Localization and Localizability in Sensor and Ad-hoc Networks

Ph.D. Dissertation Defense

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“The success of a retail store depends on three factors: **location**, **location**, and **location**. ”

— anonymous

“So does wireless networking. ”

— Zheng Yang

Outline

- ☐ Introduction
- ☐ Localization
- ☐ Localizability
 - Network Localizability
 - Distributed Localizability Testing
 - Node Localizability
- ☐ Conclusion and Future Study

What is a Sensor Node?

- Sensor is a tiny electronic device with four major components

What is a Sensor Node?

- Different kinds of sensor nodes

What is a WSN?

- Wireless Sensor Network (WSN)
 - *a large amount, spatially distributed, and autonomous* sensors
 - cooperatively monitor physical world.

What is a WSN?

WSN Applications

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Localization

- Determine the locations of wireless devices in a network

Why Is Localization Important?

- Wireless sensor networks
 - Application
 - Environmental monitoring, object tracking, ...
 - “*Sensing data without knowing the sensor location are meaningless.*” [IEEE Computer, Vol. 33, 2000]
 - Localization aids other network functions
 - Routing, topology control, clustering, ...

Why is Localization a Non-Trivial Problem?

- ☐ Manual configuration
 - Unscalable and sometimes impossible
- ☐ Why not use GPS?
 - Increasing hardware costs
 - Obstructions to GPS satellites
 - ☐ Indoor
 - ☐ Underground
 - GPS accuracy (10-20 feet) poor for short range application

Network Localization

- ☐ Network Localization has been proposed for WSN
 - Beacons
 - ☐ special nodes at known locations
 - Non-beacon nodes
 - ☐ Determine locations by measuring geographic information to nearby nodes

Network Localization

- Network localization consists of two steps

1. Physical Measurement

2. Location Computation

- This study focuses on range-based localization

Distance Measuring

- Ranging techniques
 - Radio Signal Strength (RSS)
 - Time Difference of Arrival (TDoA)
- Ranging systems

UCLA medusa mote

Yale XYZ mote

MIT Cricket mote

Distance Graph Model

- Distance graph G_N of a wireless network N
 - Vertices: wireless devices (e.g., laptops, PDAs, or sensor nodes)
 - Edges: an edge connecting two vertices (i and j) if the distance $d(i, j)$ between corresponding nodes can be measured

Distance Graph Model

□ Example

Location Computation

□ Trilateration

■ Idea

- A location of an object can be determined if distances to three anchors are known.

■ Advantages

- Efficient
- Distributed
- Easy to implement

Location Computation

☐ Iterative trilateration

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Localizability

Definition

A network is *localizable* if it has a **unique** realization (or embedding) that respect the pairwise distance constraints and beacon locations in some metric space.

Localizability

□ **Localizability** V.S **Localization**

- If a network is **NOT** localizable, by no means it can be localized.
- If a network is localizable, it can be localized in theory (but may be computationally infeasible).

Conditions of Localizability

☐ Sufficiency

- What properties make a graph localizable?

☐ Necessity

- What properties a localizable graph has?

Localizability and Graph Rigidity

Solution:

G must be *rigid*.

G must be 3-connected.

G must be *redundantly rigid*:
It must remain rigid upon
removal of any single edge.

Localizability and Graph Rigidity

Global rigidity (by Jackson and Jordan, 2003)

A graph is generically globally rigid in 2D plane iff. it is 3-connected and redundantly rigid.

The necessary and sufficient condition of localizability.

Network localizability (Eren, 2004)

A network is localizable iff. its distance graph is globally rigid and it contains at least three beacons.

Localizability Test Algorithm

- Network localizability can be tested
 - Polynomial time to the graph size
 - Rigidity: $O(n^2)$ by the pebble game algorithm by Jacobs and Hendrickson (1997)
 - Redundant rigidity: $O(n^2)$ algorithm by Hendrickson (1991)
 - 3-connectivity: $O(n)$ algorithm by Tarjan (1972)
- So far, it seems ...

