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UNMANNED SYSTEMS WEEK

WELCOME TO
GNSS/INERTIAL+ INTEGRATION FOR UNMANNED SYSTEMS

Wednesday, June 4, 2014

11 am–12:30 PDT
Noon–1:30 pm Mountain
1 pm–2:30 pm Central
2 pm–3:30 pm Eastern

Audio is available via landline or VoIP—For VoIP: You will be connected to audio using your computer's speakers or headset. **For Landline:** Please select Use Audio Mode Use Telephone after joining the Webinar. **US/Canada attendees** +1 (480) 297-0022, Access 805-720-632

WELCOME TO
GNSS/Inertial+ Integration for Unmanned Systems

Maarten Uijt de Haag
Cheng Professor
Ohio University

Andrey Soloviev
Principal
QuNav

Sandy Kennedy
Director of Core Cards
NovAtel Inc

Co-Moderator: Lori Dearman, Sr. Webinar Producer

Who's In the Audience?

A diverse audience registered from 42 countries, 28 states and provinces representing the following industries:

21% GNSS Equipment Manufacturer

17% Professional User

17% System Integrator

17% Product/Application Designer

28% Other

Welcome from *Inside GNSS*

Richard Fischer
Director of Business Development
Inside GNSS

GNSS/Inertial+ Integration for Unmanned Systems

Mark Petovello
Geomatics Engineering
University of Calgary
Contributing Editor
Inside GNSS

Poll #1

What kind of environment are you most interested in operating your unmanned system in? (select top two)

- *Open Sky*
- *Indoor*
- *Underwater*
- *Urban*
- *Under foliage*

Overview of June 2

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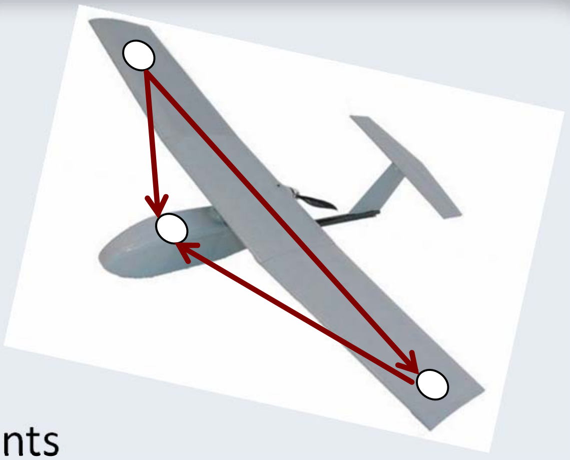
- Overview of unmanned systems
  - Applications
  - Appropriate metrics
- Positioning requirements
  - Key challenges/issues of GNSS in different environments
  - Role of multi-GNSS systems
  - Importance of having a reliable system
- GNSS accuracy requirements
  - Standalone & differential processing
  - Attitude systems
- Application to aerial and marine systems



What to expect today…

- Role of integrated systems in unmanned applications
- GNSS + inertial + other sensors/systems
  - Role & benefit of various sensors
- Integration approaches
  - Limitations of GNSS/INS and how to include other sensors
- Product development
  - How do you actually go about selecting components and building a system

GNSS/Inertial+ Integration

Maarten Uijt de Haag
Cheng Professor, *Ohio University*

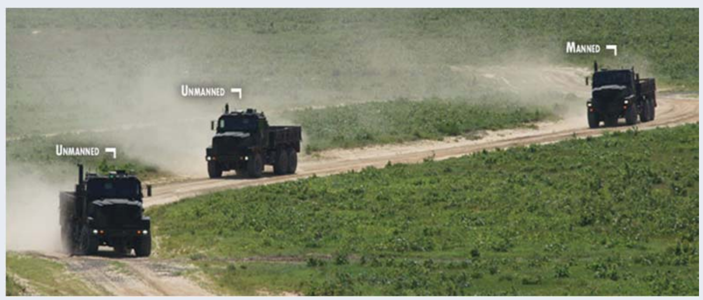
GNSS/Inertial+

- GNSS in unmanned vehicles summary
- Presence of additional sensor for other unmanned vehicle platform functions
- Operational requirements with respect to the required navigation performance based on GNSS
- Why GNSS inertial integration?
- GNSS/Inertial+

GNSS in Unmanned Vehicles

- Many commercial platforms rely on GNSS for various purposes:
  - Navigation
  - Surveillance
  - Conflict detection and resolution
  - Geo-referencing
  - Time-keeping/synchronization
  - Etc.

Courtesy of Amazon



Courtesy of Oshkosh Defense

Courtesy of OrbitGIS

Geo-referenced LIDAR map of OU football stadium

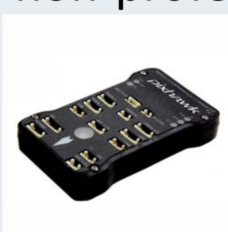
GNSS in Unmanned Vehicles

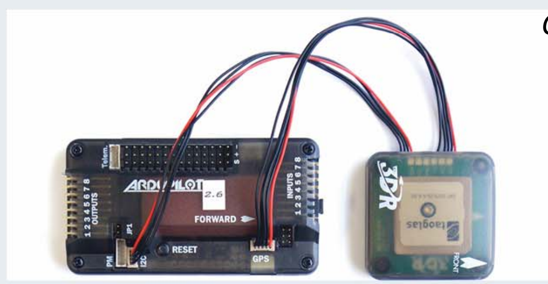
LOA	Computer	Human
1	Offers no assistance	Does all
2	Suggests alternative	Chooses
3	Selects way to do task	Schedules function
4	Selects and executes	Consents
5	Executes unless vetoed	Has possibility to veto
6	Executes immediately	Is informed upon execution
7	Executes immediately	If informed if asked
8	Executes immediately	Is ignored by computer

Levels of Automation, LOA (Sheridan, 2002)

Courtesy of 3DR robotics

- Low-cost GNSS has enabled the execution of automatic UAV/UGV flight plans for even the non-professional user.





Typical Additional Sensors

- Most unmanned vehicles already include an **inertial sensor** (e.g. an inertial measurement unit or IMU) to support the vehicle controller;
- Additional sensors are used for environment mapping, surveillance, conflict detection and avoidance.

Google car

3D maps, obstacles and traffic:
- Velodyne laser scanner

Fast traffic:
- Four radars (front and rear bumper)

Traffic lights:
- Camera (near the rear-view mirror),

Navigation/motion:
- GPS, Inertial measurement unit (IMU), Wheel encoder

Operational Environments

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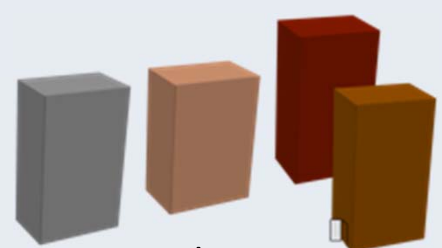
Environment	Ground vehicles	Aerial vehicles	GNSS
National airspace		X	Available
Rural, open-sky	X	X	Available
Rural, foliage	X	X	Challenged
Suburban	X	X	Available
Urban	X	X	Challenged
Indoor*	X	X	Not available/very low signal strength

Important note: where GNSS is normally available, service could possibly be denied by interference (intentionally or unintentionally) or, worse, spoofed.

*includes structured environments such as buildings and unstructured environments such as mines and caves



Urban

Operational Environments

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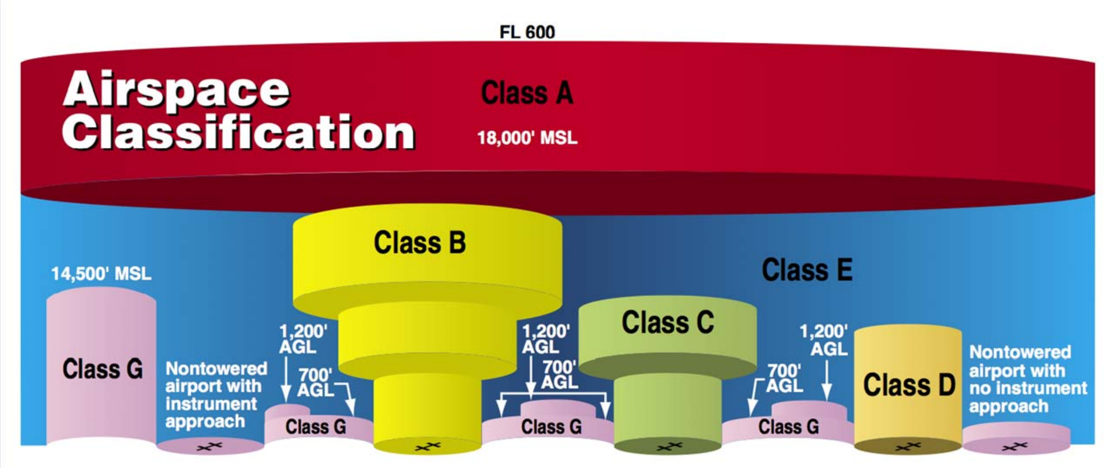
Environment	Ground vehicles	Aerial vehicles	GNSS
National airspace		X	Available



