MSFUSION

Next Generation Motion Sensors for Hybrid GNSS/INS Solutions in high accuracy machine control applications [NAVISP-EL1-042]

Table Of Contents

Project Objectives

- Sensor data fusion techniques based on GNSS, INS and complementary sensor data for improved position estimates in challenging use cases.
- Benchmark data fusion methods in indoor, outdoor and mixed scenarios.
- Engineering BreadBoard (EBB) with multiple heterogeneous sensors.
- Emphasis on analysing classical and stochastic approaches, with additional focus and investigation of AI / ML techniques.
  - ML in Filters
  - ML applied to vision-based localization
- Architectures and techniques exploiting clusters of multiple low-cost sensors of the same type.
- Stable timing references (Miniaturized Atomic Clocks) for improved PNT availability in case of reduced number of PNT satellites.
- Simulations for data from different sensors and GNSS

MSFUSION Applications and Use Cases

- Applications
  - Autonomous cars, robots, ships, railways
  - Challenging environments without GNSS coverage, large errors (multipath, low satellite number), intermittent coverage
  - Low cost MEMS IMUs
- Use Cases:
  - Pedestrian
  - Vehicle
- Scenarios:
  - Urban
  - Port
  - Mixed indoor
  - Partial Outdoor

Urban Use Case

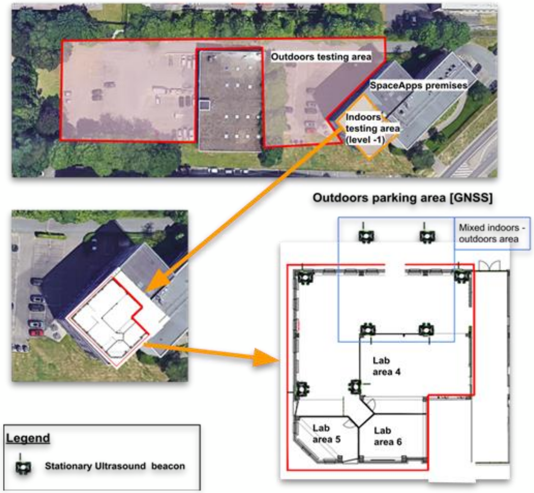
- Applications & Challenges
  - Autonomous cars, robots, transport
  - Challenging environments with limited and partial GNSS coverage (multipath, low satellite number)

Port Use Case

- Applications & Challenges
  - Narrow spaces between containers with large amount of metal objects (avg. 3 containers high)
  - Limited and sporadic GNSS coverage
  - Large moving vehicles and trucks in the field of view

Mixed Use Case

- Applications & Challenges
  - Autonomous cars, trucks, industrial area, warehouse
  - No GNSS coverage when indoor
  - Transition between indoor and outdoor
  - Large errors (multipath, low satellite number), intermittent coverage



Light Indoor Use Case

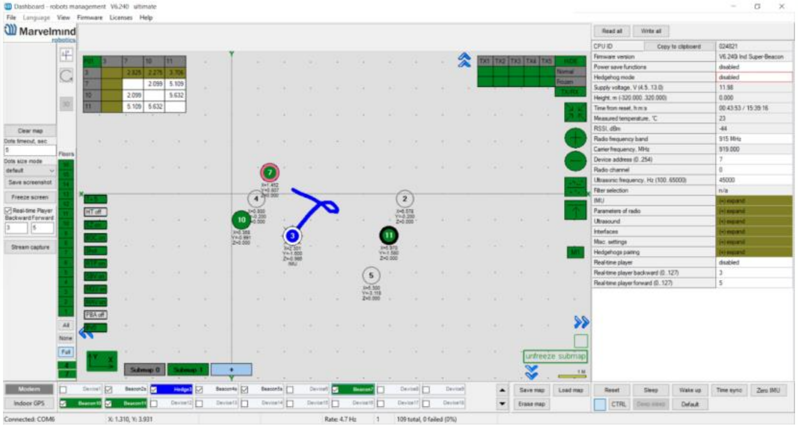
- Applications & Challenges
  - Industrial setting with partially covered areas for storage of vehicles and goods
  - Partial GNSS signals with dead spots
  - Warehouse optimisation, equipment tracking

Ground Truth System

- Open-Sky: RTK + High-Grade IMU (cm-level precision)

Xsens AHRS
MTI-300-2A8G4

- Indoor: Ultra-sound system (4 beacons set-up)



Selection of sensors Analysis for EBB Arch.

- Use case driven technical analysis
  - Broad range of scenarios
  - Lighting conditions
  - GNSS outage/multi-path
  - Visual and ranging
  - Computation limits
- Cost driven
  - VIMU – new development
  - Wifi RTT
  - Cameras
- Real time – more focus than post processed
- Investigate of ML approaches over classical

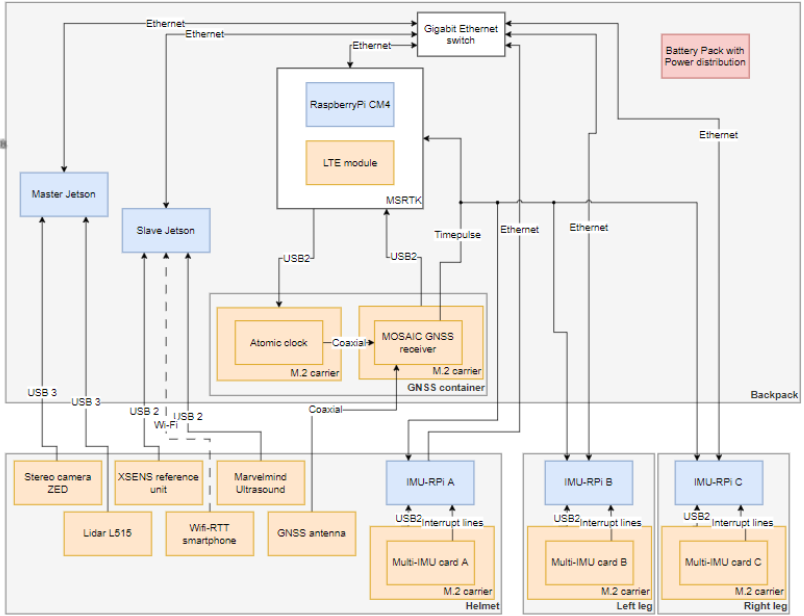
Table Of Contents

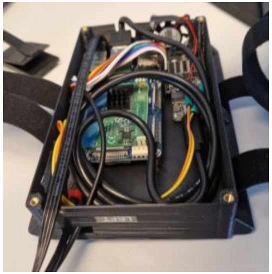
Trade off for Hardware selection

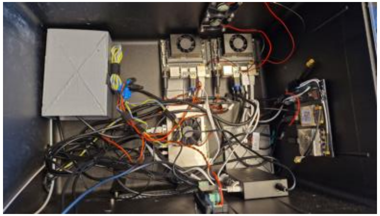
- Jetson Orin NX
  - Octa core processor with 16GB memory
  - 1024 GPU cores operating at 100 TOPs
  - Power rating of 25W
- Zed Stereo camera
  - Low cost
  - High resolution
  - SDK with multiple features
- Velodyne VLP16 (vehicle EBB)
  - Low cost when compared to other 360° LIDARs
  - Dense enough for good feature extraction and sparse enough for real time processing
  - Low power LIDAR sensor
- Intel L515 (pedestrian EBB)
  - Low-weight and low-cost SSL
- Multi-IMU
  - Combined low-cost sensors
  - Benchmark w.r.t. medium / high grade IMUs
- GT
  - Ultrasound – low cost, mobile system, good accuracy

