Content of 4-WP01 Advanced localization and driver assistance systems for trams

Coordinator of the WP

Czech Technical University, Faculty of Electrical Engineering, prof. Ing. Vladimír Havlena, CSc.

Participants of the WP

Skoda Digital, Dr. Ing. Daniel Pachner

FEE CTU, Dept. of Control Engineering, doc. Ing. Zdenek Hurak, PhD.

FEE CTU, Dept. of Cybernetics, doc. Radim Šára

CIIRC CTU, Dept. of Industrial Informatics, Dr. Ing. Michal Sojka

FAS UWB, Dept. of Cybernetics, doc. Ondřej Straka

Main Goal of the WP

Design of reliable, resilient localization system based on fusion of GPS, IMU, odometry, Lidar and other data, fully integrated with on-board real time data sources. Design of a set of advanced driver assistance systems, particularly anticollision system.

Partial Goals for the Current Period

Selection of sensors and on-board unit, design of core algorithms, collection of data and evaluation of core algorithms on simulated and real data.

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverables

- 4-WP01-001 | Sensor head demo implementation, G-funk
  Due 12/2025 | CTU FEE 0.4 | UWB FAS 0.2 | Skoda Digital 0.4 |
- 4-WP01-002 | Core fusion algorithms for advanced position estimation, O
  Due 12/2025 | CTU FEE 0.4 | UWB FAS 0.2 | Skoda Digital 0.4 |
- 4-WP01-003 | Enhanced algorithms for advanced position estimation and situation awareness, O
  Due 12/2025 | CTU FEE 0.4 | UWB FAS 0.2 | Skoda Digital 0.4 |
- 4-WP01-004 | Rapid prototyping platform for sensor head implementation, O
  Due 12/2024 | CTU FEE 0.1 | CTU CIIRC 0.4 | UWB FAS 0.1 | Skoda Digital 0.4 |
- 4-WP01-005 | Periodic system demo / performance evaluation of sensor head operation, O
  Due 12/2025 | CTU FEE 0.4 | UWB FAS 0.2| Skoda Digital 0.4 |
- 4-WP01-006 | Reporting and dissemination, O
  Due 12/2025 | CTU FEE 0.4 | UWB FAS 0.2 | Skoda Digital 0.4 |

- 4-WP01-007 | Programmable hardware platform for tests of vehicle communication channels
  Due 12/2025 | CTU FEE 0.3 | SkodaAuto 0.6 | TUV 0.1 |
- 4-WP01-008 | Dynamic multimodal transport optimization – specification of optimized means of transport
  Due 12/2025 | CTU FEE 0.5 | CTU FME 0.5 |

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-001 (Gfunk, Daniel Pachner, Skoda Digital)

Sensor head demo implementation

Sensor head software will be focused on algorithms for decimeter scale localization with high integrity and availability, and simultaneous-localization-and-mapping (SLAM) system based on map-aided, surface-aided (Radar, Lidar, video) for trams following predefined routes. Obstacle detection and mapping, estimating their position and velocity will be based on fusing relative measurement with absolute position/velocity estimates.

Methods: HW design, instrumentation selection, testing and certification with rail authority

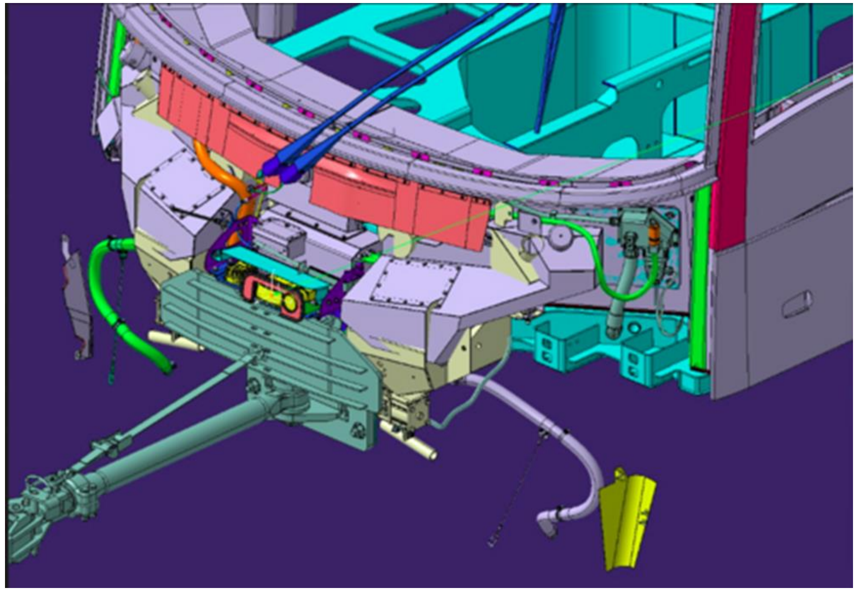
Due 12/2025 | CTU FEE 0.4 | UWB FAS 0.2 | Skoda Digital 0.4 |

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-001

Sensor head demo implementation

- Goal
  - Implement and validate advanced multiple sensor head for tram anti-collision system
- State
  - Certification with railway authority
  - Implementation in ROS
  - HW upgrade (Lidar, embedded platform)
  - Advanced localization
  - Lidar-based odometry, alternative routing
  - Virtual GNSS for SLAM



Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-001

Sensor head demo implementation

Certification process

2.9.2024

20.11.2024

10 000 km / 2 měsíce

Fáze 1

Jízda v tzv. Tichém režimu

- Jízda v provozu s cestujícími ACS zapnuté s omezením tj. nepípá, nebrzdí, nezasahuje do řízení
- ŠDIG vzdáleně monitoruje a sbírá data

15 000 km / 2,5 měsíce

Fáze 2

Jízda v CWNB

- Jízda v provozu s cestujícími ACS zapnuté v režimu „No Braking“
- ŠDIG vzdáleně monitoruje a sbírá data

5 000 km / 1 měsíc

Fáze 3

Jízda v CWAB

- Jízda v provozu s cestujícími ACS zapnuté v režimu aktivní brzdy s omezením na maximální deceleraci
- ŠDIG vzdáleně monitoruje a sbírá data

10 000 km / 2 měsíce

Fáze 4

Jízda v CWAB

- Jízda v provozu s cestujícími ACS zapnuté v režimu aktivní brzdy bez omezení
- ŠDIG vzdáleně monitoruje a sbírá data

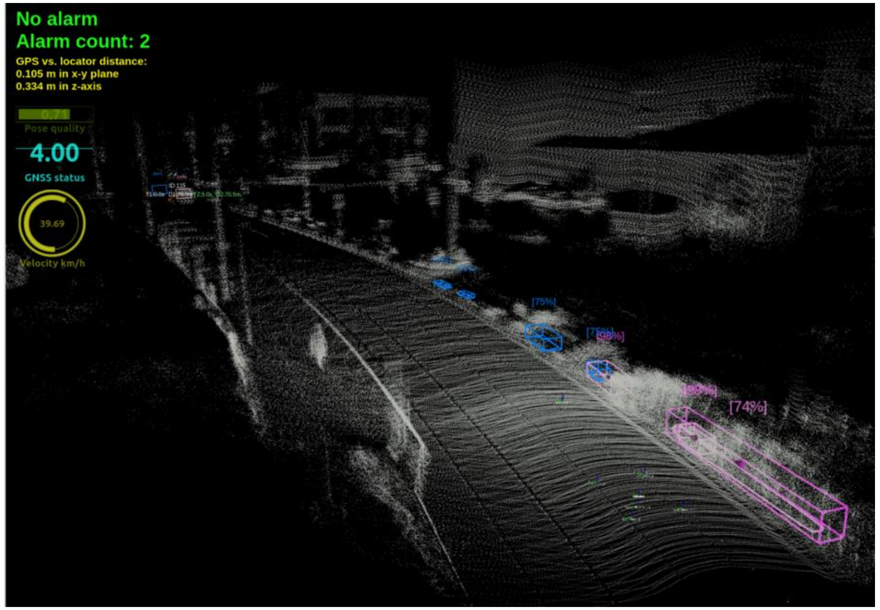
Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-001

Sensor head demo implementation

HW upgrade

- Livox HAP LiDAR (detection range 150m, field of view 120° x 25°, angular resolution: 0.18° x 0.23°)
- Control Unit HYPEX.ACS (HYPEX modular concept, ARM-based processor, internal development by SD)



Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-001

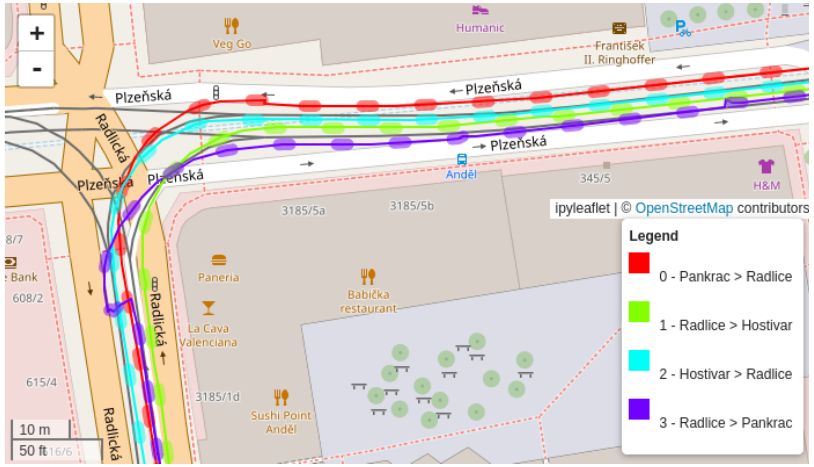
Sensor head demo implementation

Localization, odometry, routing

- Localization on railway map
- Design of precise train model
- Evaluates alternative routes

Possible inputs

- GNSS
- IMU
- Wheel odometry
- Lidar localization
- Ultra-wideband localization
- Balise (electronic beacon)



Map 'Tampere' version 1728313476, created 2024-10-07 15:04:36

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-002 (O, Zdenek Hurak, FEE CTU)

Core fusion algorithms for advanced position estimation

This result will cover the development of

- motion model for estimation incl. sensor noise
- core fusion of GNNS, IMS, odometry, RFID points (balises)
- fusion with map data, 1D real-time position/speed estimation on a fixed track
- partial smoothing, Sav-Gol filter, 1D delayed position/ speed/acceleration estimation
- final integration with other sensing subsystems

Methods: algorithmic development, prototype SW development, testing

Due 12/2025 | CTU FEE 0.4 | UWB FAS 0.2 | Skoda Digital 0.4 |

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-002

Core fusion algorithms for advanced position estimation

- Goals
  - Core fusion algorithms of GNNS, IMS, odometry and map data, 1D real-time position
  - Validation on real time data
- Activities
  - Algorithm for localization base on multisensory fusion using IEKF
  - Implementation of the estimators/filters in rapid prototyping environment
  - Generation of code for ROS 2 environment
  - More advanced GNSS data processing

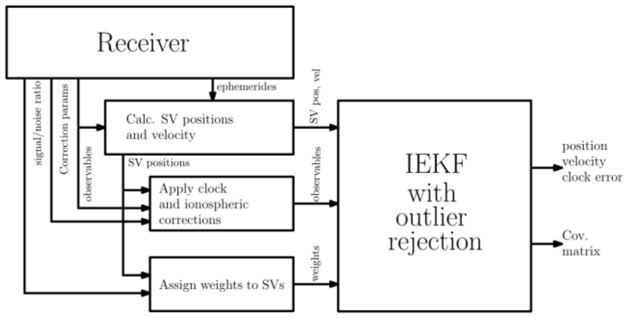
Content of 4-WP01 Advanced localization and driver assistance systems for trams

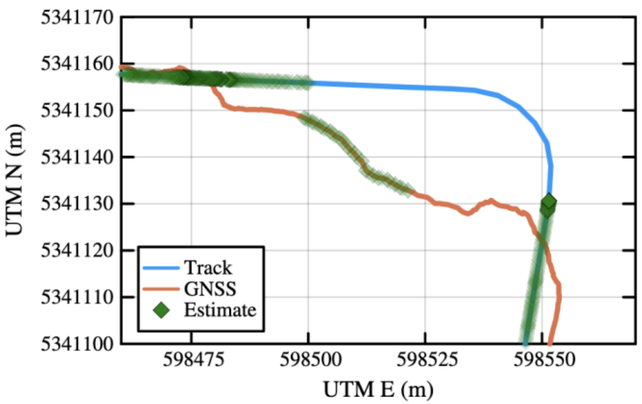
Deliverable 4-WP01-002

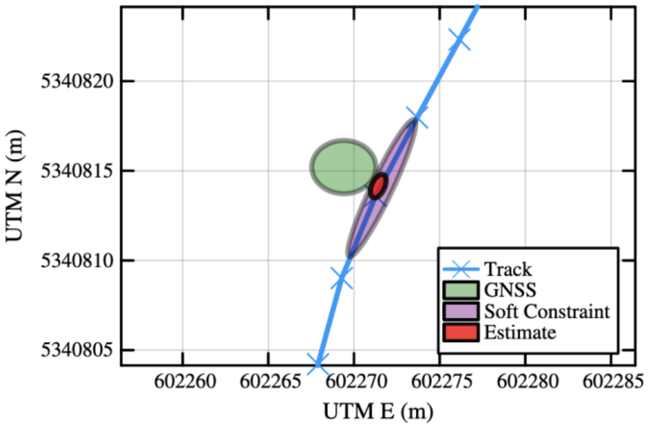
Core fusion algorithms for advanced position estimation