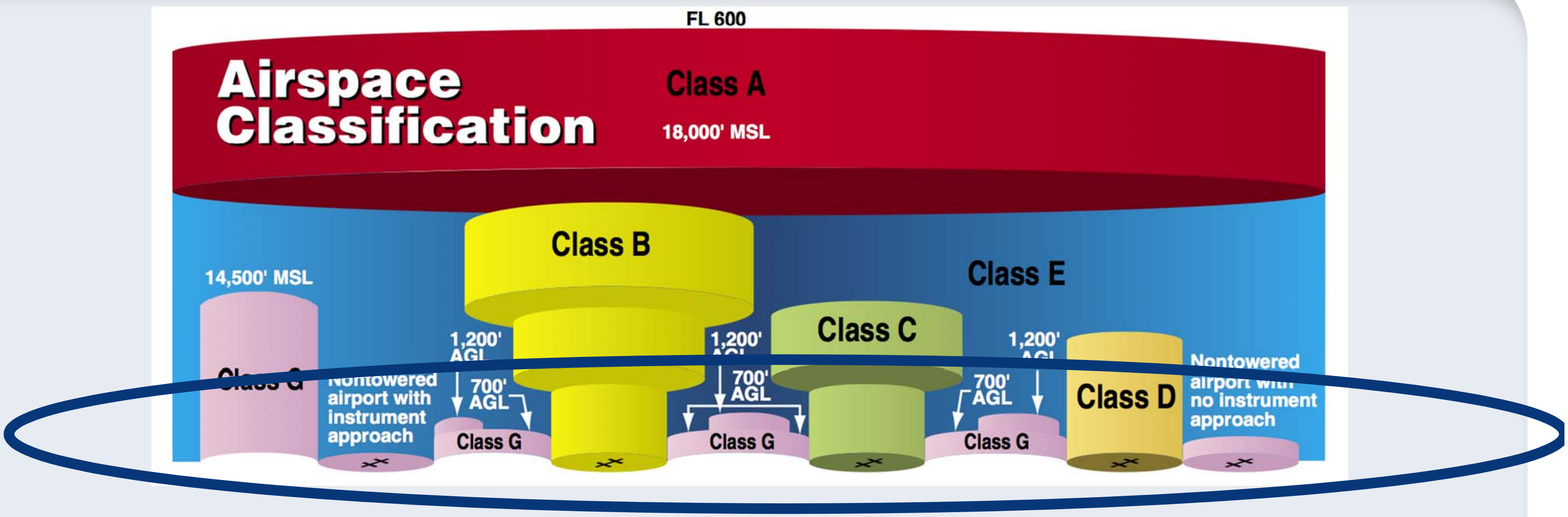
From FAA:

- Model aircraft below 400ft, away from populated areas and full scale aircraft, not for business purposes.
- Scan Eagle and Aerovironment's Puma have been certified for commercial use (only authorized to fly in the Arctic)
- Public entities (federal, state and local governments and public universities) may apply for a Certificate of Waiver or Authorization (COA)

But also:

- An NTSB judge dismissed the $10,000 fine the FAA levied against UAV operator …

Lower Altitude and Ground Operation



Many operations are envisioned that require (semi-)autonomous operation at low altitudes over or even in populated areas (urban/suburban)

Environment	Aerial vehicles	GNSS
Rural, open-sky	X	Available, vulnerable
Rural, foliage	X	Challenged
Suburban	X	Available, vulnerable
Urban	X	Challenged
Indoor	X	Not available/low signal strength/multipath

Why GPS/Inertial Integration?

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Objective of a navigation system is to provide an accurate Position, Velocity, Attitude, and Time (PVAT) expressed in the coordinates of some geometric reference: ***Position, Velocity, Attitude, Time***

↓

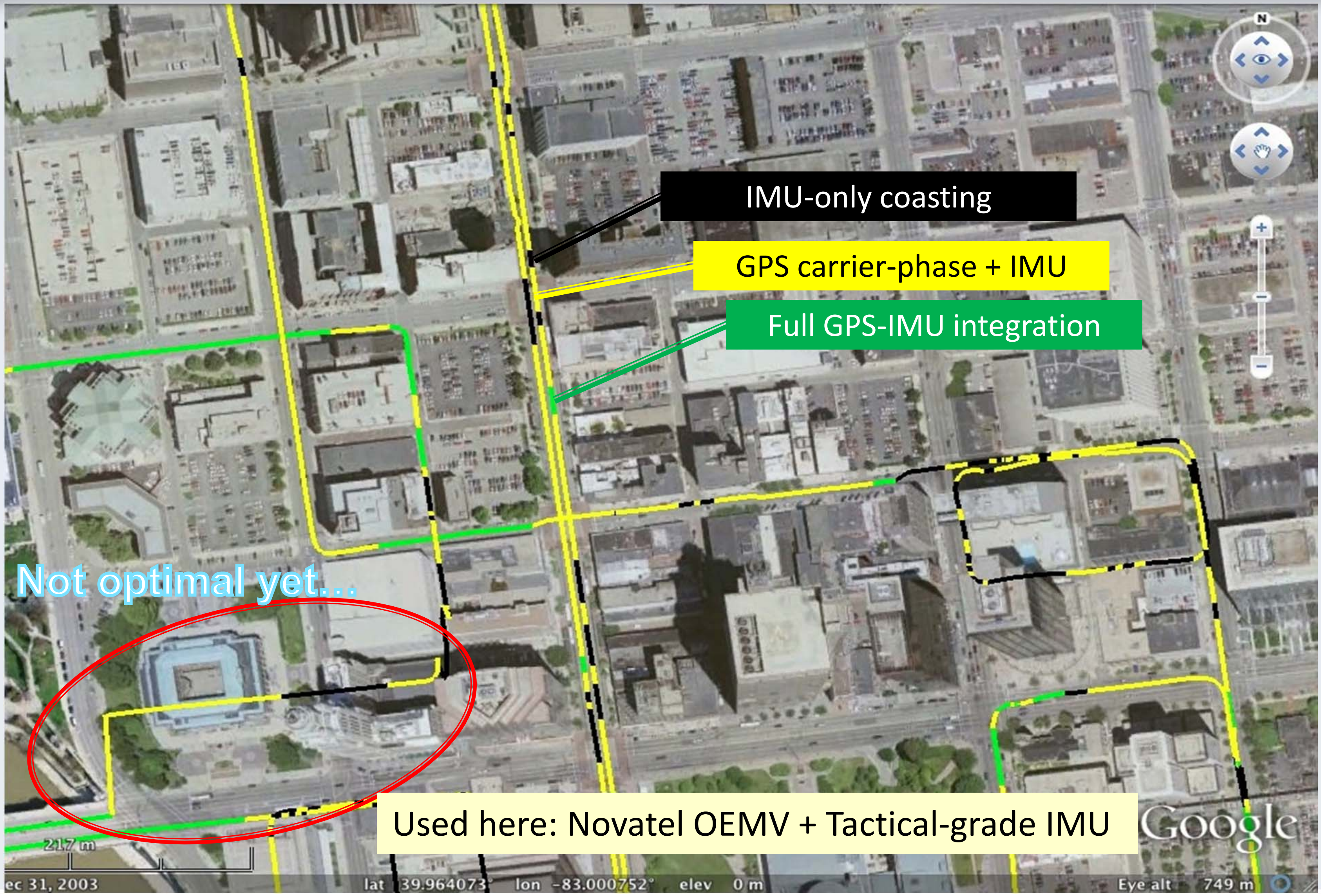
Required Navigation Performance:
Accuracy, ***Integrity, Availability, Continuity, etc.***

↓

Integrated Navigation
Combine (integrate or fuse) data from multiple sensors (or navigation aids) in such a way that the Required Navigation Performance of the intended operation can be met.

But also robust surveillance, collision avoidance, path planning, control, communication, etc.

