Next Generation Vehicle Positioning in GPS-Degraded Environments for Vehicle Safety and Automation Systems

Kickoff Meeting with FHWA

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GPS-Denied Navigation
Low Cost & Small Form Factor
High Accuracy
360° Situational Awareness

Human-Robot Collaboration

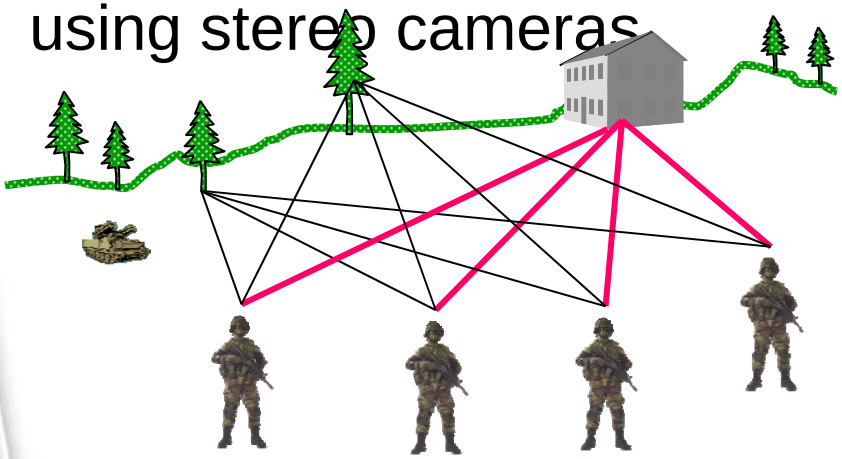
Core Features:

- Operates Indoors and Outdoors using GPS Denied Navigation.
- Navigation through Complex Environments with 6 Degrees of Freedom Localization (0.1% Drift Rates)
- Highly Accurate following using Visual Landmarks. (5cm Accuracy)
- Automatic Safety-Stop to avoid hitting anyone. Automatic restart when obstacle is out of the way.
- Obstacle avoidance using real-time stereo processing

Visual Aided Navigation: Warfighter Geo-Location and Gaze Estimation

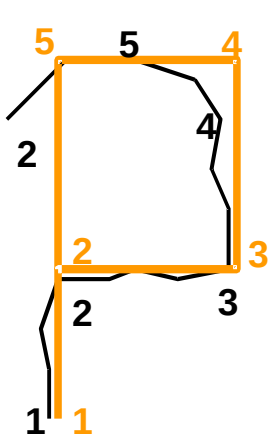
Relative Pose Estimation:

3D ego-motion (6 DOF pose) estimated in real-time using stereo cameras

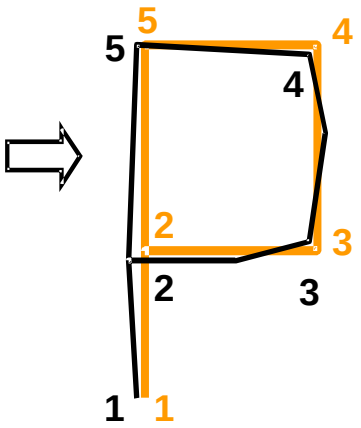


Absolute Pose Estimation:

- Automatic Detection and Matching of Visual Landmarks
- Landmark database created on the fly
- Opportunistic use of GPS when available

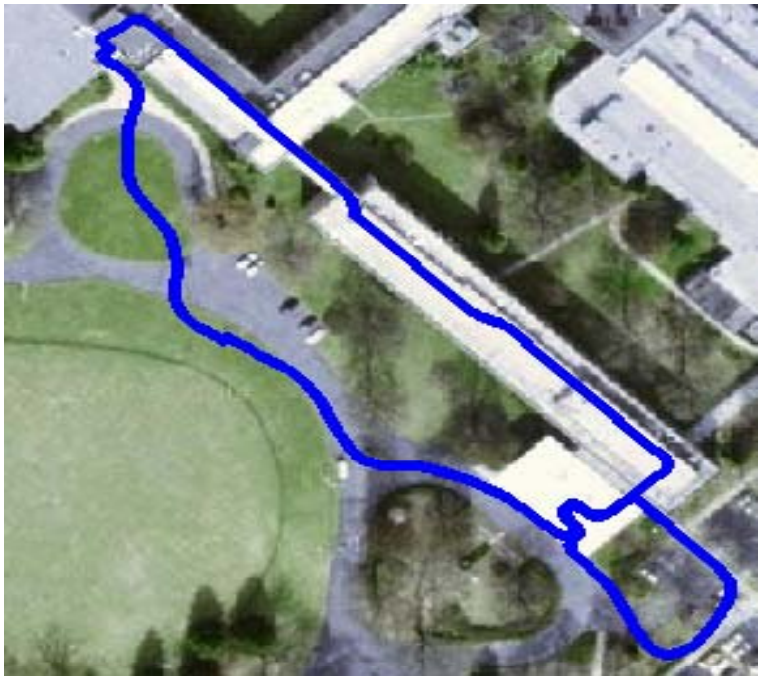


Raw relative Location Estimates



Drift correction in relative position estimates with visual landmark matching

GPS Challenged 3D Localization and Orientation Estimation (6 DOF)



Integrated Navigation System Performance at 0.1% Drift
Drift reset by landmark matching

Accuracy Results * GPS at 2 points

Duration: 435s (7.15 minutes)

Distance (3D): 545.51m

Loop closure accuracy (over start-to-end distance)

Stereo- Camera+ On-the-Fly-Landmarks: 0.54 m

- Experiment Scenario
  - –Outdoor & indoor
  - –Opening doors, White Walls
  - –Moving Objects

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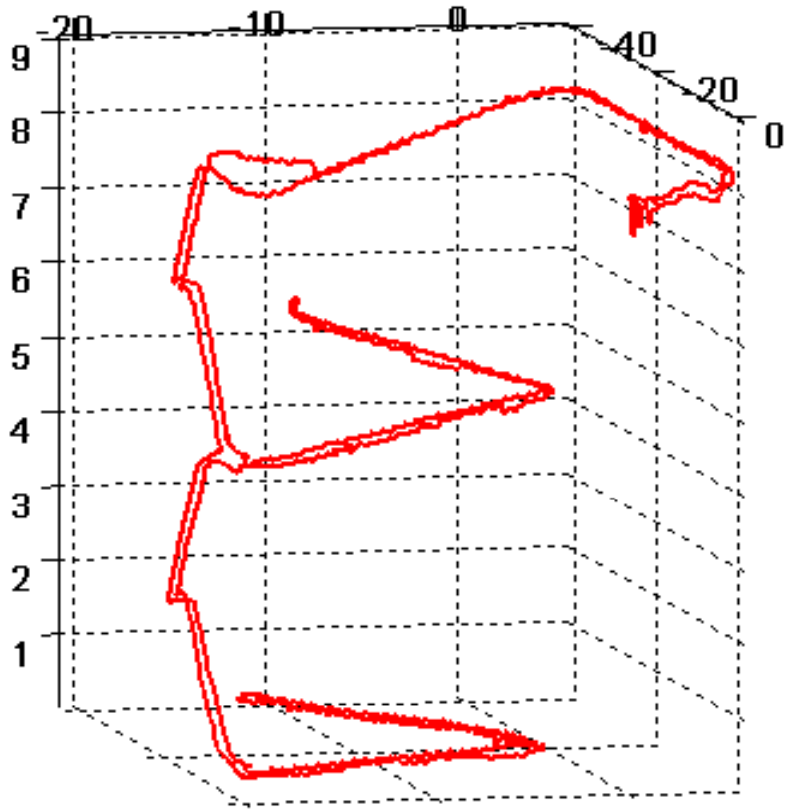
Performance in Building & Stairs

Building

Video



Estimated 3D track of path in building&Stairs

- **Experimental results**
  - Duration: 404s (6 minutes 44 seconds)
  - Distance (3D): 361.43m

