The PermaSense Project
Low-power Sensor Networks for Extreme Environments

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PermaSense - Alpine Permafrost Monitoring

- Cooperation with Uni Basel and Uni Zurich
PermaSense - Aims and Vision

Geo-science and engineering collaboration aiming to:
- provide long-term high-quality sensing in harsh environments
- facilitate near-complete data recovery and near real-time delivery
- obtain better quality data, more effectively
- obtain measurements that have previously been impossible
- provide relevant information for research or decision making, natural hazard early-warning systems
To Better Understand Catastrophic Events...

Eiger east-face rockfall, July 2006, images courtesy of Arte Television
PermaSense Deployment Sites 3500 m a.s.l.

A **scientific instrument** for **precision sensing** and data recovery in environmental extremes.
PermaSense - Key Architectural Requirements

• Support for ~25 nodes

• Different sensors
  - Temperatures, conductivity, crack motion, ice stress, water pressure
  - 1-60 min sensor duty-cycle

• Environmental extremes
  - −40 to +65°C, ΔT ≤ 5°C/min
  - Rockfall, snow, ice, rime, avalanches, lightning

• Near real-time data delivery

• Long-term reliability
  - ≥99% data yield
  - 3 years unattended lifetime

Relation to other WSN projects

• Comparable to other environmental monitoring projects
  - GDI [Szewczyk], Glacsweb [Martinez], Volcanoes [Welsh], SensorScope [Vetterli], Redwoods [Culler]

• Lower data rate
• Harsher, higher yield & lifetime
• Data quality/integrity
Reliable Sensor Networks Architecture

PermaSense Technology
PermaSense - System Architecture

Sensor network | Base station | Backend

- Sensor Node
- Access Node
- Embedded PC
- GSM Modem
- PV Controller
- 5V DC-DC Converter
- Backup GSM
- System Monitoring
- 12V Battery
- PV Cells
- Server

Technologies:
- GSN
- Java
Base Station with Stacked Mikrotik WLAN Router

- Gumstix Verdex
- TinyNode
- WLAN Router
- GSM
- EMP Protectors
- IP68 Enclosure and Connectors
PermaSense - Base Station Overview

- Powerful embedded Linux (Gumstix)
- 4 GB storage, all data duplicated
- Solar power (2x 90W, 100 Ah, ~3 weeks)
- WLAN/GPRS connectivity, backup modem
The Big Picture – Network System Integration
PermaSense – Sensor Node Hardware

- **Shockfish TinyNode584**
  - MSP430, 16-bit, 8MHz, 10k SRAM, 48k Flash
  - LP radio: XE1205 @ 868 MHz

- **Waterproof housing and connectors**

- **Protective shoe, easy install**

- **Sensor interface board**
  - Interfaces, power control
  - Stabilized measurements
  - 1 GB memory

- **3-year life-time**
  - Single battery, 13 Ah
  - ~300 µA power budget
PermaSense Sensors

- Sensor rods (profiles of temperature and electric conductivity)
- Thermistor chains
- Crack meters
- Water pressure
- Ice stress
- Self potential

- Data: Simple sensors, constant rate sampling, few integer values
PermaSense Sensors – Sensor Rod Example
Geoscience: Fast localized thaw by advection

Near-surface temperature/conductivity

Combination with lab experiments and models
PermaSense Sensors - Crack Meter Example
Geoscience: Cryogenic rock movement/weathering

Moisture saturation and freezing dynamics captured by sensor rod

Dilatation data with cleared thermal signal

Temperature [°C] vs. Distance [mm]

Resistance [MOhm] vs. Temperature [°C]

[NI COP2008]
Installation work on Matterhorn 09/ 2007

PermaSense installation 2007, images courtesy of Arte Television
Key PermaSense Challenges

System Integration

Correct Test and Validation

Actual Data

Interdisciplinary Team
Counting Beans with Energy

Reliable Low-power Wireless
It’s a thin line to success...
Dozer Low-Power System Integration

- Dozer ultra low-power data gathering system
  - Beacon based, 1-hop synchronized TDMA
  - Optimized for ultra-low duty cycles
  - 0.167% duty-cycle, 0.032mA

- System-level, round-robin scheduling
  - “Application processing window” between data transfers and beacons
  - Custom DAQ/storage routine

[Burri – IPSN2007]
Visualization Using Simultaneous Power Traces

Target Current Consumption with Fixed Voltage Supply at 3.3V (profiled by CruiseControl)

1. Receive parent beacon
2. Send beacon to children
3. Send data to parent
4. Sampling sensor (DAQ)

Timeline (10,000,000 samples with a resolution of ~1 ms)
Wireless is Not the Only Contributor - Sensing

- ADC calibration
- Sys
- Volt
- Temp
- Humid
- External ADC channels
- Digital protocol

**Current consumption [mA]**
- Earthpressure cell: 4.58 mA (avg)
- Sensor rod: 3.90 mA (avg)
- Digital sensor: 1.92 mA (avg)

**Time [s]**
- 0
- 1
- 2
- 3
- 4
- 5
PermaDozer - Total Power Performance Analysis

### Operating Mode Characterization [mA]

<table>
<thead>
<tr>
<th>Mode</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleep</td>
<td>0.026</td>
</tr>
<tr>
<td>DAQ active&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.086</td>
</tr>
<tr>
<td>Dozer RX idle</td>
<td>13.64</td>
</tr>
<tr>
<td>Dozer RX</td>
<td>14.2</td>
</tr>
<tr>
<td>Dozer TX</td>
<td>54.6</td>
</tr>
</tbody>
</table>

