WELCOME TO
Case Studies in GNSS/INS Integration

Co-Moderator: Lori Dearman, Sr. Webinar Producer
Who’s In the Audience?

A diverse audience of over 500 professionals registered from 43 countries, 30 states and provinces representing the following industries:

23% System Integrator
19% Product/Application Designer
18% Professional User
15% GNSS Equipment Manufacturer
25% Other
Welcome from *Inside GNSS*

Glen Gibbons

Editor and Publisher

*Inside GNSS*
Welcome from NovAtel

Sheena Dixon
Product Manager
NovAtel
Case Studies in GNSS/INS Integration

Demoz Gebre-Egziabher
Aerospace Engineer and
Mechanics Faculty
University of Minnesota
Poll #1

Which of the following are true of design requirements for an integrated GNSS/INS system? *(Please select all that apply)*

- *For a given hardware (GPS receiver and IMU) are independent of the application*
- *For a given application are independent of the hardware used*
- *Are “cast in stone” and never change once the design process starts*
- *May be determined iteratively as the design process evolves.*
- *All are true*
Design process for two integrated INS/GNSS systems
- GNSS + Tactical grade inertial sensors.
- GNSS + Consumer (Automotive) grade inertial sensors.

How and why are the integration architectures & design process different?
INS/GPS Integration in High Dynamic Environments
Modular System Design for a Range of High Dynamic Applications

Thomas Jakel
Sr. Systems Engineer
Honeywell Sensor Guidance and Navigation COE
• Produce an integrated inertial navigation system architecture which:
  1) Is adaptable to various high dynamic applications
  2) Minimizes free inertial drift during GPS outages
  3) Is configurable to use various inertial measurement unit and GNSS types
Iterative Design Process

System Design

Define Dynamics and Requirements

Simulation

Algorithm Design

Evaluation
Define Dynamics

- **Trajectory**
  - Time history of 6 Degree of Freedom Motion

- **Inertial Forces**
  - Strapdown Navigation means sensors experience motion of the body with some attenuation due to mounting
  - Specific force modeling fidelity – tactical vs. navigation
  - Transport Rate

- **High frequency dynamics**
  - Vibration
  - Shock
Define Requirements

- **SWAPC**
  - Size, Weight, Power and Cost

- Dynamic Range and Bandwidth
  - Driven by platform dynamics

- **Performance**
  - Navigation Performance (Position, Velocity, and Attitude)
    - Circular Error Probability or Segment RMS Error

- **Performance**
  - Inertial
  - Measurement (GNSS)

- **Other Considerations**
  - Reliability, Technology Readiness, and Ease of Adoption
## Select Candidate IMUs

<table>
<thead>
<tr>
<th>Volume (in³)</th>
<th>HG1930</th>
<th>HG1900</th>
<th>HG1700</th>
<th>HG9900</th>
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<tbody>
<tr>
<td>ARW (°/√hr)</td>
<td>0.09</td>
<td>0.06</td>
<td>0.125</td>
<td>&lt;0.002</td>
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<td>0.3</td>
<td>0.03</td>
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<tr>
<td>G_SF (ppm)</td>
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<td>150</td>
<td>5</td>
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<tr>
<td>G_NO (μrad)</td>
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<tr>
<td>A_Bias (mg)</td>
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<td>1</td>
<td>&lt;0.025</td>
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<tr>
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<td>0.05</td>
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<td>A_SF (ppm)</td>
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<td>100</td>
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<tr>
<td>A_NO (μrad)</td>
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<td>100</td>
<td>100</td>
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<tr>
<td>Start Time (ms)</td>
<td>350</td>
<td>750</td>
<td>1500</td>
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<tr>
<td>VRC (μg/g²)</td>
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<td></td>
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<tr>
<td>Power (W)</td>
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<td>3.5</td>
<td>6.5</td>
<td>&lt;10</td>
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</table>
The HG1930 MEMS IMU has been successfully deployed on a wide range of guidance, navigation, control, and pointing applications on commercial and military platforms.

