Hierarchical Localization Algorithm based on Inverse Delaunay Tessellation

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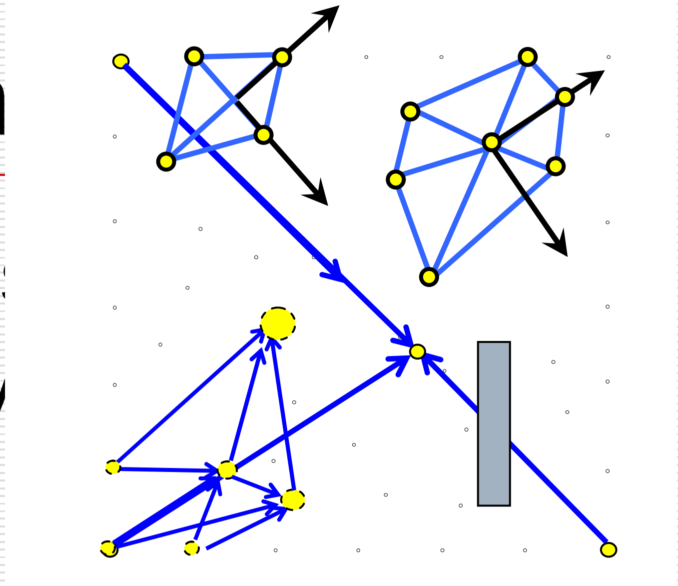
Motivation

- Monitor civil infrastructures
- Spread numerous nodes
  - Area: whole city
  - Accuracy in location: below 10[cm]
- Cost effective localization method

Existing Localization



- GPS for all nodes … co
- Range-free … accuracy
- Range-based
  - Landmark … line of sight, power
  - Incremental … noise accumulation
  - Local Cluster
    - Robust Quadrilateral --- Moore et al.(2004)

We developed…

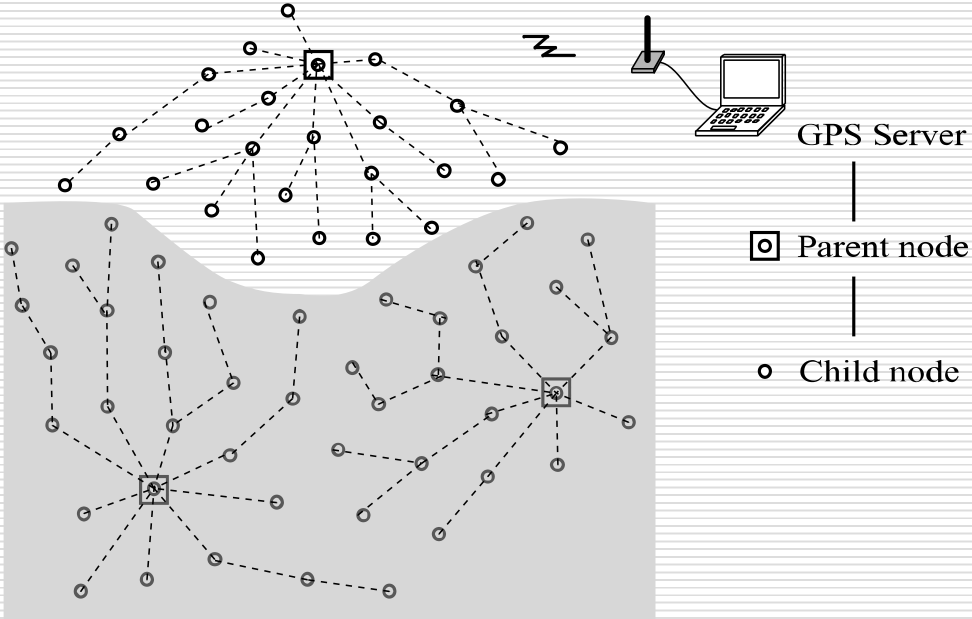
Relative Localization --- Local Cluster (Delaunay clusters)

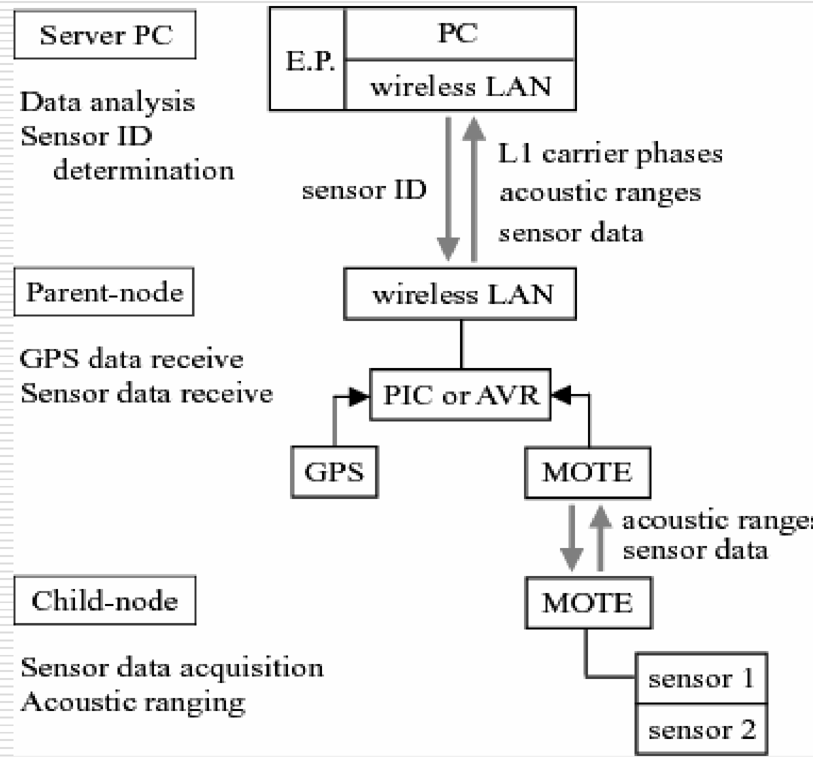
Gloabal Localization --- Small number of GPS working as pivots

System Overview

- Hierarchical sensor network
  - Server
    - PC+TCP/IP Wireless LAN
      - Data sink for parent nodes, computation for (GPS, child node localization)
  - Parent Node (approx. 20)
    - GPS+TCP/IP Wireless LAN+MOTE base station
      - Data sink for child nodes, data processing/compression
  - Child Node (approx. 1000)
    - MOTE + sensors (accel., temp., sound, light)
      - Wireless communication, ranging between child nodes, other measurement

Graphically…





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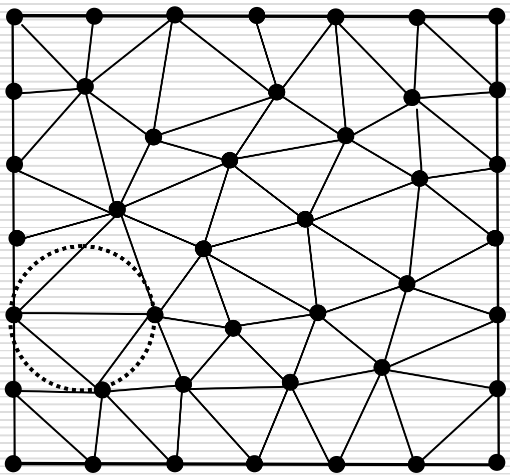
Relative Localization
--Inverse Delaunay Algorithm--

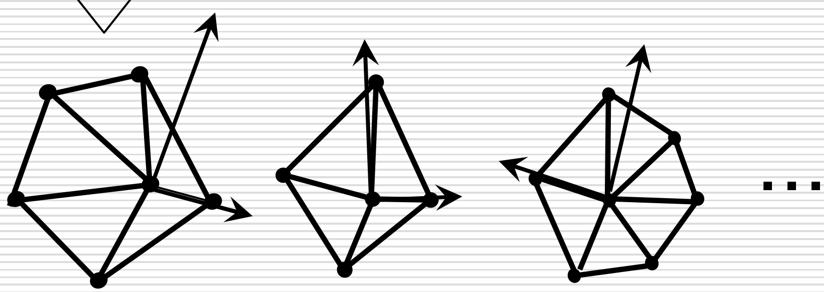
Nodal Coordinates

Inter-node distance

Tessellation by
Delaunay triangles
no point in circumscribed circle

Surround a node by
Delaunay Triangles





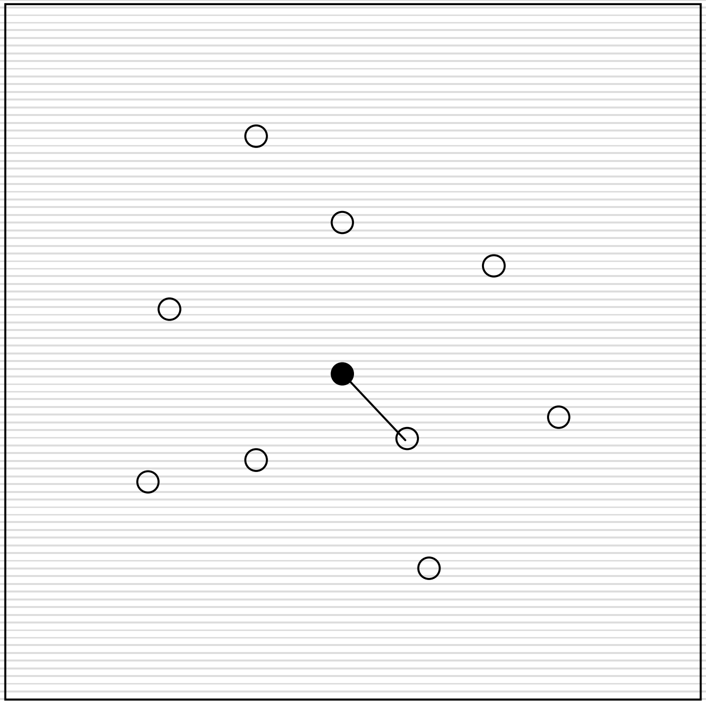
Delaunay Clusters

Merge the clusters
“Jigsaw puzzle”

