Developing Low-Cost Reliable Localization Systems for Increased Accuracy in Railway Operations and Maintenance

9th June 2021

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DLR

Train Localization for Track Monitoring and Predictive Maintenance

- In-service trains with sensors record data from the tracks.
- Data analysis computes the condition of the track continuously.
- Localization is required for the data association of the track data from multiple train runs.

Types of Train Localization

Train localization with **track**-side components

vs.

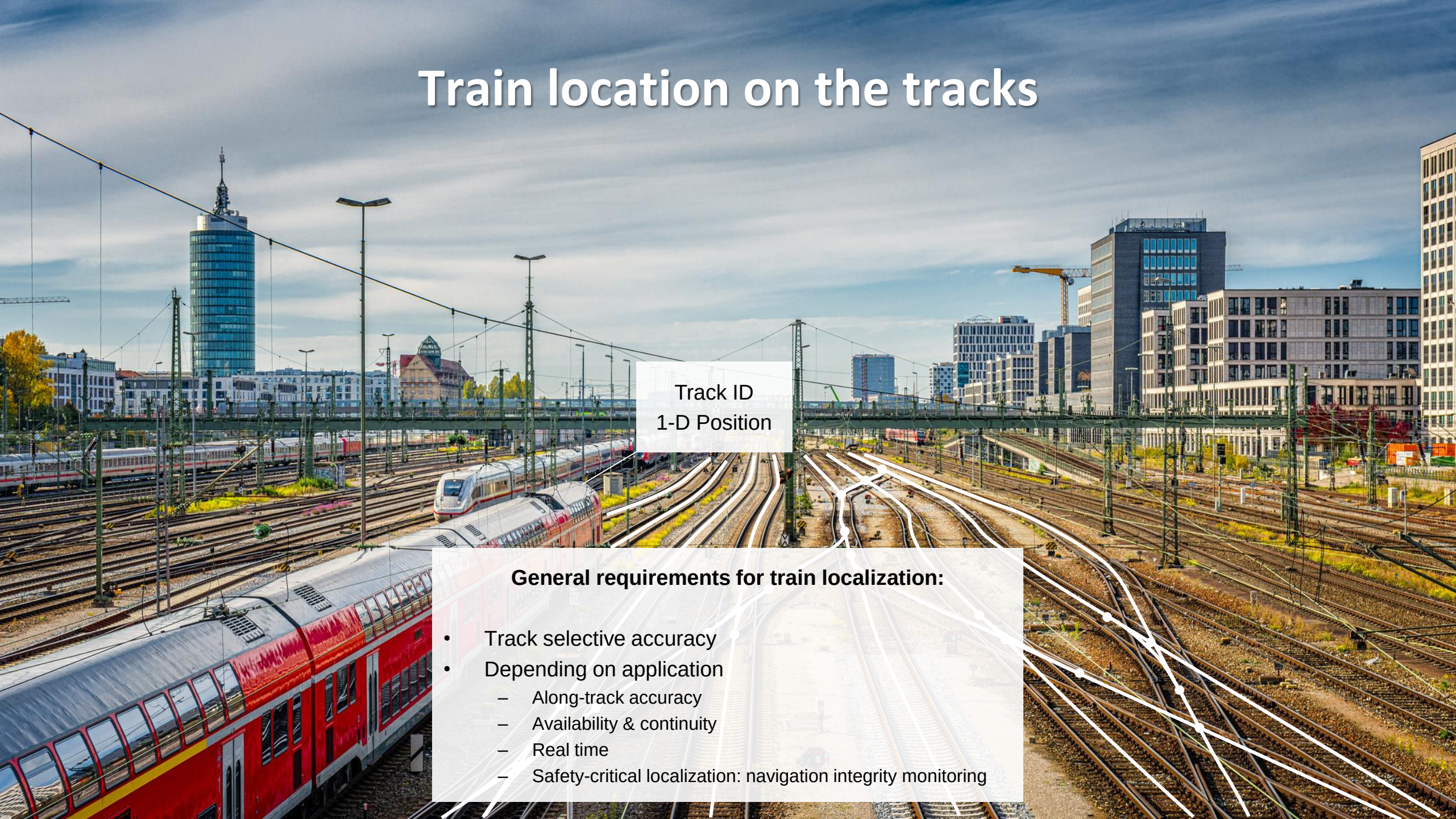
Onboard train localization with exclusive **train**-side components

Train localization for safety-critical systems

vs.

Train localization for non safety-critical systems

Train location on the tracks



Track ID
1-D Position

General requirements for train localization:

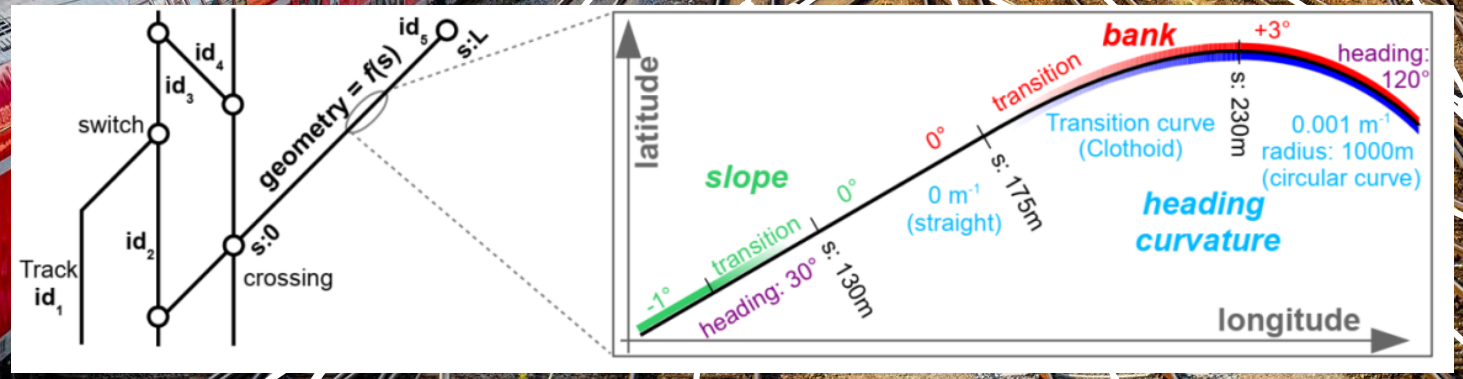
- Track selective accuracy
- Depending on application
  - Along-track accuracy
  - Availability & continuity
  - Real time
  - Safety-critical localization: navigation integrity monitoring