- Extended operating range versions available
- Specified performance is over all environments – many of which are severe
  - Performance under benign conditions is even better
- Gyro rate limited ECCN 7A994 version
  - Entry in service late 2016

<table>
<thead>
<tr>
<th>Physical Parameters</th>
<th>CA50</th>
<th>BA50</th>
<th>AA50</th>
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<tr>
<td>Volume (cubic inches)</td>
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<td></td>
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<tr>
<td>Weight (lbs)</td>
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<td>Power (Watts)</td>
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<table>
<thead>
<tr>
<th>Gyro Performance Overview</th>
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<tr>
<td>Operating Range (dps)</td>
</tr>
<tr>
<td>Bias Repeatability (dph (1-sigma))</td>
</tr>
<tr>
<td>Bias In-run Stability (dph (1-sigma))</td>
</tr>
<tr>
<td>Scale Factor Repeatability (PPM (1-sigma))</td>
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<tr>
<td>Scale Factor In-run Stability (PPM (1-sigma))</td>
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<tr>
<td>Non-orthogonality (urad (1-sigma))</td>
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<tr>
<td>Angle Random Walk (deg/sqrt(hr))</td>
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</table>

<table>
<thead>
<tr>
<th>Accelerometer Performance Overview</th>
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<td>Operating Range (g’s)</td>
</tr>
<tr>
<td>Bias Repeatability (milli-g (1 sigma))</td>
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<tr>
<td>Bias In-run Stability (milli-g (1 sigma))</td>
</tr>
<tr>
<td>Scale Factor Repeatability (PPM (1-sigma))</td>
</tr>
<tr>
<td>Scale Factor In-run Stability (PPM (1-sigma))</td>
</tr>
<tr>
<td>Non-orthogonality (urad (1-sigma))</td>
</tr>
<tr>
<td>Velocity Random Walk (fps/sqrt(hr))</td>
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</tbody>
</table>
Navigation Architecture centered around Strapdown Navigation and Extended Kalman Filter (EKF)

- Proven navigation performance in past high dynamic applications
- State Selection
  - PSI Error Model – Direct observation of Earth to Body states
  - Modeling of inertial sensor and measurement errors
  - Dynamics and observation dependent
- Selectable Navigation Iteration Frequency
  - Modeling of transport rate and gravity

GNSS measurements can be incorporated with different mechanizations

- **Ultra-Tightly Coupled (UTC)** – Navigation solution drives the GPS receiver replicas (NCO)
- Tightly coupled – Pseudorange and Deltarange incorporated as measurements to the EKF
- Loosely coupled – Position and Velocity used as measurements in the EKF
- Accept NCO commands from external sources
- Output $I_s$ and $Q_s$ at 50 Hz or greater (for signals with nav data on them)
- Bias estimation and application consistent with estimation performed in centralized EKF
- Small SWAP
- Oscillator Stability under dynamic conditions
- Receiver only needs to track the errors in the inertial solution
- Signal acquisition time may not be critical
  - Dependent on performance requirements post initialization
Simulation Tradeoffs

- **Covariance simulation**
  - Linear models of error characteristics
    - $s = g(x)$
  - Single run statistical assessment

- **Time domain simulation**
  - Non-linear models and events
    - $y = f(x)$
  - Direct visibility to application software implementation
    - Higher-order languages allow actual flight software to be simulated
      - Issue: Simulation is not usable until flight software is complete
  - Sensitive to signs and implementation
  - Monte-carlo provides statistical assessment
EKF State Selection – Covariance Analysis

- Initial development in late 1970’s
- Used extensively within Honeywell over last 35 years
- Gradual evolution to add features and enhance ease of use

Mission Profile

Trajectory Generator

File

Vehicle Dynamic Variables

Navigation Error Model

Sensor Error Models

Kalman Filter

Covariance Analysis

Real World/Filter World (1stPass)

Real World/Filter World (2nd Pass)

