A Comprehensive Framework for Dependable Nomadic Computing

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Nomadic systems pose many problems

- Localization (Sextant, [Mobihoc 2005])
- Programming Model (MagnetOS, [MobiSys 2005])
- Routing (SHARP, [Mobihoc 2002])
- Path Selection (DPSP, [Mobihoc 2001])
- Simulation (SNS, [WSC 2003, TOMACS 2004])
- ...

Need to figure out the location of nodes in order to provide novel location-based services

Need a new programming model for performing long-lived computations in mobile networks
Challenges in Localization

**Hardware**
- Expensive
- Power Consuming

**Infrastructure**
- Initial setup required
- Not always available

**Modeling**
- Irregular wireless coverage area
- Introduces error
Sextant Approach

- Extract geometric constraints
- Disseminate them transitively
- Solve in a distributed manner
Contributions

- Unified Node and Event localization
  - Accurate
    - Negative as well as positive information
    - Explicit representation
  - Practical
    - Constraint extraction
    - Deployed on MICA-2 motes, laptops and PDAs
Sextant Approach

Positive constraint

Negative constraint

Contributions

- Unified Node and Event localization
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  - Explicit representation
- Practical
  - Constraint extraction
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Sextant Approach

- Need not be convex
- May have holes
- May have disconnected components

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Node Localization

Positive Information
Node Localization

Intersection of Positive Information
Node Localization

Negative Information
Subtraction of Negative Information
Node Localization

Transitive Dissemination of Positive Information
Node Localization

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Transitive Dissemination of Positive Information
Node Localization

Transitive Dissemination of Positive Information
Combining Positive and Negative Information
Combining Positive and Negative Information
Transitive Dissemination of Negative Information
Node Localization

Transitive Dissemination of Negative Information
Node Localization

Reﬁning Location Estimates
Refining Location Estimates
Sextant: Node and Event Localization

Polygons with Bézier boundaries

Each Node $x$

- Location Estimate: $\mathcal{E}_x$
  - Positive Constraint: $\mathcal{P}_x$
  - Negative Constraint: $\mathcal{N}_x$
  - Set of positive constraints: $\Gamma_x$
  - Set of negative constraints: $\Theta_x$

Invariant

$$\mathcal{E}_x = \bigcap_{p \in \Gamma_x} p \setminus \bigcup_{n \in \Theta_x} n$$
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Union of circles in $\mathcal{E}_x$

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Sextant Approach

Intersection of circles in $E_x$

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Event Localization

<table>
<thead>
<tr>
<th>Similarity to Node Localization</th>
</tr>
</thead>
<tbody>
<tr>
<td>▶ Constraints from sensing hardware vs. wireless radio</td>
</tr>
<tr>
<td>▶ Boolean sensed/not-sensed signal vs. boolean connectivity</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Differences from Node Localization</th>
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<td>▶ Annotate resultant areas with probabilities</td>
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Event Localization

Positive Contribution
Sensor somewhere in $\mathcal{E}$ detects event; probability event in grid $\mathcal{G}_i$.

Negative Contribution
Sensor somewhere in $\mathcal{E}$ does not detect event; probability event in grid $\mathcal{G}_i$.

Solution
Product of positive and negative contributions from sensors sensing and not-sensing the event.

Bayesian Probability
Feedback
Feedback
Events as a Source of Constraints
Events as a Source of Constraints
Optimizations

Annulus for range x

Wireless Hardware
- Range Measurements
- Angle of Arrival

Sensor Hardware
- Event Distance
- Directional Sensors

Emin Gün Sirer  Sextant: Node and Event Localization
Optimizations

Wireless Hardware
- Range Measurements
- Angle of Arrival

Sensor Hardware
- Event Distance
- Directional Sensors

Sector for angle $x$
Wireless coverage area is non-convex and has holes.

- All reachable nodes ≤ $R$ away
- All unreachable nodes ≥ $r$ away

Wireless Radio
- Boolean packet-received / packet-not-received.
Modeling

Wireless Radio

Boolean packet-received / packet-not-received.

