Positioning and Navigation in GPS-challenged Environments: Cooperative Navigation Concept

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Cooperative navigation: outline

- Collaborative/cooperative navigation
  - Concept, needs and objectives
  - Navigation sensors used by network nodes (users)
  - Inter-nodal range measurement methods
- Preliminary performance evaluation
  - Simulation scenario
  - Individual navigation results
  - Collaborative navigation results
- Centralized vs. decentralized integration methods
- Collaborative/cooperative navigation: challenges

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Proliferation of wireless technologies, mobile computing devices and mobile Internet has fostered a new growing interest in *location-aware systems and services*

- ✓ Autonomous navigation of remote sensing platforms
  - ❖ Unmanned Aerial Vehicles (UAVs)
  - ❖ Unmanned Land-Based and Underwater vehicles
- ✓ Personal/pedestrian navigation (PN)
- ✓ Asset location and tracking
- ✓ Intelligent Transportation Systems (ITS)
- ✓ Location Based Services (LBS)
- ✓ Etc.

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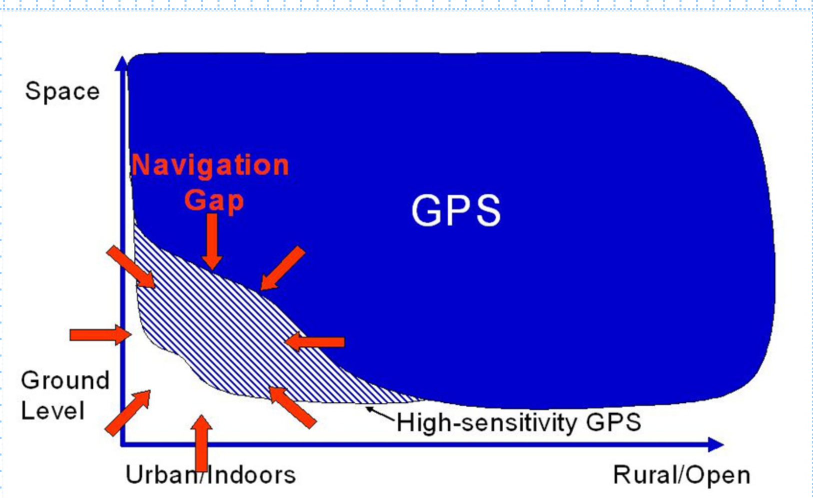
Need for GPS augmentation



Courtesy: John Raquet, AFIT

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Collaborative navigation: background

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- In GPS-challenged and indoor environments, where loss of lock due to interference, jamming, strong multipath or direct line-of-sight blockage, stand alone GPS will not provide reliable and continuous navigation solution
- Sensor augmentation (IMU/INS, magnetometer, barometer, Artificial Intelligence methods, image-based augmentation, etc.) has been used to support a single user navigation task
  - Accuracy limitations (dead reckoning navigation)
- **Recent trend**: cooperative/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
  - All users are time synchronized
  - **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 solution

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Collaborative navigation: concept

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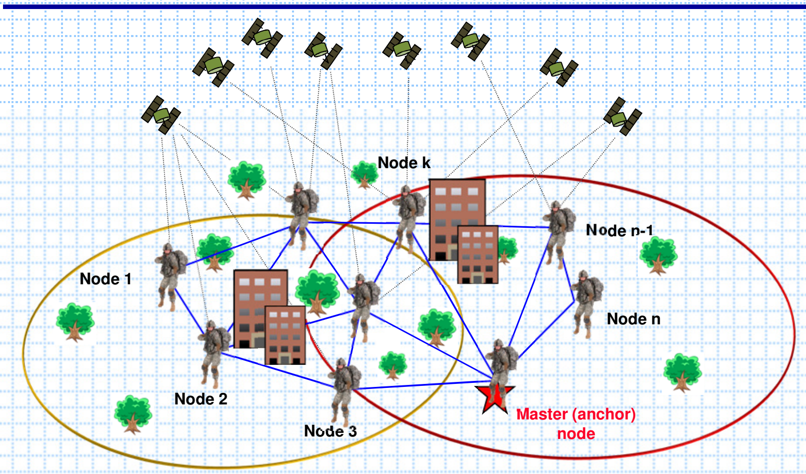

Example network: dismounted soldiers, emergency crew, formation of robots or UAVs collecting intelligence, disaster or environmental information, etc.

