WPI Precision Personnel Location System: Inertial Navigation Supplementation

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funded by
US Department of Justice
National Institute of Justice

May 6, 2008

Outline

- PPL System Overview
  - Project Goals
  - System Architecture
  - Position Estimate Performance
- Tracking with PPL system
  - Position Only Tracking
  - Inertial Supplementation

Position-Finding Technology for Emergency Personnel is a Critical Need

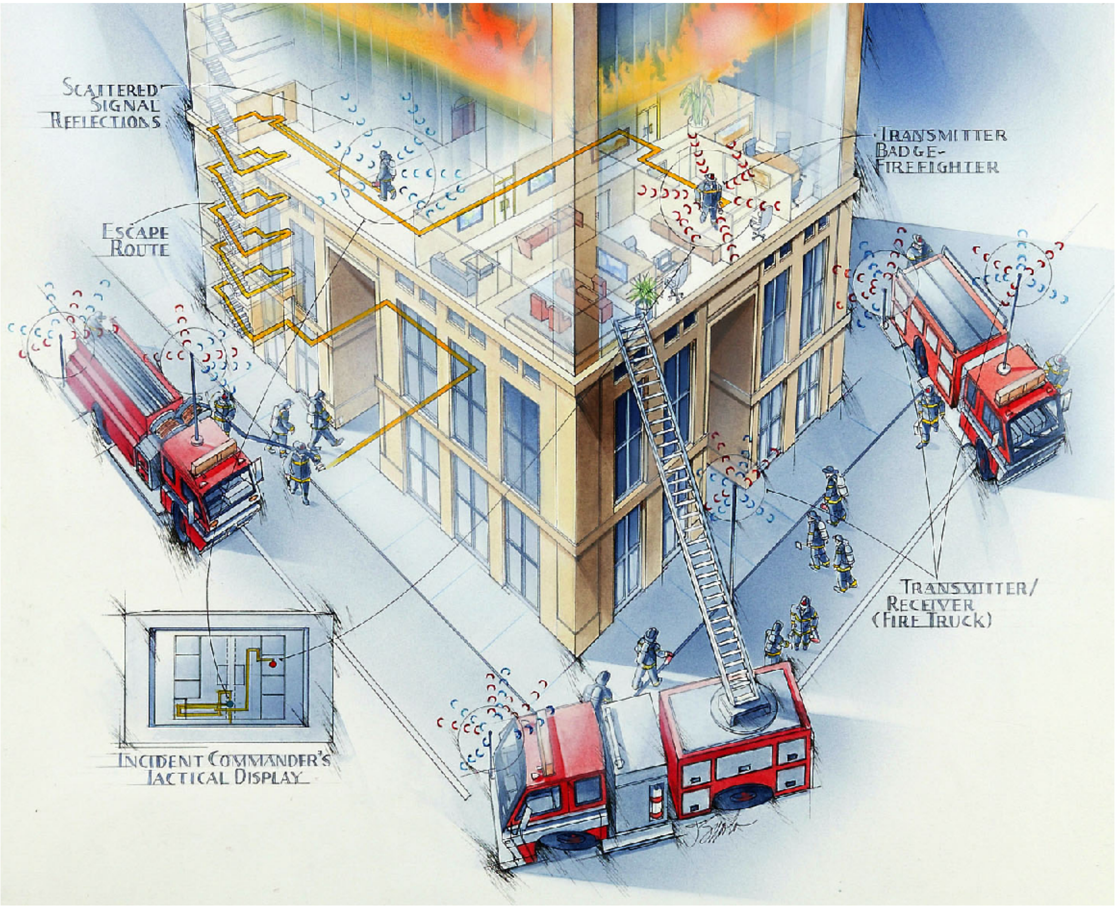
- 12/3/99: Six fire-fighters died in a warehouse fire literally within a few feet of safety in Worcester, MA.
- A too common problem:
  - NFPA: lost/trapped 3rd ranking cause of fire-fighter fatalities
- Can we track the locations of emergency responders inside buildings?