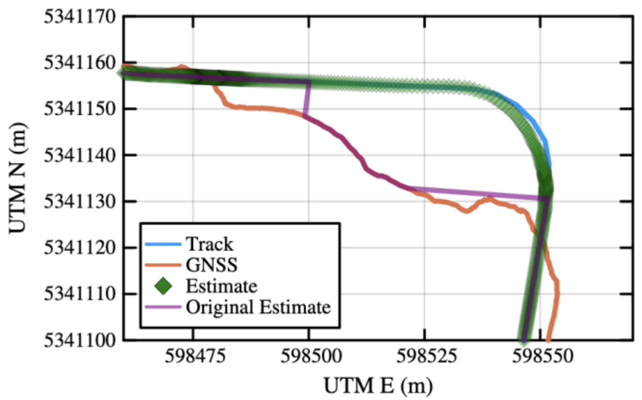
Deficiency of the low-cost off-the-shelf localization units

- GNSS reception in “urban canyons“
  - Non-line-of-sight (NLOS)
  - Multipath signal propagation
- Solution: projection on the rail map
  - IEKF algorithm
  - Realistic estimate of position covariance









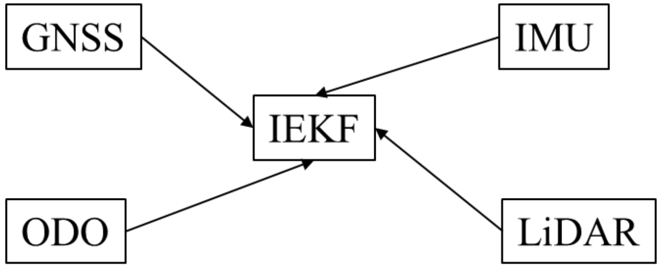
Content of 4-WP01 Advanced localization and driver assistance systems for trams

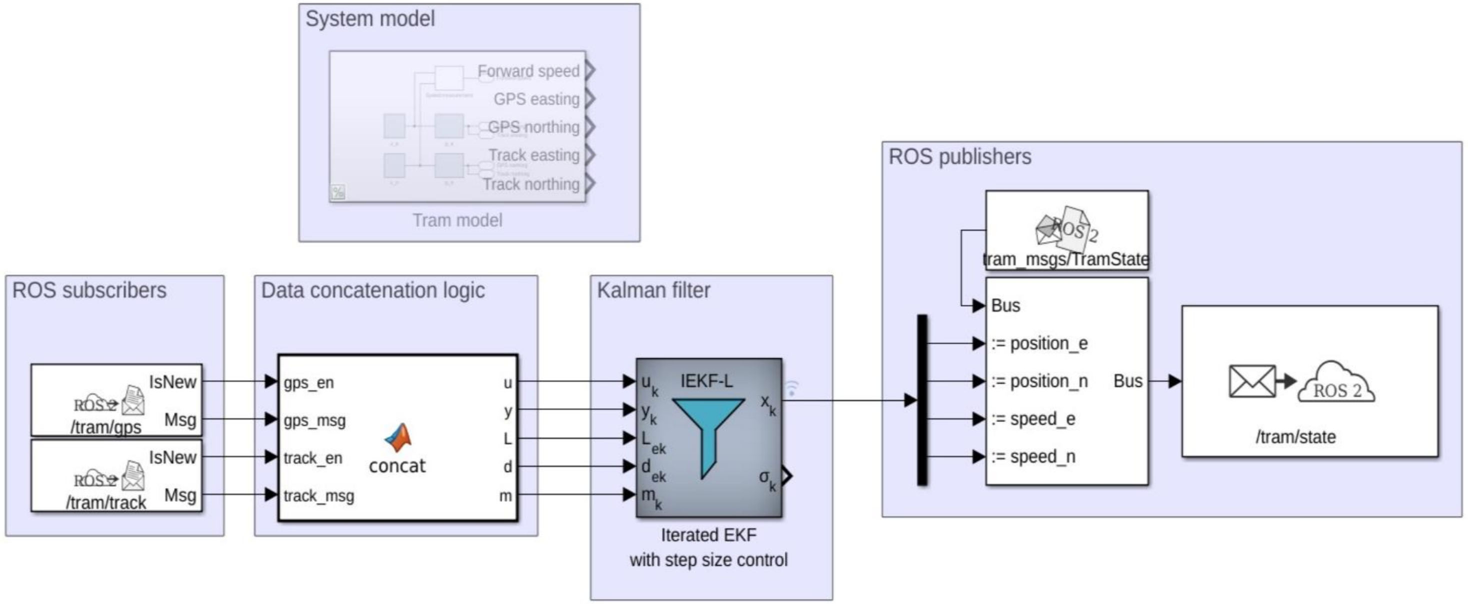
Deliverable 4-WP01-002

Core fusion algorithms for advanced position estimation

Implementation of multisensor fusion in ROS2

- Matlab NLCM toolbox
  - Reusable components
  - Kalman filters, MPC controllers etc.
- Automated differentiating (CasADi)
- Automatic code generation (C, ROS)





Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-003 (O, Radim Sara, FEE CTU, Ondrej Straka, UWB FAS)

Enhanced algorithms for advanced position estimation and situation awareness

This result will cover the development of

- LIDAR/video subsystem
- Efficient SLAM (Simultaneous Localization and Mapping) module
- Doppler RADAR absolute speed measurement subsystem
- Localization of multiple objects using mutiple sensors with missing / false measurements

Methods: Algorithmic development, SW prototype develpment, testing

Due 12/2025 | CTU FEE 0.4 | UWB FAS 0.2 | Skoda Digital 0.4 |

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-003

Enhanced algorithms for position estimation and situation awareness

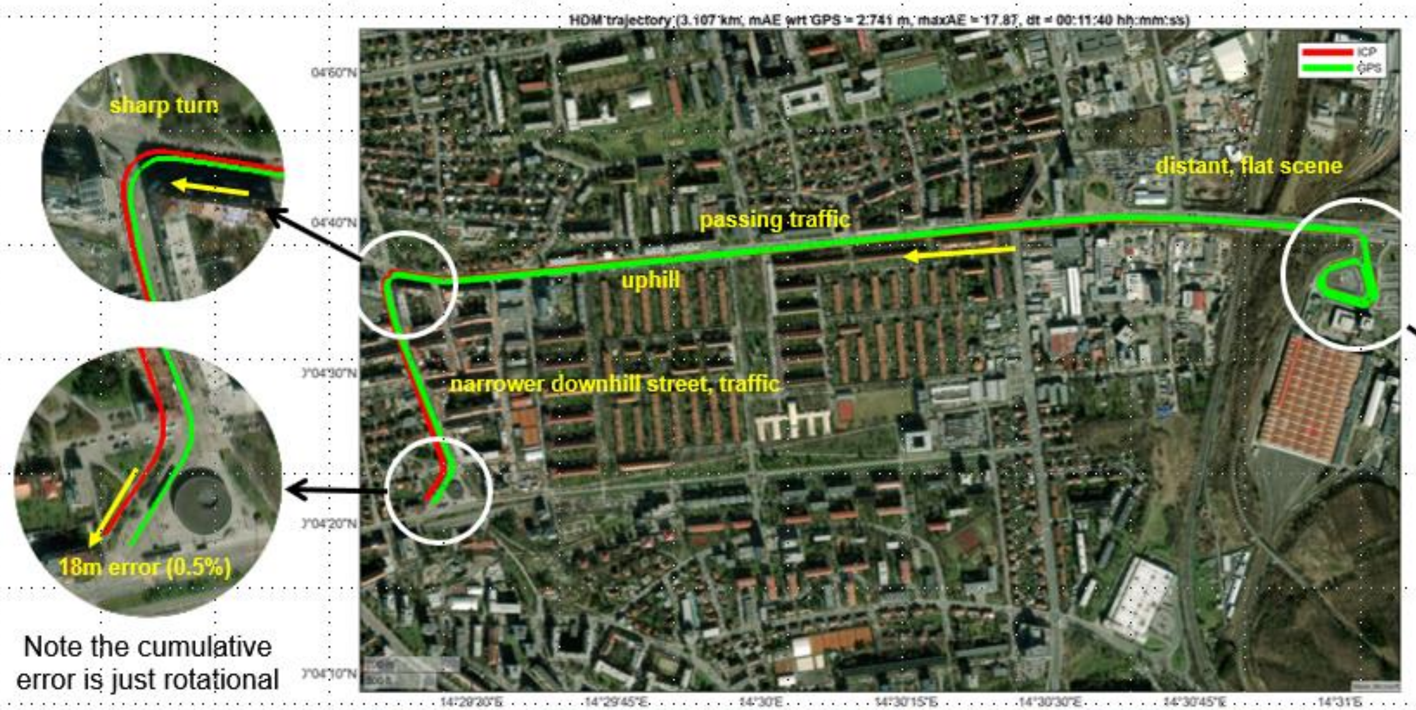
- Goals
  - Processing Lidar data from Skoda Digital sensor head
  - Tools for evaluation of minimum set of sensors providing required performance
- Activities
  - LiDAR calibration
  - LiDAR odometry and self-localization
  - HD mapping
  - Navigation in 3D and along track (1D)
  - Simulator of „ground truth“ data
  - Sensor error models

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-003

Enhanced algorithms for position estimation and situation awareness

Geometric Perception: Trajectory computed from LiDAR data vs. GPS reference



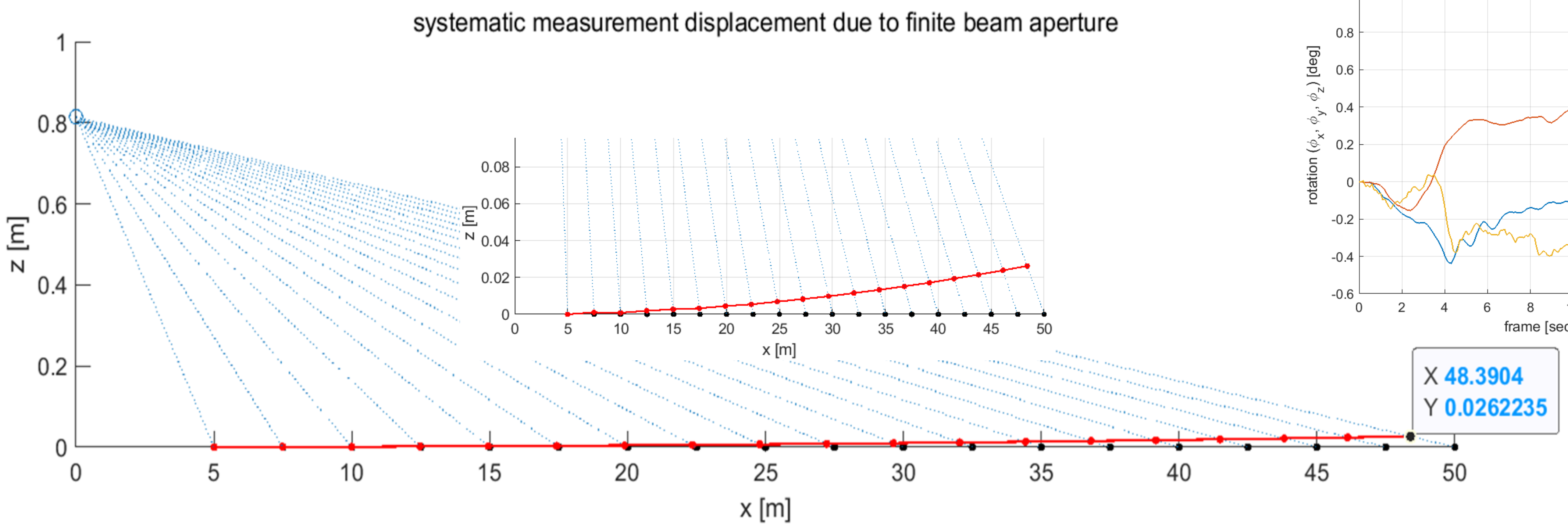
- Robust ICP (in red)
- Motion compensation
- No GPS, IMU in ICP
- No loop closing
- 3 km length
- 11 min drive
- Variable speed, stops

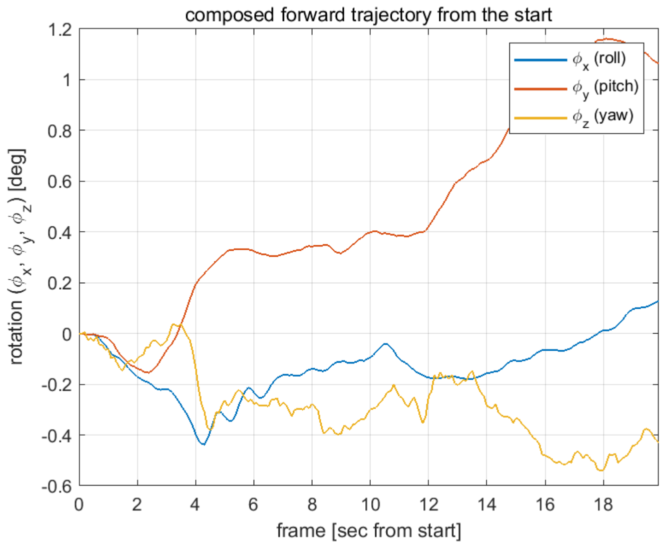
Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-003