Kalman Gains

Covariance Analysis

1σ Performance

File
- Gyroscope Scale Factor

- Maneuver – 180° Roll

- No state in EKF – Scale Factor for HG1930 AA50 from Specification – 1000 PPM
  - Attitude Error = 1000 PPM * 10^-6 PPM/Part*180° = 0.18°
  - Velocity Error ≈ 0.18°*π/180 rad/° * 9.81 = 0.03 m/s

- State in EKF – Estimated to Scale Factor In-Run from AA50 Specification – 250 PPM
  - Attitude Error = 250 PPM * 10^-6 PPM/Part*180° = 0.05°
  - Velocity Error ≈ 0.05°*π/180 rad/° * 9.81 = 0.01 m/s

- Modeling Gyro Scale Factor State provides significant performance benefit
  - When trajectory excitation and measurement observability allow estimation
- Examples of inertial states modeled
  - Bias, Scale Factor, Repeatable Scale Factor Non-Linearity, Misalignment, Non-Orthogonality, Gyroscope G-Sensitivity

- Examples of GNSS Measurement States
  - Clock Drift, Clock Drift Rate, Range Bias, Oscillator G-Sensitivity

- State selection is a trade-off between performance and processing
  - Observability of states is trajectory dependent
Test Environments

Off-line Simulation Tools
- Filter Design and Analysis
- Provides controlled and repeatable environment.
- Provides “user friendly” tools.
- Output information only as good as input drivers.

Laboratory Test
- Access to actual hardware and real-time software.
- Offers exposure to controlled environments
  - Temperature
  - Vibration
  - Humidity etc.

Van Test
- Access to low dynamic motion for visibility into timing errors etc.
- Cheaper than flight test.
  - Easy retest capability
- Good data collection/storage.

Flight Test
- True application environment

- Development utilizes all of the above environments

- Results from laboratory, van and flight test are fed back into off-line simulation tools to assist in analysis and provide better tools to use in the future.
Introduction to HG1930P/N

- Two new variants to the HG1930 family
  - HG1930P = Enhanced Processor
  - HG1930N = Integrated Navigator
- Small size, weight and power (SWaP)
  - HG1930 form factor
- Drop-in replacement of the HG1930 micro board
  - Multi-core System-on-Chip (SoC)
  - Secure dual processor architecture
- Flexible I/O options
- Honeywell MEMS sensors
  - Capable of using external IMU

Honeywell’s new flexible low cost, small SWaP, MEMS INS
Dual Processor Architecture

Secure and open INS architecture
Flexible External I/O

- 14 Pin Connector
- Design decision for volume, commonality of production and cost
- Mitigate limitations with configurability

- Up to 5 UARTs
  - 4 Mbaud capable – useful for low latency NCO commands
- SDLC port
- Additional pin options
  - Time Mark Input/Output
  - Discrete Input/Out
  - IMU Strobe/External Sync
- Both single-ended and differential signals supported on ports 3, 4 & 5
- Additional I/O supports varied Navigation usage
Navigation performance is expected to be similar to the Honeywell BG1930 GPS Aided Inertial Navigation System (INS).

Preliminary simulation analysis shows comparable performance.

1 minute free inertial performance: 18 m CEP, 12 m Altitude Error (1σ)
Product Roadmap: Future Developments

- Top-hat options
  - Personality card
  - Federated GPSR
  - Other aiding sensors
  - Tailored for customer applications

- USB On-The-Go software

- Software services via a Platform API

- HG1930P/N concept to other Honeywell IMU product families, e.g., HG1900 and HG1700

System architecture supports hardware/software expandability
INS/GNSS design for dynamic systems is an iterative trajectory dependent process
- High fidelity simulations provide a low cost means to iterate on the design

Modeling of inertial sensor error characteristics which are dynamics dependent is critical

