Inertial Sensing and Mapping of Railway Track Properties

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Introduction

Swiss Federal Railways (SBB) spend about CHF 700 Mio. per year for infrastructure maintenance. Properly maintained infrastructure is the foundation for safe and economical operation of passenger and cargo transport [1].

Infrastructure Managers monitor a variety of track parameters such as gauge, cant, conicity, track head profile and others taking samples at discrete time intervals, usually involving special equipment and vehicles. Today maintenance action is inferred from map and sensor data collected twice a year. Through continuous monitoring track deterioration would be detected at earlier stages track health could be preserved though light rather than corrective maintenance.

This paper provides a brief overview of track infrastructure monitoring and maintenance methods with focus on the DACH region (Germany, Switzerland and Austria). Research & development undertaken by the Swiss Federal Railway (SBB) within the GLAT PoC Project is presented [5]. Inertial measurement units are used to augment train localization. Using a track parameter derived from a SBB database of Swiss railway tracks and advanced data processing methods inertial sensing is utilized to map track parameters for integrity purposes but also with the potential to support track maintenance. Combining precise sensor-fusion based localization and attitude determination with imaging Light Detection and Ranging (LiDAR) technology and Artificial Intelligence (AI) / Machine Learning (ML) big data processing enables even further opportunities in railway infrastructure maintenance.

1. Monitoring and Maintaining Railway Infrastructure

Railway Operations including maintenance developed from initially private companies in the 19th century to national railway companies in the early 20th century. Regulations including those for maintenance operations are not (yet) harmonized despite significant effort undertaken by the European Commission. Track Monitoring and Surveying to date are rather based on manual and labor intense processes [2], see figure 1. Continuous monitoring methods using advanced sensors including inertial measurement units have only been recently developed and introduced e.g. in measurement trains, see figure 2.

Figure 1: From upper left, counterclockwise: examples of hand operated manual measurement/surveying of track parameters, Upper right: plastically deformed rail tracks [2]

Figure 2: Measurement Trains of Deutsche Bahn AG (DB): from left clockwise, LIMEZ III train, RAILLab, Advanced TrainLab - all equipped with Inertial Sensing from iMAR Navigation GmbH

In the European Union, railway infrastructure managers must comply with the applicable EN norms, thus with the TSIs (Technical Specifications for Interoperability). TSIs serve to guarantee a minimum standard of the technical facilities. These regulations also include the requirement for infrastructure managers to draw up a maintenance plan. Maintenance plans regulate the required inspections and their frequency, the qualification of the staff and the measurement methods. In addition, the infrastructure managers must define action thresholds for safety-relevant parameters and subsequent measures if they are exceeded, see figure 3 (left).

The EN 13848-5 standard defines three main intervention thresholds:

Immediate action threshold (IAL): If a certain value is exceeded, immediate action is required to reduce the risk of derailment to an acceptable level. This can be done either by blocking the track, by reducing the speed or by correcting the track geometry.

Intervention threshold (IL): If a certain value is exceeded, corrective maintenance measures are required so that the immediate intervention threshold cannot be reached before the next inspection.

Attention threshold (AL): Exceeding a certain value requires an analysis of the geometric track condition. This must be considered in the regularly planned maintenance work.

As standard requires measurements to be taken on loaded tracks, inspection measurements are usually carried out with track measurement vehicles. Measurement vehicles are self-propelled or towed vehicles with permanently installed measuring equipment and systems for measuring, evaluating, and recording track geometry parameters under load, which provide measurement results in accordance with the requirements of EN 13848-1, see figure 2.

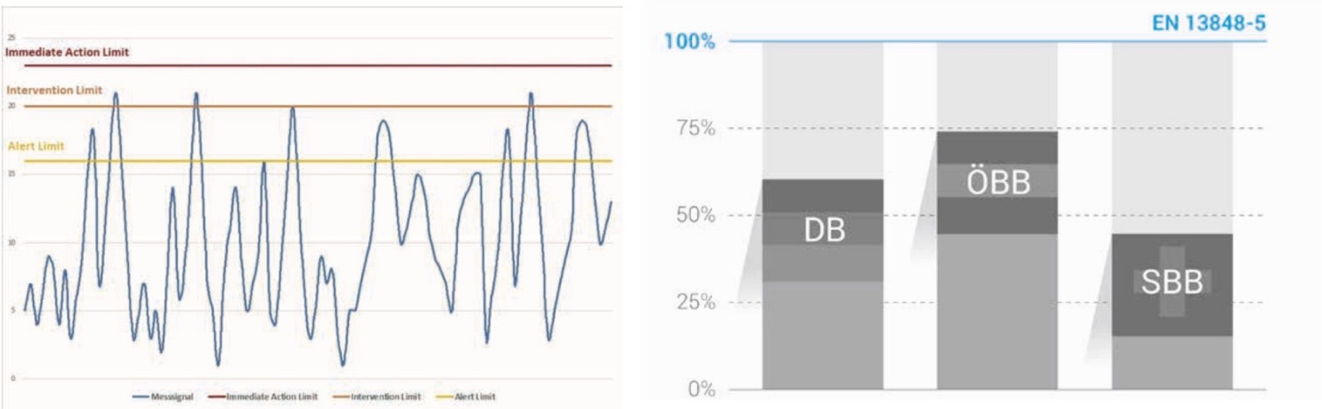


Figure 3: Example of Intervention Thresholds and measurements (left), Utilization of Tracks (vertical track limits) of infrastructure managers of the DACH region (right) [2]

Today corrective maintenance actions are taken rather early not to exceed regulative limits and to guarantee safety, see figure 3, right picture.

