Information Processing in Microsensor Networks: an introduction

Feng Zhao
Palo Alto Research Center
(formerly Xerox PARC)
http://www.parc.com/zhao
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.*

**Smart Sensors and Sensor Net**

- **Environmental sensing**
  - Traffic, habitat, hazards, security, anti-terrorism
- **Industrial sensing**
  - Machine monitoring and diagnostics
  - Power/telecom grid monitoring
- **Human-centered computing**
  - Context-aware environment
Wireless sensor trend

- Of 9.6 billion uP 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 MICA mote
  4 MIPS CPU (integer only)
  8KB Flash
  512B RAM
  Sensors: on board stack

  Super-cheap & tiny
  
  Smart Dust (in progress)
  CPU, Memory: TBD
  (LESSI)
  Sensors: integrated
Sources of constraints:

• Energy and physics of sensing, processing, and communication

• Task requirements from application domains
Sample Sensor Hardware: Berkeley motes

- **CPU:**
  - 8-bit, 4 MHz Atmel processor
  - No floating-point arithmetic support

- **Radio:**
  - 916 MHz RFM @10Kbps
  - Distance 30-100ft
  - Adjustable strength for RF transmission & reception

- **Storage:**
  - 8 KB instruction flash
  - 512 bytes data RAM
  - 512 bytes EEPROM (on processor)

- **OS:**
  - TinyOS, event driven (3.5KB code space)

- **Sensors:**
  - 10-bit ADC mux’d over 7 analog input channels
  - Sensing: light, sound, temperature, acceleration, magnetic field, pressure, humidity, RF signal strength
### Power Breakdown...

<table>
<thead>
<tr>
<th></th>
<th>Active</th>
<th>Idle</th>
<th>Sleep</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CPU</strong></td>
<td>5 mA</td>
<td>2 mA</td>
<td>5 µA</td>
</tr>
<tr>
<td><strong>Radio</strong></td>
<td>7 mA (TX)</td>
<td>4.5 mA (RX)</td>
<td>5 µA</td>
</tr>
<tr>
<td><strong>EE-Prom</strong></td>
<td>3 mA</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>LED’s</strong></td>
<td>4 mA</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Photo Diode</strong></td>
<td>200 µA</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Temperature</strong></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: \((7\text{mA} \times 3\text{V}/10\text{e}3) \times 8 = 16.8\mu\text{J} \text{ per 8bit}\)
  - Comp: \(5\text{mA} \times 3\text{V}/4\text{e}6 = 3.8\text{ nJ} \text{ per instruction}\)
  - Ratio: 4,400 instruction/hop

- **Sensoria nodes:**
  - Comm: \((100\text{mW}/56\text{e}3) \times 32 = 58\mu\text{J} \text{ per 32bit}\)
  - Comp: \(750\text{mW}/1.1\text{e}9 = 0.7\text{nJ} \text{ per instruction}\)
  - Ratio: 82,000 instruction/hop

This means

- Lithium Battery runs for 35 hours at peak load and years at minimum load, a three orders of magnitude difference!
Distributed sensor net: multi-hop RF advantages

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:

\[ \frac{P_{\text{send}}(Nr)}{N \cdot P_{\text{send}}(r)} = \frac{(Nr)^\alpha P_{\text{receive}}}{N \cdot r^\alpha P_{\text{receive}}} = N^{\alpha - 1} \]
Distributed sensor net: detection and SNR advantages

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):

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

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

$$\frac{\text{SNR}}{\sqrt{N}} - \frac{\text{SNR}_r}{\sqrt{N}} = 20\log \frac{r}{r} = 10\log N$$
Tracking as a canonical problem for studying information processing in sensor networks
Sensor Network Tracking

- 17 nodes (6 DOA, 11 amplitude)
- Scale: 1 square=5 ft.
- 0.5 sec update interval
- Packet loss significant

**Leader Node**
**Non-leader Node**
**GPS ground truth**

**parc**
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**Data Packet**
**Control Packet**
**Broadcast control**
A tracking scenario

Constraints:
- Node power reserve
- RF path loss
- Packet loss
- Initialization cost
- ...

1. **Discovery**: Node \( a \) detects the target and initializes tracking
2. **Query processing**: User query \( Q \) enters the net and is routed towards regions of interest
3. **Collaborative Processing**: Node \( a \) estimates target location, with help from neighboring nodes
4. **Communication protocol**: Node \( a \) may hand data off to node \( b \), \( b \) to \( c \), …
5. **Reporting**: Node \( d \) or \( f \) summarizes track data and send it back to the querying node

What if there are obstacles?

What if there are other (possibly) interfering targets?
Fundamental issues to address

- What do nodes know when they wake up
  - How do nodes discover each other, time synch, location?
- What is routing
  - Address-centric or data-centric? Is TCP/IP appropriate? What are the performance metrics?
- What is information theory for sensor nets?
  - What is the minimum number of sensors for recovering a continuous signal field? Nyquist sampling theorem for sensor net?
  - What are the compression schemes?
- What is data base for sensor net?
  - How is the data stored, organized, and retrieved? Is there a SQL interface?
- How is it connected to the Internet?
  - What are the edge network protocols? BGP?
  - How will a user browse the data? Google™ for physical world?
- How is it programmed
  - Is there an OO programming model for embedded systems?
  - What are the abstraction layers? What is the “sensor net stack”?
What is routing in a sensor net?
What is unique about sensor networks?

