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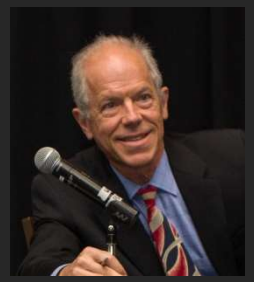
INERTIAL + SLAM: CREATING THE ROADMAP FOR AUTONOMOUS VEHICLES

Wednesday, October 2, 2019

10:00 a.m. PT • 11:00 a.m. MT
12:00 p.m. CT • 1:00 p.m. ET

WELCOME TO

Inertial + SLAM: Creating the Roadmap for Autonomous Vehicles



Alan Cameron
Editor in Chief
Inside GNSS
Inside Unmanned Systems

Raphaël Siryani
Chief Software Architect
Co-Founder
SBG Systems

Jérôme Ninot
Mapping Chief
Founder
Viametris

Pierre Lefevre
Chief Technical Officer
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

Today's Moderator

Alan Cameron
Editor in Chief
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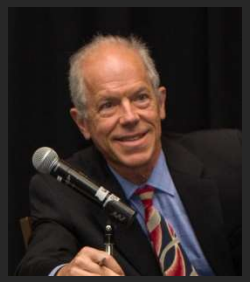

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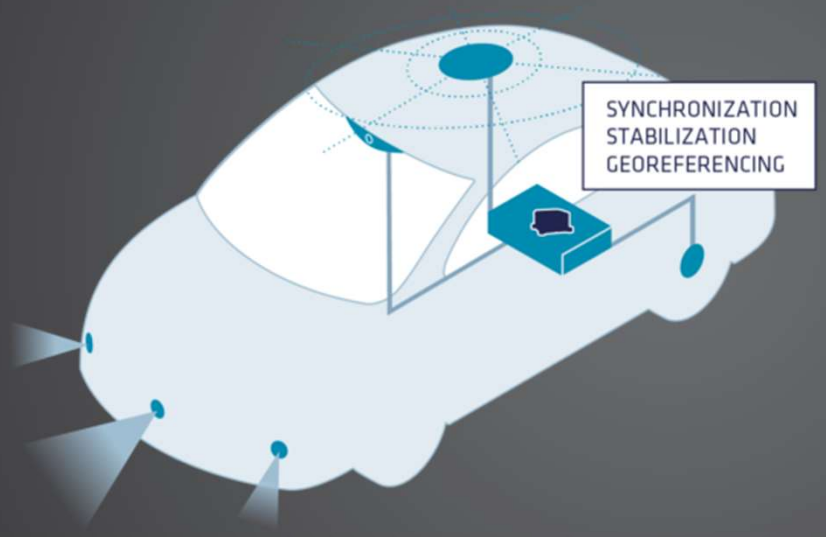
Poll #1

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**.