Train Localization with Train-side Sensors

Onboard sensors

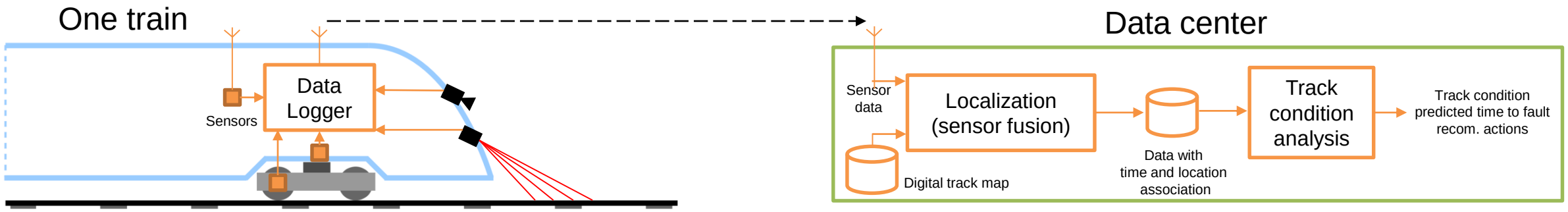
Digital track map

Localization method



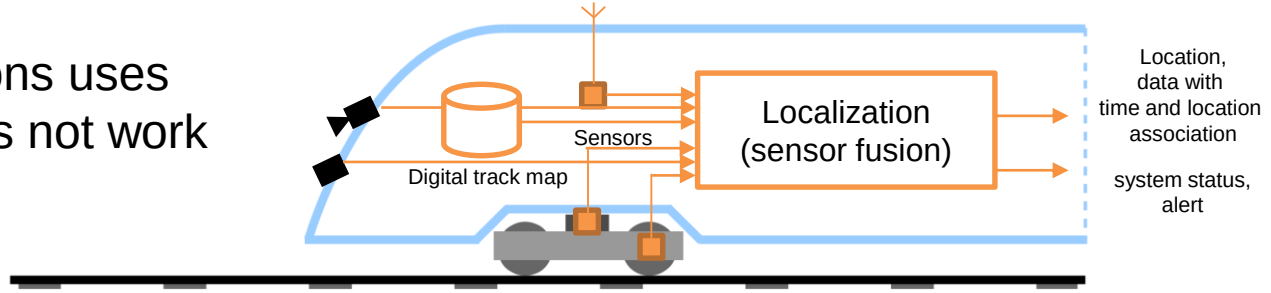
Train Localization System Achitectures

- Offline and central train localization with train-side sensors



- Real-time train localization system with train-side sensors

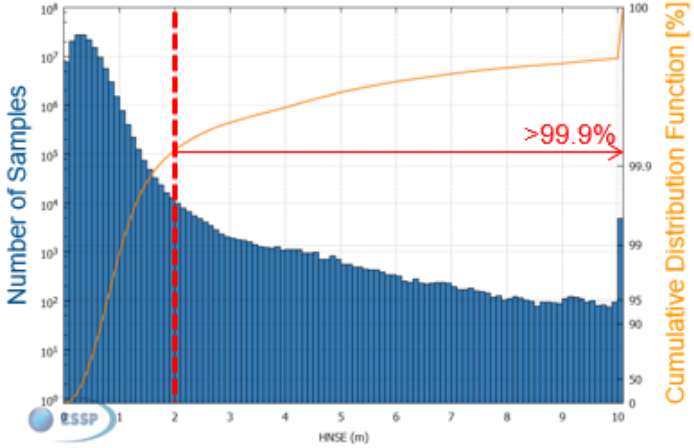
- Reliable train localization for **safety-critical** applications uses navigation **integrity monitoring**: alerts if system does not work as intended, values are off the defined limits



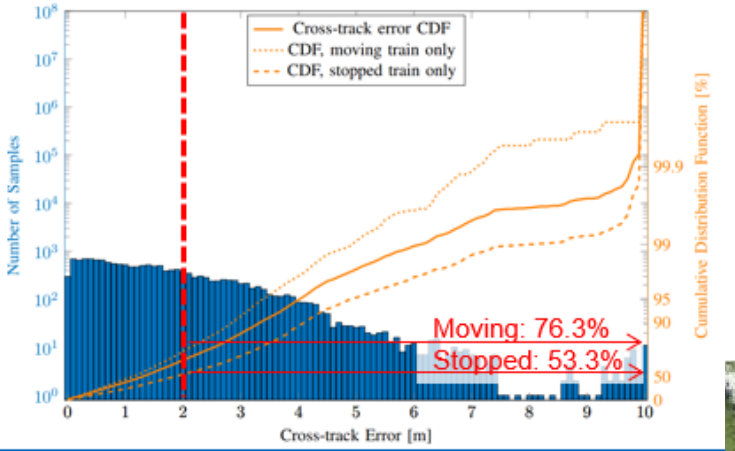
Sensors: GNSS (Global Navigation Satellite System)

- GNSS: GPS (US Navstar), GALILEO (EU), GLONASS (RU), BEIDOU (CN)
- Current state-of-the-art GNSS receiver: multi constellation, multi frequency
- GNSS measurements contribute to train localization with:
  - Position
    - along-track localization
    - absolute track identification (single tracks, problems with parallel tracks)
  - Train speed (relative along-track over time)
  - Motion direction/heading (track identification at the switch)
- Limitations in availability and accuracy in the railway environment
  - signal obstruction (station, below bridge, tunnel),
  - multipath (reflections)

Horizontal error of ideal GPS (EGNOS reference station)



Cross-track error of GPS measurements on train



Sensors: IMU – Inertial Measurement Unit

- Measurements: accelerations, turn rates in three axes (x,y,z)
  - Low-cost: MEMS (micro electro-mechanical systems)
  - High-end: FOG (fiber optical gyroscopes)

