Embedded System Design and Synthesis

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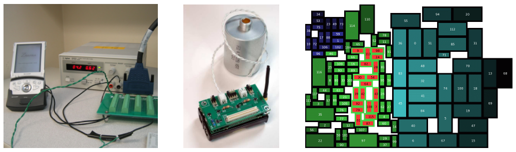

Sensor network goals and conditions

- 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

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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

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

Collaborators on project

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Civil and Environmental Engineering Dept.
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Charles Dowding

Low-power event-driven applications

- Conventional sensor network operation: poll and sleep
- 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× 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.

Past structural integretity work

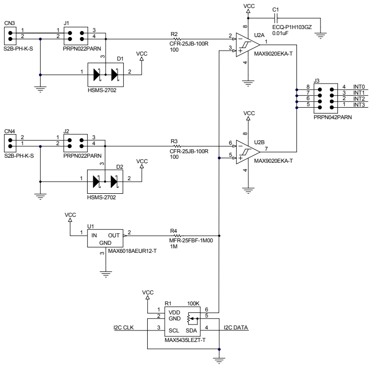
- N. Kurata, B. F. Spencer Jr., M. Ruiz-Sandoval, Y. Miyamoto, and Y. Sako. A study on building risk monitoring using wireless sensor network MICA mote. In *Proc. Int. Conf. on Structural Health Monitoring and Intelligent Infrastructure*, pages 353–357, November 2003
- J. P. Lynch, K. H. Law, A. S. Kiremidjian, 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

Short battery life. Two-day deployments and explosives.

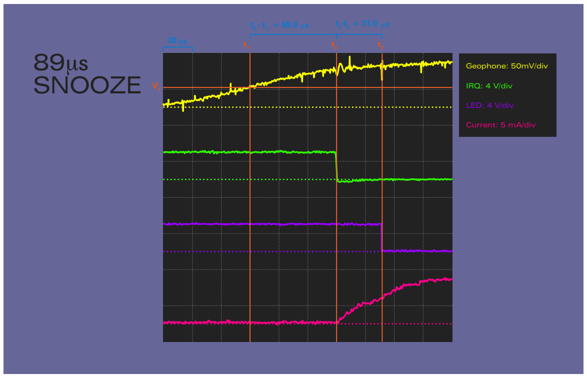
Past low-power event detection work

- 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

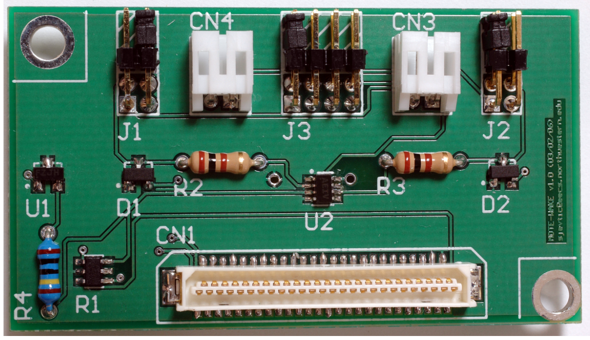
Schematic



Vibration event

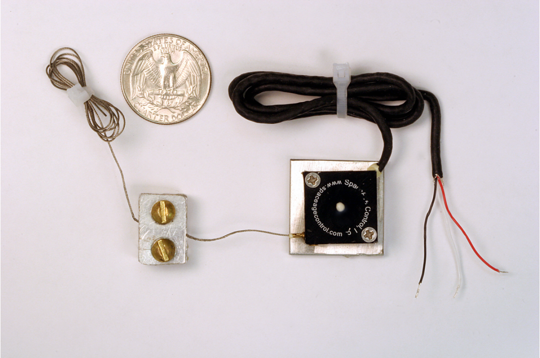


Circuit board

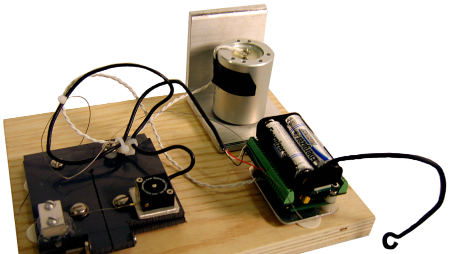


Board and large geophone

Primary sensor

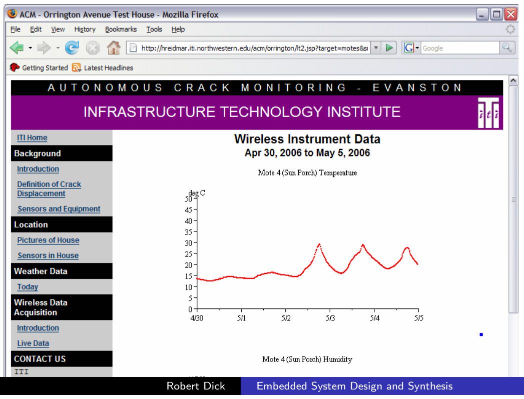


Demonstration board



System in case

Web interface screen shot



AUTONOMOUS CRACK MONITORING - EVANSTON

INFRASTRUCTURE TECHNOLOGY INSTITUTE

Wireless Instrument Data
Apr 30, 2006 to May 5, 2006

Mote 4 (Sun Porch) Temperature

Mote 4 (Sun Porch) Humidity

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

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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

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

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

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.