  Loop closure accuracy (over start-to-end distance)
  - **Multi-Stereo-Camera + on-the-fly Landmarks: 0.48 m**

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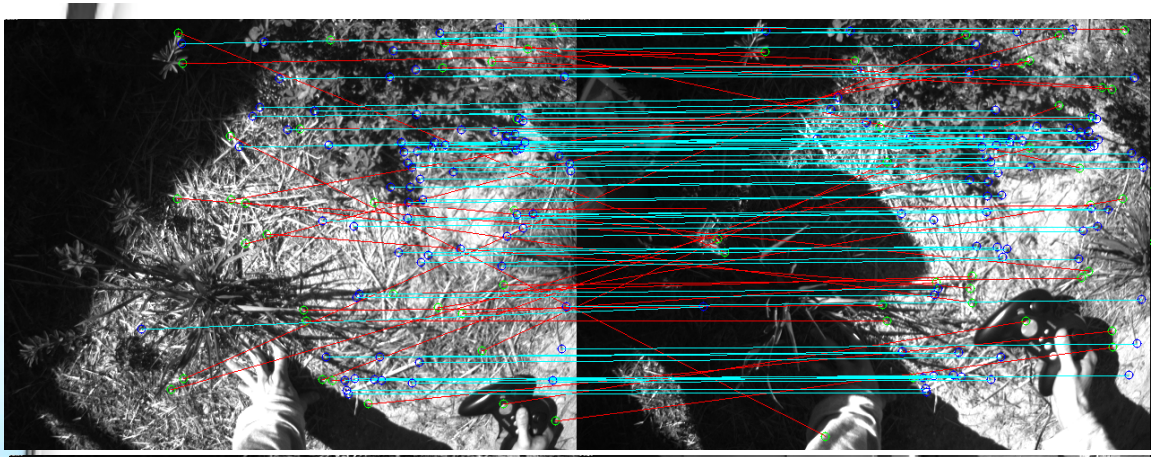
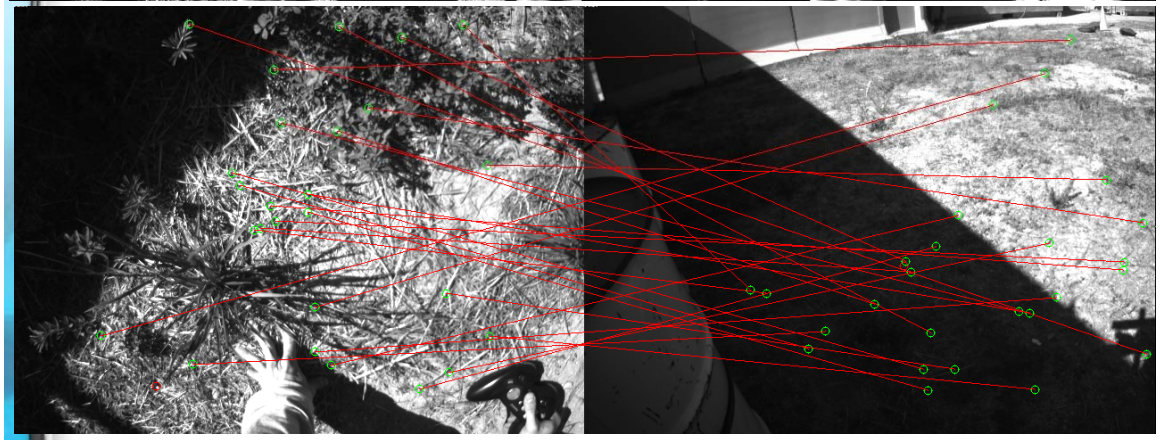
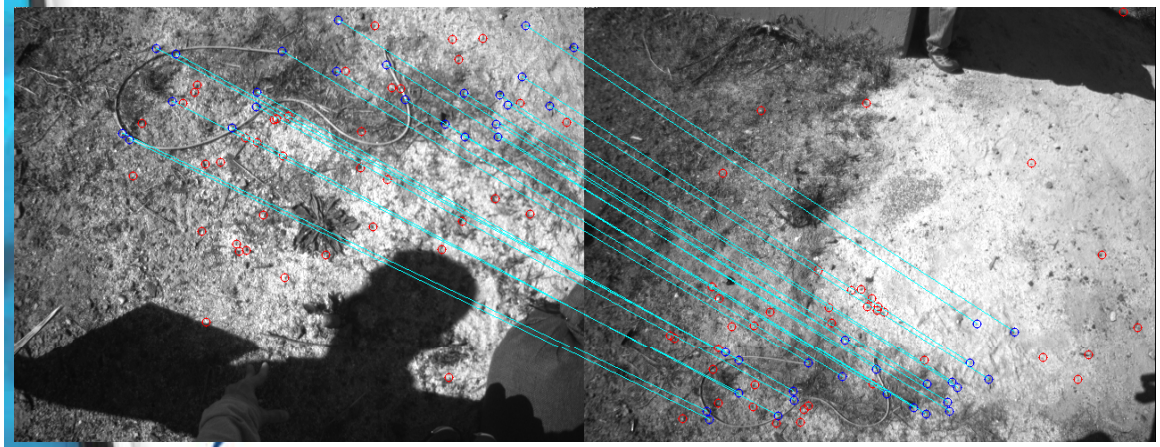
Landmark Matching Examples



Matching Similar Views



Matching Different Views



Matching Views with Large Scale and Orientation Change

Green Points or Red Lines: *false matches (can be eliminated successfully).*
Blue*: the final matches that satisfy geometry constraints (good matches).*

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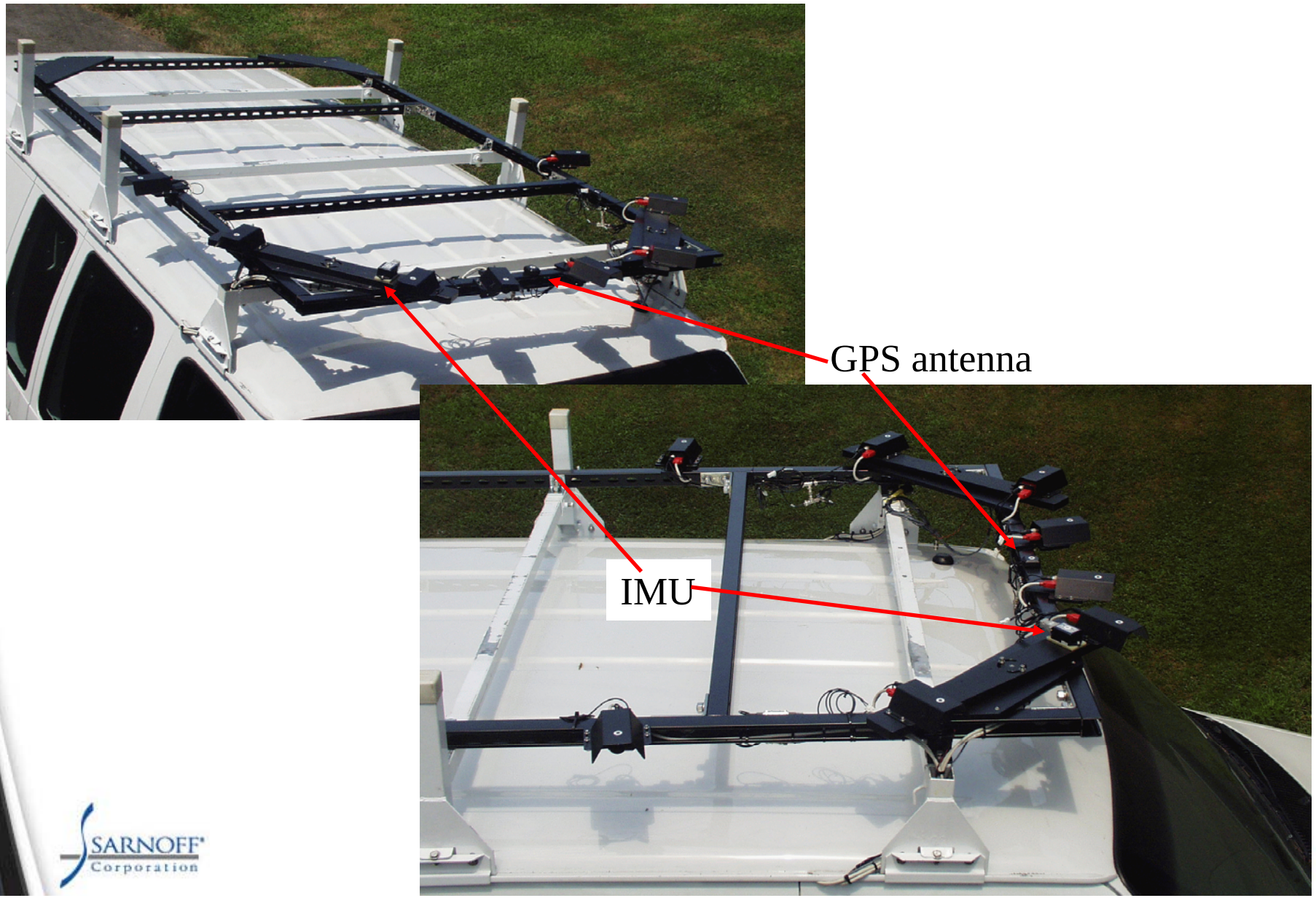
Data collection system