1. Inertial Navigation System (INS/GNSS, INS/X/map):

- INS/GNSS computes position, velocity and attitude

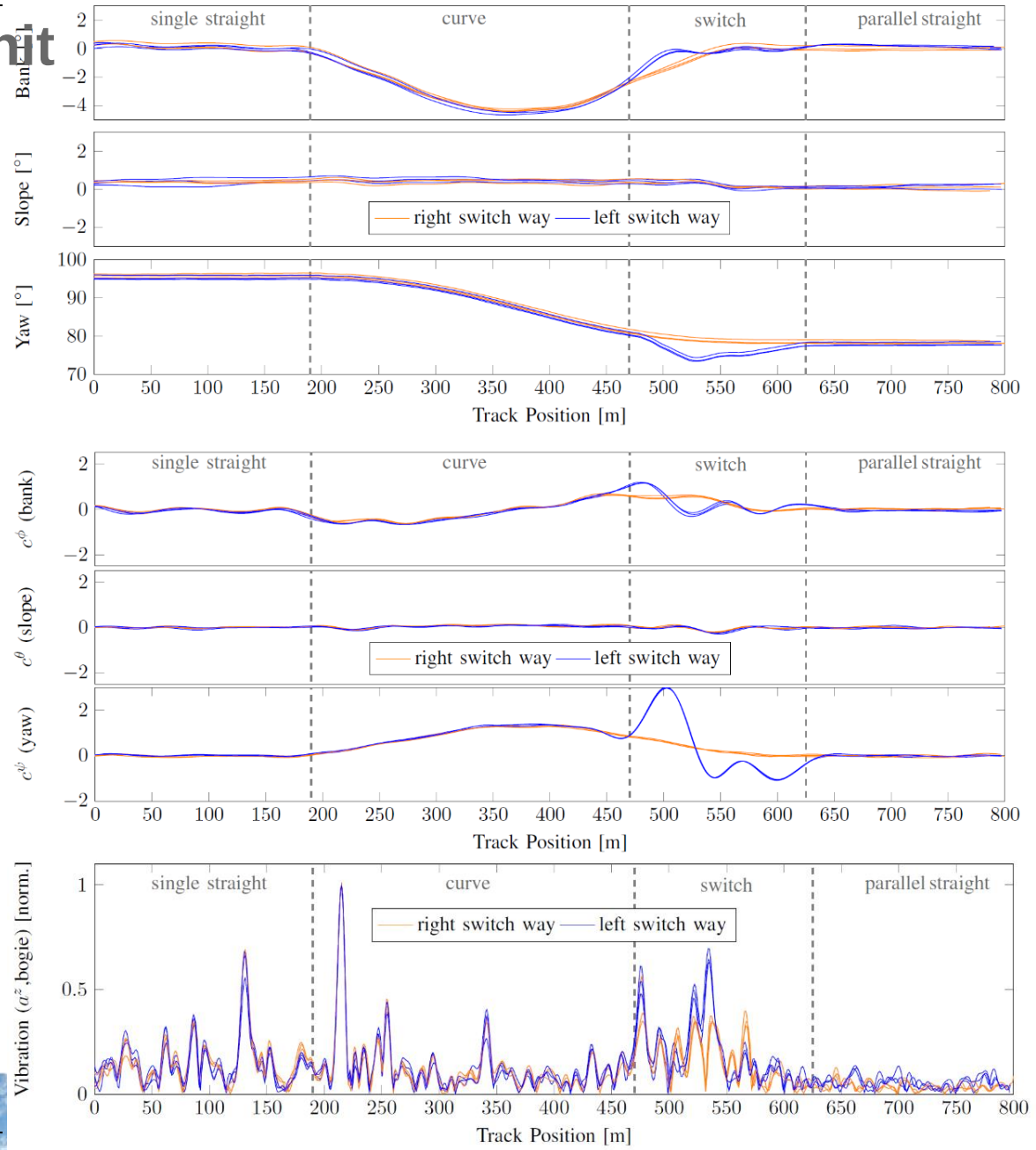
2. Kinematics of track geometry

- No integration required: suitable for low-cost MEMS IMUs
- Curvatures can be processed from turn rates and velocity

3. Vibrations

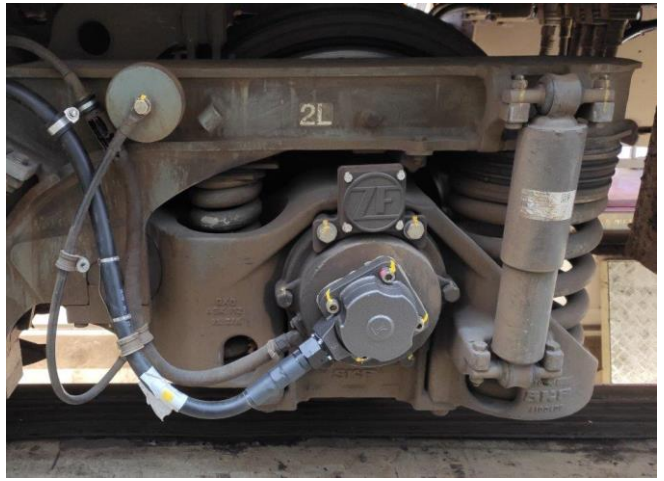
- Characteristic vibration intensity

Inertial Signatures

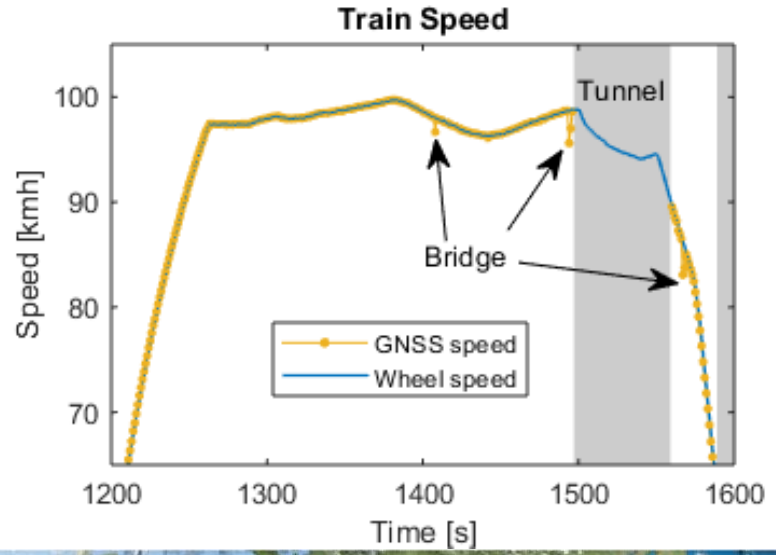


Sensors: Odometer

- Wheel odometer measures speed and displacement from rotary encoder



- Works in all environments, complimentary to GNSS (speed & displacement)
- Continued estimate of the wheel diameter is recommended (e.g. GNSS speed)
- Incorrect measurements from slip and slide