Track Parameters monitored by railway infrastructure management companies are defined in the Technical Specifications for Interoperability (TSIs).

Examples of important parameters are:

- Minimum Clearance Outline (EN 15273), see figure 4
- Distance between Tracks (EN 15273)
- Longitudinal Gradient
- Curve Radii
- Gauge
- Cant
- Conicity (Track Head to Wheel Contact)

However, parameters are not (yet) be harmonized across national networks For example in Austria, a track spacing of 4.00 m is required on the OeBB network for speeds below 160 km/h on open tracks. At higher speeds, this distance is extended to 4.50 m. On the DB network, a track spacing of 4.50 m applies for new and upgraded lines with design speeds above 200 km/h.

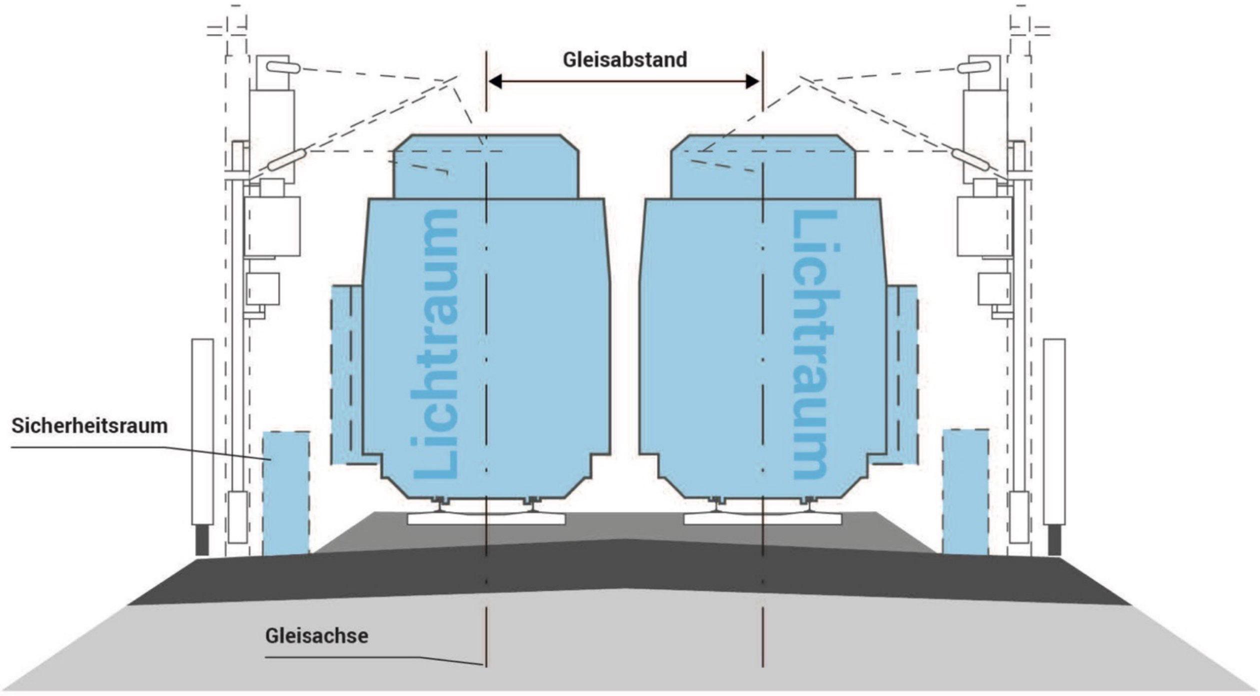


Figure 4: Track Clearance (Lichtraum) Definitions [3]

2. Track Position

The track position is largely dependent on the quality of the ballast used and the load applied, see figure 5. Permanent load causes permanent (plastic), uneven deformations in the ballast bed. In contrast to the desired elastic deflection of the track panel, the plastic deformation remains in the system even after the load has been removed, thus causing an unwanted change in the track position. This not only has a negative effect on ride comfort, but also increases the impact on the system, comparable to a pothole on the road.