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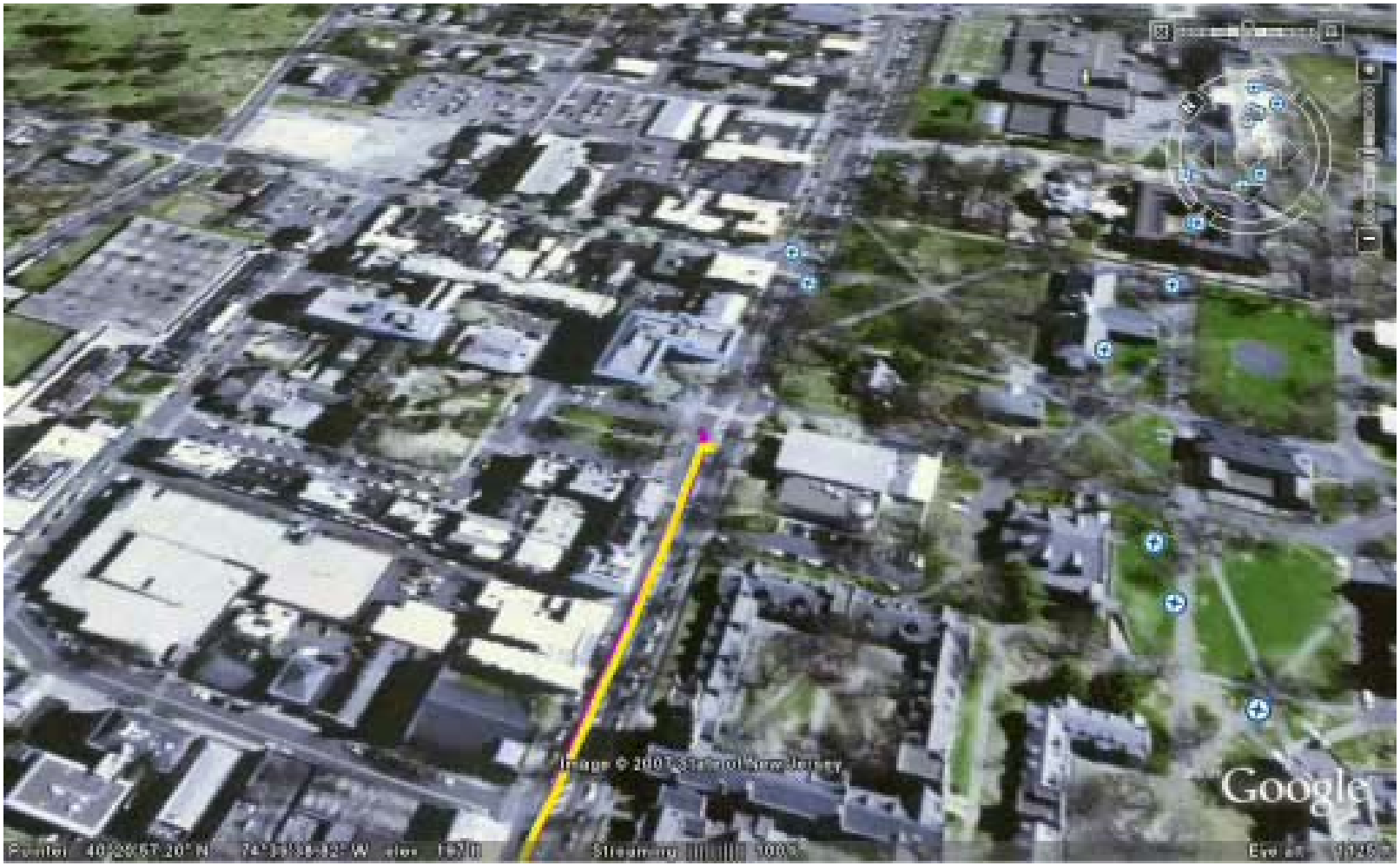
Real-Time Google Display



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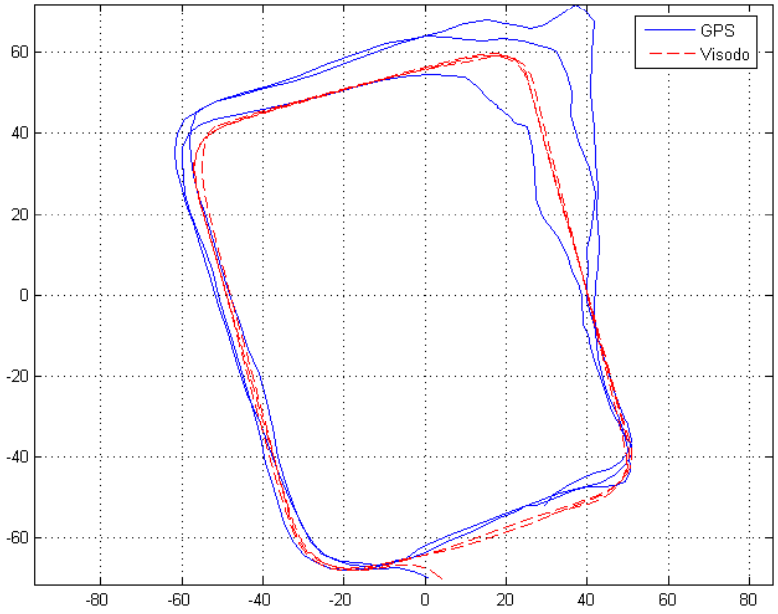
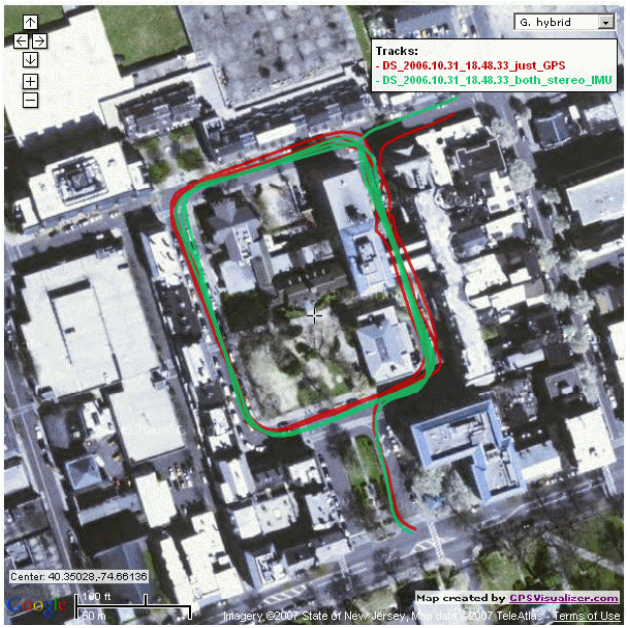
Visual Odometry
Palmer Square

