Indoor navigation supported by image-based and Artificial Intelligence (AI) techniques

Dorota A. Grejner-Brzezinska, Charles K. Toth, J. Nikki Markiel, Shahram Moafipoor

Satellite Positioning and Inertial Navigation (SPIN) Laboratory
The Ohio State University

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Outline

- Overview of the Personal Navigator (PN) system
  - Human dynamics model as navigation tool supported by Artificial Neural Networks (ANN) and Fuzzy Logic (FL)
    - Step length (SL) and Step Direction (SD)
- Dead Reckoning (DR) navigation: algorithm and calibration procedure
- Imagery-based navigation using ranging laser (Flash LADAR)
  - Research problem
  - Approach and algorithm
- Extending DR capabilities by Flash LADAR data
- Indoor and outdoor experiments
- Summary and current trends
PN System Overview: Backpack Configuration

Sensors used in the current prototype:
- Honeywell HG1700 IMU
- HMR3000 magnetometer
- Vaisala PTB220 barometer
- Dual-frequency GPS
- Canon digital camera
- SR3000 flash LADAR
DR navigation procedure: overview

1. Detect operator’s step
   - Stationary period, performing static ZUPT calibration

2. Determine dynamic locomotion pattern:
   - Walking
   - Jogging
   - Running
   - Climbing stairs etc.

3. Utilize KBS for accurate determination of SL:
   - Artificial neural network
   - Fuzzy logic (FL)

4. Utilize a combination of gyro/magnetometer measurements to provide heading (SD)
   - Fuzzy KF

5. Determine altitude

6. Reconstruct the navigation trajectory

KBS = Knowledge Based System
DR and primary navigation modes

- Human as navigation sensor
- During GPS availability
  - On-the-fly sensor calibration
  - Training of the Knowledge Based System (KBS)
  - Human locomotion modeling (i.e., measurable parameters, such as SL, SD, step interval, step cycle, etc.)
Image-based navigation with Flash LADAR

- Utilize pulsed light emissions which reflect back from features in the sensor field of view
- Time of Flight (TOF) principle utilized to measure distances
- Provides 3D measurement data
  - Based upon a particular position in the camera frame of reference
- Enables reconstruction of the sensor environment
Flash LADAR-based navigation: approach

✓ Navigation based on 3D features
  ❖ Selection of static features from a time series of Flash LADAR images

✓ Approach
  ❖ Segmentation of 3D image – linear feature extraction based on eigenvalue “signatures”)
  ❖ Feature matching of “n” features from first image from “m” possible features in a second image
    • Leverage INS solution to constrain the search space
    • RANSAC (RANdom SAmple Consensus) approach to identify best eigenvector “fit”
    • Final adjusted transformation for an image
  ❖ Trilateration/Triangulation of user position

Acquisition

Image Segmentation

EKF

Coordinate Transformation

Feature Matching

Determination of Position & Orientation
Extending DR navigation by Flash LADAR data

- GPS
- IMU
- Barometer
- Magnetometer
- Step sensors

Adaptive EKF

KBS training

Human locomotion model

Navigation solution

DR navigation

Feedback to nav. filter

Frame-to-frame navigation

SL/SD prediction

Apply sensor calibration

Sensor calibration

Outdoor

Indoor

Environment

SR3000 Flash LADAR

Feature extraction

Feature matching

- Feature extraction
DR navigation accuracy (1/2)

- Statistical results of recent outdoor experiments
  - Different users with variable walking patterns and different speeds, in different environments (mixed outdoor/indoor)
- Reliability of measurements evaluated as a function of
  - Terrain configuration
  - Step count along the trajectory
  - Error accumulation as a function of distance traveled

<table>
<thead>
<tr>
<th>Test data</th>
<th>Terrain type</th>
<th>User</th>
<th>SL modeling mean ± std [cm]</th>
<th>Step count</th>
<th>Total reference trajectory length [m]</th>
<th>Total fuzzy-based trajectory length [m]</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>flat</td>
<td>S</td>
<td>2 ± 7</td>
<td>426</td>
<td>277.7</td>
<td>260.7</td>
<td>4</td>
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<tr>
<td>2</td>
<td>flat</td>
<td>E</td>
<td>3 ± 8</td>
<td>528</td>
<td>341.0</td>
<td>361.4</td>
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<tr>
<td>3</td>
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<td>A</td>
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<tr>
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<tr>
<td>5</td>
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<td>S</td>
<td>2 ± 6</td>
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<td>6</td>
<td>flat</td>
<td>S</td>
<td>0 ± 5</td>
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<td>287.1</td>
<td>287.4</td>
<td>0.1</td>
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<tr>
<td>7</td>
<td>flat</td>
<td>E</td>
<td>1 ± 5</td>
<td>535</td>
<td>378.2</td>
<td>391.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Example indoor trajectory (no LADAR-based feedback included)

Statistical fit to reference indoor trajectory of 473 m (four indoor loops) to DR trajectories generated using SL predicted with FL and ANN, with gyro and integrated gyro/compass heading.

