Energy Scavenging from Vibrations

Lecture 1
Energy Harvesting or Energy Scavenging

The process by which ambient energy is captured and stored. This term is often used when dealing with small amounts of energy.

This introduction slide is intended to spark the students’ interest on the topic of this project. The “Spy-bat” shown in the figure is being developed at the University of Michigan. This is a 6 inch plane powered by energy scavenged from the sun, wind, and vibrations. It is built to gather data from sights, sounds and smells and transmit information in real time.
Energy Harvesting

- Wind
- Water
- Solar
- Temperature
- Vibration
Energy Scavenging Estimates

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Harvested Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration/Motion</td>
<td></td>
</tr>
<tr>
<td>Human</td>
<td>4 uW/cm²</td>
</tr>
<tr>
<td>Industry</td>
<td>100 uW/cm²</td>
</tr>
<tr>
<td>Temperature Difference</td>
<td></td>
</tr>
<tr>
<td>Human</td>
<td>25 uW/cm²</td>
</tr>
<tr>
<td>Industry</td>
<td>1 – 10 mW/cm²</td>
</tr>
<tr>
<td>Light</td>
<td></td>
</tr>
<tr>
<td>Indoor</td>
<td>10 uW/cm²</td>
</tr>
<tr>
<td>Outdoor</td>
<td>10 mW/cm²</td>
</tr>
<tr>
<td>RF</td>
<td></td>
</tr>
<tr>
<td>GSM</td>
<td>0.1 uW/cm²</td>
</tr>
<tr>
<td>WiFi</td>
<td>0.001 uW/cm²</td>
</tr>
</tbody>
</table>

The instructor should ensure that all students understand well the meaning of “mili” and “micro” used in the units shown in this figure.
Wind energy harvesting has been used for a very long time, e.g. to power sailboats in ancient Egypt (3200 BC), to grind grain in medieval times.
Solar

According to recent studies, an array of solar panels in the Sahara dessert can meet all the power needs of Europe.

Some scientists think they can use the sun’s light to cheaply propel an unmanned craft deep into the interstellar ether.
NASA’s Solar Sail Video

This is a an embedded video that was last accessed from:
http://www.youtube.com/watch?v=eq2DATxcft0 on January 17, 2010
At Oregon State University, Sea Grant engineering researchers have been developing wave energy extraction devices.

Worldwide, hydropower plants produce about 24 percent of the world's electricity and supply more than 1 billion people with power.
Temperature

Heat pumps move heat from one place to another, e.g. from outside to inside a home.

Geothermal heat relies on the stable, even heat of the earth to provide heating, air conditioning and, in most cases, hot water.
Geothermal Heating Video

This is an embedded video that was last accessed from:
http://www.youtube.com/watch?v=-ajqiPe_9Ko on January 17, 2010
Temperature – Micro scale

A thermoelectric generator is made of thermopiles sandwiched between a hot and a cold plate. Thermopiles are made of a large number of thermocouples connected thermally in parallel and electrically in series.

Thermal energy scavengers are thermoelectric generators (TEGs) which exploit the Seebeck effect to transform the temperature difference between the environment and the human body into electrical energy. A thermoelectric generator is made of thermopiles sandwiched between a hot and a cold plate. Thermopiles are in turn made of a large number of thermocouples connected thermally in parallel and electrically in series, as shown schematically in the figure on the right side. The red and blue pillars represent the two types of thermoelectric materials, and the metal interconnects are drawn in gold. The pink and blue plates are respectively the cold and hot sides of the device. The load is the device that consumes the power generated. In the example illustrated here the load is the wireless sensor device fitted with a pulse oximeter sensor. More information about the examples shown here can be found in [http://www imec be/ScientificReport/SR2007/html/1384155.html](http://www.imec.be/ScientificReport/SR2007/html/1384155.html) last accessed on January 17, 2010.
Harvesting energy from an electrostatic effect cannot be explained in detail to engineering freshman level students. An slide with more information about this type of energy harvesting is included in this presentation.
Vibration - Electromagnetic

The movement of the oscillating weight is passed through a high gear ratio to turn a miniature electromagnetic generator.