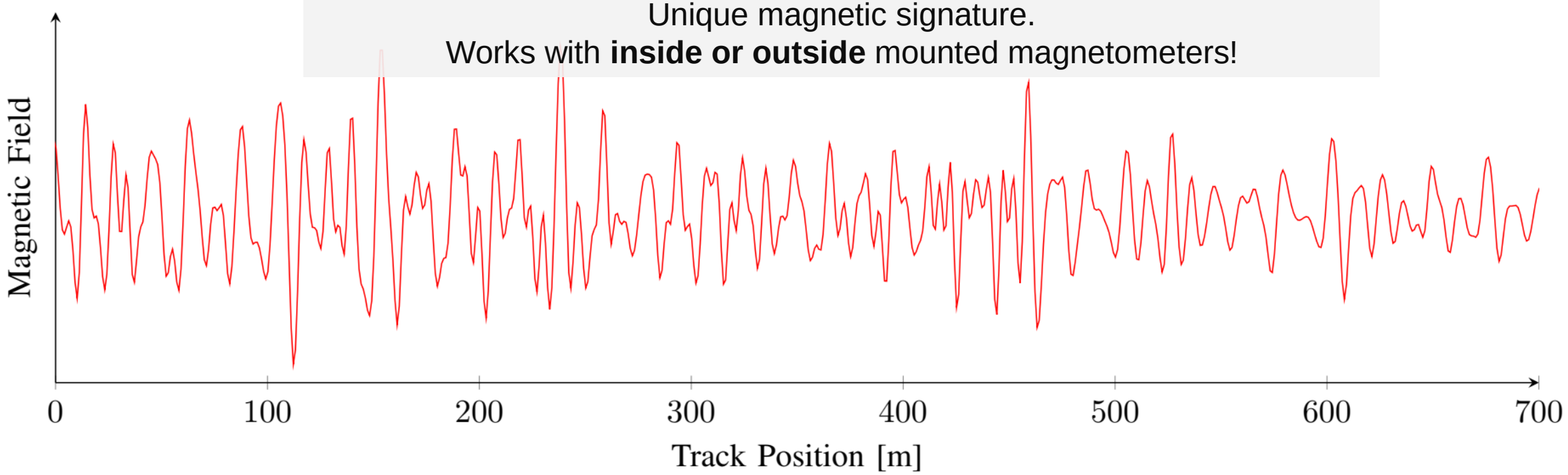
- Higher effort for mounting and approval process
- Mounting synergies possible: axle-box acceleration sensor for track condition monitoring

Sensors: Magnetometer

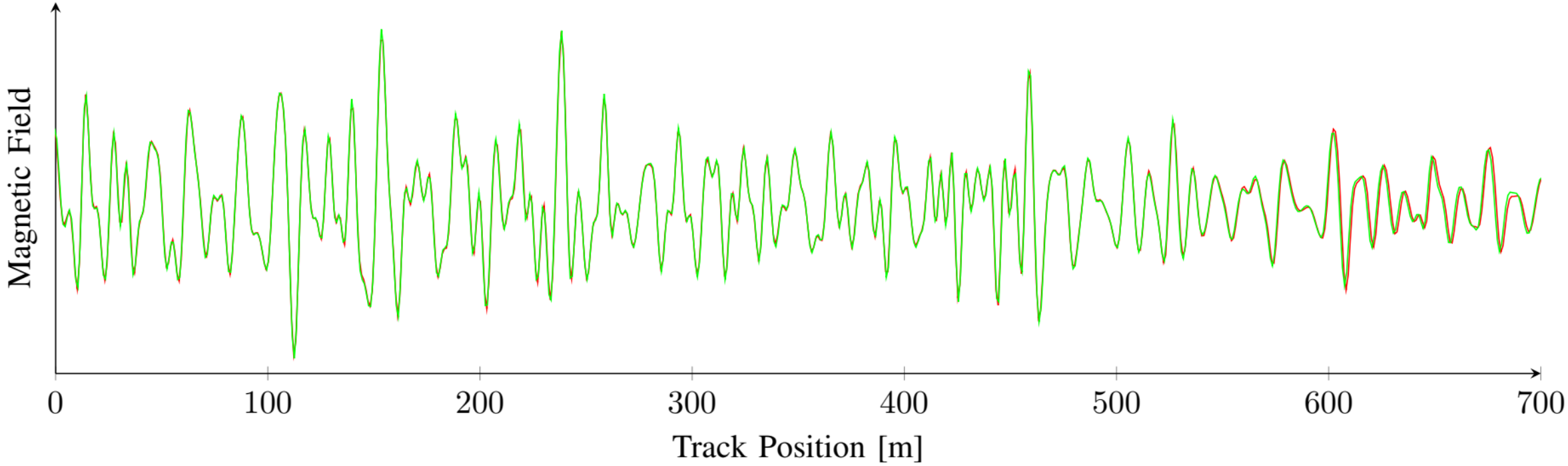
- Measurements: magnetic field density (Tesla) in three axes (x,y,z)
- Sensor elements are used in an electronic compass
- Railway environment creates characteristic distortion of the magnetic Earth field

Sensors: Magnetometer, Magnetic Signature
1st Run

Unique magnetic signature.
Works with **inside or outside** mounted magnetometers!