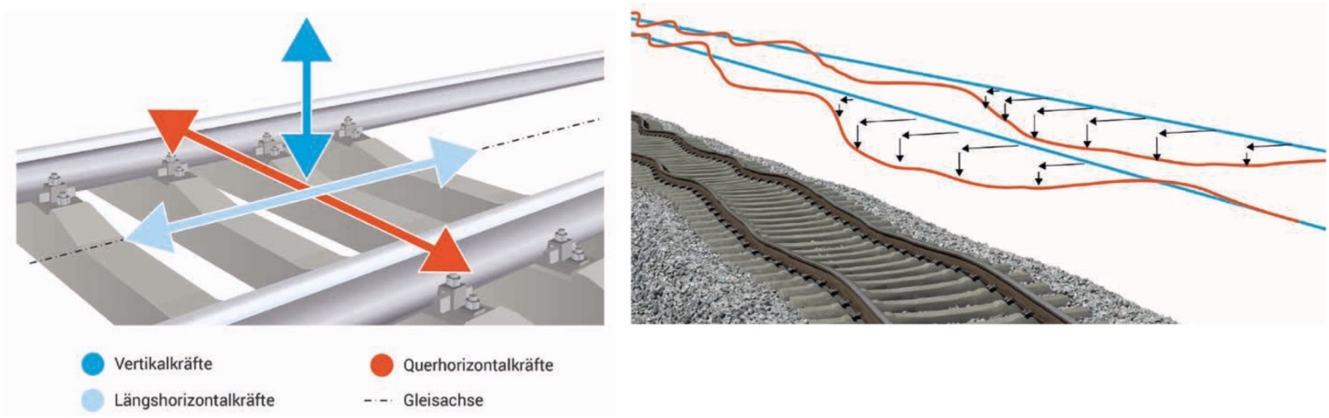


Figure 5: Loads (left) and Plastic Deformations of Tracks (right) [2]

Employing various maintenance measures e.g., «Stopfen», it is possible to regain the track position to its original position or to reduce the errors in the track position, see figure 6.

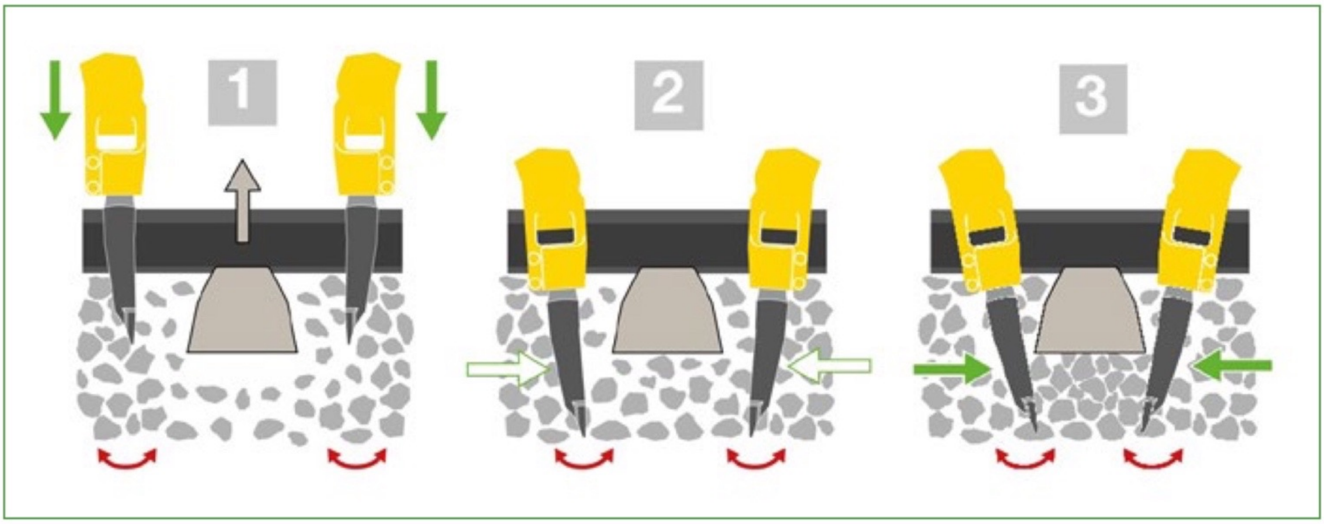


Figure 6: Ballast Bed Maintenance Action [4]

Depending on the speed travelled, the vehicle can compensate for irregularities in the track. However, if these exceed defined threshold values, safe driving on the track is no longer possible and the permissible speed must be reduced. Slow speed sections influence the timetable and reduce the availability of the system. Delays are the result.

The track position changes from «as built» to «as is» over time. This can be «sensed» with inertial measurements.

3. GLAT PoC and Track Parameter Monitoring

During 2018 to 2020 SBB undertook the project «GLAT PoC (Proof-of-Concept)» [5], a two year effort to systematically evaluate sensor fusion technologies aimed for safe railway vehicle positioning and in the wider context to optimize railway operations towards the European Train Control System (ETCS), Level 3 [6], see figure 7.