Unmanned Ground Vehicle: Urban Operation



Further Limitations

Outdoor with and without foliage

Transition to indoor

"Structured" indoor with multiple path options

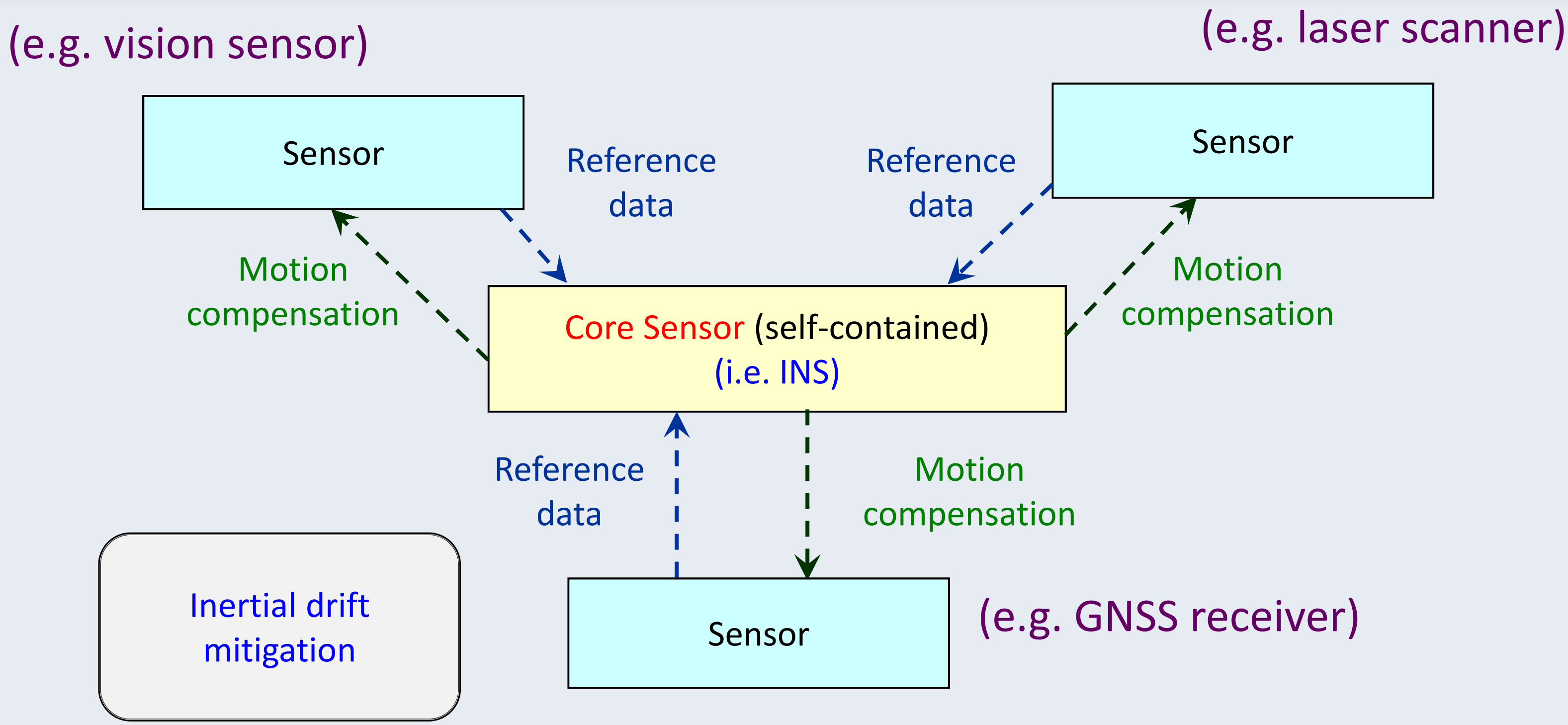
Transition to indoor

Exploit Additional Sensors

General classification	Sensor/Sensor System
Tactile sensors (detection of physical contact or closeness)	Contact switches, bumpers, optical barriers, non-contact proximity sensors
Wheel/motor sensors (wheel/motor speed and position)	Brush encoders, potentiometers, synchros, resolvers optical encoders, magnetic encoders, inductive encoders, capacitive encoders
Orientation sensors (orientation of the robot in a fixed reference frame)	Compass/magnetometers, **gyroscopes**, inclinometers
Acceleration sensors	**Accelerometers**
Beacons (localization in a fixed reference frame)	**GNSS**, active optical or RF beacons, active ultrasonic beacons, reflective beacons
Active Ranging (reflectivity, time-of-flight, geometric triangulation)	Reflectivity sensors, ultrasonic sensors, **laser rangefinders** (1D, 2D and 3D), optical triangulation (1D), structured light (2D)
Motion/speed sensors (speed relative to fixed or moving objects)	Doppler radar, Doppler sound
Visual sensors (visual ranging, object recognition, feature extraction, segmentation, etc.)	**CCD/CMOS cameras**, Visual ranging packages, Object tracking packages

Based on: R. Siegwart et al, Introduction to Autonomous Robotics, Second Edition.

Basic Integration Architecture



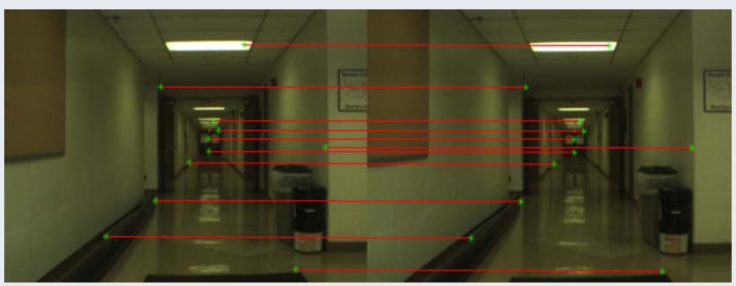
- Integrated navigation to satisfy the RNP requirements
- In addition:
  - Secondary sensors can be used for their original primary function such as 3D mapping, collision avoidance, precision agriculture, etc.
  - And exploit the robust (and in case GNSS is present absolute and accurate) position, velocity and timing solution.

GNSS/Inertial+ Example 1

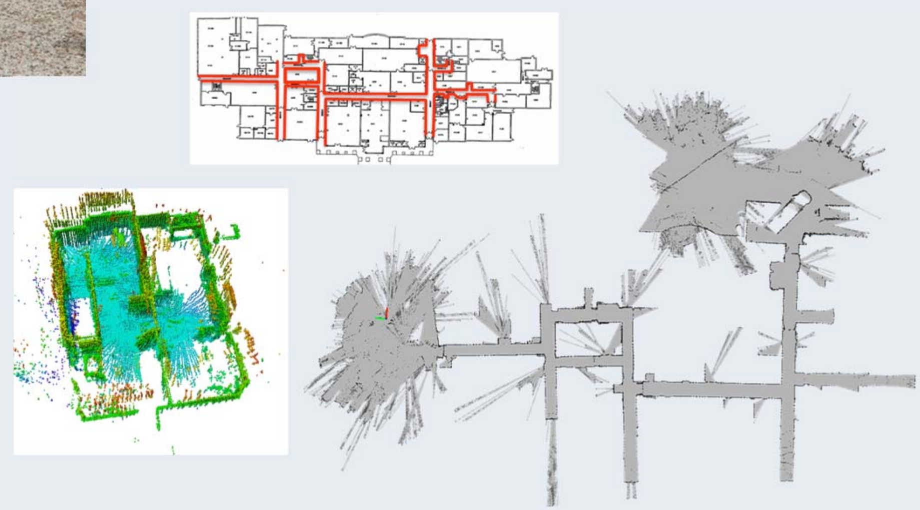
OU 3DR Hexacopter

Payload:

- NovAtel OEMSTAR
- NovAtel L1 antenna
- Hokuyo laser scanner (3)
- Firefly MV camera
- Xsens IMU
- Atom onboard processing unit running Ubuntu and ROS
- APM 2.5 Ardupilot



Vision-based navigation

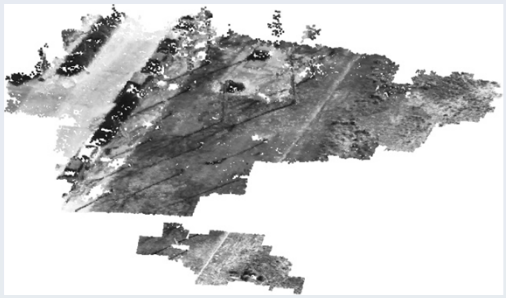


6DOF SLAM

GNSS/Inertial+ Example 2


CTAE/ASCAMM ICARUS Quadcopter


Mapping mission


3D Structure-from-motion results


3D Structure-from-motion results

Collaboration between Ohio University and CTAE/ASCAMM Barcelona, Spain

GNSS/Inertial+ Integration

Andrey Soloviev
Principal, *QuNav*

GNSS/INS Integration

- Main integration approaches:
  - ***Loose integration***: solution-level data fusion;
  - ***Tight integration***: measurement-level data fusion;
  - ***Deep integration***: data fusion at the level of signal processing
- Main benefits
  - PNT availability (bridging over GNSS outages);
  - Redundant information to reject “bad” measurements (including potential protection against spoofing);
  - Improved robustness of signal processing (weak signals, jamming)