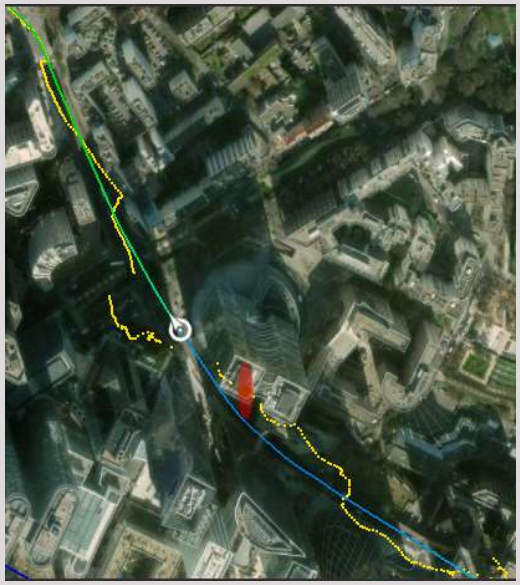
Safe & Reliable Navigation

- 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

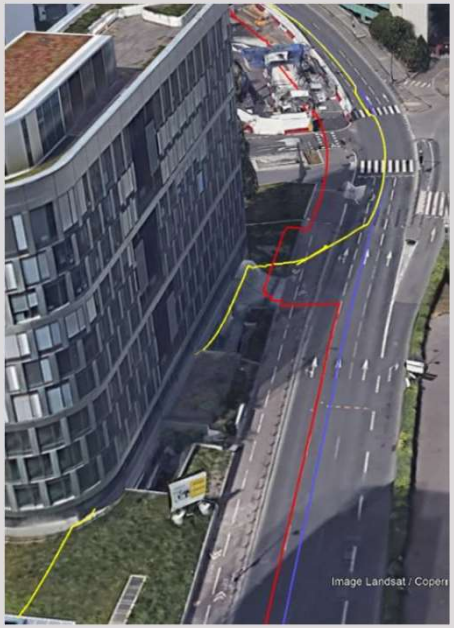


Safe & Reliable Navigation

- Certifications in mind

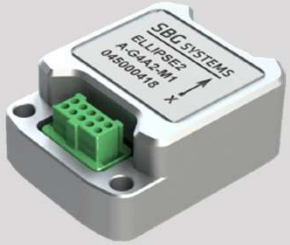
Localization Layer

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

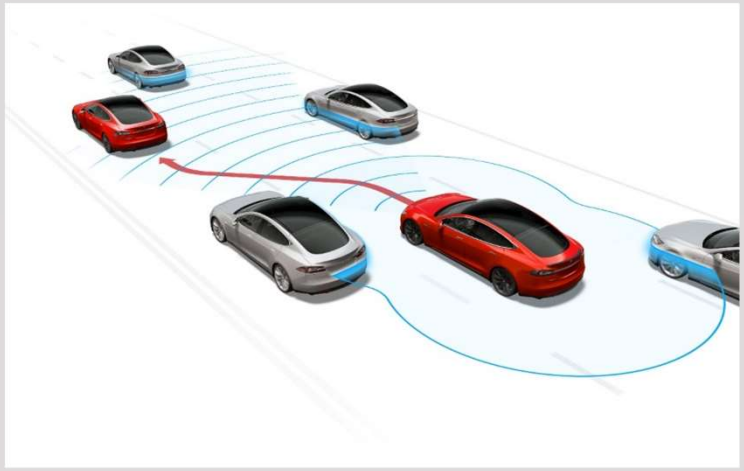


Real time INS Navigation

- 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

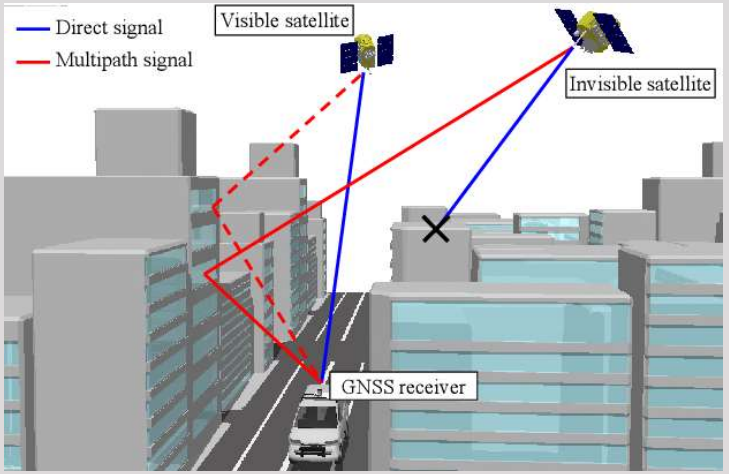
12 years research



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

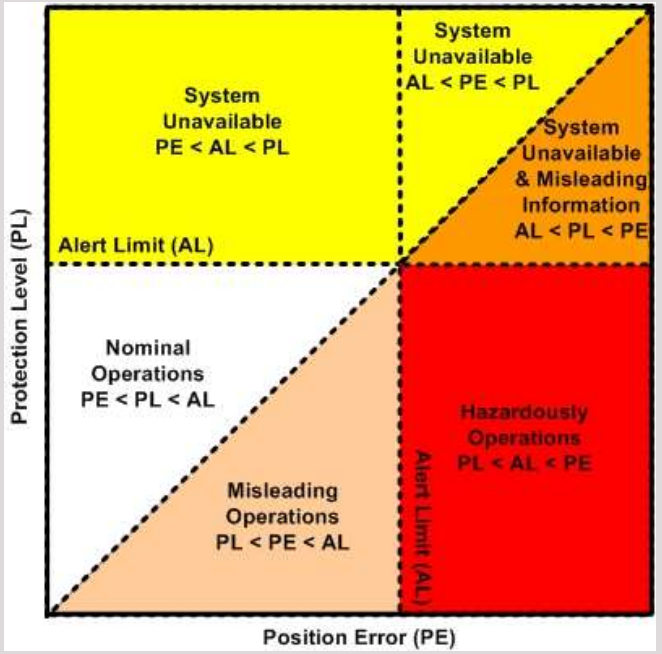


Protection Level & Reliability

- 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

Mandatory for certifications

The Stanford diagram

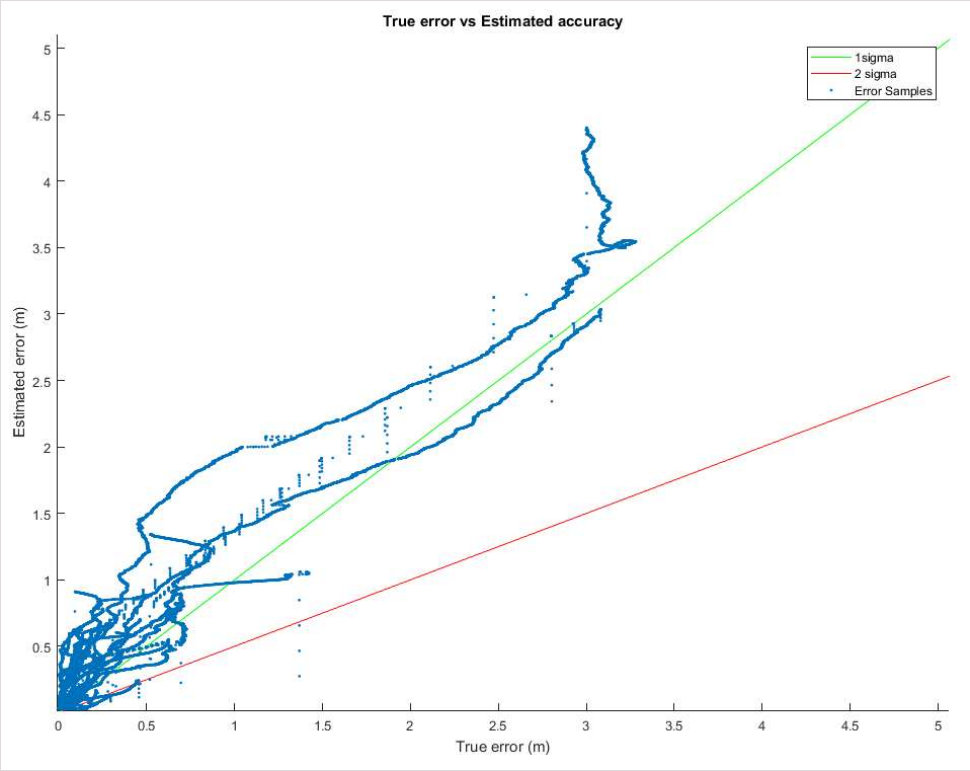


Protection Level & Reliability

- 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

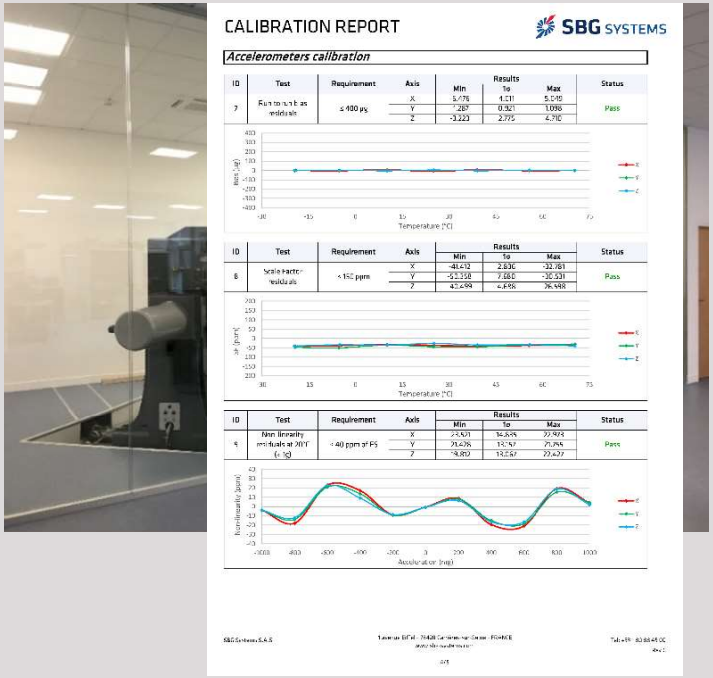
1-Sigma (68%)	2-Sigma (95%)	3-Sigma (99.7%)
< 93.3%	< 98.5%	< 99.7%