Kinetic watches such as the one depicted in this slide are timepieces that utilize the power from the human body to keep the watch running. There are no batteries needed and one does not have to wind the watch to keep it going. Kinetic watches have oscillating weights that are turned by constant movement from the wrist. The constant movement turns into a magnetic charge in the watch and then into electricity. Kinetic watches are powered by kinetic energy.

The concepts of rotor stator are beyond the freshman level background thus the instructor may just say they are used to change mechanical motion into electricity. The “high gear ratio” means that the motions of the oscillating weight are “amplified” many times (using the gears) to turn the rotor.
Electrostatic energy harvesting relies on the changing capacitance of a variable capacitor which is initially charged. As its plates separate, because of vibrations, mechanical energy is transformed into electrical energy.

To properly explain the electrostatic principle, to freshman students, it might suffice to mention what is in this image. This type of harvesting energy is very active and deals with MEMs, a subject that might be well beyond the background that freshman students have. The instructor might decide not to discuss this principle at all.
Cantilever Piezoelectric Energy Scavenger

The principle of operation of the energy scavenger is based on the movement of the mass in the vertical direction that results in stretching of the piezoelectric layer and a voltage being generated.
Output Power

![Graph showing output power vs frequency for different weights (2.0 g, 1.0 g, 0.5 g, 0.25 g). The graph indicates peak power at specific frequencies for each weight.](image)
Piezoelectric

Piezoelectricity is the ability of certain materials to produce a voltage when subjected to mechanical stress.

Piezoelectric materials also show the opposite effect, where application of an electrical field creates mechanical stress (size modification) in the crystal.
Discovery of the Piezoelectric Effect

The effect known as piezoelectricity was discovered by brothers Pierre and Jacques Curie when they were 21 and 24 years old in 1880.

Pierre Curie (15 May 1859 – 19 April 1906) was a French physicist who received a Nobel prize in Physics in 1903.

Pierre’s wife was Marie Skłodowska Curie, the only person who has won TWO Nobel prizes in different scientific fields, one in Physics and the other one in Chemistry. She did fundamental work in the area of radioactivity.
The Meaning of Frequency

Frequency means the number of times something occurs within a given time period. Frequency for waves is usually measured per second. The unit for frequency is Hertz (Hz), which means per second.

\[ T = \frac{1}{f} \]
Spectrum Decomposition

\[ \sin(2\pi f_0 t) \]

\[ \sin(4\pi f_0 t) \]

\[ \sin(2\pi f_0 t) + \sin(4\pi f_0 t) \]

Time

Frequency (Hz)

\[ f_0 \]

\[ 2f_0 \]
Spectrum of Square Wave

\[
\frac{4}{\pi} \left( \sin(\omega t) + \frac{1}{3} \sin(3\omega t) + \frac{1}{5} \sin(5\omega t) + \frac{1}{7} \sin(7\omega t) + \ldots \right)
\]

Only odd harmonics are shown here due to the location in time of the square signal being represented. If the square wave is displaced a small amount to the left of the right of the time axis the representation will have odd and even harmonics.
Spectrum of a Voice Signal

Voice waveform

Spectrum

Seconds

Hertz

decibels
Footbridges such as the one at the Sao Carlos Engineering School, University of Sao Paulo, Brazil are predominantly affected by pedestrians. Vibrations induced by rhythmical body motions such as walking, marching and jumping, are of great importance.

In the study where this bridge was used the objective was to compare the measurements taken using the displacement transducers and the ones derived from the GPS receivers, thus the reason those receivers are showed in the diagram.
Footbridge Vibrations

Measurements showed that pedestrians walking over the footbridge caused a vibration of 2.1 Hz and a second harmonic frequency of 4.2 Hz. Vibrations can strongly affect the serviceability and, in rare cases, structural fatigue behavior and safety.
The Willis Family bridge is a footbridge that connects the campus to the students dorms at Indiana University – Purdue University Fort Wayne. The instructor at a different institution could use as an example a different footbridge that can be easily recognized by the students.
Willis Family Bridge Vibrations

