CS321: Information Processing for Sensor Networks

Leonidas Guibas
Computer Science Dept.
Stanford University
Wireless Sensor Networks
Embedded Networked Systems

Distributed algorithms
Networking
Databases
Cognitive/smart radios
Software design
...

Low-power processors
Signal processing
Wireless communication
Information theory
Estimation theory
...

CS

EE
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
Wireless Sensor Network Deployment

Advantages:

- Sensors can be close to signal sources, yielding high SNR
- Phenomena can be monitored that are widely distributed across space and time
  - A `macroscope' [D. Culler]
- Mobility can allow even wider, or more adaptive coverage
- A distributed architecture provides for scalable, robust and self-repairing systems
- Significant installation advantages: deployment speed, savings on cabling, etc.

British Columbia winery with networked temperature sensors

Other data collection and monitoring: temperature in data centers (HP), oil tanker vibrations (BP/Intel), soil contaminants, etc.
Petrel Nesting Behavior at Great Duck Island

An Analysis of a Large Scale Habitat Monitoring Application

Robert Szczupak, Alan Isham, Brian Berg, John Anderson, and David Cutler

ABSTRACT
Habitat and environmental monitoring is a diverse application involving various sensor networks. We present an analysis of data from a neural network sensor network deployed during the manned and manned ground phases of the U.S. Army’s Operation Mosaic. The network included both acoustic and biological sensors. The data focuses on peak bird and aircraft performance, with emphasis on different weighting schemes in applying neural network solutions to sensor network data. We compare the results collected to specific events during the field deployment, and the data is used to assess the impact of different weighting schemes on the neural network solution. The network also included several other sensors and devices, including the deployment of a high-precision GPS receiver to assess the accuracy of the neural network solution. The key aim of the experiment was to use the data from the neural network to determine the effect of different weighting schemes on the data collected during the field deployment.

Categories and Subject Descriptors:
C.1.1 [Computer-Communication Networks]: Network Architecture and Design; C.4 [Performance of Systems]: Design Studies

General Terms:
Performance, Design, Implementation

Keywords:
Sensor Network, Habitat Monitoring, Network Architecture, Neural Network Monitoring, network management, large scale systems, application analysis

1. INTRODUCTION

Petrel nests in a complex habitat exhibit a neural network sensor network. The network includes both acoustic and biological sensors. The data focuses on peak bird and aircraft performance, with emphasis on different weighting schemes in applying neural network solutions to sensor network data. We compare the results collected to specific events during the field deployment, and the data is used to assess the impact of different weighting schemes on the neural network solution. The network also included several other sensors and devices, including the deployment of a high-precision GPS receiver to assess the accuracy of the neural network solution. The key aim of the experiment was to use the data from the neural network to determine the effect of different weighting schemes on the data collected during the field deployment.

Categories and Subject Descriptors:
C.1.1 [Computer-Communication Networks]: Network Architecture and Design; C.4 [Performance of Systems]: Design Studies

General Terms:
Performance, Design, Implementation

Keywords:
Sensor Network, Habitat Monitoring, Network Architecture, Neural Network Monitoring, network management, large scale systems, application analysis

1. INTRODUCTION

Petrel nests in a complex habitat exhibit a neural network sensor network. The network includes both acoustic and biological sensors. The data focuses on peak bird and aircraft performance, with emphasis on different weighting schemes in applying neural network solutions to sensor network data. We compare the results collected to specific events during the field deployment, and the data is used to assess the impact of different weighting schemes on the neural network solution. The network also included several other sensors and devices, including the deployment of a high-precision GPS receiver to assess the accuracy of the neural network solution. The key aim of the experiment was to use the data from the neural network to determine the effect of different weighting schemes on the data collected during the field deployment.
Great Duck Island Deployment

[From Ganesan]
Storm Petrel Monitoring

Questions
- What environmental factors make for a good nest? How much can they vary?
- What are the occupancy patterns during incubation?
- What environmental change occurs in the burrows and their vicinity during the breeding season?