Consistent Protection Level



Protection Level & Reliability

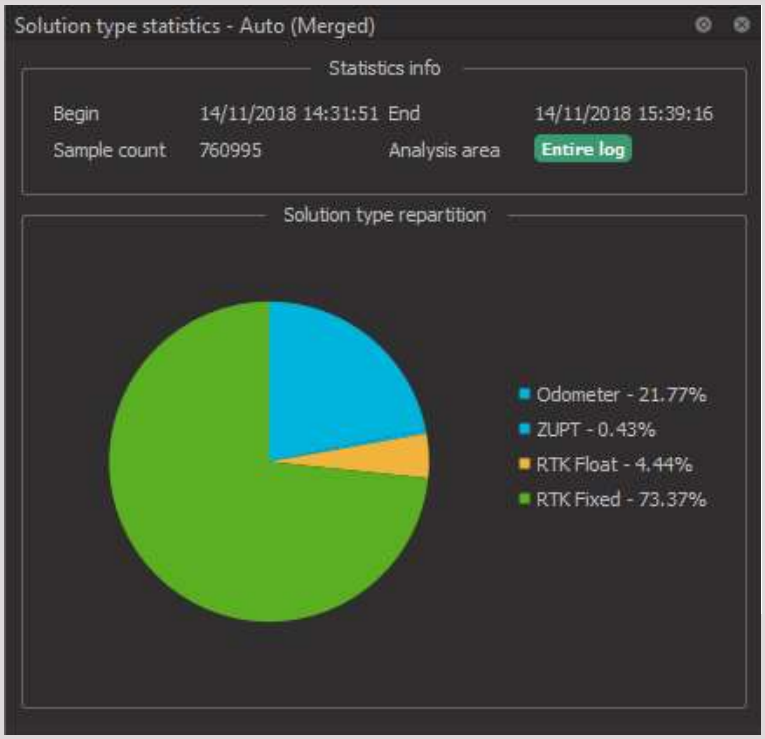
- Focus on resilience & reliability
  - IMU performance has to be well qualified
  - Avoid adding too much states in the EKF
  - Screening and calibrations mandatory
  - Maintain accuracy over temperature
  - And other life-time (15 to 30 years)
- SBG Systems expertise in MEMS IMU
  - Fully automated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

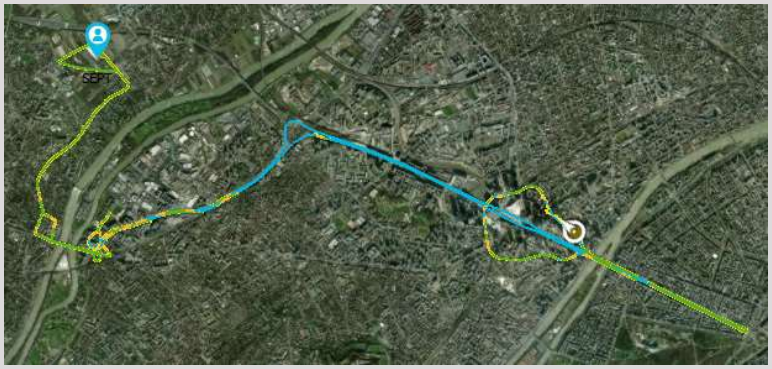
- In house post processing software
- Access the most accurate solution
- Replay scenarios to evaluate behavior
- Add/remove sensors & aiding data
- Powerful quality assessment display
- Consistency checks such as separation
- Several processing modes from PPK to PPP



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

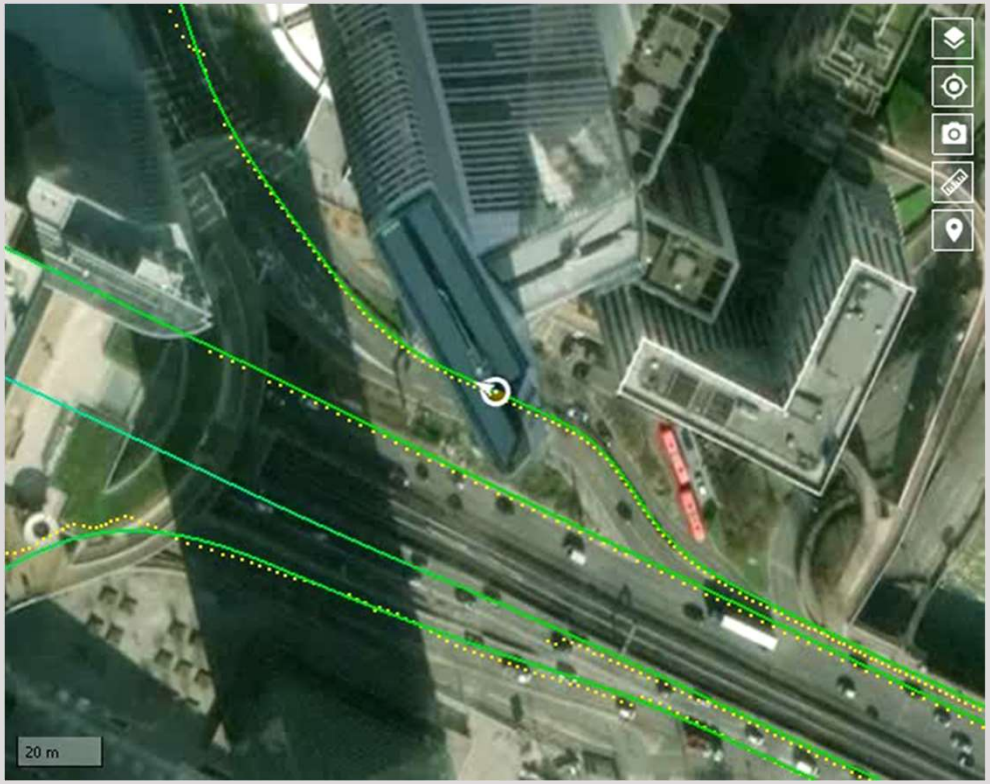


Estimated accuracy	Separation			
	Average	Std.	RMS	Max
Roll/Pitch	0.0024°	0.0006°	0.0024°	0.0043°
Heading	0.0069°	0.0002°	0.0069°	0.0074°

Estimated accuracy	Separation			
	Average	Std.	RMS	Max
Horizontal	1.13 cm	0.20 cm	1.15 cm	2.22 cm
Vertical	1.49 cm	0.37 cm	1.53 cm	3.66 cm

