On the Information Quality of Energy-harvesting-based Sensing in Motion-powered IoTs

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What do these IoTs have in common?

- Smart Shoe from InstepNanopower
- Wireless Switch from EnOcean
- Swiss Watch about to be released
- Track Monitoring IoT from ReVibe Energy
They are all *motion-powered* IoTs!

- **Smart Shoe from InstepNanopower**
- **Wireless Switch from EnOcean**
- **Swiss Watch about to be released**
- **Track Monitoring IoT from ReVibe Energy**

*Keynote, PERCOM WORKSHOP IQ2S, 19 March 2018*
The essence of motion-powered IoTs

Convert mechanical to electrical energy
Power Data → Machine Learning → Information

1. Kinetic Energy Harvester
2. Motion
3. Electric Power
4. Power Generation Pattern
5. Machine Learning
6. Information
Questions

• What information can be mined?
• How is the information quality?
• What factors can influence the information quality?
  – E.g., machine learning: features and classifiers
  – E.g., source of power data (time-series AC voltage vs. single-shot capacitor voltage)
  – Simultaneous sensing and energy harvesting
Types of power data for machine learning

- Transducer
  - AC Voltage
  - AC Time-series
- Capacitor
  - Capacitor Voltage
- Machine Learning
  - Information

Motion
Overview

- Information quality of activity detection
  - transducer output (AC voltage) data
  - capacitor data
  - Filtering need for AC-voltage-based sensing, Case study: gait recognition
- Information quality of other type of information (if time permits)
  - Data communication
  - Voice detection
- Survey of future directions in energy harvesting and new opportunities for high quality sensing
Can we infer human activity from kinetic energy harvesting?

EXPERIMENTING WITH REAL ENERGY HARVESTERS AND HUMANS

HARKE, TMC2017

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KEH Data Logger (samples AC voltage values)

Piezoelectric Energy Harvester (vibration-based)

- Piezoelectric Energy Harvester (vibration-based) diagram
- AC Rectifier
- Capacitor
- Mide.com
- Not Implemented

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Data Collection: 10 subjects, 5 activities, 2 positions
KEH AC Voltage Time Series
Features and classifiers matter

OFS: Original feature set in literature for accelerometer-based activity recognition
VFS: Vibration-based features (peak-to-peak etc.)

<table>
<thead>
<tr>
<th>Classifier</th>
<th>with OFS</th>
<th>with OFS+VFS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hand</td>
<td>Waist</td>
</tr>
<tr>
<td>NN</td>
<td>70.21</td>
<td>83.51</td>
</tr>
<tr>
<td>DT</td>
<td>76.34</td>
<td>79.27</td>
</tr>
<tr>
<td>SVM</td>
<td>72.89</td>
<td>75.74</td>
</tr>
<tr>
<td>NB</td>
<td>70.58</td>
<td>69.15</td>
</tr>
</tbody>
</table>
Activity Recognition Confusion Matrix (waist)

Activity matters: Going up and down the stairs difficult to detect, but walking/running/standing can be detected easily

<table>
<thead>
<tr>
<th>Activity</th>
<th>Classified as</th>
<th>TP Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WALK</td>
<td>RUN</td>
</tr>
<tr>
<td>WALK</td>
<td>48</td>
<td>0</td>
</tr>
<tr>
<td>RUN</td>
<td>0</td>
<td>54</td>
</tr>
<tr>
<td>STAND</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SU</td>
<td>17</td>
<td>0</td>
</tr>
<tr>
<td>SD</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>
Activity Detection from Capacitor Data


CapSense: Mobiquitous 2017
Key idea

• Different activities generate energy at different rates
• Energy generation rate can be used to detect activities
• Capacitors accumulate energy over time
• One-shot capacitor reading can classify activities (significantly more power efficient compared to AC sensing)
  – Avoid processing of time-series, computation of features, and training classifiers with large set of features
Non-linearity of capacitor voltage

R: resistance of resistor
C: capacitance of capacitor

Design capacitor circuit to operate within 0.5 RC (linear)
Data Logger --- Shoe-based

Capacitor voltage data is saved in SD card for post-processing
Linear capacitor voltage curves for different activities

The longer we wait, the more distinctive the activities become

Higher information quality costs less!
No classifier bias! 7 sec. achieves 92% accuracy irrespective of the choice of classifier. Lower the sampling rate, higher the accuracy!!
Impact of Capacitor Charging on the Quality of AC-voltage-based Sensing

Capacitor voltage affects AC voltage

We propose AC data filter to improve information quality: case study gait detection
Data Logger
Gait Similarity

![Graph showing Gait Similarity](chart.png)

(DTW distance)

- Original Signal
- Filtered Signal

Subjects

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Filtering improves gait detection accuracy
Gait recognition can be improved using Sparse Representation Classifier (SRC)

<table>
<thead>
<tr>
<th>Classifier</th>
<th>Original signals</th>
<th>Filtered signals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PEHFront</td>
<td>PEH Rear</td>
</tr>
<tr>
<td>KNN</td>
<td>54.3%</td>
<td>50.7%</td>
</tr>
<tr>
<td>SVM</td>
<td>66.7%</td>
<td>65.8%</td>
</tr>
<tr>
<td>SRC</td>
<td>76.28%</td>
<td>76.01%</td>
</tr>
</tbody>
</table>
Sensing from Acoustic Energy Harvesting
If the energy harvester can recognize known sound vibrations, it can detect communication symbols (acts as a receiver)
Impact of Transmitted Sound on Energy Harvester
Communication Performance

5bps at 80 cm for BER < 1%
(laptop to wearable)
Natural Immunity Against Noise

*Even loud music didn’t affect the communication performance*

![Graphs showing frequency and time measurements for different scenarios](image-url)
Hotword detection

**Quiet Room Conditions**

**Hotword:** “OK Google”
**Non-hotwords:** “Good morning”, “how are you”, “fine, thank you”

8 subjects: 4 m, 4 f
60 instances (30 hotword, 30 non-hotword) per subject
Speaker orientation

(a) Flat orientation.  
(b) Vertical orientation.
## Results

<table>
<thead>
<tr>
<th>Speaker</th>
<th>Flat</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independent</td>
<td>78%</td>
<td>62%</td>
</tr>
<tr>
<td>Dependent</td>
<td>85%</td>
<td>73%</td>
</tr>
</tbody>
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Conclusion

• KEH data contains a lot of information about ambient context

• Information can be mined from two distinct sources within KEH
  – AC voltage [HARKE: TMC in press]
  – Capacitor voltage [CAPSENSE: MOBIQUITOUS 2017]
  – AC voltage can detect complex phenomena, such as human gait, but requires more intense processing; simpler information can be obtained from capacitor more efficiently

• Capacitor voltage interferes with AC voltage [SEHS: IOTDI 2018]
  – Need for AC voltage data filtering
Future Directions

① Advanced machine learning → increase range and quality of information

② Advanced energy harvesters → increase both power and information content
   ▶ Multi-axial, array, nanotechnology, broadband, hybrid (more details in IEEE Computer 2018)
References

Questions?
Power Measurements (KEH vs accelerometer)

TI Sensor Tag

96% power saving