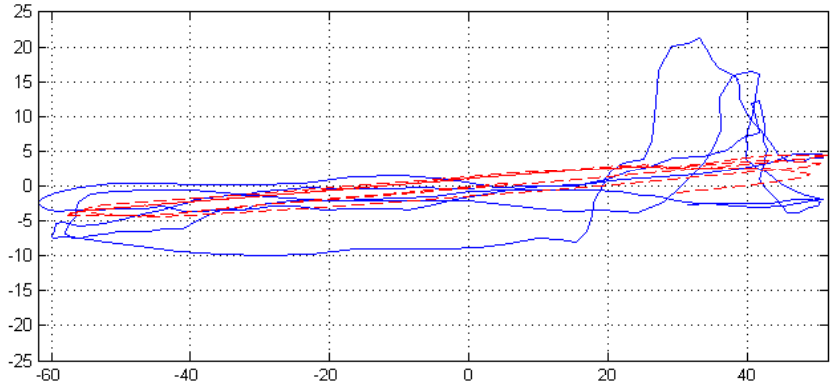
Recovered trajectory: GPS (blue), Visual Odometry (red).

All dimensions in meters



Top view





Side view

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3D Moving Target Detection

Moving objects / Pop-Up targets automatically detected after compensation of the 3D motion of the vehicle.

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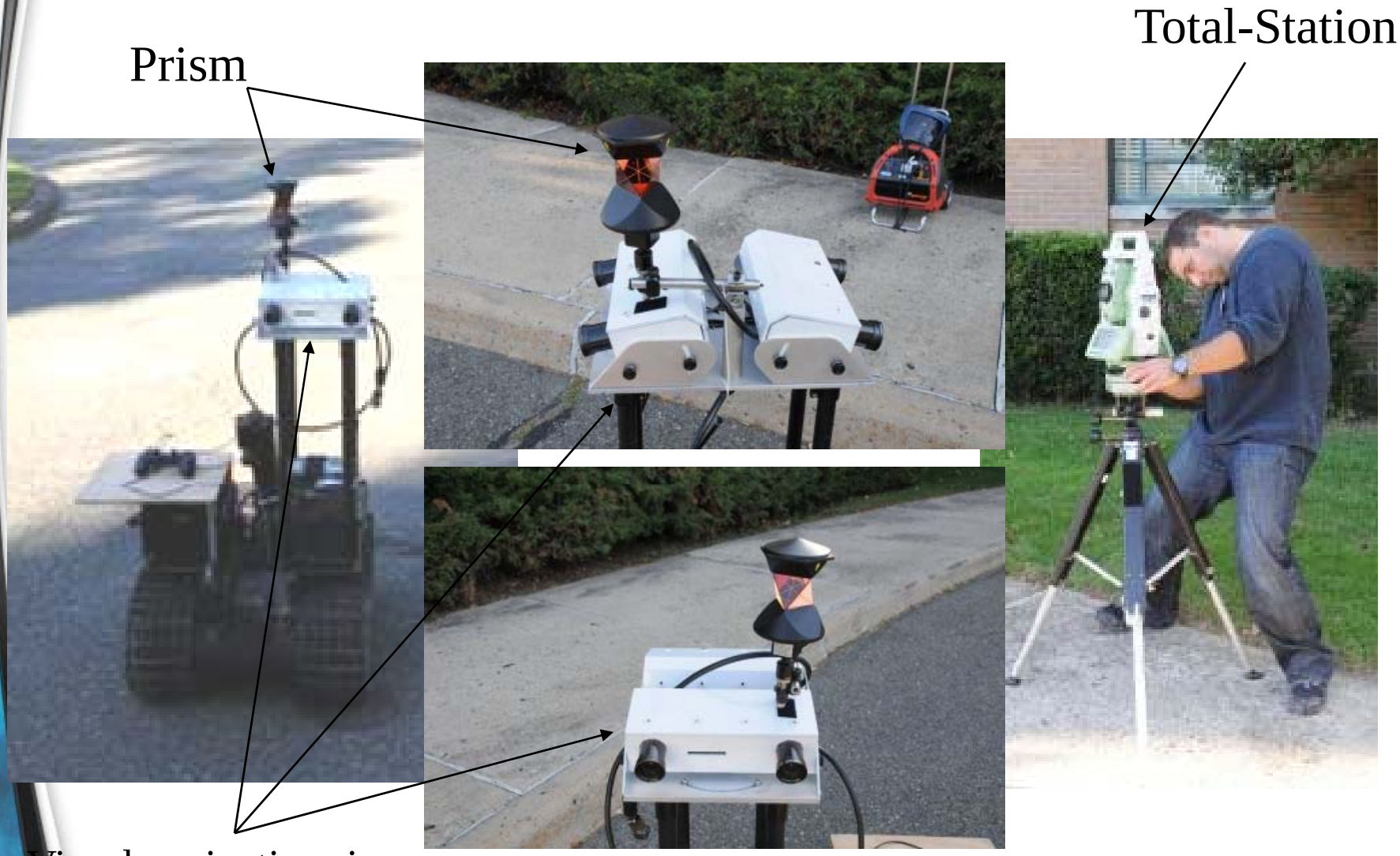
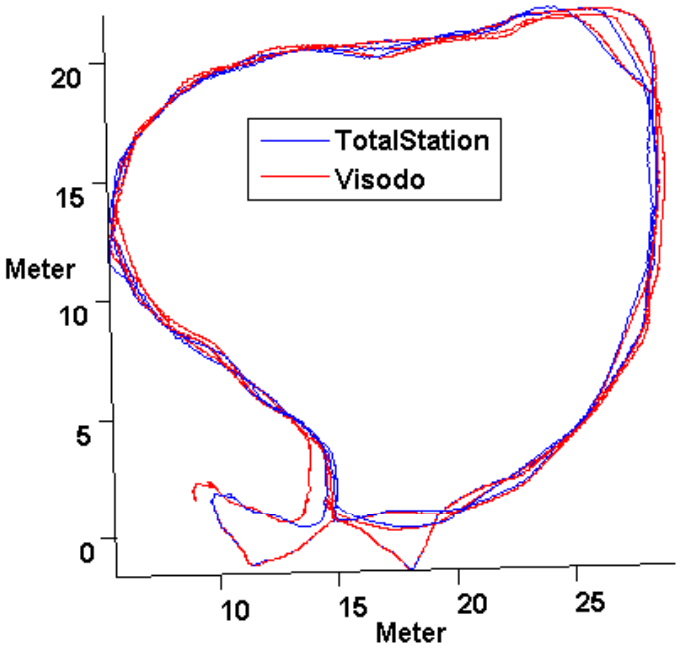
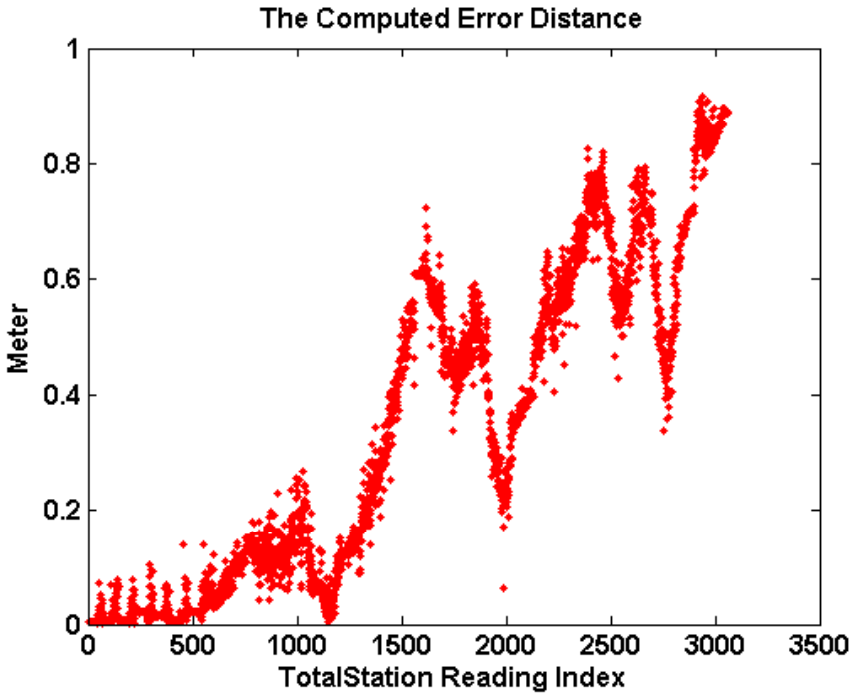
System Accuracy: Robot/Sensor Setup