- All reachable nodes ≤ R away
- All unreachable nodes ≥ r away
## Protocol

### Neighborhood Discovery

- Nodes transmit periodic beacons
- Threshold beacon reception required for boolean connectivity

### Gossip

Disseminate constraints as long as they are useful
- Positive information – used only at first hop
- Negative information – used within the first few hops
## Validation of Node Localization

### Implementation

- Implemented on MICA-2 motes, laptops and PDA
- About 2kB of storage per node
- About 80kB data transmitted per node until convergence

### Setup

- 50 MICA2 motes placed in a grid pattern
- Landmarks chosen at random
- 80% packet reception threshold chosen for connectivity
### Comparing Node Localization

- **Triangulation** – Centroid of neighbor nodes
  - GPSLess

- **Single-hop** – No transitive dissemination
  - Active Badge, Cricket, GPSLess, Localization Using Moving Target

- **Positive-constraints** – No negative information
  - APS, Convex position estimation, N-hop Multilateration, Robust Positioning

- **Sextant**
Validation of Node Localization

Sextant locates more nodes accurately

Node Localization

- Accurate
- Efficient
- Scalable
Validation of Node Localization

- Accurate
- Efficient
- Scalable

Sextant requires few landmarks

Sextant: Node and Event Localization
Validation of Node Localization

Node Localization

- Accurate
- Efficient
- Scalable

Sextant requires fixed landmark density
Validation of Event Localization

Setup

- 50 MICA2 motes placed in a grid pattern
- Event is a flash of light
- Appreciable change in analog value triggers sensor

Comparing Event Localization

- **Triangulation** – Centroid of sensors reporting the event
  - Acoustic Ranging
- **Sextant**
Validation of Event Localization

Sextant locates more events accurately

Event Localization
- Accurate
- Efficient
- Robust
Validation of Event Localization

Accuracy improves with nodes

Event Localization

- Accurate
- Efficient
- Robust
Validation of Event Localization

Sextant independent of sensing range

Event Localization
- Accurate
- Efficient
- Robust
Current state of the art is to view the network as a system of systems

- Forces all applications to implement their own mechanisms for state migration
  - Tedious, error-prone
  - Multiple applications may conflict

Fundamental problem stems from lack of an arbiter

- Need a system layer to perform resource mediation
MagnetOS Approach

Contributions

- Programmer writes monolithic application for a single JVM
- MagnetOS statically partitions the application into communicating objects
  - Objects can reside anywhere in the network
- MagnetOS dynamically finds a good placement of objects on nodes in the network
  - Energy efficiency is the key goal
MagnetOS Approach

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Implemented most of the system
  ▶ Static rewriter (50K loc)
  ▶ Space-optimized JVM for x86 and StrongARM (30K loc)
  ▶ Dynamic runtime (25K loc)

Working on adding transparent replication
  ▶ Based on message logging
  ▶ Driven initially by programmer annotations
Summary

- Sextant is a localization framework that achieves high accuracy and scalability
  - Explicit representation of regions using Bézier curves
  - Conservative and comprehensive extraction of negative as well as positive constraints
  - Transitive dissemination of constraints
  - Use of events to refine node location
- Sextant is practical
- MagnetOS simplifies programming mobile systems
  - Many new directions based on transparent rewriting

http://www.cs.cornell.edu/People/egs/sextant/
http://www.cs.cornell.edu/People/egs/magnetos/
## Positive Information

- **GPS-Free** ’01: Capkun, Hamdi and Hubaux
- **APS** ’01: Niculescu and Nath
- **Convex Position Estimation** ’01: Doherty, Pister and Ghaoui
- **Robust Positioning** ’02: Savarese, Rabay and Langendoen
- **N-hop Multilateration** ’02: Savvides, Park and Srivastava
- **APS-AoA** ’03: Niculescu and Nath
- **Mere Connectivity Localization** ’03: Shang, Ruml, Zhang and Fromherz
- **Connectivity-Based Positioning** ’04: Bischoff and Wattenhofer
- **Unit Disk Approximation** ’04: Kuhn, Moscibroda and Wattenhofer
- **Virtual Coordinates** ’04: Moscibroda, O’Dell and Wattenhofer
**Single-Hop**

- **Active Badge** ’92: Want, Hopper, Falcão and Gibbons
- **GPS-Less** ’00: Bulusu, Heidemann and Estrin
- **RADAR** ’00: Bahl and Padmanabhan
- **Cricket** ’00: Priyantha, Chakraborty and Balakrishnan
- **RF-Based Location Tracking** ’04: Lorincz and Welsh
- **VORBA** ’04: Niculescu and Nath
- **Localization Using a Moving Target** ’04: Galstyan, Krishnamachari, Lerman and Pattem
Related Work

Event Localization

- **Fine-grained Localization** '01: Savvides, Han and Srivastava
- **Collaborative Processing** '03: Zhao, Liu, Guibas and Reich
- **Acoustic Ranging** '04: Sallai, Balogh, Maroti and Ledeczi
- **Countersniper** '04: Simon, Maroti, Ledeczi et al.
- **Entity Tracking** '02: Brooks, Griffin and Friedlander
- **Energy-Efficient Surveillance** '04: He, Krishnamurthy, Stankovic et al.