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Difficulties of Localizability Test

- Global knowledge is needed
 - Connectivity
 - Rigidity
- Hard to design distributed approaches
 - Trilateration as a compromise
 - Nodes located by TRI are localizable

Limitation of Trilateration

- Only identify a subset of localizable networks (*trilateration extension*)

Limitation of Trilateration

- ❑ Fails to identify border nodes as localizable

Motivation

- Motivate a novel approach for testing localizability
 - Efficient
 - Distributed
 - Capable: identifying a larger number of localizable nodes than TRI

Wheel graphs

- A wheel graph W_n consists of
 - A hub vertex
 - $(n-1)$ rim vertices

Wheel graphs

- Model 1-hop neighborhood abstract
 - From the standpoint of the hub vertex
 - All elements are in its 1-hop neighborhood
 - vertices and edges
- Wheel graphs are globally rigid
 - They are 3-connected and redundantly rigid.

Identify localizable vertices based on
the **wheel** instead of **TRI** !

Network-wide Localizability

Within
Neighborhood

Entire
Network

Wheel Extension

Definition 1.

A graph G is a *wheel extension* if there are

- (a) three pairwise connected vertices, say v_1 , v_2 , and v_3 ; and
- (b) an ordering of remaining vertices, say v_4 , v_5 , v_6 , ..., such that any vertex v_i is included in a wheel graph containing three early vertices in the sequence.

Wheel Extension

The wheel extension is globally rigid.

The above network is a wheel extension
but **NOT** a trilateration extension.

WHEEL Protocol

☐ Iterative localization

Advantages of WHEEL

□ Optimality

- Optimal among **ALL** algorithms that use only 1-hop information.

□ Efficiency

- $O(n)$ for ad-hoc networks
- n : the network size

□ Low cost

- no extra cost compared with TRI

Advantages of WHEEL

- Using WHEEL, node 1 and 2 can be identified as localizable

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Node Localizability

Observations

from a working WSN: OceanSense

Almost **all the time** the network is **NOT** entirely localizable.

A large portion, on average nearly **80%**, of nodes are actually localizable.

Node Localizability

☐ Node localizability

- To answer the question that *whether a particular node has a unique location.*
- Node localizability focuses on single node;
- Network localizability considers entire network

Why Is Node Localizability Important?

- ☐ Partially localizable networks
 - They are not localizable.
 - A portion of nodes have unique locations while others do not.
- ☐ Application
 - Some nodes draw remarkable attentions
 - ☐ Abnormal readings
 - ☐ Border area

Node Localizability

- Which one is harder?

Why Node Localizability Difficult?

- A straight-forward solution (RR3B)
 - Find a sub-network that is localizable
 - Identify all nodes in the sub-network localizable

- Correct? **YES, BUT...**

Why Node Localizability Difficult?

□ Missing localizable nodes

- G is not 3-connected
- u does not satisfy RR3B
- u is localizable

Some conditions *essential* to network localizability are *no longer necessary* for node localizability.

Conditions of Node Localizability

☐ Necessity

- Degree = 3
- 3 vertex-disjoint paths to 3 distinct beacons [Goldenberg, 2005]

☐ Sufficiency

- Trilateration
- Localizable sub-network (RRT-3B) [Goldenberg, 2005] .
- Implicit edge [Eren, 2005]

Previous work

Necessary Conditions

- 3 vertex-disjoint paths (3P)
 - Goldenberg et al., 2005

- Redundant Rigidity (RR)
 - Yang et al., 2010
 - If a vertex is localizable, it is included in the redundantly rigid component of beacon nodes.

Necessary Conditions

□ Necessity

- The combination of 2 necessary conditions is also a necessary condition

RR-3P

Theorem

In a distance graph $G = (V, E)$ with a set $B \subset V$ of $k \geq 3$ vertices at known locations, if a vertex is localizable, it is included in the **redundantly rigid** component that contains B and has **3 vertex-disjoint paths** to 3 distinct vertices in B .

Necessary Conditions

□ RR-3P is **NOT** sufficient

(a) The vertex u satisfies RR-3P.

(b) u suffers a discontinuous flexing.

Sufficient Conditions

□ RR3P

- All 3 paths are inside the RR component

Summary (1)

- Difference between RR-3P and RR3P

Necessity

RR-3P

Sufficiency

RR3P

All paths are strictly included

Summary (2)

Testbed experiment

- OceanSense: A wireless sensor network for ocean monitoring

Figure 12: System Deployment. The upper right figure shows an encapsulated waterproof sensor mote.