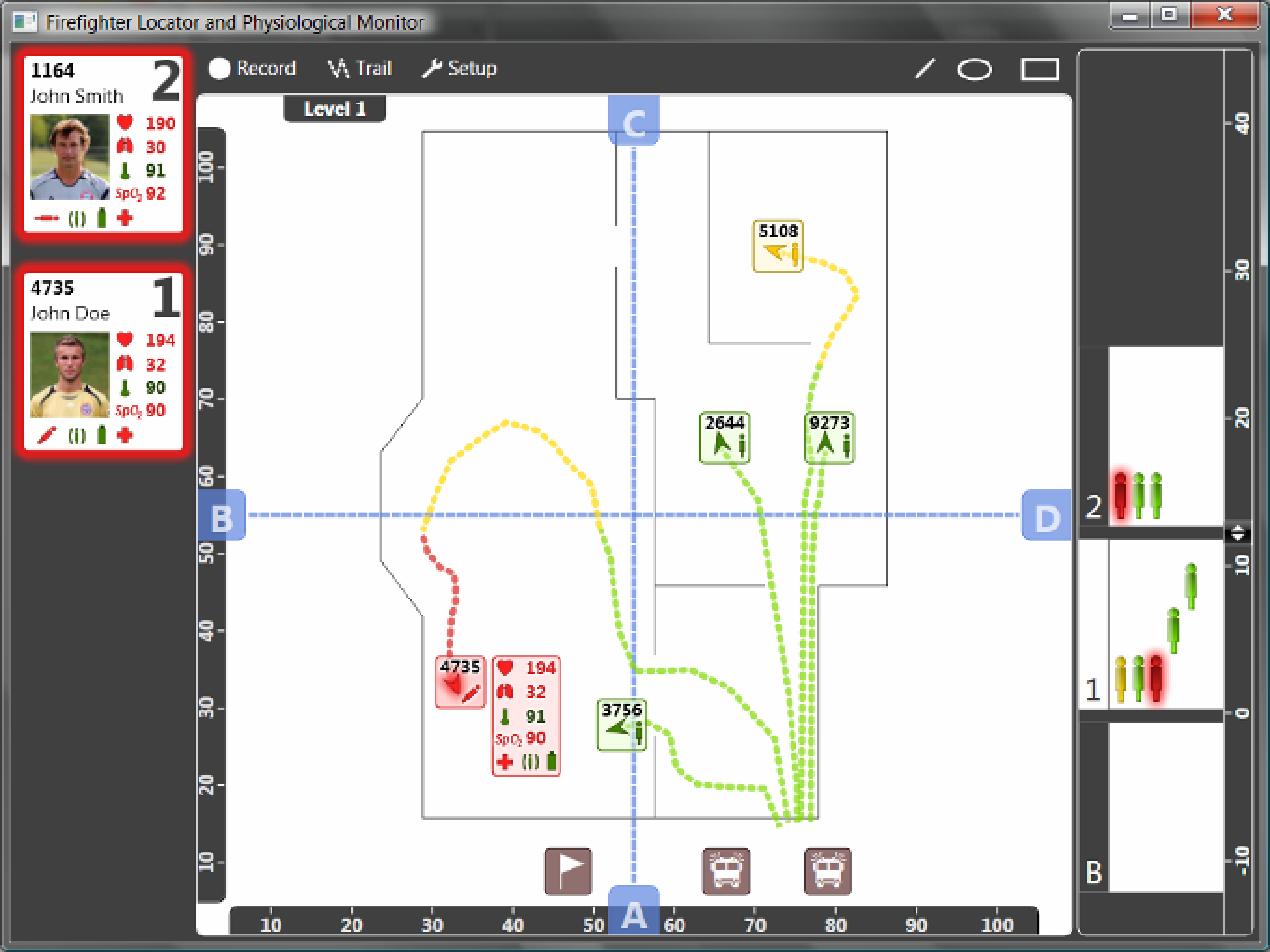
WPI PPL Goal

- A location and tracking system which
  - displays locations, paths, accurate to +/- 1 ft
  - for multiple responders
  - in 3 dimensions
  - requiring no pre-installed infrastructure
  - minimal set-up
  - physiological monitoring

System Overview

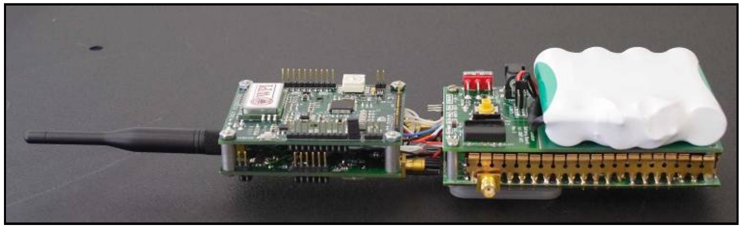
- RF Approach
- Transmitter on personnel
- Receivers outside
- Position based on received signals
- Local coordinate system

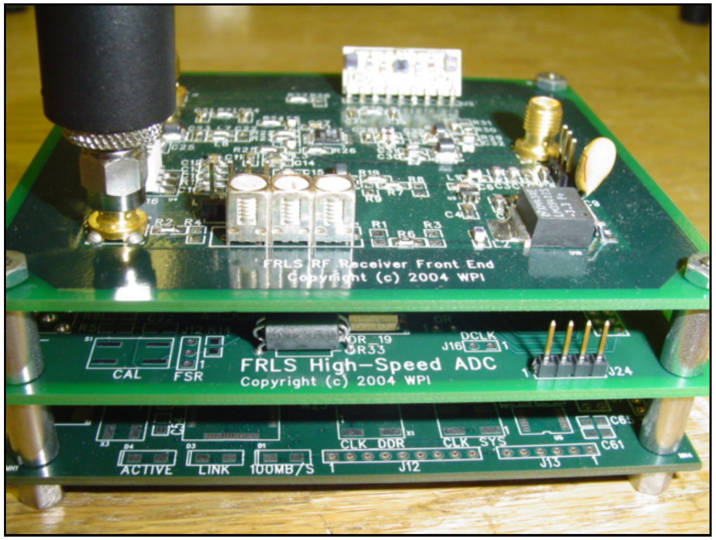


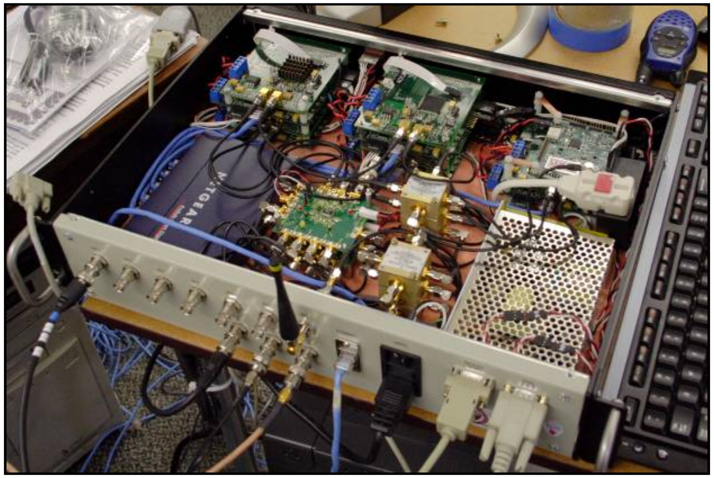


Firefighter Locator and Physiological Monitor
1164
John Smith
2
190
30
91
SpO2 92
4735
John Doe
1
194
32
90
SpO2 90
Record
Trail
Setup
Level 1
C
B
D
A
5108
2644
9273
4735
194
32
91
SpO2 90
3756
10
20
30
40
50
60
70
80
90
100
40
30
20
10
0
-10
2
1
B