Enhanced algorithms for position estimation and situation awareness

Geometric Perception: compensation of accommodated pitch bias



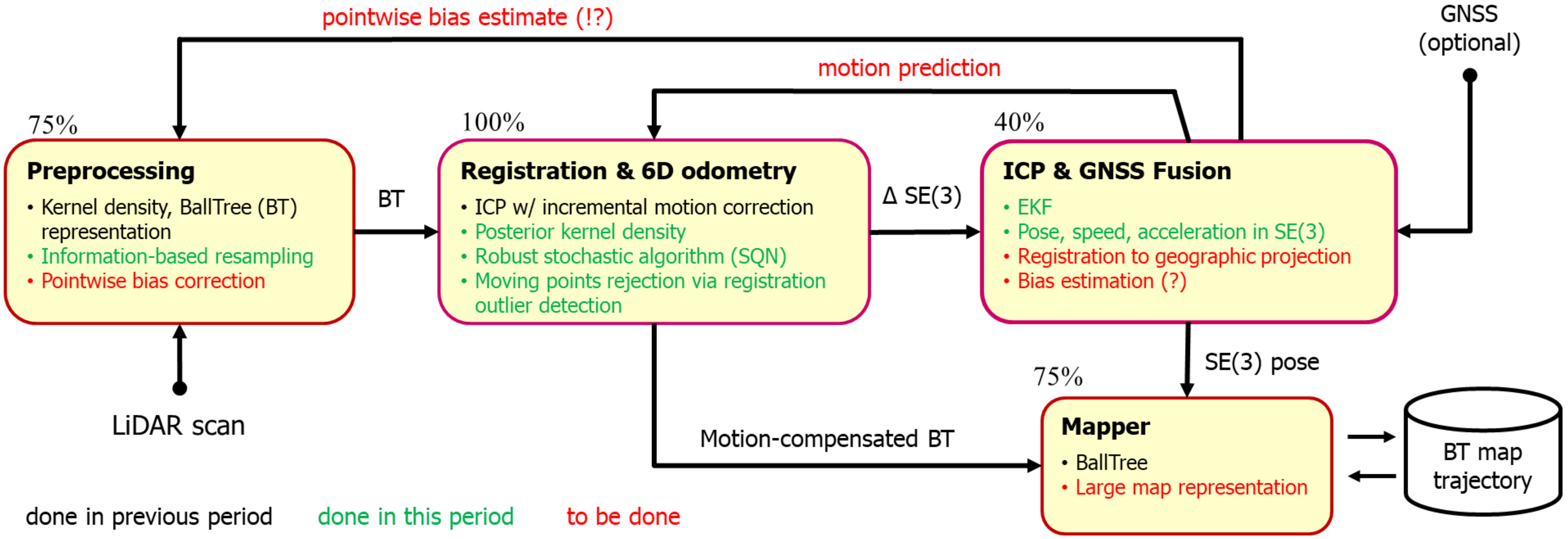


Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-003

Enhanced algorithms for position estimation and situation awareness

Geometric Perception: proposed architecture

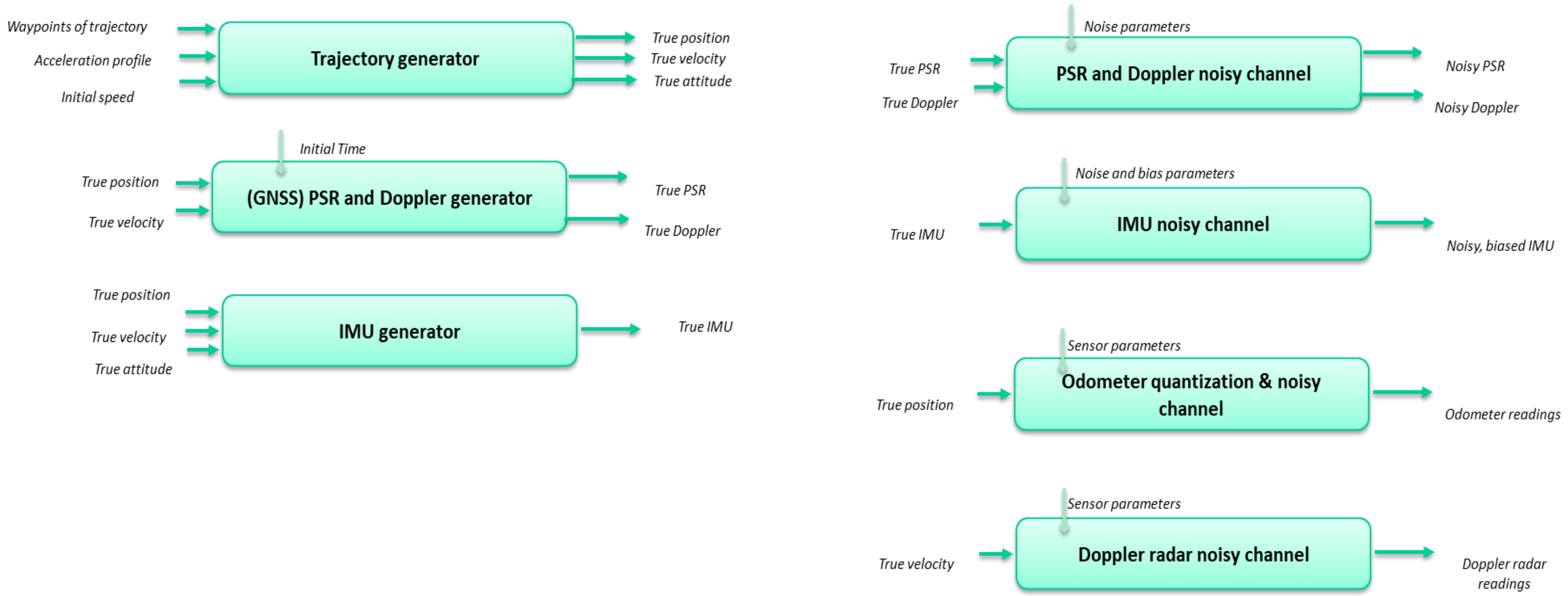


Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-003

Enhanced algorithms for advanced position estimation and situation awareness

Advanced localization techniques – software simulator for testing



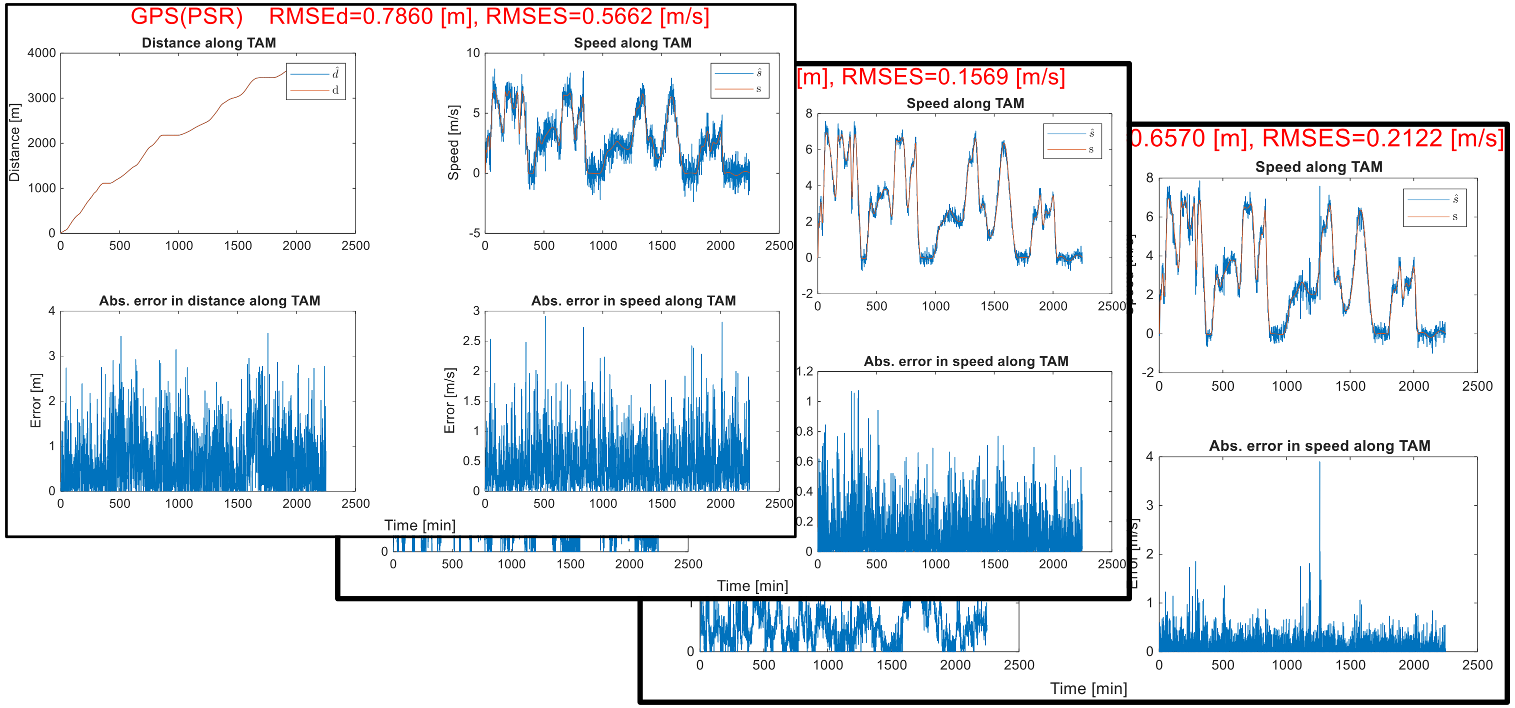
Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-003

Enhanced algorithms for position estimation and situation awareness

Advanced localization techniques – impact od Doppler radar on localization accuracy

- Comparison of multiple sensor configurations



w/o IMU	PSR	PSR+DR	PSR+PSRR	PSR+PSRR+DR
RMSE - distance	0,7860	0,5773	0,6555	0,6570
RMSE - speed	0,5662	0,1569	0,2069	0,2122

with IMU	PSR	PSR+DR	PSR+PSRR	PSR+PSRR+DR
RMSE - distance	0,7860	0,9316	0,6555	0,8265
RMSE - speed	0,5662	0,0297	0,2069	0,0291

Content of 4-WP01 Advanced localization and driver assistance systems for trams

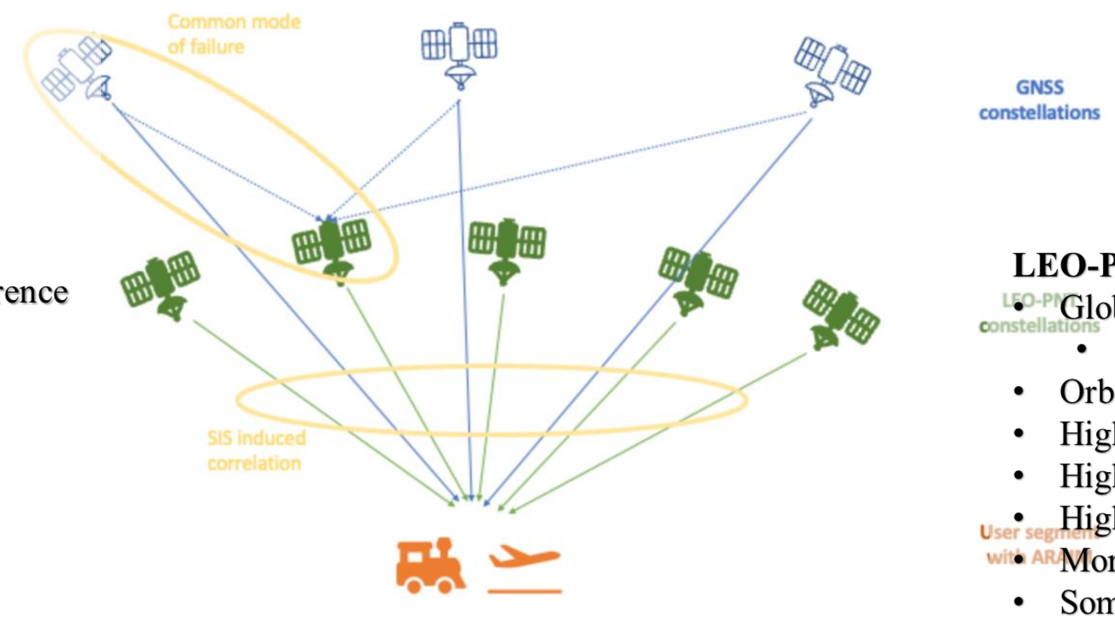
Deliverable 4-WP01-003

Enhanced algorithms for position estimation and situation awareness

Use of GNSS and LEO-PNT satellites

GNSS Constellations (Upper Layer)

- Global and regional constellations
  - GPS, Galileo, GLONASS, BeiDou
  - QZSS, NavIC
- Orbiting at high altitudes ~ 20, 000[km]
- Lower dynamics
- Lower number of satellites (SVs)
- Lower signal-to-noise ratio (SNR)
- Prone to intentional or accidental interference



LEO-PNT Constellations (Lower Layer)

- Global (multi-)constellations
  - Xona, Iridium, CentiSpace, Geespace
- Orbiting at low altitudes ~ 1, 000[km]
- Higher dynamics
- Higher number of satellites
- Higher SNR
- More resilient against interference
- Somehow independent of GNSS

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-003

Enhanced algorithms for position estimation and situation awareness

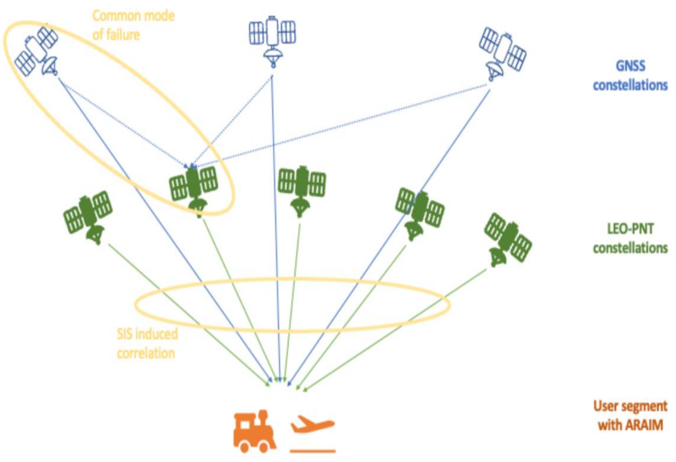
Use of GNSS and LEO-PNT satellites

Integrity Assessment

- Integrity can be expressed in term of protection level (PL).
- PL is bound guaranteeing $P(|\varepsilon| > \text{Alert Limit})$ is smaller than or equal to the *allowed* integrity risk (w.r.t. f).