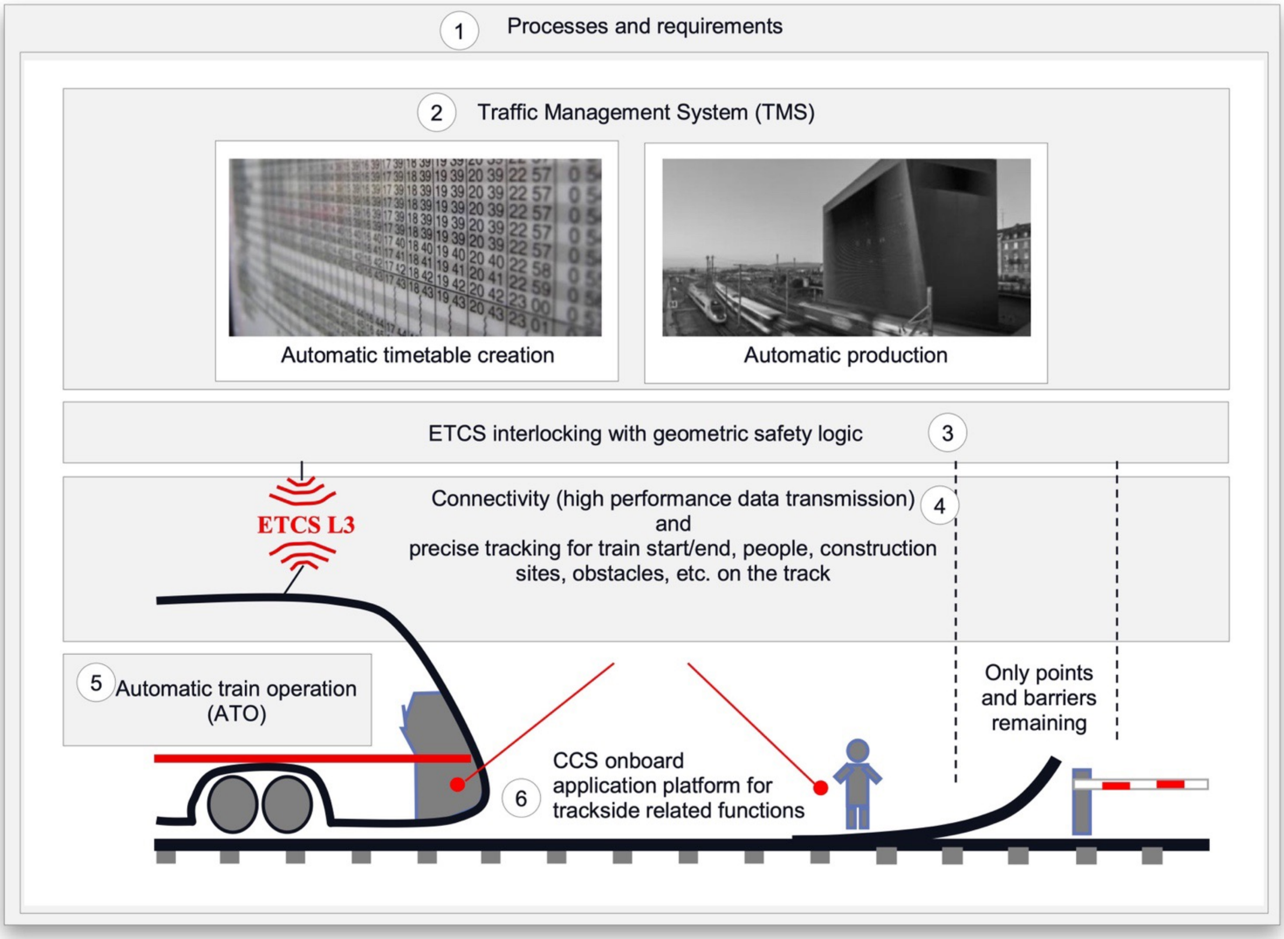


Figure 7: Optimized Railway Operations including ETCS Level 3 Train Operations

Within GLAT PoC large amounts of operational data was collected to evaluate and optimize positioning accuracy (and integrity) in the railway context primarily using GNSS, inertial measurement units and wheel odometry, see figure 8.

In addition, the entire SBB track topology was available in digital format [7]. To handle the large amount of data collected a big-data post-processing platform was established, see figure 10.