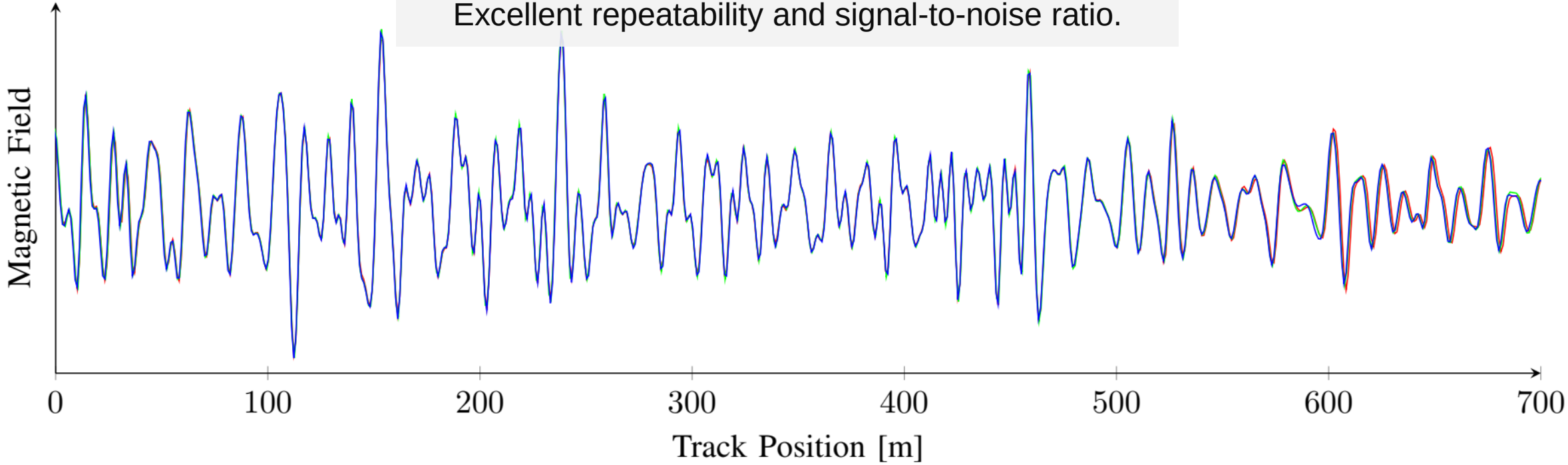


Sensors: Magnetometer, Magnetic Signature
1st Run + 2nd Run

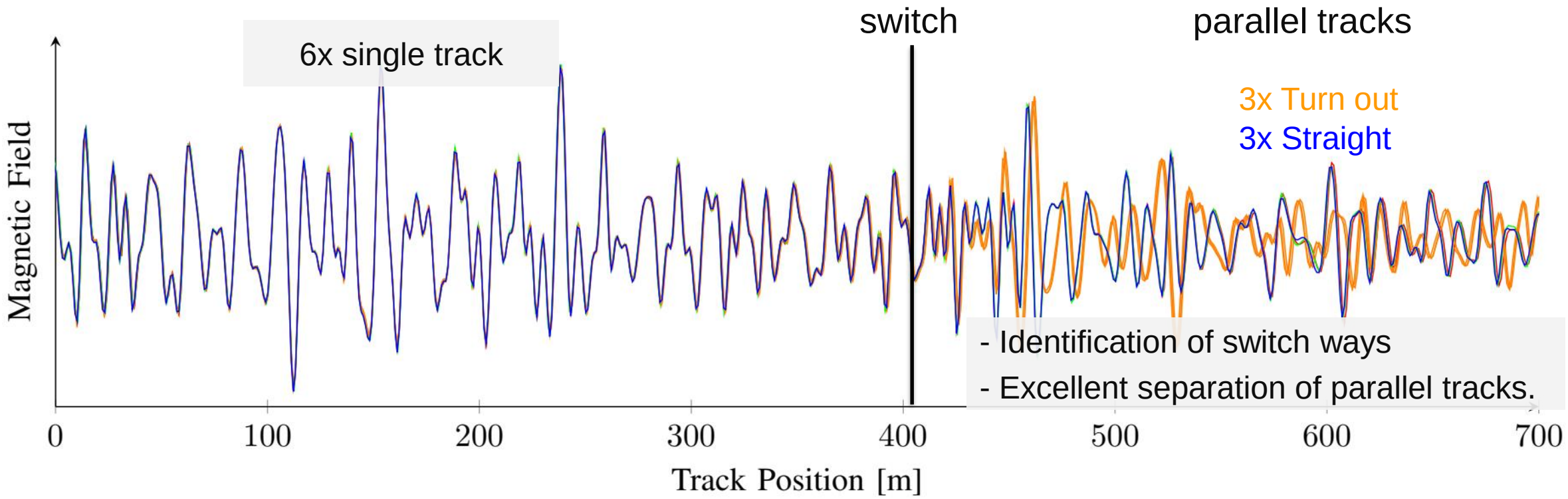


Sensors: Magnetometer, Magnetic Signature
1st Run + 2nd Run + 3rd Run

Excellent repeatability and signal-to-noise ratio.

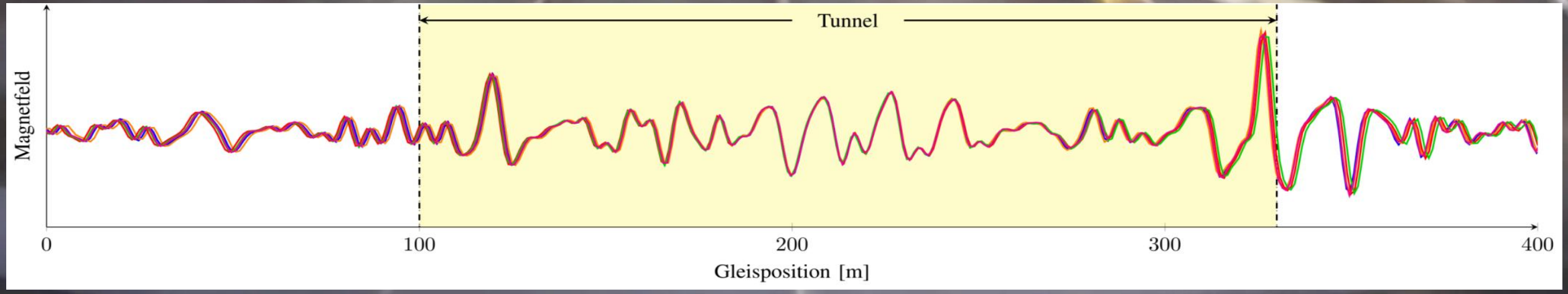


Sensors: Magnetometer, Magnetic Signature
6 rain runs



- Identification of switch ways
- Excellent separation of parallel tracks.