Pedestrian EBB Overview

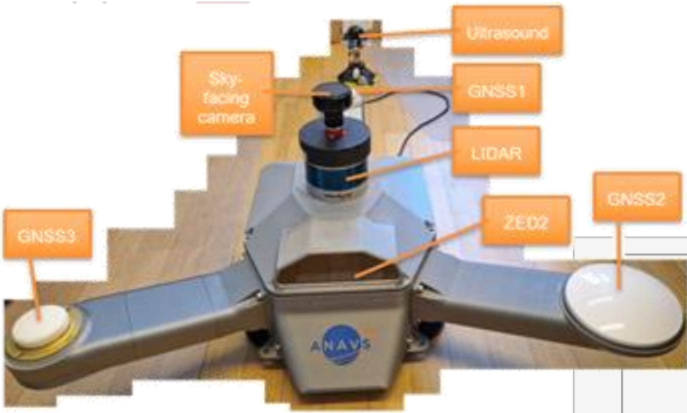
Backpack size driven by the battery (room for improvement)

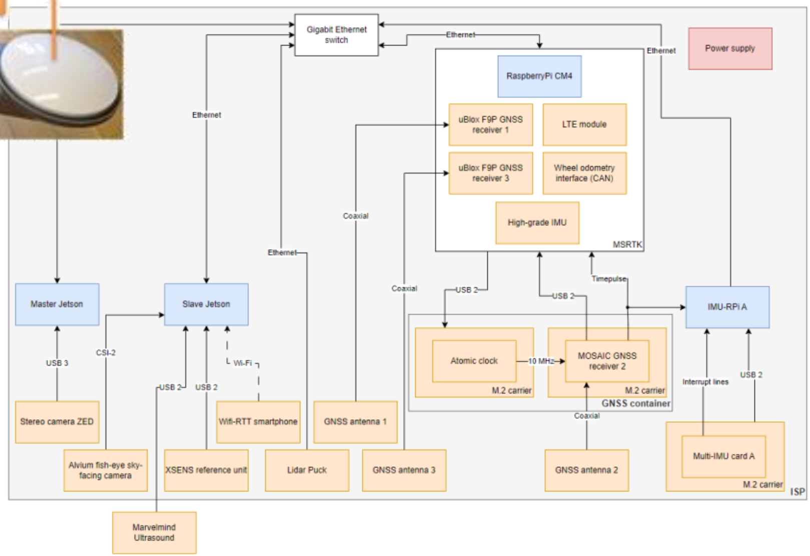




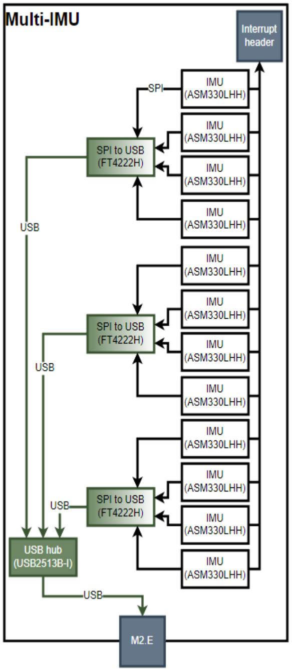


Vehicle EBB Overview





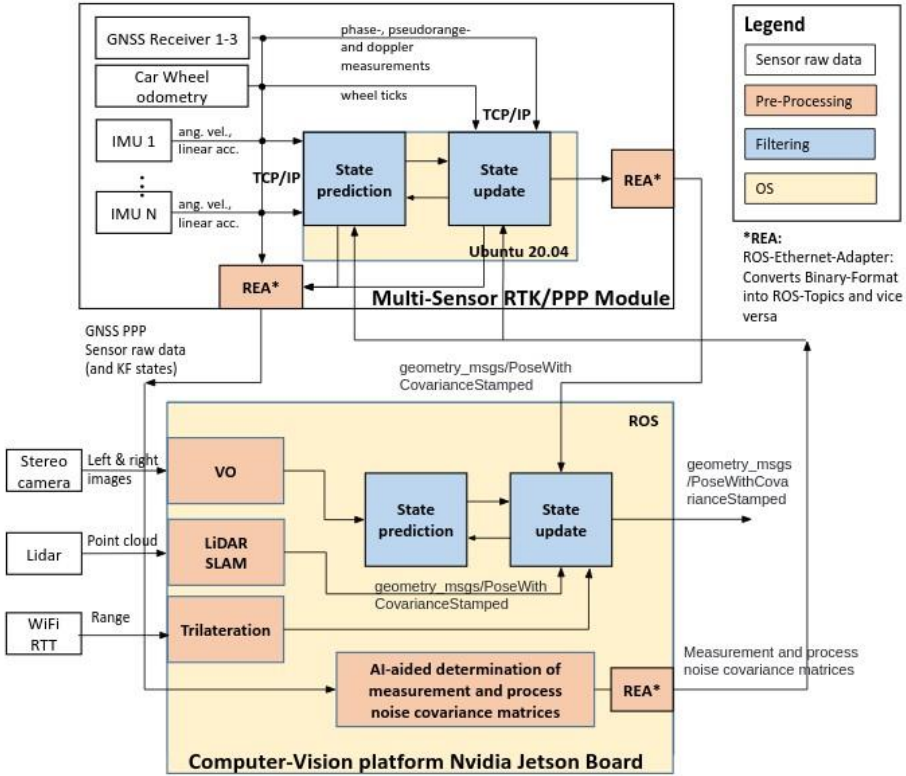
Project Designed Components



- Multi-IMU (STM -ASM330)
- Helmet
- Backpack
- Foot-IMUs
- M2 to USB-C Adapter
- Atomic Clock and MOSAIC-T M2 Card
  - Atomic clock is useful when indoors over a long time to reduce timing drift
  - NTP time sync could also be done but lower precision than atomic clock and needs a local/internet server

Table Of Contents

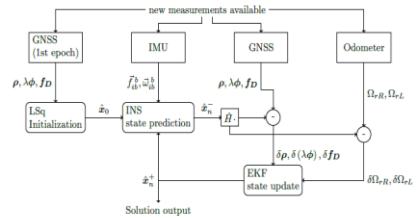
Global Software Arch

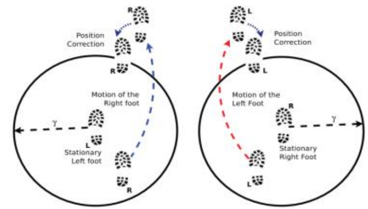


*REA:
ROS-Ethernet-Adapter: Converts Binary-Format into ROS-Topics and vice versa