<table>
<thead>
<tr>
<th>SD modeling</th>
<th>SL modeling</th>
<th>Mean [m]</th>
<th>Std [m]</th>
<th>Max [m]</th>
<th>End misclosure [m]</th>
<th>CEP50 [m]</th>
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</thead>
<tbody>
<tr>
<td>Gyro/magnetometer</td>
<td>FL</td>
<td>5.12</td>
<td>4.23</td>
<td>4.97</td>
<td>4.40</td>
<td>4.95</td>
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<tr>
<td></td>
<td>ANN</td>
<td>5.23</td>
<td>4.15</td>
<td>5.13</td>
<td>4.56</td>
<td>5.04</td>
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<tr>
<td>Gyro</td>
<td>FL</td>
<td>5.32</td>
<td>4.34</td>
<td>4.87</td>
<td>4.50</td>
<td>5.16</td>
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<tr>
<td></td>
<td>ANN</td>
<td>5.38</td>
<td>4.41</td>
<td>4.94</td>
<td>4.43</td>
<td>5.12</td>
</tr>
</tbody>
</table>
Flash LADAR-based navigation

- Linear feature based matching exhibits robust performance
- Processing time 4~5 seconds per frame (718 kb per image)
- Example: indoor – person moving down the hall
Strong result which accurately reflects forward motion w/ periodic stops.
LADAR-based navigation results 2/2

Uncertainty of Position Error “Y”

Uncertainty of Position Error “X”
Navigation results: trajectory

- Poor Feature Extraction (Image Saturation)
- Loss of Imagery (Saturation) ~250 frames (50 s)
- INS Only (Drift)
LADAR-based approach provides effective solution to feature identification/matching, which serves as an essential link towards enabling navigation from 3D ranging imagery

- cm-level drift for long sequences of image
- source of calibration data for IMU sensors

**Goal:** Finalize the augmentation of DR with the image-based solution to achieve a back-up system for QA/QC and to increase the reliability of the DR module.
Current trend: collaborative navigation

- In GPS-challenged and indoor environments, stand alone GPS will not provide reliable and continuous navigation solution
- Sensor augmentation (IMU, magnetometer, barometer, AI methods, image-based augmentation, etc.) has been used to support a single user navigation task
  - Accuracy limitations (dead reckoning navigation)
- **Recent trend**: collaborative navigation of multiple users equipped with different sensors
  - All users operate together as a network, and all of them are considered nodes in the network
  - **Premise**: collectively, a network of GPS users may receive sufficient satellite signals, augmented by inter-nodal ranging and other sensory measurements, to form joint position determination
  - Network of GPS users, represents a *distributed antenna aperture* with large inter-element spacing – some advantages and many drawbacks
    - Challenge: develop approaches for combined beam pointing and null steering using distributed GPS apertures
Collaborative navigation: concept

Example network: dismounted soldiers, emergency crew, formation of robots or UAVs collecting intelligence, disaster or environmental information, etc.

Primary objective: sustain sufficient level of collaborative navigation accuracy in GPS-denied environments
Team of 5 ground-based platforms moving on a plane (2D case)
Platforms A1, A2, A3: equipped with GPS and tactical grade IMU
Platform B1: equipped with GPS and consumer grade IMU
Platform C1: equipped with consumer grade IMU only
Assumed: wireless communication, time synchronization and inter-nodal range measurements between the nodes
GPS position solution: 1Hz sampling rate, accuracy of 1.0m/coordinate (1σ)
Inter-nodal range measurements: available at 1Hz sampling rate with accuracy of 0.10 m (1σ)
Inter-nodal ranges: ~5 to ~ 20 m
Multiple scenarios tested; examples shown next
Performance evaluation: collaborative navigation

tight integration of inter-nodal ranges (1/2)

Statistics of collaborative navigation solution for C1 (131-600 second)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Min. [m]</th>
<th>Max. [m]</th>
<th>Mean [m]</th>
<th>Std. [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No GPS outage</td>
<td>0.011</td>
<td>0.860</td>
<td>0.250</td>
<td>0.170</td>
</tr>
<tr>
<td>Outage on A3</td>
<td>0.028</td>
<td>0.976</td>
<td>0.272</td>
<td>0.184</td>
</tr>
<tr>
<td>Outage on A2 and A3</td>
<td>0.022</td>
<td>1.715</td>
<td>0.526</td>
<td>0.378</td>
</tr>
</tbody>
</table>

