NAVISP-EL1-055

ATTITUDE CONTROL OF AUTONOMOUS SHIPS NAVIGATING IN PORTS (MAPP)

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ANAVS Advanced Navigation Solutions

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MAPP Project Objectives

- Development of an advanced multi-sensor positioning system for Maritime Autonomous Surface Ships (MASS).
- Positioning, attitude and integrity estimation
- GNSS-PPP, Visual, Lidar, IMU with EKF and Particle filters; RTK as ground truth.
- Performance assessment based on real-world data from the test campaign.
- Future integration into the ship navigation system

Application Scenarios or Use cases

Port Approach

Port Navigation

Docking

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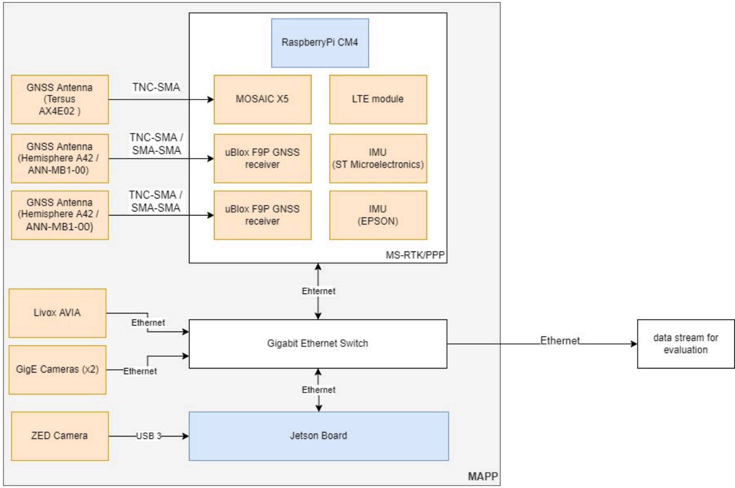
Sensors Set-up

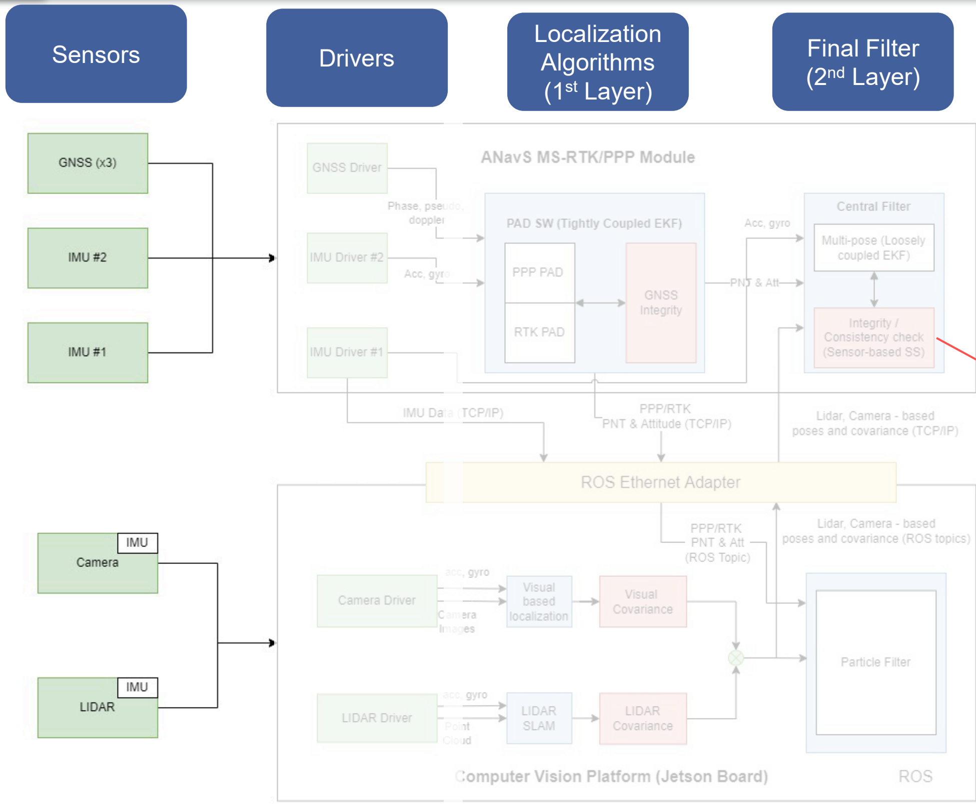
- 3D GNSS set-up for attitude determination
- 2 IMUs
- 2 cameras (stereo vision)
- 1 Solid State Lidar

HW Architecture

- 2 Interconnected Processing platform
  - ANavS MSRTK/PPP Platform
  - Jetson Board (LiDAR and Visual Based Localization)
- Dockerized system
- ROS-based communication
- Real-time and post-processing support



