Embedded System Design and Synthesis

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Outline

1. Sensor networks
2. Lucid dreaming
3. Homework

Section outline

Sensor network goals and conditions

- Distributed information gathering
- Frequently no infrastructure
- Battery-powered, wireless common
- Battery lifespan of central concern
- Scavenging also possible
- Communication and data aggregation important

Sensor network hardware power consumption

- Power consumption central concern in design
- Processor?
  - RISC μ-controllers common
- Wireless protocol?
  - Low data-rate, simple: Proprietary, Zigbee
- OS design?
  - Static, eliminate context switches, compile-time analysis

Sensor network software power consumption

- Power consumption central concern in design
- Runtime environment?
  - Avoid unnecessary dynamism
- Language?
  - Some propose compile-time analysis of everything practical
  - Others offer low-overhead run-time solutions

Key problems

- Low-power design
- Self-organization
- Data management, compression, aggregation, and analysis

Section outline

1. Sensor networks
   - Introduction
   - Recent work

Prototype networks

Biology: monitor seabirds

- Senses: temperature, humidity, infrared
- Developers: Intel, Berkeley
- Size: 150 nodes

Monitor activity of elderly

- Senses: motion, pressure, infrared
- Developer: Intel
- Size: 130 nodes

Credit to Randy Berry for slide.

Prototype networks

Detect source of gunshot

- Senses: sound, shock wave, location
- Developer: DARPA, Vanderbilt
- Size: 45 nodes

Structural integrity monitoring

- Senses: vibration, precise displacement
- Developer: Northwestern University
- Size: Deployed in six buildings, constantly growing
  - Approximagely 30 nodes

Habitat monitoring

Joseph Polastre, Robert Szewczyk, Alan Mainwaring, David Culler, and John Anderson. Analysis of wireless sensor networks for habitat monitoring. *Wireless sensor networks*, pages 399–423, 2004

- Application: Monitor petrels on Great Duck Island
- Mica motes used
- High failure rate
- 50% packet loss, with spatial and temporal variation

Virtual machines for sensor networks

P. Levis and D. Culler. Mate: A tiny virtual machine for sensor networks. In *Proc. Int. Conf. Architectural Support for Programming Languages and Operating Systems*, October 2002

- How to support rapid in-network programming?
- Virtual machine
- Great idea if reprogramming frequent compared to normal duty cycle
- Generally not the case

Wireless demand paging

Yuvraj Agarwal, Curt Schurgers, and Rajesh Gupta. Dynamic power management using on demand paging for networked embedded systems. In *Proc. Asia & South Pacific Design Automation Conf.*, pages 755–759, January 2005

- Use two wireless interfaces
- One fast but high-power, one slow but low-power
- Awaken node using low-power interface
- Report 20–50% power savings
- Cannot beat 50% because processor consumes half of power
- Are there better alternatives?

Routing and media access

Too many routing and media access articles to count. Key problems:

- Reliability on unreliable components with varying network structure
- Tight power constraints
- Limited communication rates
- Self-organization

Other active areas

- Blind callibration
- Localization
- Operating system design: TinyOS, MANTIS OS, etc.
- Simulation environments
- Efficient implementation of media encoding algorithms
- Security: encryption power implications
- Applications: structure monitoring, security, biology, geology
- Small-scale robotics
- Biomotion capture

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Collaborators on project

EECS Dept.
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Peter Dinda

Civil and Environmental Engineering Dept.
Mat Kotowsky
Charles Dowding

Section outline

2. Lucid dreaming
   - Introduction, motivation, and past work
   - Lucid dreaming desgin
   - Results

Low-power event-driven applications

- Conventional sensor network operation: poll and sleep
- Many real applications must detect unpredictable events
- How?

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Periodically awaken?

Misses events

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Always remain awake?

Two days of battery life

Low-power event-driven applications

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- Many real applications must detect unpredictable events
- How?

Periodically awaken?

Misses events

Always remain awake?

Two days of battery life

Goal

Always awake but with ultra-low power consumption

Application: Structural integrity monitoring

- Buildings and bridges have cracks
- Most not dangerous, but could become dangerous
- Widths change in response to vibration
- 300 μm common, 3$\times$ width of human hair

Detecting dangerous conditions

Inspectors monitor cracks to determine when dangerous

- Expensive
- Infrequent

Could use wireless sensor networks

- Inexpensive
- Constant

Problem: Event-driven application. Only a few days of battery life.