Delaunay Tessellation

Inverse Delaunay

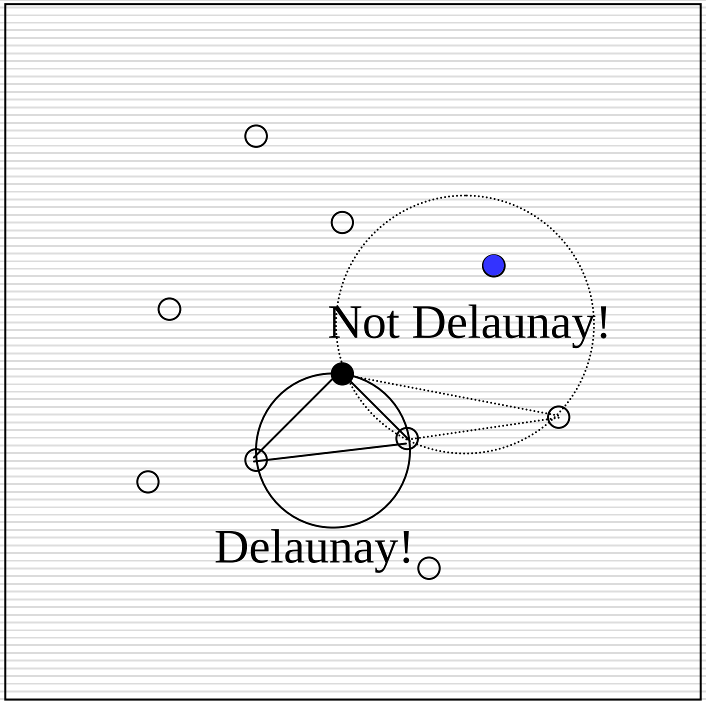
Construction of Delaunay cluster



Pick up a node (filled circle) and find the closest neighbor

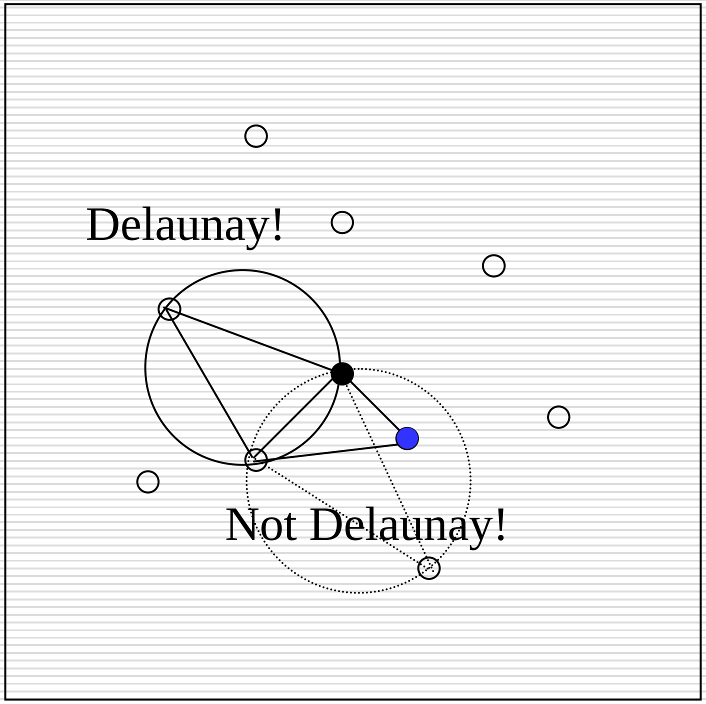
Construction of Delaunay cluster

Delaunay triangle -- No other point in circumscribed circle



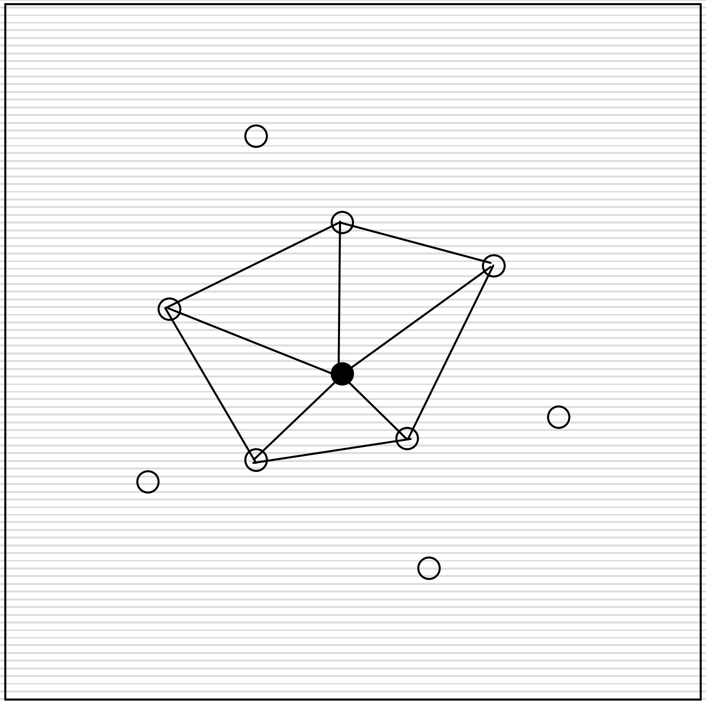
Scan other points to check Delaunay-ness

Construction of Delaunay cluster



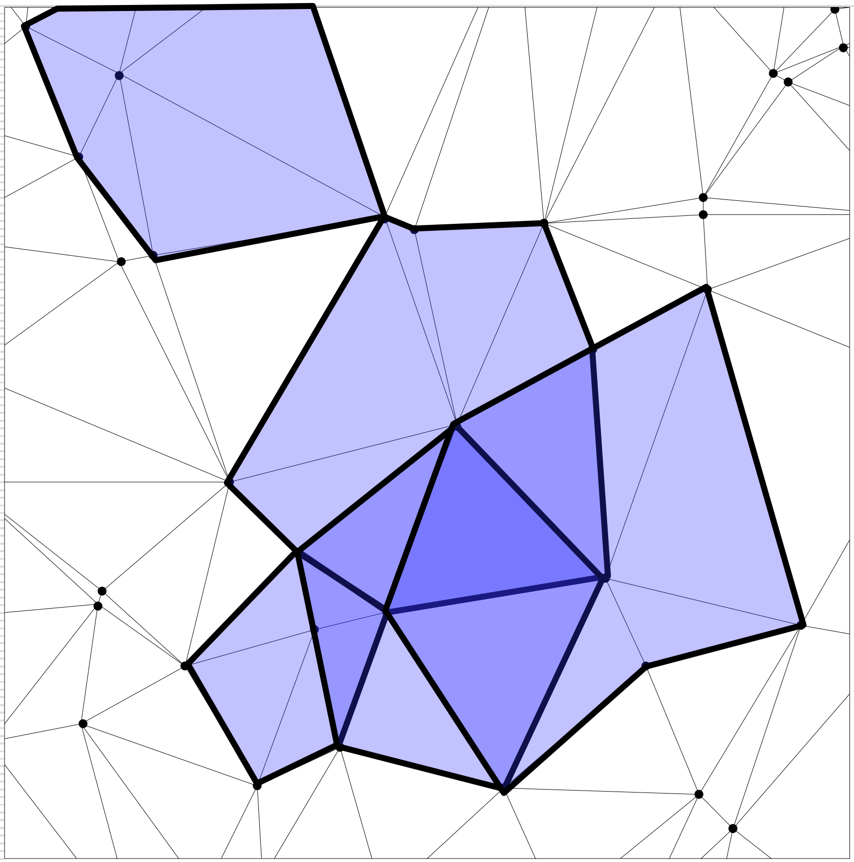
Incremental growth

Construction of Delaunay cluster



A cluster consisting of Delaunay triangles is made

How to merge Delaunay clusters (actual geometry)