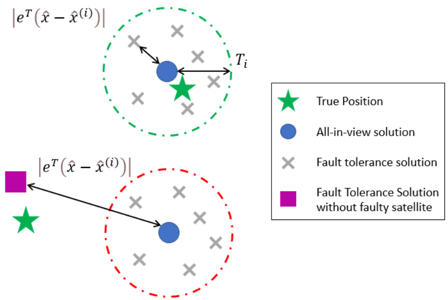
SW Architecture



MHSS-based **Integrity** scheme applied both at PAD SW (tightly coupled EKF) and Central Filter level (loosely coupled EKF)

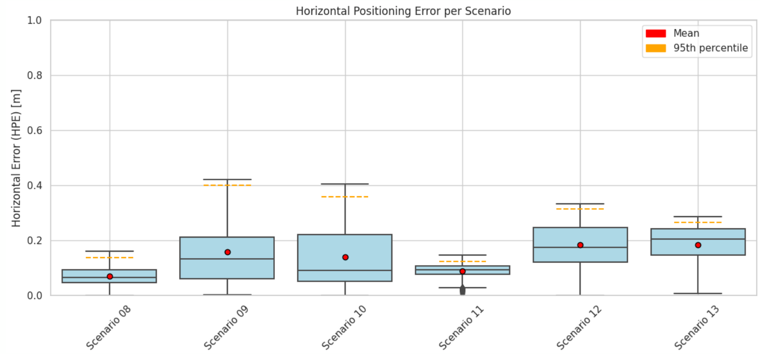
Position and Attitude Determination (PAD) SW

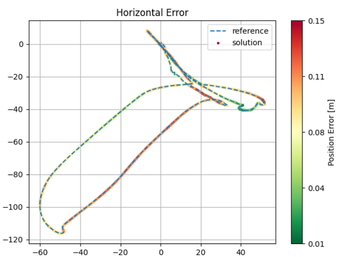
- GNSS+IMU Tightly coupled EKF
- Supports both PPP and RTK positioning modes
- 3D and 2D set-ups for precise attitude determination
- MHSS Based Integrity Scheme
  - Bank of Kalman Filter
  - GNSS undifferenced scheme
  - Fault Detection and Exclusion Mechanism
  - Protection Levels Estimation

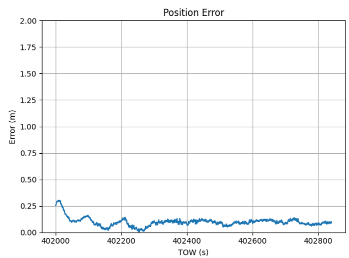


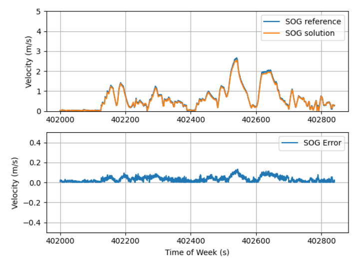
PAD SW Accuracy Results

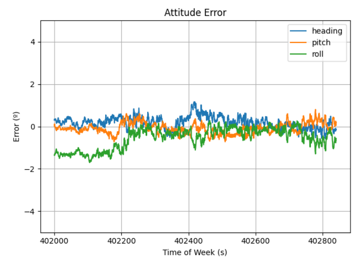
- Consistent position error accuracy across scenarios
- Attitude and SOG error well below the defined KPIs for the different operations