Example of Faults

- Narrow (SV) failure is $P(H_{\text{GPSnarrow}}) = 10^{-5}$.
- Wide (const.) failure is $P(H_{\text{GPSwide}}) = 10^{-8}$.
- For GNSS known, for LEO-PNT *assumed*.
- Due to clock synchronisation of LEO-PNT with GNSS, the constellations and the faults might be dependent.



Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-004 (O, Michal Sojka, CIIRC CTU)

Rapid prototyping platform for sensor head implementation

Rapid prototyping is considered the most efficient alternative in the development of complex cyber-physical systems, consisting of HW and SW modules. For the task of multiple sensor fusion and obstacle detection, the ROS operation system is selected as the platform of choice. Software modules can be implemented using Simulink Coder environment, with efficient and reliable ROS node target code generation.

Methods: HW design, SW platform enhancements (ROS), testing using dedicated tracing tools

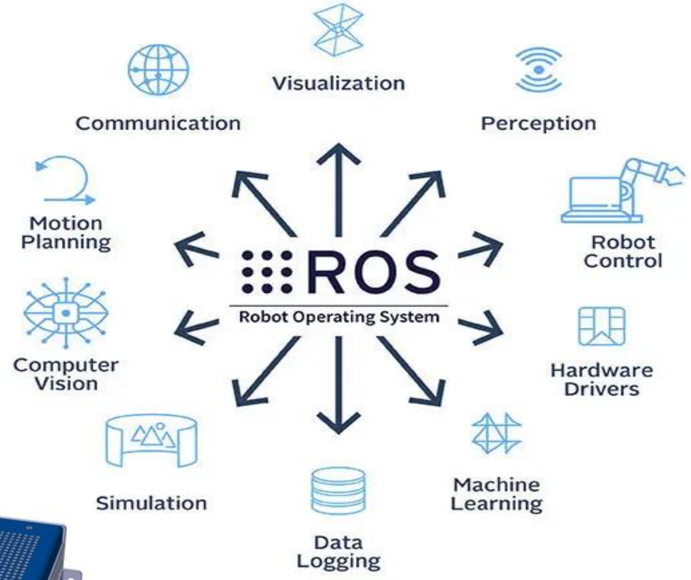
Due 12/2024 | CTU FEE 0.1 | CTU CIIRC 0.4 | UWB FAS 0.1 |Skoda Digital 0.4 |

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-004

Rapid prototyping platform for sensor head implementation

- Goals
  - Develop rapid prototyping platform for autonomous driving (sensor fusion, SLAM, visual localization, object detection)
  - Solution meeting industrial standards
- Activities
  - New custom embedded CPU development
    - NXP LX2160A 16 cores bases processing unit
    - Rail Operation Certified
  - ROS2 considered as integration environment
    - Organized ROS 2 workshop for all WP partners
    - Discussion of component integration
  - Contributions to the ROS open source ecosystem
    - Minimize the risk of compliance issues



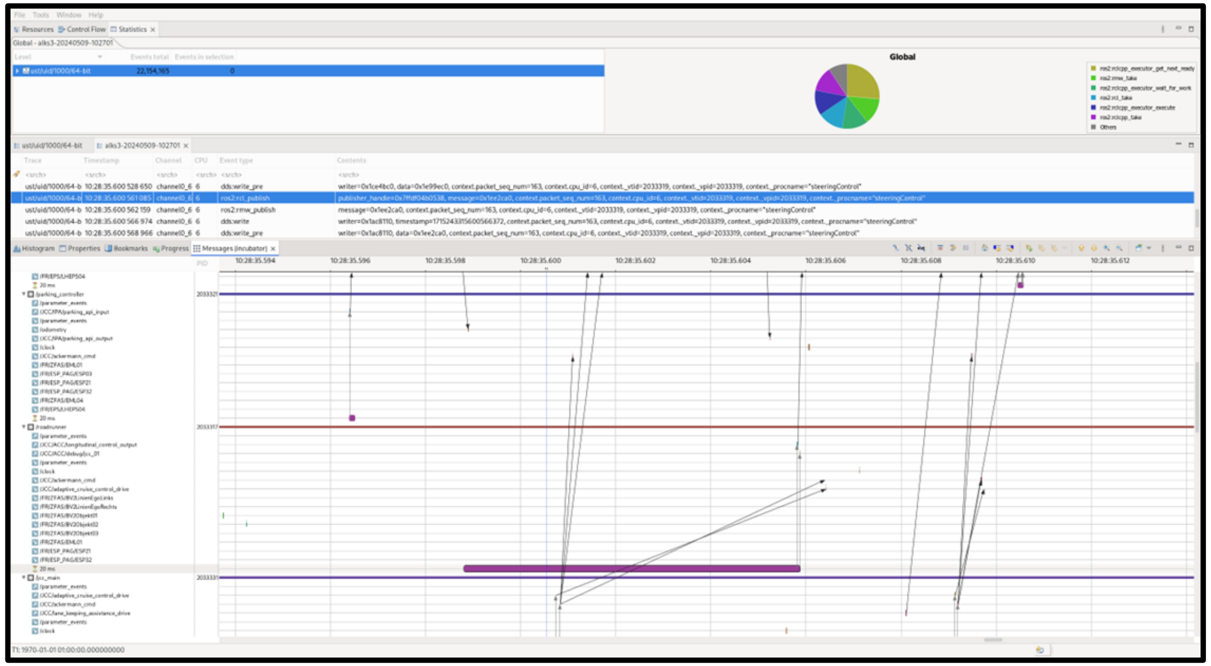
Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-004

Rapid prototyping platform for sensor head implementation

ROS tracing tool

- Recording of events about execution and communication of ROS nodes, in real-time with minimal overhead
- Can be used for analysis of latencies, anomalies, bugs
- Supported in ROS Jazzy (2024) for C++ applications
- Figure: Visualization of a trace of our application
  - Boxes = execution
  - Arrows = communication (publish/subscribe)



Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-005 (O, Daniel Pachner, Skoda Digital)

Periodic system demo / performance evaluation of sensor head operation

This periodic system demo/ performance evaluation will provide real-life evaluation of the performance limits of individual generations of the on-board software modules for localization and obstacle detection. It will be planned on 12 month basis. Results will be mapped to requirement specification for the next phase of algorithmic development.

The final demo will provide hard data for the selection of the production level instrumentation and algorithms used in driver assistance / collision avoidance system productization in 2026-2028.

Methods: Real-life evaluation of ADAS performance, use of digital twin and HW-in-the-loop approach

Due 12/2025 | CTU FEE 0.4 | UWB FAS 0.2 | Skoda Digital 0.4 |

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-005

Periodic system demo / performance evaluation of sensor head operation

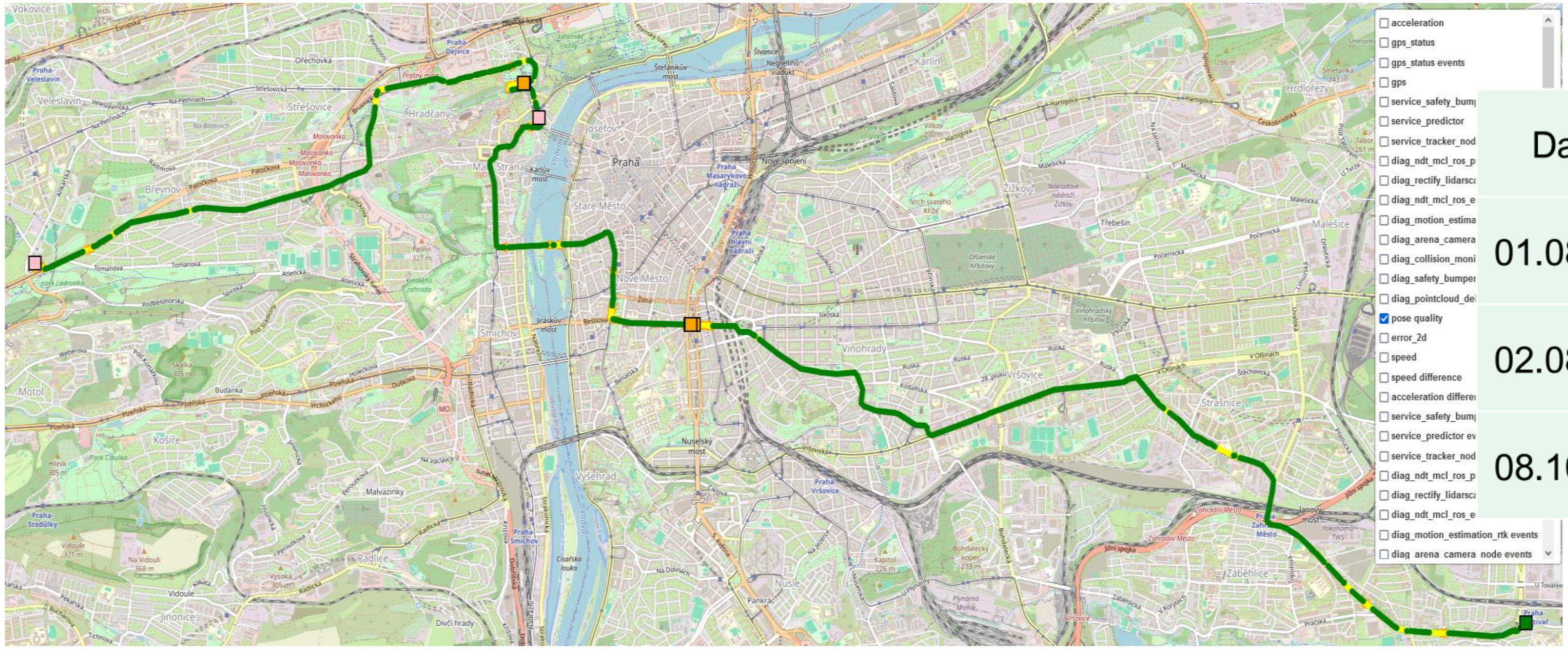
- Goals
  - Validate advanced multiple sensor head for tram anti-collision system in on-road operation
  - Provide requirement specification for the next phase of algorithmic development
- Activities
  - Running tests in Prague and Tampere
  - Breaking force control for anticollision system
  - Tram simulator
  - Breaking force control validation

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-005

Periodic system demo / performance evaluation of sensor head operation

System Demo Prague – data evaluation



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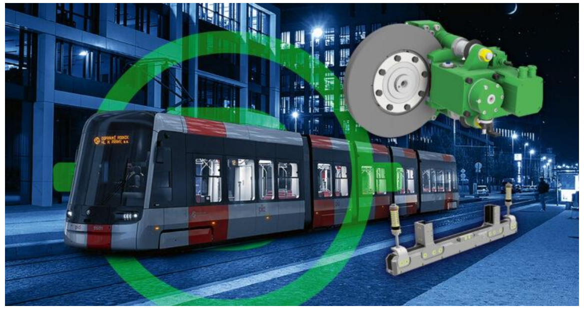
02.08.2024	109	6:30:00
08.10.2024	35	12:40:00

Content of 4-WP01 Advanced localization and driver assistance systems for trams

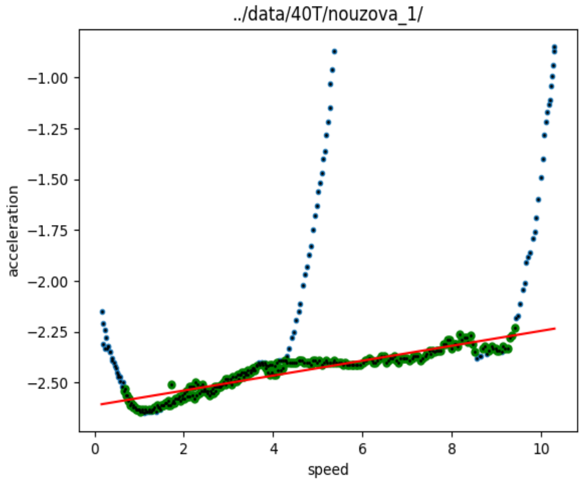
Deliverable 4-WP01-005

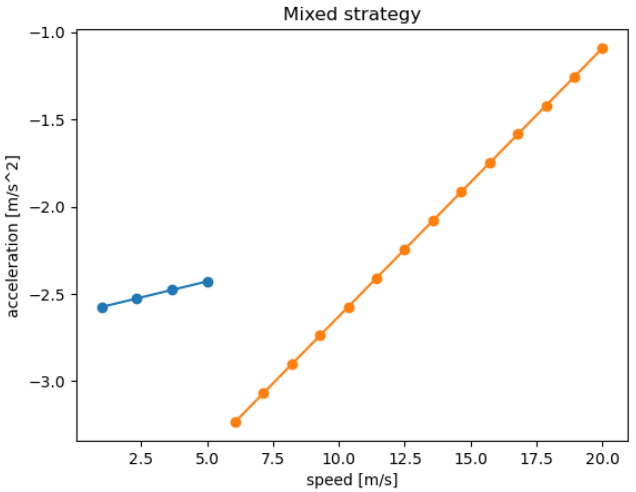
Periodic system demo / performance evaluation of sensor head operation

Braking force control for ACS



- Independent brakes
  - electrodynamic
  - mechanical disk
  - rail emergency brake
- Speed dependent brake efficiency
- Blended braking strategy
  - avoid the collision
  - minimize shock





Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-005

Periodic system demo / performance evaluation of sensor head operation

Digital twin – test of braking force control

- 3D model with realistic physics
- HYPEX controller – Hardware in the Loop

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-006 (O, Vladimir Havlena, FEE CTU)

Reporting and dissemination

Interim reports on individual project milestones, publications in journals and conferences, diploma and PhD theses.