Selection of ultra-tightly coupled integration has significant design impact

Ask the Experts – Part 1

Tom Jakel
Senior Systems Engineer
Honeywell Aerospace

Andrey Soloviev
Principal
QuNav
Poll #2

Which of the following are true about the INS mechanization used in an integrated GNSS/INS system? (Please select all that apply)

- The same for a given application regardless of the quality of IMU used
- The same for a given quality IMU regardless of the application in question
- Always the same for a given quality IMU and GNSS receiver regardless of the application
- Depend on the customer requirements
- None are true
GNSS/Inertial Integration for Land Vehicles

Andrey Soloviev
Principal, QuNav
Example Automotive Applications

- Navigation
  - Road-level accuracy
- Self-driving cars
- Automotive safety:
  - Connected cars
  - Lane-level accuracy
- Decimeter-level accuracy
Connected Cars

... V2V ...

Next Gen Vehicle-to-Vehicle Communication

Operates in advisory mode

No direct visibility needed

Preventing accidents using V2V REQUIRES lane level accuracy
Limitations of GNSS

GNSS is often unreliable!
GNSS is augmented with inertial sensors

Consumer-grade inertial sensors must be used due to cost limitations

Typical performance specs are:
- 0.1 deg/s gyro drift (360 deg/hr)
- 0.1 m/s² accelerometer bias

As compared to higher-grade inertials:
- **Strapdown navigation mechanization** is **easier**: non-inertial effects and high-precision gravitation models do not have to be included
- **INS error model** is **easier**: high-order terms such as, for example, cross-axis sensitivity can be omitted
- The role of **aiding data** becomes much more **critical**
Non-inertial effects and sophisticated gravity models do not have to be considered since they are below the level of sensor biases.
This simplifies strapdown INS mechanization.

**Diagram:**

- **Accelerometers** to **Coordinate transformation**
- **Specific forces**
- **Gravity compensation**
- **Gyros** to **Angular rates**
- **“∫”** to **Attitude**
- **Initial attitude**
- **g = 9.8 m/s²**
- **Initial velocity**
- **Velocity**
- **Initial position**
- **Position**
How to determine initial attitude?
- Traditionally, it is done based on gravitational acceleration and Earth rate.
- However, low-cost gyros are not accurate enough to measure the Earth rate.

**Alternative alignment approach** uses *gravity* and *vehicle velocity*:
- Navigation-frame velocity: measured by GNSS;
- Body-frame velocity: assumed to be aligned with the front axis of the vehicle.
Integration with other sensors

- Stand-alone operation of INS is extremely limited

Example consumer grade IMU

MicroStrain 3DM-GX1

- Efficient integration with other sensors (including GNSS) is critical
What is the right integration mode?

- **Loose Integration**: Fusion of *navigation solutions*
- **Tight Integration**: Fusion of *navigation measurements*
- **Deep Integration**: Integration at the *signal processing level*

Loose integration has limited capabilities in GNSS-challenged environments

*Example: sparse GNSS position fixes in urban canyon*

- No GNSS data for loose integration
- Some data may be still available (e.g. 2-3 satellites) for tight and deep modes

*Tight and deep integration are more suitable for GNSS-challenged environments and integration of inertial with other sensors*
Deep Integration

Key features:
- **Sensor fusion at the signal processing level**;
- **Inertial aiding of GPS signal accumulation**;
- Complete tracking status including **tracking of the carrier phase**
Benefits of Deep Integration

- **Deep integration** recovers weak (attenuated) **GNSS signals** thus increasing the number of GNSS measurements.
- It is **beneficial** in environments such as under **dense tree coverage**.

However, it is very challenging to fully recover GNSS signals attenuated by buildings in dense urban environments.
Carrier phase vs. pseudoranges:

- Carrier phase provides two-to-three orders of magnitude noise reduction;
- This significantly shortens noise averaging interval;
- The use of carrier phase is especially beneficial for integration with low-grade INS:
  - Sensor errors change quicker than time intervals required to average pseudorange noise!
How To Apply Carrier Phase?

especially when a limited number of SVs is available

*GNSS observables*
Implementation of measurement quality control is critical to mitigate the influence of multipath.