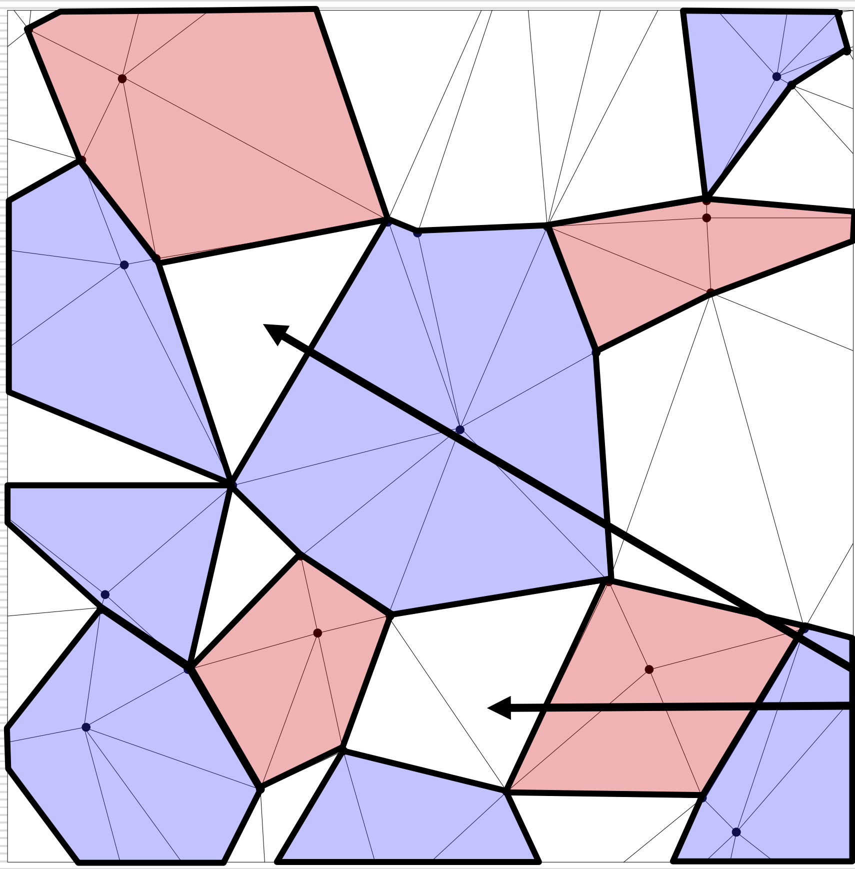
Clusters overlap each other

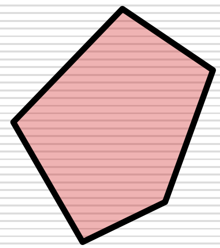
Jigsaw puzzle with redundant pieces

This works, but…

$O(N^2)$ -- Moore et al.(2004)

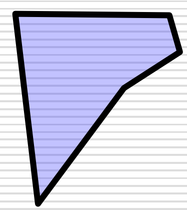
How to merge Delaunay clusters (classification → No overlap)





···· Atomic cluster

No common node



···· Bridging cluster

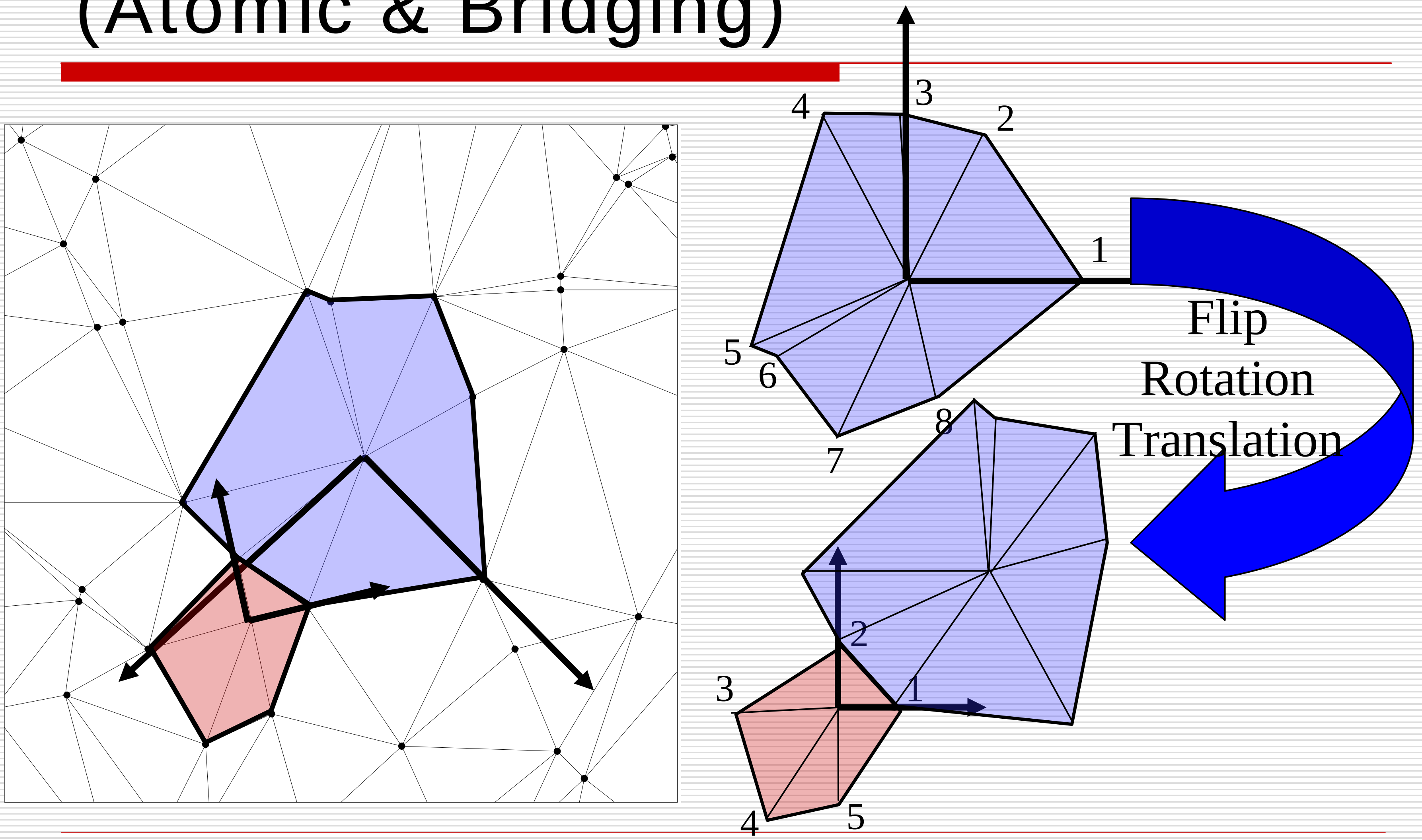
Common nodes

No common area

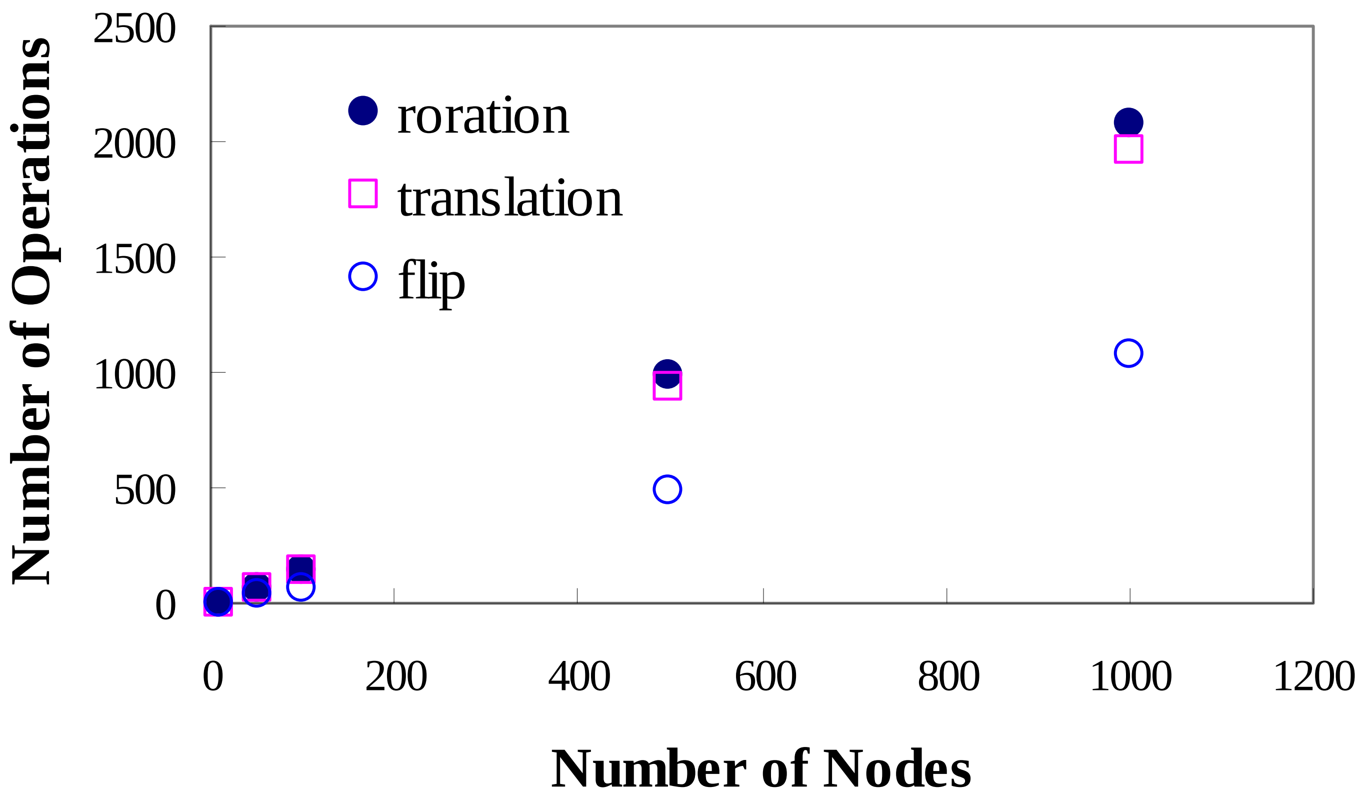
Not all the clusters are used but no node is missed

Redundancy is eliminated while necessary condition is satisfied

How to merge Delaunay clusters (Atomic & Bridging)