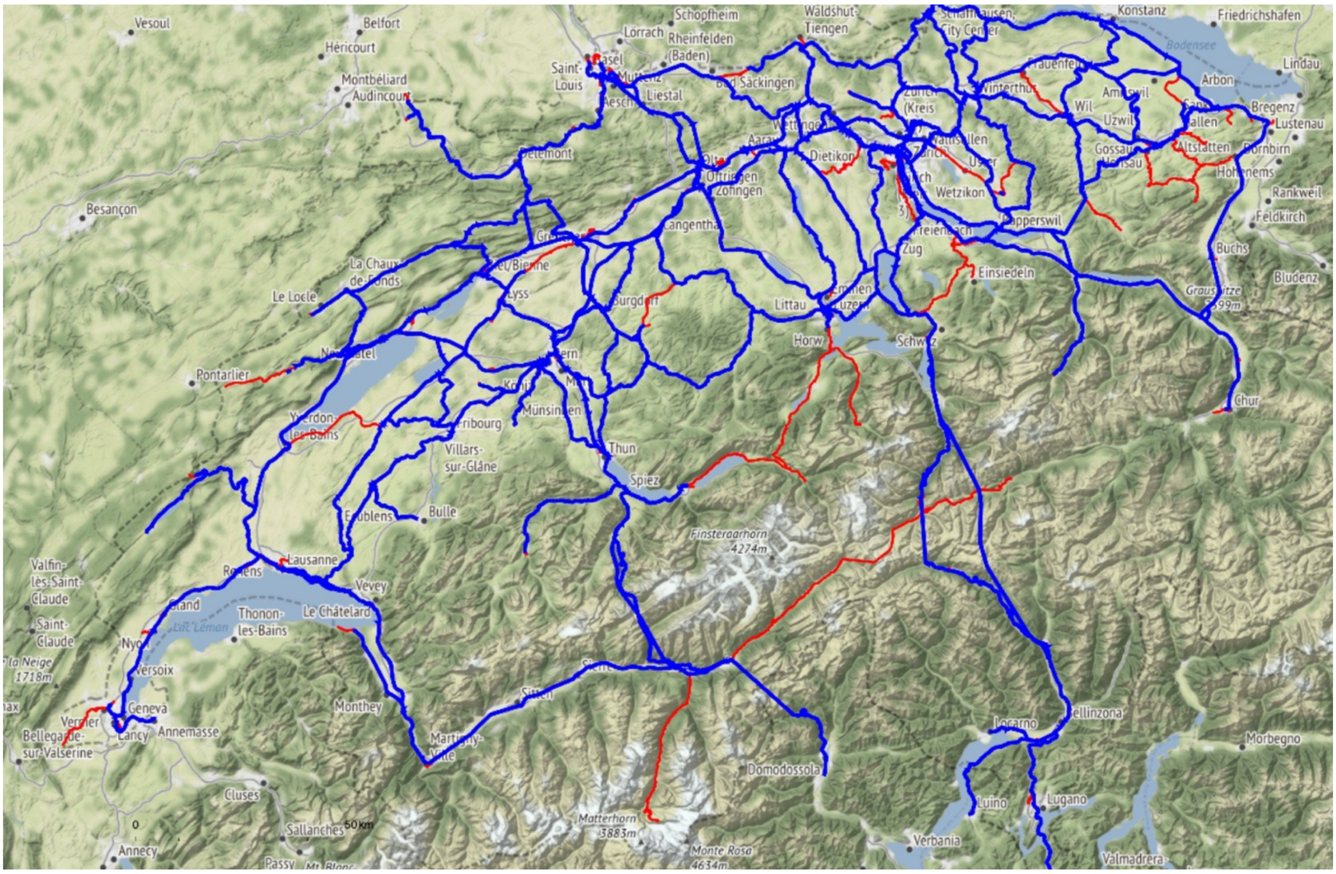


Figure 8: Data Collection and Coverage within GLAT PoC

Technologies such as Eurobalises and Global Navigation Satellite Systems (GNSS, e.g., Galileo, GPS) enable absolute localization. Inertial navigation and odometry provide relative localization between known locations. The track topography is an integrative part of for safe localization, like «Simultaneous Localization and Mapping (SLAM)» approaches used in robotics [8]. Figure 9 shows the multi-sensory design and the functions realized.

