Personal Dead-reckoning (PDR) System for Firefighters

Presented by
Johann Borenstein
Research Professor at the University of Michigan
28 years experience in GPS-free position estimation for mobile robots and pedestrians
Personal Dead-reckoning (PDR) System

- Uses in-heel Inertial Measurement Unit (IMU)
- Two key innovations:
  1. PDR removes drift from IMU’s accelerometers
  2. PDR removes drift from IMU’s gyros
- Performance:
  - Heading errors: ~0° in walks of unlimited duration (at steady state, indoors)
  - Three modes of elevation estimation (typical Z-axis error: < 1 m)

IMU is fully embedded in heel of firefighter boot

Small-sized processor pack with built-in radio
PDR System - Implemented Features

- PDR system works with
  - walking backwards, sideways, or in any direction;
  - crawling on hands and knees, in any direction;
  - crawling up and down stairs on hands and knees;
- Fast system initialization: = 10 seconds
  (immediately prior to mission)
- Does not require setup of equipment on location
- Does not require any user-specific calibration
  - Any user can just put on the boots, perform
    the 10-second initialization, and start walking
  - Live demos today 3:30 pm – 5:00 pm as part of
    Demonstrations & Exhibits II (in Room Odeum C)
What’s New Since 2010 PPL Workshop

- Corrected major bugs affecting performance with crawling
  - Result: Much better accuracy during crawling
- New IMU: Better performance, 10-sec initialization (was 25 sec)
  - But: obtained new IMU only 3-4 weeks ago, have not yet adapted footfall detection software to match the new IMU.
- New estimates on accuracy (based on large database of tests, applicable for trips longer than ~100 m)
  - Normal walking
    > Average Return Position Error (RPE) = 1% of total travel
  - Walking backwards, sideways, or in any direction
    > Average RPE = 1% of total travel
  - Crawling on hands and knees, in any direction;
    > Simple crawling: Average RPE = 3% of total travel
    > Erratic crawling: Average RPE = 5% of total travel
Floorplan Mode

- Allows incident commander to define regions that are not rectilinear
Live Demo of Walk and Crawl

Presenter performed a live demo of a short walk and crawl.

Trajectory of live walk (~50 m long). RPE < 0.4 m (<1% of distance traveled)

Trajectory of live crawl in continuation of the walk. Total travel, ~85 m long. RPE < 3 m (3.5% of distance traveled)
Example

5-minute Walk/Crawl through office building: RPE = 2.70 m (1.1%)

See video clips of firefighters testing PDR at: http://www.engin.umich.edu/research/mrl/PE_PDR_Video.htm
### Elevation Estimates (Z-axis)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quick Mode (QM)</td>
<td>Average errors: &lt;1.0 m. No need for floor height measurements.</td>
<td>Uses barometer – therefore not compatible with pressurization techniques</td>
</tr>
<tr>
<td>Precision Mode (PM)</td>
<td>Average errors &lt; 0.2 m.</td>
<td>Requires measurement of floor heights and uses differential barometer</td>
</tr>
<tr>
<td>Firefighter Mode (FM)</td>
<td>Works without barometer. Average errors: &lt;1.5 m.</td>
<td>Reliability decreases in high risers. Requires measurement of floor height.</td>
</tr>
</tbody>
</table>

**Test Set Walk D4HT, Duration: 22 min, Floors: 13, vertical distance traveled: 108 m**

**Walk up and down the staircase of a 13-story building**

- **UC error = 1.98 m**
- **QM error = 0.23 m**
- **PM error = 0.14 m**
- **FM error = 0.20 m**
Urban Locator (UL) Mode for Police & First Responders

- PDR system can track walking emergency responders in GPS-denied urban environments.
- Same features as original PDR system, except that UL mode is optimized for urban streets, not buildings.

Examples of PDR system tracking a person walking along urban streets. Pink trajectory: Raw IMU output. Black trajectory: PDR using UL mode.
Rural Locator Mode for Police & Firefighters

- Three of our PDR systems with magnetometers were tested by the California Department of Forestry & Fire Protection (CAL FIRE).
- Test terrain: Stone Wall Peak, a mountainous hiking trail 3.2 km (2.0mi) long and located near San Diego, California.

Results for all 3 PDR systems:
- Maximal error: 45 m (~1.4% of distance traveled)
- Average error: ~20 m

See details and video at http://www.engin.umich.edu/research/mrl/PE_Outdoor.html
Summary

♦ U of Michigan personal dead-reckoning (PDR) system

♦ Two key innovations:
  1. Removes drift from IMU’s accelerometers
  2. Removes drift from IMU’s gyros
  3. Measures elevation with excellent accuracy
  4. Work will every conceivable kind of legged motion, including crawling

♦ Results:
  • Position errors: <1% of distance traveled
  • Heading errors: ~0°
    (at steady state, indoors, in >99.5% of buildings)
  • Three modes of elevation estimation
    (typical Z-axis error: < 1 m)
Backup Slides

The following slides are not part of the oral presentation but may be useful in the Q&A session
Dominant Directions in HDE Algorithm

The HDE algorithm is based on the concept of Dominant Directions (DDs)

- Two sub-sets: primary and secondary DDs
  - “Primary DDs” are those that one notices immediately when looking at the floor plans of most buildings, and they are usually the same as the directions of the outside walls of the building.
  - Most corridors in buildings are parallel to primary DDs (see floor plan to the right).
  - In rare cases, corridors intersect with primary DDs at angles of 45°. Those are called “secondary DDs.”

- Typically, a walk with the PDR system must be confined to just one building. That is because the DDs must be the same throughout a walk.
  - If adjacent buildings have the same DDs, then a single walk may stretch across all of these buildings.

Floor plan of the conference center of an unnamed hotel. The general direction of the corridors is highlighted by thick red lines. The four primary dominant directions (0°, 90°, 180°, and 270°) are typically those that are parallel to the walls and main corridors of the building. Secondary dominant directions (45°, 135°, 215°, and 315°) intersect primary ones at angles of 45°.
More Experimental Data

PDR-based trajectory of a 31-minute/1.1-mile walk through UM buildings, overlaid over a satellite photo. Average heading error: <2°. Final position error: 4 m (0.22% of distance traveled).

Precision Indoor Personnel Location and Tracking for Emergency Responders, Worcester, MA, August 1-2, 2011
More Long-duration Walks

Walk duration: 45 min, Distance: 3,000 m, Heading error: 1.7°,
Final position error: 3.3 m (0.11% of distance traveled)

Walk duration: 42 min, Distance: 2,528 m,
Heading error: 2.1°
Final position error: 10 m (0.4% of distance traveled)
Challenging Walks

- Subject emulated actions of a firefighter searching for victims in a large factory.
- Subject walked around to look behind every machine on the factory floor.
- Subject spent ~70% of the time not walking along straight corridors.

Walk duration: 31 min, Distance: 1,685 m.
Average heading error: 3.1°. Final position error: 2.5 m (0.15% of distance traveled).