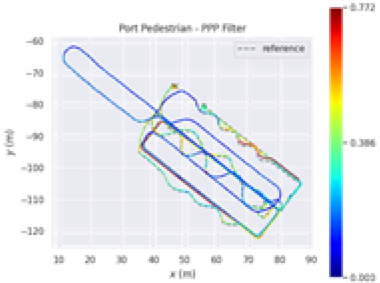
PPP PAD SW

- Tightly Coupled EKF filter (GNSS PPP, multi-IMU and Odometer)
- Vehicle EBB: Attitude determination with the 2 baselines spanned by the 3 GNSS antennas
- Pedestrian EBB. 1D setup. Feet IMU filter
    - Zero-velocity detector to identify the steps
    - Spatial constraint (feet distance within a sphere of pre-defined radius) to minimise the drift
    - Velocity of the left foot fused with PPP filter to reduce drift during GNSS outages



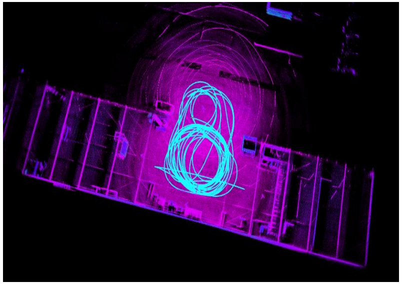


[Source: Prateek G V, et.al., Data Fusion of Dual Foot-Mounted INS to Reduce the Systematic Heading Drift]

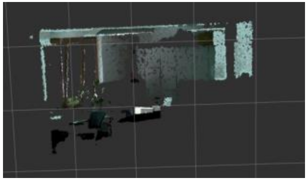


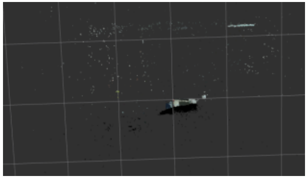
Lidar Odometry

- Vehicle EBB
  - Sensor: VLP16 (mechanical)
  - Point Lio Algorithm
    - Tightly coupled lidar inertial approach
    - Point by point LiDAR feature extraction with state update computation
    - LiDAR state update fused with inertial state update to compute high frequency odometry
    - ikd-Tree for map point insertion/deletion to make the algorithm lightweight.
    - Adaptive voxel parameter tuning for indoor outdoor transitions
    - Adaptive IMU noise parameter tuning to fit accumulated IMU drift.
    - Distortion model to cater to high-speed motions



- Pedestrian EBB:
  - Sensor: Intel L515 (SSL) – useless under ambient light conditions
  - Note: VLP16 was large/heavy to mount on head
  - Fast Lio Algorithm

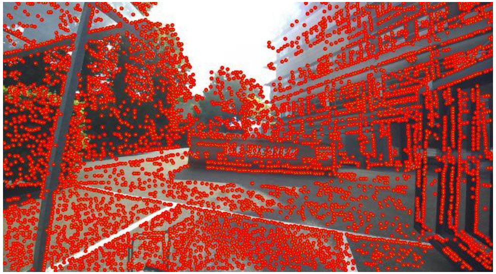


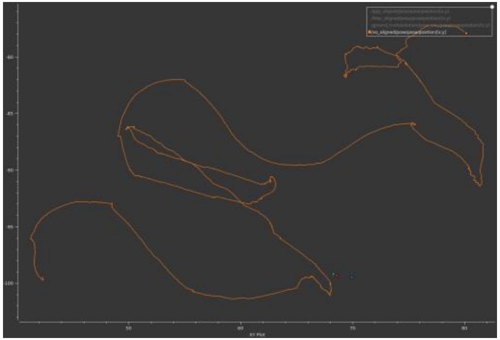


Vision Odometry

- Sensors:
  - Zed2 Camera
  - Zed2 internal IMU

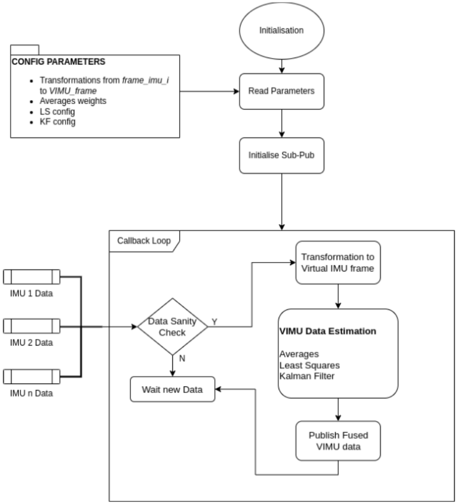
- Visual Localisation track:
  - Full ML algorithm prototyped -> Non-acceptable performance
  - ML combined with classical CV prototyped -> No features tracked
  - MSCKF was tested -> Unstable due to calibration issues
  - ZED package -> Stable solution with minor relative drifts





Virtual IMU

- Fusing the measurements of N imus into one:
  - Three fusing techniques implemented:
    - Averages
    - Least Squares
    - Extended Kalman Filter
- It offers an improved estimation (reduced error metrics compared to a high-grade IMU), redundancy and robustness

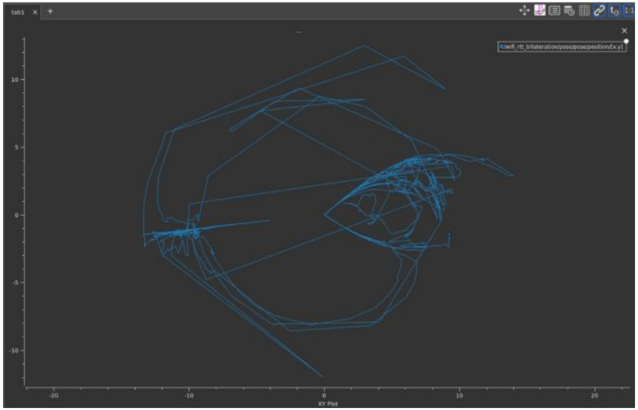


RMSE	VIMU EKF	VIMU Least Squares	VIMU Average	Best IMU	Worst IMU
Angular Velocities	0.309	**0.125**	0.346	0.332	0.342
Linear Acceleration	1.177	**0.881**	1.23	1.163	1.264

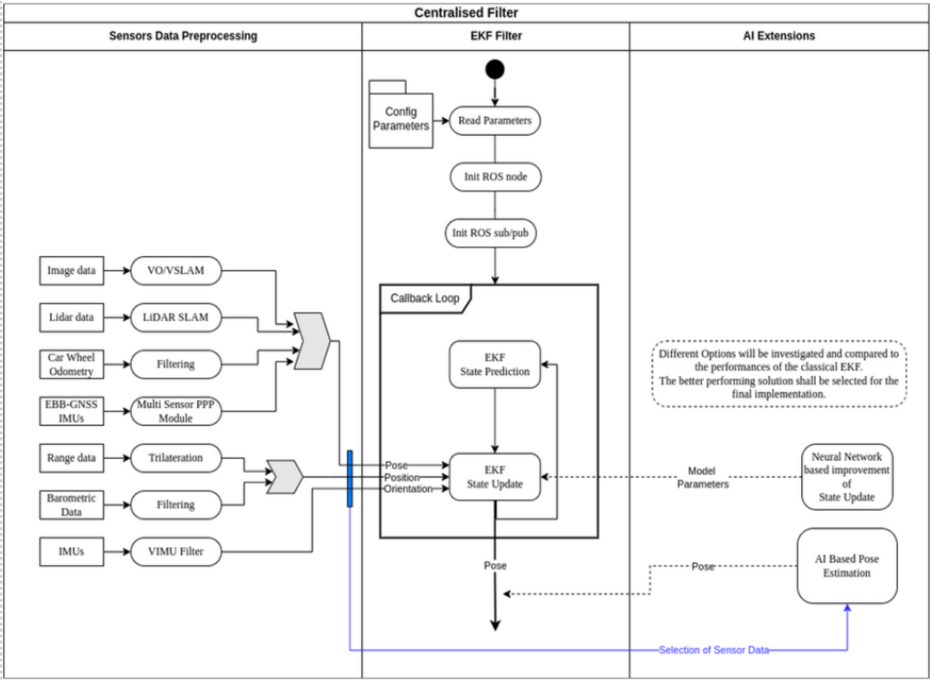
Comparison between RMSE of 3 VIMU methods and Best and Worst IMUs of the group of 10 (benchmarked against a XSens MTi 300) in the Vehicle EBB.