Due 12/2025 | CTU FEE 0.4 | UWB FAS 0.2 | Skoda Digital 0.4 |

State summary

- Presentation for project review, presentation for FACME colloquium (TBD)
- Interim report (TBD)
- Conference presentations (ZCU 1)
- Papers in impacted journal (CTU 2, Q1 and Q2)
- Software (published in githab)

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-006

Reporting and dissemination

Conference papers

Duník, J.; Punčochář, I.; Král, L.; Straka, O.; Daniel, O.; Prol F. S.; Liaquat, M.; Bhuiyan, Z.: Multi-layer GNSS and LEO-PNT Positioning: Integrity under Constellations' Correlation. 27th International Conference on Information fusion, July 2024, Venice, Italy

Journal papers

Moravec, J.; Šára, R.: Online Camera-LiDAR Calibration Monitoring and Rotational Drift Tracking. IEEE Transactions on Robotics, 2024. ISSN 1552-3098.

Moravec, J.; Šára, R.: High-recall calibration monitoring for stereo cameras. Pattern Analysis and Applications, 2024. ISSN 1433-7541.

Software

Moravec, J.; Šára, R.: Online Camera-LiDAR Calibration Monitoring and Rotational Drift Tracking, 2024. https://github.com/moravecj/OCaMo

Škoudlil, M.: R2r_tracing: add tracepoints to the r2r library. https://github.com/skoudmar/r2r/tree/lttng-ust

Škoudlil, M.: Trace-futures: adds lttng tracepoints to the user application code. https://github.com/skoudmar/trace-futures

Sojka, M.: Automatic creation of Nix packages from ROS packages. https://github.com/wentasah/ros2nix

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-008 (O, Vaclav Jirovsky, FME CTU)

Dynamic multimodal transport optimization – specification of optimized means of transport for dynamic multimodality in transport

A report summarizing a definition of a minimum set of sensors for identifying the state of the environment affecting the choice of means of transport and the potential of using specific means of transport within the entire journey and identification of similarities and differences in the field of micro-logistics, "last-mile" logistics and human mobility, leading to the definition of optimized means of transport.

Methods: use case definition, optimization method selection, validation in simulated environment

Due 12/2-25 | CTU FEE 0.5 | CTU FME 0.5 |

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-008

Dynamic multimodal transport optimization – specification of optimized means of transport for dynamic multimodality in transport

- Goals
  - Target use-case: traffic management and transport organization in highly populated areas
  - Optimization of dynamic and permanent multimodal transfer nodes, vehicle fleet composition and positioning
  - Design of optimization algorithm for number of different types of vehicles and locations
  - Multilevel transport optimization with heterogenous vehicle types and spatio-temporal dynamics
- Activities
  - Definition of multimodal transport optimization as multicriteria optimization problem
  - Design/adoption of effective multicriteria optimization algorithm
  - Creation of selected use-case dataset
  - 2 scenarios - one with available datasets ready, second generated (work-in-progress)
  - Evaluation of the algorithm and simulation of the scenario (work-in-progress)
  - Problem is non-tractable on large instances (new heuristics and algorithms under development)

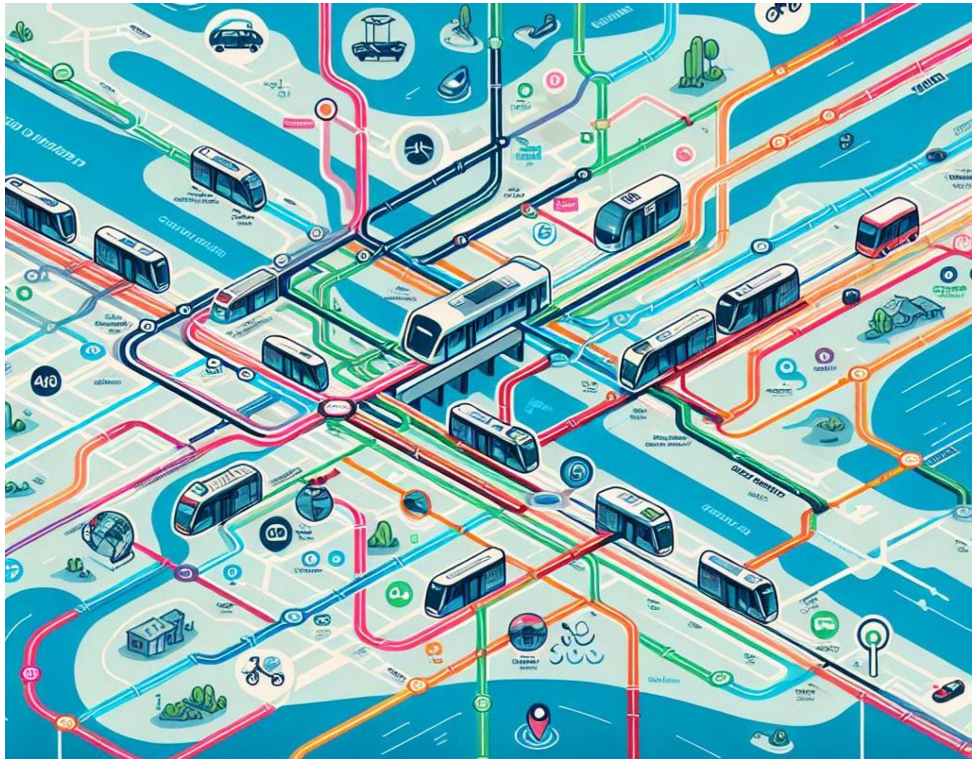
Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-008

Dynamic multimodal transport optimization – specification of optimized means of transport for dynamic multimodality in transport

Scenario 1 – personal transportation in populated areas

- Dynamic public transport (PT) network
  - Dynamic routes/stops, time schedules
- Mobility on Demand (MoD) in last-mile
  - Ride-sharing, vehicle routing with time windows
- Dynamic mode-change (where and when?)
- Combination of MoD-PT-MoD
- SotA works focus on
  - Small scale MoD with fixed origin-destinations
  - PT optimization (rotes and/or timetables)
- Simulation and datasets
  - Available for several metropolitan cities/areas



Content of 4-WP01 Advanced localization and driver assistance systems for trams

Deliverable 4-WP01-008
Dynamic multimodal transport optimization – specification of optimized means of transport for dynamic multimodality in transport

Scenario 2 – logistics in populated areas

- Multilevel transport optimization
  - Heterogenous vehicle types and spatio-temporal dynamics
- High-capacity (HC) transport network
  - Trucks, standard high-capacity vans
- Last-mile (LM) on demand delivery
  - Light transport vehicles, drones, automated logistic center etc.
- Dynamic mode-change (where and when?)
  - Combination of LM-HC-LM
- SotA works focus on
  - High-capacity fleet routing (classic logistics)
  - Small scale on-demand routing
- Simulation and datasets
  - Maps for several metropolitan cities/areas, transport demand to be generated

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Conclusions and future outlook

- HW platform (sensor head) design completed
- Certification with railway authority TBD by the end of 2024
- High fidelity simulation tool for GNSS and IMU units
- Collection of real time data for performance evaluation
- Ongoing / future efforts:
  - Advanced positioning (sensor fusion, GNSS data reconciliation)
  - Lidar data processing (SLAM)
  - Design of software architecture and core algorithms
  - Validation on simulated and real trafic data

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Current State of Deliverables and Fulfillment of Goals

- No binding deliverables (Gfun, R) in 2024, 1 binding deliverable O
- 7 additional deliverables O (publications, software)
- Goals for 2024 completed, no major delays
  - HW platform prototypes implemented (sensor head)
  - Collection of real time data for performance evaluation running
  - First results from sensor fusion and Lidar data processing (SLAM)
  - Design of software architecture and core algorithms

Added Value of 4-WP01 results

- Advanced Driver Assistant functionality is becoming compulsory part of public sector tenders
- 4-WP01 deliverables provide enabling technology for implementation of base level Advanced Driver Assistance and Colision Avoidance System to meet the minimum tender requirement
- Estimated production of vehicles enabled with advanced systems in 2026 and the following years is 60 units per year

Content of 4-WP01 Advanced localization and driver assistance systems for trams

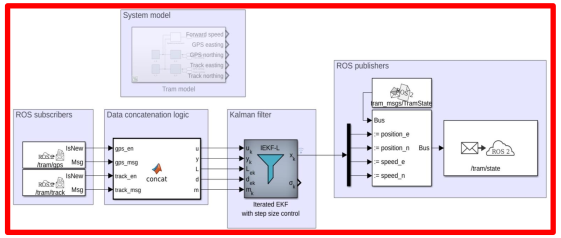
List of Due Deliverables and Their Added Value

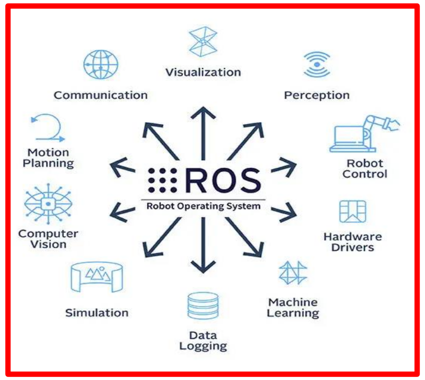
4-WP01-004 | Rapid prototyping platform for sensor head implementation, O

- **Due 12/2024** | CTU FEE 0.1 | CTU CIIRC 0.4 | UWB FAS 0.1 | Skoda Digital 0.4 |

Rapid prototyping platform HYPEX

- HW solution based on
  - NXP LX2160A 16 cores bases processing unit
  - Rail Operation Certified
- SW integration environment
  - ROS / ROS2
  - ROS 2 workshop for all WP partners
  - Prototyping platform also for academic partners
- Added value
  - Integration of sw modules from all WP participants
  - Extensive debugging / testing / tracing support
  - Manual / automated code generation (MATLAB/Simulink)





Content of 4-WP01 Advanced localization and driver assistance systems for trams

Assessment of the Contribution of Deliverables

- 4-WP01-002/003 Advanced localization developed in this WP by academic partners will be also used in OBU development in 3-WP01 (scaled down version, no Lidar and optical sensors)
- 4-WP01-001/005 V2X technology expertise in 3-WP01 will be used in this WP by Skoda Digital partner
- 4-WP01-008 Datasets and scenario area selection - possible mutual benefits with other TAČR project FW06010535 – Automatizované řídicí centrum provozu minibusů autonomní MoD
- 4-WP01-008 Application of car-sharing data from previous internal ČVUT project Uniqway

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Assessment of the Formal/Administrative Goals of the Work Package

	Skoda Digital	FEE + CIIRC CTU	FAS UWB
Finance	OK	OK	OK
Commercialization	OK	OK	OK
Deliverables	OK	OK	OK

Content of Work Package 4-WP01 – "Tools for Integration of Vehicles into Multimodal Systems with Increased Safety (including cybersecurity) and Subjected to LCA"

4-WP01 – Tools for Integration of Vehicles into Multimodal Systems with Increased Safety (including cyber security) and Subjected to LCA

Coordinator of the WP

Czech Technical University in Prague, prof. Ing. Vladimír Havlena, CSc.

