Energy Scavenging for Wireless Sensor Nodes with a Focus on Vibration-to-Electricity Conversion

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Motivation and Objective

• Wireless sensor and computing networks

“As people find more ways to incorporate these inexpensive, flexible and infinitely customisable devices into their lives, the computers themselves will gradually ‘disappear’ into the fabric or our lives.”


• Small, low power, low cost, low data rate wireless platforms are being developed in many places

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Motivation and Objective

• Effective, long term, power supplies are lacking
  – Example: At an average power consumption of 100 $\mu$W, you need more than 1 cm$^3$ of lithium battery volume for 1 year of operation.

• “The pervasiveness and near-invisibility of computing will be helped along by new technologies such as … inductively powered computers that rely on heat and motion from their environment to run without batteries.”
  

• Goal: To investigate power “scavenging” technologies that can provide an average of 100 $\mu$W/cm$^3$ indefinitely.
## Comparison of Energy Scavenging Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Power Density ($\mu W/cm^3$)</th>
<th>Source of information</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power Density (1 Year lifetime)</strong></td>
<td>15,000 - direct sun</td>
<td>Commonly Available</td>
</tr>
<tr>
<td></td>
<td>150 - cloudy day</td>
<td></td>
</tr>
<tr>
<td><strong>Power Density (10 Year lifetime)</strong></td>
<td>15,000 - direct sun</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150 - cloudy day</td>
<td></td>
</tr>
<tr>
<td>Solar (Outdoors)</td>
<td></td>
<td></td>
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<tr>
<td>Solar (Indoors)</td>
<td>6 - office desk</td>
<td>Experiment</td>
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<td>Vibrations</td>
<td>100 - 200</td>
<td>Experiment and Theory</td>
</tr>
<tr>
<td>Acoustic Noise</td>
<td>0.003 @ 75 Db</td>
<td>Theory</td>
</tr>
<tr>
<td></td>
<td>0.96 @ 100 Db</td>
<td></td>
</tr>
<tr>
<td>Daily Temp. Variation</td>
<td>10</td>
<td>Theory</td>
</tr>
<tr>
<td>Temperature Gradient</td>
<td>15 @ 10 °C gradient</td>
<td>Starner 1996</td>
</tr>
<tr>
<td>Shoe Inserts</td>
<td>330</td>
<td>Shenck &amp; Paradiso 2001</td>
</tr>
<tr>
<td>Batteries (non-recharg. Lithium)</td>
<td>89</td>
<td>Commonly Available</td>
</tr>
<tr>
<td>Batteries (rechargeable Lithium)</td>
<td>13.7</td>
<td>Commonly Available</td>
</tr>
<tr>
<td>Gasoline (micro heat engine)</td>
<td>403</td>
<td>Mehra et. al. 2000</td>
</tr>
<tr>
<td>Fuel Cells (methanol)</td>
<td>560</td>
<td>Commonly Available</td>
</tr>
</tbody>
</table>

Yellow area denotes sources with a constant **power** output.
Blue area denotes sources with a fixed amount of **energy**.
Continuous Power / cm³ vs. Life Several Energy Sources

- Lithium
- Alkaline
- Lithium rechargeable
- Zinc air
- NiMH
- Solar
- Vibrations

Years

microWatts

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5

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Merits of Batteries, Solar, Vibrations

- If outdoor sunlight, or relatively intense indoor light it available, solar cells appear to be the best alternative.
  - Solar cells are a mature technology and a mature research area.

- If projected lifetime is longer than 1 year, vibrations offer an attractive alternative for certain environments. It was therefore decided to pursue research into the conversion of vibrations to electricity.
Vibrations – What’s available?

Microwave Oven Casing

Base of Milling Machine

Vibrations from microwave oven (2.25 m/s² at 120 Hz) used as the standard source with which to compare designs and report power density numbers.