System Accuracy: Sequence 2 Error for VisOdo only



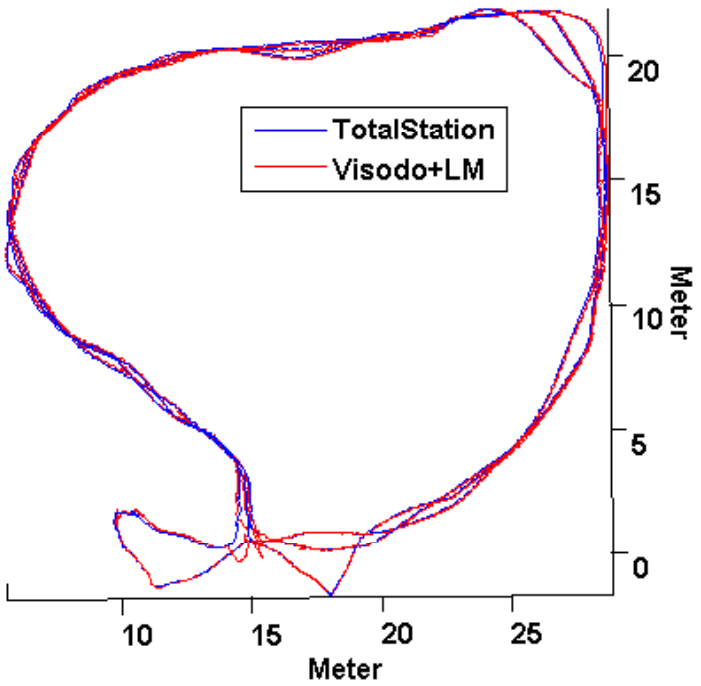


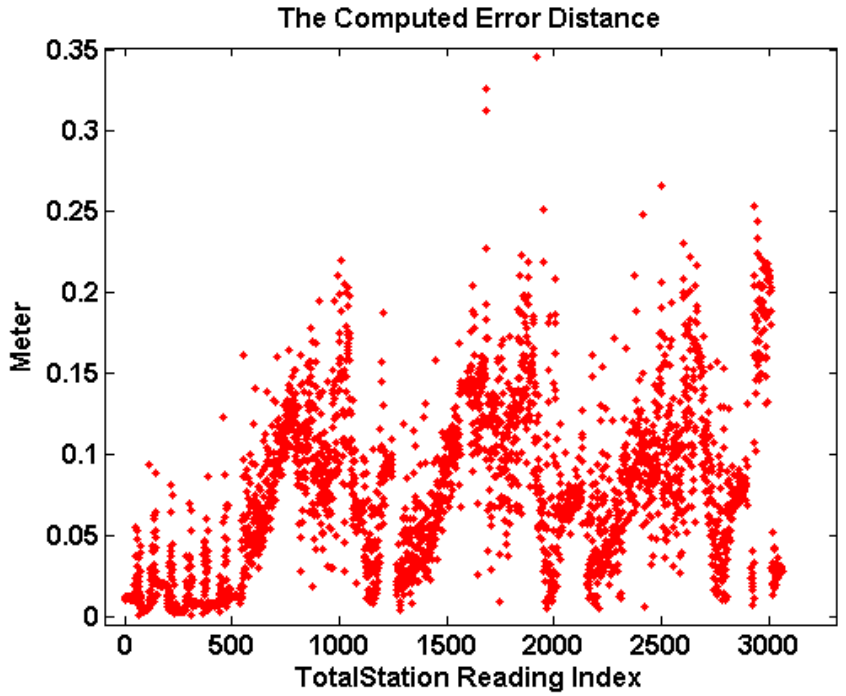
The trajectories after the alignment.

The Computed Errors (meter)

Distance Traveled	Min	Max	Median	Mean
266.62	0.000267	0.91672	0.32611	0.34266

System Accuracy: Sequence 2 Error for Visodo+LM





The trajectories after the alignment.

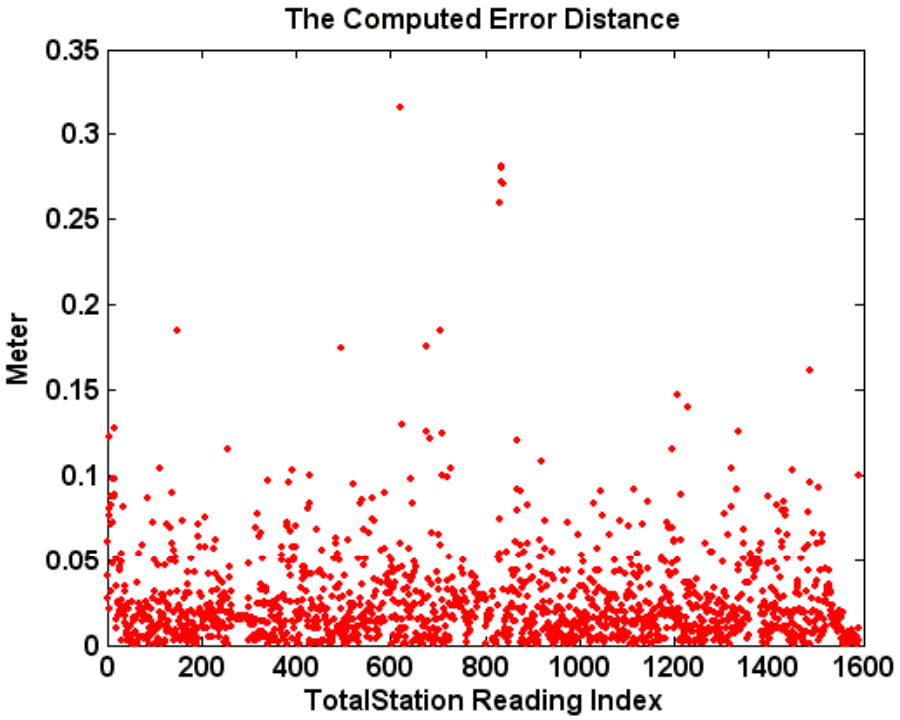
Note: Visodo+LM refers to visodo with online-built landmark database.

The Computed Errors (meter)

Distance Traveled	Min	Max	Median	Mean
266.62	0.00142	0.34655	0.07399	0.09577

System Accuracy: Sequence 2 Landmark Matching Accuracy

- There are landmark matches whenever there are common path segments during traversal.