Participants of the WP (4 – WP01 – 007 only)

CTU FEE – doc. Jiří Novák, Ing. Jan Sobotka, Bc. Tomáš Veselý, Bc. Šimon Pecháček
ŠKODA AUTO a. s. – Ing. Jiří Blecha, Ing. Jaroslav Hrbek, Ing. Adam Šťáva
TÜV Süd – Ing. Dalibor Zeman, Ing. Vladislav Kocián, Ing. Petr Lockenbauer

Main Goal of the WP

R&D of a communication technology enabling seamless integration into in-vehicle networks while providing for monitoring with hardware accelerated filtering, PTP support and real-time data manipulation/insertion.

Partial Goals for the Current Period

Implementation of monitoring (with HW accelerated filtering) capability on development kit. Implementation and validation of PTP support for Automotive Ethernet link. Implementation of HW accelerated aggregation (based on CMP protocol) of monitored data onto the 10Gb Ethernet. Schematic design of custom motherboard supporting simultaneous monitoring of 4 Ethernet links and their aggregation onto 10Gb Ethernet port.

Content of Work Package 4-WP01 – "Tools for Integration of Vehicles into Multimodal Systems with Increased Safety (including cybersecurity) and Subjected to LCA"

Deliverable 4–WP01–007

Programmable hardware platform for (non-)intrusive tests of vehicle communication channels.

The hardware platform provides for intrusive and non-intrusive tests of various security aspects of in-vehicle communication. It is equipped with high number of various type (CAN, LIN, Ethernet …) communication interfaces, allowing low-latency monitoring and on-the-fly data manipulation at selected OSI layers (while non-manipulated layers are not influenced). Seamless integration into the vehicle networks will guarantee that normal vehicle functionalities are not affected by test equipment. The platform allows implementing the attacks from the threat catalog R155 as well as from the VW threat catalog. An API providing for particular threats testing is defined and example test cases are implemented.

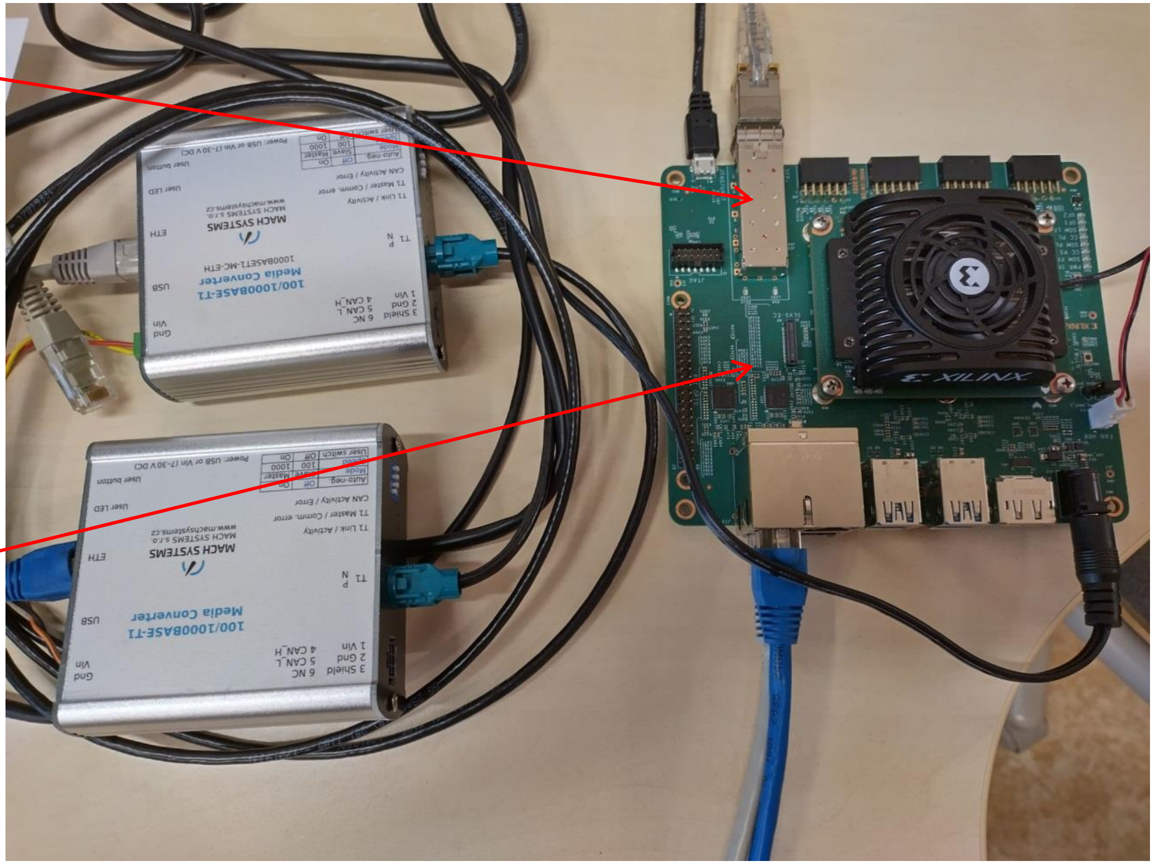
Methods: HW design, SW development, implementation testing

Due 12/2025 | CTU FEE | Skoda Auto | TÜV Süd |

Content of Work Package 4-WP01 – "Tools for Integration of Vehicles into Multimodal Systems with Increased Safety (including cybersecurity) and Subjected to LCA"

Activities to reach 4 – WP01 – 007 - Programmable hardware platform for (non-)intrusive tests of vehicle communication channels.

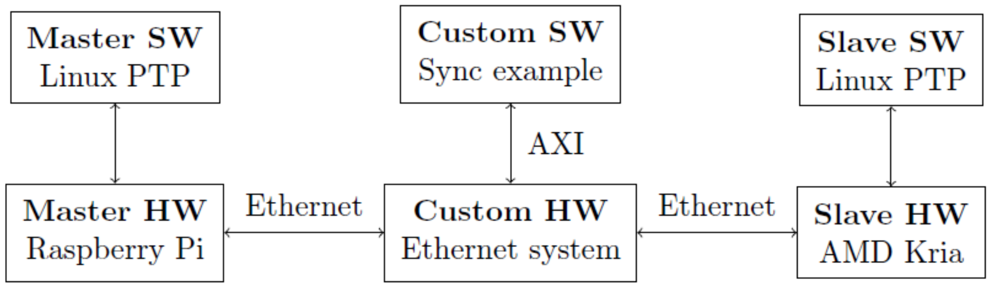
- data acquisition (monitoring) implementation
  - LNK implementation in FPGA (including 10Gbps)
  - per 1Gbps link HW accelerated filtering
  - links data aggregation into 10Gbps port with HW accelerated filtering and CMP protocol packaging
- PTP (Precision Time Protocol) support
  - PTP packets are directed (using HW accelerated filtering) into the processing system, processed and forwarded to destination
- application specific motherboard design for KRIA system-on-chip module
  - 4 variable-speed Automotive Ethernet links
  - 4 USB3.0 subsystems for external peripherals
  - 2 10Gbps Ethernet SFP+ interfaces



Content of Work Package 4-WP01 – "Tools for Integration of Vehicles into Multimodal Systems with Increased Safety (including cybersecurity) and Subjected to LCA"

Activities to reach 4 – WP01 – 007 - Programmable hardware platform for (non-)intrusive tests of vehicle communication channels.

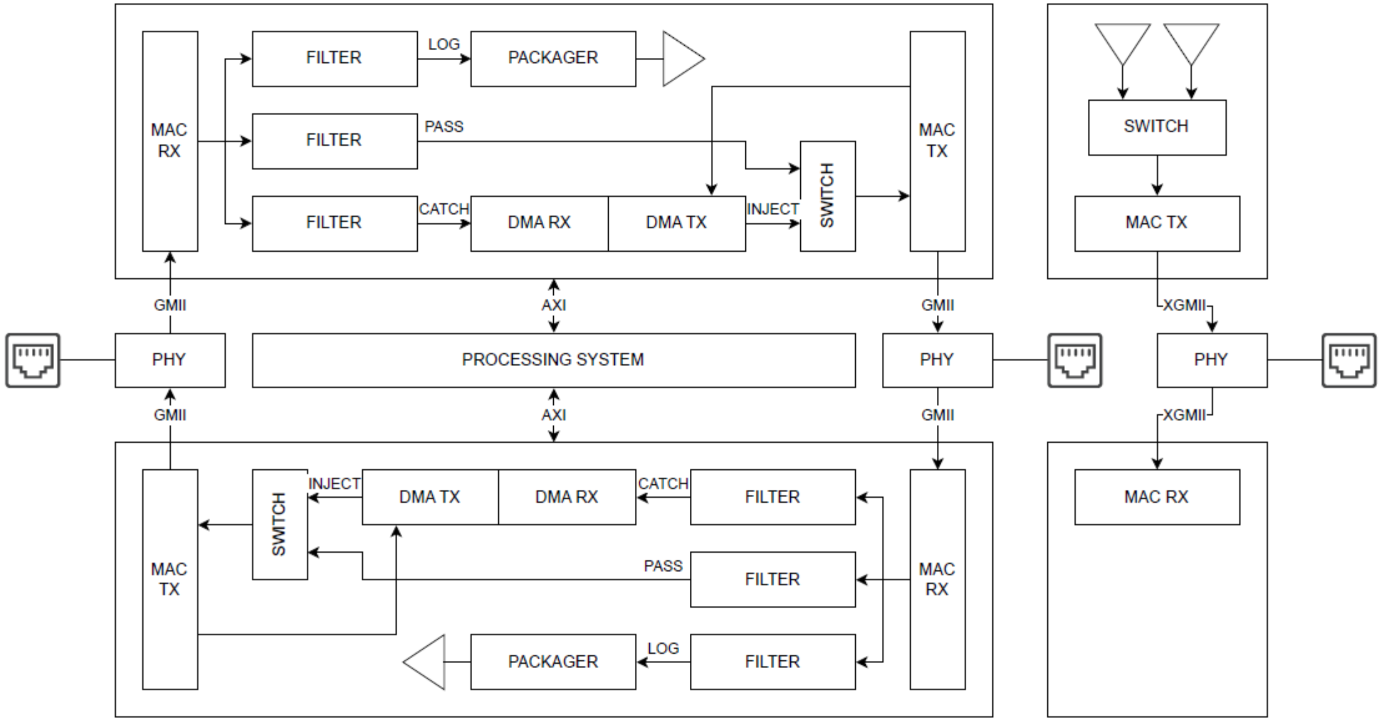
- PTP (Precision Time Protocol) support
  - PTP packets are directed (using HW accelerated filtering) into the processing system, processed and forwarded to destination
  - PTP transparent clock functionality was implemented on processing system
- PTP implementation testing
  - test setup prepared, basic PTP functionality was tested
  - influence on quality of time synchronization was evaluated
    - peak to peak time adjustment was within ±20 ns without the module inserted in link
    - peak to peak time adjustment was within ±30 ns with the module inserted in link – slightly worse
    - but still deeply below limit (±500 ns) – no improvement is necessary



Content of Work Package 4-WP01 – "Tools for Integration of Vehicles into Multimodal Systems with Increased Safety (including cybersecurity) and Subjected to LCA"

Current State of Deliverables and Fulfillment of Goals

- 4-WP01-007 | Programmable hardware platform for (non-)intrusive tests of vehicle communication channels., Gfunc, XII./2025, CTU FEE 0.3; SA 0.6; TUV 0.1 – **in progress & no major delays:**
- data acquisition and monitoring
  - per 1Gbps link HW accelerated filtering
  - links data aggregation into 10Gbps port with HW accelerated filtering and CMP protocol packaging
  - per link HW accelerated packet filtering and transfer to and from the processing system
  - VHDL design is ready to be extended for up to 4 1Gps Automotive Ethernet links and their aggregation into CMP stream



Content of 4-WP01 Advanced localization and driver assistance systems for trams

Acknowledgment

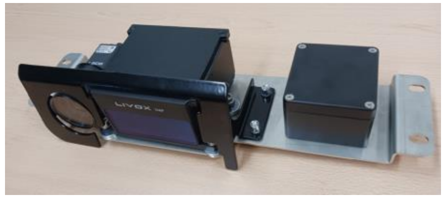
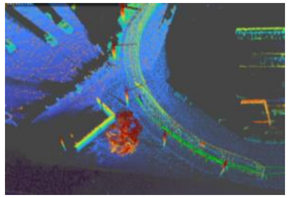
This research has been realized using the support of Technological Agency, Czech Republic, programme National Competence Center II, project # TN02000054 Božek Vehicle Engineering National Center of Competence (BOVENAC).

