Energy Harvesting for Embedded Systems

Powering your Devices with Ambient Energy

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SHA2017 Hardware Hacking
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Incentives: toxic waste
Incentives: environmental destruction
Environmental Energy

- **Light**
- **Thermal**
- **Kinetic**
- **Radiation**
- **Chemical**
Energy Harvesting = renewable energy on a small scale
Challenge: scaling renewable energy technology to low power levels
Energy Harvesting vs. Energy Scavenging

Harvesting from an otherwise wasted source

Harvesting a fraction of a useful energy source

Harvesting from a dedicated energy source

Problem: conversion efficiency of many harvesters is very low!!
Autonomous Electronic Systems
The 5 Pillars of Autonomous Electronics

1. Harvesters
2. Sensors
3. Processing
4. Storage
5. Actuators
Harvesting light
## Solar Cell Types

<table>
<thead>
<tr>
<th>Material</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>pc-Si</td>
<td>20.4%</td>
</tr>
<tr>
<td>mc-Si</td>
<td>25.0%</td>
</tr>
<tr>
<td>a-Si</td>
<td>13.4%</td>
</tr>
<tr>
<td>CdTe</td>
<td>21.0%</td>
</tr>
</tbody>
</table>
Solar Cell Types (cont’d)

Emerging technologies

- Multijunction cells (Sharp, 44.7%)
- CIGS (ZSW, 21.7%)
- DSSC (Sharp, 11.9%)
- Perovskite (KRICT, 17.9%)
- Organic (IBM, 11.1%)
- Quantum dots (MIT, 8.6%)

Thin Film technology enables low cost **flexible** cells
Harvesting vibrations

Harvesting vibrations with **piezoelectricity** through elastic mechanical deformation of appropriate materials

<table>
<thead>
<tr>
<th>Natural materials</th>
<th>Synthetic materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Quartz, topaz, ...</td>
<td>• PZT</td>
</tr>
<tr>
<td>• Sugar</td>
<td>• PVDF</td>
</tr>
<tr>
<td>• Bones</td>
<td>• Langasite</td>
</tr>
</tbody>
</table>

Harvestable frequency range is determined by the **frequency range** and **natural frequency** of the material
Harvesting vibrations (cont'd)

**Piezoelectric**

**Magnetic**
Harvesting heat

Seebeck effect:
using a temperature gradient to generate electric current...

...as long as a temperature difference can be maintained.
Harvesting heat (cont'd)

- Highest power density of any harvester
- Small footprint
- Retrofittable with existing heat sinks

- Heat flow may reduce Carnot efficiency
- Requires good thermal conductivity with source
Heat Sources?
New miniaturization opportunities:

**MicroElectroMechanical Systems**

MEMS Sensors
- Gyroscopes
- Accelerometers
- Gas sensors

MEMS Harvesters
- PZT cantilevers
- Thermopiles
Energy harvesting in the real world

Benchmarking the environment:

- types of ambient energy?
- how much power?
- when available?
Environmental energy data acquisition

- RF \(< 1\mu m\)
- light \((\mu m - nm)\)
- heat
- flow \((wind, water)\)
- vibrations
OpenObservatory: environmental monitoring

- Quartz, topaz, ...
- Sugar
- Bones

- Broadband light sensor
- UV sensor
- Temperature sensor
- Particle sensor
- Air pressure sensor
- Humidity sensor
- Data storage
AEM: Ambient Energy Monitor
Correlating ambient energy with harvesters

- Quartz, topaz, ...
- Sugar
- Bones

ambient energy benchmark data

ambient light spectrum

polycrystalline Si

monocrystalline Si

CIGS

selected optimal cell type
Energy balance

- Quartz, topaz, ...
- Sugar
- Bones

application’s energy requirements

energy meter

application

harvester benchmark

flowchart

harvester benchmark

harvester dimensioning

energy budget

ambient energy benchmark

benchmark

benchmark

harvester

flowchart

energy budget

ambient energy benchmark
Pattern Matching

- correlating energy harvesting with application needs

- minimizing local storage
  - secondary chemical cells
  - MLCC
  - EDLC

harvester

wireless autonomous application
Combining **multiple energy sources** offers

- increased reliability
- decreased combined harvester size
- lower production costs
Complementary balanced energy harvesting

- RF TX
- solar
- Stand-by

vibrations of passing train

sensor
Power path design

harvester

DC/DC

primary power regulator + MPPT

capacitor

solid state battery

DC/DC

secondary power regulator

embedded system
Commercial initiatives

Integrators
modules and ready to use applications

Manufacturers
• separate harvesters
• development kits
Efficiency

ambient energy source → harvester → DC/DC → DC/DC → system

- TEG @ 8%
- solar cell @ 23%
- supercap @ 60%

100% efficiency
Harvester coverage

Harvester output limited by

- physical harvester **size**
- ambient energy **flux density**
Durability

Robustness
- solid state vs. moving parts
- corrosion resistance
- mechanical durability

Autonomy
- longer life time
- less maintenance required
- lower operation costs
Storage media also have different nonlinear leakage currents
Power conversion: DC/DC buck/boost
Myths

Solar Roadways

Story | Updates 129 | Comments 3,365 | Funders 48,472 | Gallery 28

$2,200,341 USD
RAISED OF $1,000,000 GOAL

220% 0 time left

This campaign started on Apr 21 and closed on June 20, 2014 (11:59pm PT).

Flexible Funding

CAMPAIGN CLOSED
This campaign ended on June 20, 2014

SELECT A PERK

Email Embed Link Follow
Opportunities

• **Retrofitting** existing applications
  - **Removing cables**, thus increasing reliability
  - Turning them **green** by removing primary chemical batteries

• **Improving harvesters** allow **new applications**
  - Combinations with other progressing fields (i.e. LED's)
  - Miniaturization through increased harvester efficiency
Development Cycle

Prototype design

Harvester field benchmarking

Harvester size adjustment

Power budget adjustment
# State Awareness

## Time
- Energy budget estimation
- Active duty cycle regulation
- Autonomous operations

## State of Charge (SoC)
- Energy budget estimation
- Active duty cycle regulation
- Task scheduling

## State of Health (SoH)
- Energy budget estimation
- Lifetime estimation
- Preventive maintenance
Environmental Awareness

- Snow height logger
  - low sample frequency
  - local storage
  - low reliability demands

- INES event detector
  - continuous sampling
  - wireless communication
  - high reliability required
Summary

Energy harvesting can offer...

- Nearly unlimited life time without batteries
- Power scalability for any application
- Low cost deployment without cables or wires
- Intelligent environment aware user interaction

Q&A

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