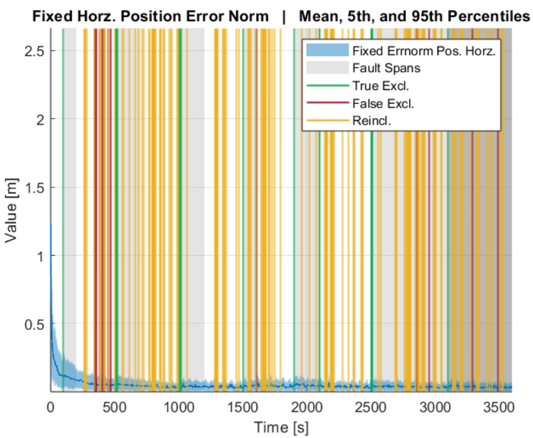


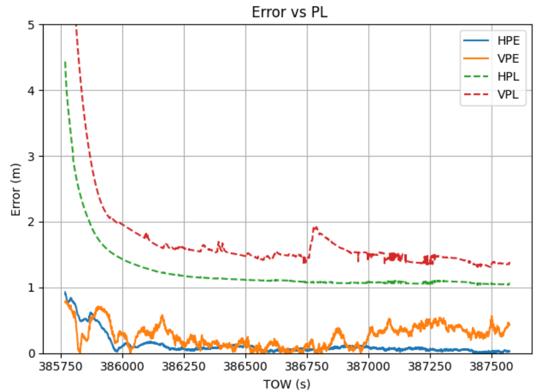


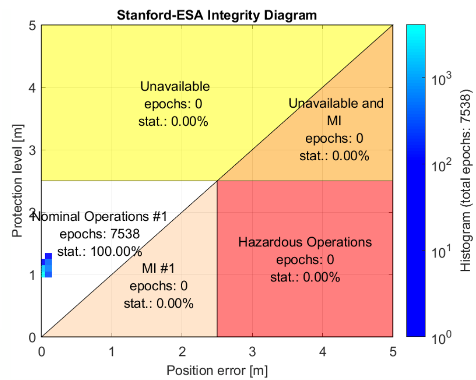


PAD SW Integrity Results

- **FDE** tested with simulated data (multiple and wide variety of faults)
- 20 Montecarlo iterations
- All faults detected and properly reincluded
- No impact on the position error



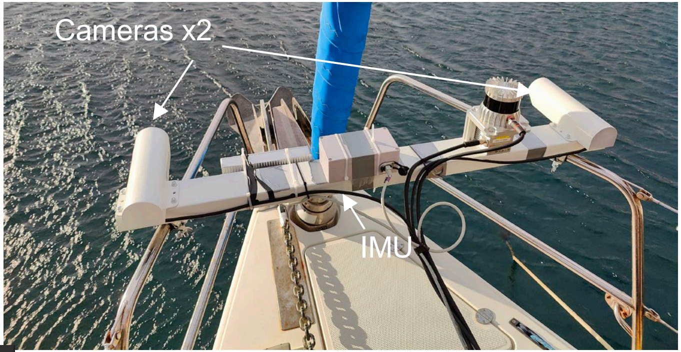


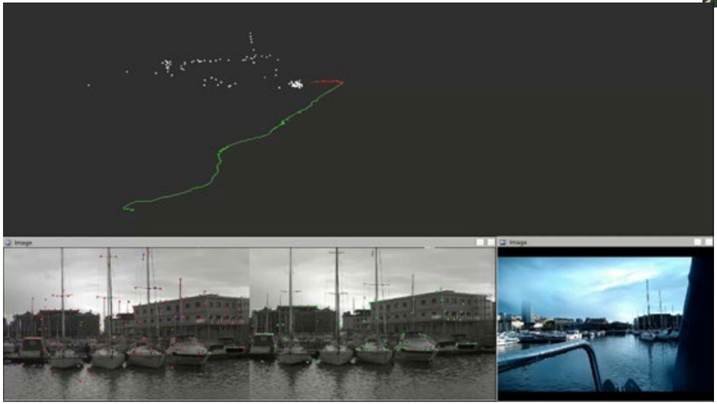


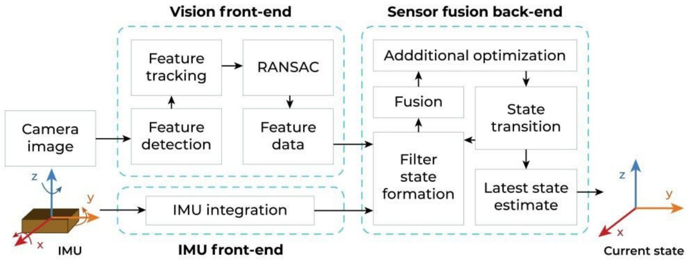
- PLs overbound position error (no HMIs detected)
- 100% availability (PL < AL) for port approach and navigation scenarios
- 25 cm HAL for docking scenario not met → relative approaches might be more convenient to support such stringent requirement

Visual-Based Localization

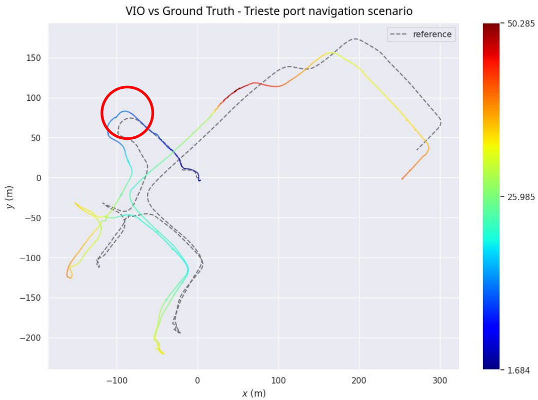
- Core System: **VINS-Fusion** chosen for 6-DoF pose estimation with covariance
- Tested in Trieste and Palma de Mallorca using Basler camera stereo baseline (1 m)