Wifi RTT

- Set Up:
  - 4 Static Access Points
  - 1 Mobile-phone to track the position
- Algorithm:
  - Signal trilateration -> Mobile2AP distance based
- Issues:
  - Not stable -> Jumps of meters
  - Clustered regions (in and out)

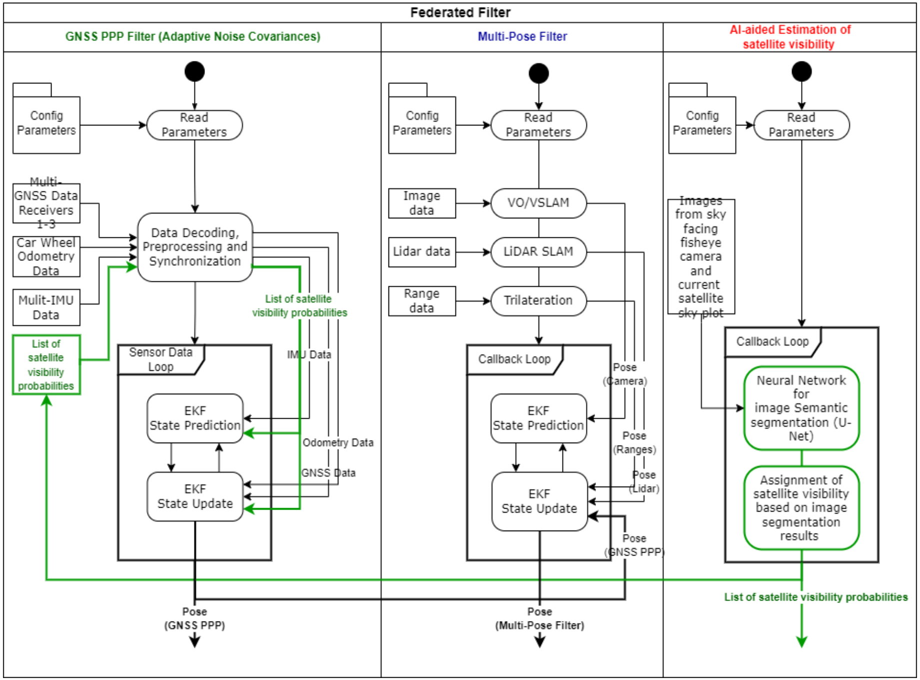


Central Filter



- Prediction step : VIMU Update step: PPP+IMU, Lidar, RTT, and VO.
- In the update, the AI extension KalmanNet was introduced.
- The classical EKF model and KalmanNet model were assessed across all scenarios.
- EKF model demonstrating consistent performance was chosen.

Federated Filter



- Loosely Coupled EKF Filter
- Lidar fusion method
  - Absolute (drift - ↑uncertainty)
  - Relative (stochastic cloning approach)
- Fisheye visibility information used to underweight non direct LOS measurements

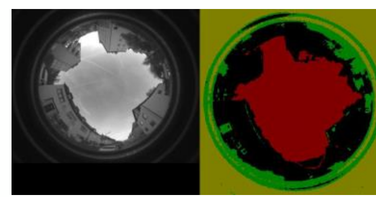
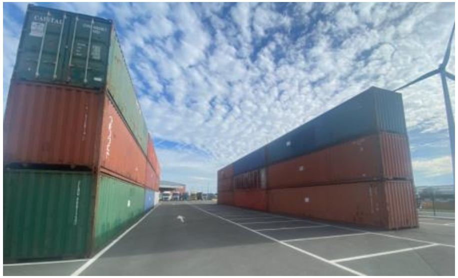


Table Of Contents

Test Campaign Overview (I)

Urban

Port



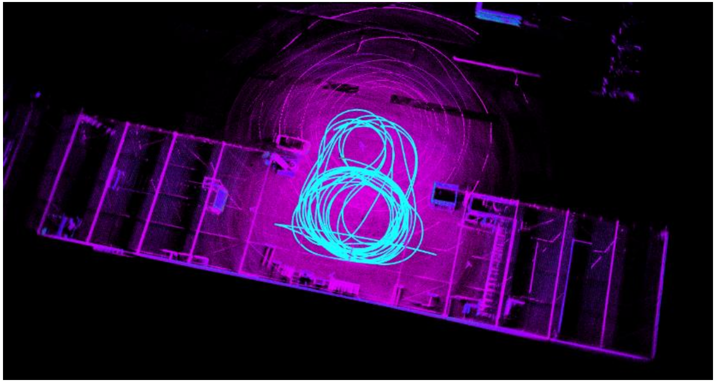
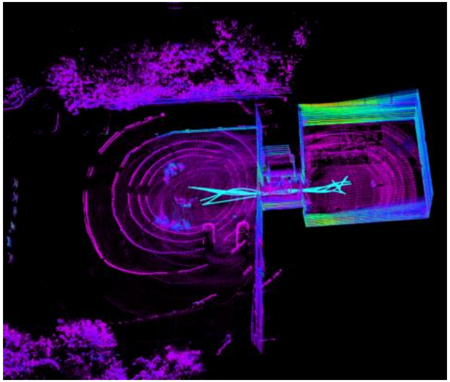
Test Campaign Overview (II)