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Past structural integretity work

- N. Kurata, B. F. Spencer Jr., M. Ruiz-Sandoval, Y. Miyamoto, and Y. Sako. A study on building risk monitoring using wireless sensor network MICA mote. In *Proc. Int. Conf. on Structural Health Monitoring and Intelligent Infrastructure*, pages 353–357, November 2003
- J. P. Lynch, K. H. Law, A. S. Kiremidjian, T. W. Kenny, E. Carryer, and A. Partridge. The design of a wireless sensing unit for structural health monitoring. In *Proc. Int. Wkshp. on Structural Health Monitoring*, September 2001
- Ning Xu, Sumit Rangwala, Krishna Kant Chintalapudi, Deepak Ganesan, Alan Broad, Ramesh Govindan, and Deborah Estrin. A wireless sensor network for structural monitoring. In *Proc. Conf. on Embedded and Networked Sensor Systems*, November 2004

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- J. P. Lynch, K. H. Law, A. S. Kiremidjian, T. W. Kenny, E. Carryer, and A. Partridge. The design of a wireless sensing unit for structural health monitoring. In *Proc. Int. Wkshp. on Structural Health Monitoring*, September 2001
- Ning Xu, Sumit Rangwala, Krishna Kant Chintalapudi, Deepak Ganesan, Alan Broad, Ramesh Govindan, and Deborah Estrin. A wireless sensor network for structural monitoring. In *Proc. Conf. on Embedded and Networked Sensor Systems*, November 2004

Short battery life. Two-day deployments and explosives.

Past low-power event detection work

- B Schott, M Bajura, J Czarnaski, J Flidr, T Tho, and L Wang. A modular power-aware microsensor with $> 1000\times$ dynamic power range. In *Proc. Int. Symp. Information Processing in Sensor Networks*, pages 469–474, April 2005
  - Wake-up timer based
- P. Dutta, M. Grimmer, A. Arora, S. Bibyk, and D. Culler. Design of a wireless sensor network platform for detecting rare, random, and ephemeral events. In *Proc. Int. Conf. on Information Processing in Sensor Networks*, April 2005
  - Big project, rebuilt sensor nodes from scratch
  - However, low-power event detection is hard
  - 880–19,400 μW

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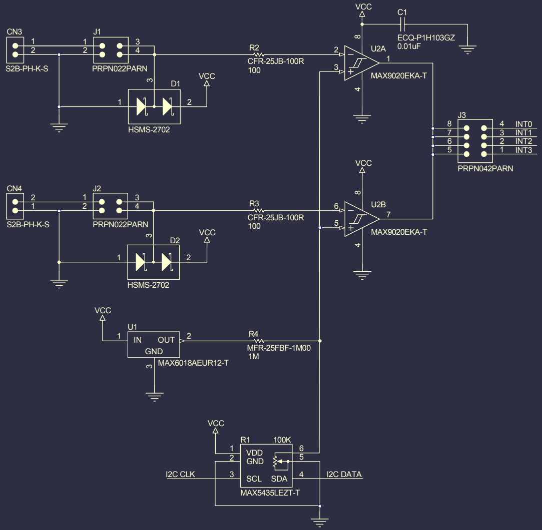
Schematic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R2
CFR-25JB-100R
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VCC
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ECQ-P1H103GZ
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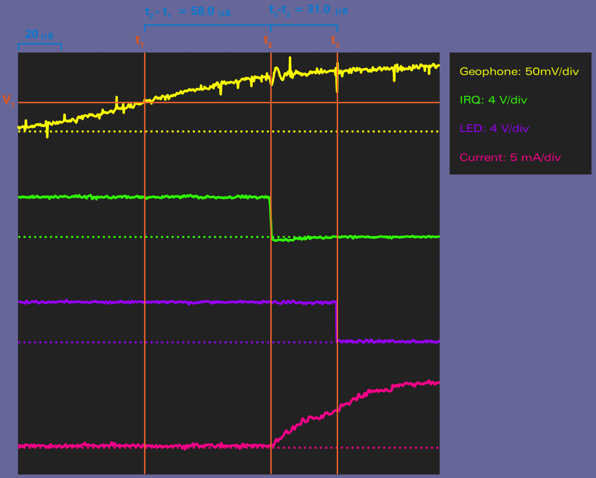
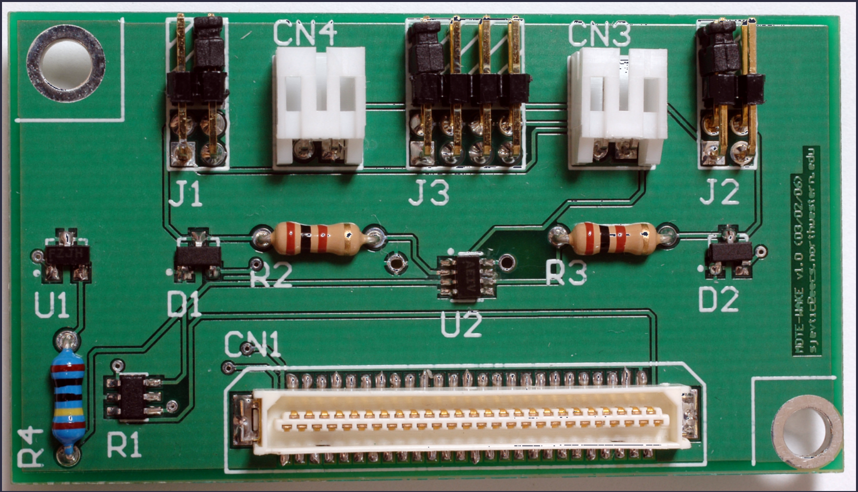
S2B-PH-K-S
PRPN022PARN
D1
HSMS-2702
J3
INT0
INT1
INT2
INT3
PRPN042PARN
CN4
J2
R3
CFR-25JB-100R
100
U2B
MAX9020EKA-T
S2B-PH-K-S
PRPN022PARN
D2
HSMS-2702
U1
IN
OUT
GND
MAX6018AEUR12-T
R4
MFR-25FBF-1M00
1M
R1
100K
VDD
GND
SCL
SDA
I2C CLK
I2C DATA
MAX5435LEZT-T