### Measured Average Values [mA]

<table>
<thead>
<tr>
<th>Mode</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAQ only (2min)</td>
<td>0.110</td>
</tr>
<tr>
<td>Dozer only (30sec/2min)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.072</td>
</tr>
<tr>
<td>PermaDozer total (30sec/2min)</td>
<td>0.148</td>
</tr>
</tbody>
</table>

<sup>a</sup> Averages power consumption measured over a complete DAQ routine execution without attached sensor

<sup>b</sup> Dozer only includes communication, not including network initialization and access to flash memory

1/120 sec

1/30 sec

148 uA average power
Getting Even More Physical on Real Devices

Emulating the Environment
WSN Design and Development Tools

**Simulation**
- TOSSIM [Levis2003]
- PowerTOSSIM [Shnayder2004]
- Avrora [Titzer2005]

**Virtualization & Emulation**
- EmStar arrays [Ganesan2004,Cerpa03/04]
- BEE [Chang2003,Kuusilinna2003]

**Test Grids**
- moteLab [Werner-Allen2005]
- Twist [Handziski2006]
- Kansei [Dutta2005]

**Can we Emulate Reality in the Lab?**

**DSN Wireless Testbed**

Figure abridged from D. Estrin/J. Elson
Remember: We can’t bring our patient to the lab!
Physical Emulation Architecture

- Influence of power sources/quality
- Detailed physical characterization
- Emulation of environment and resources
  - Temperature Cycle Testing (TCT)
  - Controlled RF attenuation
  - Sensor stimuli and references

Integration and automation with DSN Testbed

[EmNets2007]
Validation of Detailed Traces using Formal Bounds

- Assertions based on reference traces/specification
- Integrated with each build (regression testing)

\[ f_i(t) = \begin{cases} 
  a_0 + a_1 \cdot t + \ldots & \text{if } t \in [t_{i-1}, t_i) \\
  0 & \text{if } t \notin [t_{i-1}, t_i) 
\end{cases} \]

\[ f_i^-(t) = \begin{cases} 
  f_i(t) - \Delta y^- & \text{if } t \in [t_{i-1}, t_i) \\
  0 & \text{if } t \notin [t_{i-1}, t_i) 
\end{cases} \]

\[ f^-(t) = \sum_{i=1}^{n} f_i^-(t) \]

\[ \forall \delta \in [-\Delta t, \Delta t], \forall i \in \mathbb{N} : \]

\[ f^-(t + \delta t_k) = \begin{cases} 
  f_i^-(t_i^-) & \text{if } -f(t_i^-) + f(t_{i+}) \leq 0 \\
  f_i^+(t_i^+) & \text{if } -f(t_i^-) + f(t_{i+}) > 0 
\end{cases} \]

The upper bound \( f^+ \) follows accordingly with a bound value \( \Delta y^+ \).

[WEWSN2008, SUTC2008]
Visualizing Behavior - Quantification of Change
Conformance Testing using Timed Automata
Conformance Testing using Timed Automata

- Power trace
- Model of observed behavior
- UPAAL
- Model of expected behavior

\[ \exists \pi \in \prod_{Sys} \parallel PT : s \xrightarrow{\pi} t \iff PT \models Sys \]

Automated Power Trace Verification

- System in operation
- Expected behavior

[FORMATS 2009]
Why should we care?
Communication Details – Dangerous Voltage Drops

Vcc$_{\text{min}} = 2.8$ V
Physical Reality Impacting Performance

- **Ambient Temperature**
- **DAQ Duration**
- **Storage Duration**
- **Watchdog Resets**
Power Optimization - A Squeeze with Implications

- Regulator uses 17uA quiescent current
- Bypass used to shutdown regulator -> ~1uA in standby
- No Bypass increases ADC accuracy: std dev 0.8844 -> 0.0706
The Result - Power Quality Increases Data Accuracy

Before

After

Std dev = 24.0 µm

Std dev = 1.0 µm
Seeing is believing...
Experience - Node Health Data From The Field

- System Outages
- Lost Packets
- Battery Voltage & Temperature
Node Health Data - Root Cause Failure Analysis

- System Outages
- # Lost Packets
- Network Disconnect
- Nodes Reset
Visibility is key!
Understanding the Exact Causes is Hard...

- Missing EMP protector – broken radio chip?
  - If so is it snow/wind or lightning induced?
  - Long-term software bug – buffer overflow; timing?
  - Misunderstood “feature” of the implementation?
  - Hardware breakdown?
- Energy-supply dependent?
  - Spring-time behavior based on the environment?
  - Cosmic rays at 3500 m a.s.l. ?
  - Can external effects trigger the reed contact on the reset?
  - ...

Probably not feasible to test/ reproduce this in the lab!
Up and coming stuff

NEXT GENERATION PERMASENSE SENSING
WLAN and high-resolution imaging

[EWSSN 2009]
Precision GPS Movement Detection

Distance: REFD-DIR2
horizontal: 360m 285m
vertical: 130m 50m

DIR2 (2550m)
DIR3 (2630m)
Using Commodity GPS Receivers and WSNs

June 2009
Thank you
Please look at our live demo outside http://www.permasense.ch
Interested to join our team?
beutel@tik.ee.ethz.ch