Light-Indoor

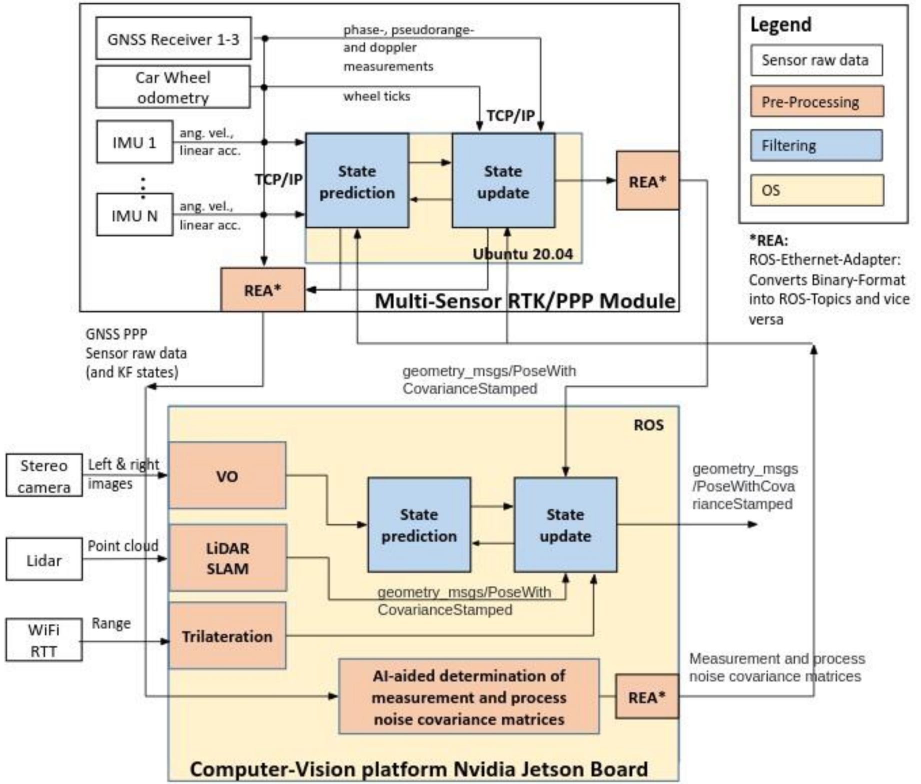
Mixed





Global Software Architecture (Recap)

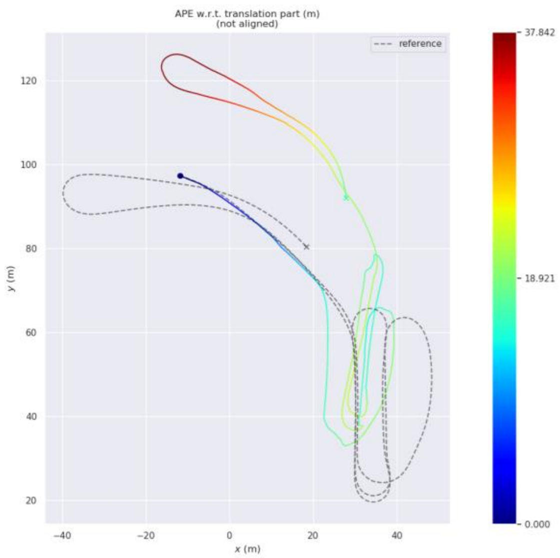


Which subset of results are we showing next

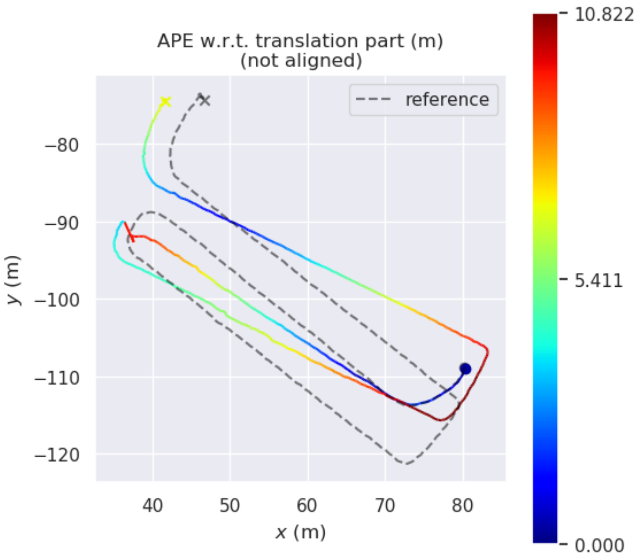
- Results Focus on Port Scenario – has characteristics of outdoor, mixed and partial indoor scenarios
- Results:
  - Individual Algorithm performance
  - Central fusion output performance
- For both EBBs
  - Human
  - Vehicle

Port Scenario – Visual Odometry

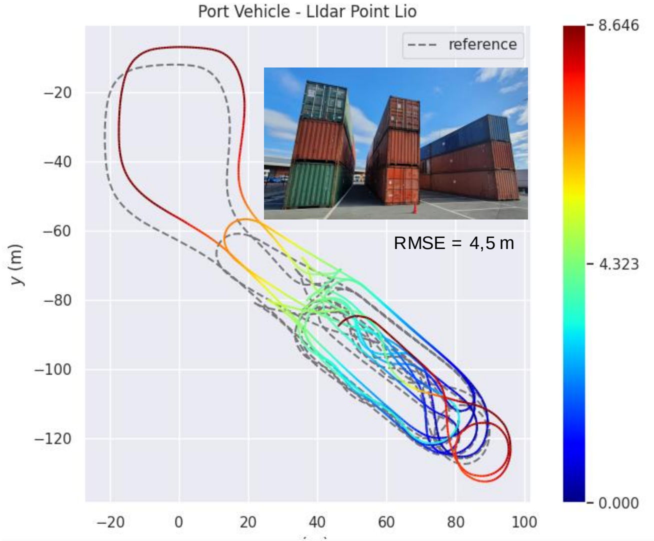
Vehicle EBB



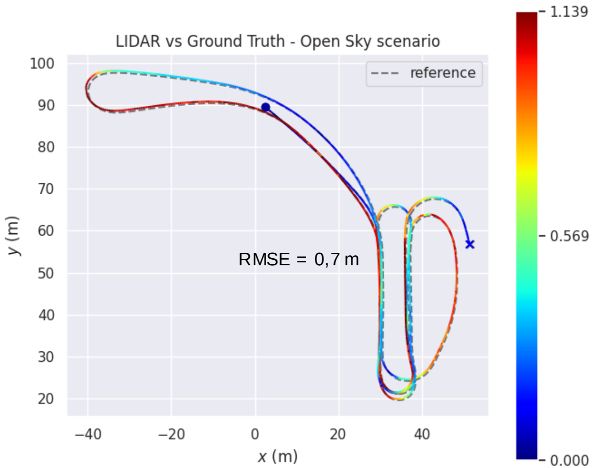
Pedestrian EBB



Port Scenario – Lidar



Excellent results achieved in a port less-challenging conditions (single level containers and more diverse environment)

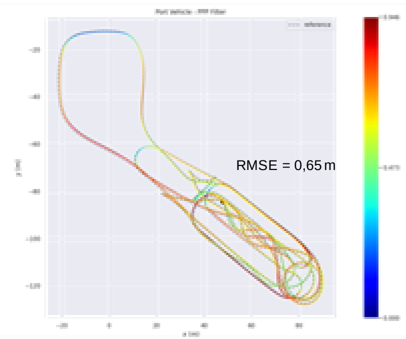


Lidar-algorithm follows very well the reference path

Drift starts when the car drives between containers (planar surfaces with no defined features available).

