INERTIAL + SLAM: CREATING THE ROADMAP FOR AUTONOMOUS VEHICLES

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WELCOME TO
Inertial + SLAM: Creating the Roadmap for Autonomous Vehicles

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Coast Autonomous

Co-Moderator: Lori Dearman, Executive Webinar Producer
Who's In the Audience?

A diverse audience of over 450 professionals registered from 45 countries, representing the following industries:

29% System Integrator
24% GNSS Equipment Manufacturer
15% Product/Application Designer
7% Professional User
5% Government
20% Other
Welcome from Inside Unmanned Systems

Richard Fischer
Publisher
Inside GNSS
Inside Unmanned Systems
WELCOME TO
Inertial + SLAM: Creating the Roadmap for Autonomous Vehicles

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Poll #1

What is your status in autonomous vehicles, R&D or product development? (select one)

A. I am in early exploration
B. I am in R&D phase and looking for a localization solution
C. I am in R&D phase and already have a localization solution
D. I have an autonomous product already released
Safe & Reliable worldwide positioning

Raphaël Siryani
SBG Systems
Chief Software Architect
Summary

- Safe & Reliable Navigation
- Real time INS navigation
- Protection Level & Reliability
- Urban Test Results
- HD Map for SLAM
- Roadmap & future work

SBG Systems is a leading supplier of Orientation, Stabilization & Navigation solutions.
Safe & Reliable Navigation

- Redundancy, cooperation, multi-layers

**Relative**
- Lane detection
- Vehicle spacing

**SLAM & Map Matching**
- Vision and Lidar based
- For the most demanding area
- Impossible to cover all roads

**GNSS / INS Navigation**
- Only practical absolute positioning
- Tightly coupled GNSS / INS
- Odometer + Lidar / Vision aiding
- Available everywhere
Safe & Reliable Navigation

- Certifications in mind

**Relative**
- Completely isolated building blocks
- Real time consistency checks

**SLAM & Map Matching**
- Very accurate but needs HD maps
- Reliability improved by INS data
- Still some corner cases to assess

**GNSS / INS Navigation**
- Below 10 cm in light urban & countryside
- Below 1 to 2 m in dense urban canyon
- Requires very light infrastructure
- Reliable quality indicators / PL
**Real time INS Navigation**

- INS basic principle
  - Integrate accelerations to get a position
  - Correct for position drift using GNSS
- Absolute position accuracy driven by GNSS
  - < 10 cm needs GNSS augmentation data
  - RTK for dense urban environments
  - PPP for countryside & open sky conditions
- Loosely vs Tightly coupled INS
  - Loosely: combines GNSS positions with IMU
  - Tightly: combines space vehicle pseudo ranges with IMU
Real time INS Navigation

- 100% in house designed tightly coupled solution (RTK/PPP/INS)
- Built-in support for all constellations & signals (L1/L2/L5)
  - GPS, GLONASS, Galileo, BeiDou, QZSS
  - Ublox, Septentrio, Novatel, Trimble
- Car odometer aiding using ODB-II
- Advanced vehicle motion constraints
- Automotive lever arm / alignment estimations
- Support for any IMU or GNSS (consumer/automotive)
- C library integrated in Qinertia & real time products

Hardware Agnostic
Protection Level & Reliability

- RTK offers the best accuracy
  - Robust algorithm with fast convergence
  - But needs base stations every 20 km
- PPP is available worldwide
  - Fixed PPP is accurate (2-10cm) after convergence
  - But is very sensitive to GNSS signals disturbances
  - Can’t be safely used in urban environments
- Tightly coupling & RAIM
  - IMU data helps predict vehicle position
  - Leverage on new signals & constellations
  - Improve RTK availability & avoid bad fixes

Focus on reliability, resilience and repeatability
Protection Level & Reliability

- Reliable localization is the key for self driving vehicles
- Tightly coupled INS can provide reliable Protection Level (PL)
- RTK/PPP RAIM greatly improved by tightly coupling
- Good IMU modeling guarantee confidence during outages
- IMU model is continuously validated online
  - Sensor bias
  - Scale Factor
  - Orthogonality
  - etc

The Stanford diagram

Mandatory for certifications
Protection Level & Reliability

- Stanford diagram for INS
- Estimated vs Real Horizontal error
- Harsh Urban Test Result
- 1-Sigma accuracy is conservative
- 3-Sigma is perfectly in line
- Very few outliers but to improve