Methodology
- Characterize the climate inside and outside the burrow
- Collect detailed occupancy data from a number of occupied and empty nests
- Spatial sampling of habitat – sampling rate driven by biologically interesting phenomena
- Validate a sample of sensor data with a different sensing modality
- Augmented the sensor data with deployment notes (e.g. burrow depth, soil consistency, vegetation data)
- Try to answer the questions based on analysis of the entire data set

[From Ganesan]
BP Shipboard Vibration Monitoring
Embedded Networked Sensing

- Micro-sensors, on-board processing, wireless interfaces feasible at very small scale—can monitor phenomena “up close”
- Enables spatially and temporally dense environmental monitoring

**Embedded Networked Sensing**

will reveal previously unobservable phenomena

- Ecosystems, Biocomplexity
  - [NIMS]
- Marine Microorganisms
  - [NAMOS]
- Contaminant Transport
- Seismic Structure Response

[From Estrin]
NIMS: Networked InfoMechanical Systems

- **NIMS Architecture**: Robotic, aerial access to full 3-D environment
  - Enable sample acquisition
- **Coordinated Mobility**
  - Enables self-awareness of Sensing Uncertainty
- **Sensor Diversity**
  - Diversity in sensing resources, locations, perspectives, topologies
  - Enable reconfiguration to reduce uncertainty and calibrate
- **NIMS Infrastructure**
  - Enables speed, efficiency
  - Low-uncertainty mobility
  - Provides resource transport for sustainable presence

(Kaiser, Pottie, Estrin, Srivastava, Sukhatme, Villasenor)

[From Estrin]
More Data Extraction Applications

- Industrial automation (conditional maintenance)
  - Sensors on assembly lines, machines
  - Early failure detection
- Asset tracking
- Building security
- Automated meter reading
- Homeland defense
Networks for Data Extraction

Data collection
- from untethered networked sensor devices
- without hard latency constraints
- For users remote from the observation site
More Demanding Sensor Network Applications

- Beyond simple data collection and aggregation
  - dynamic, high-speed phenomena
  - simultaneous tracking of multiple objects
  - 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 Networks in Human Spaces

A sensor network is deployed to provide situational awareness.

Users are embedded and operate in the same space as the network.

Both event capture by the network and the users’ need for information arise in a distributed fashion.

Users also act as sensors and provide both information as well as data interpretation to the network (community sensing).

Multiple device classes
Action Webs: A New Setting

- Closing the loop around sensor networks by providing real-time information to users, so as to enable timely action
- Enabling multi-user collaboration in deriving value from sensor data
Ex.: Shooter Localization

Objective: Locate shooters within an urban environment via weapon muzzle blast and shockwave data

Operational Scenario:
1. Soldiers move within an urban environment with limited situational awareness
2. Prior to advancing, Sensor Network is deployed (e.g., via UAV)
3. Sensor Network nodes self-configure and initialize
4. When a shot is detected, Sensor Network gathers data and transmit that to soldiers
5. Sensor Network data provides soldiers with exact location of shooter(s)
6. Soldiers adjust tactics based on enhanced situational awareness provided by the Sensor Network

Enhanced Situational Awareness and Greater Ability to Neutralize OPFOR Assets
Ex.: Mobility Prediction for Data Delivery to Mobile Users

Mobility graph (MG): data structure that represents possible movement patterns within the network

Mobility graph is different from connectivity graph:

- People can take shortcuts outside coverage area
- Radio signals can pass through walls
Routing Trees Under Mobility

- We use harmonic functions to establish implicit routing trees to users.
- Static user → periodically update gradient, compensating for link dynamics.
- Mobile user → increase frequency of gradient updates.
- What connectivity patterns support fast gradient updates?

Local Case: information gradient changes little as the user moves → fast updates.

Non-Local Case: information gradient takes long time to update.
Some Sensor Net Companies

- Dust Networks ([http://www.dustnetworks.com/](http://www.dustnetworks.com/))
- Ember ([http://www.ember.com/](http://www.ember.com/))
Integration with Current Networks

Access to unfiltered information, highly localized in time and space
Sensor Network
Hardware
Where are the CPUs?

An estimated 98% of 8 Billion CPUs produced in 2000 were used for embedded apps.

Where Has CS Focused?
- Interactive Computers
- Servers, etc.
- In Vehicles
- Embedded
- In Robots

Where Are the Processors?
- Direct 2%
- Robots 6%
- Vehicles 12%
- Embedded Computers 80%
- 8.5B Parts per Year
- 200M per Year

Look for the CPUs...the Opportunities Will Follow!