Reduction of Computational Cost



# of operation

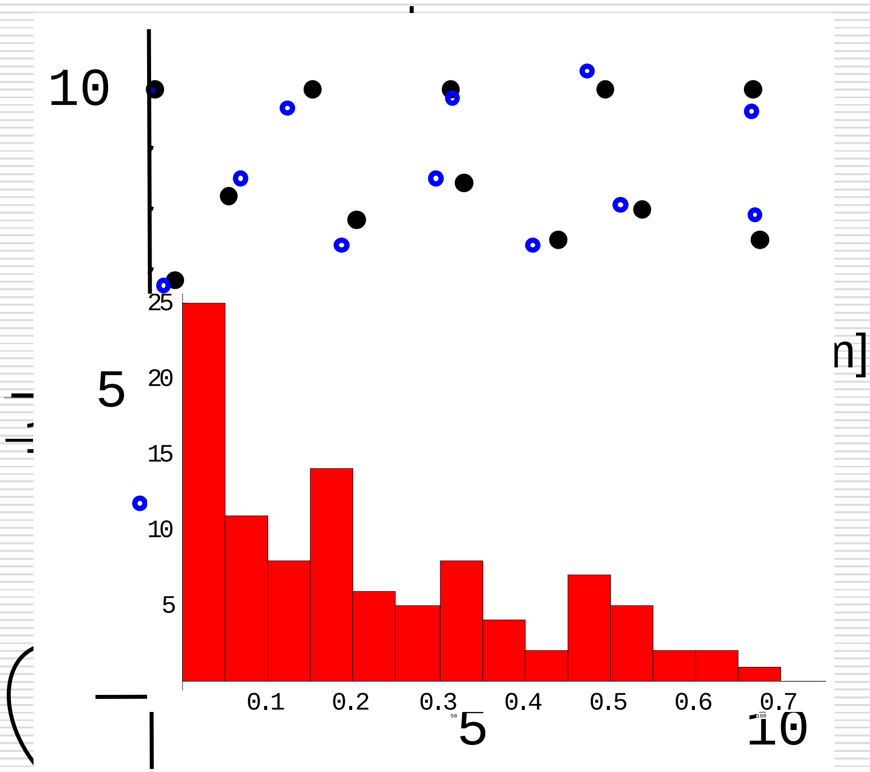
$O(N)$

$\cong 5N$

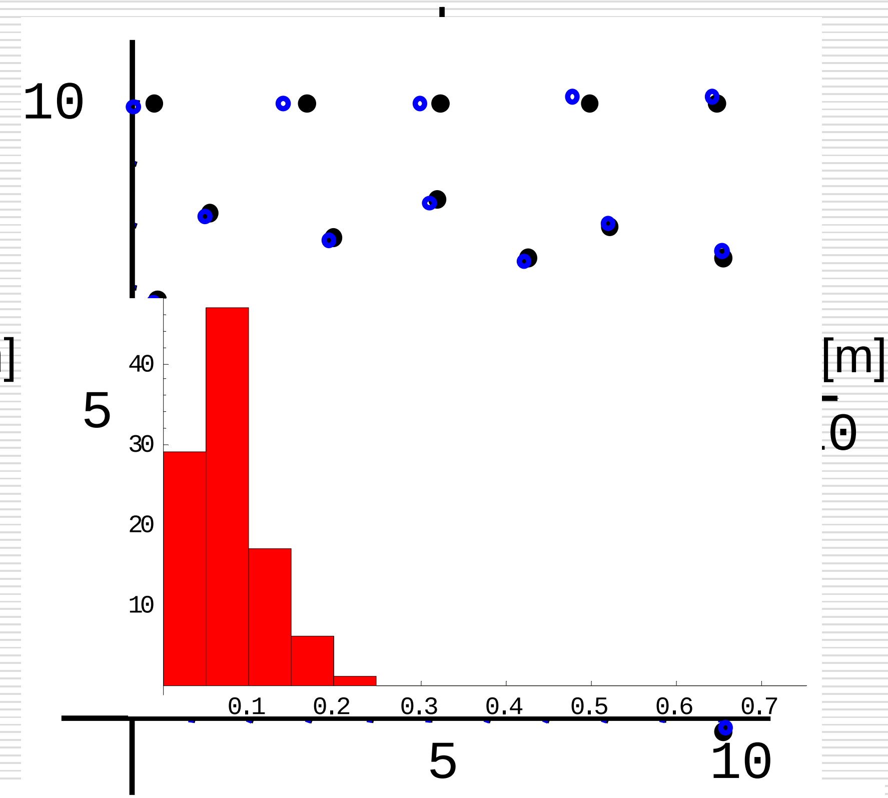
conf. $O(N^2)$ -- Moore et al.(2004)

Noise Accumulation Suppressed?

Consecutive triangulation

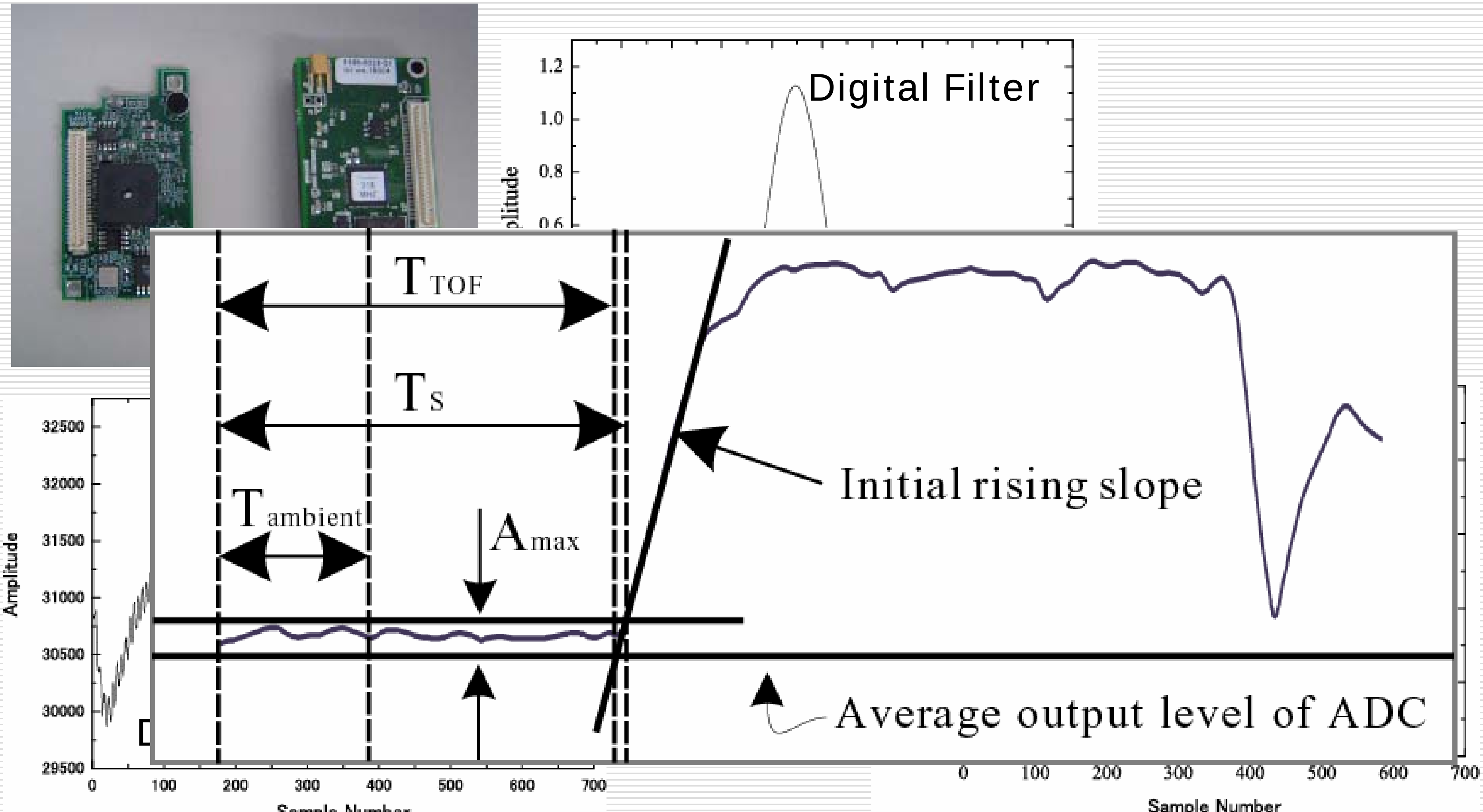


Inverse Delaunay



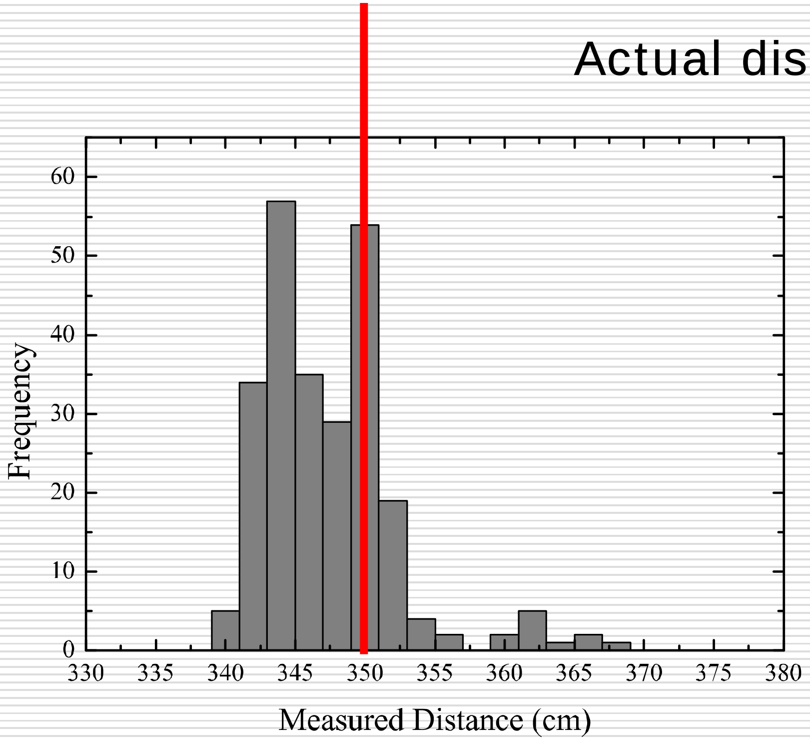
Inverse Delaunay Algorithm suppresses the noise accumulation