- **Unique characteristics**
  - Coverage
    » Distance/area covered, number of events, number of active queries
  - Spatial diversity
    » Dense spatial sampling, multi-aspect sensing, multiple sensing modalities
  - Survivability
    » Robust against node/link failures
  - Ubiquity
    » Quick/flexible deployment, ubiquitous access, info timeliness

- **Particularly suited for detecting, classifying, tracking**
  - Non-local spatio-temporal events/objects
    » *Simultaneous dense spatial sampling* to identify and track large, spatially extended event
    » *Continuous spatio-temporal sampling* to track moving objects
  - Low-observable events
    » *Distributed information aggregation*
    » *Non-local information validation*
Sensor network research is largely driven by applications ...
Habitat monitoring: www.greatduckisland.net

Great Duck Island, 10 miles off the coast of Maine:
Remote wireless sensors are being used to find out more about birds in their natural habitat.

“IT will enable us to study ecosystems at a level that has not been conceived.”
Steve Katona, College of the Atlantic biologist and president

BBC News, October 10, 2002
Monitoring Plants at Huntington Botanical Garden

Huntington Botanical Gardens Nursery Area Sensor Web (see map).

Sensor Webs Data Applet, version 1.0

- **AirTemp** (deg C)
  - Pod 1
  - Pod 15
  - Pod 17

- **LightFlux** (relative)
  - Pod 1
  - Pod 15
  - Pod 17

- **Battery** (Volts)
  - Pod 1
  - Pod 15
  - Pod 17

Graph Options

Choose a Measurement: AirTemp

Use same Pods for all Graphs

Input Pod # and press Enter:

- Pod 1
- Pod 15
- Pod 17

Auto Scale

Manual Scale: Min. [ ] Max. [ ]

Please input dates as "mm-dd-yyyy+hh:mm:ss"

Start time: 03-31-2002+00:00:00

End time: real-time

(For real-time graphs, leave "End time" blank)

Hours wide (for real-time graphs): 48
The Valley Authority just declared a region-wide emergency: A large-scale chemical gas leak has been detected at a plant 20 minutes ago.

National Guard has been activated to evacuate nearby towns, and to close roads/bridges.

To get a real-time situational assessment of the extent and movement of the gas release and inform the evacuation, the CS428 SWAT Team is called in.

Three small UAVs are immediately launched from an open field 15 miles south of the attack site, each equipped with 1000 tiny chemical sensing nodes.

Upon flying over the vicinity of the attack site, the sensor nodes are released.

The nodes self-organize into an ad hoc network, while airborne, and relay the tracking result back to the emergency response command center.

– Where is the plume, how big, how fast, which direction?
Some of the possible project ideas

- Counting distinct objects
- Routing around “forbidden” zones
- Mobile sensor to improve object localization
- Query optimization for multi-object tracking
- CCW relation tracking
- “Am_I_Surrounded” tracking
Assumptions

- Each node has a number of on-board sensors (in case there is only one sensor, we use “sensor” and “node” interchangeably)
- Each node can communicate wirelessly with other nodes within a fixed radius $R$ (larger than the mean inter-node distance)
- Nodes are time-synchronized to a global clock
- Targets are point sources of signals; target signals propagate isotropically in the physical space, and attenuate as a monotonically decreasing function of the distance from the source
- Each sensor has a finite sensing range, determined by a fixed minimal amplitude a sensor can sense. Signals of two targets sum at a sensor. Here we assume amplitude sensing (e.g. to infer distance to the target). DOA or restricted-view sensing (e.g., camera) may provide new constraints.
- Onboard battery power is the main limiting factor, as well as network bandwidth and latency
Routing around “forbidden” zones

Problem spec
- Each node knows locations of nodes within RF range and that of destination node
- There are two forbidden zones where nodes are not available for sensing or comm.
  - Stationary zones (e.g., holes in the net)
  - Moving zones (e.g., quiet zones to evade enemy eavesdropping)

Task
- Discover routing path with minimal # hops
- Maintain path, when the forbidden zones move, requiring
  - minimal repair to the current path
- **Bonus point:** Suppose data along the path is aggregated for locating a stationary target in the middle of the field. Do the same as above, plus optimizing for localization accuracy as well
Mobile sensor to improve object localization

Problem spec
- Sensors track boundary of a polygon with \( n \) sides
- Each sensor can detect whether it is covered by the object or not, and can move in physical space

Task
- Determine which subset of sensors to move, to maximize estimation improvement while minimizing the total distance traveled
- **Bonus point**: Suppose only a fraction of the sensors can move, determine the optimal fraction for detecting a given shape
Query optimization for multi-target tracking

Problem spec
• Assume two or more targets
• Query how many targets are present

Task
• Route query towards each of the targets, optimizing for the total number of hops
• Determine when to split a query (targets are too far apart?), and when to merge
• Consider both stationary and dynamic target cases

Range sensors (eg. Omni-microphone)
Target Localization for CCW Relations

Problem Spec
Many complex spatial relations among targets can be understood by sensing CCW relations.

Task
The task is to experiment with sensor selection strategies for optimally sensing CCW relations.
Tracking the “Am_I_Surrounded” Relation

Problem Spec
We want to maintain a cage of three black vehicles containing the white vehicle

Task
When the white vehicle escapes its cage, we want to search for a new red vehicle completing the new cage.
Preview of the classes

- Week 1: Class organization; SN introduction and applications
- Week 2: Localization and tracking
- Week 3: Networking I; class project discussion
- Week 4: Networking II
- Week 5: Network initialization and services
- Week 6: Information management I
- Week 7: Information management II
- Week 8: SW/HW architecture; resource constraints
- Week 9: Localization and tracking II
- Week 10: Applications; Final project reports