Vibration event

89µs
SNOOZE

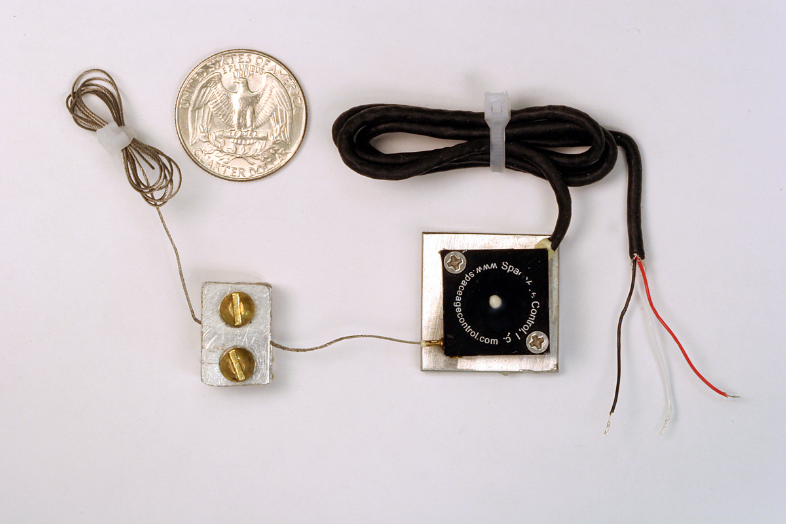


Circuit board

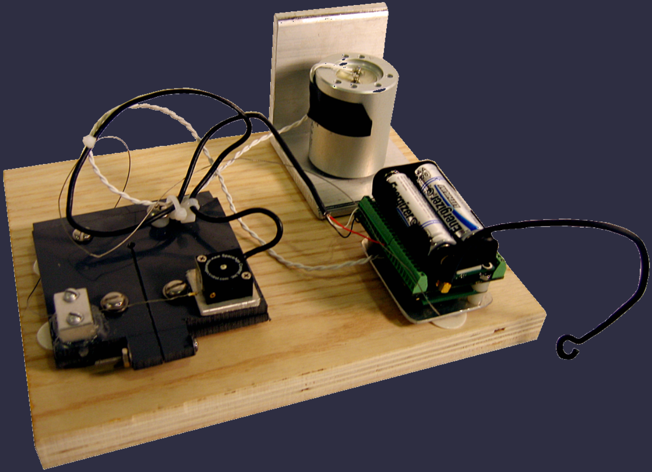


Board and large geophone

Primary sensor

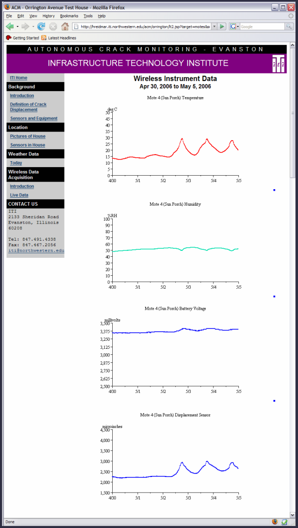


Demonstration board

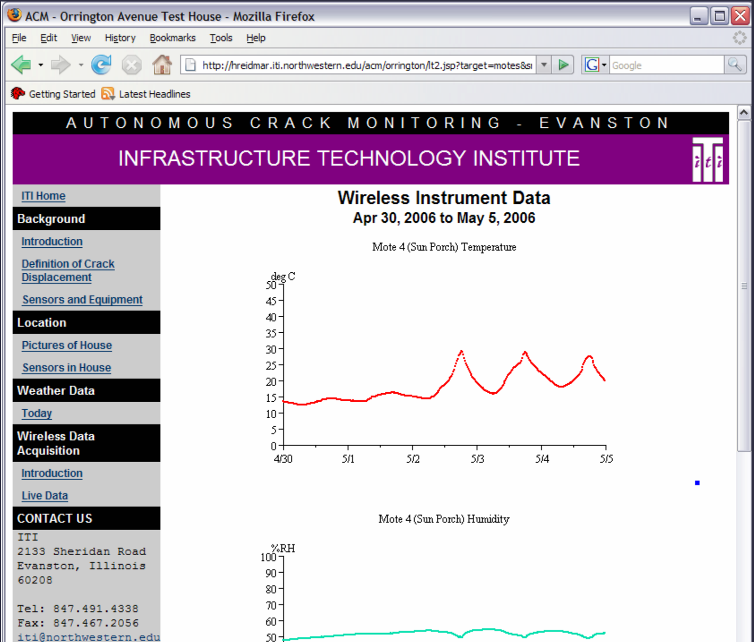


System in case

Web interface screen shot



Web interface screen shot



Power values for mote hardware

Variable	Description	Example value for ACM
P_{AVG_LD}	Average power consumption for lucid dreaming	1.3×10^{-4} W
P_{AVG_SO}	Average power consumption for polling solution	3.0×10^{-2} W
P_{AVG_PR}	Average power consumption for event prediction	No example value
P_{RT}	Power consumption of mote radio in transmitting state	3.0×10^{-2} W
P_{AC}	Power consumption of mote CPU in active state	2.4×10^{-2} W
P_{ZZ}	Power consumption of mote CPU in sleeping state	3.0×10^{-5} W
P_{S1}	Power consumption of primary sensor and data acquisition system	5.7×10^{-3} W
P_{S2}	Power consumption of secondary/wakeup sensor	0 W
P_{MW}	Power consumption of Shake 'n Wake hardware	1.6×10^{-5} W
F_{DC}	Average frequency of an event resulting in data collection	1.2×10^{-4} Hz
F_{MC}	Average frequency of a communication transmission	1.2×10^{-5} Hz
D_{DC}	Average duration of an event resulting in data collection	3.0 s
D_{MC}	Average duration of a communication transmission	104.0 s
F_{TP}	Average frequency of true positives	No example value
F_{FP}	Average frequency of false positives	No example value
Γ_{FN}	False negative probability (type I error)	No example value
Γ_{FP}	False positive probability (type II error)	No example value
