CS321: Information Processing for Sensor Networks

Leonidas Guibas
Computer Science Dept.
Stanford University
Introduction

CS
- Distributed algorithms
- Networking
- Databases
- Software radios
- Software design

EE
- Low-power processors
- Signal processing
- Wireless communication
- Information theory
- Estimation theory
Smart Sensors and Sensor Networks

- **Environmental sensing**
  - Traffic, habitats, pollution, hazards, security
- **Industrial sensing**
  - Machine monitoring and diagnostics (IC fab)
  - Power/telecom grid monitoring
- **Human-centered computing**
  - Smart, human-aware spaces and environments

Untethered micro sensors will go anywhere and measure anything -- traffic flow, water level, number of people walking by, temperature. This is developing into something like a nervous system for the earth. -- Horst Stormer in *Business Week, 8/23-30, 1999.*
Wireless Sensor Networks

Distributed systems consisting of small, untethered, low-power nodes capable of sensing, processing, and wireless communication.
Monitoring the World

- Monitoring the **environment** and other spaces
- Monitoring **objects**
- Monitoring **interactions** between objects, or between objects and their environment
Petrel Nesting Behavior at Great Duck Island
Wireless Sensor Network Deployment

Advantages:
- sensors can be close to signal sources, yielding high SNR
- can monitor phenomena widely distributed across space and time
- distributed architecture provides for scalable, robust and self-repairing systems
- significant savings on cabling, etc are possible

British Columbia winery with networked temperature sensors

Other data collection and monitoring: temperature in data centers (HP), oil tanker vibrations (Exxon), soil contaminants, etc.
Integration with Current Networks

Access to unfiltered information, highly localized in time and space
More Demanding Sensor Network Applications

- Beyond simple data collection and aggregation
  - acting on the world
  - simultaneous tracking of multiple objects
  - distributed, wide-area phenomena
  - distributed attention: focus and context
- Network must adapt to highly dynamic foci of activity
- Sensing and communication tasks must be allocated
- Resources must be apportioned between detection, tracking, etc.
Sensor Network Hardware
Wireless Sensor Trends

Of 9.6 billion µP’s to be shipped in 2005, 98% will be embedded processors!

Riding on Moore’s law, smart sensors get:

- **More powerful**
  - Sensoria WINSNG 2.0
    - CPU: 300 MIPS
    - 1.1 GFLOP FPU
    - 32MB Flash
    - 32MB RAM
    - Sensors: external

- **Easy to use**
  - HP iPAQ w/802.11
    - CPU: 240 MIPS
    - 32MB Flash
    - 64MB RAM
    - Both integrated and off-board sensors

- **Inexpensive & simple**
  - Crossbow Mica2dot mote
    - 4 MIPS CPU (integer only)
    - 8KB Flash
    - 512B RAM
    - Sensors: on board stack (accel, light, microphone)

- **Supercheap & tiny**
  - Smart dust (in progress)
    - CPU, Memory: TBD (LESS!)
    - Sensors: integrated
Most Popular: Crossbow Motes

- Chipcon CC2420
  802.15.4 Radio
- 51-pin MICA2 / GPIO Connector
- Atmel ATmega128L (under)
- Buzzer
- Light & Temperature Sensor
- Microphone
Crossbow Stargate - Top View

- Ethernet RJ-45
- USB
- PCMCIA SLOT
- Serial Port RS-232
Crossbow Stargate - Bottom View

- Compact Flash Slot
- SA 1111 StrongArm I/O Chip
- Intel PXA255 Xscale Processor
- 51-pin MICA2 / GPIO Connector
Specifications

**MicaZ Mote**
- TinyOS
- 16 Mhz Atmel ATMega128L
- 128 kB Program FLASH
- 512 kB Serial FLASH
- Current Draw
  - 8 mA – Active Mode
  - <15 uA – Sleep Mode
- Chipcon CC2420 802.15.4 Radio
  - 250 kbps
  - 26 Channels – 2.4 Ghz
  - Current Draw – 15 mA