Acoustic Ranging

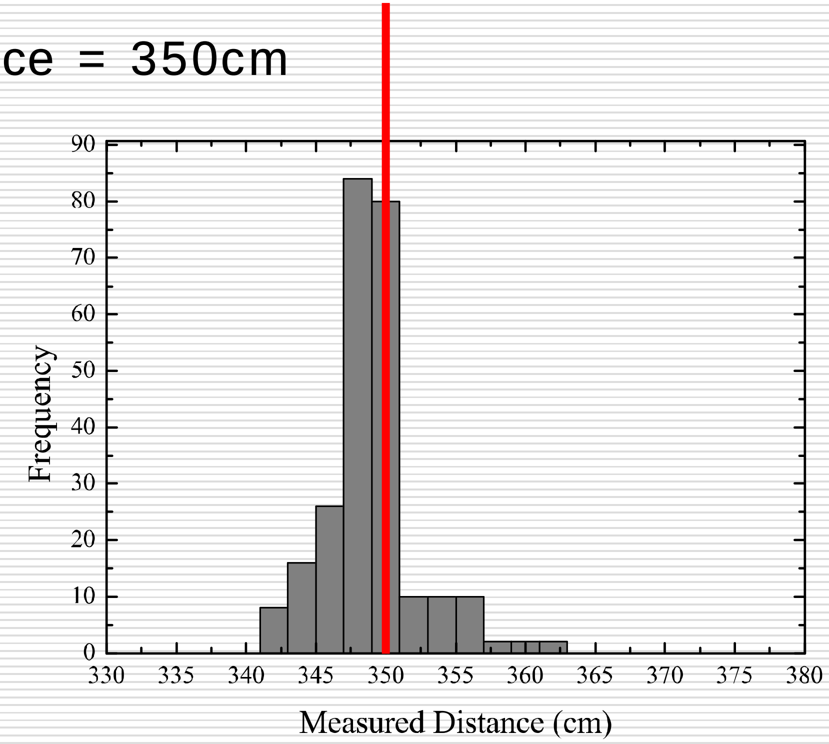


Accuracy of Acoustic Ranging

Actual distance = 350cm

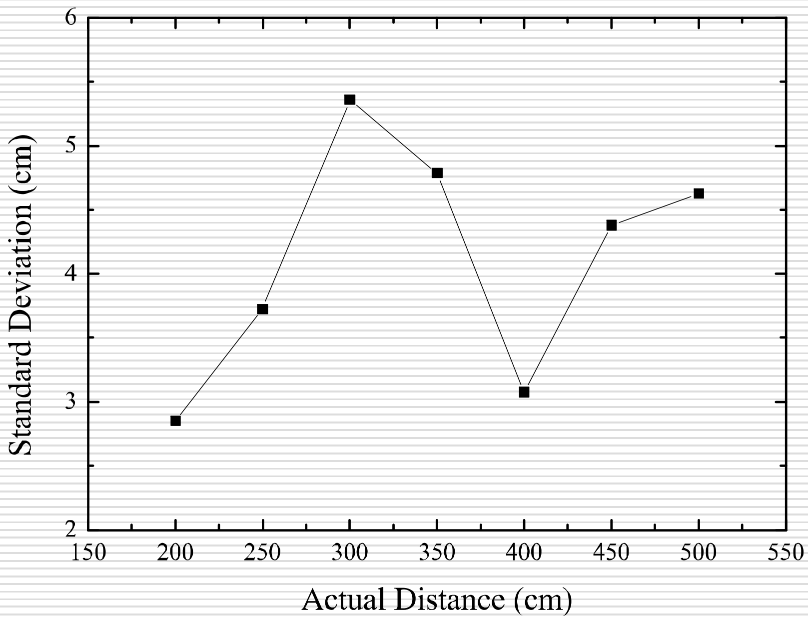


indoor

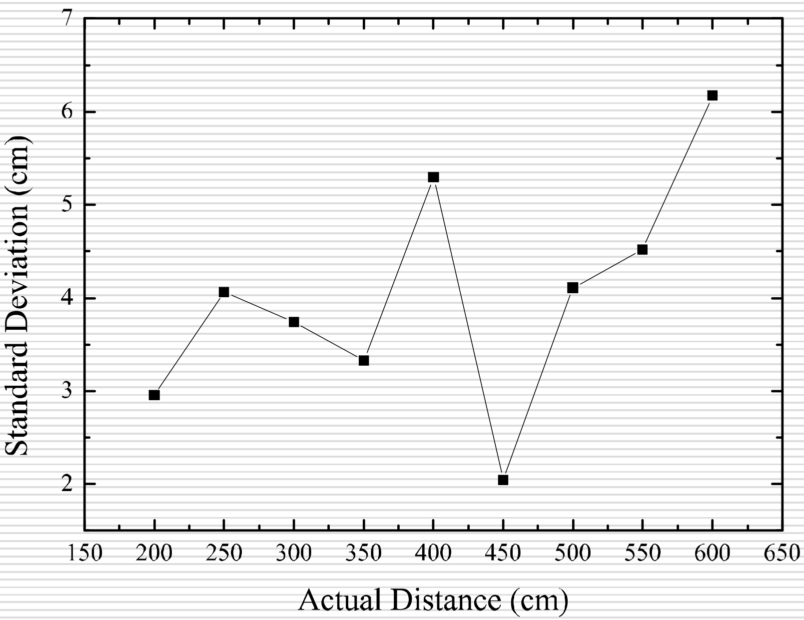


outdoor

Accuracy of Acoustic Ranging

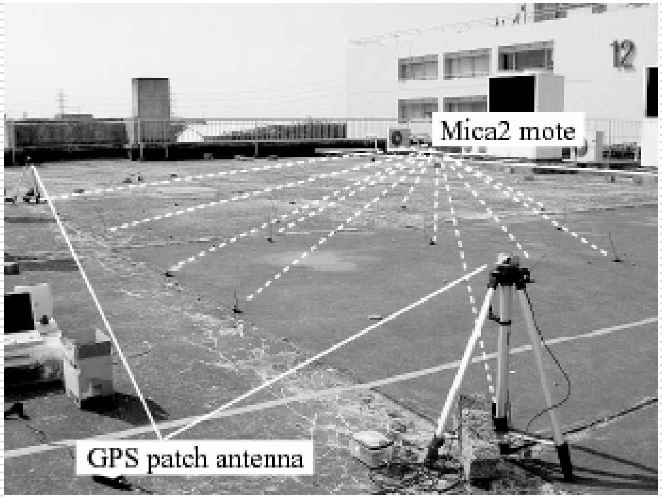


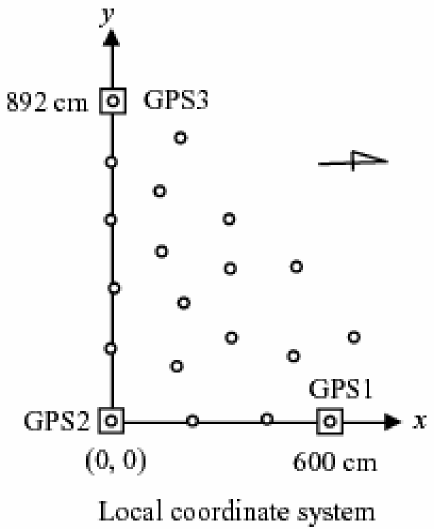
indoor

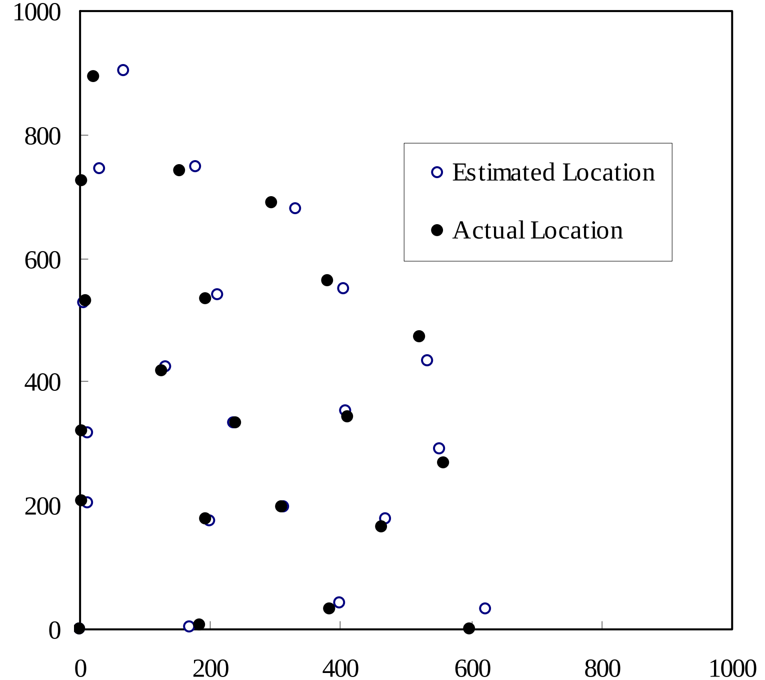


outdoor

Field experiment for validation

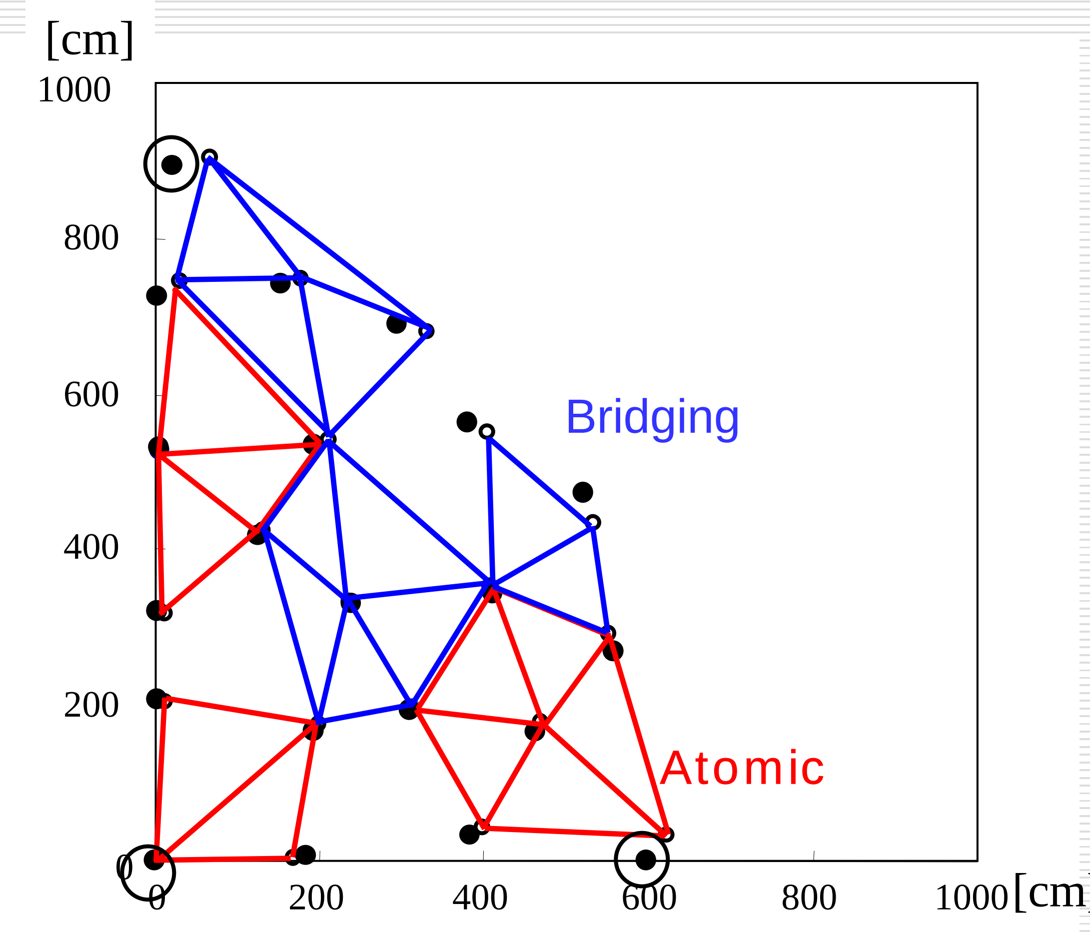