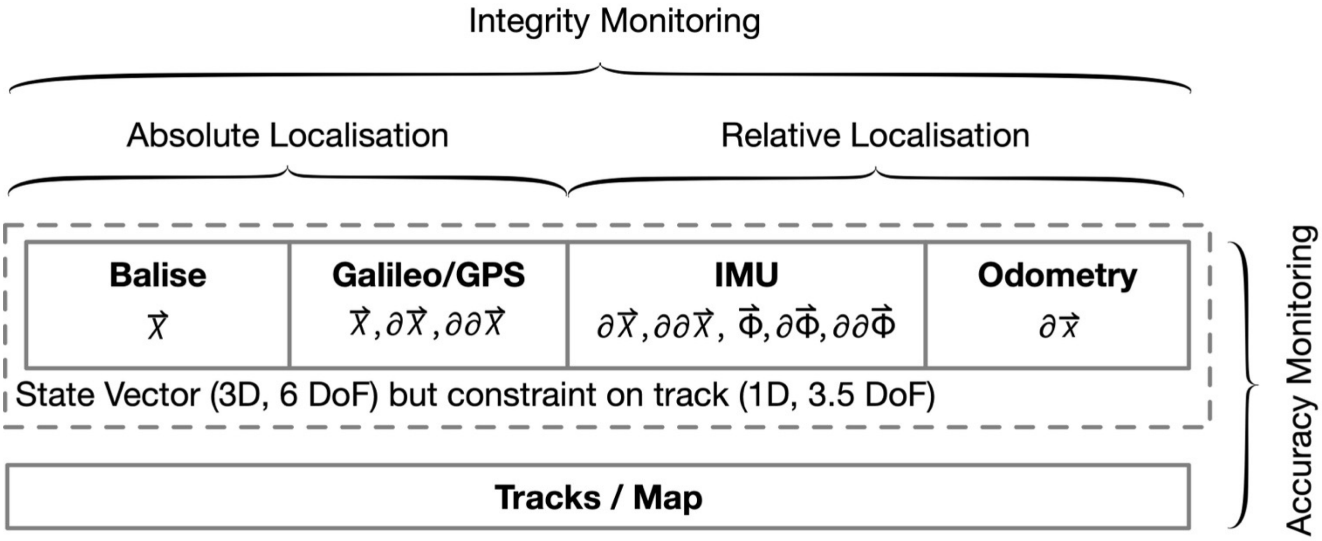


Figure 9: PLAT PoC Sensors and Functions

Eurobalises, are fixed localization points like "radio beacons" in nautics with a defined quality of localization.

GNSS are "globally" available satellite-based localization systems, with a nominally defined quality of localization and velocity measurement (in the Doppler method), which is highly dependent on the local and temporal conditions of the application.

Inertial navigation basically means relative localization from a known location. The quality of the relative localization depends on the sensor types used (MEMS, RLG, etc.) and the conditions of the application. Accelerations and rotation rates are measured, which can be used to determine the speed of the system and its position in space (direction of movement, inclination) through integration.

Odometry (from the ancient Greek ὁδός hodós "path" and μέτρον métron "mass" - i.e. "path measurement") allows a relative measurement of the distance travelled along a defined trajectory. The quality of the relative localization depends on the sensor technology used and its measurement error with regard to the detection of the change in location (e.g. slip). In the case of wheel odometry in rail traffic, a speed along the track is inferred by measuring the rotation rate of the wheel.

The track topography as a digital projection of the track-side infrastructure defines the trajectory along which the trains move largely in translation, as well as their properties in space (e.g., curvature, cant and gradient).

By combining the inertial sensor technology with the track topography, monitoring of the accuracy and integrity of the localization can be realized.