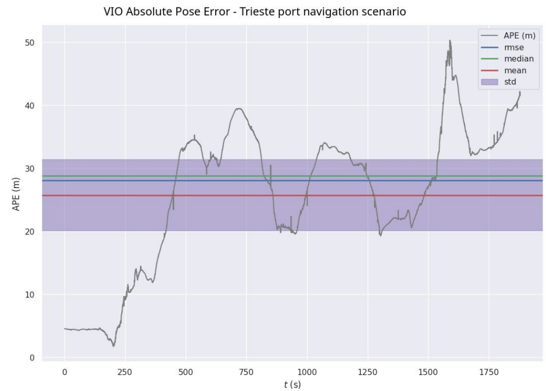




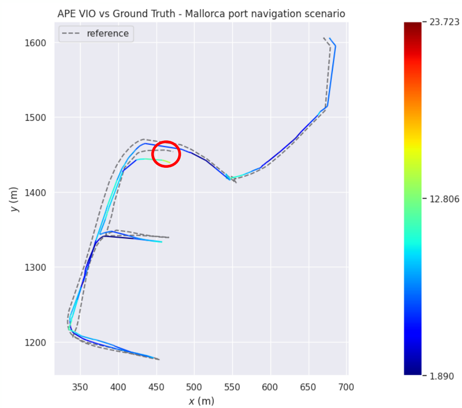


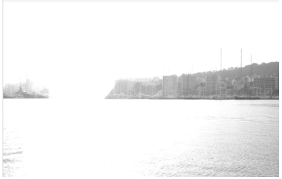
Visual-Based Localization

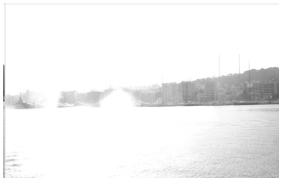




- Sensitive to low-texture areas, lighting changes, and water on lens
- Long stereo baseline requires precise and frequent calibration (mechanical misalignment during transportation)