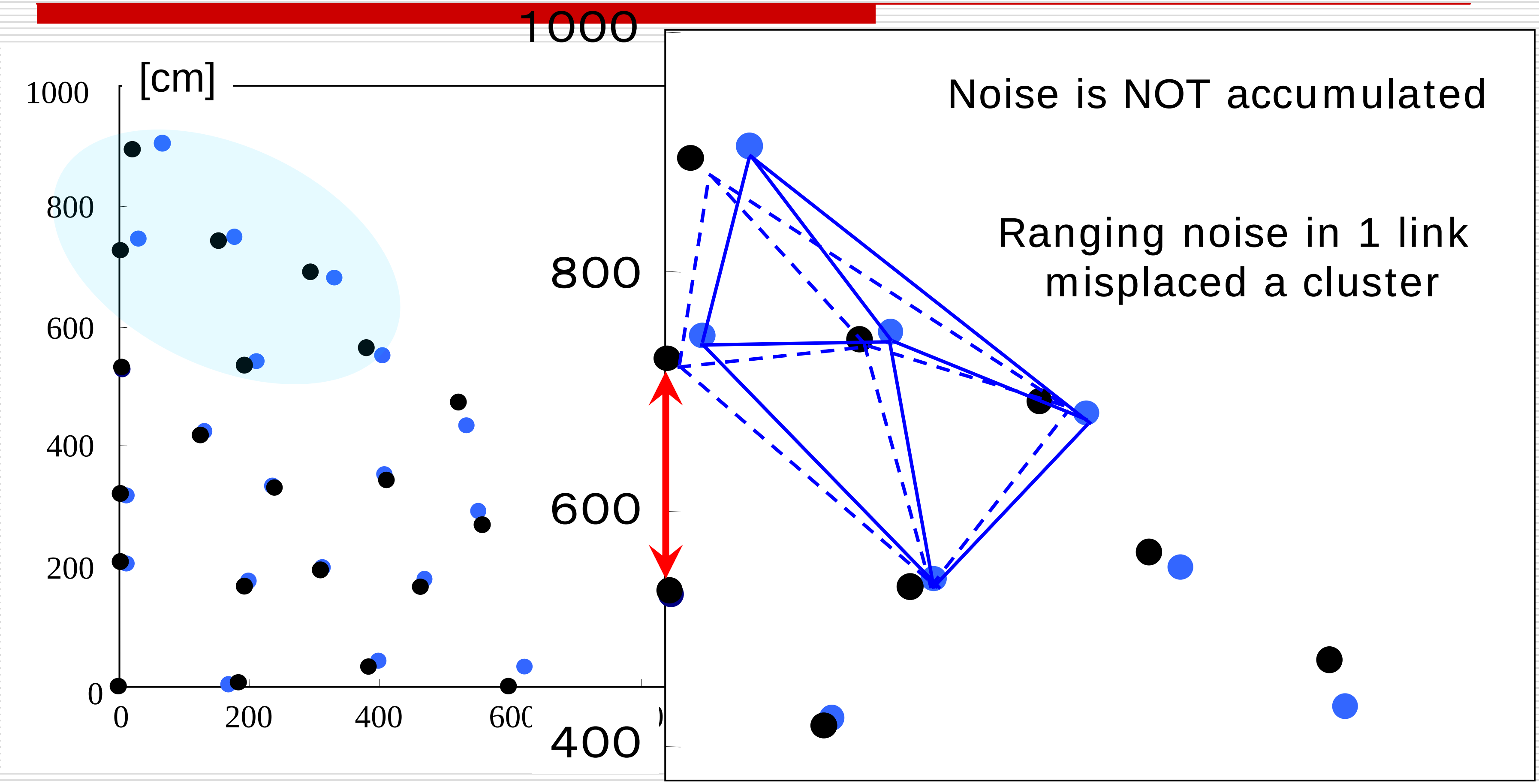


Noise in ranging: Avg. 4cm
Max. 16cm

Clusters used in Localization



Noise accumulation?



Need an algorithm to discriminate unreliable data

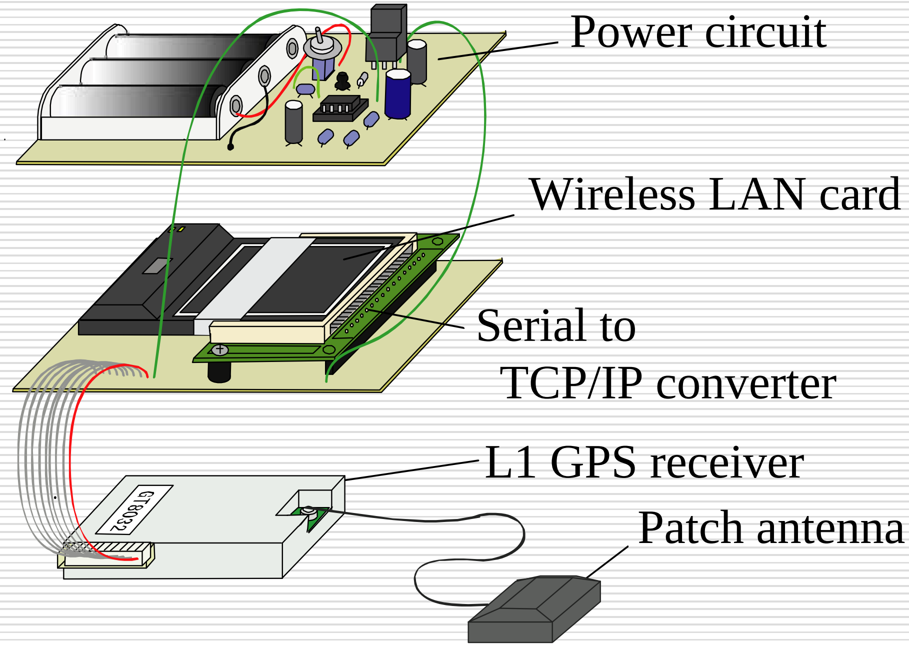
Parent Node

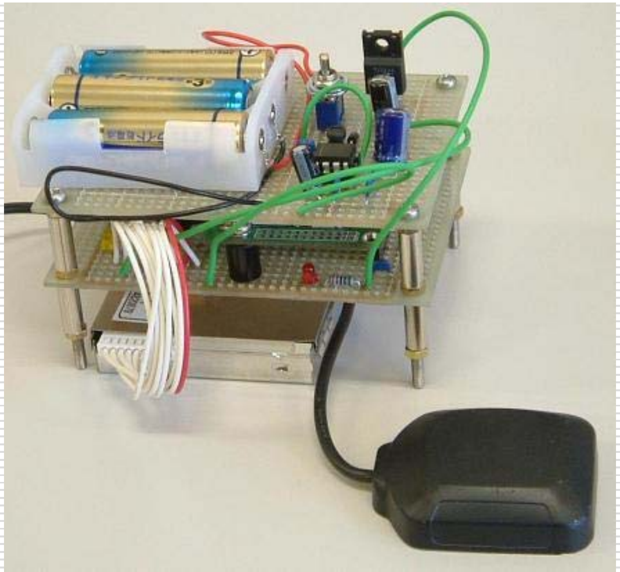
Requirements and Design

- Anchor node...
  - Accuracy : < 10cm
  - Position : static
- Gateway...
  - Power supply : Larger battery / Commercial power supply
  - Communication : Wireless LAN
- Low cost