The Computed Errors (meter)

Distance Traveled	Min	Max	Median	Mean
266.62	0.0002	0.3158	0.01716	0.0255

Lighting Change Evaluation: Reference Sequence Image Sample of Sequence One Dawn: 6:31am

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Lighting Change Evaluation:
Image Sample of Sequence Two Dawn: 6:53am

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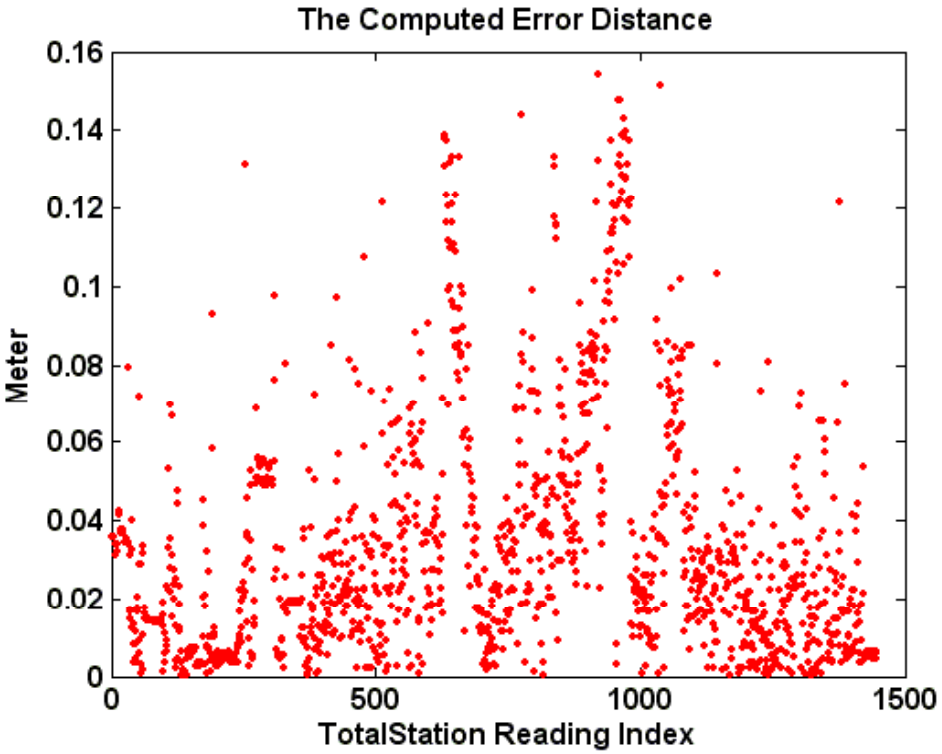
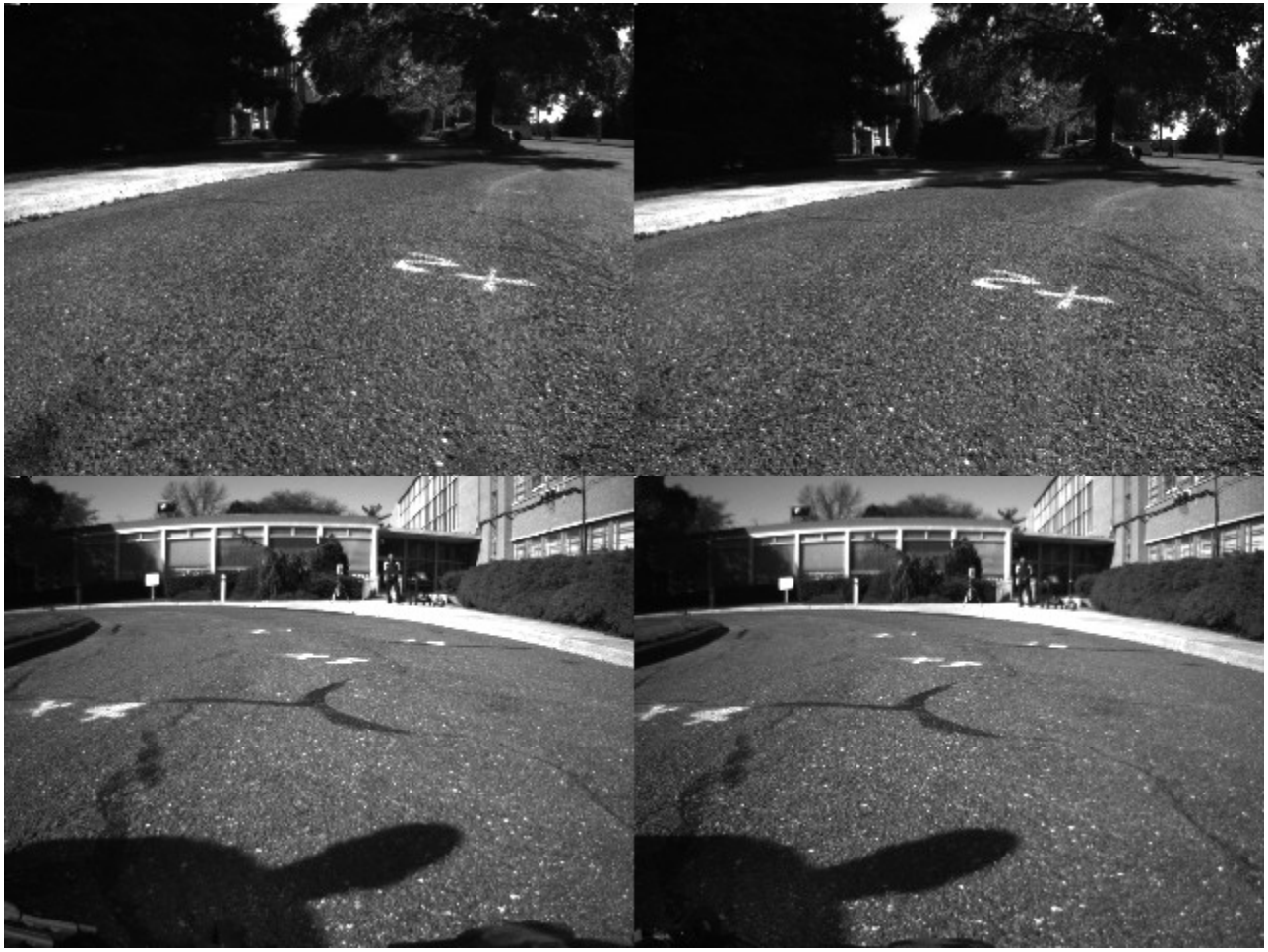
Lighting Change Evaluation: Sequence 2
Landmark Matching Accuracy



The Computed Errors (meter)

Distance Traveled	Min	Max	Median	Mean
122.39	0.000009	0.16794	0.02261	0.03092

Lighting Change Evaluation:
Image Sample of Sequence Three Noon:12:37pm



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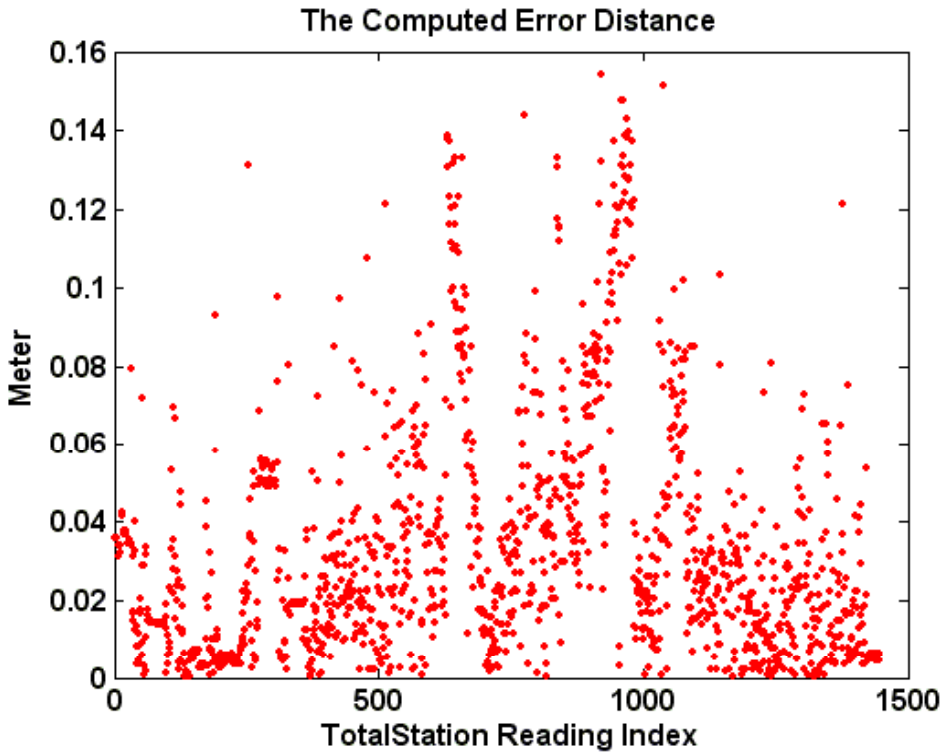
Lighting Change Evaluation: Landmark Matching Accuracy