Benefits of GNSS/Inertial Integration

- Example: navigation under dense canopy

GPS-only solution

Very sparse position fixes are obtained

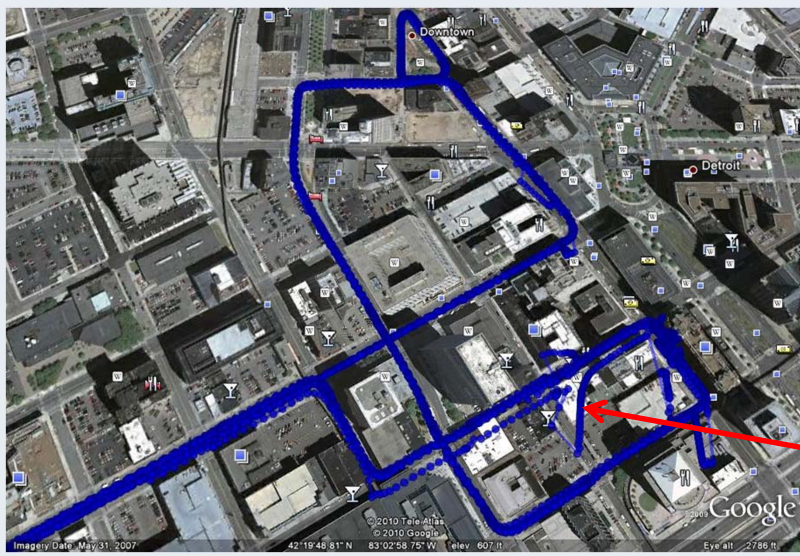
Deep GPS/Inertial Integration

Reliable trajectory reconstruction is maintained

Limitations of GNSS/Inertial

- GNSS/INS integration improves the solution availability, however, performance can be still limited (especially, when integrating with lower-cost IMUs);

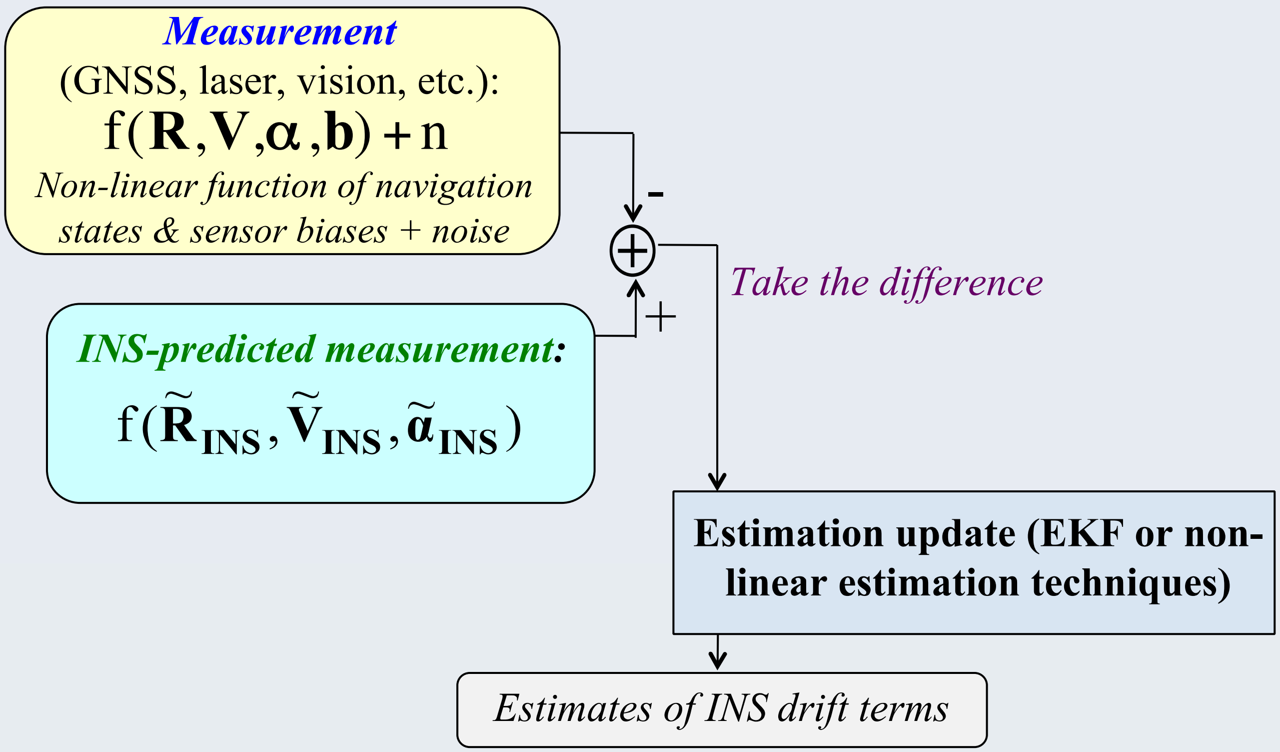
- Example: navigation in dense urban areas



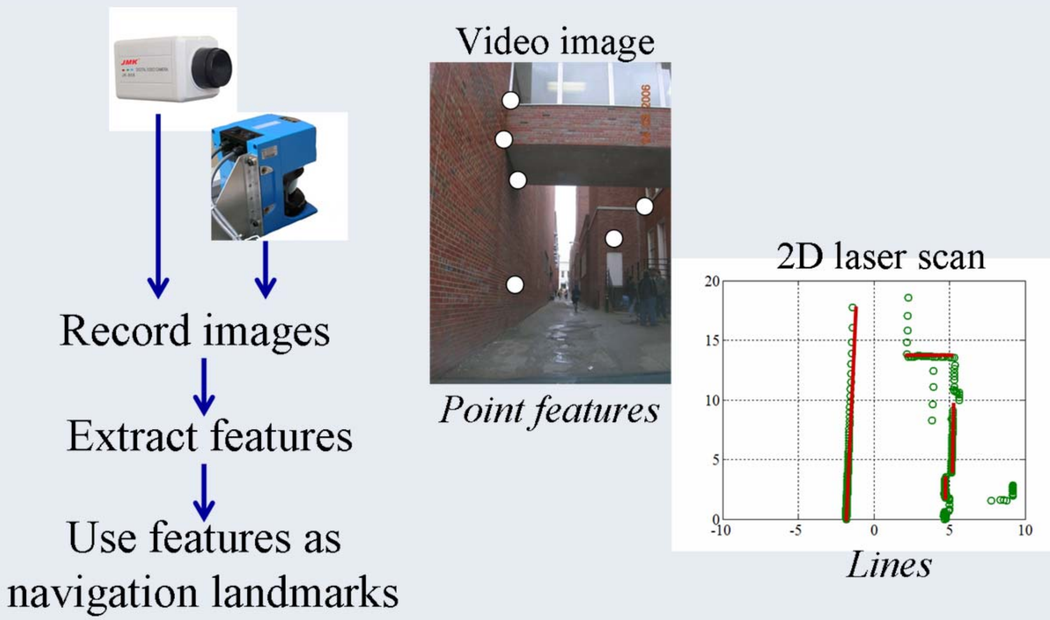
Solution discontinuities

Beyond GNSS/Inertial: GNSS/INS+

- Generic integration approach
  - INS is a core sensor;
  - Other sensors provide aiding data for the inertial drift mitigation



- *Motivation*: Image-based approaches efficiently complement the GNSS navigation
- *GNSS-denied scenarios*: **Natural or man made *obstacles attenuate satellite signals***
- *Image-based approach*: ***Obstacles* are used to *navigate***