Parent Node

Prototype model (assembly of COTS parts)



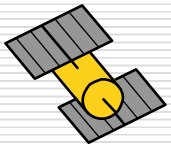


Parts	Max. power
GT-8032	450 [mW]
Wifi card	1122 [mW]

Data format	Byte / sec
NMEA	selectable
RINEX	74 [byte]

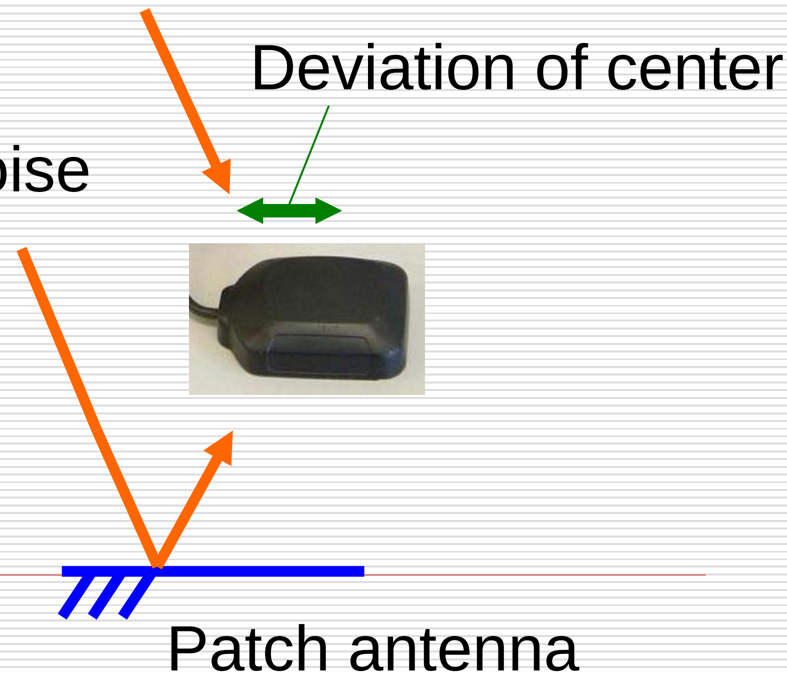
Parent Node

Multi-path noise



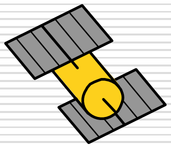
Carrier Phase :

$$\Phi_j^k = \rho_j^k / \lambda + N_j^k + \Delta_{ant,j}^k + \varepsilon$$



Parent Node

Multi-path noise & Cycle slip



Carrier Phase :

$$\Phi_j^k = \rho_j^k / \lambda + N_j^k + \Delta_{ant,j}^k + \varepsilon$$

Cycle slip ⇦ Multi-path noise

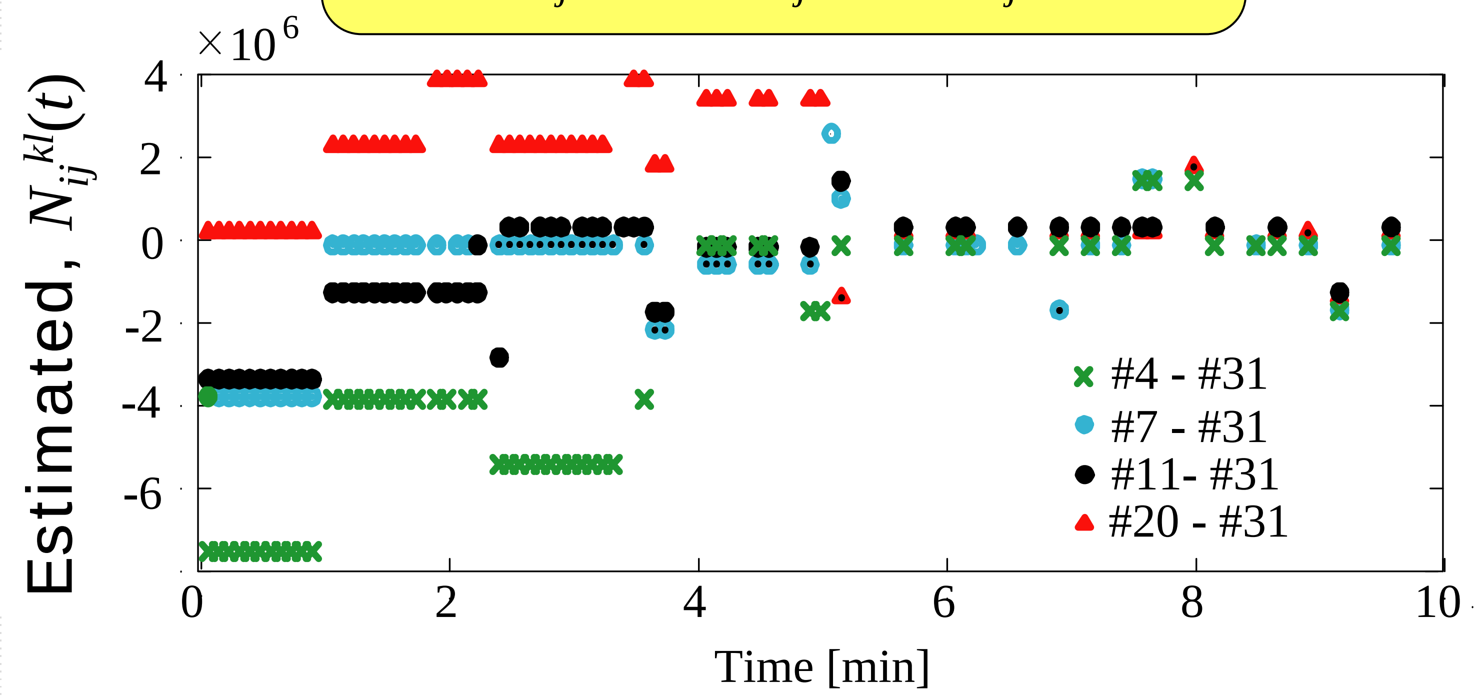
Patch antenna

Parent Node

Example of Cycle slips

Integer ambiguity :

$$N_{ij}^{kl}(t) = \Phi_{ij}^{kl}(t) - \rho_{ij}^{kl}(t) / \lambda$$



Parent Node

Linear model

$$N_{ij}^{kl} = \Phi_{ij}^{kl}(t) - \rho_{ij}^{kl}(t)/\lambda$$

$$\Downarrow$$

$$N_{ij}^{kl} = \underbrace{\Phi_{ij}^{kl}(t) - \overline{\rho}_{ij}^{kl}(t)/\lambda}_{\text{Const.}} - \frac{1}{\lambda}\underbrace{\left[\frac{\partial \rho_{ij}^{kl}(t)}{\partial x}\Delta x + \frac{\partial \rho_{ij}^{kl}(t)}{\partial y}\Delta y + \frac{\partial \rho_{ij}^{kl}(t)}{\partial z}\Delta z\right]}_{\text{Linear w.r.t. } t}$$