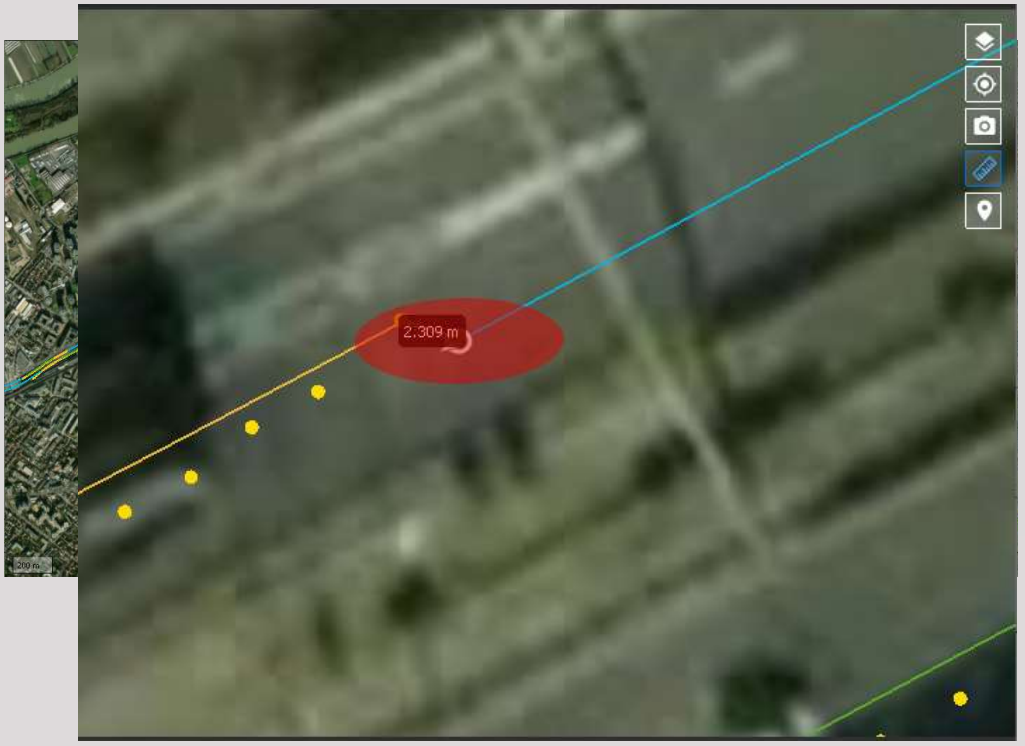
Urban Test Results

- Yellow buildings with GNSS
- Green track: the real time tightly coupled solution
- 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



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

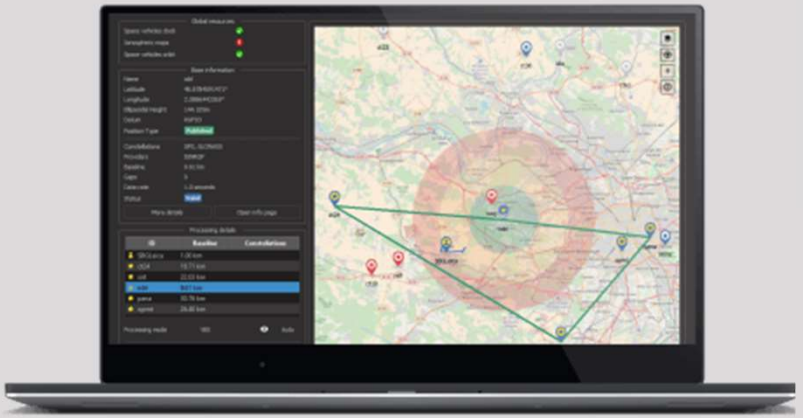
- Large area to map -> efficiency
- Continuously update HD maps
- Need for a cost effective but accurate solution
- Efficient workflow with both real time and post processing

- 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 the best achievable accuracy
  - Very easy and automated workflow
  - Fast processing time
  - Support for all use cases
  - Open to all standards & manufacturers

Qinertia



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Roll/Pitch	0.0024°	0.0006°	0.0024°	0.0043°
Heading	0.0069°	0.0002°	0.0069°	0.0074°

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

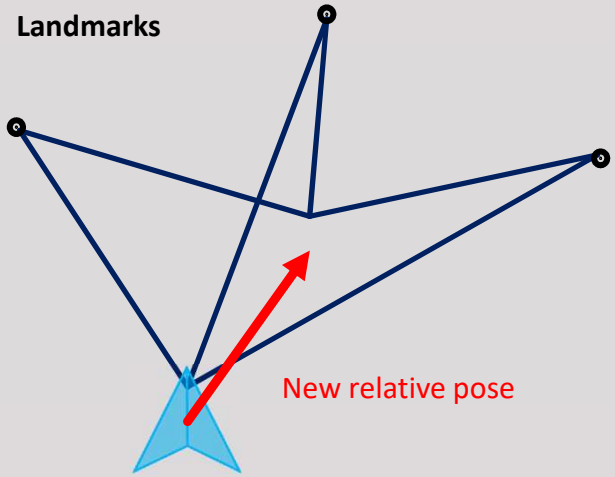
Jerome NINOT, Ph.D.
VIAMETRIS
Founder and CEO

Content

- SLAM Principle
- SLAM & INS Coupling methods
  - SLAM/AHRS
  - True-Heading by SLAM
- Use case
- HD Roadmap

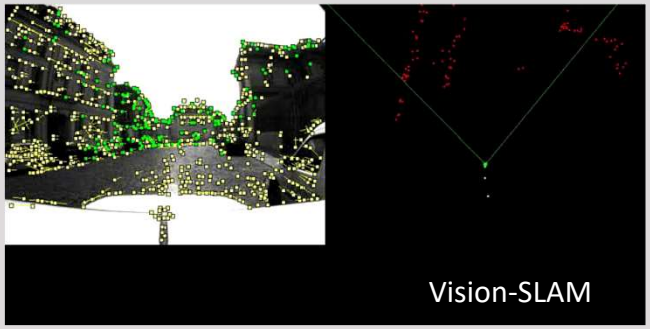
SLAM Principle

- SLAM stands for "**S**imultaneous **L**ocalization **A**nd **M**apping"
- 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



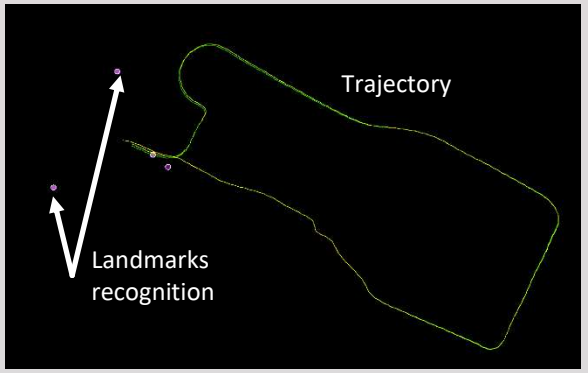
SLAM Principle

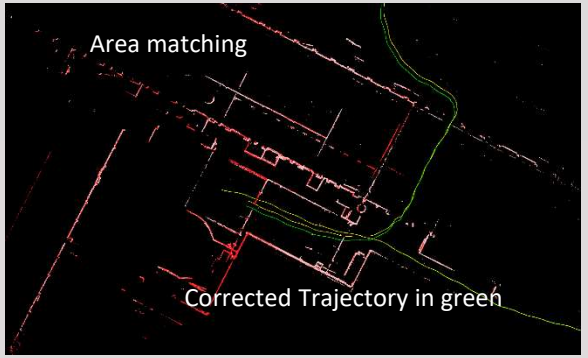
- Relative positioning: starting from (x=0,y=0,z=0) coordinates
- Orientation is without absolute reference starting arbitrarily (Roll=0, Pitch=0, Heading=0)
- Reference frame is natively metric