System Hardware

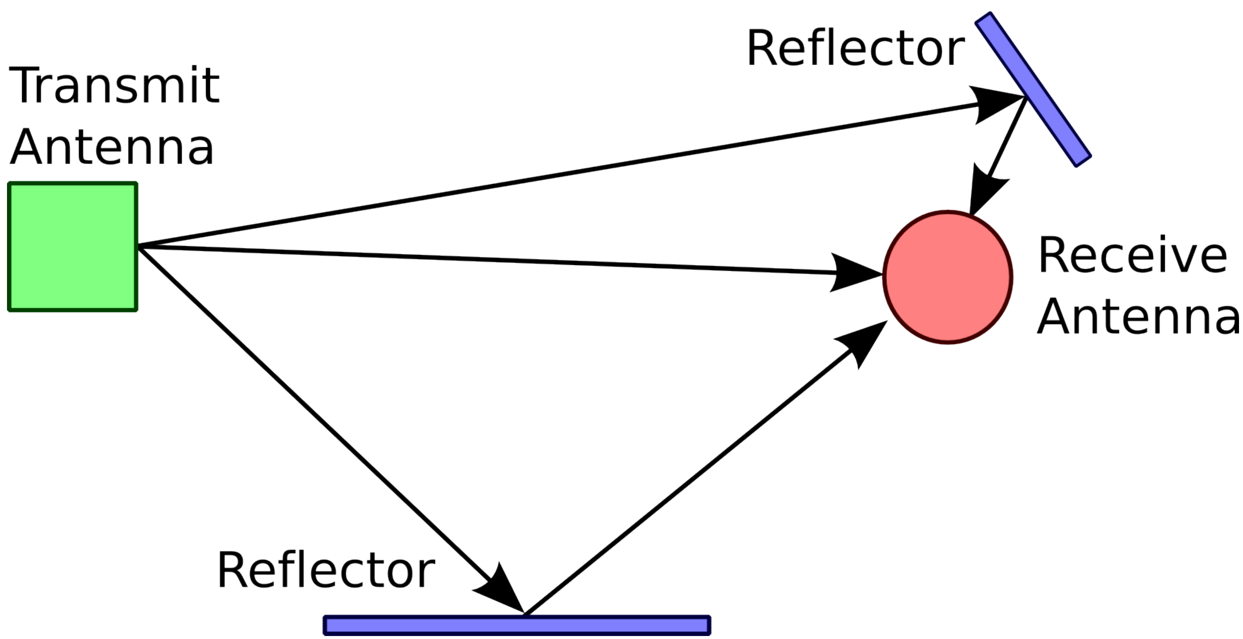






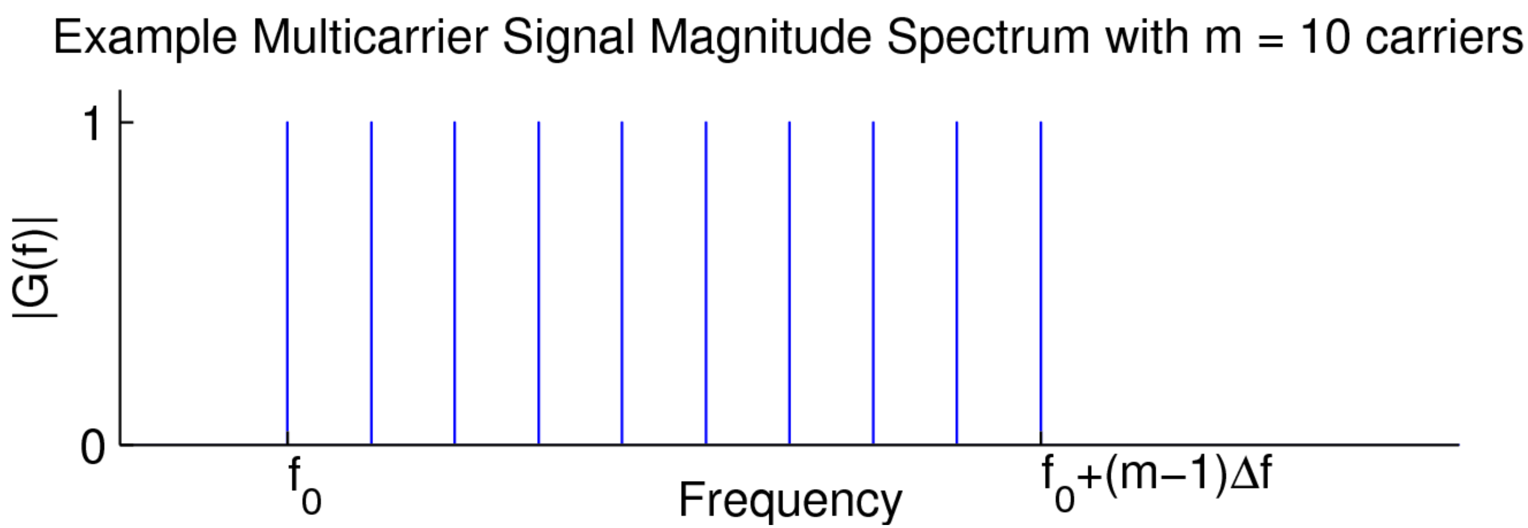
Multipath Problem

- Indoor positioning with RF very challenging due to multipath
- Metal objects act as reflectors



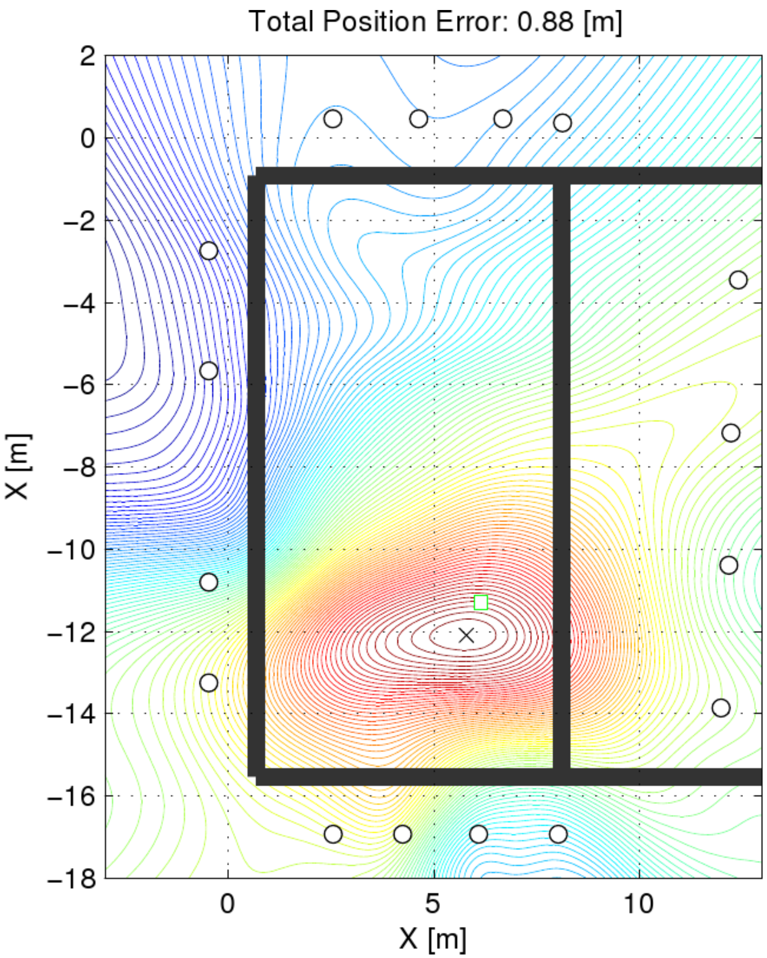
Multicarrier Ranging Signal

- Sum of unmodulated carriers evenly spaced in frequency
- Carriers may be placed around existing services
- Current system uses 98 carriers from 550-700MHz



Singular Value Array Reconciliation Tomography (σART)

- Unique algorithm developed at WPI
- Estimates positions from our RF data
- Not based upon 1-D ranging and multi-lateralization like most approaches
- See reference