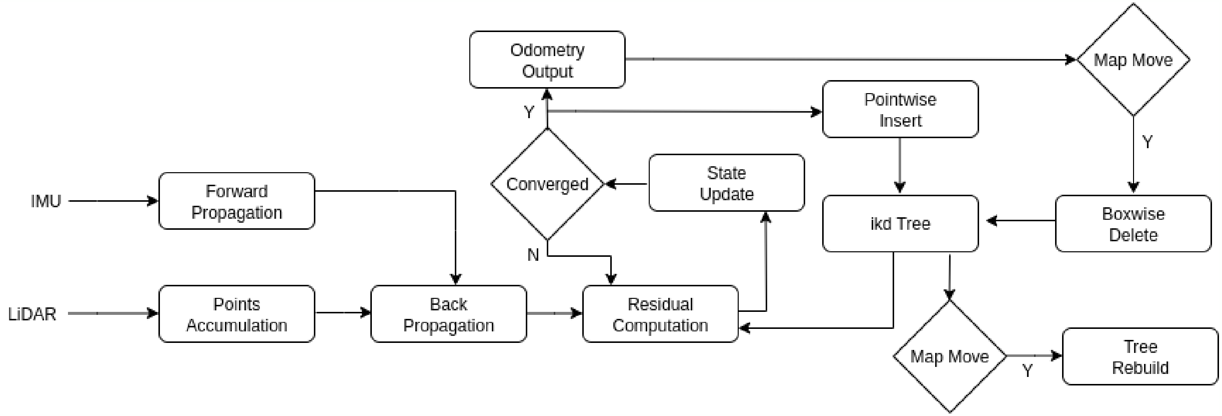




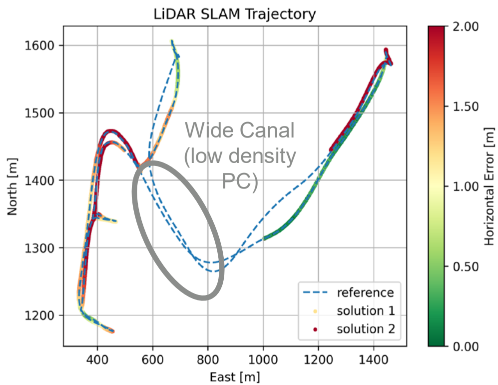


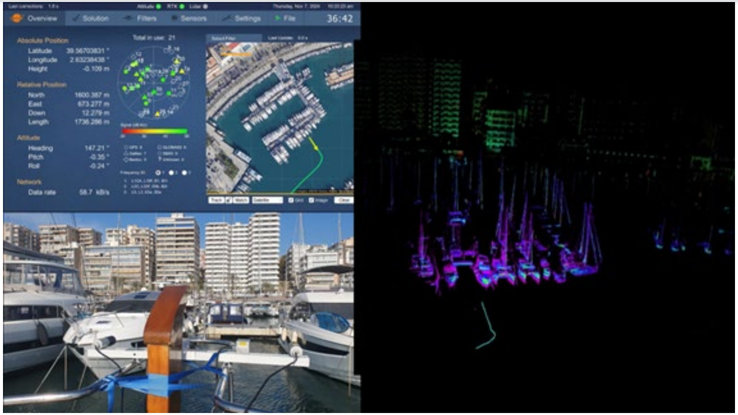
LiDAR-Based Localization

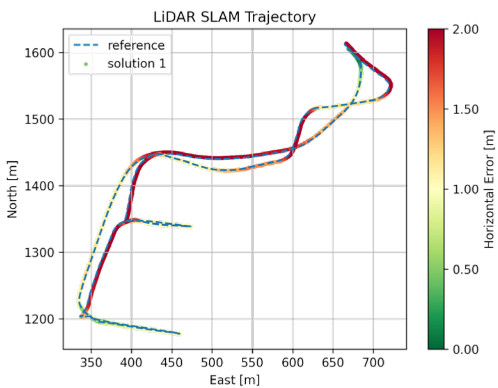
- Odometry estimated by tightly coupling LiDAR scans and inertial measurements with an iterated Extended Kalman Filter
- Scan to map registration to minimise drift
- Point-to-plane registration making the algorithm lighter and capable of running at 10Hz on the embedded platform
- Covariance estimation for central and particle filter fusion
- Smart mechanism to restart algorithm based on incoming pointclouds density

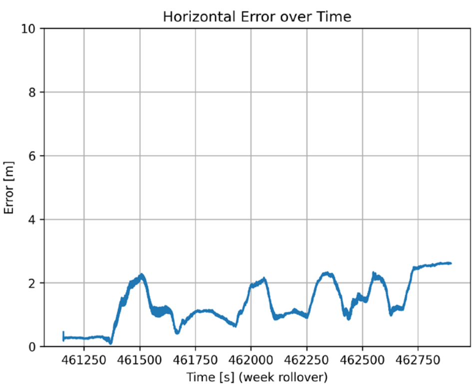


LiDAR Results





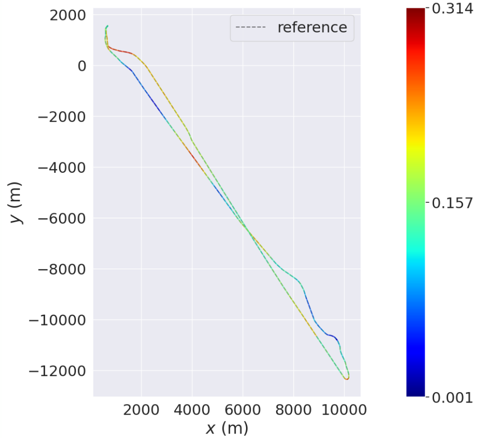


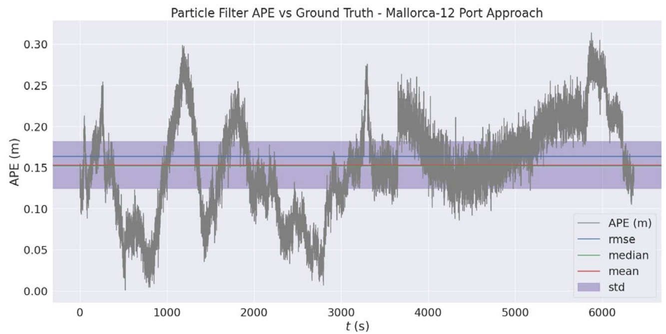


Particle Filter Results

Port Approach (Mallorca):

- Inputs:
  - PPP+IMU (High confidence) for entire trajectory;
  - Lidar SLAM (Low confidence) added near port;
  - No VINS.
- Delivered consistent, sub-meter accuracy in position and orientation estimates. [RMSE: 0.164]
- Performed reliably across varying operational conditions.





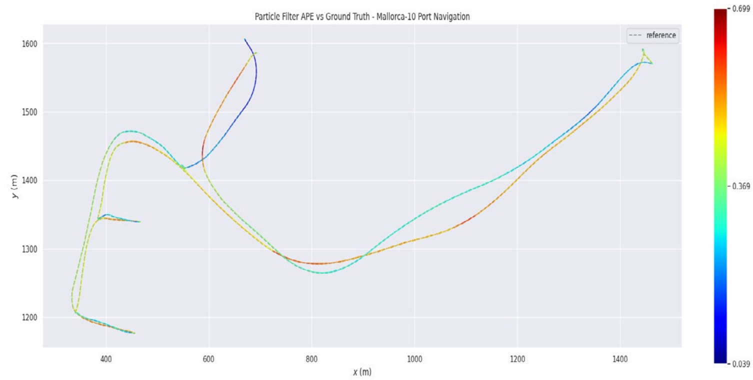
Particle Filter Results

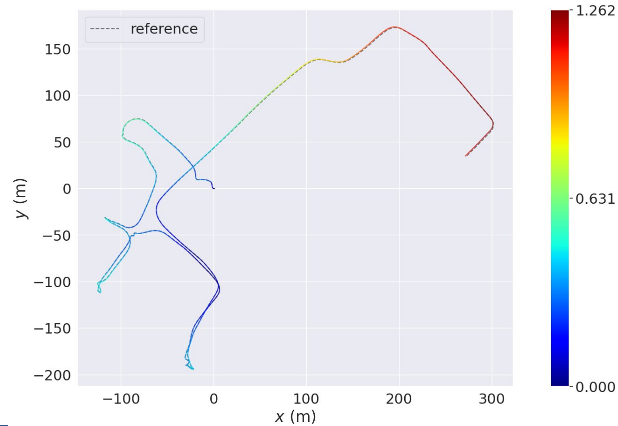
Port Navigation:

- Trieste:
  Inputs:
  - PPP+IMU (High confidence),
  - Lidar SLAM (Low confidence)
  - VINS (Low confidence)

  [RMSE: 0.558]
- Mallorca:
  Inputs:
  - PPP+IMU (High confidence),
  - Lidar SLAM (Low confidence)
  - No VINS

  [RMSE: 0.402]
- Position estimation was reliable and accurate.
- Orientation estimation faced limitations due to gimbal lock

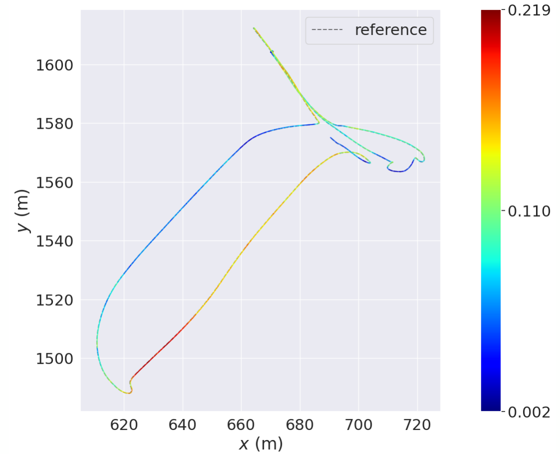


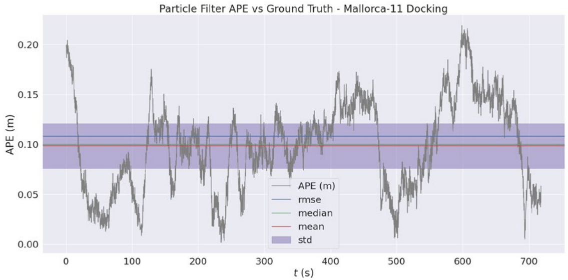


Particle Filter Results

Docking (Mallorca):

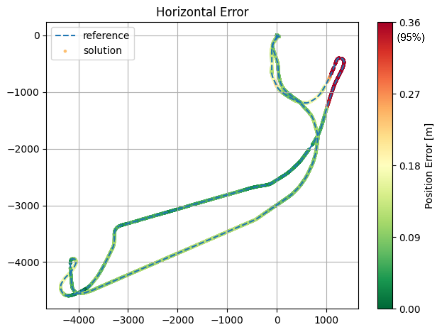
- Inputs:
  - PPP+IMU (High confidence)
  - Lidar SLAM (Low confidence)
  - No VINS
- Tested under sensor dropout conditions; maintained stable positioning.
- Demonstrated robustness in GPS-constrained environments [RMSE: 0.108].
- Observed orientation instabilities near singularities.
- Future work: adopt quaternion-based orientation modeling.