SLAM Principle

- 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



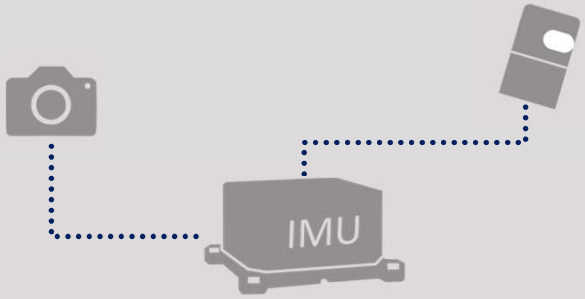


Coupling is not obvious

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

(Latitude, Longitude, Altitude)
vs
(x, y, z)

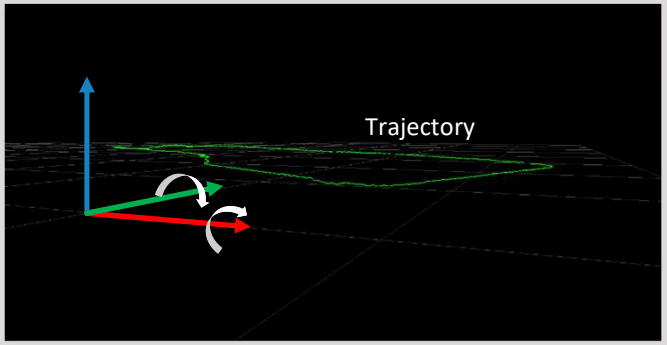
- Calibration issue:
  - SLAM works from LiDAR or camera body center
  - INS body has to be the center of the system



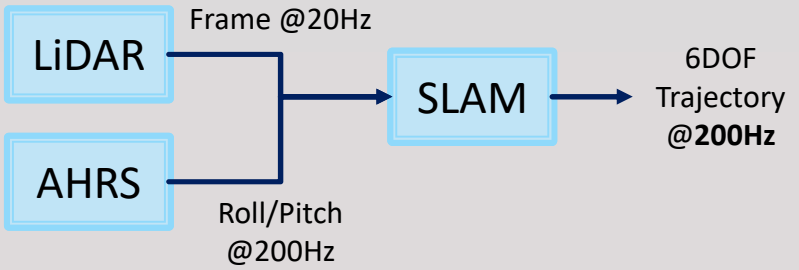
Body frame Alignment and Lever arm measurement

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

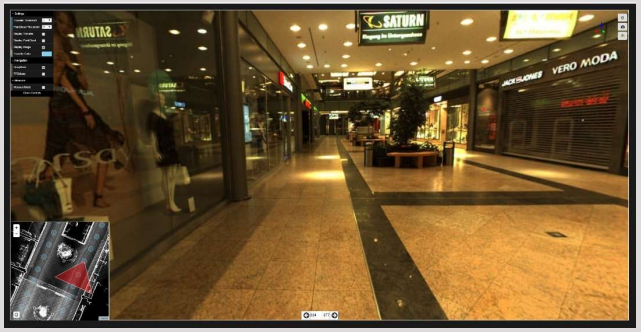


- SLAM depends on sensor frame rate
  - IMU Accelerometers and Gyros aid SLAM to lock proper landmark in case of sudden movements during the pose estimation step
  - The trajectory can be issued at 200Hz with final interpolation



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.)

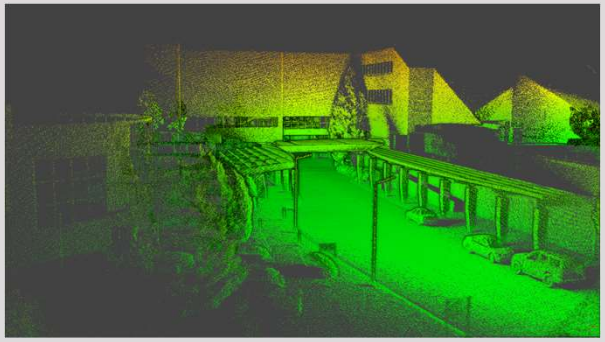


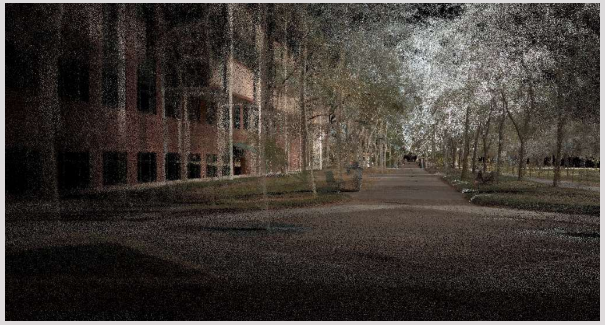
True-Heading by SLAM

- 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

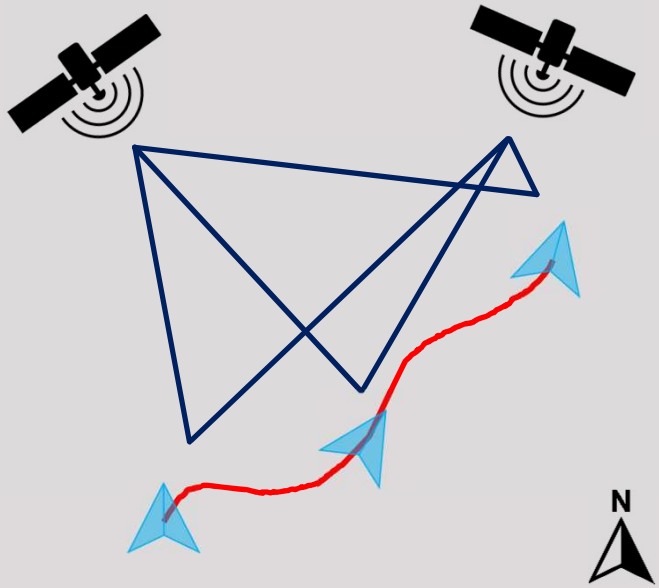
- SLAM has no drift while stationary
  - Maintaining the body heading is easy