<table>
<thead>
<tr>
<th>1-Sigma (68%)</th>
<th>2-Sigma (95%)</th>
<th>3-Sigma (99.7%)</th>
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<tbody>
<tr>
<td>&lt; 93.3%</td>
<td>&lt; 98.5%</td>
<td>&lt; 99.7%</td>
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</tbody>
</table>

Consistent Protection Level
Protection Level & Reliability

- Focus on resilience & reliability
  - IMU performance has to be well qualified
  - Avoid adding too much states in the EKF
  - Screening and calibrations mandatory
  - Maintain accuracy over temperature
  - And other life-time (15 to 30 years)

- SBG Systems expertise in MEMS IMU
  - Fully automated calibration process
  - Low end to very high-end sensors (MEMS to FOG)
  - Civilian and military IMU/INS

Calibration mandatory for certification
Performance Assessment with Qinertia

- In house post processing software
- Access the most accurate solution
- Replay scenarios to evaluate behavior
- Add/remove sensors & aiding data
- Powerful quality assessment display
- Consistency checks such as separation
- Several processing modes from PPK to PPP

Provides a post processed reference trajectory
Urban Test Results

- Behavior evaluated in very harsh urban environment
- Several INS levels are compared to a FOG reference
- Real time RTK is available through cellular network
- More than 20% underground
- Large tunnel of 6 km long - 330s
Urban Test Results

- Yellow dots are the GNSS
- Green track is the real time tightly coupled solution
- GNSS unable to provide Fixed RTK
- Tightly coupled INS is able to Fix RTK even in difficult conditions
- Tall buildings with glass
- GNSS completely lost
- GNSS estimated error < 12 meters
- Real GNSS error 100 meters
- INS error below 60 cm 2-Sigma
- 210s of unusable GNSS
- INS solution is perfectly reliable with consistent reported SD

Improved RTK availability
Urban Test Results

- Long tunnel of 330s and almost 6 km
- Accuracy evaluated in real life application
- Very challenging compared to simulated outages
- Real error less than 2.5 meters
- Reported SD is consistent

Provides aiding data to SLAM
HD Map for SLAM

- Large area to map -> efficiency
- Continuously update HD maps
- Need for a cost effective but accurate solution
- Efficient workflow with both real time and post processing

- SBG Systems offers a full solution
  - Navsight for straight integration
  - High end Horizon FOG IMU
  - APOGEE INS for most applications
  - EKINOX for less demanding situations
HD Map for SLAM

- Qinertia post processing software
  - The best achievable accuracy
  - Very easy and automated workflow
  - Fast processing time
  - Support for all use cases
  - Open to all standards & manufacturers
Roadmap & Future work

- Increase low cost GNSS/IMU test database
- Vision / Lidar aiding for INS alignment & outage
- Autonomous SLAM to address parking/private areas
- Beacons (radios/visual) to overcome SLAM limitations
- Improved protection level validation
- Continue to qualify in challenging conditions
- Deep PPP limitations evaluations with PL
- Evaluate hazardous weather & conditions (drifting)

Brings repeatable & qualified absolute localization solution
Coupling INS & SLAM for Mobile Mapping
Part I
Content

- SLAM Principle
- SLAM & INS Coupling methods
  - SLAM/AHRS
  - True-Heading by SLAM
- Use case
- HD Roadmap
SLAM stands for “Simultaneous Localization And Mapping”

Algorithms family initially developed for mobile robots in order to be able to build a map while locating itself inside

4 main steps:
- Landmark extraction
- Current pose estimation
- Landmark matching
- Pose update and map update
- Relative positioning: starting from (x=0, y=0, z=0) coordinates
- Orientation is without absolute reference starting arbitrarily (Roll=0, Pitch=0, Heading=0)
- Reference frame is natively metric
6DOF SLAM is an high-grade DMI (Distance Measurement Instrument)
- accurate movement measurements in the three-axis
- accurate rotation speed measurement in the three-axis
- drift w.r.t distance and not w.r.t time compare to INS

SLAM for position drift correction (Loop Closure)
- Looping in the same area allows drift correction with global landmark matching algorithm
- Drift can be spread on the hole trajectory
Coupling is not obvious