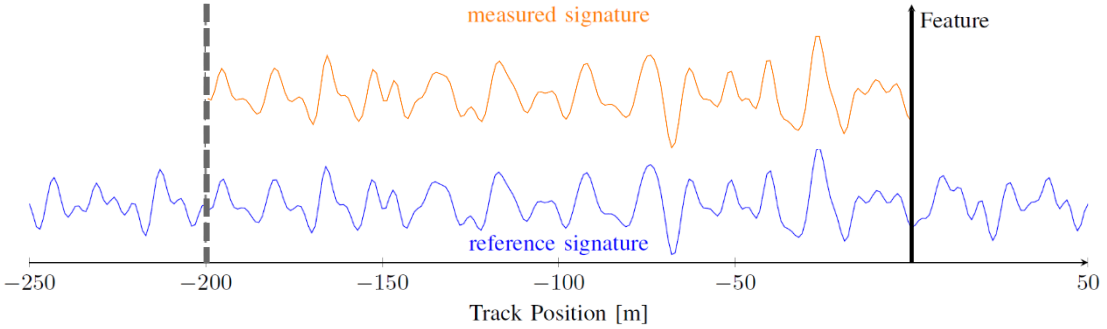
Sensors: Magnetometer, Tunnel



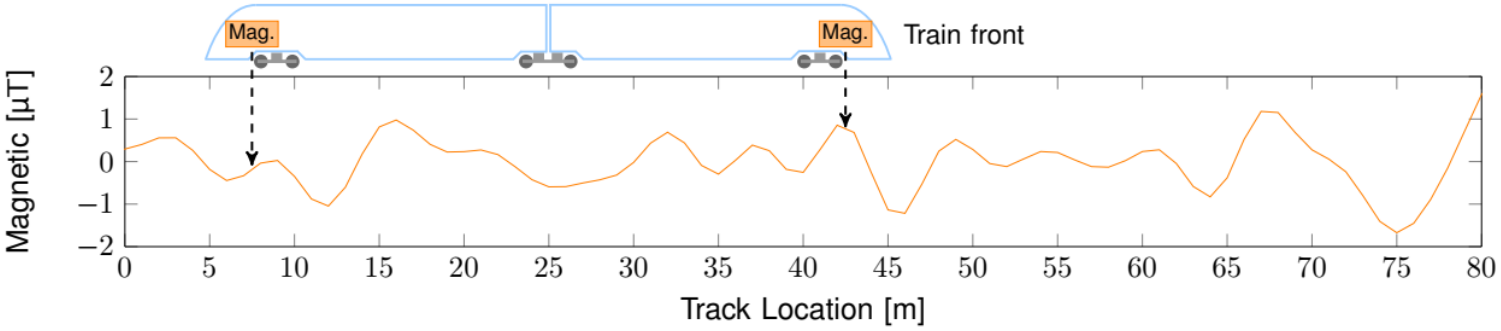
Works in Tunnels!

Magnetic Signature based Train Localization

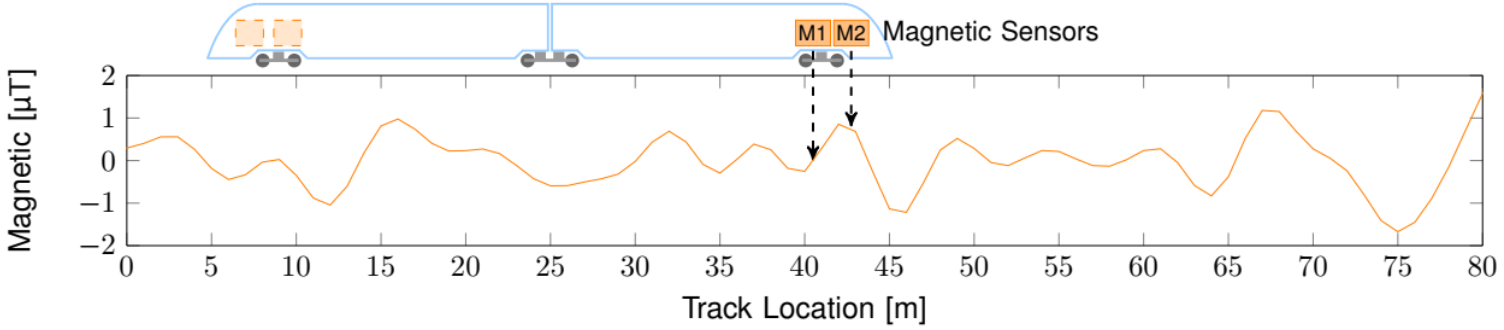
- Absolute train localization:
  - Along-track estimation
  - Track identification (switches, parallel tracks)



- Relative train localization:
  - Used for train length, train distance
  - Two sensors, front and end
  - Map free



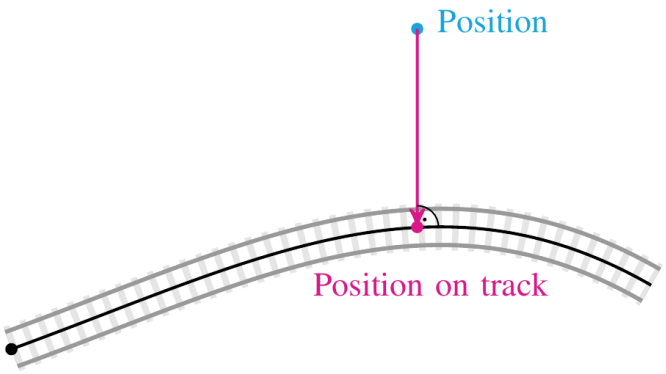
- Train speed
  - Setup with two sensors, along-track
  - Map free



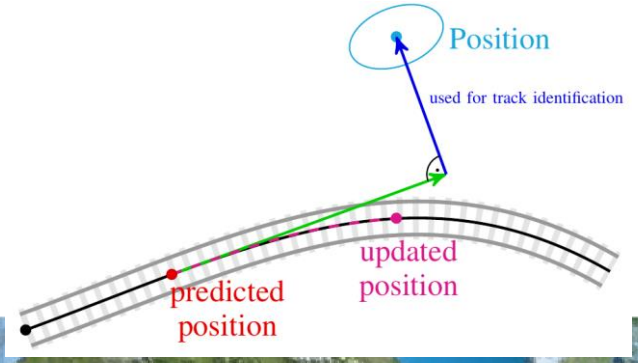
Sensor Fusion and Localization Methods

- Sensor fusion with complimentary measurements
  - Probabilistic filters with state estimation (e.g. Kalman Filter)
    - Prediction step: expected evolution over time
    - Update step evaluates a deviation between expected estimate and measurement
  - Offline processing: smoothing with forward-backward filtering
  - Advanced methods: data quality checks, fault detection and exclusion

- Localization approach 1: Map-matching
  - Step 1: Sensor fusion for position
  - Step 2: Map-matching of the position to the nearest point on the track

