Controlled Mobility in Sensor Networks
http://nsrc.cse.psu.edu/

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- Coverage
- Reliability
- Future work
Wireless Sensor Networks

- Sensor/actuator
- CPU and memory
- Wireless interface
- Battery

Dependability
- Sufficient coverage
- Fault tolerance
- Security
Mobile Sensors

Controllable Mobile Sensors

- Power consumption:
  Movement >> Communication

- Communication:
  - Range: 10ft~100ft
  - Bandwidth: 40kpbs

- Sensing range < Comm range/2

- Mobility: 20cm/s

- Cost: $150

Size: 7 x 4.5 x 3.5 (cm)  
By USC

Size: 13 x 6.5 (cm) base  
By UC Berkely

Size: 2.7 x 2.1 x 4 (cm)  
By NASA
Dependable Sensor Networks

Network initialization:

Sensor Deployment for Sufficient Coverage

All sensors are mobile

A mix of mobile and static sensors

Motion Planning

ICNP’03
MASS’04

INFOCOM’04
IEEE TMC

Network operation:

Maintaining Dependability

Coordinated Detection

Sensor Relocation

INFOCOM’05

ISLPED’05

INFOCOM’04
MASS’04

MILCOM’03
Outline

- Self-deployment protocols for a mix of mobile and static sensors
- Sensor relocation
- Future research plans
Mobility for Coverage: Problem Statement

Direct the movement of mobile sensors to increase coverage

Static sensor

Mobile sensor
Our Solution

Greedy heuristic
- Moving sensors to the largest holes

Framework
- Coverage hole detection
  - Voronoi diagram
- Distributed allocation of mobile sensors to the holes
  - Basic bidding protocol
  - Proxy-based bidding protocol
Allocating Mobile Sensors to the Holes

Challenge:
- Mobile sensors do not know where the largest holes are

Idea: Bidding
- Mobile sensor: hole-healing server
  - **Base price**: area currently covered
- Static sensor: bidder
  - **Bid**: estimated size of the detected coverage hole
  - **bid > base price**
Coverage Hole Detection

Voronoi diagram

Voronoi cell

Local detection

My Voronoi cell

Initially

after hearing \( s_2 \)

after hearing \( s_3 \)

after hearing \( s_4 \)

after hearing \( s_5 \)
Basic Bidding Protocol

Initialization phase

- Mobile sensor:
  - Choose highest bid
  - Move!
  - Base price = accepted bid

- Static sensor:
  - Broadcast location

- Static sensor:
  - Compute bid
  - Target location = farthest Voronoi vertex
  - Send <bid, target location> to the closest mobile sensor;
  - Bid > base price

Mobile sensor:
  - Broadcast <base price, location>

Static sensor:
  - Compute bid
  - Target location = farthest Voronoi vertex
  - Send <bid, target location> to the closest mobile sensor;
  - Bid > base price

Mobile sensor:
  - Choose highest bid
  - Move!
  - Base price = accepted bid

Base price increases monotonically and protocol terminates when no bidder can provide a higher bid than the lowest base price of mobile sensors.
Iterative physical movement
Proxy-based bidding protocol

Key idea: Virtual movement

Proxy sensor (winning bidder):
- Processes bidding messages
- Advertises services
- Notifies the mobile sensor to move
Tradeoff between sensor coverage and cost

<table>
<thead>
<tr>
<th>Percentage of mobile sensors</th>
<th>Algorithm tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>VEC protocol ([Infocom04])</td>
</tr>
<tr>
<td>10%~50%</td>
<td>Bidding protocol</td>
</tr>
<tr>
<td>0%</td>
<td>Random deployment</td>
</tr>
</tbody>
</table>
Tradeoff between Sensor Coverage and Cost

Static sensor: $1
Mobile sensor: $n

Minimum number of sensors needed

Network cost ($)

Percentage of mobile sensors

$ for 90% coverage

Percentage of mobile sensors

coverage=90%
coverage=95%
coverage=98%
Comparisons

![Graph showing energy consumption (J) against the percentage of mobile sensors. The graph compares Basic bidding and Proxy-based bidding. The green line represents Basic bidding, and the blue line represents Proxy-based bidding. As the percentage of mobile sensors increases from 10% to 50%, the energy consumption decreases.]
Outline

• Self-deployment protocols for a mix of mobile and static sensors
• Sensor relocation
• Future research plans
Mobility for Reliability: Problem Statement

Direct the movement of sensors to overcome failures under a time/energy constraint

Challenges

– Recovery may have to occur before a deadline
– Relocation should not affect other missions supported by the network
– Relocation must consider network lifetime

Outline of Solution

• Phase I
  – Locate redundant sensors: quorum-based solution

• Phase II
  – Relocate sensors to target positions
Locating Redundant Sensors

Apply grid-quorum to reduce searching overhead
- Grids in one row form a supply quorum
- Grids in one column form a request quorum
Relocating Sensors

Directly moving the sensor to the destination may not be a good solution
  – Long delay and unbalanced power consumption

Use cascaded movement

Challenges in choosing cascading nodes
  - Bounded relocation delay
  - Energy balance
Let recovery delay of $s_4$ be $T_4$

\[ \text{distance}(s_3, s_4) \leq \text{speed} \times T_4 \]

$s_3$ can leave at $0, T_4 - \text{distance}(s_3, s_4) / \text{speed}$

Let recovery delay of $s_3$ be $T_3$

Let $s_3$ leave at $t_3 = T_4 - \text{distance}(s_3, s_4) / \text{speed}$

\[ \text{distance}(s_2, s_3) \leq \text{speed} \times (T_3 + t_3) \]

\[ \text{distance}(s_i, s_{i+1}) \leq \text{speed} \times (T_{i+1} + t_{i+1}) \]
Tradeoffs of Using Cascading

**Tradeoff between Load balance and energy efficiency**

- Maximize minimum remaining energy $E_{\text{min}}$?
- Minimize total energy consumption $E_{\text{total}}$?
Tradeoffs of Using Cascading

Heuristic: Minimize \((E_{total} - E_{min})\)

Using Modified Dijkstra’s Algorithm
Outline

• Self-deployment protocols for a mix of mobile and static sensors
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Joint Sensing and Communication

Optimize value of a network over its lifetime

- Quality of data - coverage
- Ability of data to be collected - communication
- Energy required for reconfiguration and communication
- Value of mission

\[ v_{i,j}^k = u_c(X_k) s_i(m_j, X_k) \]

\[ V = \sum_{k=1}^{K} V_k \]

\[ C_k = M(X_{k-1} \rightarrow X_k) + E(X_k) t_k \]
Summary

Sensor deployment in mixed sensor networks
  - Balancing sensor cost and coverage
  - First effort to address the problem

Sensor relocation
  - Small impact on the topology
  - In a timely and efficient way

Challenges
  - Joint optimization between sensing and communication
  - Accommodation of multiple missions
  - Value of data
Possible Extensions

Varying density requirements
  – Redundant will not mean the same thing in all grids

React to events, not just failure
  – Multiple events
  – Priorities

Proactive movement
  – Pre-position sensors in anticipation of failure or event
  – Request replacement sensor before death