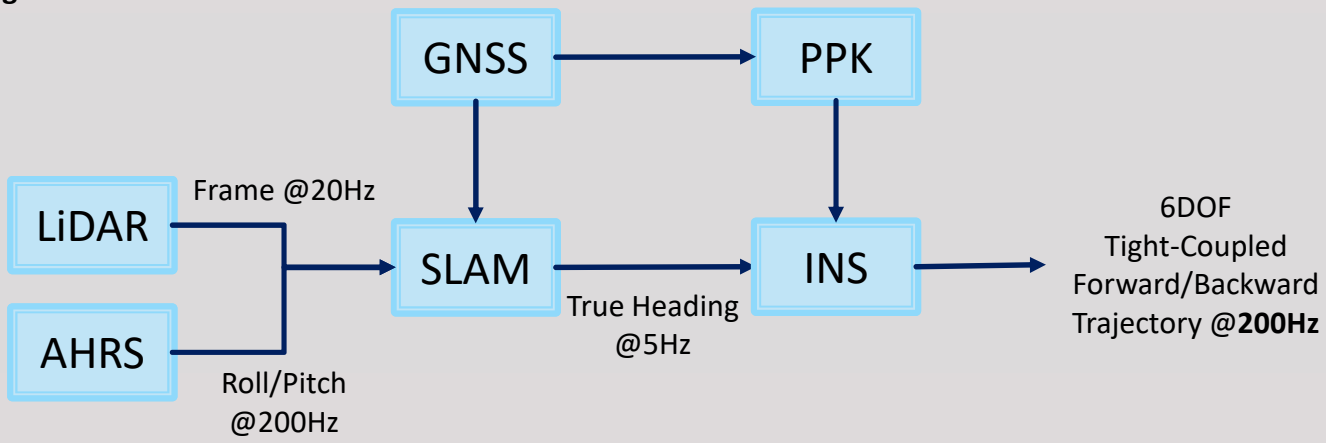
True-Heading by SLAM

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



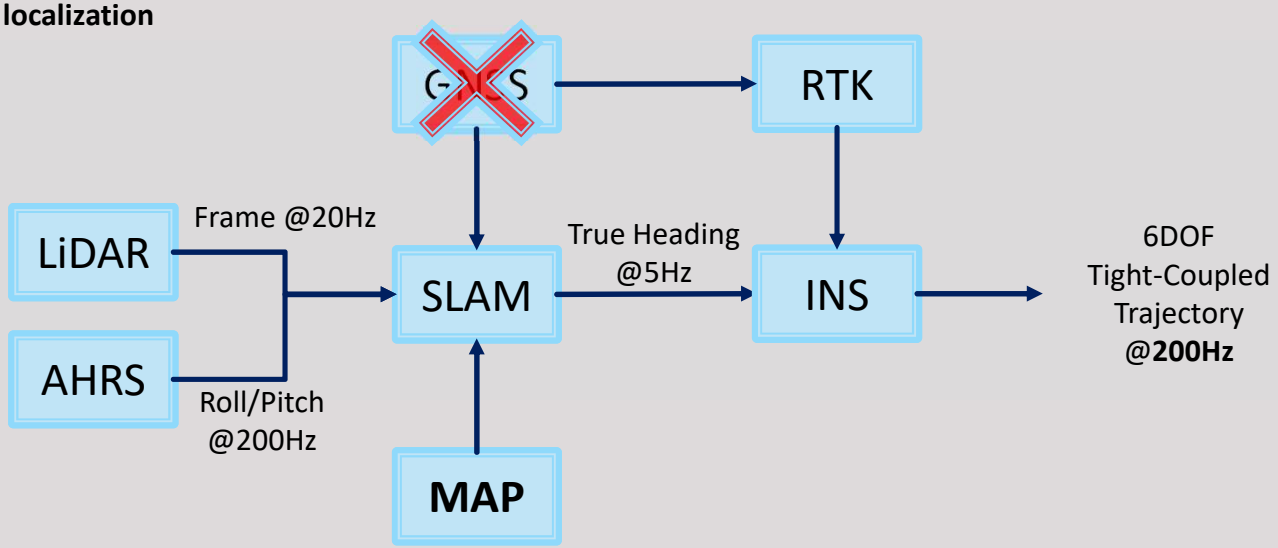
True-Heading by SLAM

CASE 1: Mapping

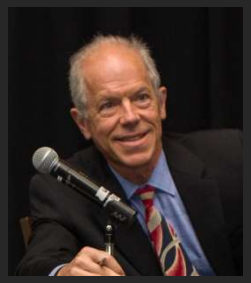


True-Heading by SLAM

CASE 2: Shuttle localization



Ask the Experts



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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

Jerome NINOT, Ph.D.
VIAMETRIS
Founder and CEO

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

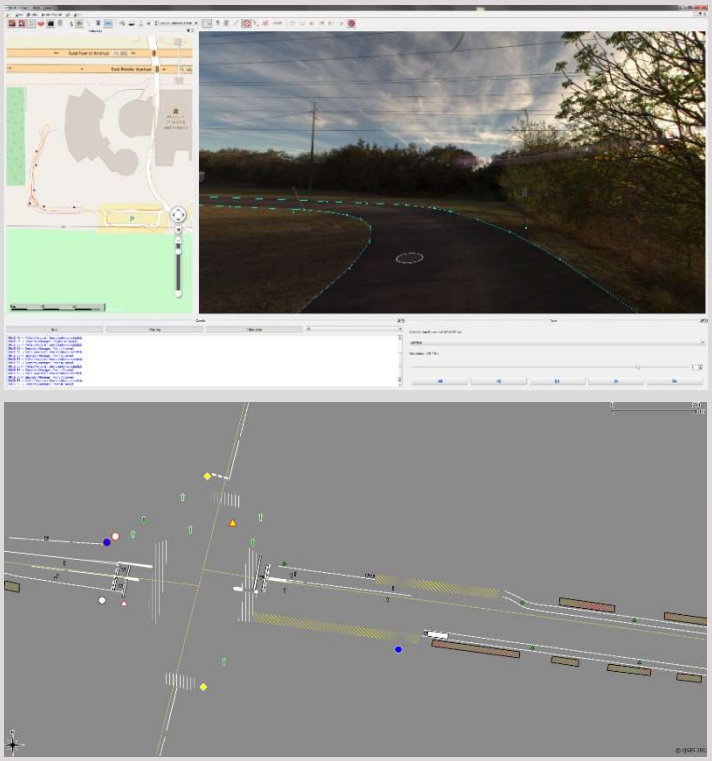
Mapping dense area for Shuttle Roadmap

- 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

From mobile mapping to HD Roadmap

Roadmap is a the 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

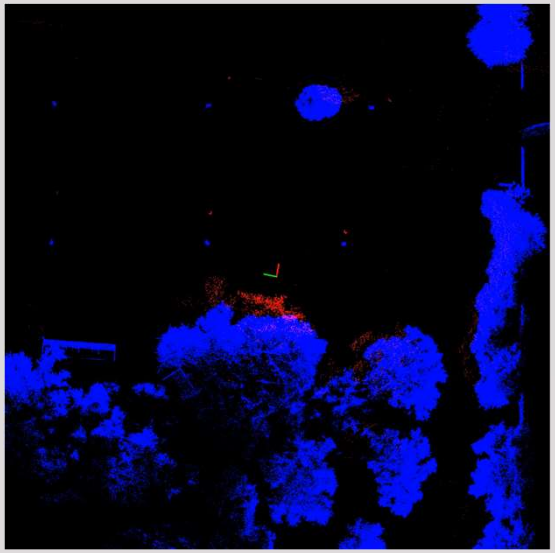


Map Matching

- 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



ViAmetris

MOBILE SCANNING TECHNOLOGY

COAST
AUTONOMOUS

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.