This is an animated GIF that shows the vibrations of this bridge.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.570 Hz</td>
</tr>
<tr>
<td>2</td>
<td>1.193 Hz</td>
</tr>
<tr>
<td>3</td>
<td>1.933 Hz</td>
</tr>
<tr>
<td>4</td>
<td>2.058 Hz</td>
</tr>
</tbody>
</table>
Tacoma Bridge Collapse Video

This is an embedded video that was last accessed from:
Take Advantage of Vibration

V is the output voltage, F is the input force.
Simple Piezo Buzzer Signals

This slide shows the piezo-buzzer that the students will be using in their project. The time signal shows the voltage output when the piezo device is subjected to motion with a vibrator built by the instructors. The frequency signal (the spectrum) shows the frequency components or content of the time signal.
Micropower Module

Consists of the piezoelectric scavenger and an energy storage system composed of a super capacitor and a rechargeable battery. The AC/DC converter consists of a rectifier built with diodes.

This a simplified diagram of a micropower module. A diode rectifier circuit is explained in more detailed in the second lecture.
Energy Scavenging from Vibrations

Lecture 2
This diagram is included here to illustrate a more formal engineering design process. These steps are followed, in a very simplified way (the colored components), in this project.
Design of a Lateral Saddle\(^1\)

1. Gathering information
2. Identify constraints and design variables
3. Preliminary design

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\(^1\) Freshman Engineering Project. Department of Civil and Environmental Engineering. Polytechnic University of Puerto Rico

The intention was to include an example of a design project carried out by freshman engineering students at another institution. We searched extensively on the internet for an example that at least had some graphics. There were not many. The one described here is the one we considered the best at the time these slides were put together. The instructor is encouraged to find an example with clearer graphics.
4. Evaluation and selection of preferred solution
5. Preparation of plan and specification

6. Implementation of the design

7. Test and evaluation
DC Motor

Lorentz force
When a current carrying wire is placed in a magnetic field, a force is generated on the wire causing it to turn.

The picture on the right is an animated GIF.
Rotary-to-Reciprocating Motion

Continuous rotary motion can be generated using motors.

Conversion between rotary motion to reciprocating motion can be achieved using an asymmetric cam.

This slide has animated (GIF) figures.
Gear Ratio

\[ G = \frac{\omega_A}{\omega_B} = \frac{N_B}{N_A} \]

This slide has animated (GIF) figures that show the gears rotating.
Gear Train

Simple gear train

\[ G = \frac{\omega_A}{\omega_C} = \frac{N_C}{N_A} \]

Compound gear train

\[ G = \frac{\omega_A}{\omega_D} = \frac{N_B}{N_A} \frac{N_D}{N_C} \]
Alternating Current vs. Direct Current

In alternating current (AC) the movement (or flow) of electric charge periodically reverses direction.

In direct current (DC) the movement of electric charge doesn’t change direction.

This slide has animated (GIF) figures to illustrate the generation and behavior of alternating current and direct current.
Diodes allow the electric current to flow in only one direction.
Capacitor

A capacitor is a device that can store electrical charge.

In a capacitor equal amounts of positive and negative charges are stored on two separate conductors.

This slide has an animated figure (GIF) that illustrates the charging (from the voltage source) and discharging of a capacitor (in the light bulb).
Rectifying Circuit

A rectifier circuit can be used to convert an AC electric signal to a DC signal.

A four diode bridge can be used as a rectifier.
This slide has an animated GIF that slowly shows the working of the diode bridge. As the instructor explains how the current follows a particular path the transitions of the figure occur. One can also explain here the general meaning of a load and its particular meaning for this project, i.e. the capacitor and the battery.
Charging Circuit

A super capacitor (0.47F 5.5v) is used to store electric charge.

A Zener diode (BZX85-C5V6) is used to protect the super capacitor.

This is the realistic circuit used in this project to store the energy harvested from the piezo buzzer, and then to charge a battery. The constructed circuit will be given to students, but it’s good to briefly explain how the circuit functions.
References