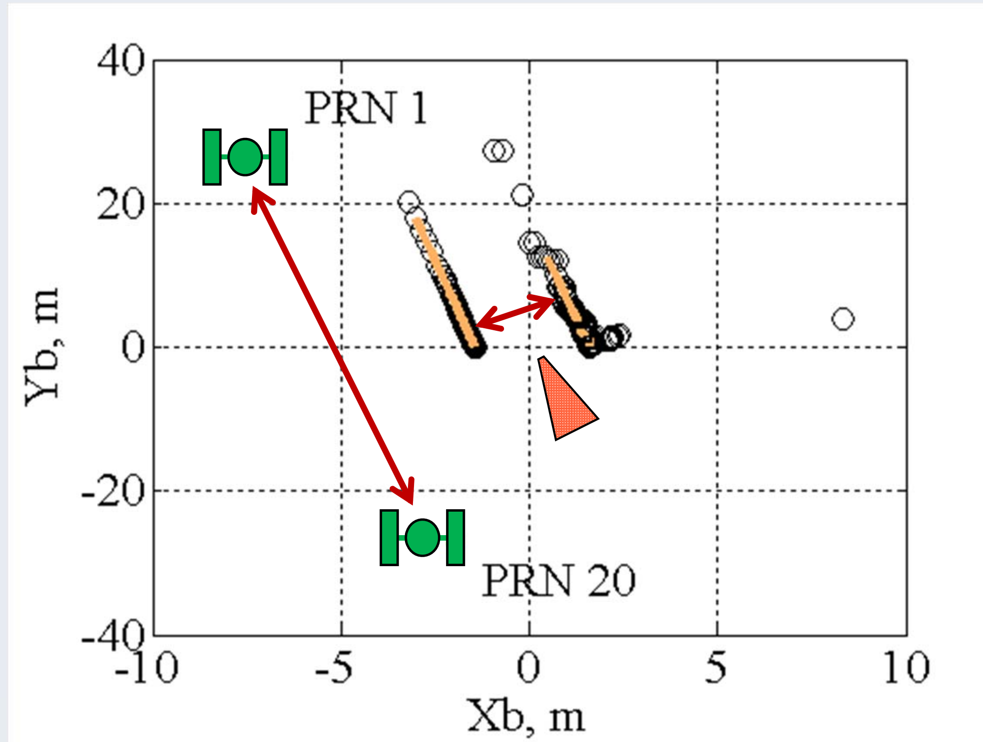
Example of Improved Availability

red segment of vehicle path

Laser measurements provide ***cross-track*** position ***observability***

GPS measurements provide ***along-track*** position ***observability***

Scan image and SV locations projected onto the scanning plane



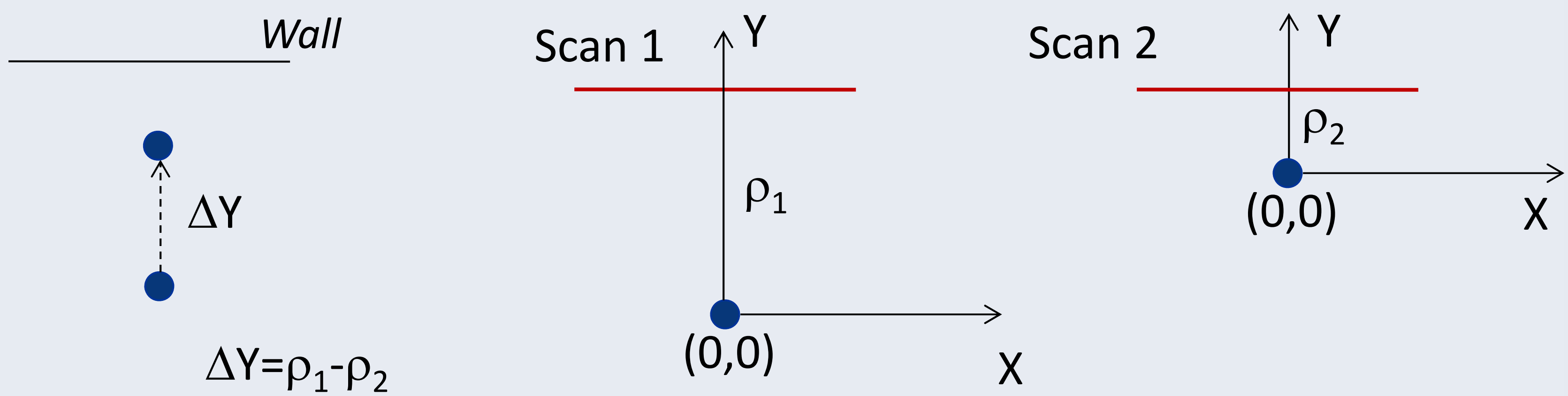
red segment of vehicle path

Image-Based Navigation Approaches

- **Feature-based approach**:
  - Use one or more images to observe features and apply feature parameters for navigation.
- **Correlation-based (or map-based) approach**:
  - Use one or more images to form a map of the environment; then correlate/compare this map to either an a priori map or a previously derived map to estimate the user position, velocity and attitude.
- **Integration with inertial sensors**:
  - Integrate the feature- or correlation-based approaches with the INS to obtain a solution that has a higher level of accuracy, availability, integrity and continuity.

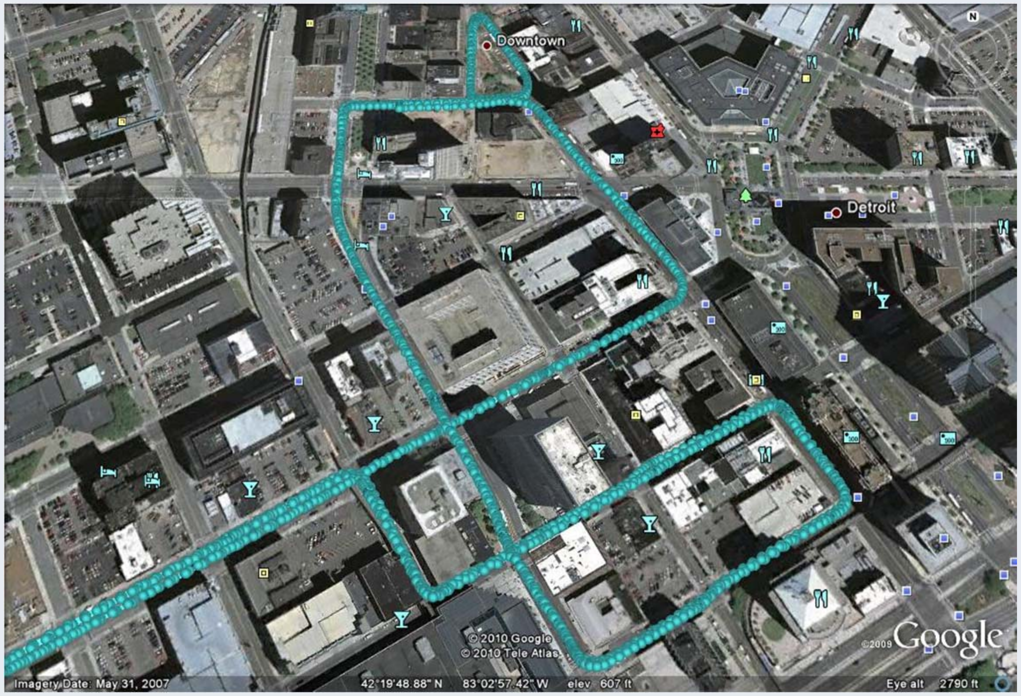
A simplified conceptual explanation

- Line-based navigation using laser scanner
- Measurement of displacement



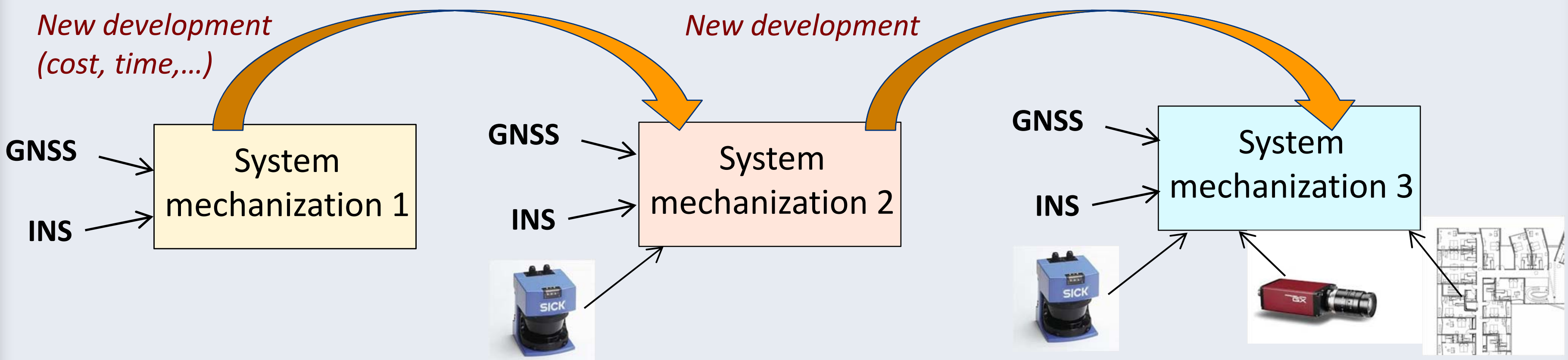
Displacement is estimated based on changes in line ranges