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Simple Model for Conversion

\[ m\ddot{z} + b_m \dot{z} + b_e \dot{z} + kz = -m\ddot{y} \]

Power in terms of magnitude and frequency of input:

\[ \zeta_T = \zeta_m + \zeta_e \]

Power assuming \( \omega = \omega_n \):

\[ P = \frac{m \zeta_e A^2}{4 \omega \zeta_T^2} \]

\( z = \) transducer displacement
\( y = \) magnitude of input

\( k \) = spring constant
\( b_m \) = damper constant
\( b_e \) = damper constant

\( \omega \) = angular frequency
\( \omega_n \) = natural frequency
\( \zeta \) = damping ratio

\( m \) = proof mass

\( M \) = mass

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Observations from Simple Model

Power vs. Mechanical and Electrical Damping

Observations

1. If acceleration magnitude is relatively constant with frequency, output power is inversely proportional to frequency.

2. There is an optimal level of electrically induced damping that is designable.

3. It is better to have too much electrical damping than too little.
Three Ways to Convert Vibrations

**Piezoelectric**
Strain in piezoelectric material causes a charge separation (voltage across capacitor)

![Piezoelectric generator diagram]

**Capacitive**
Change in capacitance causes either voltage or charge increase.

![Capacitive circuit diagram]

**Inductive**
Coil moves through magnetic field causing current in wire.

![Inductive circuit diagram]

Amirtharajah et. al., 1998

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The Basic Idea:

\[ C = \frac{\varepsilon_0 A}{d} \quad V = \frac{Q}{C} \quad E = \frac{1}{2} QV \]

Design a variable capacitor in which A or d change when subjected to mechanical vibrations. If Q is kept constant, V (and E) will increase according to:

\[
\frac{V_{\text{max}}}{V_{\text{min}}} = \frac{C_{\text{max}} + C_{\text{par}}}{C_{\text{min}} + C_{\text{par}}}
\]
Circuit pumps charge from input voltage to higher voltage. The increase in energy is due to mechanical work done on \( C_v \).

\[
E = \frac{1}{2} V_{in}^2 (C_{\text{max}} - C_{\text{min}}) \left( \frac{C_{\text{max}} + C_{\text{par}}}{C_{\text{min}} + C_{\text{par}}} \right)
\]

\[
m\ddot{z} + f_m(z, \dot{z}) + f_e(z, z^2, \ldots) + kz = -m\ddot{y}
\]
Three Types of MEMS Converters

In-plane, overlap type:
Capacitance changes by changing overlap area of fingers.

5 – 10 mm
100 µm

In-plane, gap closing type:
Capacitance changes by changing gap between fingers.

5 – 10 mm

Out-of-plane, gap closing type:
Capacitance changes by changing gap two large plates.

2 µm

Observations:
1. Max power at large spring deflections (high Q).
2. Very sensitive to $C_{par}$

Observations:
1. Optimal spring deflection at 10 – 20 $\mu$m (low Q)
2. Less sensitive to $C_{par}$
Overlap vs. In Plane Gap-Closing

**In-plane Overlap**

Power Density vs. Dielectric Gap

- Maximum power occurs for very small dielectric gaps.
- The combination of large spring deflections and small dielectric gaps creates a potential stability problem.

**In-plane Gap Closing**

Power Density vs. Minimum Dielectric Gap

- Maximum power occurs for very small dielectric gaps.
- Power output is higher than either of the other two design concepts.
- Optimized design - 100 µW/cm³
Process for MEMS Converters

1. **Remove mask.**
2. **Apply metal w/ shadow mask or thick PR process.**
3. **Etch away portions of the handle wafer.**
4. **Timed oxide etch to free structures.**

**Legend**
- Single Crystal Silicon
- Silicon Dioxide
- Mask, PR and/or oxide
- Metal

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A MEMS in-plane gap-closing test structure fabricated in the microlab at UC Berkeley.
Another full size test device with tungsten proof mass attached.

- **Tungsten Mass**
- **Interdigitated fingers**
- **4mm**
Piezoelectric Conversion

Constitutive Equations

\[ \delta = \frac{\sigma}{Y} + d E \]

\[ D = \varepsilon E + d \sigma \]

\( \delta = \text{strain} \)
\( \sigma = \text{stress} \)
\( Y = \text{Young’s modulus} \)
\( d = \text{piezoelectric coeff.} \)
\( D = \text{electrical displacement} \)
\( \varepsilon = \text{dielectric constant} \)
\( E = \text{electric field} \)
**Piezoelectric Benders**