- Reference issue:
  - GNSS/INS natively in **global geographic** Coordinate frame
  - SLAM is natively in **local metric** coordinate frame

- Calibration issue:
  - SLAM works from LiDAR or camera body center
  - INS body has to be the center of the system

Body frame Alignment and Lever arm measurement
SLAM & AHRS (Attitude and Heading Reference System)

- SLAM has no reference frame
  - INS is then coupled to provide Roll/Pitch reference
  - Trajectory can keep horizontal plan reference

- SLAM depends on sensor frame rate
  - IMU Accelerometers and Gyros aid SLAM to lock proper landmark in case of sudden movements during the pose estimation step
  - The trajectory can be issued at 200Hz with final interpolation
SLAM & AHRS (Attitude and Heading Reference System)

- Applications:
  - Indoor mapping
  - Indoor mobility (Indoor Shuttles, autonomous wheelchairs) in airport/shopping mall/Subways
  - Urban mobility in Deep Urban canyons (NYC, HongKong, Paris La Defense, etc.)
**True-Heading by SLAM**

- Low dynamics shuttles
- Repeated static stations (bus stop)
- Difficult GNSS environment
- True-heading from GNSS double-antenna not available

- SLAM overcomes in bad GNSS conditions
  - While GNSS works fine in open-sky area, tight areas and indoor are favorite place for SLAM

- SLAM has no drift while stationary
  - Maintaining the body heading is easy
**True-Heading by SLAM**

1. SLAM trajectory is computed
2. SLAM trajectory is globally oriented w.r.t the north using GNSS position
3. SLAM orientation around z-axis becomes equal to the true-heading
4. SLAM algorithm maintains true-heading along the time
5. Next GNSS reception can be used to update global heading measurement
True-Heading by SLAM

CASE 1: Mapping

SLAM and INS Coupling
**True-Heading by SLAM**

CASE 2: Shuttle localization

- **LiDAR**
  - Frame @20Hz
- **AHRS**
  - Roll/Pitch @200Hz
- **SLAM**
  - True Heading @5Hz
- **INS**
  - 6DOF Tight-Coupled Trajectory @200Hz
- **RTK**
  - C-INS
- **MAP**
Ask the Experts

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Coast Autonomous
Poll #2

In your opinion, which localization technology is the most important to achieve certified autonomous driving? (select one)

A. Vision-based SLAM
B. LiDAR-based SLAM
C. Inertial + GNSS
D. Beacons (radio, road signs)
Coupling INS & SLAM for Mobile Mapping
Part II
Mapping dense area for Shuttle Roadmap

- GNSS reception
  - Outages of up to 50 seconds
  - Corridors 5 meters wide
  - Buildings up to 18 meters high

- Low dynamics
  - Walking speed around 1 meter per second
SLAM is used to compute body true heading
- No true heading outage
- High Consistency
- Independent from GNSS reception
- Accuracy of true heading < 0.1°
- No need for binding initialization to align INS body
- No need for high dynamics

INS/GNSS tight coupling starts properly
- INS enters in Full Navigation mode while the true heading is provided

Accuracy compare to control points < 5cm RMS
Roadmap is a high definition knowledge database:

- It contains landmarks for map-matching algorithm
- It contains lane borders and speed limits
- It contains knowledge to adapt shuttle behavior (GNSS covering, caution zone, crossings, etc.)
- Traffic lights position
- It contains the road network to compute routes
Map Matching

- True heading SLAM to be injected in the INS/GNSS real-time positioning
- SLAM keeps positioning while GNSS outages
- Map-matching using landmarks affords global coordinates at centimeter accuracy

In blue, landmarks in the roadmap

Map Matching in progress after initialization
Pierre Lefevre
Chief Technical Officer
COAST Autonomous
COnnected Autonomous Shared Transportation

Self-driving technology for last-mile mobility

Invented to give cities back to people
With new technologies, distance disappears.
As a result of this kind of proximity we no longer live in the same space as our parents did.

CITIES ARE NOW VERTICALS...

It can be more efficient to live in Bruxelles (Belgium) and work daily in London that living in some suburb in London.