Content of 4-WP01 Advanced localization and driver assistance systems for trams

Summary of results 2023-2025

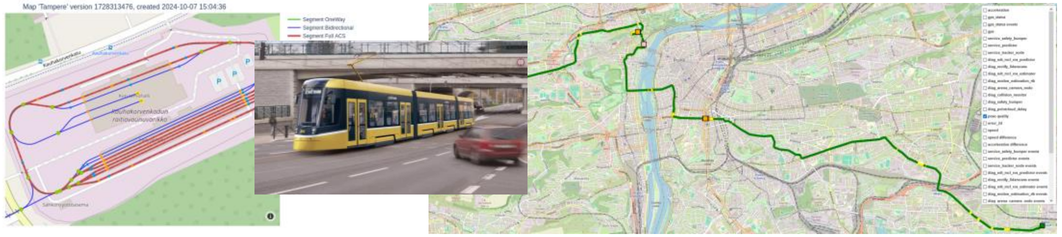
CTU + SD: Advanced driver assistance systems

Sensor head, Lidar (collision avoidance)

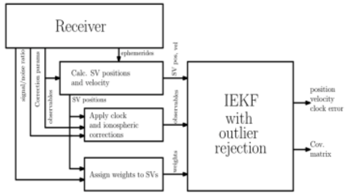

HYPEX onboard computer, SW implementation in ROS

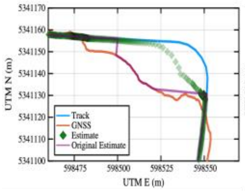
Testing, performance evaluation

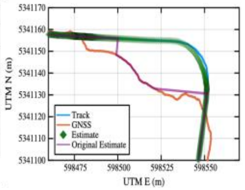


CTU + SD + ZCU: Advanced localization

Robust GNSS processing, information fusion, urban canyons

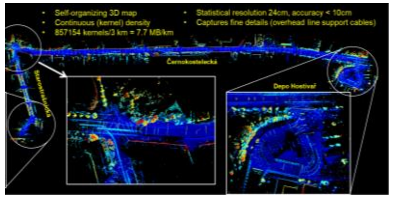
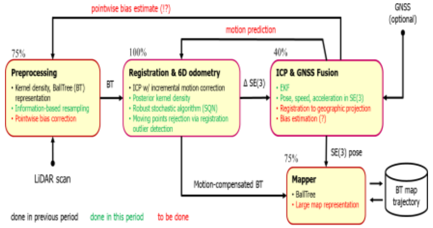


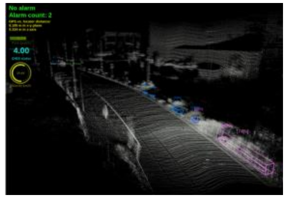




Geometric perception

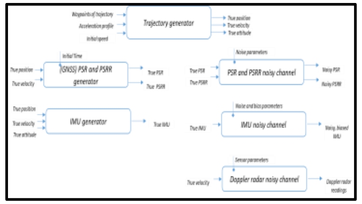
LIDAR data processing, SLAM

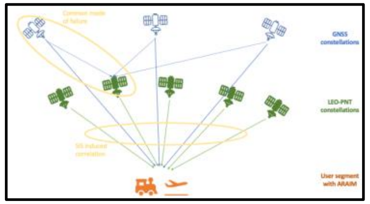


Advanced localization

GNSS/IMU simulator



GNSS and LEO PNG

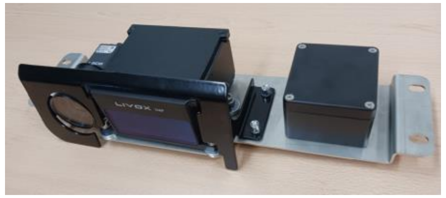
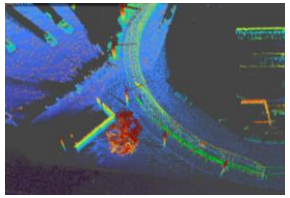


Content of 4-WP01 Advanced localization and driver assistance systems for trams

Výtah z prací 2023-2025

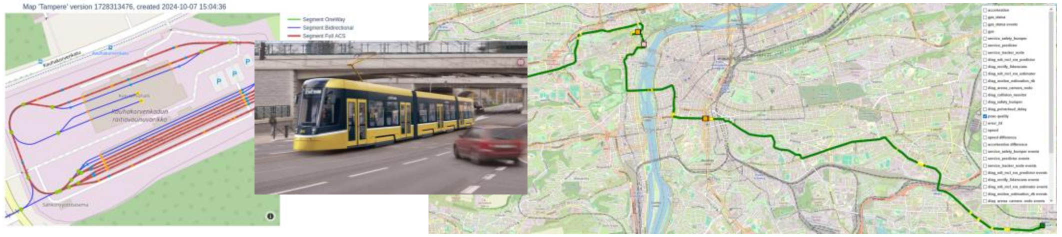
CTU + SD: Pokročilé asistenční systémy

Sensorová hlava, upgrade Lidaru

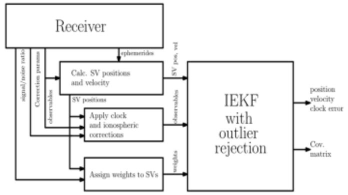

HYPEX palubní počítač, implementace SW v ROSu

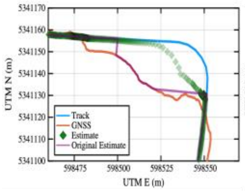

Testování, vyhodnocení přínosů

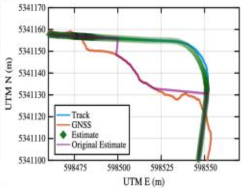


CTU + SD + ZCU: Pokročilá lokalizace

Robustní zpracování GNSS signálu, fůze informací, městské prostředí

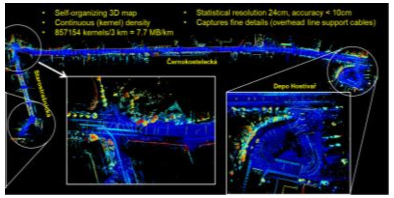
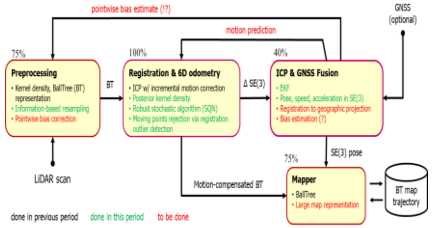
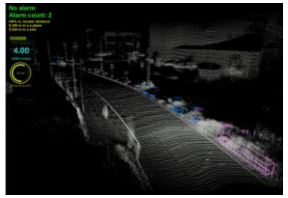






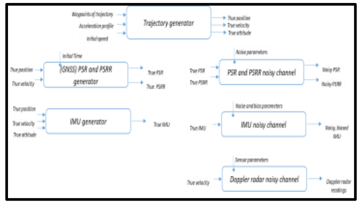
Geometrické vnímání

Zpracování dat LIDARu, SLAM

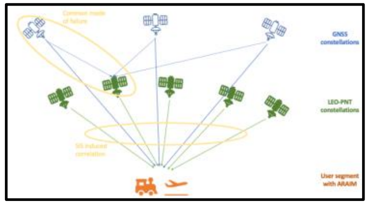





Pokročilá lokalizace

GNSS/IMU simulátor



GNSS a LEO PNG

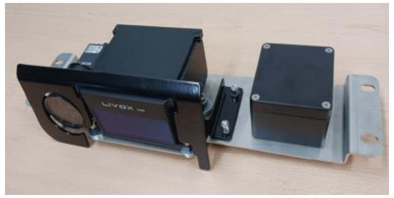


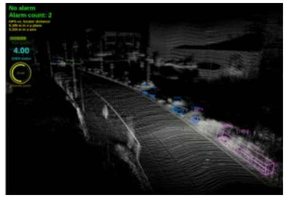
Content of 4-WP01 Advanced localization and driver assistance systems for trams

Summary of results 2024

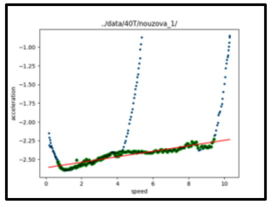
CTU + SD: Advanced driver assistance systems

Sensor head, Lidar upgrade (LIVOX)

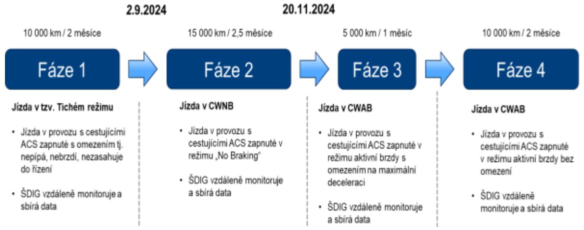


HYPEX onboard computer, breaking force optimization

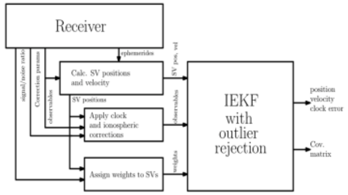



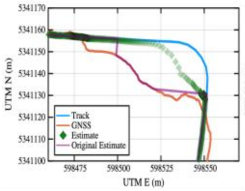
Testing, certification

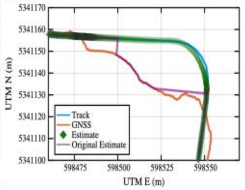



CTU + SD + ZCU: Advanced localization

Robust GNSS processing, IMU-ODO-map information fusion





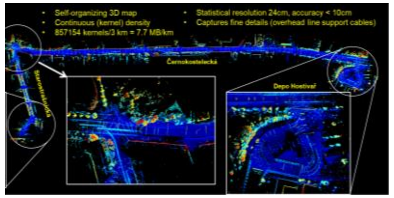
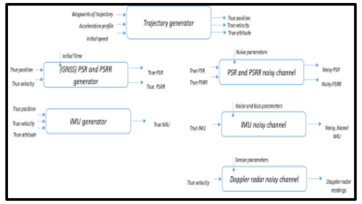


Geometric perception

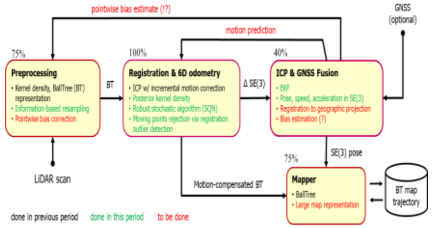
LIDAR data processing, SLAM

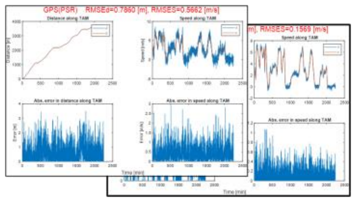
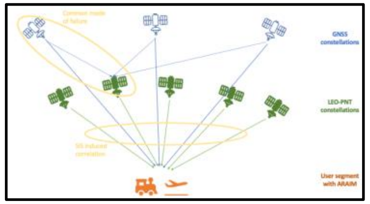
Advanced localization

GNSS/IMU simulator

GNSS and LEO PNG



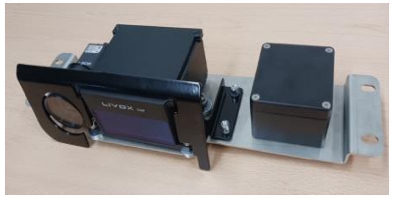



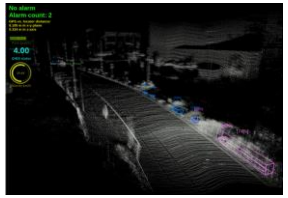
Content of 4-WP01 Advanced localization and driver assistance systems for trams

Výtah z prací 2024

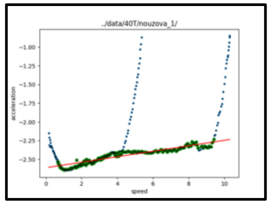
CTU + SD: Pokročilé asistenční systémy

Sensorová hlava, upgrade Lidaru (LIVOX)

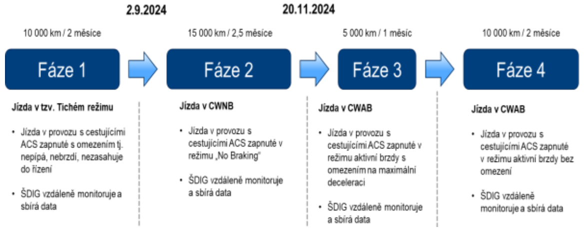


HYPEX počítač, optimalizace brzdění pro antikolizní systém

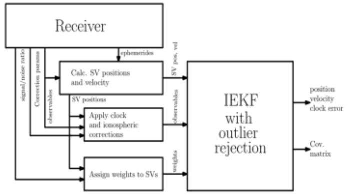



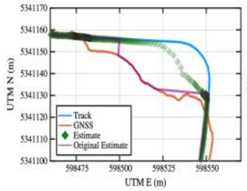
Testování, certifikacew

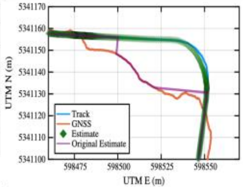



CTU + SD + ZCU: Advanced localization

Robustní zpracování GNSS signálu, fůze informací IMU/ODO/mapa

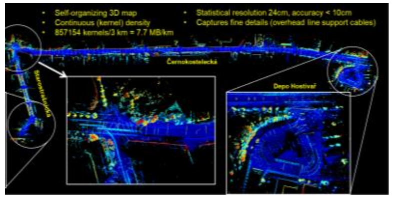
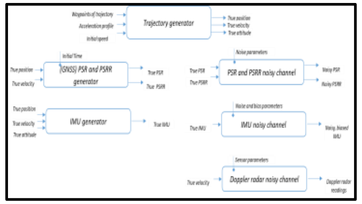




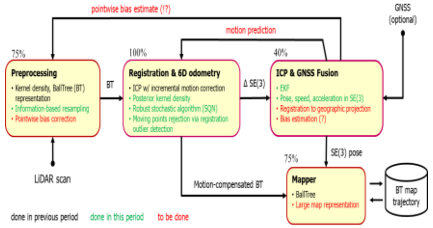


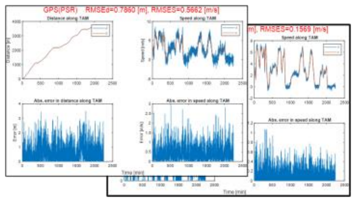
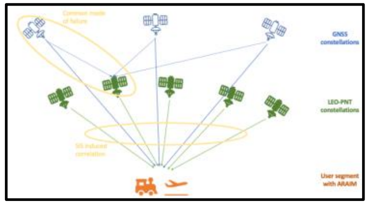
Geometrické vnímání
Zpracování dat LIDARu, SLAM

Pokročilá lokalizace
GNSS/IMU simulátor

GNSS a LEO PNG



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Radek Chládek: Odhadování sklonu vozovky multisenzorickou fúzí na palubě vozidla (bak. práce FEL, 2023)

Tato bakalářská práce se zaměřuje na odhad sklonu vozovky na základě multisenzorické fúze na palubě kolejového vozidla. Znalost sklonu vozovky se ukazuje být kritickou informací pro vývoj antikolizních systémů, a to zejména pro odhad brzdné dráhy. Dále se tato znalost může využít při plánování energeticky optimálních rychlostních profilů. Práce shrnuje vybrané související texty (články, knihy). Je zde popsán a navržen matematický model podélného pohybu kolejového vozidla. Tento model je v práci využit pro vygenerování syntetických průběhů relevantních veličin. Dále jsou popsány a implementovány tři konkrétní metody, které tyto průběhy využívají pro odhad sklonu vozovky. Jmenovitě Luenbergerův pozorovatel, rozšířený Kalmanův filtr (EKF) a EKF s průměrováním z více průjezdů stejné trasy. Metody jsou naimplementovány v prostředí Matlab a Simulink a mezi sebou porovnány.

