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Consistency-based Localization in Sensor Networks

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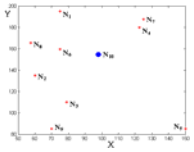
Introduction: Error modeling and optimization-based localization with range measurement errors

Sub-problem to location discovery is *Error Modeling*

- Location Discovery Problem is NP-complete even when no mirroring complications are associated.
- Traditional approached focus on new optimization mechanisms
- Sub-problem particularly difficult when *no prior knowledge of error distributions* is known.



Courtesy to: Lewis Girod

ID	LOCATION	REAL	GAUSSIAN	STAT 1	STAT 2
N_1	(75, 195)	45.893	45.791	56.697	44.193
N_2	(60, 135)	42.5	43.432	42.895	42.043
N_3	(79, 110)	48.654	78.066	49.008	39.964
N_4	(122.5, 180)	35.355	35.294	34.355	42.139
N_5	(150, 85)	87.5	86.362	56.988	87.479
N_6	(75, 159.4)	22.926	53.285	23.001	27.077
N_7	(125, 187.5)	42.573	42.938	43.837	41.992
N_8	(87.5, 165.4)	41.337	42.831	41.111	49.604
N_9	(70, 85)	75.208	71.427	87.449	74.574

GAUSSIAN	***0.0208***	7.993	4.258	0.0424
STAT 1	8.179	***0.0117***	5.275	0.0315
STAT 2	7.658	6.042	***0.0303***	0.0396

Approach: On-line location discovery with simultaneous error model construction

Solely based on the concept of consistency

- **Error models are constructed using non parametric statistical techniques**
  - indicate the most likely error
  - provide the likelihood distribution of particular errors occurring
- **Localized localization algorithm where a specified communication cost or the location accuracy is guaranteed while optimizing the other.**

- **3 main phases:**
  1. **Location discovery (LD) phase**
  2. **Measurement gathering (MG) phase**
  3. **Result dissemination (RD) phase**

Centralized Algorithm

Centralized (*Limit*)

1. The *Gateway* initiates the *Level Discovery phase* (*LD-phase*)
2. *while* (the current BFS level < *Limit*)
3. level discovery messages propagate
4. The leaf nodes initiate the *Measurement Gathering phase* (*MG-phase*)
5. Optimization / Solving at the *Gateway*
6. The *Gateway* disseminates the results - *Result Dissemination phase (RD-phase)*

Localized Algorithm:

A simple modification of the centralized approach

1. A random node Initiates the *Level Discovery phase* (*LD-phase*) invoking *Centralized* (*Level_Limit*)
2. *while* (there exists boundary node *i* has not initiated the procedure)
3. node *i* invokes *Centralized* (*Level_Limit*)
4. Procedure ends when no more messages progagate

Evaluation: Comparison in 4 scenarios, including state-of-the art localization approaches

Application Task: Location Discovery

k dimensional space, two sensor nodes *i* ($x_{i1}, x_{i2}, \ldots, x_{ik}$) and *j* ($x_{j1}, x_{j2}, \ldots, x_{jk}$) have measured distance d_{ij}.

Linear/nonlinear optimization-based formulation
OF: min/max $F = M(\varepsilon_{ij})$
for pairs of nodes *i* and *j* that have measured distance d_{ij}.

On-line Localization Preliminaries

Equation-based Localization Formulation

- $F = M(\varepsilon_{ij})$ where $\varepsilon_{ij} = \sqrt{\sum_{l=1}^{k}(x_{il}-x_{jl})^2} - d_{ij}$

for pairs of nodes *i* and *j* that have measured distance d_{ij}.

The Definition of Consistency

- Two pairs of points $P_1(x_1, y_1)$ and $P_2(x_2, y_2)$
  - $(x_1 \geq x_2)$ $(y_1 \geq y_2)$ $(x_1 \leq x_2)$ $(y_1 \leq y_2)$

Equation-based On-line Localization

$$c_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

$$c_{kl} = \sqrt{(x_k - x_l)^2 + (y_k - y_l)^2}$$

for pairs of nodes *i* and *j* that have measured distance d_{ij}, & pairs of nodes *k* and *l* that have measured distance d_{kl}

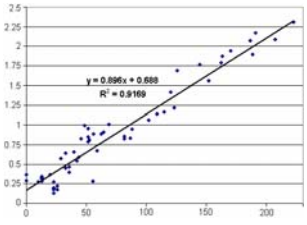
$if\ ((c_{ij}-c_{kl})\cdot(d_{ij}-d_{kl}) < 0)$
$F \mathrel{+}= [-((c_{ij}-c_{kl})\cdot(d_{ij}-d_{kl})]$

$F_2 = F + \sum \varepsilon_s$
where $\varepsilon_s = \sqrt{(x_s'-x_s)^2 + (y_s'-y_s)^2}$, for all hidden beacons *s*
(x_s', y_s') is the location proposed by the optimization mechanism;
(x_s, y_s) is the real location of beacon *s*.

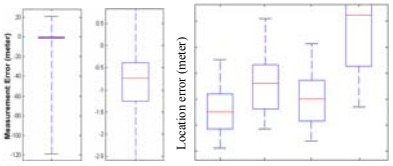
- Min: F_2

Experimental Results

On-line OF Evaluation



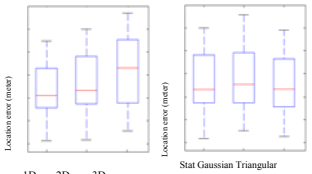
Overall Comparison with Input Measurement Error



Input error
- Average: -6.73m
- Median: -0.74m

kernel on-line on-line localized
GPS-based GPS-less

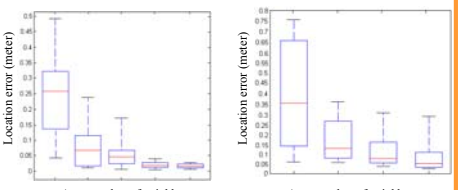
Dimension and Input Error Type Study



1D 2D 3D

Stat Gaussian Triangular

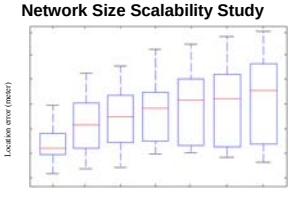
Average Localization Neighbor Study



Ave. number of neighbors
GPS-less

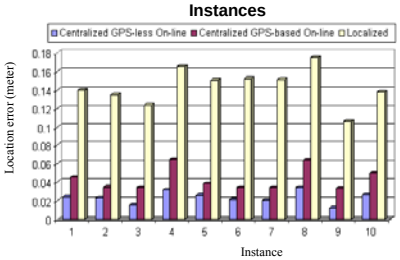
Ave. number of neighbors
GPS-based

Network Size Scalability Study



Network size

Performance Comparison Cross Other Instances



Instance

Evaluation approach performed 4 ways:

1. **In both GPS-based and GPS-less scenarios**
2. **Using both centralized and localized optimization**
3. **In 1-D, 2-D, and 3-D spaces**
4. **In the case when error models are not available a-priori**

- **Acoustic ranging-based distance measurements recorded by actual deployed sensor networks.**
- **Localization of only a few cm is consistently achieved**
  - **Average and median distance measurement errors are more than 1 meter**
- **Comparison of location accuracy with several state-of-the-art localization approaches.**