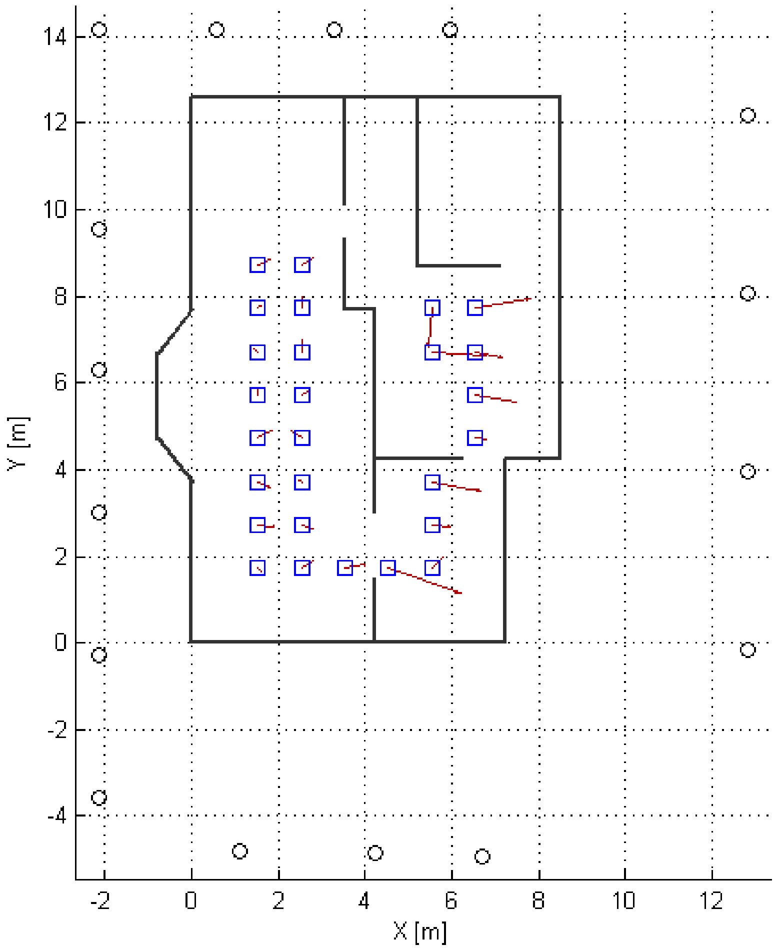
•http://www.ece.wpi.edu/Research/PPL/Publications/