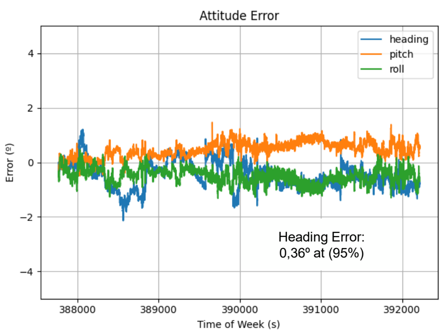




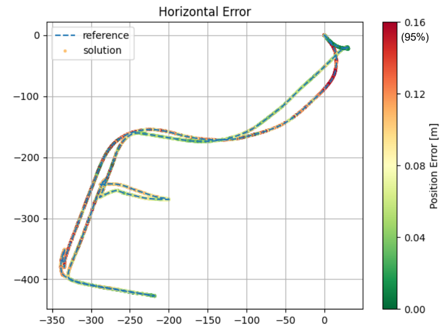
Central Filter – Accuracy Results

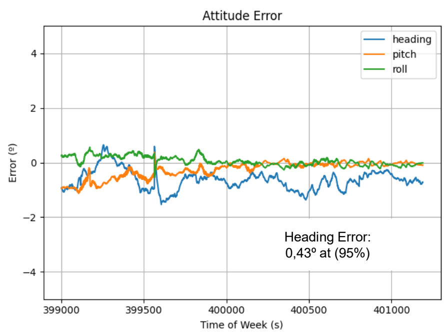
Port Approach



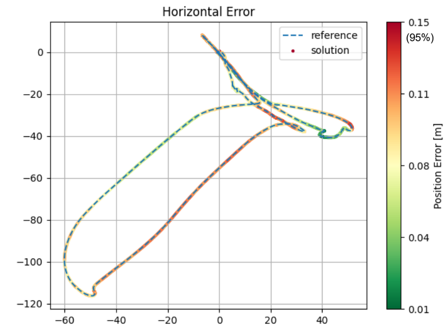


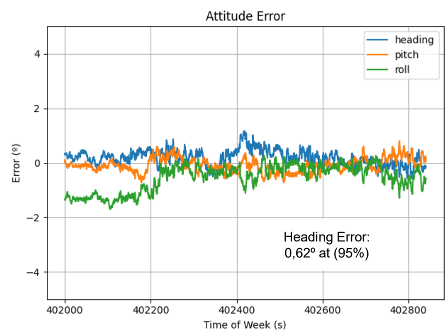
Port Navigation





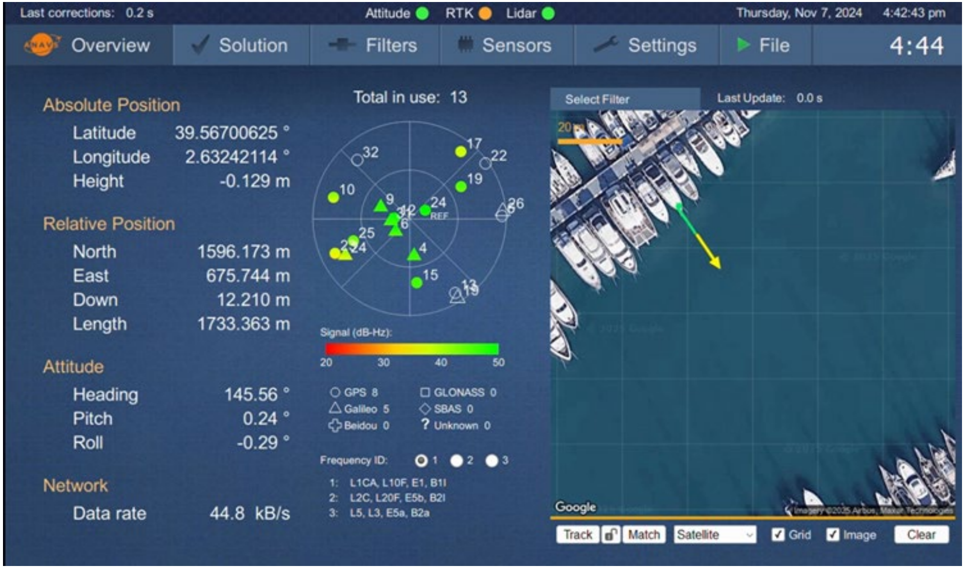
Docking





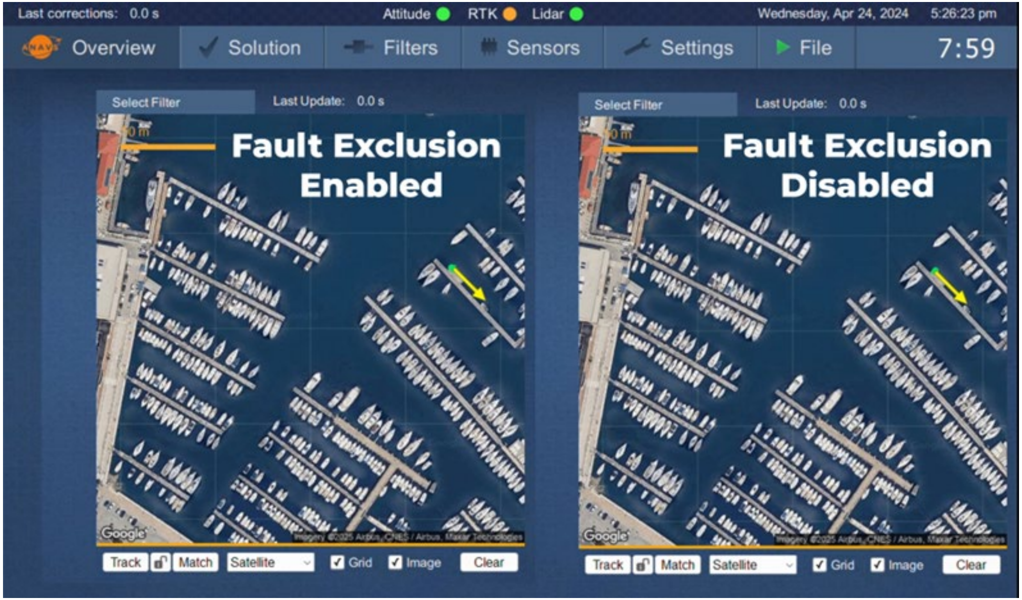
Central Filter Robustness

- Robust to GNSS outages and other sensors failures
- Filter maintains stable with minimal drift, thanks to the integration of inertial, LiDAR and Visual poses