This bachelor thesis focuses on road grade estimation by multisensor fusion onboard a railway vehicle. The knowledge of road grade proves to be critical information for the development of collision avoidance systems, namely for estimation of braking distance. Furthermore, this knowledge can be used for designing energy-optimal speed profiles. The thesis summarizes methods used today (described in articles or books). A mathematical model of the longitudinal motion of a railway vehicle is described and designed here. The model is then used for generating synthetic measurements of relevant variables. Additionally, three specific methods, that are using the above mentioned variables, are described and implemented in the thesis. Namely the Luenberger observer, the extended Kalman Filtr (EKF), and the EKF with averaging from multiple runs over the same route. All of the methods mentioned above are implemented in the Matlab and Simulink environments and compared against each other.

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Matouš Vondrášek: Odhadování decelerace vozidla fúzí měření z akcelerometru a odometrie (bak. práce FEL, 2023)

Tato práce se zabývá odhadem decelerace vozidla. Toho je dosaženo fúzí měření z akcelerometru a odometrie. Měření z odometrie je nejprve zpracováno na rychlost. K potlačení šumu a samotné fúzi následně poslouží komplementární filtr.

This work is focused on estimation of vehicle deceleration. The goal is achieved by accelerometric and odometric data fusion. Odometric data are at first processed in order to extract angular velocity. Noise suppression and fusion itself is done by complementary filter.

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Vít Fanta: Energeticky efektivní řízení kolejových vozidel (diplomová práce FEL ČVUT, 2023)

Cílem této práce je představit problém optimálního řízení vlaku a implementovat open-source softwarový balíček, pomocí něhož je jej možno řešit. Řešením je rychlostní profil, který bere v úvahu trakční limity vlaku, celkový čas cesty a výškový profil tratě a zároveň minimalizuje celkovou vynaloženou energii. Optimální strategie spočívá v přepínání několika jízdních režimů: maximální trakce, držení rychlosti, optimální brzdění, výběh a maximální brzdění. Na ploché trati má optimální strategie podobu maximální trakce – (držení rychlosti) – výběh – maximální brzdění. Na obecné trati může docházet k většímu množství přepnutí kvůli příliš strmým úsekům. Řešení bylo implementováno v jazyce Julia a je dostupné veřejnosti v podobě balíčku na GitHub. I přes to, že je program obecně funkční a příklady výpočtu jsou uvedeny. Některé funkcionality stále chybí (především možnost zahrnout rychlostní omezení). Současné řešení je však možno dále vyvíjet díky jeho open-source povaze.

The goal of this thesis is to present the problem of optimal train control and implement an open-source software package able to solve it. The solution is a speed profile which takes train’s traction capabilities, total journey time and the track gradient into account while minimising the total required energy.

The optimal control strategy is a switching strategy between a small number of modes: Maximum Power, Cruising, Optimal Braking, Coasting and Maximum Braking. On a flat track, the optimal strategy has the form Maximum Power – (Cruising) – Coasting – Maximum Braking. On a general track, more switching can occur due to the steep uphill and steep downhill sections of the track. A solution has been implemented in the Julia programming language and is available to the public in a form of a package accessible on GitHub. The solution is functional and examples of speed profile calculation are shown. Some features are still missing, most notably inclusion of speed limits. Functionality of the implemented solution can be further developed thanks to its open-source nature.

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Oliver Kost, Jindřich Duník, Ondřej Straka, Ondřej Daniel: Identification of GNSS Measurement Error: From Time to Elevation Dependency. *IEEE Transactions on Aerospace and Electronic Systems*, 2023

This paper deals with the identification of the GNSS measurement error properties. For this purpose, an extended version of the measurement difference method, which does not rely on knowledge of the state dynamics, is developed. The method provides elevation-dependent estimates of the pseudorange and pseudorange-rate measurement error properties in the form of both; the autocovariance function and the parametric model including the correlation time constants. The identification method is thoroughly discussed and verified using simulated and real Galileo E5b data and the identified models are utilised in the positioning solution. The identified measurement model improves the positioning accuracy by more than twenty percent.

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Duník, J.; Punčochář, I.; Král, L.; Straka, O.; Daniel, O.; Prol F. S.; Liaquat, M.; Bhuiyan, Z.: Multi-layer GNSS and LEO-PNT Positioning: Integrity under Constellations' Correlation. *27th International Conference on Information fusion*, July 2024, Venice, Italy

This paper deals with the initial integrity evaluation of the navigation information provided by the multilayer GNSS and LEO-PNT constellation. Although, the global satellite navigation systems (GNSS) play indispensable role in almost all aspects of today's society, their signals are prone to intentional or accidental interference. Therefore, low Earth orbit (LEO) constellations aiming at position, navigation, and timing (PNT) solution have recently been introduced as their extension. The LEO-PNT constellations are planned to contain hundreds of SVs with better interference resilience and geometric diversity. As a consequence, the multi-layer GNSS and LEO-PNT constellation was shown to offer more accurate PNT solution. In this paper, we focus on another important aspect of the multi-layer navigation information, which is its integrity assessment. In particular, we analyse possible dependencies between GNSS and LEO-PNT constellations and their impact on the integrity evaluated using the solution separation. The analysis is supported by the numerical simulations using GPS and LEO-PNT constellations with 32 and 441 satellites, respectively.

Tento článek se zabývá počátečním hodnocením integrity navigačních informací poskytovaných vícevrstvou konstelací GNSS a LEO-PNT. Ačkoli globální družicové navigační systémy (GNSS) hrají nezastupitelnou roli v téměř všech aspektech dnešní společnosti, jejich signály jsou náchylné k

k úmyslnému nebo náhodnému rušení. Proto byly nedávno zavedeny jako jejich rozšíření konstelace na nízké oběžné dráze (LEO), které jsou zaměřeny na určování polohy, navigaci a časování (PNT). Plánuje se, že konstelace LEO-PNT budou obsahovat stovky SV s lepší odolností vůči rušení a geometrickou diverzitou. V důsledku toho vícevrstvé GNSS a LEO-PNT konstelace nabízí přesnější PNT řešení. V tomto článku se zaměřujeme na další důležitý aspekt vícevrstvých navigačních informací, kterým je posouzení jejich integrity. Konkrétně analyzujeme možné

závislosti mezi konstelacemi GNSS a LEO-PNT a jejich dopad na integritu vyhodnocenou pomocí separace řešení . Analýza je podpořena numerickými simulacemi s použitím konstelací GPS a LEO-PNT s 32 a 441 družicemi.

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Abstracts of publications 2023-2025

Moravec, J.; Šára, R.: Online Camera-LiDAR Calibration Monitoring and Rotational Drift Tracking. *IEEE Transactions on Robotics*, 2024. ISSN 1552-3098.

The relative poses of visual perception sensors distributed over a vehicle's body may vary due to dynamic forces, thermal dilations, or minor accidents. This article proposes two methods, Online CAlibration MOnitoring (OCAMO) and LTO, that monitor and track the LiDAR–camera extrinsic calibration parameters online. Calibration monitoring provides a certificate for reference-calibration parameters validity. Tracking follows the calibration parameters drift in time. OCAMO is based on an adaptive online stochastic optimization with a memory of past evolution. LTO uses a fixed-grid search for the optimal parameters per frame and without memory. Both methods use low-level point-like features, a robust kernel-based loss function, and work with a small memory footprint and computational overhead. Both include a preselection of informative data, which limits their divergence. The statistical accuracy of both calibration monitoring methods is over 98%, whereas OCAMO monitoring can detect small decalibrations better, and LTO monitoring reacts faster on abrupt decalibrations. The tracking variants of both methods follow random calibration drift with an accuracy of about 0.03◦ in the yaw angle.

Relativní polohy a orientace senzorů pro robotické vidění, které jsou rozmístěny na těle vozidla se mohou v čase měnit vlivem účinku dynamických sil, teplotní roztažnosti nebo lehkých poškození. Tento článek popisuje dvě třídy metod, OCAMO a LTO, pro dvě úlohy: (1) monitoring a (2) sledování geometrické kalibrace mezi LiDARem a kamerou. Monitor kalibrace průběžně poskytuje online certifikát, že referenční (tovární) kalibrace je stále platná. Sledovač měří změny parametrů kalibrace v čase. Třída OCAMO je založena na adaptivní online stochastické optimalizaci s pamětí. Třída LTO je založena na prohledávání okolí referenční kalibrace v prostoru parametrů a nemá paměť. Obě metody z obou tříd používají jednoduché lokální vlastnosti snímku a kernelizované kritérium optimality robustní vůči vychýleným hodnotám, mají dále malé nároky na výpočetní paměť a na výpočetní výkon. Monitor i sledovač jsou doplněny o mechanismus selekce informativnách snímků, který zvyšuje jejich stabilitu. Statistická přesnost monitorování dosáhla 98%, přičemž OCAMO je schopná detekovat menší odchylky od reference a LTO reaguje rychleji na náhlé dekalibrace. Sledovací verze dosahují chyby 0.03 stupně v úhlu bočení na simulovaném náhodném driftu kalibračních parametrů.

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Abstracts of publications 2023-2025

Moravec, J.; Šára, R.: High-recall calibration monitoring for stereo cameras. *Pattern Analysis and Applications*, 2024. ISSN 1433-7541.

Cameras are the prevalent sensors used for perception in autonomous robotic systems, but their initial calibration may degrade over time due to dynamic factors. This may lead to a failure of downstream tasks, such as simultaneous localization and mapping (SLAM) or object recognition. Hence, a computationally lightweight process that detects the decalibration is of interest. We describe a modification of StOCaMo, an online calibration monitoring procedure for a stereoscopic system. The method uses robust kernel correlation based on epipolar constraints; it validates extrinsic calibration parameters on a single frame with no temporal tracking. In this paper, we present a modified StOCaMo with an improved recall rate on small decalibrations through a confirmation technique based on resampled variance. With fixed parameters learned on a realistic synthetic dataset from CARLA, StOCaMo and its proposed modification were tested on multiple sequences from two real-world datasets: KITTI and EuRoC MAV. The modification improved the recall of StOCaMo by 25 % (to 91 % and 82 %, respectively), and the accuracy by 12 % (to 94.7 % and 87.5 %, respectively), while labeling at most one-third of the input data as uninformative. The upgraded method achieved the rank correlation between StOCaMo V-index and downstream SLAM error of 0.78 (Spearman).

Kamery jsou nejběžnější senzory pro vidění v autonomních robotických systémech, ale parametry jejich tovární geometrické kalibrace se v čase mění vlivem dynamických faktorů. To může vést k selhání návazných procesů vnímání, jako je například lokalizace a mapování (SLAM) nebo rozpoznávání objektů. Předmětem výzkumu je výpočetně nenáročná procedura, která tyto odchylky sleduje v čase. V tomto článku popisujeme modifikaci metody StOCaMo pro online monitorování kvality kalibrace stereoskopického systému. Metoda používá robustní kernelizované kritérium optimality založené na epipolární podmínce a validuje parametry geometrické kalibrace na základě jediného stereopického snímku. Hyperparametry metody byly naučeny na realistické syntetické datové sadě vytvořené na simulátoru CARLA. Původní StOCaMo a její modifikace byly pak porovnány na souboru sekvencí ze dvou reáných datových sad: KITTI a EuRoC MAV. Navržená modifikace zlepšila celkový statistický recall o 25 % (na 91 % a 82 % po sadách), a statistickou accuracy o 12 % (na 94.7 % a 87.5 %, po sadách), přičemž za neinformativní data označila nejvýše 30% snímků. Statistický recall se výrazně zlepšil hlavně na malých dekalibracích. Modifikace dále zvýšila rankovou korelaci mezi StOCaMo V-indexem a chybou návazujícho procesu SLAM na hodnotu 0.78 (Spearman).