**Stargate**
- Embedded Linux OS
- 400 Mhz Intel Xscale
- 64 MB SDRAM
- 32 MB FLASH
- Many different interfaces
  - RS-232, Ethernet, USB,…

www.xbow.com
http://computer.howstuffworks.com/mote4.htm
Power Breakdown …

<table>
<thead>
<tr>
<th></th>
<th>Active</th>
<th>Idle</th>
<th>Sleep</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU</td>
<td>5 mA</td>
<td>2 mA</td>
<td>5 μA</td>
</tr>
<tr>
<td>Radio</td>
<td>7 mA (TX)</td>
<td>4.5 mA (RX)</td>
<td>5 μA</td>
</tr>
<tr>
<td>EE-Prom</td>
<td>3 mA</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LED's</td>
<td>4 mA</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Photo Diode</td>
<td>200 μA</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Temperature</td>
<td>200 μA</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Rene motes data, Jason Hill

Computation/communication ratio:

• Rene motes:
  • Comm: \((7\text{mA}*3\text{V}/10\text{e3})*8=16.8\text{μJ}\) per 8bit
  • Comp: \(5\text{mA}*3\text{V}/4\text{e6}=3.8\text{nJ}\) per instruction
  • Ratio: 4,400 instructions/hop

• Sensoria nodes:
  • Comm: \((100\text{mW}/56\text{e3})*32=58\text{μJ}\) per 32bit
  • Comp: \(750\text{mW}/1.1\text{e9}=0.7\text{nJ}\) per instruction
  • Ratio: 82,000 instructions/hop

This means

— Lithium Battery runs for 35 hours at peak load and years at minimum load, a three orders of magnitude difference!
Architectural Challenges
Sensor Network Challenges

- Power management
  - communication 1000s of times more expensive than computation
  - load balancing
  - coordinated sleeping schedules
  - correlated sensor data
- In-network processing
  - data aggregation
  - overcounting of evidence
- Difficult calibration
  - localization
  - time-synchronization
- Constant variability
  - networking
  - sensing
Distributed Sensor Communication: Multi-Hop RF Advantage

RF power attenuation near ground:

\[ P_{\text{receive}} \propto \frac{P_{\text{send}}}{r^\alpha}, \quad \alpha : 3 - 5 \]

Or equivalently,

\[ P_{\text{send}} \propto r^\alpha P_{\text{receive}} \]

Power advantage:

\[
\frac{P_{\text{send}}(Nr)}{N \cdot P_{\text{send}}(r)} = \frac{(Nr)^\alpha P_{\text{receive}}}{N \cdot r^\alpha P_{\text{receive}}} = N^{\alpha-1}
\]
Semantic Routing and Networking

- We want to address spatial locations or information, not individual nodes
- Content and address in a message get intermixed
- How do we help information providers and clients find each other?

Directed diffusion
Geo-routing
In-Network Processing

- Information aggregation can happen on the way to a destination
- Need to balance quality of paths with quality of information collected
- Are there “application-independent” paradigms of information aggregation?

Temperature aggregation
Networking Sensor Networks

- Network support for a small number of collaborative tasks.
- Data-centric, (as opposed to a node-centric) view of the world.
- Monitoring processes may migrate from node to node, as the phenomena of interest move or evolve.
- Communication flow and structure is dictated by the geography of signal landscapes and the overall network task.
Distributed Sensor Networks: Detection and SNR Advantage

Sensors have a finite sensing range. A denser sensor field improves the odds of detecting a target within the range. Once inside the range, further increasing sensor density by $N$ improves the SNR by $10\log N$ db (in 2D). Consider the acoustic sensing case:

Acoustic power received at distance $r$: $P_{\text{receive}} \propto \frac{P_{\text{source}}}{r^2}$

Signal-noise ratio (SNR):

$$SNR_r = 10\log P_{\text{source}} - 10\log P_{\text{noise}} - 20\log r$$

Increasing the sensor density by a factor of $N$ gives a SNR advantage of:

$$\frac{SNR_r}{\sqrt{N}} - SNR_r = 20\log \frac{r}{\sqrt{N}} = 10\log N$$
Collaborative Estimation

Structuring communication is very important:

In a setting where each node wishes to communicate some data to another node at random, interference hinders scaling:

the per node throughput scales as \( \frac{1}{\sqrt{N}} \) \cite{Gupta & Kumar '99}

Effectively each node is using all of its energy to route messages for other nodes.