Testbed experiment

- OceanSense
 - Ocean monitoring
 - 100+ sensors on sea surface
 - Environmental data
 - Temperature
 - Humidity
 - Ambient illumination
 - Sea depth
 - Restricted mobility

Testbed experiment

- Sensor node platform: TelosB
 - Long lifetime
 - Low power
 - Low cost
 - Robust
 - Standard compliant

TelosB Mote

Controller

TI MSP430
8MHz
10K RAM

Radio

CC2420
802.15.4
2.4GHz

Sensor

Light
Humidity
Temperature

Interface

USB
External flash
1 MB
OS
TinyOS 1.1

Testbed experiment

□ Transceiver: Chipcon CC2420

- 802.15.4 compliant
- RF power: -24dBm to 0dBm
- Receiving sensitivity: -94dBm
- Outdoor range: 75m to 100m
- Indoor range: 20m to 30m

ZigBee/802.15.4

- ZigBee is suitable for wireless sensor networks

Testbed experiment

- All non-beacon nodes are identified as either localizable (**black**) or non-localizable (**red**).

Testbed experiment

□ GreenOrbs

- A WSN in a forest
- Long-term: over 1 year
- Large-scale: 1000 nodes

Simulations

☐ Metrics

- Number of nodes that can be identified (either localizable or non-localizable)

☐ Comparison

- Necessary conditions

- ☐ **3P** V.S. **RR-3P**

- Sufficient conditions

- ☐ **TRI** V.S. **RR3P**

Simulation

- RR-3P outperforms 3P; RR3P outperforms TRI
 - Network with a “Z” hole
 - **Blue:** non-localizable; **Red:** localizable; **Grey:** unknown

3P and TRI

RR-3P and RR3P

Simulation

- We conduct more simulations and the results are consistent.

Figure 15: Testing 3P and TRI on network instances with "Z" holes.

Figure 16: Testing RR-3P and RR3P on network instances with "Z" holes.

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Conclusion

- Distributed localizability testing
 - We propose a new algorithm: WHEEL
 - Efficiency: communication and computation
 - Optimality: the best of all distributed approaches
 - A nice substitute of TRI:
“All gains, no pains”

WHEEL

Conclusion

□ Node localizability

- Analyze Limitations of network localizability
- Propose the concept of node localizability
- Derive necessary and sufficient conditions

Graph
Rigidity
Theory

Node
Localizability
Application

Future Work

- Research issues related to localizability
 - Localizability under noisy ranging
 - Localizability-aided localization
 - Min cost localizable networks

Selected Journal Publication

- Beyond Trilateration: On the Localizability of Wireless Ad-hoc Networks
Zheng Yang, Yunhao Liu, and Xiang-Yang Li
IEEE/ACM Transactions on Networking (ToN)
- Quality of Trilateration: Confidence based Iterative Localization
Zheng Yang and Yunhao Liu
IEEE Trans. on Parallel and Distributed Systems (TPDS)
- Location, Localization, and Localizability
Yunhao Liu, Zheng Yang, Xiaoping Wang, and Lirong Jian
Journal of Computer Science and Technology (JCST)
- Beyond Rigidity: Obtain Localizability with Noisy Ranging Measurement
Xiaoping Wang, Zheng Yang, Jun Luo, and Changxiang Shen
International Journal of Ad Hoc and Ubiquitous Computing (IJAHUC)

Selected Conference Publication

- Understanding Node Localizability of Wireless Ad-hoc Networks
Zheng Yang and Yunhao Liu
INFOCOM 2010
- Beyond Trilateration: On the Localizability of Wireless Ad-hoc Networks
Zheng Yang, Yunhao Liu, and Xiang-Yang Li
INFOCOM 2009
- Quality of Trilateration: Confidence based Iterative Localization
Zheng Yang and Yunhao Liu
ICDCS 2008
- Sea Depth Measurement with Restricted Floating Sensors
Zheng Yang, Mo Li, and Yunhao Liu,
RTSS 2007

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