- Example results: GPS/Inertial/Lidar data fusion in urban canyons

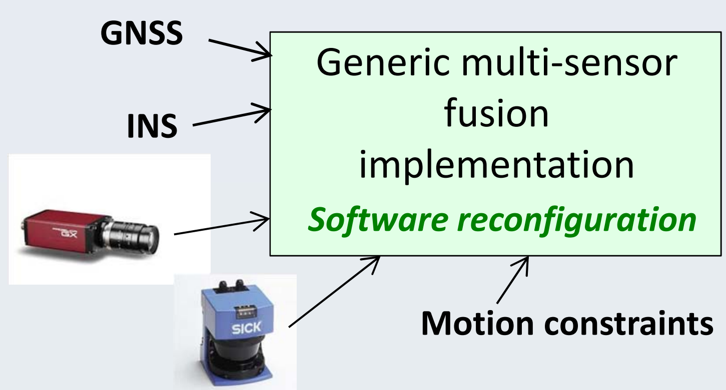


Continuous trajectory reconstruction

Current state-of-the-art multi-sensor mechanizations: ***sensor specific***



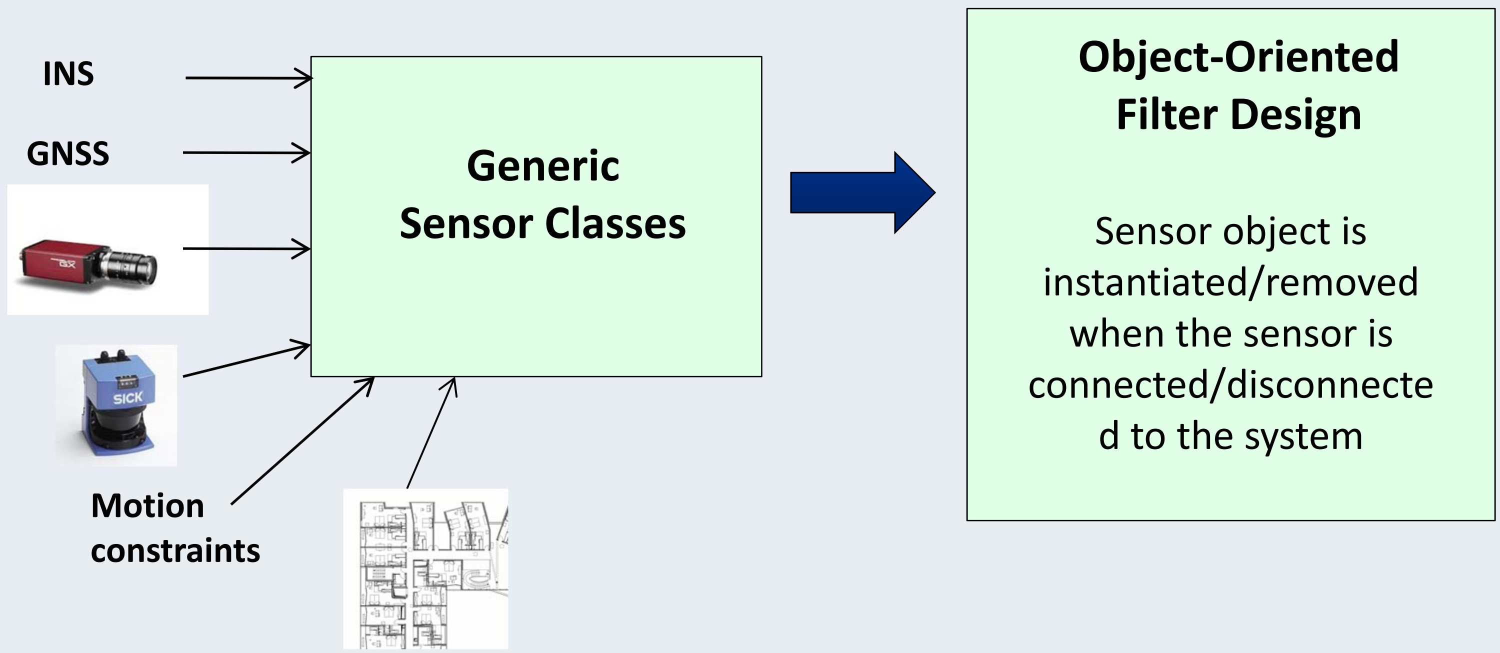
*From **sensor-specific** implementations to **generic plug-and-play** navigation*



- ***System can be reconfigured*** for a specific sensor set (prior to the mission) and/or on-the-fly as sensors are connected/disconnected;
- ***No additional design efforts are required to incorporate new sensors!***

Reconfigurable Integration Filter Engine (RIFE)*

- It is difficult, if not ***impossible***, to create an ***exhaustive list of all aiding sensors***;
- Yet, it is ***possible*** to categorize ***aiding measurements*** into ***generalized types***;
- Hence, *RIFE design is abstracted for generic sensors* that are grouped into classes according to the type of their measurements



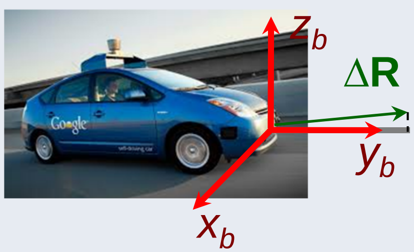
*Developed under DARPA All Source Positioning and Navigation (ASPN) program

Example Generic Measurement

Relative position observables: change in position vector projected onto some axis (or axes) of the navigation or body-frame

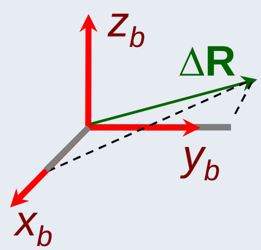
Examples

Odometer



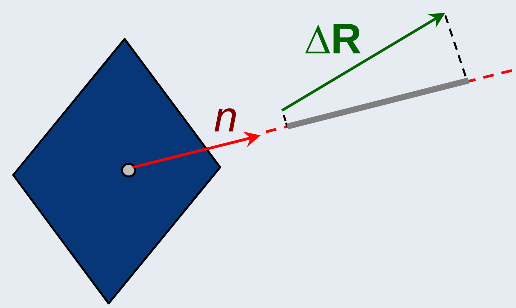
Position change projected onto forward axis

