Multi-Epoch Decentralized Collaborative Localization using 3D Mapping Aided (3DMA) GNSS and Inter-Agent Ranging

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3D Mapping Aided Navigation

- Shadow Matching (SM)[1]
- Intelligent Urban Positioning[2]
- Multi-epoch 3DMA GNSS using a grid filter[3]

Mitigate effect of signal blockage and multipath

Position Ambiguity in SM

Ambiguity due to symmetry in building structure

Ambiguity not always resolved with inclusion of satellite ranging\(^4\)

\(^4\) Groves, Paul D. ION ‘15
Jump Discontinuities in DC-SM\textsuperscript{[5]}

\textbf{Snapshot} algorithms have jump discontinuities

\textsuperscript{[5]} Tanwar and Gao, ION GNSS+’18
Our Scope

Agent motion estimation with temporal correlation

Extend DC-SM algorithms to a **Multi-Epoch Algorithm**
Objectives

• **Mitigate ambiguity** and **improve accuracy** in 3DMA techniques with multi-agent cooperation in a multi-epoch fashion

• Analyze **impact of connectedness** and **scale of network** on navigation solution accuracy

• Design system to ensure operability with **scalability**, **constraints on communication** and **low computation overhead** for large networks
Contributions

- Designed a multi-agent grid-based 3DMA localization architecture that is
  - multi-epoch
  - decentralized
- Applied discrete Bayesian Filtering incorporating motion models
- Deployed a bank of Kalman Filters for velocity distribution estimation
Outline

• Multi-Epoch Decentralized Collaborative 3DMA Localization
  ▪ System Architecture
  ▪ Velocity Distribution Calculation
  ▪ Prediction Step
  ▪ Update Step

• Setup and Results
  ▪ Simulation Setup
  ▪ Results

• Summary
Overall Architecture

Agent i

- 3D Map
- GPS Receiver
- Ranging sensor

Prediction Step

Update Step

Private Update Step

Relative Update Step

Velocity Distribution Calculation

Information Exchange

Agent j

- Rel. Update Step

Agent k
Overall Architecture

- **Agent $i$**
  - 3D Map
  - GPS Receiver
  - Ranging sensor

- **Prediction Step**
- **Update Step**
  - **Private Update Step**
  - **Relative Update Step**
- **Velocity Distribution Calculation**

- **Agent $k$**

- **Agent $j$**
  - Information Exchange

- **Rel. Update Step**

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Info. exchanged only during inter-agent ranging
Overall Architecture

- **Agent i**
  - 3D Map
  - GPS Receiver
  - Ranging sensor

  - Prediction Step
  - Update Step
    - Private Update Step
    - Relative Update Step
    - Velocity Distribution Calculation

  - Information Exchange
    - Agent j
    - Agent k

- Rel. Update Step
Velocity Distribution Calculation

For each grid point $r \in G_i$

$G_i(r)$

$V_i^t(r)$

$S_i^t$ (Extended Kalman Filter)

$V_i^{t*}$
Velocity Distribution Calculation

For each grid point $r \in G_i$

$G_i(r)$

$V_i^t(r)$

$S_i^t$

Process Satellite Data

Satellite position, velocity, pseudorange, received SNR, pseudorange rate

$V_i^{t*}$

GPS Receiver

Extended Kalman Filter
Velocity Distribution Calculation

For each grid point $r \in G_i$

- $G_i(r)$
- $V_i^t(r)$

Previous velocity estimate (assumed Gaussian) for $r^{th}$ grid coordinate

Extended Kalman Filter

Satellite position, velocity, pseudorange, received SNR, pseudorange rate

Current velocity distribution estimate over the entire grid

Process Satellite Data

$S^t_i$
Prediction Step

Discrete Bayesian Filter over grid of positions

For each grid point \( r \in G_i \)

\[ \Lambda_i^t(r) \quad : \text{Probability distribution of position from last time step} \]

\[ V_i^t(r) \quad : \text{Velocity distribution over the grid} \]

\[ G_i \quad : \text{Grid Coordinates} \]

\[ \Lambda_i^{t*}(r) \quad : \text{Probability distribution of position after prediction step} \]
Private Update Step

GPS Receiver

3D Map

Grid Coordinates $G_i$

Process Satellite Data

Intelligent Urban Positioning\cite{2}

Probability Distribution $\Lambda_i$

Hypothesis Integration

Output Probability Distribution $\Lambda_i^*$

\cite{2} Adjrad and Groves, ION GNSS+ ’16
Relative Update Step

Derives from ambiguity mitigation step in DC-SM\[^{[5]}\]

\[ \Lambda^t_j \]

Agent \( j \)

\[ \Lambda^t_i \]

Ranging sensor

\[ G_i \]