The Computed Errors (meter)

Distance Traveled	Min	Max	Median	Mean
145.57	0.0006771	0.1542	0.0231	0.0333

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Lighting Change Evaluation:
Image Sample of Sequence Four Dusk: 4:56pm

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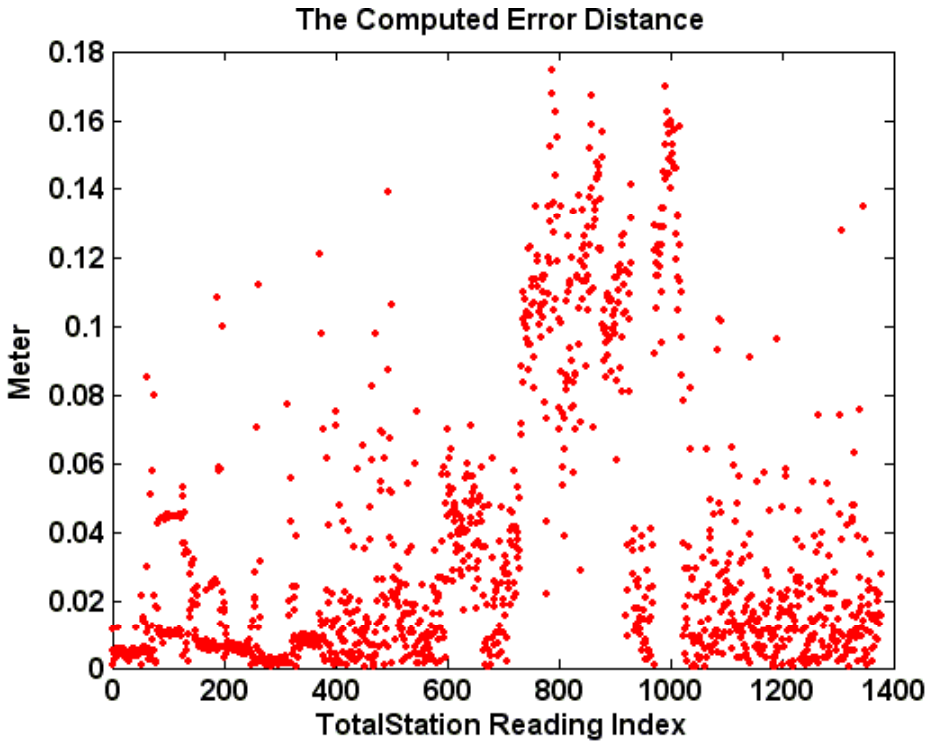
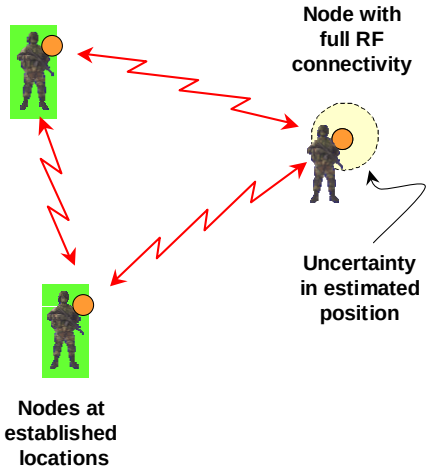
Lighting Change Evaluation: Landmark Matching Accuracy



The Computed Errors (meter)

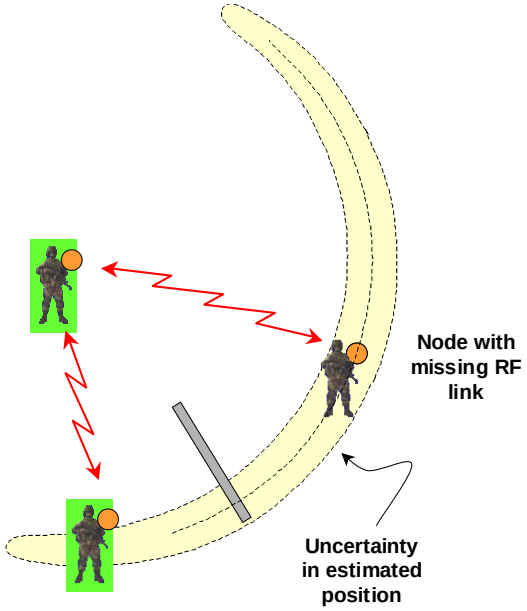
Distance Traveled	Min	Max	Median	Mean
144.73	0.0000523	0.17423	0.01691	0.03588

Visual Odometry and INS Enables Underconstrained RF Ranging



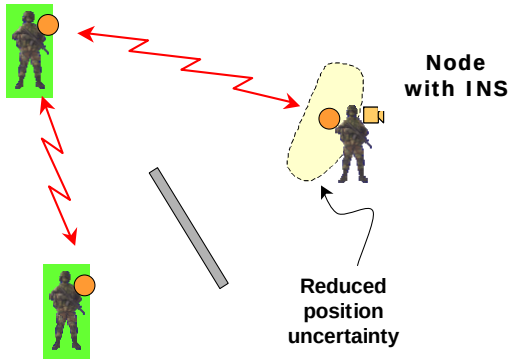
A) Fully connected RF

Mobile node location is established to high precision



B) RF with missing link

Position is uncertain along circumference of circle centered on the established link



C) RF + INS

RF provides constraint in radial direction, INS along the circumference

RF+INS also provides position reference for dynamically located fixed nodes

The Teamwork Effect

- The "Teamwork Effect" enables platforms operating in groups to achieve significantly better navigation accuracy than when operating individually
- Opportunistic Peer-to-Peer Ranging Constrains INS Drift
  - Range estimate between two platforms serves as a "Wireless Tether" between them and bounds their otherwise independent drifts
  - Using multiple inter-asset range estimates constrain INS drift further