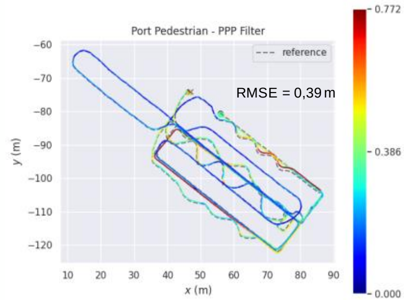
Port Scenario – PPP & IMU Filter

Vehicle EBB



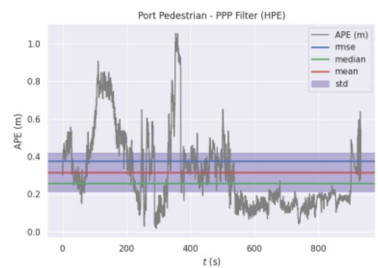
High-accurate results even in very low visibility conditions (GNSS signals occluded by the containers)

Pedestrian EBB



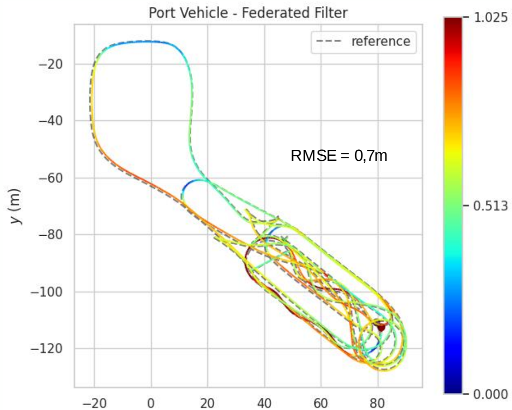
<20 cm horizontal accuracy in open-sky conditions

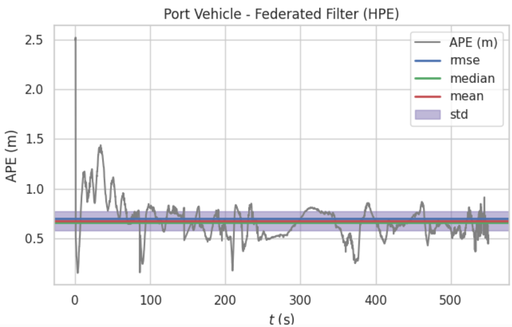
Sub-meter level accuracy when walking through the containers with degraded geometries



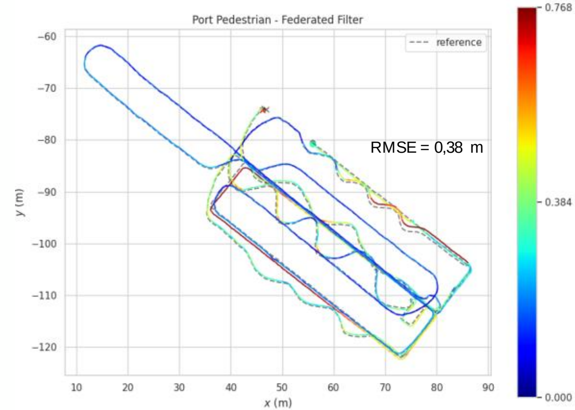
Port Scenario – Federated Filter

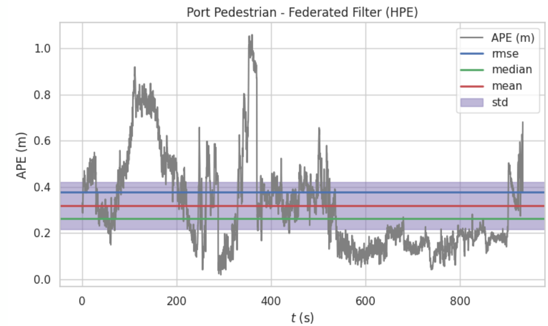
Vehicle EBB





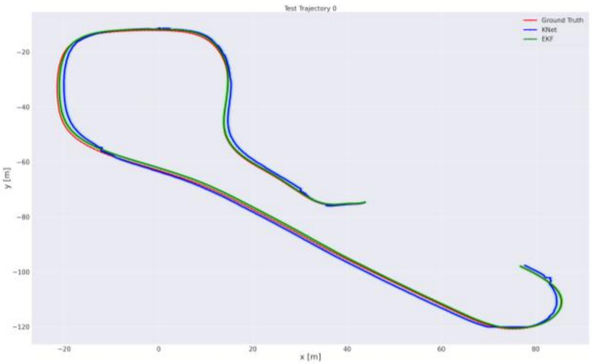
Pedestrian EBB





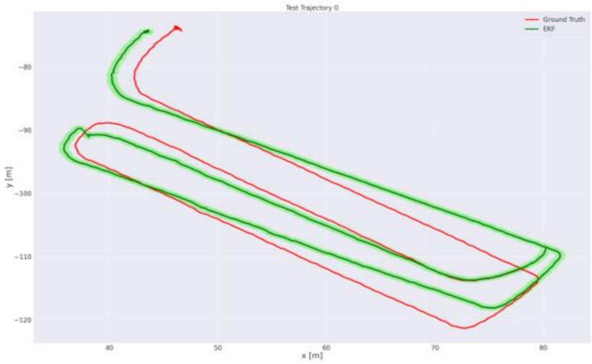
Port Scenario – Central Filter

Vehicle EBB



MSE [dB]: -2.697	
RMSE: 0.733	
x [m]: 0.357	
y [m]: 0.540	

Pedestrian EBB



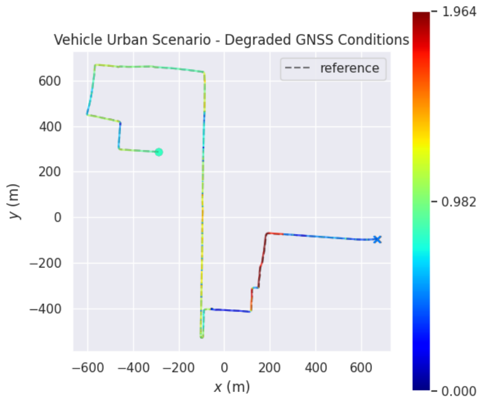
MSE [dB]: -0.613	
RMSE: 0.932	
x [m]: 0.334	
y [m]: 0.686	

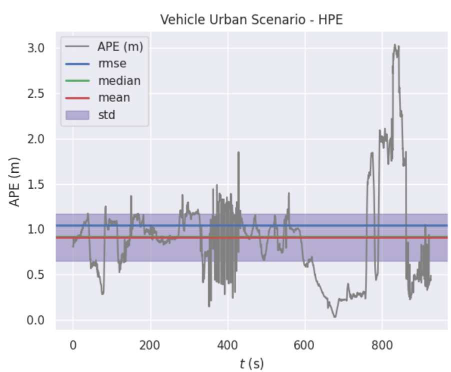
Consolidated Vehicle EBB Results for 3x scenarios

- Previous Slides – provided detailed results of Vehicle & Pedestrian EBB in Port scenario

- Consolidated results of EBBs for other 3 scenarios in the next slides
  - Urban
  - Mixed
  - Partial-indoor

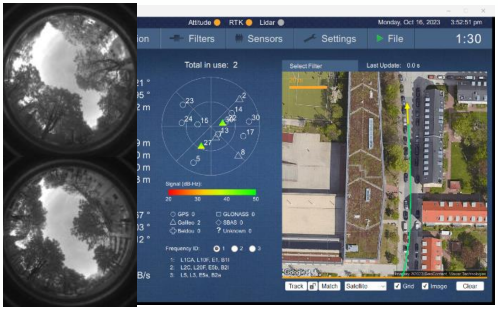
Urban Scenario Results (Vehicle)





- Federated and Central filter solutions relying mostly on the PPP + IMU filter

- Low number of satellites in many parts of the track (inc. initialization)