Performance - Residential Building

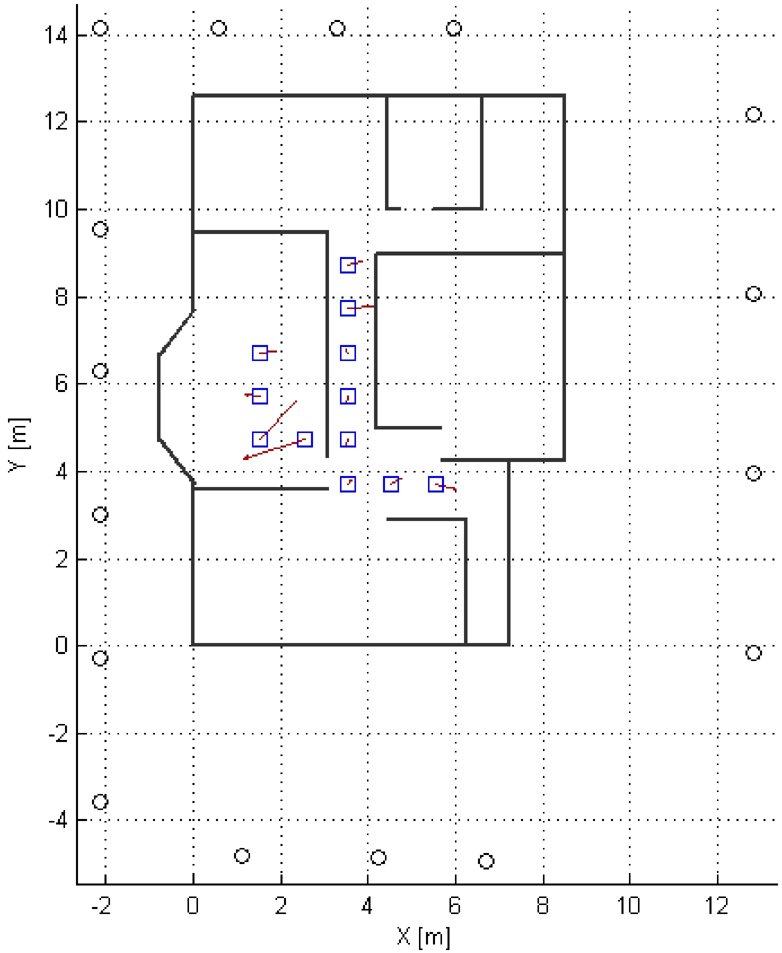
- 16 by 14m coverage

Performance - Residential Building

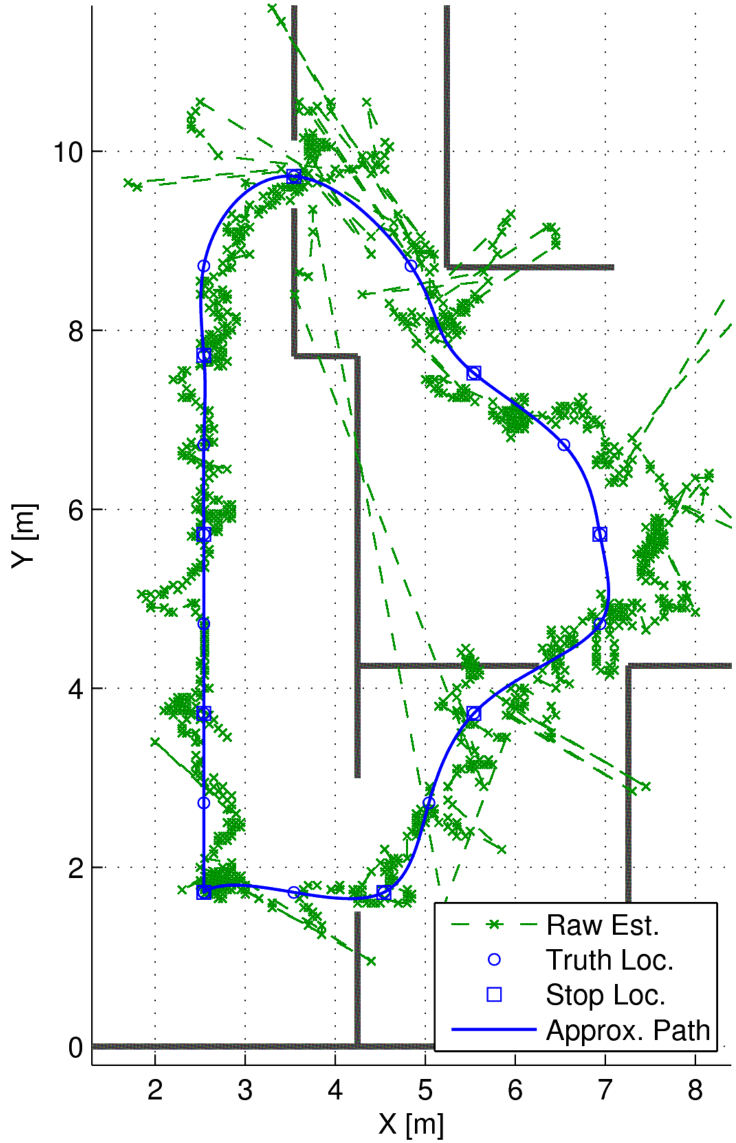
1st floor error: 0.49m



2nd floor error: 0.46m



Continuous Data Capture



- Transmitter moved about first floor
- 30 captures per second
- Estimates needs to be filtered

Filtered Tracking

- Can filter RF position estimates based on motion constraints
- Kalman Filter
  - Optimal estimator for linear systems with Gaussian noise
  - Tracks state variables
    - Position, velocity, acceleration
  - Low-pass filter

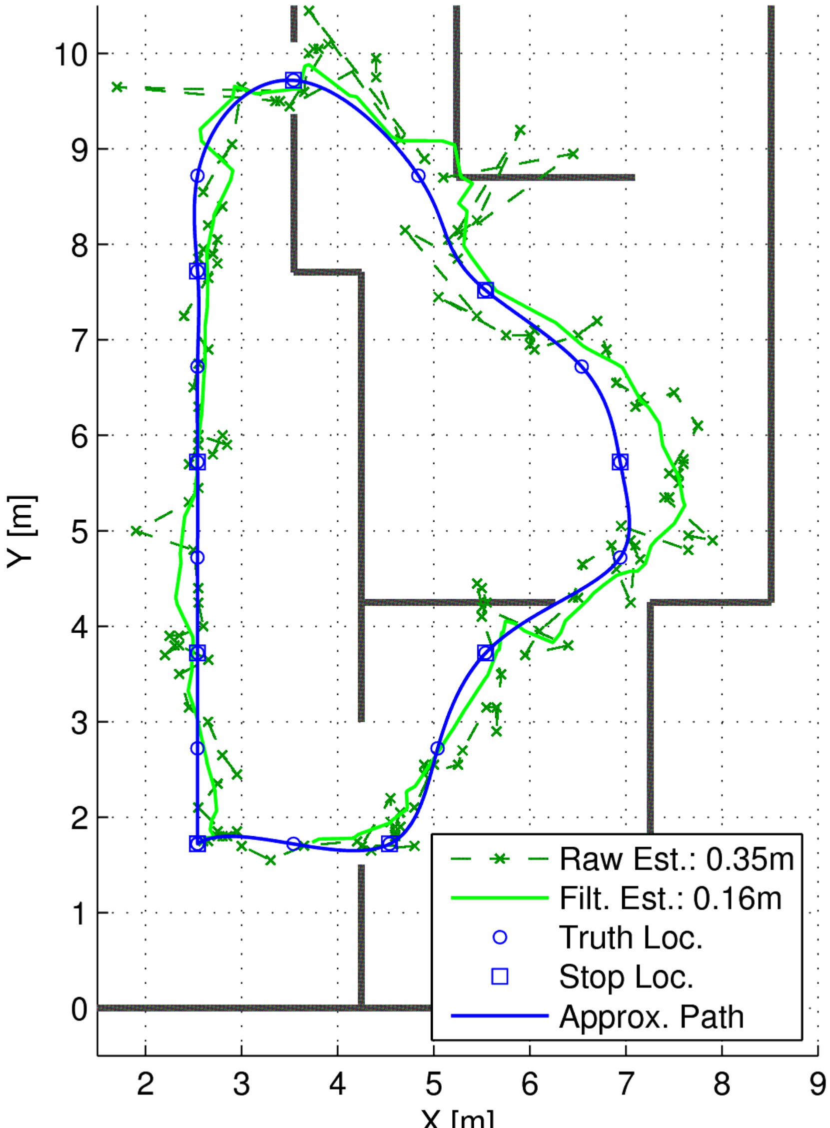
Kalman Filter Model

- Measurements
  - Position only for now
  - Fusion of measurements from different sources
- Must know covariance matrices of measurement and process noise
- Measurement noise
  - Error on position estimates
- Process noise
  - Random changes in true state

Kalman Filter: Algorithm

- Discrete Time Recursive Algorithm
  - Predict current state from previous state
  - Merge prediction with measurement based on covariances
  - Also tracks covariance of states
- These phases are repeated for each time index
- We also use outlier rejection logic

Position Only Filtering



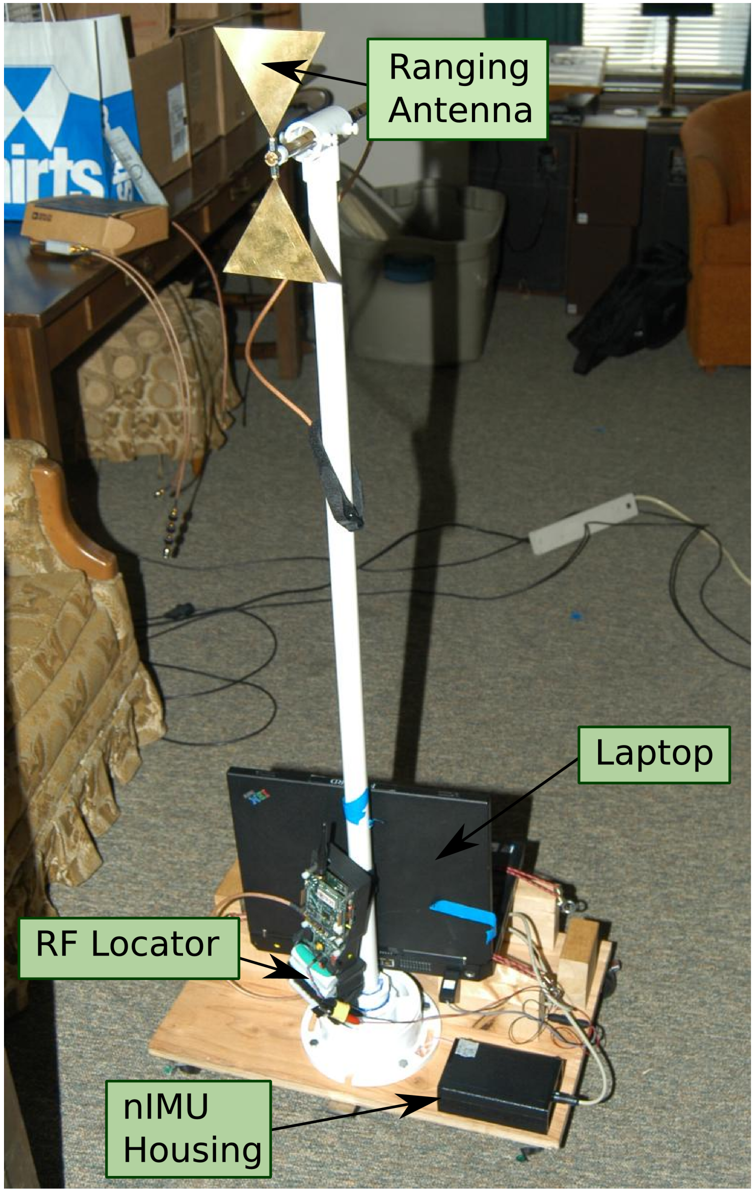
- Mean Abs. Error
- Raw Estimates: 0.35m
- Filtered: 0.16m
- Better than 1 foot
- Still seek improvement for worse RF environments