**System Equations**

\[ \ddot{\delta} = \frac{-k}{m} \delta - \frac{b_m}{m} a_1 \dot{\delta} - \frac{k}{m} d_{31} V_R + a_2 \ddot{y} \]
\[ \dot{V}_R = \frac{Yd_{31} t_c}{\varepsilon} \dot{\delta} - \frac{1}{RC} V_R \]

Where:

- \( k \) = equivalent spring stiffness of beam
- \( m \) = attached proof mass
- \( b_m \) = damping coefficient
- \( a_1 \) = geometric constant
- \( a_2 \) = geometric constant
- \( d_{31} \) = piezoelectric coefficient
- \( t_c \) = thickness of one piezo-ceramic layer
- \( V_R \) = voltage across load

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First Prototype

Note: All tests and simulations were performed with input acceleration of 2.25 m/s² at 120 Hz. (Vibrations from microwave oven casing.)

Output voltage is 4 to 6 volts. Max power output is 70 µW/cm³
Test Results and Model Verification

Optimized Prototype
- overall size < 1cm³
- total length < 1.5cm

Output voltage is 6 to 10 volts.
Max power output is 200 µW/cm³
Test Results and Model Verification

Optimized Prototype
- overall size < 1cm³
- total length < 3cm

Output voltage is 12 to 16 volts.
Max power output is 375 µW/cm³
“Real” Circuit for Piezo Converters

Piezoelectric generator

DC-DC Converter

Load

Vs

C

Rs

Cs
Test Results: Capacitive Load Circuit

Piezoelectric generator

$C$  $Rs$

$Vs$

$Cs = 3.3\, \mu F$

Power Transfer vs. time

180 $\mu W$

Capacitor Voltage vs. time
Piezo Generator, Power ckt, & Transmitter
Piezo Generator and Transmitter Traces

The storage capacitance was 200 µF.
Charge time of Storage Capacitor

Time to charge from 2 volts up to 6 volts is about 8.5 – 9 seconds. Time for radio to discharge back to 2 volts is about 85 mSec. Supportable duty cycle for 10 mA radio at 1.2 volts is about 1%.
Generators to be Embedded in Tires

Acceleration vs. time

\[ a_c = \omega^2 r_p \]

Acceleration vs. frequency

- 100 Km/hr
- 80 Km/hr
- 60 Km/hr
- 40 Km/hr
Generators to be Embedded in Tires

Clamp
Piezoelectric Bimorph
Proof Mass

4mm

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Test Results with a Resistive Load
Conclusions to this point

• Scavenging the power from commonly occurring vibrations for use by low power wireless systems is both feasible and attractive for certain applications.

• Piezoelectric converters appear to be the most attractive for meso-scale devices with a maximum demonstrated power density of approximately 200 µW/cm³ vs. 100 µW/cm³ for capacitive MEMS devices.

• A custom designed radio transceiver has been successfully operated using power from vibrations of 2.25 m/s² at 120 Hz.
Future Work

Application areas over next 10 years:
building env. control, emergency response in commercial buildings, manufacturing monitoring and control, inventory tracking, “smart” homes, fatigue monitoring on aircraft, ubiquitous data access for people, etc.
Applications for Vibration Scavenging

- Fatigue monitoring on aircraft.
- “Smart” automobile tires.
- Robotics for manufacturing.
- Real time sensing and control for machine tools.
- Monitoring of brakes on cargo trains
- Intelligent environment control in buildings.
- Emergency response in buildings.
Future Work

Actively tuning resonance frequency of generator

Novel actuator and control structure.
Would the increase in power justify the cost of tuning?
Many possible applications outside of Energy Scavenging
Future Work

Further exploration of alternative design topologies.

Nonlinear compliant structure translates motion (force) in vertical direction to horizontal direction.

Input excitation

Piezoelectric stack

Fr
Future Work

MEMS implementations of piezoelectric converters.

Improve robustness and performance of MEMS electrostatic converters.

Thinfilm PZT

Input excitation

Substrate

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Future Work

Optimization of power electronics for energy scavenging systems.

MEMS structures that have a large, high Q, effective inductance.
Conclusions

• Acceptable power sources remain perhaps the most challenging technical hurdle to the widespread deployment of wireless sensor networks.

• While significant progress has been made in many areas including indoor photovoltaic systems, micro-fuel cells, thermoelectrics, micro-heat engines, and vibration-to-electricity conversion, much more research and new approaches need to be pursued.