*MICHEL SERRES is a member immortel of L’Académie Française and has been a professor at Stanford University, in the heart of Silicon Valley, since 1984.
Pro-Urban segments of the US Population are becoming Dominant

The share of automobile miles driven by Americans has dropped from 20.8 to 13.7 percent in less than 15 years*
The number of nineteen-year-olds who have opted out of earning driver’s licenses has Tripled over 40 years*
1.5 million Americans are turning 65 every year*

THEY WANT TO LIVE IN WALKABLE CITIES

* Walkable City, How downtown can save America, one step at a time, Jeff Speck
So are cities for **Cars or People?**
COAST’s Mission is to Give Cities Back to People and Allow Communities to Thrive

We believe the answer is People

COAST’s Vision is Autonomous Mobility-as-a-Service for People and Goods in Urban and Campus Environments.
So how do we give our Cities
Back to People?
Hi.
The Self-Driving Shuttle...

- ...we brought it to New York city:
  - COAST’s P-1 was the first autonomous vehicle to operate in Manhattan
  - The perfect place to show COAST’s vision for future mobility
  - Fleets of P-1 Shuttles can be more cost effective and flexible than Light Rail or BRT*

“Broadway is exactly where our vehicle was designed for”

*BRT = Bus Rapid Transit
While **COAST** was invented for City Centers...
We focus on **5 key principles:**

1. Safety First
2. Not Dependent on GPS
3. People-Centric
4. Available & Affordable
5. Flexible

If you consider a vehicle with no driver at all & no operator, ... accurate **LOCALIZATION** is mandatory.
COAST vehicles do not DEPEND on GPS or use beacons:

- They can navigate indoors, under tree canopies or next to tall buildings (e.g. in city canyons)
- The system uses 7 complementary layers methods of “localization”
- The system’s Intelligence determines the most significant method in any given environment
LOCALIZATION

- LOCALIZATION LAYERS
  - GNSS Dual Antennas with Speed Sensor
  - SBG Ellipse 2 D
  - Odometry (Dead Reckoning)
  - Map Matching
  - 2D Lidar SLAM
  - 3D Lidar SLAM
  - Optical SLAM

DYNAMIC EVALUATION OF RESPECTIVE EFFICIENCY INCLUDING LEARNING PROCESS
## Autonomous Vehicle **Localization** Situations

<table>
<thead>
<tr>
<th>Situation</th>
<th>Localization</th>
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<tbody>
<tr>
<td>Plane desertic area</td>
<td>GNSS, IMU, Odometry</td>
</tr>
<tr>
<td>Indoor (Airport)</td>
<td>Map Matching, 2D SLAM, 3D SLAM</td>
</tr>
<tr>
<td>Urban canyon</td>
<td>Map Matching, 2D SLAM, 3D SLAM</td>
</tr>
<tr>
<td>Parking lot – no infrastructure</td>
<td>GNSS, IMU, Odometry, Optical SLAM</td>
</tr>
<tr>
<td>Tunnel</td>
<td>IMU, Odometry, Map Matching (lateral), Optical SLAM (longitudinal)</td>
</tr>
</tbody>
</table>
...Our Technology is also perfect for Campuses and Private Sites.
SOUTHEAST ASIAN GAMES

NEW CLARK CITY, PHILIPPINES:
- COAST has been selected by BCDA to provide a fleet of shuttles to move athletes from the village to the athletic stadium & aquatic center
- A pilot that can lead to full-scale deployment in the Philippines' first “Smart City”
KINNEY COUNTY RAILPORT, TEXAS:

- COAST has been selected by Harbor Rail to provide AV service at a 500-acre Union Pacific railyard in Texas
- AVs will move materials from the warehouse to where men are working to repair and maintain the railcars
- AVs will allow Harbor Rail to deploy its personnel more efficiently
- Other tasks identified include cutting grass and perimeter security
COAST has been awarded a 3-year contract by the Florida Department of Transportation to operate P-1 Shuttles on the UCF campus.

- The shuttles will begin by providing autonomous service along two routes.
- UCF is the largest campus in the USA by enrollment, with 68,000 students.
Visit us during our next shows:

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Novi - Michigan

**SINGAPORE 2019**
26th ITS World Congress
21-25 October

Smart Mobility, Empowering Cities

**2020 CES**

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Poll #3

On which autonomous vehicle segment do you mainly focus?

A. Public Transportation - Autonomous Shuttles
B. Trucks and fleets
C. Driverless Cars
D. Mine and Construction
E. Agriculture