Inertial Supplementation

- Can we add inertial sensors to our system to improve performance?
- Let's us measure acceleration states
- nano Inertial Measurement Unit by MEMSense
  - Three-axis accelerometer, gyroscope and magnetometer
  - Internal ADC
  - Built-in temperature compensation

[www.memsense.com]

Transmitter Cart



Inertial Data Processing

- Two coordinate frames to reconcile
  - Our System's Local frame
  - Cart frame nIMU measures in
- Orientation of cart frame relative to local frame must be tracked
  - Can be represented as three Euler angles (yaw, pitch and roll)
  - Can be represented as a rotation matrix
  - Convert acceleration measurements to local frame

$$\mathbf{a_l} = \mathbf{R}_c^l \mathbf{a_c}$$

Orientation Tracking

- Gyroscopes measure angular rates

$$\left(\omega^l_{c_x} \omega^l_{c_y} \omega^l_{c_z}\right)$$

- Relates to derivative of rotation matrix

$$\dot{\mathbf{R}}^l_c(t) = \mathbf{R}^l_c(t)\boldsymbol{\Omega}^l_c \qquad \boldsymbol{\Omega}^l_c = \begin{bmatrix} 0 & -\omega^l_{c_z} & \omega^l_{c_y} \\ \omega^l_{c_z} & 0 & -\omega^l_{c_x} \\ -\omega^l_{c_y} & \omega^l_{c_x} & 0 \end{bmatrix}$$

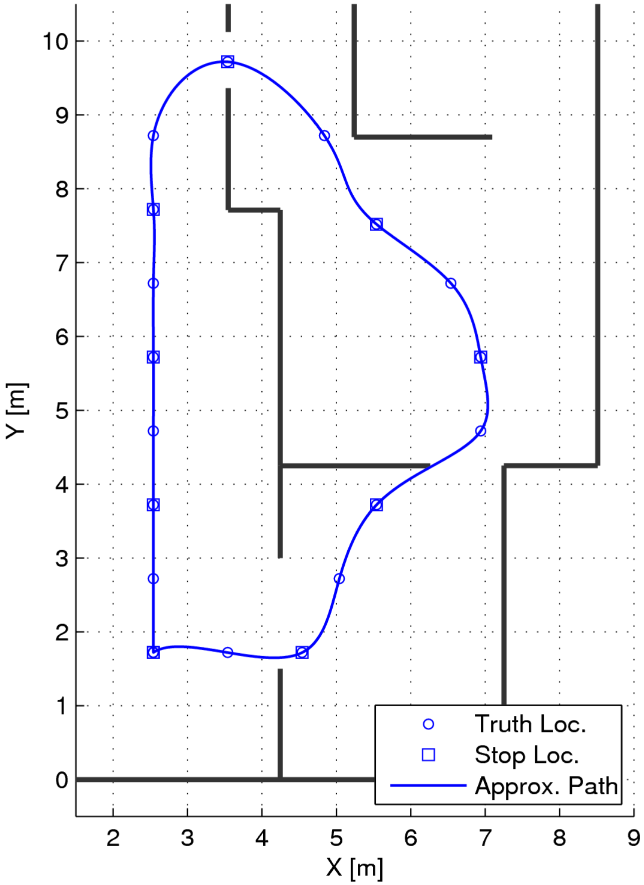
- Estimate orientation in discrete time

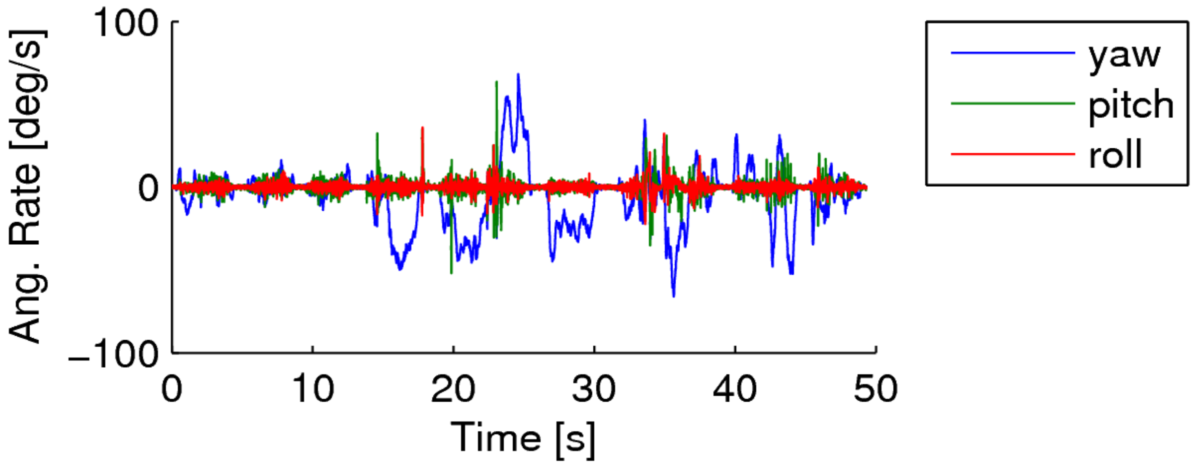
$$\mathbf{R}^l_{c,k} = \mathbf{R}^l_{c,k-1}\left(2\mathbf{I_3} + \boldsymbol{\Omega}^l_{c,k}\tau\right)\left(2\mathbf{I_3} - \boldsymbol{\Omega}^l_{c,k}\tau\right)^{-1}$$