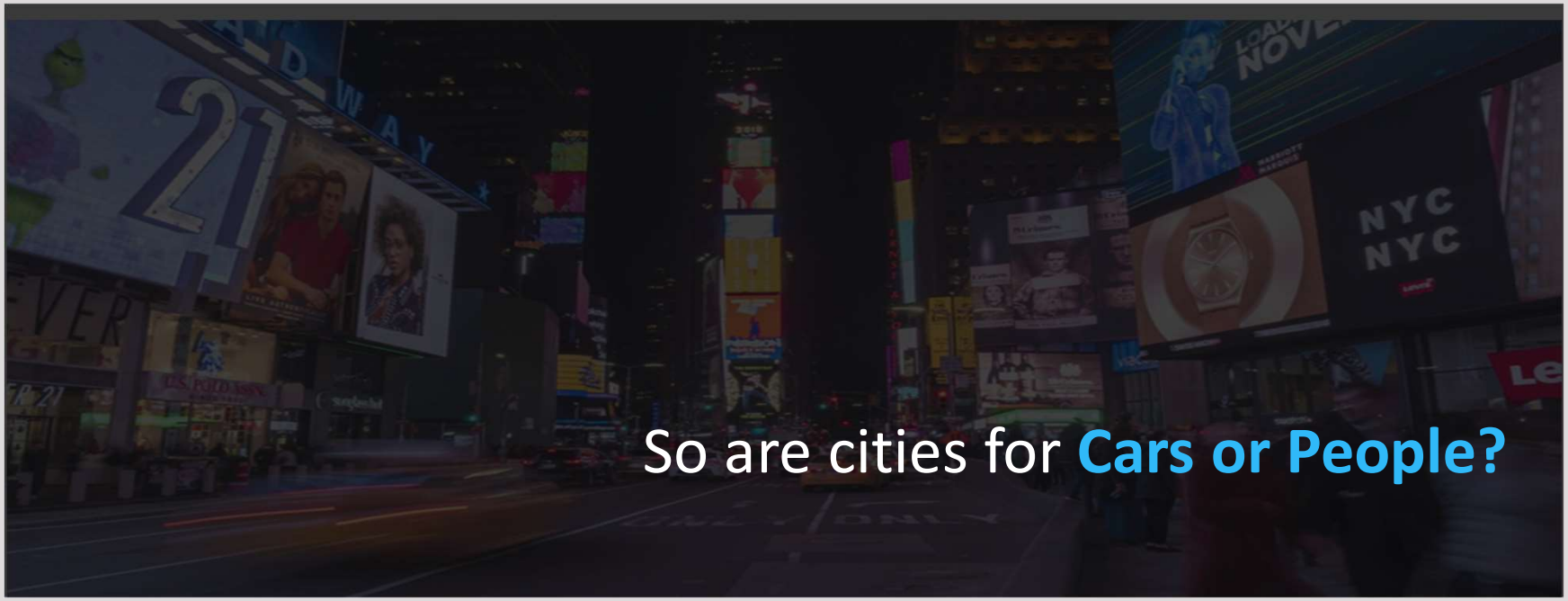
**MICHEL SERRES is a member immortel of L'Académie Française and has been a professor at Stanford University, in the heart of Silicon Valley, since 1984.*

Pro-Urban segments of the US Population are becoming **Dominant**

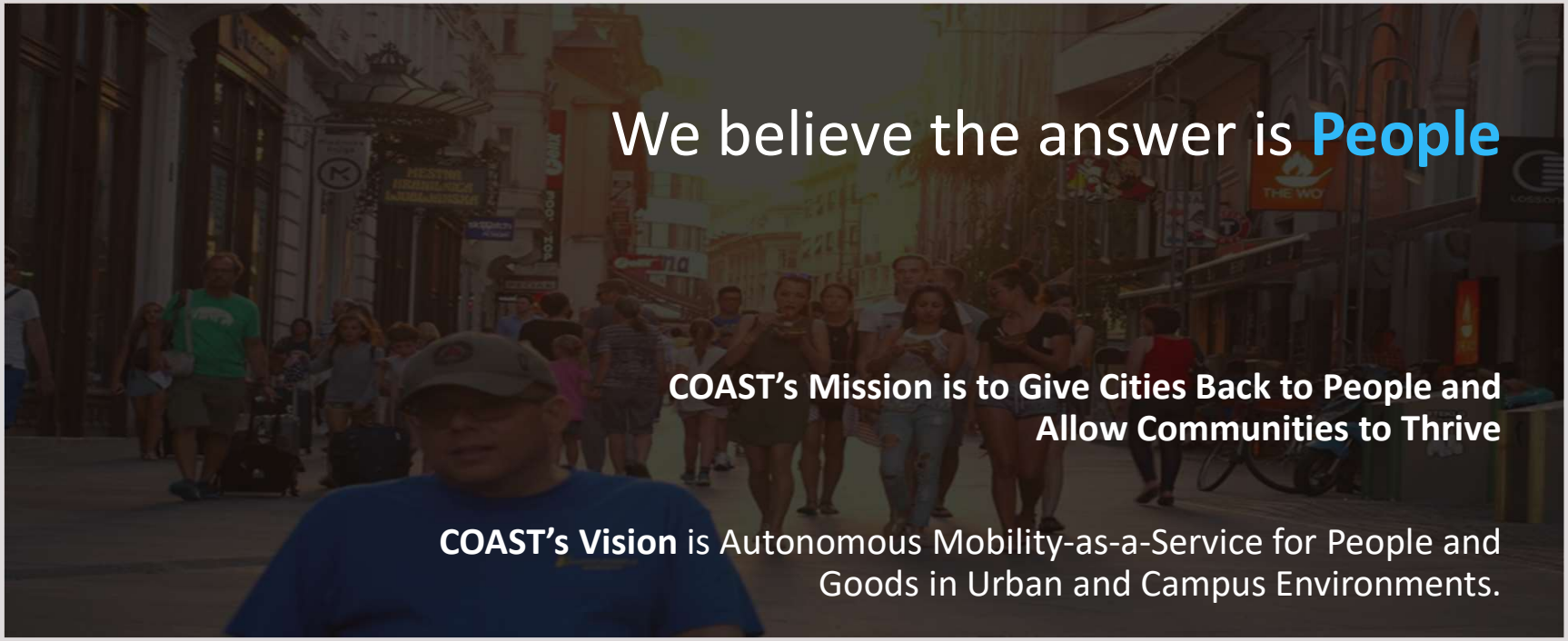
The share of automobile miles driven by Americans has dropped from **20.8 to 13.7** percent in less then 15 years*
The number of nineteen-year-olds who have opted out of earning driver's licenses has **Tripled** over 40 years*
1.5 million Americans are turning **65** every year*

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?**



We believe the answer is **People**

COAST's Mission is to Give Cities Back to People and Allow Communities to Thrive

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.
COAST P-1

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"