Grid Coordinates

Output

Probability Distribution

\[ \Lambda^{t+1}_i \]

\[ \text{ Obtain Modes } \]

\[ \text{ Find Pair } \]

\[ \text{ Generate Radial Gaussian Probabilities } \]

\[ \text{ Hypothesis Integration } \]

[5] Tanwar and Gao, ION GNSS+’18
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Simulation Setup – 3D Map

Search area for candidate positions

Open Street Map\textsuperscript{[6]}

Illinois LiDAR Data\textsuperscript{[7]}

Level of Detail (LOD)-1 3D Map

\textsuperscript{[6]} www.openstreetmap.org
\textsuperscript{[7]} https://clearinghouse.isgs.illinois.edu/
Simulation Setup – Specifications

- Number of Agents $N$: 10
- 4 vehicle agents with velocity $\sim 7$ m/s
- LOS and range-limited communication and ranging between agents

A scenario with 10 agents
Simulation Setup – Network

Sparsely non-singly connected network
Simulation Setup – Sensors

**Pseudorange**

\[
\rho_{LOS} = \| x_s - x_i \| + c \cdot b_i^t + \epsilon_{si}^t
\]
\[
\rho_{NLOS} = \| x_s - x_i \| + c \cdot b_i^t + \epsilon_{si}^t + \delta_{si}^t
\]

where

- \( b_i^t \): receiver clock bias
- \( \epsilon_{si}^t \): Additive white noise
- \( \delta_{si}^t \): Additive skew normal noise

**SNR**

- **N-LOS:**
  - chosen between 25-45 dB-Hz
- **LOS:**
  - chosen between 40-45 dB-Hz

**Ranging**

\[
d_{ij} = \| x_i - x_j \| + \psi_{ij}^t
\]

where \( \psi_{ij}^t \): Additive white noise

Sky Plot of visible SVs for clear sky
Results – Position Accuracy

Error v/s connectivity for Agent 5

Reduced localization error to ~3m

[2] Adjrad and Groves, ION GNSS+ ’16
[5] Tanwar and Gao, ION GNSS+’18
Results – Impact of Connectivity

Increased connectivity reduces localization errors
Results – Impact of Connectivity

Increased connectivity reduces localization errors
Results – Qualitative

- Ground Truth

IUP\textsuperscript{[2]}
(Pseudorange + SNR)

CSM\textsuperscript{[5]}
(Multi-agent Snapshot)

ME-CSM
(Proposed Method)

Error reduces as estimates get temporally correlated

\textsuperscript{[2]} Adjrad and Groves, ION GNSS+ ’16
\textsuperscript{[5]} Tanwar and Gao, ION GNSS+’18
Summary

• Designed an architecture to associate temporal correlations between multiple agents for grid-based 3DMA GNSS navigation

• Developed a discrete Bayesian filtering based prediction step and velocity calculation using Kalman Filter banks to augment previous work

• Validated the improvement in position accuracy for all agents in the network through an urban simulated dataset

• Analyzed the impact of network connectivity on localization error over time
Acknowledgment

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Thank You
Results – Position Accuracy

Reduced localization error to ~3m

- **Proposed Method:**
  - Snapshot Multi-Agent
  - Intelligent Urban Positioning
  - Shadow Matching

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<th>IUP</th>
<th>SM</th>
<th>RMS error in estimation (in m)</th>
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- [2] Adjrad and Groves, ION GNSS+ ’16
- [5] Tanwar and Gao, ION GNSS+’18
Simulation Setup – Agent Motion

- \( t = 0 \) s
- \( t = 5 \) s
- \( t = 2.5 \) s
- \( t = 10 \) s
Results – Impact of Connectivity

Increased connectivity reduces localization errors
Discrete Bayes Filter - Prediction

\[ \overline{\text{bel}}(x_t) = \sum_{x_{t-1}} P(x_t|x_{t-1}) \cdot \text{bel}(x_{t-1}) \]

Current Predicted Belief

Previous Belief

Prediction Probability
Discrete Bayes Filter - Prediction

\[
\overline{\text{bel}}(x_t) = \sum_{x_{t-1}} P(x_t | x_{t-1}) \cdot \text{bel}(x_{t-1})
\]

Current Predicted Belief          Previous Belief

Prediction Probability

Uses motion model

\[
\frac{1}{\sqrt{(2\pi)^k|\Sigma|}} \exp \left( -\frac{1}{2}(x - \mu)^T \Sigma^{-1} (x - \mu) \right)
\]
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Results – Impact of Connectivity

Reduced connectivity does not lead to increase in error
Results – Impact of Connectivity

Connectedness reduces localization errors
Results – Impact of Connectivity

Connectedness reduces localization errors