In a sensor network, however, because data from nearby sensors are highly correlated and more intelligent information dissemination strategies are possible.
Power-Aware Sensing and Communication

- Variable power systems
- Let most sensors sleep most of the time; paging channels
- Exploit correlation in readings between nearby sensors
- Load-balance, to avoid depleting critical nodes
Sensor Tasking and Control

Decide which sensors should sense and communicate, according to the high-level task – a non-trivial algorithmic problem.

Direct sensing of relations relevant to the task – do not estimate full world state.
Enable Data-Base Like Operations

Data only available right after sensing operation

Dense data streams must be sampled, or otherwise summarized

Must deal with distributed information storage – “where is the data?”

(a) Lossless Isobars

Field isolines
Self-Configuration for Ad-Hoc Deployment

- Network size makes it impossible to configure each node individually.
- Environmental changes may require frequent re-calibration.
- Network must recover after node failures.

Iterative localization
Structure Discovery

A sensor network is a novel type of computing device -- a sensor computer.

One of its first tasks is to discover its own structure and establish
- information highways
- sensor collaboration groups

as well as adapt to its signal landscape.
New System Architectures

Resource constraints require close coupling between the networking application layers.

Can we define application-independent programming abstractions for sensor networks?

A sensor net stack?

<table>
<thead>
<tr>
<th>Phy: comm, sensing, actuation, SP</th>
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</thead>
<tbody>
<tr>
<td>MAC, time and location services</td>
</tr>
<tr>
<td>Adaptive topology, geo-routing</td>
</tr>
<tr>
<td>Data dissemination, storage, caching</td>
</tr>
<tr>
<td>In-network: application processing, data aggregation, query processing</td>
</tr>
<tr>
<td>User queries, external databases</td>
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</tbody>
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A sensor net stack?
Various Issues

- Integration of sensors with widely different modalities
  - High data-rate sensors (cameras, laser scanners)
- Sensor mobility
- Actuation

Distributed robotics
What Defines Sensor Networks?

- Multi-hop communication
  - Many nodes act as routers
  - Multiple paths exist and must be considered
- Bandwidth limitations
  - Volume of data sensed exceeds to capacity of the network to transport
- Power limitations
  - (At least some) nodes operate untethered and energy conservation must be considered in all of sensing, processing, and communication
- A cooperative system
  - All nodes serve one, or a small number of tasks
Sensor Network Research

- power awareness
- sensor tasking and control
- formation of sensor collaboration groups
- in-network, distributed processing
- node management, service establishment, software layers
- coping with noise and uncertainty in the environment

A key algorithmic problem is how to sense and aggregate only the portions of the world-state relevant to the task at hand, in a lightweight, energy-efficient manner.
CS321: The Course
Course Outline, I

- Networking sensor networks (topology discovery, MAC layer issues, routing, energy considerations)
- Information brokerage (directed diffusion, distributed hash tables)
- Infrastructure establishment (time-synch, localization)
- Sensor network hardware (Motes/Stargates and other common node types, power issues)
Course Outline, II

- Sensor network software (TinyOS, programming abstractions)
- Probabilistic state estimation with sensor data (Kalman and particle filters)
- Sensor tasking and control (value of information, collaborative signal processing)
- Distributed data processing and storage (in-network data aggregation, range searching)
- Applications (incl. camera networks)
Course TextBook

Wireless Sensor Networks: An Information Processing Approach

Geng Zhao and Leonidas Guibas

Morgan-Kaufmann 2004
Course Format

- Lectures by the instructor, plus a few guest lecturers
- Student presentations of current research papers
- A course project is required. Can be
  - an implementation on actual mote hardware
  - an extensive simulation
  - a more theoretical investigation
- Alternate meeting for Monday’s class
Course Personnel

Instructor: Leonidas J. Guibas

TA: Qing Fang

Course web page:

http://graphics.stanford.edu/courses/cs321-05-fall
http://www.stanford.edu/class/cs321
The End