Position change from 2D lidar



Position change projected onto x and y axes of the body-frame

Planar surfaces extracted from consecutive 3D lidar images



Position change projected onto the plane normal vector

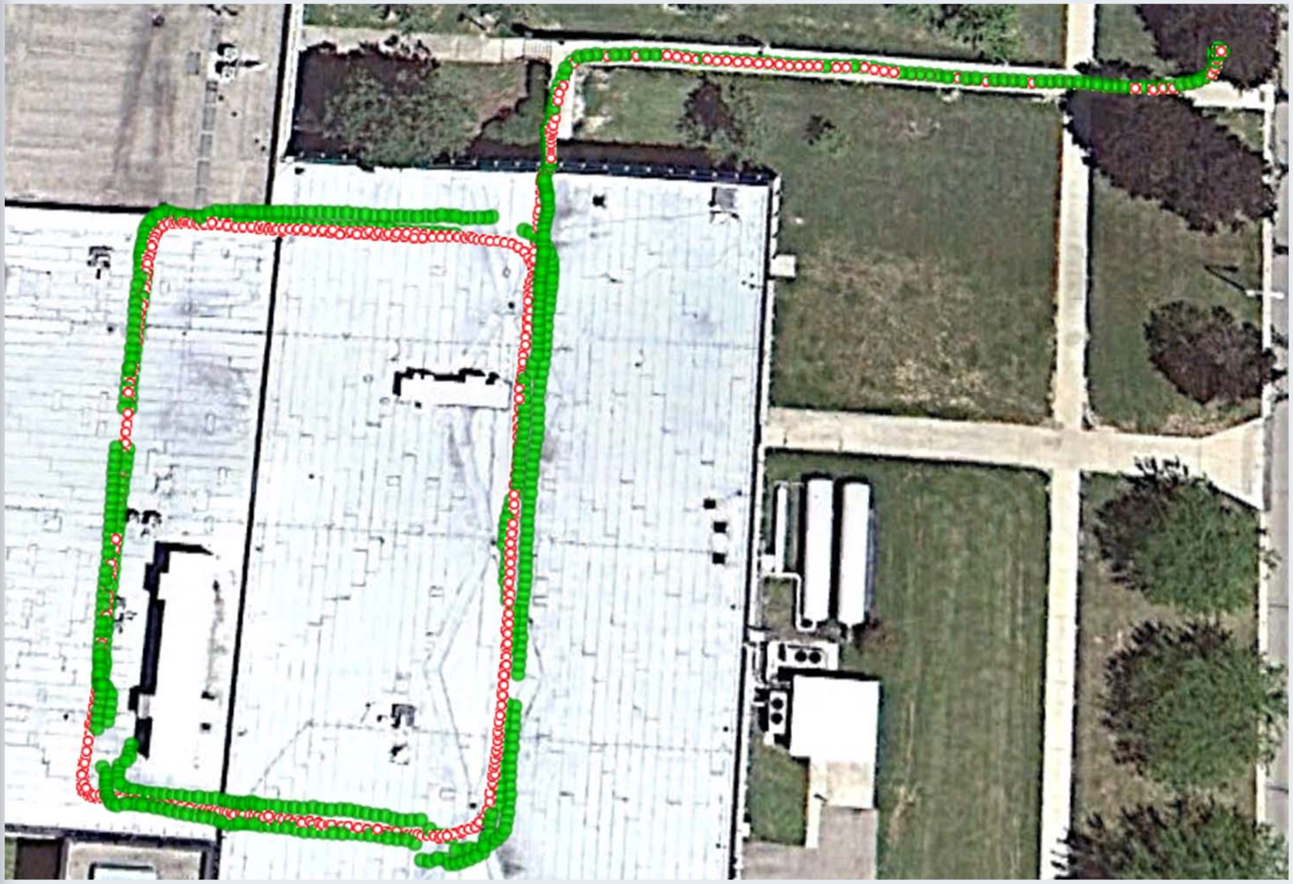
Urban navigation

Sensors

IMU: HG764G
GPS Pos Vel: Novatel-5
Camera: Prosilica-1
Camera: Prosilica-5
Stereo: Prosilica-6-7
Stereo: Prosilica-3-4
Laser 2d: Sick360
Odometer-2
Mag compass: HMR2300-2

Reference
RIFE solution

Indoor navigation



Sensors
IMU: HG1700
GPS Pr Dr: SPAN
Camera: CasioCam
Camera: MS Kinect
Barometer
Magcompass
RFID

Reference
RIFE solution

Ask the Experts – Part 1

Maarten Uijt de Haag
Cheng Professor
Ohio University

Andrey Soloviev
Principal
QuNav

Sandy Kennedy
Director of Core Cards
NovAtel Inc

Poll #2

What other sensors are you most interested in other than using GNSS+ Inertial? (select your top two):

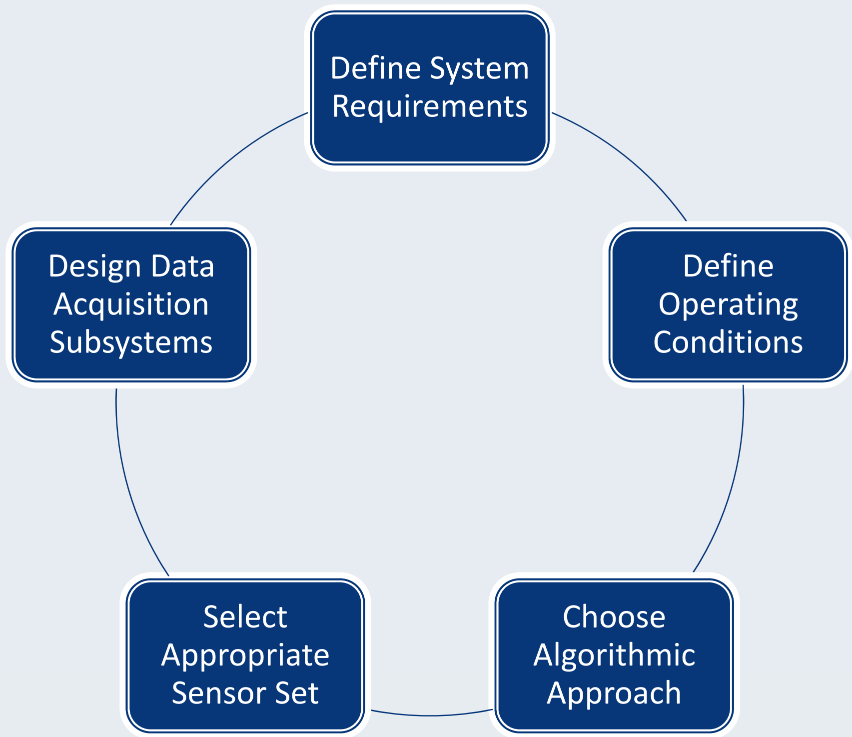
- *Odometer*
- *Vision*
- *Lasers or Radar*
- *Maps*
- *Magnetometer and Pressure Sensor*

GNSS/INS+ Product Development

Sandy Kennedy
Director, Core Cards
NovAtel Inc.

- The benefits of a GNSS/INS+ system are clear, but how do we build it into a product that the marketplace needs?
- The system must be useful and effective
  - Needs to work within specification
  - Every time without onerous setup requirements
  - Not assured of ideal operating conditions
- Must be manufacturable and testable.
  - Low unit to unit variability
  - Repeatable build process

Product Development: Design Phase



Data Acquisition Considerations

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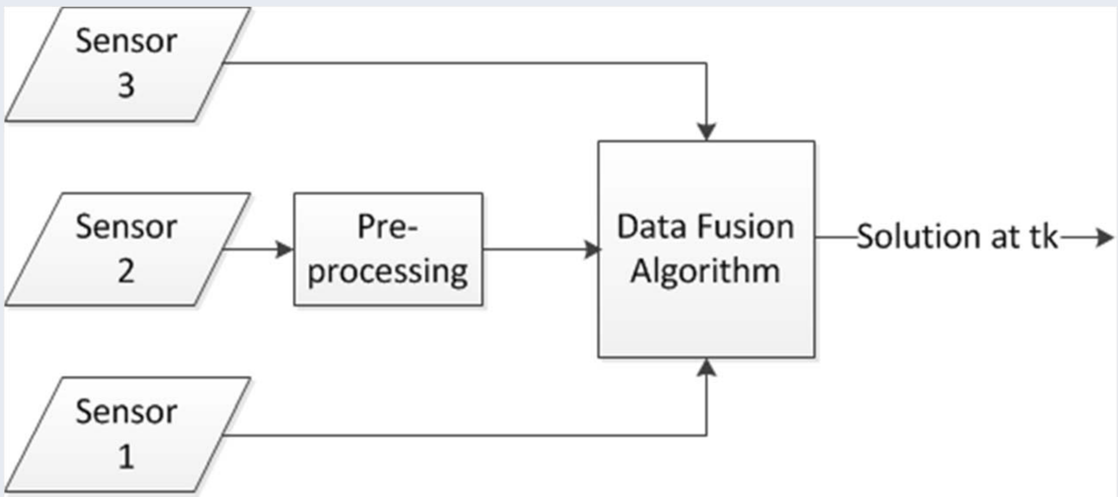
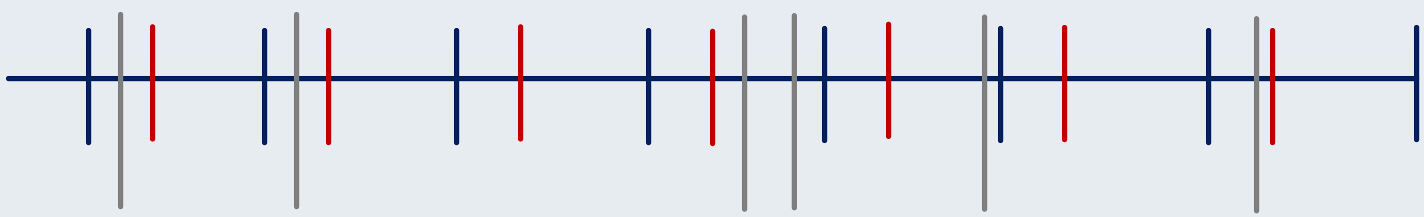
- Data Acquisition details are often glossed over when discussing algorithmic approaches
  - Reliable system operation hinges on this!



