ADVANCED GNSS ALGORITHMS FOR SAFE AUTONOMOUS VEHICLES

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SESSION A5: Autonomous and Assisted Vehicle Applications
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MOTIVATION
INTEGRITY IN AUTONOMOUS DRIVING

- Autonomous Driving main concern → Safety of human beings
- Safety depends on a wide variety of factors
- Different sensors to measure dozens of parameters
- Accurate knowledge of these parameters is a key to safety, but even more important is to ensure their reliability ↔ integrity
- The implementation of an integrity layer is crucial

Integrity is the key enabler

- In safety-critical applications it can be more important to know whether information is reliable than the precise information itself.
Dirty compared with aeronautical
- multi-path, NLoS, interference...

Especially in urban and suburban areas:
- Reduced satellite visibility
- Heavy multi-path (especially NLoS)
- EGNOS and future GPS integrity concepts cannot be (directly) applied
- RAIM not appropriate for these conditions

GMV has been working for a decade in developing GNSS-based navigation technologies for automotive applications where integrity and accuracy are top-priority requirements.
ESCAPE PROJECT

- Objective: present the performances achieved with GMV navigation technologies, which are an input to automotive applications → ESCAPE project

**European Safety Critical Applications Positioning Engine** (ESCAPE) is a project co-funded by the European GNSS Agency (GSA) under the European Union’s Fundamental Elements research and development programme

- ESCAPE main objective is to develop a localization system to be employed in safety critical applications like Autonomous Driving (AD) or Advanced Driving Assistance Systems (ADAS)

- Ability to exploit the Galileo OS authentication service

- GNSS/Galileo multi-constellation multi-frequency chipset for road applications

- Hybridization of cameras, maps, vehicle sensors, and GNSS integrated in a tight coupling filter

- Also compatible with Galileo E6 service

- Provision of an integrity layer to the exploited technologies
KIPL
INTEGRITY
ALGORITHM
INTEGRITY BOUND (PROTECTION LEVEL)

1- Compute error distribution
2- Derive PL

\[ P(\text{Error} > PL) \leq IR = 1 - CL \]

- Kalman Filters:
  - Real distribution not known \( \rightarrow \) use statistical model
  - Dependent on the conditions
KIPL INTEGRITY ALGORITHM

- **Driving principle** → new errors are introduced in the solution at each epoch, while the errors in the previous solution are also carried over to the new solution.

- KIPL method introduces a probability distribution for each of the error sources: measurement errors, propagation errors, etc.

- Each distribution is processed and updated separately and provides a contribution to the total Protection Level, requiring:
  - **Characterization** of the measurements errors (dynamically monitored)
  - Update of the different errors distributions → requires a detailed knowledge of the KF update operations

- Once the distribution for the solution errors is known → obtain the protection level associated to any given Integrity Risk.
KIPL INTEGRITY ALGORITHM

- KIPL method is a reliability bound computation algorithm that offers integrity to any Kalman navigation solution.

\[ S_k = K_k X_k + U_k S_{k-1} \]
HYBRID GNSS/INS NAVIGATION + KIPL RESULTS
FIELD CAMPAIGNS

MADRID
- **Hybrid GNSS/INS Kalman Filter** + KIPL
  - using a low cost high sensitivity GPS&GLONASS receiver (STM Teseo-II)
- Environments: Open-sky/Motorway, inter-urban and deep urban
- More than 150,000 samples (42 h)
- Reference track based on NovAtel SPAN with tactical grade IMU (iMAR FSAS)

LONDON
- **GNSS Kalman Filter** + KIPL (without INS)
  - using GPS&GLONASS measurements generated with the SRX software receiver and the TRITON L1 FE
- Environments: Motorway and deep urban
- 400,000 samples (110 h)
- Reference track based on NovAtel GPS&GLONASS L1/L2 with SPAN-CPT IMU and wheel sensor
Accuracy

- Motorway/Open-sky: best accuracy, HPE is typically a few meters
- Urban: HPE reaches 10-15 m around 10% of the epochs
- The use of inertial sensors improves the performances in all the cases
- The results are good for a low-cost receiver given the harshness of the environment
HORIZONTAL PROTECTION LEVELS (HPLs)