Primary objective: sustain sufficient level of collaborative navigation accuracy in GPS-denied environments

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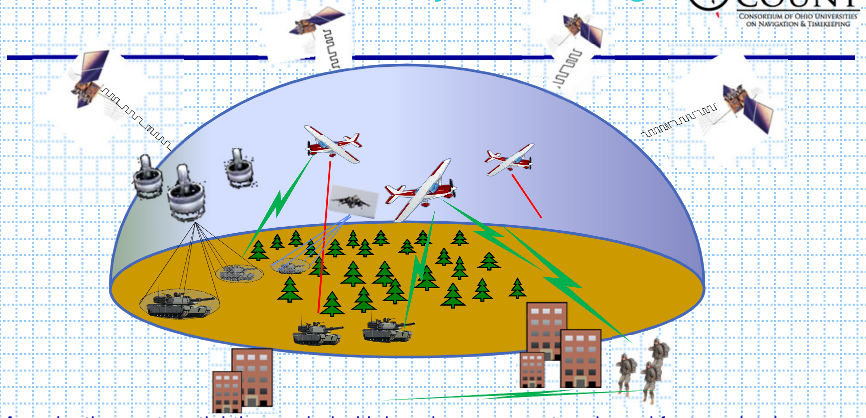
Collaborative navigation, layered sensing



- A navigation system tightly coupled with imaging sensors, terrain and feature databases, and networked with other sensing platforms
  - ***Layered multi-platform sensing systems*** or the ***system of systems***
- **Objective**: maintain the required navigation performance for a network of sensing systems (e.g. multi-platform geolocation, multi-platform image mosaics, etc.) when GPS is degraded or not available
  - Suitable for land-based (including ground personnel) and airborne platforms
  - Seamless transition between different environments
  - Seamless transition between various sensors and platforms = plug-and-play concept

Collaborative navigation: sensors

	Technique/sensor	Navigation information	Typical accuracy	Selected characteristics
Radio frequency (RF)	GPS/GNSS	X,Y, Z Vx Vy, Vz	~10 m (1-3 m DGPS) ~0.05 m/s , ~0.2 m/s	Line-of-sight system Results in a global reference system
Radio frequency (RF)	Pseudolites	X,Y, Z Vx,Vy, Vz	Comparable to GPS	Line-of-sight system Operate at GPS and non-GPS frequencies
Radio frequency (RF)	WLAN	X,Y,Z	2-6 m (strength method) 1-3 m (Fingerprinting method)	Penetration through walls, signal attenuation due to distance, multipath interference from other 2.4GHz band
Radio frequency (RF)	UWB	X,Y,Z	dm at 10-20 m range (theoretically)	Resistant to multipath fading, strong signal penetration, possible interference with GPS
IMU	Accelerometer	a_{tan}, a_{rad}, a_z	<0.03 m/s^2	Subject to drifts
IMU	Gyroscope	Heading φ	0.5° - 3°	Short term accuracy stability, subject to drifts
Optical Sys.	Image based	X, Y, Z	few meters	Line-of-sight system, network approach is geometry-dependent
Optical Sys.	Optical sensor network	X, Y (Z)	few meters	Image overlap required for 3D
Optical Sys.	Laser	X, Y, Z	cm to dm	Local or global reference system
Others	Digital compass /magnetometer	Heading	0.5° - 3°	Long term accuracy stability, subject to magnetic disturbances, sensitive to tilt
Others	Digital barometer	Z	1-3 m	Requires calibration by a given initial height

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Collaborative navigation: typical sources of range and angular measurements

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Type	Method	Typical accuracy	Comment
Range Measurement	RF Signal/ RFID/ WLAN/ WiFi	meter level	Based on the signal strength or TOA (time of arrival). Relatively poor accuracy
	UWB	submeter at 100 m range (ideal)	RTOA (round trip TOA) is more practical than TOA. Potential for short- to medium range localization. Robust and accurate
	Terrestrial Laser	mm~cm level	High accuracy, Navigation grade (compact (1.2kg) and short range (~30m)) , Survey grade (long range ~800m), Wide scan angle (80~360 deg)
	Ultrasound	cm level	Short range (3m~ a few 10s of meters)
	LADAR	mm~cm level	Compact (~10cm), High data rate (30~3 fps) , Short range (3~30m), Relatively small FOV (Field Of View): ~43deg
Angle measurement	RF signal, directional or multiple antennas	~degree	Relative orientations can be determined through angle of arrival (AOA) estimation
	Laser	sub degree	Transformation between subsequent imagery provides change in orientation and location
	camera, LADAR	~degree	Transformation between subsequent imagery provides change in orientation and location