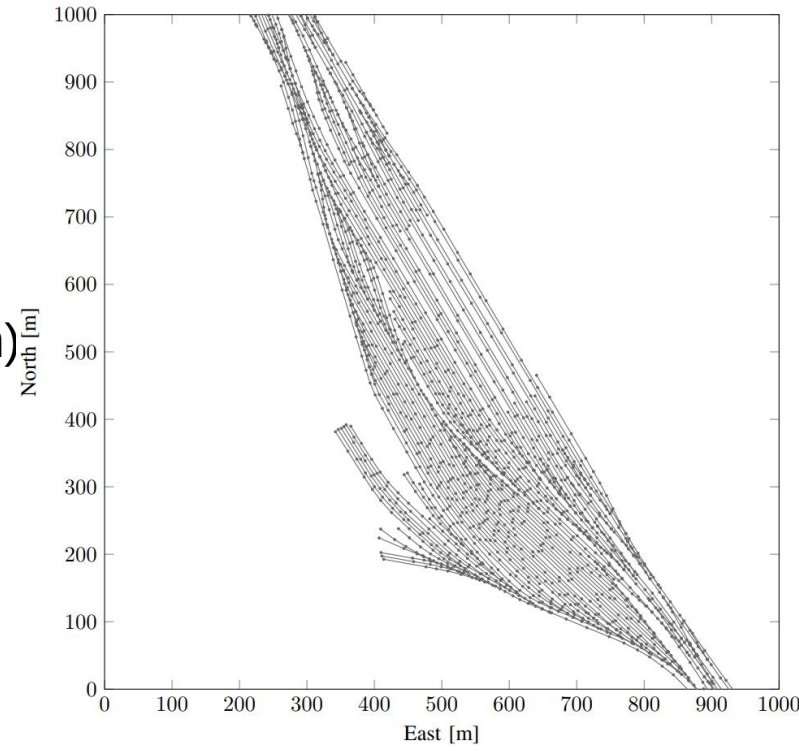


- Localization approach 2: sensor fusion with the map
  - Direct estimation of track ID and 1D-position co-ordinante
  - Motion model includes the map (constrains)
  - Update step evaluates deviations of positions and signatures between map and measurements
  - Filter can handle multiple track hypothesis (e.g. after passing a switch facing)

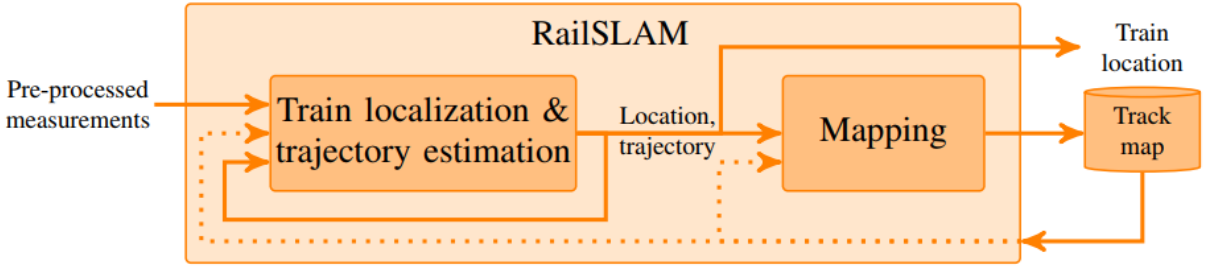


Mapping Approach

- First: Initial map with interconnections and coarse positions.
- Track positions from
  - Open-street-map, or
  - geo-referenced aerial photos, or
  - train measurements with an automated approach (req. switch estimation)



- Later: Improved and up-to-date map is achieved from train sensor data (iterative map)



What means low-cost localization? What will save costs?

- Track-side or train-side based localization?
  - Track-side components: difficult installation, maintenance & power supply, costs per kilometer/mile and per train
  - Train-side components: easier installation & maintenance at the workshop, easier supply, costs per train

- Certification:
  - Safety critical systems require a certification of the complete system (design, HW/SW), operations, etc…
  - Non safety-critical systems can be built out of certified & approved hardware components for railways (e.g. cables, antenna, CPU)

- Lower or less restrictive requirements for localization for pred. maintenance
  - Accuracy: Is a small number of incorrect track identifications acceptable? (e.g. 1% wrong is treated as data outlier in the analysis)
  - Availability: 99.973% needed? Is 95% of the time good enough? Savings on non-redundant sensor setups. Every train in the fleet?
  - Continuity: (ability of uninterrupted service) Is it really required?
  - Real time: Needed? A delay of 1hr or 1day may be still considered as live data of a slow changing infrastructure state

- Hardware components
  - COTS (commercial-off-the-self) components,
  - Integrated components & products (e.g. inertial navigation system, data logger)
  - Mounting synergies: wheel odometer and axle-box acceleration sensor, IMU

- Shared resources with other applications: e.g. passenger info system, energy monitoring, pred. maintenance of the vehicle
  - GNSS antenna (signal splitter)
  - data link
  - sensor data

Current activities, state of science

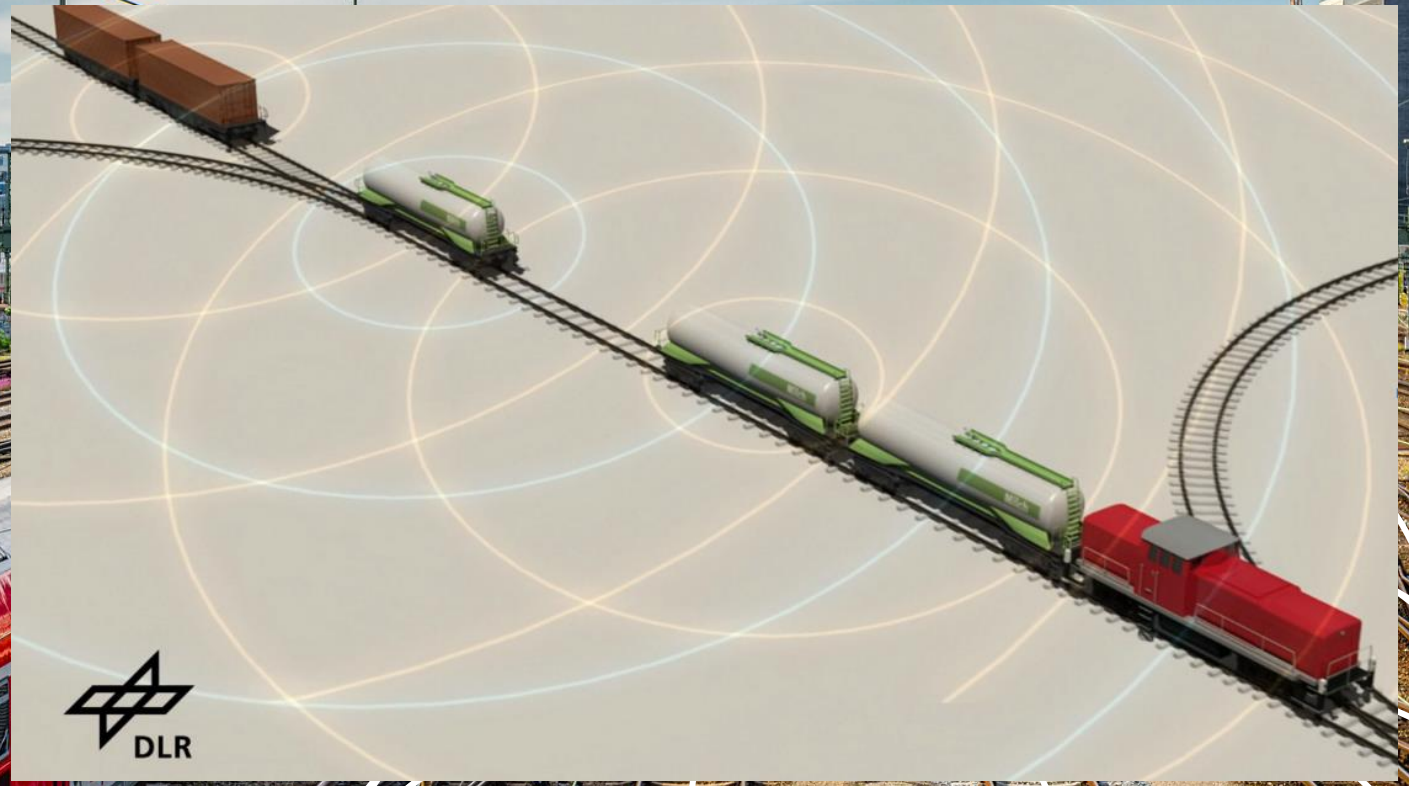
- DLR, Institute of Communications and Navigation, Oberpfaffenhofen (near Munich)