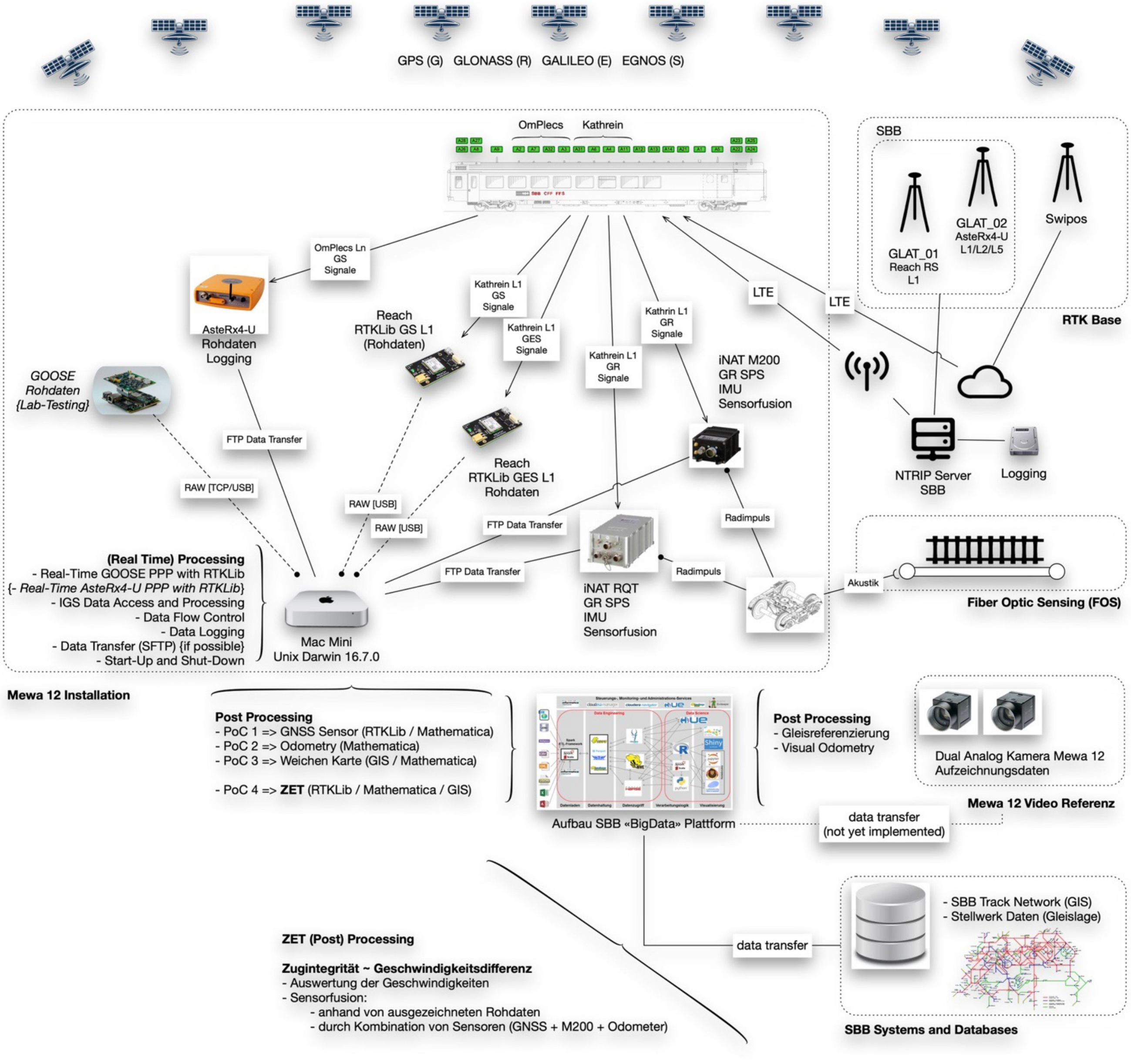


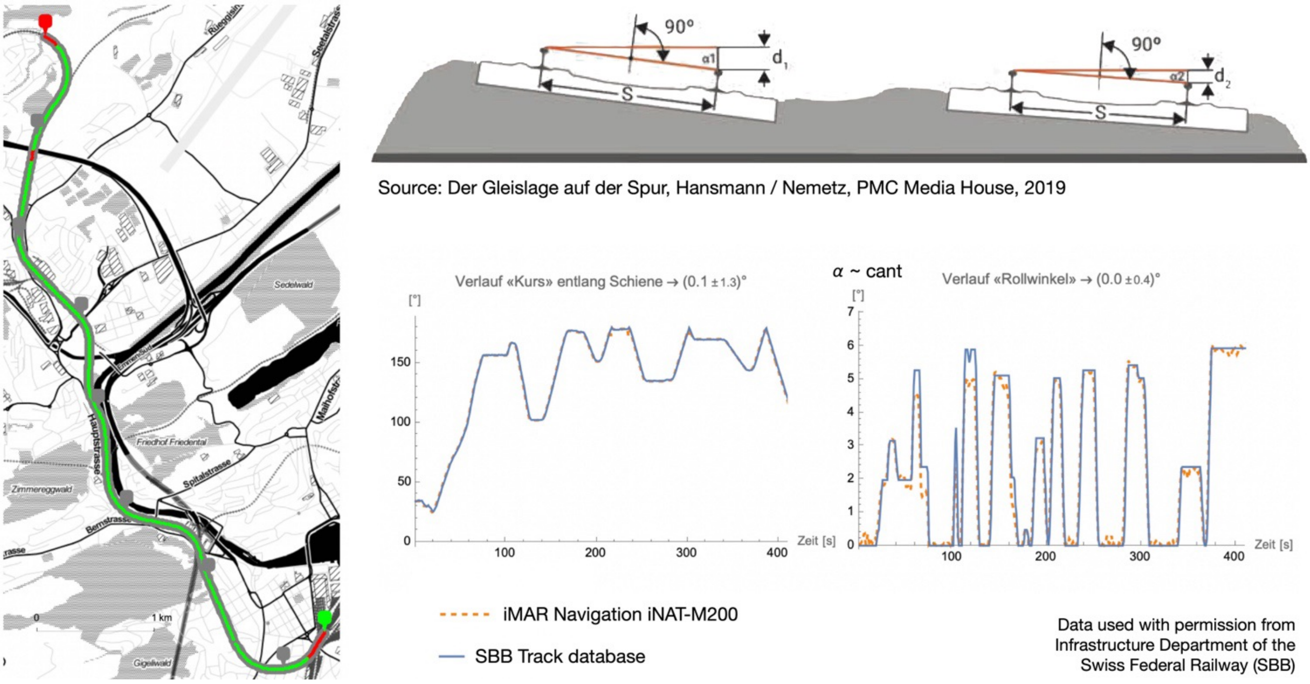
Figure 10: GLAT PoC Data Collection and Processing Environment

The route of the train is determined a posteriori using operational data from the SBB train control systems. The data defines the chronological, local sequence of track sections and associated properties. Translated to GLAT, the track is an accumulation of the a priori "ETCS Movement Authorities" by the interlocking for the respective train.

The track topography is the digital representation of the infrastructure as a geometric sequence of points and lines. The track is "mapped" as a chronological sequence of lines and the associated sequence of three-dimensional track properties (radii, superelevation and gradients).

In contrast to localization in (aero-)navigation, objects, i.e., vehicles/trains, move one-dimensionally along rails. The route is a combination of track objects uniquely defined in time and place. Assuming a correct representation of the real conditions, a digital representation of the rail, i.e., track topography, uniquely defines the measured variables of sensors that are permanently mounted on a vehicle and move along the infrastructure in terms of time and location. The interaction of sensors and track topography defines the location of the vehicles/trains in time and space. Vice versa, the actual track properties can be measured and any changes from «as built» to «as is» are precisely monitored with position and time.