RF – radio frequency
WLAN – wireless local area system
UWB –ultra-wide band

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Preliminary test results

based on OSU SPIN Lab implementation

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Performance evaluation: simulation scenario

- A team of five 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 (platforms)
- GPS position solution in navigation frame: 1Hz sampling rate, accuracy of 1.0 m/coordinate (1σ)
- Repeated GPS gaps
- Inter-nodal range measurements: available at 1Hz sampling rate with accuracy of 0.10 m (1σ)
- ***Centralized and decentralized integration*** modes were used
- Inter-nodal ranges: ~7 to ~ 70 m
- Multiple scenarios tested; examples shown next

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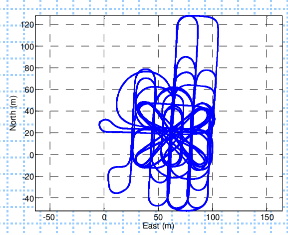
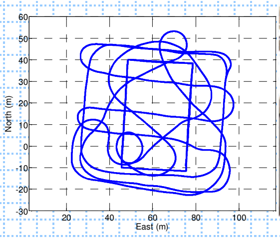
Field test deployment

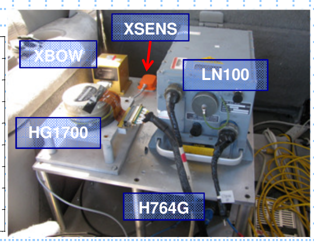
- Five-node network
  - A1, A2, A3: GPS, navigation-grade and tactical-grade IMUs
  - B1: GPS, navigation-grade and consumer-grade IMUs
  - C1: navigation-grade and consumer-grade IMUs



Reference trajectory of B1



Reference trajectory of C1



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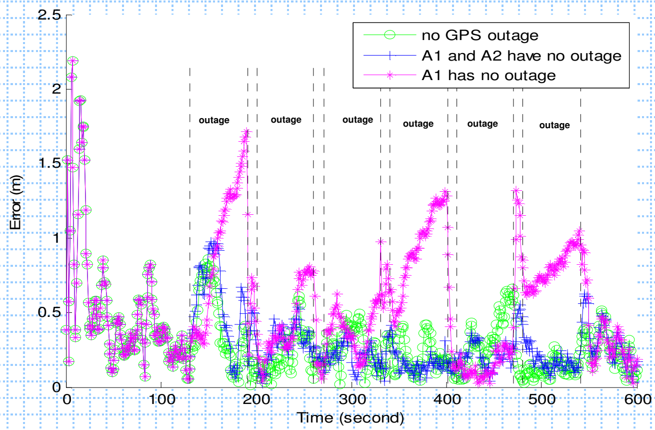
Performance evaluation: collaborative navigation tight integration of inter-nodal ranges (1/3)

- 600 seconds of simulated test data
  - Repeated 60-sec GPS gaps
  - Inter-nodal ranges < 20m
  - IMU errors estimated based on inter-nodal ranges during GPS gaps
  - Anchor nodes assumed (GPS signals always available)
- C1 node: consumer grade IMU
  - Ranging to A1, A2, A3
  - **In inertial-only mode**: error of ~250 km (2D) in the end of the test
- B1 node: consumer grade IMU and GPS (600-sec gap assumed)
  - Ranging to A1, A2, A3
  - **In inertial-only mode**: max error of ~10 m (2D)

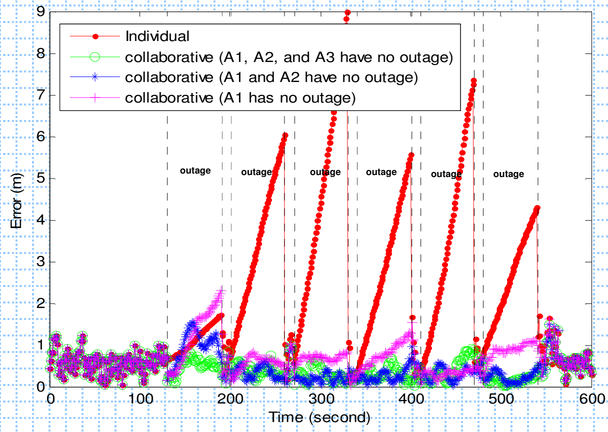
Performance evaluation: collaborative navigation tight integration of inter-nodal ranges (2/3)