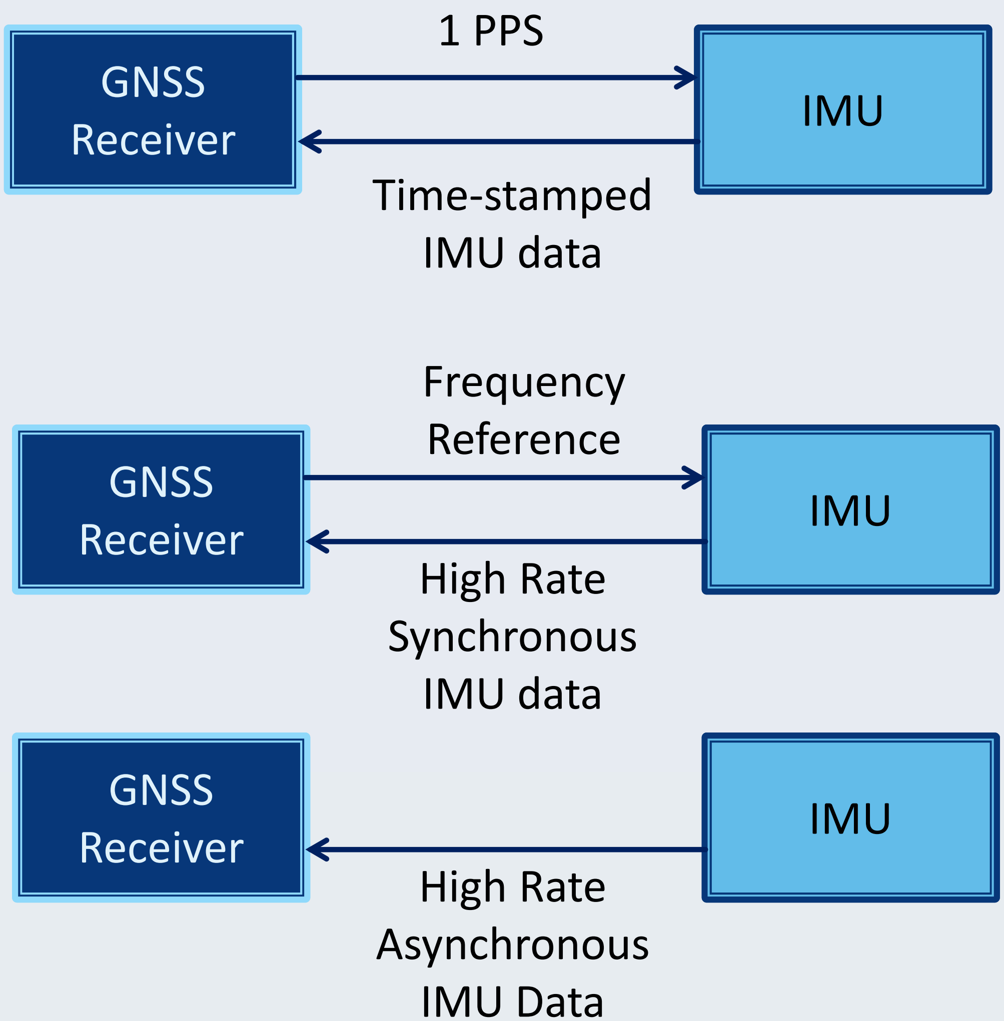
- What is the interface to each sensor?
- Associated latencies?
- Need correct time of validity on each data stream

Time Synchronization

- Synchronous data
  - GNSS data and solutions (ie raw carrier phases and attitude solution)
  - Some IMUs can be synced to GPS time
- Asynchronous data
  - Some IMU data is asynchronous to GPS time
  - External events (ie camera exposure)



Example: IMU Data



- IMU clock interpolates between 1PPS boundaries
- Known offset from synchronous trigger to data ready
- Need leading input pulse to precisely time stamp data via a mark input

Sensor Set

- IMU – yes!
- GNSS receiver and antenna – yes!
- Other sensors
  - Wheel sensor (odometer)?
  - Dual GNSS antenna and receiver (for attitude)?
  - Magnetometer?
- Perhaps better to think of what input measurements would be useful
  - External position
  - External attitude
  - External position displacement or range

Inertial Sensor Selection

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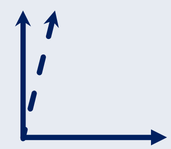
- Bias Stability

- Non-orthogonalities/misalignments in the gyro and accel triads

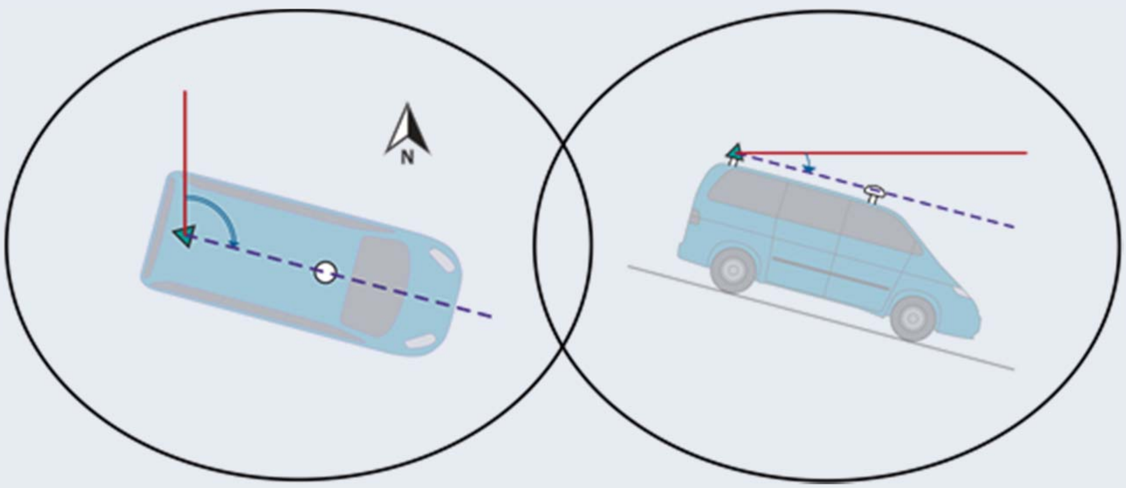


- Scale factor errors
- Noise
- Size
- Cost
- Export classification
- MTBF

Alignment Method?
Convergence Time?
Expected GNSS coverage?
High dynamics?
High Accuracy Attitude?
Position Bridging Only?

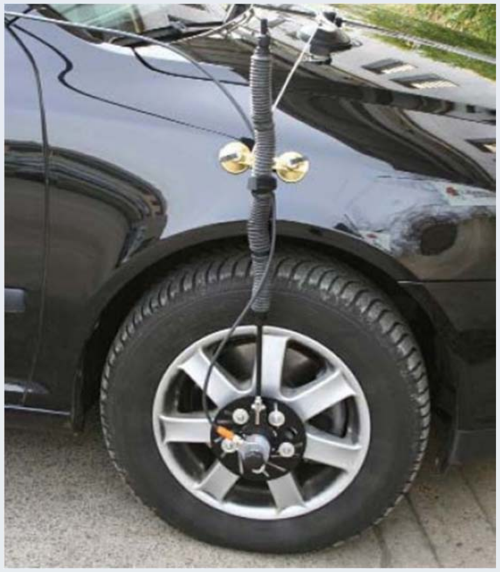
Additional Sensor Selection: 2nd Antenna

- 2nd GNSS antenna (and reciever)
  - Useful for alignment
    - Must measure or estimate angular offset between GNSS baseline and IMU axes
  - Attitude updates
    - Do you expect to be stationary (or constant velocity) for long periods?
  - But can the application bear the size of 2 antennas with sufficient separation?



Additional Sensor Selection: Odometer

- Wheel sensor/odometer/velocity sensor
  - Do you have wheels? Can you mount an external wheel sensor? Does an onboard odometer sensor have sufficient resolution/accuracy? Do you expect extended total GNSS outages?
  - HW input (pulses/ticks) or data record input?
  - Velocity update – instantaneous velocity measure or average over last epoch?



Additional Sensors: Magnetometer or Barometer

- Magnetometer
  - Quality control of data – are you near a lot of electricity and metal?
  - Accuracy of useful heading update
- Altimeter/barometer
  - Can you expose the sensor to the ambient air? Does your vehicle change height rapidly? (ie what is response time of sensor to changes)

Or Generic Update Support?

- Instead of interfacing to various sensors, you can accept a generic input that the overall system user has derived
  - External position (of the IMU or known point)
  - External attitude (of the IMU or known frame)
- Provided this external input data can be time stamped correctly and provided to the GNSS/INS fast enough
- Provided this external input data has a correct quality indicator with it
  - A standard deviation that truly reflects the error
  - Doesn't add any more unknowns to be modeled
- If these criteria are not met, you can get sub-optimal performance
  - Which means customer support calls ....

Take Aways

- Select the appropriate sensor set
  - Know the requirements of your target application
  - Understand how individual sensor errors impact the overall system error budget
- Make a reliable data acquisition sub system
  - HW and FW
- Implement reliable/robust data processing algorithms
- Test, test, test!

Next Steps

Visit www.insidegnss.com/webinars for a PDF of the presentations

Register for Unmanned Systems Week Sessions 3 at www.insidegnss.com/webinars

- Fri, June 6th : Unmanned Solutions & Applications Day

Contact Info:

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- **Andrey Soloviev – soloviev@qunav.com**
- **Maarten Uijt de Haag – uijtdeha@ohio.edu**

Poll #3

Which best describes your GNSS+ Inertial application?

- *Low dynamic and High accuracy*
- *Low dynamic and low accuracy*
- *Highly dynamic and high accuracy*
- *Highly dynamic and low accuracy*

Ask the Experts – Part 2

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Cheng Professor
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Sandy Kennedy
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www.insidegnss.com
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