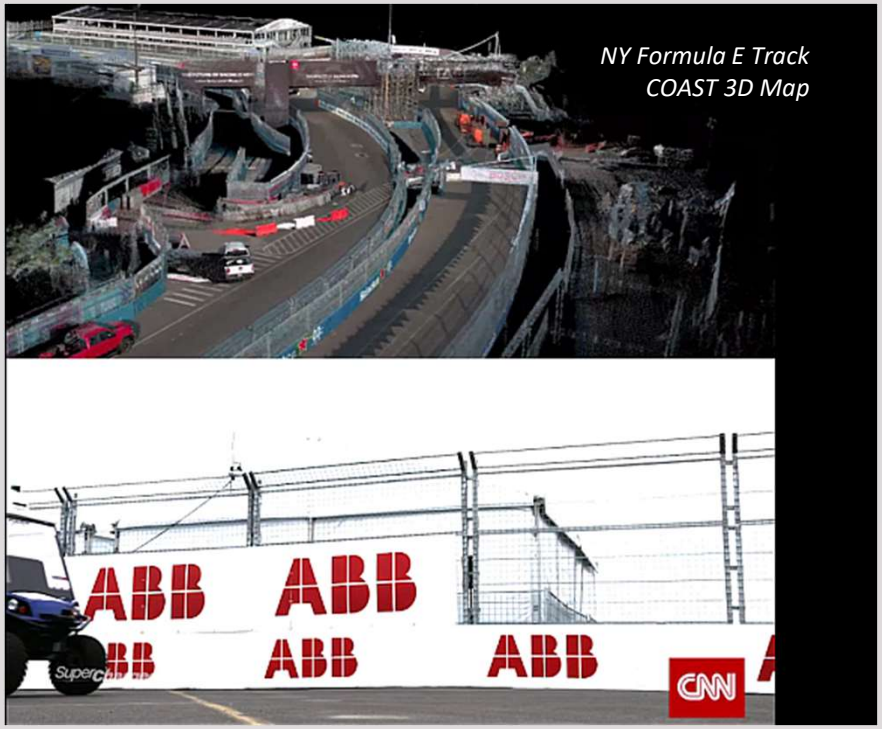
*BRT = Bus Rapid Transit

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



LOCALIZATION

- 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

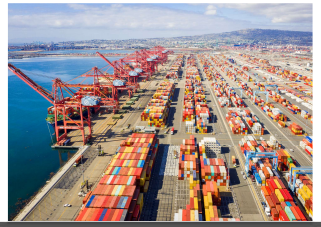
Autonomous Vehicle Localization Situations

Situation	*Localization*
Plane desertic area	GNSS, IMU, Odometry
Indoor (Airport)	Map Matching, 2D SLAM, 3D SLAM
Urban canyon	Map Matching, 2D SLAM, 3D SLAM
Parking lot – no infrastructure	GNSS, IMU, Odometry, Optical SLAM
Tunnel	IMU, Odometry, Map Matching (lateral), Optical SLAM (longitudinal)

University Campuses

Airports

Ports



Retirement Communities

…Our Technology is also perfect for Campuses and Private Sites.

Business Parks

Industrial Parks

Resorts

Theme Parks

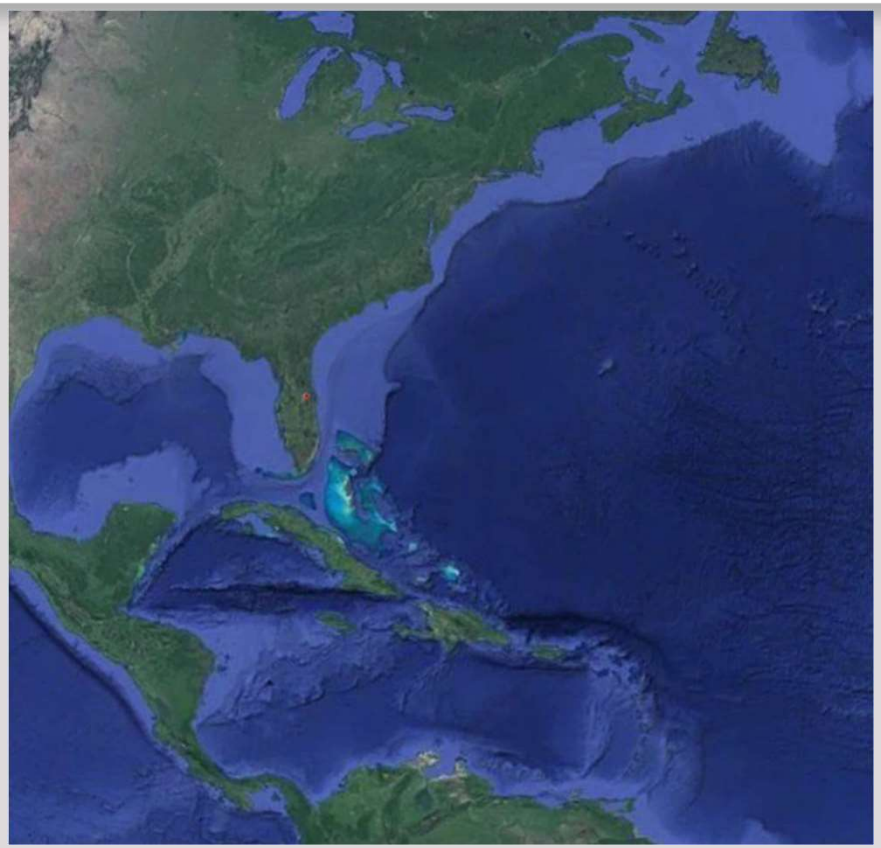
Railyards

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"

UNION PACIFIC RAILYARD

- 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



FLORIDA DOT & UCF

- UNIVERSITY OF CENTRAL FLORIDA, ORLANDO, FLORIDA
  - 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

FDOT

UCF UNIVERSITY OF CENTRAL FLORIDA


SBG SYSTEMS
InsideGNSS
inside unmanned systems
COAST
AUTONOMOUS
COAST P-1
COAST
AUTONOMOUS
Thank You!

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Visit us during our next shows:

Autonomous Vehicle TECHNOLOGY EXPO 2019
Novi - Michigan

SINGAPORE 2019
26th ITS World Congress
21–25 October
Smart Mobility, Empowering Cities

2020 CES®

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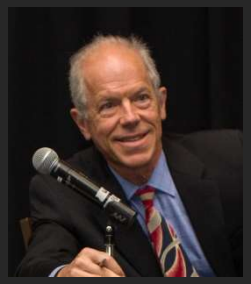
Poll #3

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*

Ask the Experts – Part 2



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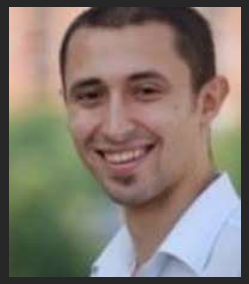

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