Γ_{TP}	True positive probability $(1 - \Gamma_{FN})$	No example value
Γ_{TN}	True negative probability $(1 - \Gamma_{FP})$	No example value

Power estimation

Power for software polling

$$\begin{aligned} P_{AVG\_SO} =&(F_{DC} \cdot D_{DC})(P_{AC} + P_{S1})+ \\ &(F_{MC} \cdot D_{MC})(P_{AC} + P_{RT}) + (1 - F_{DC} \cdot D_{DC} \\ &- F_{MC} \cdot D_{MC})(P_{AC} + P_{S1}) \end{aligned}$$

Power for lucid dreaming

$$\begin{aligned} P_{AVG\_LD} =&(F_{DC} \cdot D_{DC})(P_{AC} + P_{S1})+ \\ &(F_{MC} \cdot D_{MC})(P_{AC} + P_{RT})+ \\ &(1 - F_{DC} \cdot D_{DC} - F_{MC} \cdot D_{MC})(P_{ZZ})+ \\ &P_{S2} + P_{MW} \end{aligned}$$

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Power reduction

- Always on: 24 mW
- Lucid dreaming hardware: 16.5 μW
- Best existing work: 2.64 mW
- Lucid dreaming in system: 121.8 μW

Implications

Original situation

Missed events or battery replacement after a few days

Current status

- Battery life of months
- Many boards fabricated
- Deployed in multiple buildings already

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Deregulation and user-driven power optimization

- Seunghoon Kim, Robert P. Dick, and Russ Joseph. Power deregulation: Eliminating off-chip voltage regulation circuitry from embedded systems. In *Proc. Int. Conf. Hardware/Software Codesign and System Synthesis*, September 2007. To appear
- Arindam Mallik, Bin Lin, Peter Dinda, Gokhan Memik, and Robert P. Dick. User Driven Frequency Scaling. *IEEE Computer Architecture Ltrs.*, 5(2), December 2006

Assignment: Write a short paragraph describing the most important points in both of these articles.