- Teamwork Effect holds as team size varies
  - *Single pair to large groups*

$$\varepsilon(n,s) \propto \varepsilon(1,s)/\sqrt{n}$$

- i.e. Position accuracy improves by a factor √n for an n-node group

- General performance prediction guideline for distributed multimodal fusion

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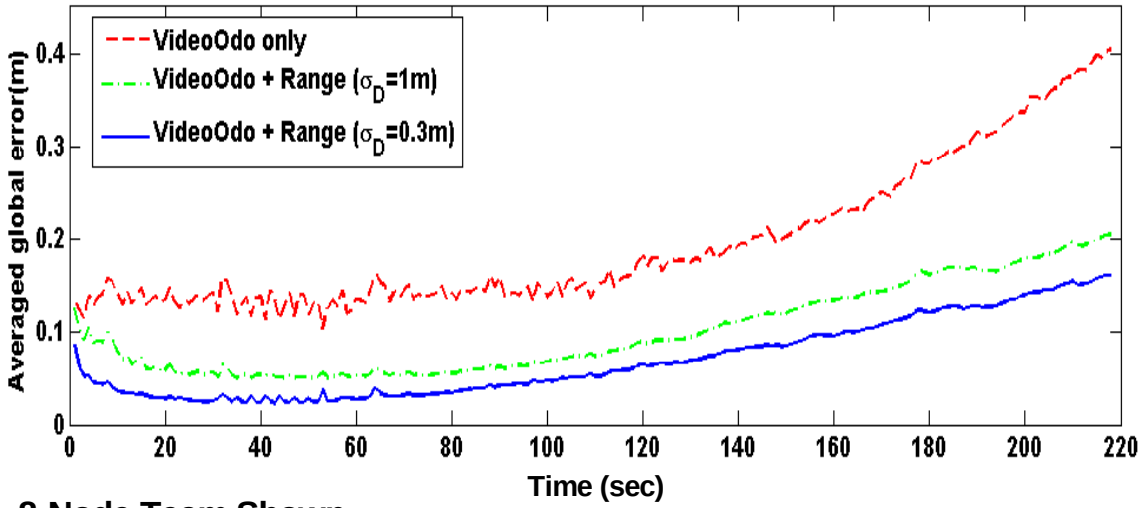
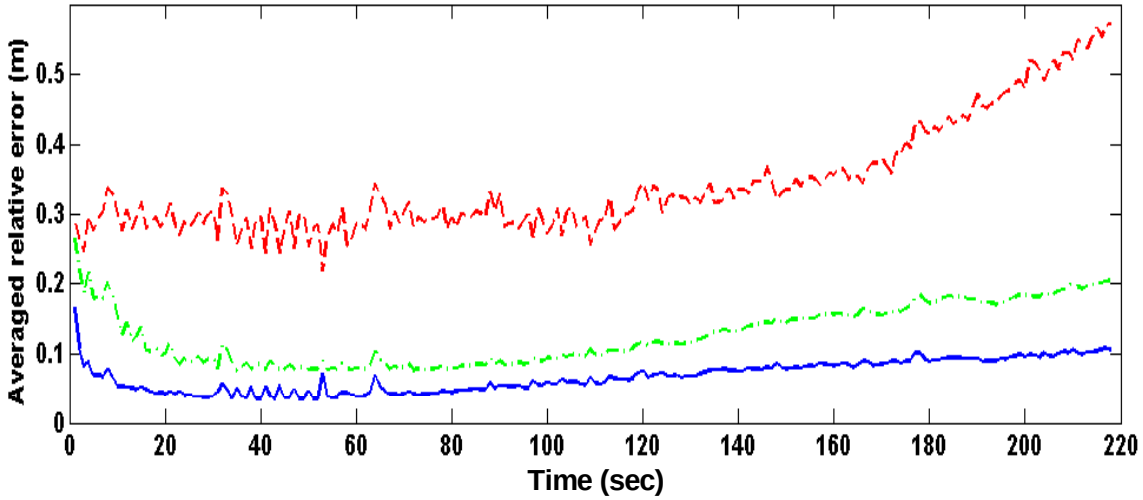
Simulation with RF-Ranging

Enhancement of Geolocation Accuracy using Distributed Navigation



8-Node Team Shown



The Anchor Effect

- Deployable Anchor Node
  - Reference beacon deployed at fixed location
  - Zero INS drift error: position estimate (and error) remains constant
  - Anchor point for mobile nodes whose position estimates degrade with time/distance
- Deployed opportunistically (pre- or during mission) as stationary wireless tethers and communication relay nodes
  - Self-calibration of deployed nodes based on best location estimate available at the time of deployment

- The use of even a single Deployable Anchor Node can increase system accuracy by a factor of 2 to 3
- The use of two Deployable Anchor Nodes can bound absolute system error to <1m SEP
- Contrast with classical Time Difference of Arrival (multilateration) and Time of Arrival (trilateration) approaches that require at least 4 constraining measurements

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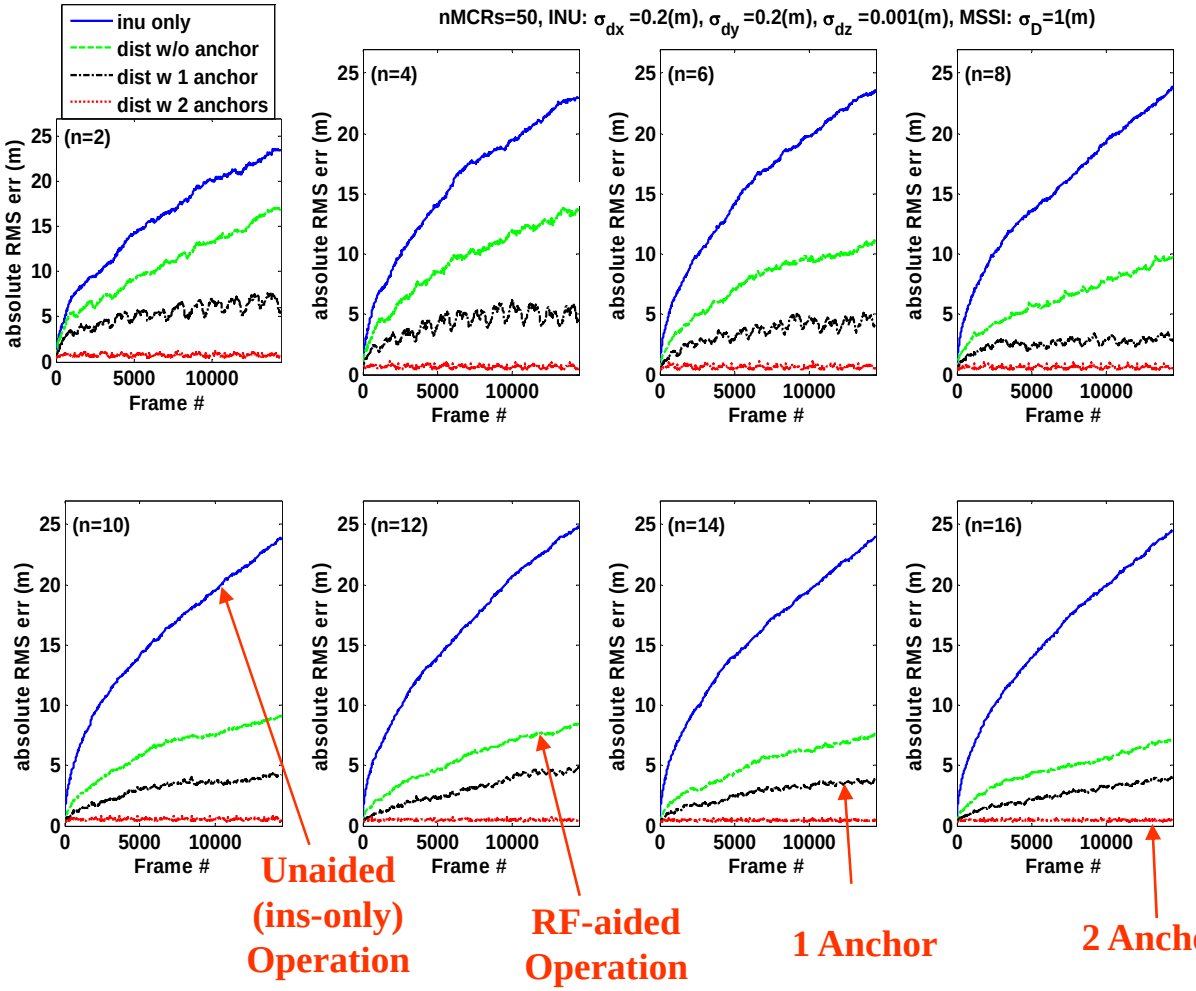
The Anchor Effect: Simulation Validation



Absolute Position Accuracy Shown

- 1 Anchor → 2-3X performance improvement
- 2 Anchors → Constant, low level error 1-2m SEP or less