In inertial-only mode: error of ~250 km (2D) in the end of the test
Performance evaluation: collaborative navigation
tight integration of inter-nodal ranges (2/2)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Min. [m]</th>
<th>Max. [m]</th>
<th>Mean [m]</th>
<th>Std. [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No GPS outage</td>
<td>0.01</td>
<td>1.48</td>
<td>0.42</td>
<td>0.26</td>
</tr>
<tr>
<td>Outage on A3</td>
<td>0.02</td>
<td>1.55</td>
<td>0.45</td>
<td>0.32</td>
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<tr>
<td>Outage on A2 and A3</td>
<td>0.03</td>
<td>2.29</td>
<td>0.68</td>
<td>0.38</td>
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</table>

Statistics of collaborative navigation solution for B1 (131-600 second)
The research on personal navigation is supported by National Geospatial-Intelligence Agency NURI grant.

The authors would like to acknowledge the Dayton Area Graduate Studies Institute (DAGSI) for providing supporting funding for this research.

The support of the Air Force Research Laboratories, Sensors Directorate (AFRL/SN) was invaluable for permitting use of the Flash LADAR camera unit, technical direction, and research support.

In particular, Dr. Jacob Campbell has been instrumental to the creation and development of this project.
Backup slides
Indoor/outdoor performance assessment

- KBS SL modeling augmented by HG1700 gyro heading
  - Outdoor gyro calibration
  - Point-to-point DR trajectory reconstruction (outdoor)
  - DR-KF trajectory reconstruction
    - Based on FL SD and SL modeling

Reference trajectory: classical surveying methods, and control points (marked with squares in the figure) established in the hallways with accuracy better than 1-2 cm in E and N, and 5 mm in height.
Flash LADAR-based navigation: approach

- Image Segmentation
  - Utilize linear based eigenvalue “signatures”
  - Threshold derived from range data
- Feature Matching
  - Leverage INS solution to constrain the search space
  - RANSAC (RANdom SAmple Consensus) approach to identify best eigenvector “fit”
    - Final adjusted transformation for an image
  - Matching based upon eigenvector signature
- Static / Non-Static
  - Matching eigenvector within expected search space
- Trilateration / Triangulation
  - Feature based navigation
### With Motion Compensation

<table>
<thead>
<tr>
<th>Image 2~3</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position Error</td>
<td>-0.0066</td>
<td>-0.0040</td>
<td>0.0175</td>
</tr>
<tr>
<td>Position σ</td>
<td>0.0114</td>
<td>0.0069</td>
<td>0.0304</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Image 3~4</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position Error</td>
<td>-0.0027</td>
<td>0.0026</td>
<td>0.0017</td>
</tr>
<tr>
<td>Position σ</td>
<td>0.0047</td>
<td>0.0045</td>
<td>0.0029</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Image 4~5</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position Error</td>
<td>-0.0045</td>
<td>-0.0014</td>
<td>-0.0012</td>
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<tr>
<td>Position σ</td>
<td>0.0078</td>
<td>0.0024</td>
<td>0.0022</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Image 31~32</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
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</thead>
<tbody>
<tr>
<td>Position Error</td>
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<td>-0.0062</td>
<td>0.0014</td>
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<tr>
<td>Position σ</td>
<td>0.0039</td>
<td>0.0108</td>
<td>0.0024</td>
</tr>
</tbody>
</table>

Drift errors remain below 1 cm for a sequence up to 30 images.
Strong solution due to excellent geometry
Master nodes or some nodes will need AJ protection to be effective in challenged EM environments. These nodes can have stand alone AJ protection system, or can use the signals received by antennas at various nodes for nulling the interfering signals;

- Network of GPS users, represents a distributed antenna aperture with large inter-element spacing – some advantages and many drawbacks
- Main advantage: increased spatial resolution which allows to discriminate between signals sources with small angular separations
- However, the increased inter-element spacing will also lead to the loss of correlation between the signals received at various nodes. *Also, there may be sympathetic nulls.*
- Challenge: develop approaches for combined beam pointing and null steering using distributed GPS apertures
Collaborative navigation: challenges

- Formulating methodology to integrate sensory data for various nodes to obtain a joint navigation solution
- Obtaining reliable range measurements between nodes (including longer inter-nodal distances)
- Limitation of inter-nodal communication (RF signal strength)
- Time synchronization between sensors and nodes
- Computational burden for the real time application