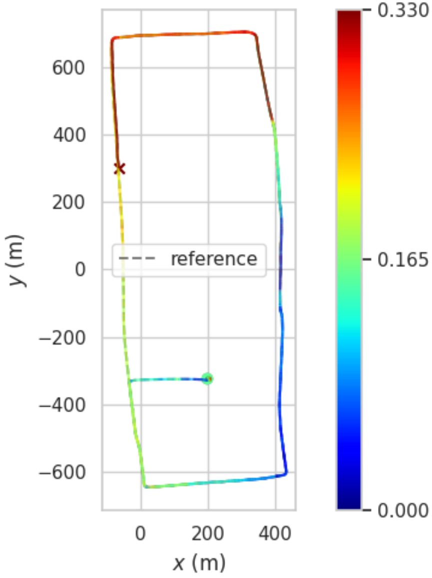


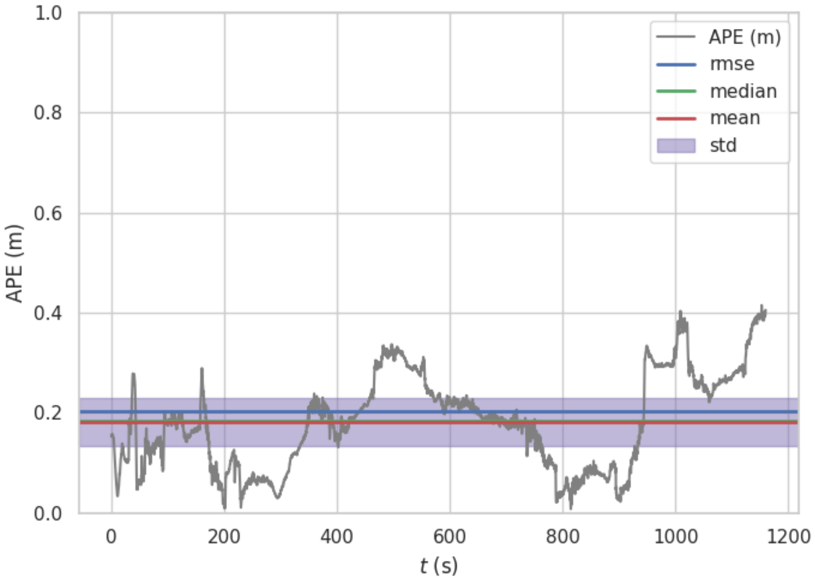
- Signal quality strongly affected by trees and other obstacles, especially in narrow streets

- Dynamical model not perfectly well adapted – tunned.

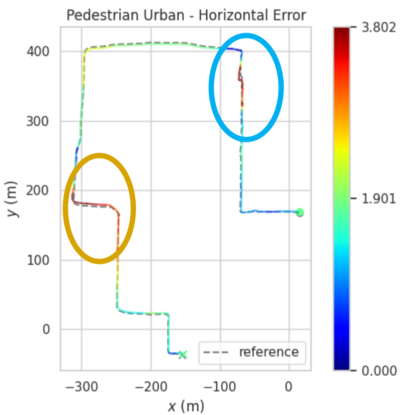
- Pretty good results obtained in any case, considering the quite challenging environment and signal acquisition conditions.

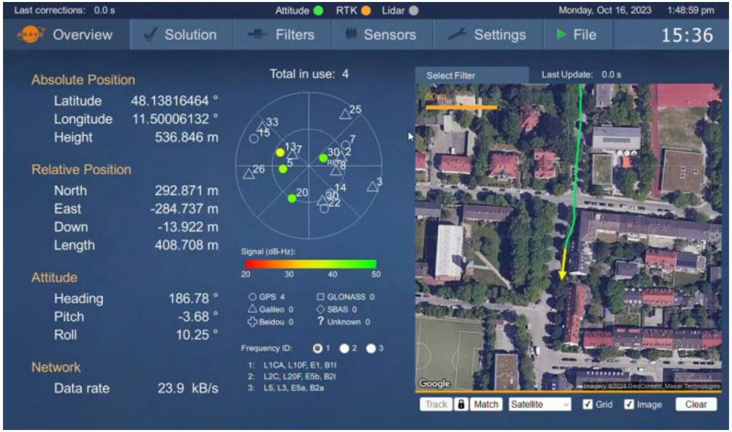
Urban Scenario – Improved Dynamical model





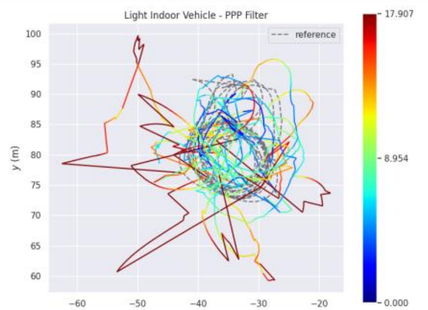
Urban Scenario Results (Pedestrian)

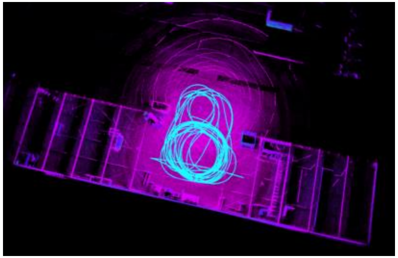




- Sudden drops in the number of valid satellites leading to high position error increase. GNSS degradations driven by **interferences** (multiple sensors and electronic equipment packed in a small area) and **environment conditions** (narrow streets with dense foliage)
- Small offsets at curves, mainly caused by noisy measurements, vibrations and dynamic effects (camera, IMU, antenna attached to helmet).
- Foot-IMU algorithms helps mitigating the solution drift during GNSS degraded situations.
- Velocity of the Foot-IMU filter is only fused when the standard deviation of the PPP position falls below a certain threshold.

Light-Indoor Results





(*) Reference trajectory: RTK for outdoor areas and ultrasound indoor.

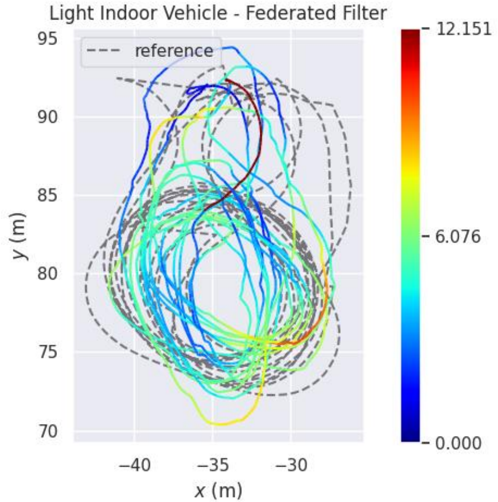
Very complex scenario from the **GNSS** point of view, with continuous transitions from outdoor, semi-outdoor (poor geometry) and indoor conditions.

Excellent **LIDAR** results.

Visual odometry captures the loops and the trajectory pattern but accumulates a large amount of drift over-time.