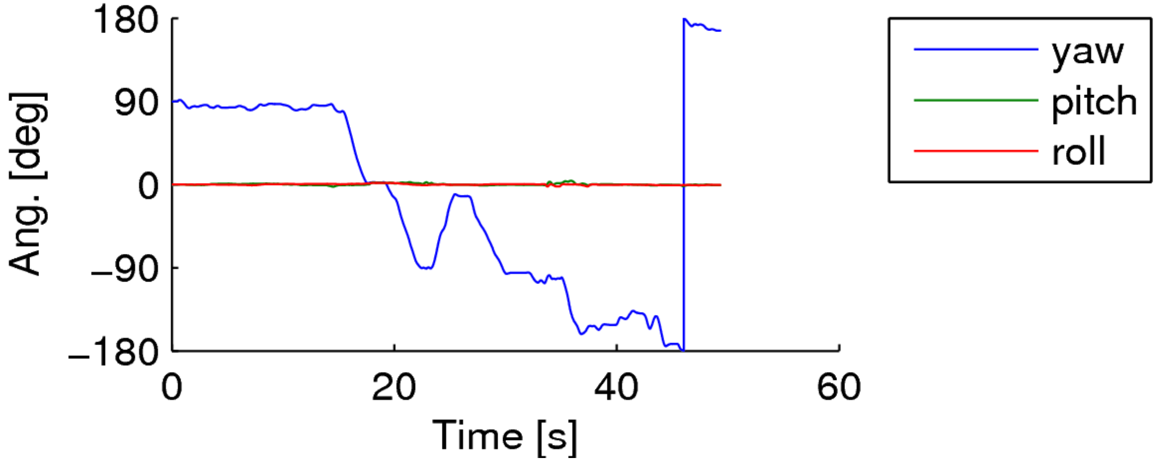
Orientation Tracking

- Currently done with gyroscope angular rate measurements
- Open loop
  - Tracking a quantity with its derivative is unstable as small errors grow over time
- For our case found to be accurate 1-2 degrees over 1 minute
- Need to close loop in future
  - Gravity, magnetomer, RF position est.
  - Extended Kalman filter

Orientation Tracking







Gravity Compensation

- Accelerometers measure acceleration due to motion and acceleration due to gravity

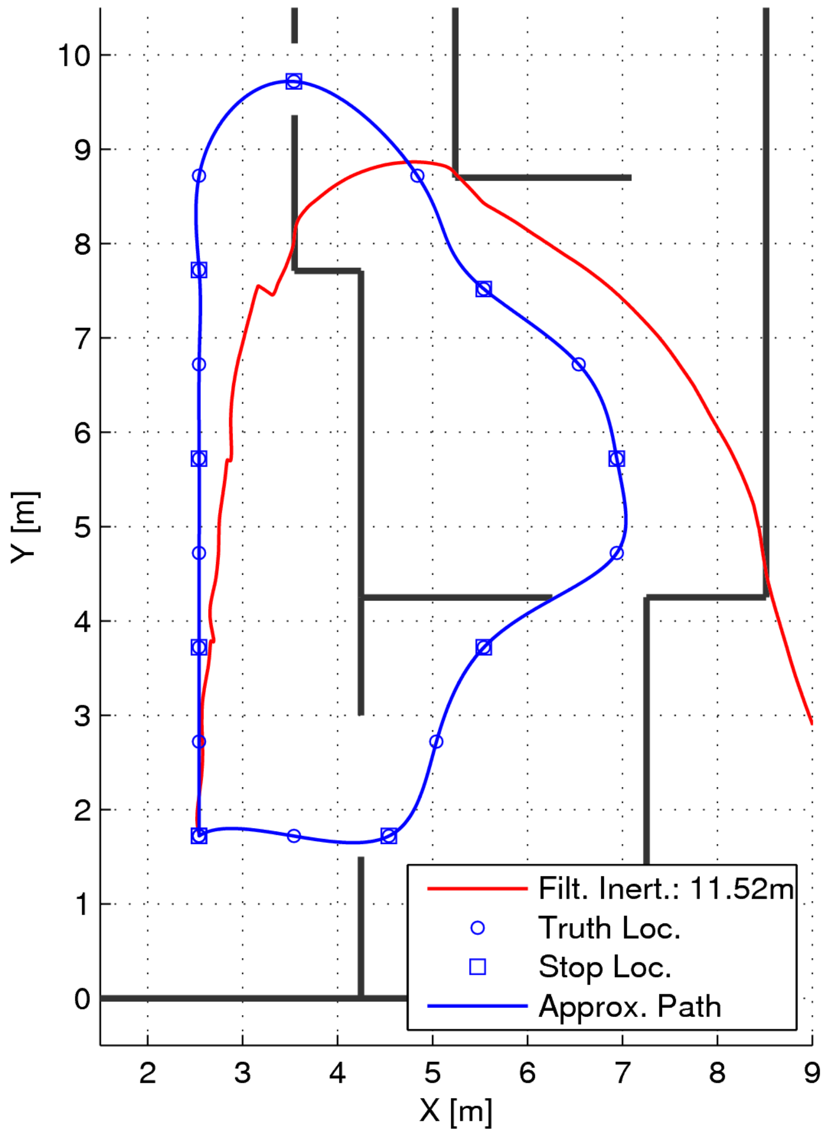
$$\mathbf{g}_l = \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix} \qquad \mathbf{f}_c = {\mathbf{R}_c^l}^T (\mathbf{a}_l + \mathbf{g}_l)$$