Scenario	Min. [m]	Max. [m]	Mean [m]	Std. [m]
No GPS outage	0.011	0.860	0.250	0.170
Outage on A3	0.028	0.976	0.272	0.184
Outage on A2 and A3	0.022	1.715	0.526	0.378

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

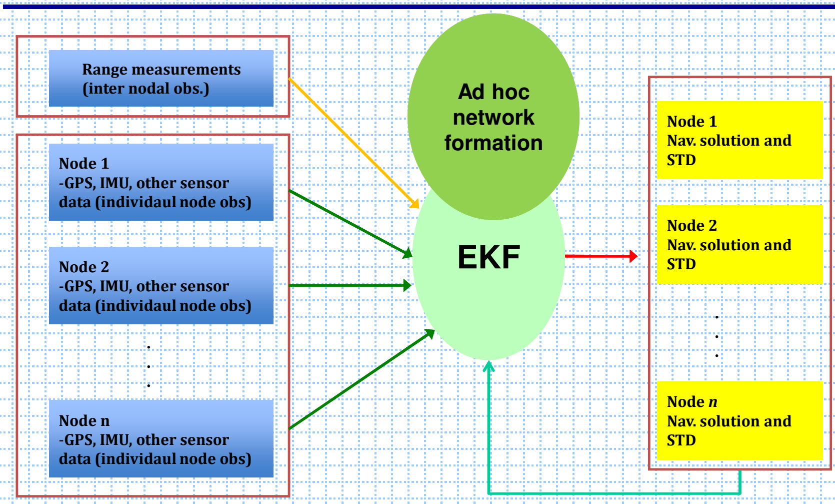
Performance evaluation: collaborative navigation tight integration of inter-nodal ranges (3/3)



Scenario	Min. [m]	Max. [m]	Mean [m]	Std. [m]
No GPS outage	0.01	1.48	0.42	0.26
Outage on A3	0.02	1.55	0.45	0.32
Outage on A2 and A3	0.03	2.29	0.68	0.38

Statistics of collaborative navigation solution for B1 (131-600 second)

Collaborative navigation: Centralized EKF



Some nodes need AJ protection to assure support for other nodes: (1) local AJ protection or create distributed aperture? (2) how many nodes should have AJ protection? (3) how many nodes and at what separation are needed to create distributed aperture? (4) master node needed to form distributed aperture

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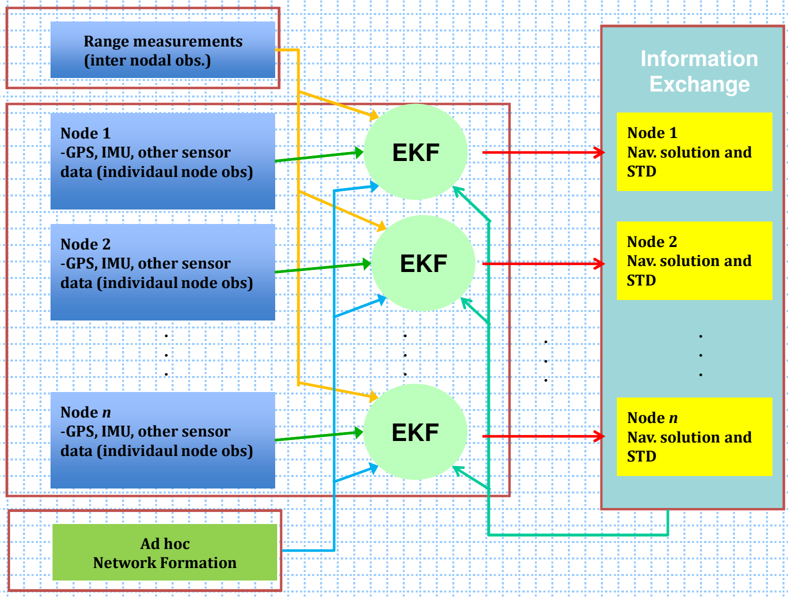
Collaborative navigation: Decentralized EKF



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Collaborative navigation: challenges

- Master nodes or some nodes will need anti-jamming (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 signal 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

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Collaborative navigation: challenges

- Formulating optimal methodology to integrate sensory data for various nodes to obtain a combined 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 applications

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