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

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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

- 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
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 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+
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

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

Levels of Automation, LOA (Sheridan, 2002)

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

Courtesy of 3DR robotics
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.

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

<table>
<thead>
<tr>
<th>Environment</th>
<th>Ground vehicles</th>
<th>Aerial vehicles</th>
<th>GNSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>National airspace</td>
<td></td>
<td>X</td>
<td>Available</td>
</tr>
<tr>
<td>Rural, open-sky</td>
<td>X</td>
<td>X</td>
<td>Available</td>
</tr>
<tr>
<td>Rural, foliage</td>
<td>X</td>
<td>X</td>
<td>Challenged</td>
</tr>
<tr>
<td>Suburban</td>
<td>X</td>
<td>X</td>
<td>Available</td>
</tr>
<tr>
<td>Urban</td>
<td>X</td>
<td>X</td>
<td>Challenged</td>
</tr>
<tr>
<td>Indoor*</td>
<td>X</td>
<td>X</td>
<td>Not available/very low signal strength</td>
</tr>
</tbody>
</table>

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

<table>
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<tr>
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<th>GNSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural, open-sky</td>
<td>X</td>
<td>Available, vulnerable</td>
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</tr>
<tr>
<td>Indoor</td>
<td>X</td>
<td>Not available/low signal strength/multipath</td>
</tr>
</tbody>
</table>
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

Many outliers

Loss of lock
Full GPS-IMU integration

IMU-only coasting

GPS carrier-phase + IMU

Not optimal yet...

Used here: Novatel OEMV + Tactical-grade IMU
Further Limitations

Outdoor with and without foliage

Transition to indoor

“Structured” indoor with multiple path options

Transition to indoor
## Exploit Additional Sensors

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

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

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

OU 3DR Hexacopter

Vision-based navigation

6DOF SLAM
Collaboration between Ohio University and CTAE/ASCAMM Barcelona, Spain

CTAE/ASCAMM ICARUS Quadcopter

Mapping mission

3D Structure-from-motion results

3D Structure-from-motion results
GNSS/Inertial+ Integration

Andrey Soloviev
Principal, QuNav
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)
Example: navigation under dense canopy

GPS-only solution

Deep GPS/Inertial Integration

Very sparse position fixes are obtained

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

**Measurement**
(GNSS, laser, vision, etc.):

\[ f(R, V, \alpha, b) + n \]

Non-linear function of navigation states & sensor biases + noise

**INS-predicted measurement:**

\[ f(\tilde{R}_{INS}, \tilde{V}_{INS}, \tilde{\alpha}_{INS}) \]

Take the difference

Estimation update (EKF or non-linear estimation techniques)

Estimates of INS drift terms
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.

- Record images
- Extract features
- Use features as navigation landmarks
Example of Improved Availability

Scan image and SV locations projected onto the scanning plane

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

GPS measurements provide **along-track** position **observability**
**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
The Ultimate Solution: **Plug & Play Sensor Fusion**

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!**
• 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
**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 the 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
Plug & Play Sensor Fusion: Example Test Results

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

1. Define System Requirements
2. Define Operating Conditions
3. Choose Algorithmic Approach
4. Select Appropriate Sensor Set
5. Design Data Acquisition Subsystems
- 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
- **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
- 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

- 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?
2\textsuperscript{nd} GNSS antenna (and receiver)

- 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?
- 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?
- 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)
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!
Visit [www.insidegnss.com/webinars](http://www.insidegnss.com/webinars) for a PDF of the presentations.

**Register** for Unmanned Systems Week Sessions 3 at [www.insidegnss.com/webinars](http://www.insidegnss.com/webinars)
- Fri, June 6th: Unmanned Solutions & Applications Day

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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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