$$\Downarrow$$

$$N(t) = \underline{a}t + \underline{b}$$

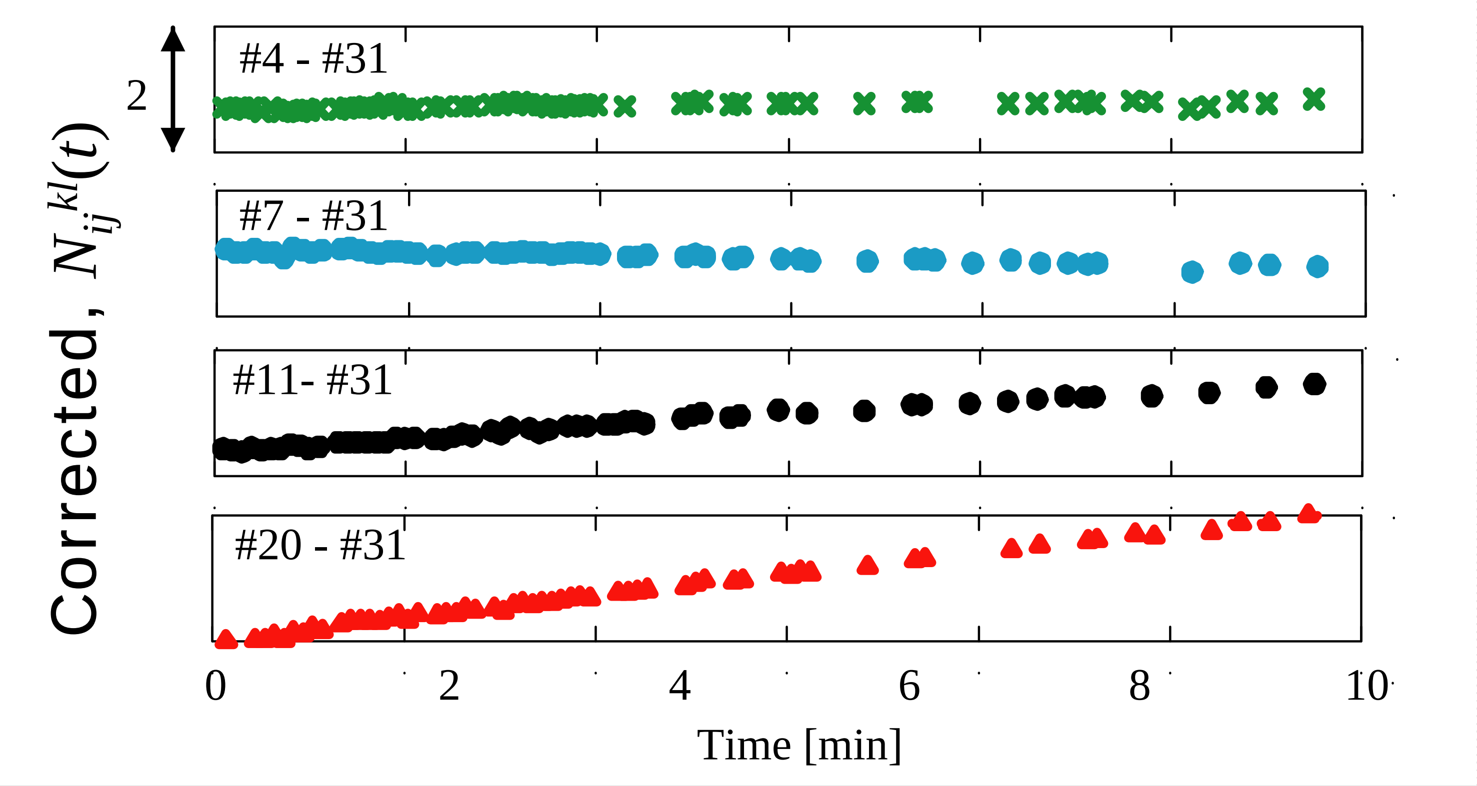
Estimate using Kalmann filter

$$\left|\underline{N_{ij}^{kl}} - N(t+\Delta t)\right| < 1/4$$

Correct N_{ij}^{kl}

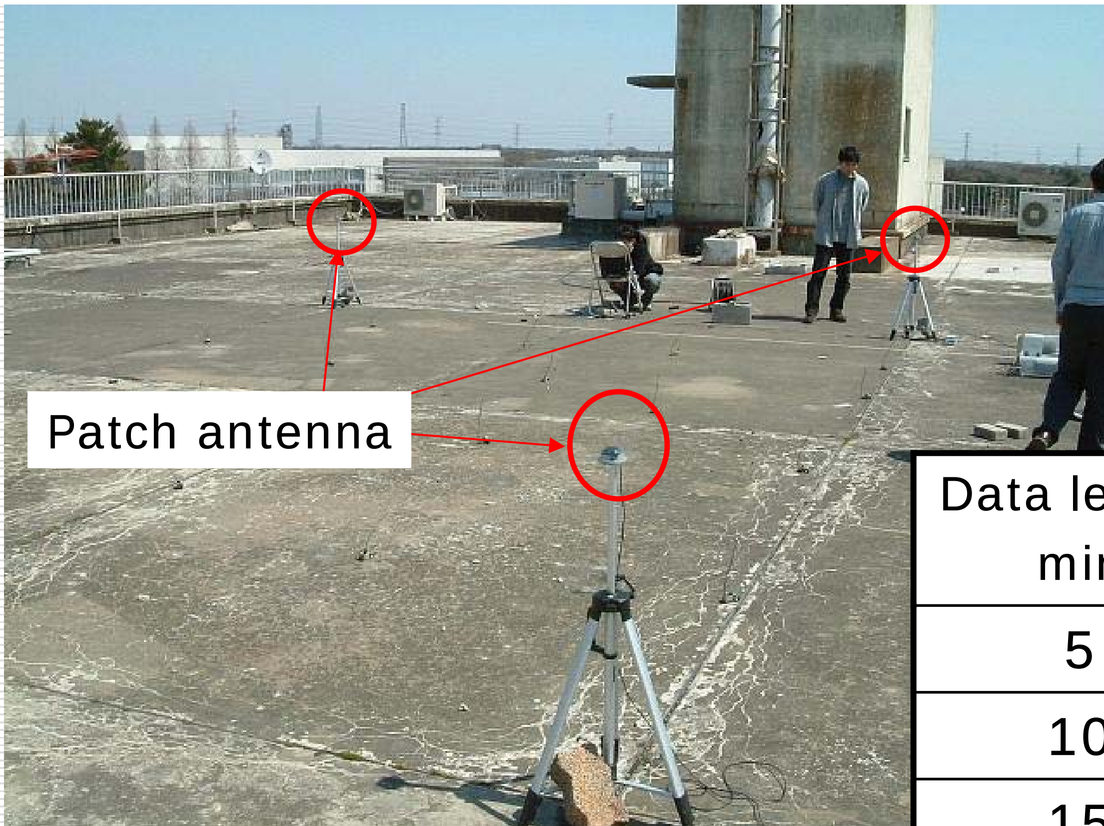
Parent Node

Corrected integer ambiguity



Parent Node

Experimental results



Data length min	Success Rate %	Accuracy, 2σ (H) cm	(V) cm
5	94.5	1.1	1.9
10	99.4	0.9	1.8
15	99.5	0.8	1.6

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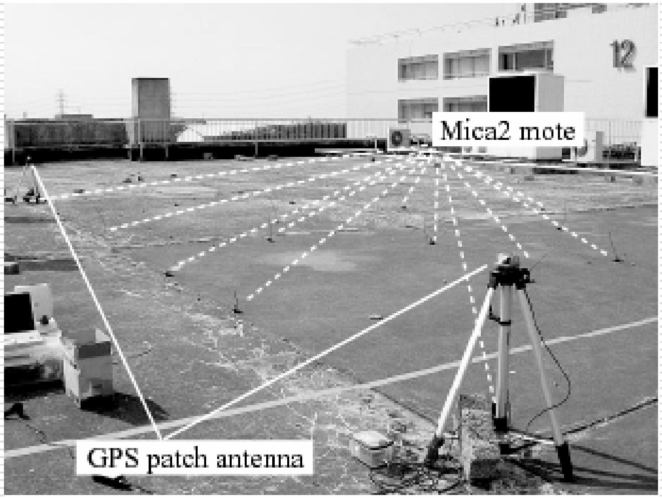

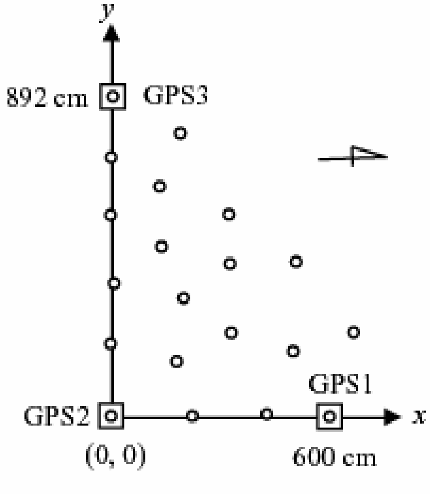

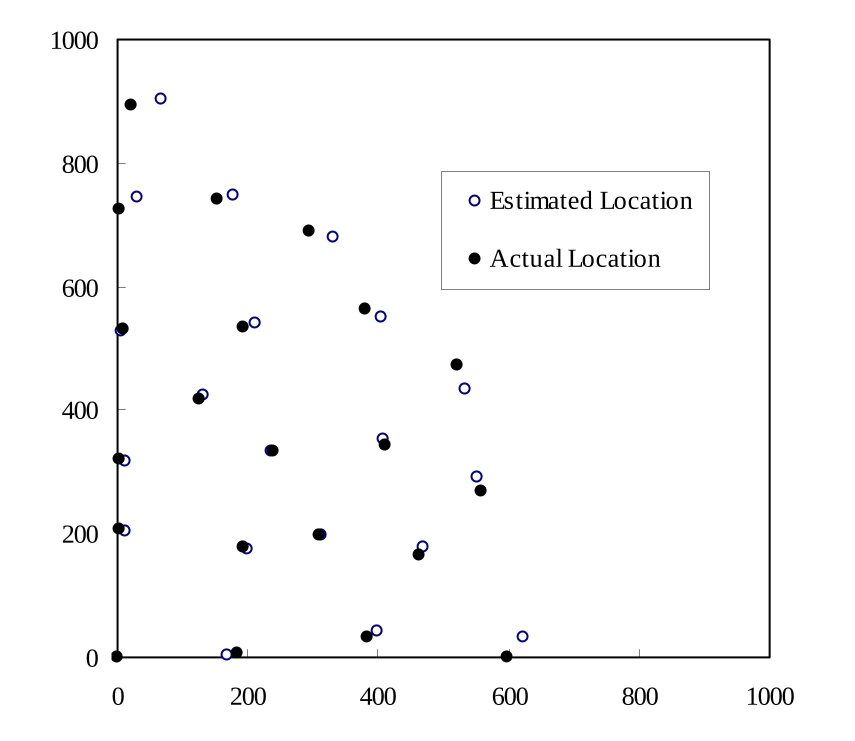

Noise in ranging: Avg. 4cm
Max. 16cm

Summary

Hierarchical Localization System

- Inverse Delaunay Algorithm
  - Computationally inexpensive
  - Noise accumulation is suppressed
- Acoustic Ranging
  - Cheap devices
  - More noise-tolerant than tone detection ranging
- Cost effective GPS
  - Patch antenna for car navigation
  - Cycle slip correction
  - Accuracy → [cm] order