**Data Quality Monitor**

- **GPS measurements (carrier phase)**
  - Redundant GPS measurements are available
    - Yes: RAIM integrity monitoring
      - Autonomous GPS receiver detection and isolation of “spiky” measurements
    - No: GPS/INS integrity monitoring
      - GPS raw measurements are compared against inertial measurement predictions

**Kalman filter**

- **Covariance propagation**
  - Raw measurements with removed spikes
    - INS error covariance
      - Corrections
        - INS position and attitude solution

**Definition**

\[
| \Delta \varphi_{GPS}^{(adj)} - \left( e, \Delta \hat{R}_{INS} \right) + \Delta \delta_{orr} | \leq 3 \sigma \rightarrow \text{fault-free case}
\]
Addition of Other Sensors

- Most modern cars have navigation-related sensors which are underutilized.

- These sensors can be applied to improve performance of GNSS/INS in GNSS-challenged environments such as urban canyons.
Addition of Other Sensors

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

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

ion update (EKF or non-linear estimation techniques)

\[ \downarrow \]

Estimates of INS drift terms
- GNSS: GPS+GLONASS
- Tight coupling (carrier phase measurements are used)
- INS error model consists of 18 states including:
  - Position errors (3)
  - Position change errors (3)
  - Velocity errors (3)
  - Attitude errors (3)
  - Gyro and accelerometer biases (6)
- Use of other sensors:
  - Motion constraints (zero lateral and vertical velocity components in the body frame)
  - Monocular video camera
Motion Constraints

- Zero cross-track velocity
- Zero vertical velocity

\[
\begin{align*}
V_{y_b} &= 0 \\
V_{z_b} &= 0
\end{align*}
\]

Motion constraints

\[
\begin{bmatrix}
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix} \cdot \hat{C}^b_N \cdot \hat{V}_{INS} = \begin{bmatrix}
0 \\
0
\end{bmatrix}
\]

- Projection matrix \((H)\)
- Coordinate transformation from navigation into body frame

Linearization

- Velocity error
- Cross product
- Attitude error

\[
\begin{align*}
\begin{bmatrix}
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix} \cdot \hat{C}^b_N \cdot \delta V_{INS} + \begin{bmatrix}
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix} \cdot \hat{C}^b_N \cdot \hat{V}_{INS} \times \delta \theta_{INS}
\end{align*}
\]

- Kalman filter measurement observable
Experimental Setup

Test vehicle

Sensor board

Vehicle mount
Example Test Scenario

Downtown Tampa, FL

GNSS-only solution
Significant performance improvement as compared to GNSS

However, some problem areas still remain
Lane-level positioning accuracy is maintained!
Stressing the system with artificial GNSS outages

Complete GNSS outage

Lane-level positioning accuracy is still maintained!
Integration with low-cost inertial sensors allows for simplification of inertial navigation mechanization and error propagation model; however, proper use of aiding data is critical; tight or deep integration have to be used; carrier phase measurements are most beneficial for mitigating the INS error growth; GNSS/Inertial generally does not support accurate positioning capabilities in challenging urban environments; low-cost augmentation with other sensors enables accurate localization for all driving scenarios.
Next Steps

• Visit www.insidegnss.com/webinars for a PDF of the presentations and a list of resources.

• Review the recorded version of today's webinar

Contact Info:

• Novatel—www.novatel.com/
• Inside GNSS- www.insidegnss.com
Poll #3

Do you believe advanced technologies i.e. chip scale atomic clocks and cold atom systems will eliminate the need for GNSS ? (please select one)

• Yes
• No
• Probably
• Probably not
• Don’t know
Ask the Experts – Part 2

Tom Jakel
Senior Systems Engineer
Honeywell Aerospace

Andrey Soloviev
Principal
QuNav

Sheena Dixon
Product Manager
NovAtel

Inside GNSS @ www.insidegnss.com/
www.novatel.com/