- Evaluations of localization algorithms with measurement data from train runs
- Sensors measurement methods & models, error models
- Error analysis and fault detection methods and models (navigation integrity)

- Contribution to visionary applications

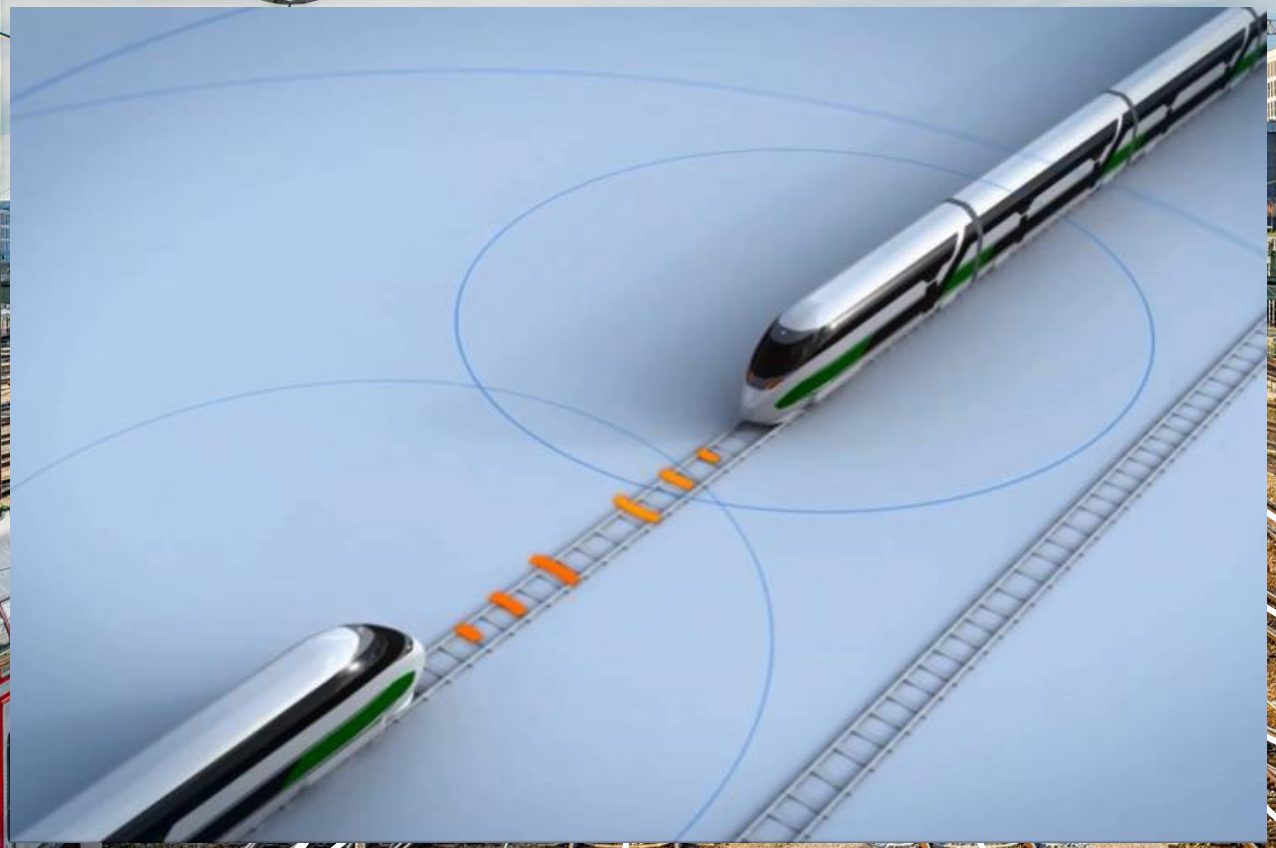
Applications Enabled by Onboard Train Localization

Automation & Autonomy



Applications Enabled by Onboard Train Localization

Vision: Virtual Coupling



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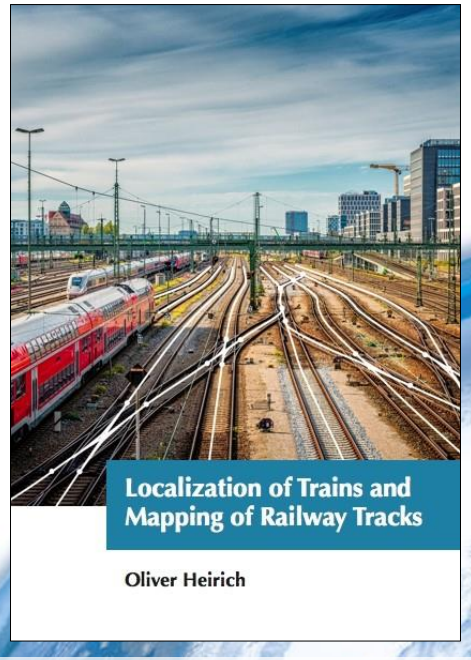

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