- We can estimate acceleration due to motion in the local frame

$$\hat{\mathbf{a}}_{l,k} = \mathbf{R}_{c,k}^l \mathbf{f}_{c,k} - \mathbf{g}_l$$

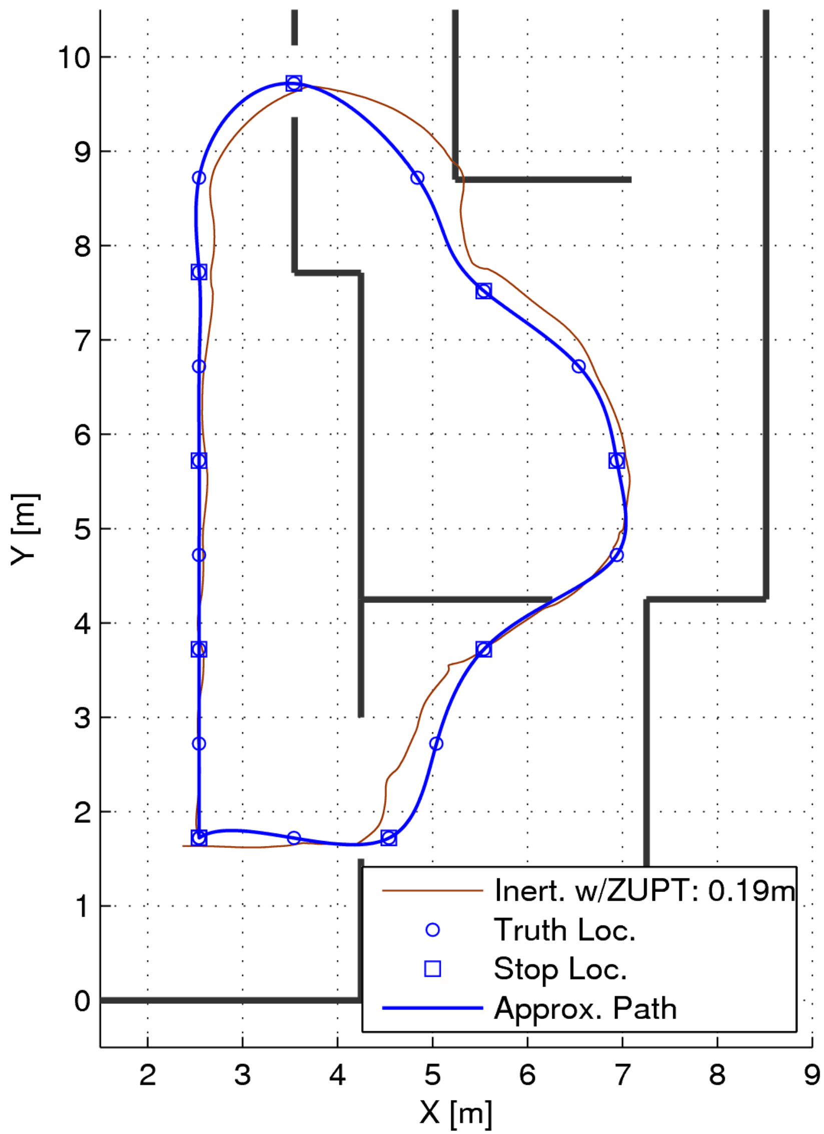
- This can be input to Kalman filter as state measurement

Inertial Only Tracking



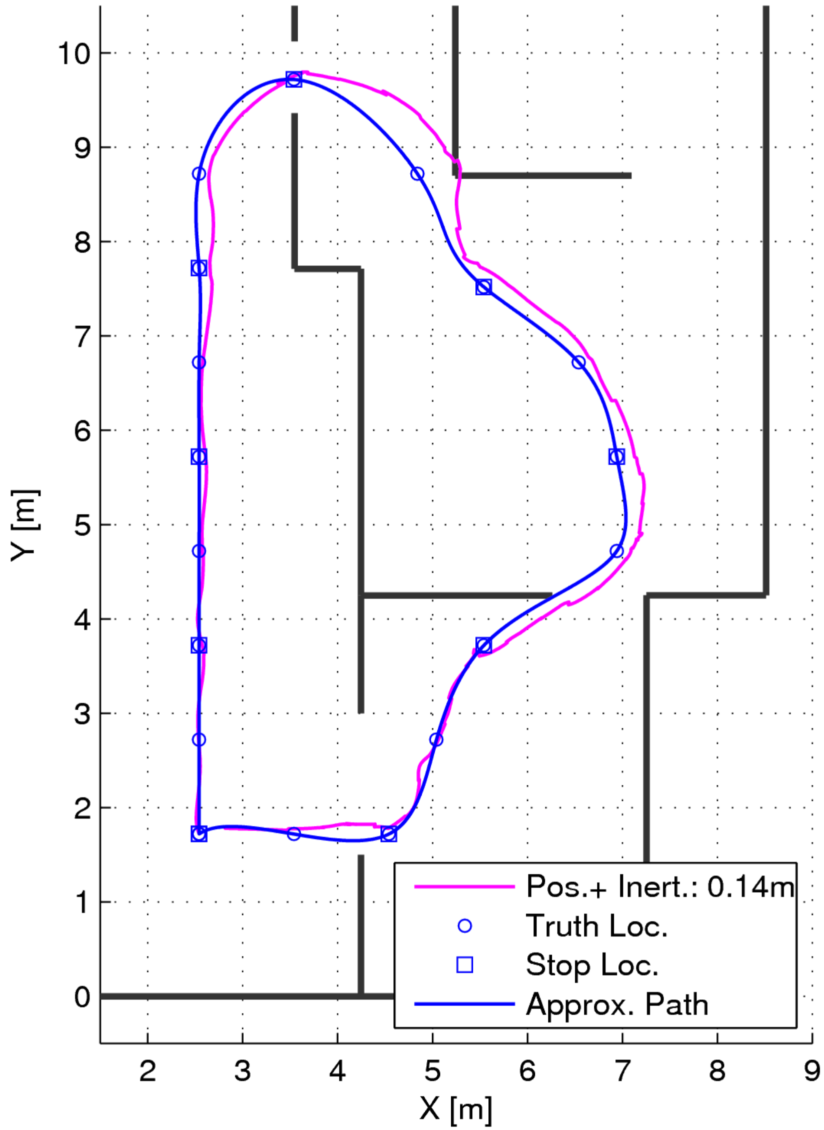
- Inertial open loop quickly drifts from true path
- Trying to track position from second derivative
- Small bias integrates to large position error
- Error grows cubically

Inertial with ZUPTs



- Can take advantage of zero velocity updates (ZUPTs)
- Still an open loop tracker, now with slower linear error growth
- Mean Abs. Error: 0.19m

Inertial and Position Tracking



- Inertial data and position estimates fused in Kalman filter
- Low weighting on RF position estimates keeps inertial from drifting
- Mean Abs. Error: 0.14m

Conclusions

- Fusion of RF and Inertial data can indeed improve tracking performance
- Zero velocity updates important
- Future Work:
  - More difficult RF environments
  - Track over longer time period
  - Close loop on orientation tracking
  - Incorporate into real-time system

Indoor Location Workshop

- WPI hosting 3rd annual workshop on *Precision Indoor Personnel Location and Tracking for Emergency Responders* in August 2008 in Worcester, Mass.
- www.ece.wpi.edu/Research/PPL

WPI Precision Personnel Locator

- Acknowledgements
  - The rest of the WPI team
  - Worcester Fire Department
  - The support of the National Institute of Justice of DOJ

- Thank you!
  - Vincent Amendolare, vamend@wpi.edu
  - www.ece.wpi.edu/Research/PPL