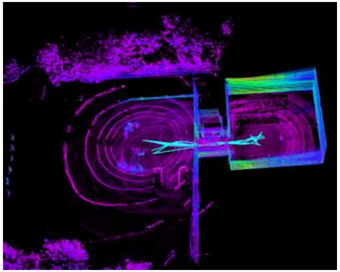
Mitigated in the federated filter - visual odometry velocity used for prediction purposes

Clear improvement shown in the **Federated Filter** performance (w.r.t. the PPP+IMU solution) thanks to visual and lidar-based information.



Mixed Scenario Results

Lidar

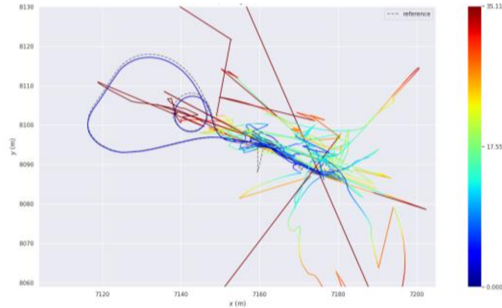


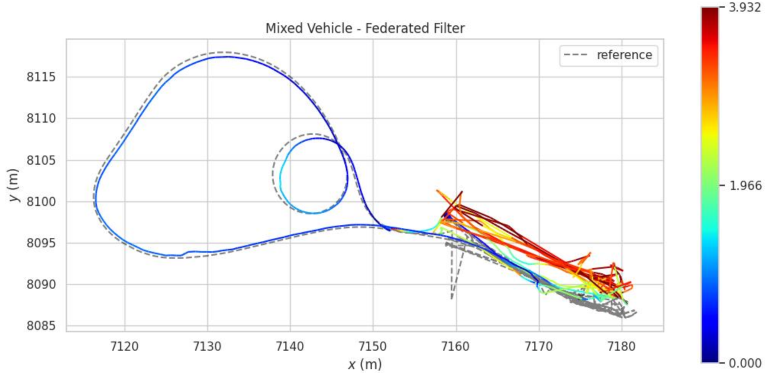
Indoor to outdoor transition and vice versa

Interesting scenario from lidar and visual-based algorithms, with a very **narrow corridor** driving forward and backward

Very challenging though for both GNSS and IMU sensors

PPP + IMU Filter

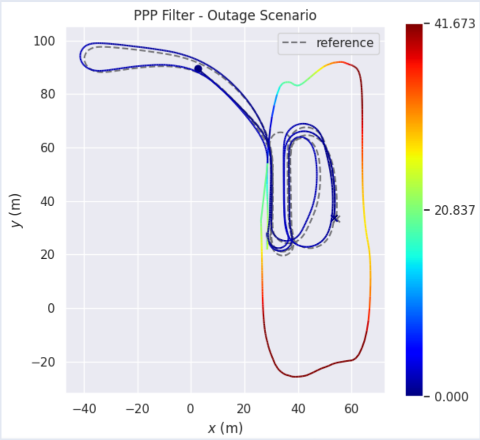


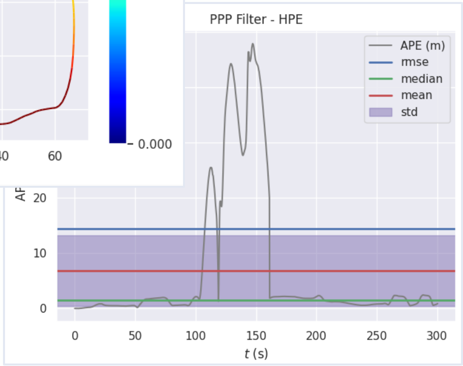


Federated and central filter, thanks to the visual odometry (prediction step) and lidar poses (update step), perform quite well, considering the very challenging conditions, keeping good track of the reference trajectory and providing a **smooth transition** between **indoor and outdoor** conditions.

Port Scenario – Federated Filter – With GNSS 60s Outage

- Performance driven by the PPP+IMU filter in the port scenario
- Artificial GNSS outage scenario tested to demonstrate the filter robustness





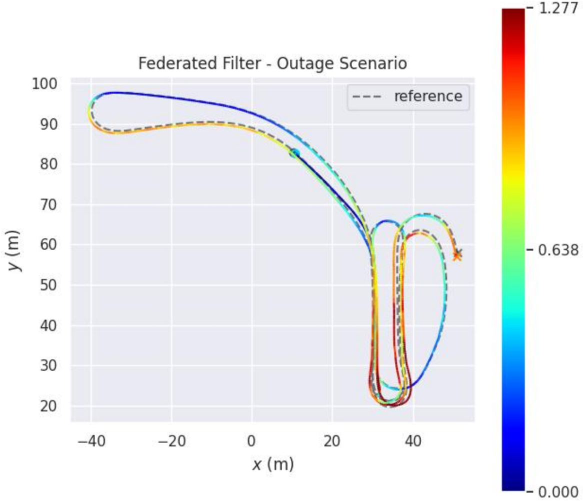


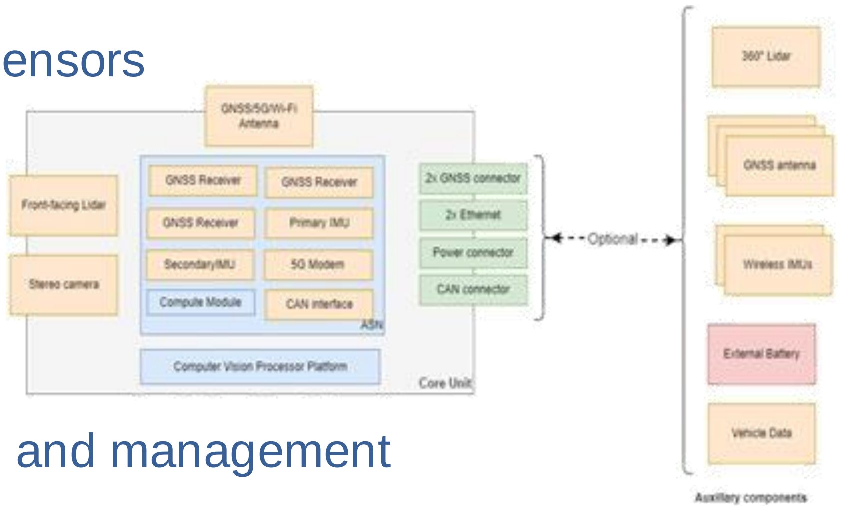
Table Of Contents

Conclusions

- PPP + IMU positioning solution achieved reasonably good performance in outdoor Port and Urban conditions across both EBBs
- Lidar solution achieved good results across all the scenarios with the vehicle EBB; Was not good in human EBB due to sensor
- Visual inertial odometry solutions was found to be strongly dependent on the visual features, camera in the environment at a short range to perform consistently.
- Kalman Net based central filter provided solutions across limited scenarios; Classical EKF based central filter performance was good
- Federated Filter achieved good performance across all scenarios
- Computation constraints and complexity in algorithms development, tuning and gathering data using the EBBs was not a trivial
- Reliable fused positioning across all scenarios was satisfactory; scope remains to improve the robustness of visual localization

MSFUSION v2

- Reduce complexity
- Compact and Flexible Architecture
- Core Unit + Optional sensors
- COTS Selection
- ROS2 Framework
- SLAM approaches
- Covariance estimation and management at central filter level
- Improved Dynamical model



Questions And Answers

BACKUP SLIDES