A Self-powered wireless bolt for smart critical fastener

Biruk Seyoum, Maurizio Rossi and Davide Brunelli
Department of Industrial Engineering
University of Trento, Italy
maurizio.rossi@unitn.it
Motivation

Critical fasteners in electromechanical systems are susceptible to
• Heating and rapid cooling which causes brittleness
• Wear and tear by being overstressed
• Become loose and unable to provide the necessary tension due to movement

Particularly in high end applications periodic maintenance and replacement are required
• Avionics
• Supercars
Motivation

Monitoring critical fasteners

- Prevent failures
- Proactive/Programmed maintenance
- Improved security

How

- Monitor temperature and understand current state from recorded temperature profile
- Monitor tension (eventually)

Titanium Fasteners for avionics applications (credits: poggipollini.it)
Objective of the work

Objective

• Designing a smart bolt
• Evaluating the feasibility of powering the smart bolt using TEGs under very low temperature gradient

Challenges

• Size (must fit the head of critical bolts few cm²)
• Energy autonomy (no wires, no recharge plug)
• *Price is not an issue in high-end applications*

Methodology

• Characterization
  • 3 commercial TEGs
  • 2 DC-DC converters
• Design and development of smart bolt “demo”
Self Powered wireless bolt for smart critical fastening

A set of smart bolts are deployed in critical structures
• Data are stored in local memory
• Forwarded wirelessly when energy available
  • Star network topology (single-hop)

Data are collected by:
• The main control unit (supercars)
• Downloaded during maintenance (aircraft, copters)
Self Powered wireless bolt for smart critical fastening

Design

- **CC1310** low power wireless SoC from TI
  - ARM cortex M3 @48MHz
  - 8KB RAM
  - 128KB flash
  - Running TI-RTOS + application
  - Sub-GHz Radio

- **LTC3108** DC-DC boost converter

- **TEG** as power supply

Data collector (or gateway) based on the same SoC
Thermoelectric Generators

**Thermocouple**

Made by conjoining two dissimilar metals (usually P and N type materials) at their free ends.

**Thermoelectric circuit**
Experimental Setup

Characterization of
- TEGs
- DC-DC converters

Characterization Challenges
- No standardized way of characterization yet
- Complex circuitry to prevent maintain junction temperature constant
- Fluctuation of thermal gradient with current
- Fluctuation of Seebeck coefficient with temperature

Novelties in Characterization
- Simple characterization without thermal regulation circuit
  - Mitigation of Peltier effect
  - Stabilized fluctuation of Seebeck coefficient with temperature
## Summary of specification of the TEGs

<table>
<thead>
<tr>
<th>Label</th>
<th>TEG specification from datasheet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model</td>
</tr>
<tr>
<td>TEG1</td>
<td>926-1216-ND</td>
</tr>
<tr>
<td>TEG2</td>
<td>926-1192-ND</td>
</tr>
<tr>
<td>TEG3</td>
<td>926-1225-ND</td>
</tr>
</tbody>
</table>
Experimental Characteristics

ΔT  ➔  TEG  ➔  Variable Load

Graphs showing the relationship between Power (mW), 10logRI (Ω), and ΔT for different values of ΔT.
TEG Characterization Results

TEGs 2 and 3 have higher power density w.r.t. TEG1
Almost linear relationship between Voc and ΔT
# TEG Characterization Results

## Comparison of results with related works

<table>
<thead>
<tr>
<th>Label</th>
<th>$R_{in}$ [Ω]</th>
<th>$\frac{P_{max}}{\Delta T_{max}}$ [μw/K²]</th>
<th>$PF$ [μw/mm²K²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEG1</td>
<td>1.4</td>
<td>40.625</td>
<td>0.0271</td>
</tr>
<tr>
<td>TEG2</td>
<td>2.3</td>
<td>6.94</td>
<td>0.404</td>
</tr>
<tr>
<td>TEG3</td>
<td>2.1</td>
<td>6.04</td>
<td>0.397</td>
</tr>
<tr>
<td>TEG4</td>
<td>2.23</td>
<td>224</td>
<td>0.14</td>
</tr>
<tr>
<td>TEG5</td>
<td>250K</td>
<td>1</td>
<td>0.015</td>
</tr>
<tr>
<td>TEG6</td>
<td>1.9</td>
<td>5.31</td>
<td>0.0033</td>
</tr>
<tr>
<td>TEG7</td>
<td>1.08</td>
<td>0.25</td>
<td>0.156</td>
</tr>
</tbody>
</table>