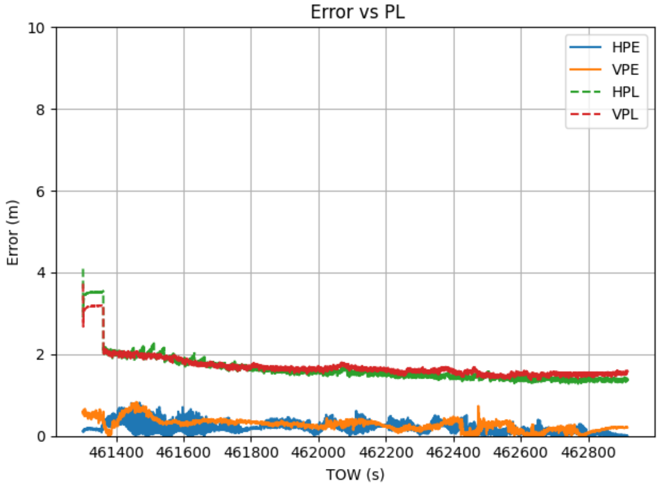
Central Filter – Feared Events

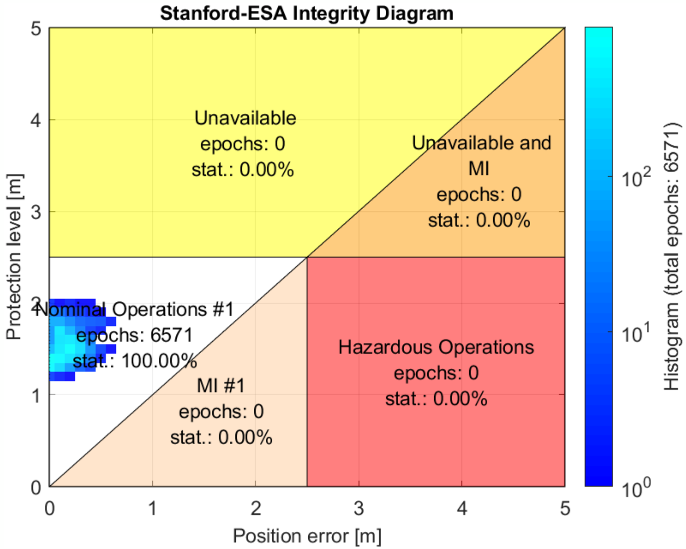
- Filter exhibits resilience to sensor faults
- Manually generated errors (both step and ramp fault profiles) introduced for the different sensors are effectively detected and mitigated



Central Filter – Protection Levels

- No HMI detected during the validation campaign
- PLs remain within the Alarm Limits for port approach and port navigation scenarios
- 0.25-meter Alert Limit defined for automated docking not met (relative approaches measuring the distance to the platform might be more convenient for this type of operations)





Technology Strengths

- MAPP architecture validated **real-time performance** on embedded systems, demonstrating reliable execution under operational conditions.
- **High-accuracy** results consistently achieved in position, attitude, and velocity across diverse maritime scenarios.
- Central and Particle Filters exhibited strong **robustness**, maintaining performance under various sensor outage scenarios.
- Key project outcome: development of a GNSS-based MHSS scheme and a novel multi-sensor **integrity framework**.
- GNSS and multi-sensor **FDE mechanisms** successfully detected and excluded a wide range of fault types, magnitudes, and sensor combinations.
- **Protection Levels** consistently overbounded position errors, staying below alarm limits in both port approach and navigation phases.

Recommendations & Further Development

- Investigate new methods for covariance estimation from visual localization
- Test in a real time loop with path and motion planning system with simulated ship navigation controller
- Include obstacle or hazard detection and position estimation methods
- Unified ROS-based framework
- Additional testing and integrity monitoring scheme refinement.
- Integrate mapping and loop-close techniques in the LiDAR-based solution

Video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Exploitation Proposed in Element 2

- Higher TRL system target with improved integrity
- Testing with large vessels
- Preliminary integration with ship navigation system

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Benefits of Working with ESA

- **Guidance in specialized areas** — in this project, for example, providing key support in the design, development, and validation of the integrity scheme
- **Access to technical expertise across domains** – Leveraging ESA's deep, multidisciplinary knowledge to ensure products are aligned with current market trends and needs.
- **Valuable feedback loops** through rigorous reviews and collaboration
- Support in **maturing prototypes** into operational systems
- Credibility and visibility at European and international levels

Questions And Answers