Source: DARPA/Intel (Tennenhouse)
Most Popular: Crossbow Motes

- Chipcon CC2420
  802.15.4 (Zigbee) Radio

- Atmel ATmega128L
  51-pin MICA2 / GPIO Connector
  (under)

- Buzzer
- Light & Temperature Sensor
- Microphone

MicaZ mote (Z for ZigBee)
Crossbow Stargate - Bottom View

- SA 1111 StrongArm I/O Chip
- Compact Flash Slot
- 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
  - 50 m range

**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
## More Comparisons

<table>
<thead>
<tr>
<th>Node Type</th>
<th>Sample “Name” and Size</th>
<th>Typical Application Sensors</th>
<th>Radio Bandwidth (Kbps)</th>
<th>MIPS Flash RAM</th>
<th>Typical Active Energy (mW)</th>
<th>Typical Sleep Energy (uW)</th>
<th>Typical Duty Cycle (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specialized sensing platform</td>
<td>Spec mm³</td>
<td>Specialized low-bandwidth sensor or advanced RF tag</td>
<td>&lt;50Kbps</td>
<td>&lt;5</td>
<td>1.8V*10–15mA</td>
<td>1.8V *1uA</td>
<td>0.1–0.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;0.1Mb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;4Kb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generic sensing platform</td>
<td>Mote 1-10cm³</td>
<td>General-purpose sensing and communications relay</td>
<td>&lt;100Kbps</td>
<td>&lt;10</td>
<td>3V*10–15mA</td>
<td>3V *10uA</td>
<td>1–2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;0.5Mb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;10Kb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-bandwidth sensing</td>
<td>Imote 1-10cm³</td>
<td>High-bandwidth sensing (video, acoustic, and vibration)</td>
<td>~500Kbps</td>
<td>&lt;50</td>
<td>3V*60mA</td>
<td>3V *100uA</td>
<td>5–10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;10Mb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;128Kb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gateway</td>
<td>Stargate &gt;10cm³</td>
<td>High-bandwidth sensing and communications aggregation Gateway node</td>
<td>&gt;500Kbs–10 Mbps</td>
<td>&lt;100</td>
<td>3V*200mA</td>
<td>3V *10mA</td>
<td>&gt;50%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;32Mb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;512Kb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Radio Comparison

[From Arora]

<table>
<thead>
<tr>
<th>Technology</th>
<th>Data Rate</th>
<th>Tx Current</th>
<th>Energy per bit</th>
<th>Idle Current</th>
<th>Startup time</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC1000</td>
<td>76.8 Kbps</td>
<td>10 mA</td>
<td>430 nJ/bit</td>
<td>7 mA</td>
<td>Low</td>
</tr>
<tr>
<td>Bluetooth</td>
<td>1 Mbps</td>
<td>45 mA</td>
<td>149 nJ/bit</td>
<td>22 mA</td>
<td>Medium</td>
</tr>
<tr>
<td>IEEE 802.11</td>
<td>11 Mbps</td>
<td>300 mA</td>
<td>90 nJ/bit</td>
<td>160 mA</td>
<td>High</td>
</tr>
</tbody>
</table>
**Communication is Expensive**

<table>
<thead>
<tr>
<th></th>
<th>1999 (Bluetooth Technology)</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication</td>
<td>(150nJ/bit) 1.5mW*</td>
<td>(5nJ/bit) 50uW</td>
</tr>
<tr>
<td>Computation</td>
<td>~ 190 MOPS (5pJ/OP)</td>
<td></td>
</tr>
</tbody>
</table>

Assume: 10kbit/sec. Radio, 10 m range.

**Large cost of communication relative to computation continues**

Source: ISI & DARPA PAC/C Program
High Data Rate Sensors

- Agilent cyclops imager
  - CMOS, medium quality
  - 128 x 128 and low power
  - 46mw active, 100nW standby
- CPLD
  - Low power frame grabber w. controlled clocking
- External SRAM
  - Image capture and manipulation buffer
  - Auto sleep
- External FLASH
  - Permanent storage for template matching

[From Ganesan]
Some of Our Hardware

- Gumstix Embedded PC
- Nokia Tablets/Phones
- Crossbow Imote2’s
- Citric motes w. cameras
- TelosB motes
A Technology Driver: Distributed Storage in Sensor Networks

Centralized Repository

On-Node Storage: Flash Memory
2-8Gb

Large and complex signal waveforms can be stored

[From Ganesan]
Data Overload

A lot more data will be captured than can or will ever be looked at.

Classical data indexing methods do not apply.

Most data must stay on the nodes.

On a mote-class device, transmitting the entire contents of a single 4GB flash chip takes approximately 110 hours of uninterrupted communication: just under five days, twice the expected lifetime of a node with 2 AA batteries [P. Levis].