- **Integrity**
  - The obtained integrity failure rate values are **always below** the Target Integrity Risk (TIR)

- **Availability (Size of the HPLs) for TIR=1E-4**
  - Size of HPLs clearly improved by the use of **IMU data**

![Availability - HPL [m] for TIR=1E-4: Motorway](image1)

![Availability - HPL [m] for TIR=1E-4: Urban](image2)
STANDFORD DIAGRAMS: OPEN-SKY/MOTORWAY

Madrid - GNSS-only

Madrid - GNSS+IMU

0.168% of 11287 epochs out of plot limits

0 20 40 60 80 100

0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.2
1.5

Normal Operation

MI
Epochs: 0

Epochs: 0
STANDFORD DIAGRAMS: DEEP URBAN

Madrid - GNSS-only

Madrid - GNSS+IMU

*Normal Operation*

- GNSS-only 1E-4 - Urban Canyon
  - Epochs: 5
  - 0.695% of 108320 epochs out of plot limits
  - Kalman-based HPL: 4.61595e-005

- GNSS+IMU 1E-4 - Urban Canyon
  - Epochs: 2
  - 0.355% of 108320 epochs out of plot limits
  - Kalman-based HPL: 1.84638e-005

Log10 of the number of points per dot.
PPP + KIPL RESULTS
PRECISE POINT POSITIONING TECHNIQUE

• Two HA Position solutions: PPP and RTK
• PPP is an absolute positioning technique
• Worldwide or Regional coverage
• Relies on the use of precise orbits & clocks + observations + detailed models
• Sparse network of reference stations for service provision
• **magicPPP** provides the necessary end-to-end services and tools for PPP processing including:
  - Multi-constellation products provision
  - End-user applications for mobile devices and workstations
  - Compatible with DF and SF receivers
  - Multi-Frequency processing **New**
  - PPP + IMU **New**
NEW magicPPP FEATURES

Multi-Frequency Processing

Individual Freqs. + IF Combinations

More data available → Better parameters estimation

magicPPP (SF + IF)
GNSS/INS Processing

**NEW magicPPP FEATURES**

- **High rate solution**
- **Normal Solution (1Hz)**

Update Step → Prediction Step → Update Step

- **Update Step**
  - GNSS Obs.
  - IMU Data
  - GNSS Obs.

**T + ΔT**
PPP + IMU RESULTS

- Deep urban scenario located in Madrid

- **Better accuracy** is obtained when using IMU measurements

<table>
<thead>
<tr>
<th></th>
<th>RMS Horizontal Error (m)</th>
<th>RMS Vertical Error (m)</th>
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</thead>
<tbody>
<tr>
<td>GNSS-Only</td>
<td>3.4</td>
<td>5.8</td>
</tr>
<tr>
<td>GNSS+IMU</td>
<td>2.9</td>
<td>4.1</td>
</tr>
<tr>
<td>Improvement</td>
<td>~14%</td>
<td>~30%</td>
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PPP + IMU RESULTS

- Output position rate
PPP + IMU RESULTS

- KIPL output rate $\rightarrow$ Horizontal PL for TIR=0.05

![Graph showing PL (TIR: 0.05) - Horizontal](image)
PPP + IMU RESULTS

- Stanford Diagram. Horizontal PL for TIR=1E-07
CONCLUSIONS

- **Extensive field campaign** (from motorway to urban)

- **High level of accuracy** achieved by GMV navigation algorithms with low cost receivers
  - [Motorway] Hybrid GNSS/INS: <5m 95%; PPP: < 30 cm 95%
  - [Urban] Hybrid GNSS/INS: <12m 95%; PPP: < 6 m 95%

- **Integrity**: very good results in all the environments
  - Integrity failures below required limits
  - Protection levels well adapted to real performances

- **Coupling** the GNSS measurements **with INS** improves the accuracy and considerably reduces the size of the PLs

- **KIPL** is a reliability bound computation algorithm that offers integrity to Kalman Filter based navigation systems
  - suitable for a wide range of applications requiring a reliable navigation solution (e.g. Autonomous Driving)
Thank you

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