectrics, an environmentally-friendly source of electrical power. *Renewable Energy*, 16,1251-1256.
- Römer, K., & Friedemann, M. (2004). The Design Space of Wireless Sensor Networks, IEEE Wireless Communications 11 (6): 54-61.
- Ruddle, J., Cass, R., & Mohammedi, F. (2007), Advanced Cerametrics Harvests Clean Energy. 109th Annual Meeting, *American Ceramic Society Bulletin*, 86 (10).
- Seebeck coefficient. (2008). Glossary of Terms. Retrieved May 30, 2008, from http://weedinstrument.com/info_central/glossary/s.html
- Self Contained Generating and Lighting Unit (1916), US patent 1,184,056, Patent and Trademark Office, 1916.
- Serway, R. A., & Jewett, Jr. J. W. (2003). Physics for Scientists and Engineers. 6th Ed. Kentucky: Brooks Cole. ISBN 0-53440-842-7.

- Schottky Diode. (2008). Glossary of Terms. Retrieved May 21, 2008, from http://www.elpac.com/resources/glossary/index.html
- Shenck, N. S., & Paradiso, J. A. (2001). Energy Scavenging with Shoe-Mounted Piezoelectrics, IEEE Micro, 21, 30-41
- Shengwen, Xu., Khai, D. T. Ngo, Toshikazu, N., Gyo-Bum, C., & AttmaSharma. (2005). Converter and Controller for Micro-Power Energy Harvesting. IEEE 0-7803-8975-1/05.
- Sim, W. Y., Kim, G. Y., & Yang, S. S. (2001). Fabrication of micro power source (MPS) using a micro direct methanol fuel cell (μDMFC) for the medical application. Technical Digest. MEMS, 341-344.
- Skoog, D. A., Holler, J. F., & Crouch, S. R. (2006). *Principles of Instrumental Analysis*. 6th Edition, Florence, KY: Cengage Learning, Brooks Cole.
- Sodano, H. A., Inman, D.J., & Park, G. (2004). A review of power harvesting from vibration using piezoelectric materials. *The Shock and Vibration Digest*, 36 (3), 197-205.
- Solar glossary. (2008). Retrieved May 30, 2008, from http://www.kyocerasolar.com/learn/glossary.html
- Starner, T. (1996). Human-powered wearable computing. *IBM Systems Journal*, 35 (3), 618-629.
- Starner, T., & Paradiso, J. A. (2004). *Human-Generated Power for Mobile Electronics*. Low-Power Electronics Design, C. Piguet, ed., CRC Press, chapter 45, 1–35.
- Sterken, T., Fiorini, P., Baert, K., Puers, R., & Borghs, G. (2003). An Electret-Based Electrostatic μ- Generator. IEEE 0-7803-7731-1/03.
- Stevens, J. (1999). Optimized Thermal Design of Small Thermoelectric Generators. Proceedings of 34th Intersociety Energy Conversion Eng. Conference. Society of Automotive Engineers, 1999-01-2564.
- Stordeur, M., & Stark, I. (1997). Low Power Thermoelectric Generator self-sufficient energy supply for micro systems. 16th International Conference on Thermoelectrics, 575 – 577.
- Sun, W., Kherani, N. P., Hirschman, K. D., Gadeken, L. L., & Fauchet, P.M. (2005). A three-dimensional porous silicon p-n diode for betavoltaics and photovoltaics. *Advanced Materials*, 17, 1230-1233.

- Supercapacitors. (2008). Retrieved January 3, 2008, from http://www.nec-tokin.com/english/product/pdf_dl/SuperCapacitors.pdf
- Switching Regulator. (2008). Glossary of Terms. Retrieved May 16, 2008, from http://www.elpac.com/resources/glossary/index.html
- Textile Glossary. (2008). Retrieved May 27, 2008, from http://www.intrend.biz/glossary.asp?letter=e
- The Crystal Lattice. (2008). Retrieved May 24, 2008, from http://hyperphysics.phyastr.gsu.edu/Hbase/Solids/lattice.html
- The lithium-ion battery. (2008). Retrieved May 13, 2008, from http://www.batteryuniversity.com/partone-5.htm
- The LMS Imagine.Lab AMESim Suite. (2007). Retrieved May 30, 2008, from http://www.lmsintl.com/imagine-amesim-platform
- Thermistor. (2008). Glossary of Terms. Retrieved May 24, 2008, from http://www.elpac.com/resources/glossary/index.html
- Thomas, J., Clark, J. W., & Clark, W. W. (2005). *Harvesting Energy from Piezoelectric Material*. University of Pittsburgh, 1536-1268 IEEE Published by the IEEE CS.
- Torres, E. O., & Rincón-Mora, G. A. (2005). Energy-harvesting chips and the quest for everlasting life. IEEE Georgia Tech Analog and Power IC Design Lab.
- Toshiba. (2003). Fuel Cell Powered Laptop computers. Retrieved January 3, 2008, from http://www.toshiba.co.jp/about/press/2003_03/pr0501.htm
- Transceiver. (2008). Glossary. Retrieved May 23, 2008, from http://fcit.usf.edu/network/glossary.htm
- UNIROSS Industrial. (2008). Retrieved May 6, 2008, from http://www.uniross.com/UK/industrial/glossary/07
- Uses for Gears. (2008). Retrieved May 13, 2008, from http://www.howstuffworks.com/gear-ratio4.htm
- What is MEMS Technology. (2008). Retrieved May 21, 2008, from http://www.memsnet.org/mems/what-is.html
- What Is NI Multisim. (2008). Retrieved May 16, 2008, from http://www.ni.com/multisim/whatis.htm

- What is RFID. (2008). Retrieved May 15, 2008, from http://www.technovelgy.com/ct/Technology-Article.asp?ArtNum=1
- What's the role of the Supercapacitor. (2008). Retrieved May 13, 2008, from http://www.batteryuniversity.com/partone-8.htm
- Yaglioglu, O. (2002). Modeling and Design Considerations for a Micro-Hydraulic Piezoelectric Power Generator. Master's thesis, Department of Electrical Eng. and Computer Science, MIT.
- Yeatman, E.M. (2004). Advances in Power Sources for Wireless Sensor Nodes. Proceedings of International Workshop on Wearable and Implantable Body Sensor Networks, Imperial College, 20–21.
- Yildiz, F., Zhu, J., & Pecen, R. (2007). Techniques of Harvesting Ambient Energy Sources & Energy Scavenging Experiments, Design and Implement an Energy Harvesting Device. Proceedings of the NAIT Conference, Panama City, Florida.