We must be highly selective on what data is sent to users.
Architectural Challenges in Embedded Networked Systems
High-level Research Questions

- What element and system behaviors must we design into these large-scale, physically coupled, inherently distributed, autonomous systems?
- How can we program large aggregates of physically distributed and dynamic elements?
- What forms of spatio-temporal processing can take advantage of the spatial distribution and organization of ENS systems?
- What are the tradeoffs between actuation and sensing in hybrid systems and what distributed control techniques apply to sensor-rich environments?
- What are the fundamental design principles relevant to ENS?
Sensor Network Challenges

- Power management
  - communication 1000s of times more expensive than computation
  - correlated sensor data
  - coordinated sleeping schedules
  - load balancing
- In-network processing
  - data aggregation
  - overcounting of evidence
- Difficult calibration
  - localization
  - time-synchronization
- Constant variability
  - networking
  - sensing
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.
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

Time Synchronization

- Propagation Time
- Physical Media

Localization

(Sender) NIC I saw it at t=4 Receiver NIC I saw it at t=5

[From Estrin]
Semantic Routing and Networking

We want to address sensor data that carry useful information, not individual nodes.

Content and address in a message get intermixed.

How do we help information providers and clients find each other?

[From Estrin]
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.
Data Aggregation and In-Network Processing

Information aggregation can happen on the way to a destination, thus saving communication energy.

Need to balance quality of paths with quality of information collected.

Are there “application-independent” paradigms of information aggregation?

Temperature aggregation
Distributed Sensor Communication: Multi-Hop RF Advantage

RF power attenuation near ground:

\[ P_{\text{receive}} \propto \frac{P_{\text{send}}}{r^\alpha}, \quad \alpha : 2 - 5 \]

Or equivalently,

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

Power advantage:

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

\[ SNR_{r/\sqrt{N}} - SNR_r = 20\log \frac{r}{\sqrt{N}} = 10\log N \]
Structuring communication is very important:

In a setting where each node wishes to communicate some arbitrary data to another node at random, interference hinders spatial reuse, and therefore limits throughput scaling:

\[ \text{the per node capacity scales as } \frac{1}{\sqrt{N}} \] (Gupta & Kumar ‘99)

Because short communications are optimal in reducing interference -- effectively each node is using most 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 (duty cycling); 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

Options:

<p>| |</p>
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>a ahead-of b</td>
</tr>
<tr>
<td>b ahead-of c</td>
</tr>
<tr>
<td>c ahead-of d</td>
</tr>
<tr>
<td>d ahead-of e</td>
</tr>
</tbody>
</table>
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
New System Architectures

- Resource constraints require close coupling between the networking application layers
- Can we define *application-independent* programming abstractions for sensor networks?

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

A sensor net stack?

[From Estrin]
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 the 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 Personnel

Instructor A: Leonidas J. Guibas
Instructor B: Omprakash Gnawali
Course Assistant: Ian Downes

Course web page:
http://graphics.stanford.edu/courses/cs321-10-winter
http://www.stanford.edu/class/cs321

Some protected parts of the web page:
  - login as user “CS321”
  - password “WSN”
Course TextBook

Wireless Sensor Networks: An Information Processing Approach

Feng Zhao and Leonidas Guibas

Morgan-Kaufmann 2004
Course Outline, I

- Basics of embedded systems; sensor node hardware and software; simulators
- Wireless links and topology control; unicast and multicast multi-hop routing; broadcasting
- Power conservation and duty cycling
- Infrastructure establishment: time synchronization
- Infrastructure establishment: localization
- Information aggregation and in-network processing
- Information discovery and query processing
- Gossiping, bloom filters, network coding
- Distributed storage
- Sensor tasking and control, collaborative processing
Course Outline, II

Applications:
- Energy and environmental monitoring
- Tracking localized and non-localized phenomena

The course emphasizes the algorithmic, protocol design, and analytical aspects of sensor networks. Many other important aspects will not be fully addressed:
- hardware design
- physical layer issues
- low-level system software
- sensor-specific issues
- application-specific issues
Some Related Stanford Courses

- Prof. Sachin Katti (EE & CS)

- Prof. Phil Levis (CS & EE)
  - CS244E: Wireless Networking, Spring 2010

- Prof. Hamid Aghajan (EE)
  - EE392Y: Vision Sensor Networks Lab

Other faculty: Abbas El Gamal (EE), Ashish Goel (MS&E), Andrea Goldsmith (EE), Teresa Meng (EE), Amin Saberi (MS&E) ...
Course Format

- Lectures by the instructors, or the assistant
- Student of current research papers (blog) and/or of project results
- A course project is required. We will provide guidance and support for a specific implementation project on actual mote hardware. However, other projects of your own design are also OK. These can be
  - an implementation on actual mote hardware, supported by simulations
  - a more theoretical/analytical investigation, supported by simulations
  - a simulation only project is not OK
Course Grading

- 20% class participation (live or blog)
- 5% warm-up project (get used to the hardware)
- 25% in class midterm
- 50% course project
- no final
It’ll Be Fun
The End