## Fluctuation of temperature with current

<table>
<thead>
<tr>
<th>Label</th>
<th>$I = 12.5mA$</th>
<th>$I = 42.7mA$</th>
<th>$I = 101.7mA$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEG1</td>
<td>1.01°</td>
<td>2.71°</td>
<td>3.6°</td>
</tr>
<tr>
<td>TEG2</td>
<td>0.82°</td>
<td>1.56°</td>
<td>2.95°</td>
</tr>
<tr>
<td>TEG3</td>
<td>0.56°</td>
<td>1.48°</td>
<td>2.78°</td>
</tr>
</tbody>
</table>


DC-DC Converter Characterization

Characterization to determine

- **Efficiency**
- Charging profile

Characterization done by supplying the converters from

- TEG
- DC source

DC-DC converters

LTC3108

NEX WPG-1
Characterization Result of LTC module

- **DC supply:** 16 minutes to reach 3V
- **TEG supply:** approximately 40 minutes
Characterization Result of Nextreme module

- **DC supply:** 12 minutes to reach 3V
- **TEG supply:** approximately 25 minutes
Considerations

In both cases, when supplied from TEG the output voltage remains stable after connecting the load

- Application becomes **energy neutral**
- Frequency of temperature TX controlled with internal clock
Converter Characterization Result

In both cases efficiency dropped with increasing input power.

When supplied from the TEG
- The Nextreme module took 25 minutes to charge the supercap.
- The LTC3108 module took 40 minutes but this was because the LTC module was getting less input power.
- LTC has higher efficiency but the WPG can extract more power from the same $\Delta T$.

LTC3108 selected because of higher efficiency.

<table>
<thead>
<tr>
<th>Supply</th>
<th>LTC 3108 characterization</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vin [mV]</td>
<td>Iout [μA]</td>
<td>Pin [mW]</td>
<td>Pout [mW]</td>
</tr>
<tr>
<td>TEG</td>
<td>78</td>
<td>250</td>
<td>1.69</td>
<td>0.83</td>
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<tr>
<td>DC</td>
<td>477</td>
<td>1000</td>
<td>42</td>
<td>3.16</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Supply</th>
<th>Nextreme WPG-1 characterization</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vin [mV]</td>
<td>Iout [μA]</td>
<td>Pin [mW]</td>
<td>Pout [mW]</td>
</tr>
<tr>
<td>TEG</td>
<td>136</td>
<td>380</td>
<td>3.4</td>
<td>0.95</td>
</tr>
<tr>
<td>DC</td>
<td>477</td>
<td>850</td>
<td>43.5</td>
<td>2.6</td>
</tr>
</tbody>
</table>
Self-Sustainable Application

CC1310

- Low power SoC
- Sub-GHz Radio
- Custom LPWAN networks

Negligible PER down to 0dBm @ 100m

<table>
<thead>
<tr>
<th>Configured Power (dBm)</th>
<th>RSSI (dBm)</th>
<th>Numbers of Packets received</th>
<th>Numbers of Packets lost</th>
<th>PER (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>-91</td>
<td>999</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>10</td>
<td>-99</td>
<td>989</td>
<td>11</td>
<td>1.1</td>
</tr>
<tr>
<td>5</td>
<td>-103</td>
<td>999</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>0</td>
<td>-107</td>
<td>998</td>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>-10</td>
<td>-117</td>
<td>851</td>
<td>149</td>
<td>14.9</td>
</tr>
</tbody>
</table>
Self-Sustainable Application

• Transmitting temperature readings at 868MHz GFSK
• System was tested by transmitting
  • 5, 20 & 64 bytes packets sizes
  • 40%, 20%, & 6.6% duty cycle by fixing the period to 500ms, 1s & 3s
  • TX power 14dBm (worst case)
Self-Sustainable Application

CC1310’s power consumption increases with packet size

- Trade-off between buffering and available energy
- Sleep mode exhibits µW consumption (when application is synchronized with clock)
Self-Sustainable Application

Computation duty-cycle

\[
E_{tot} = E_{active} + E_{sleep}
\]

\[
P_{in} T = P_{tx} t_{tx} + P_{sleep} (T - t_{tx})
\]

- \(E_{tot}\) is the total energy
- \(T\) is the total time which is the sum of transmission and sleep times
- \(t_{tx}\) is already determined from the experiment and is about 200ms
- Including conversion efficiency for LTC3108

Expected to stream temperature data every 2.8s (7.1% duty-cycle) with a \(\Delta T\) as low as 10°C
Conclusions

• This work was an investigation of designing smart safety-critical fasteners
• The powering of this system from a reliable, low cost, small size thermoelectric generators was investigated
• Accordingly the characterization of TEGs and DC-DC converters was done to determine
  • The maximum output power
  • The input resistance
  • The relationship between thermal gradient and output power
• Finally, the system was powered from one of the TEGs and its performance was tested
thank you very much for the kind attention

maurizio.rossi@unitn.it