Figure 11 shows an example of data from an iMAR Navigation GmbH iNAT-M200 unit used on the SBB Telekom-Messwagen Mewa12. The iNAT-M200 is strap-down mounted on the floor inside the Mewa12. Although this arrangement leads to errors caused by the bogie suspensions track parameters such as the vehicle bank / track cant are still mappable rather precisely.



Source: Der Gleislage auf der Spur, Hansmann / Nemetz, PMC Media House, 2019

Data used with permission from Infrastructure Department of the Swiss Federal Railway (SBB)

Figure 11: Mapping Track Parameters using SBB Telekom Messwagen (Mewa12) and iMAR Navigation GmbH iNAT-M200

The concept of measuring and mapping track parameters was evaluated for localization integrity purposes and proven to work on almost the entire SBB network [9], see figure 12.

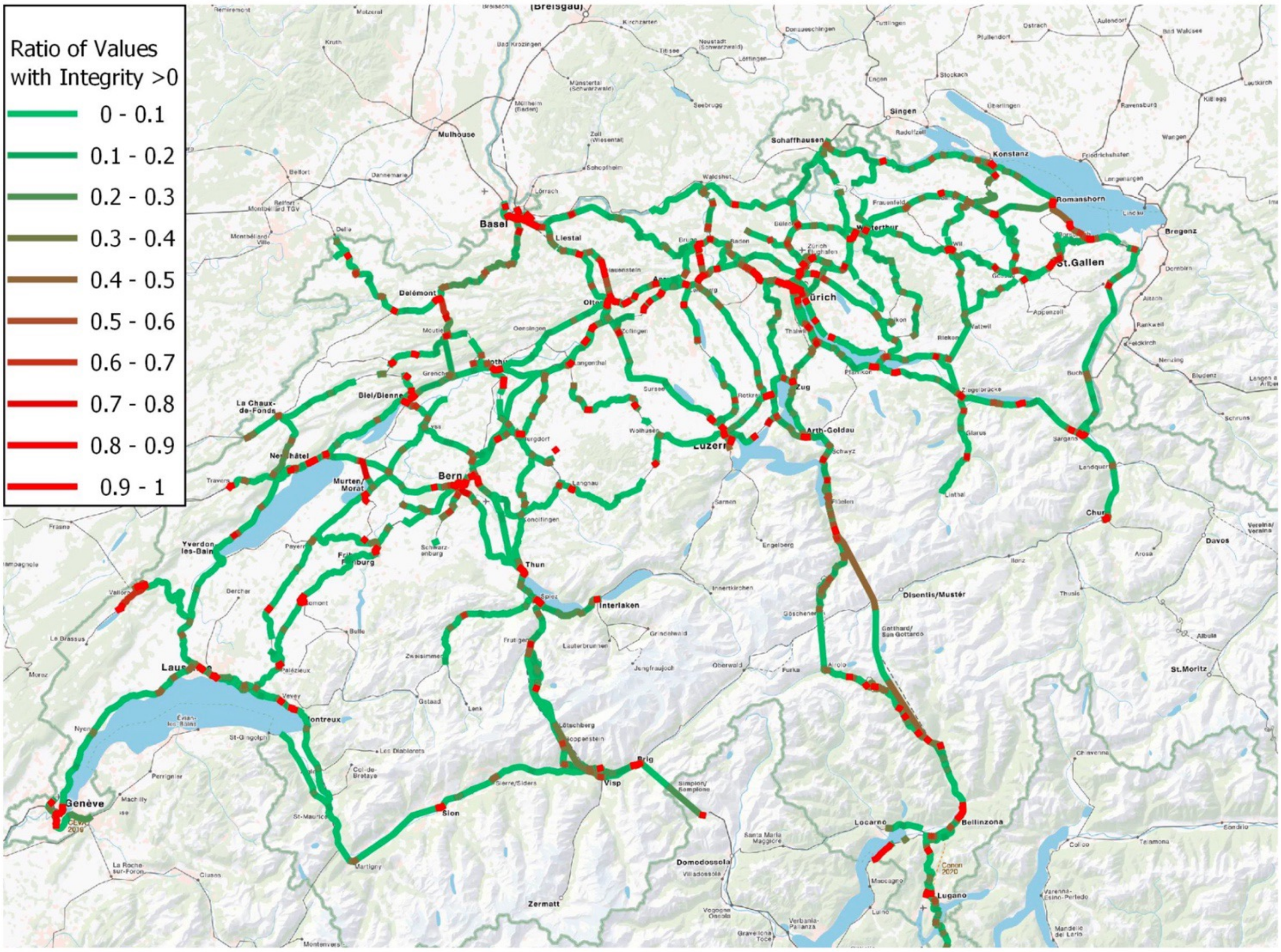


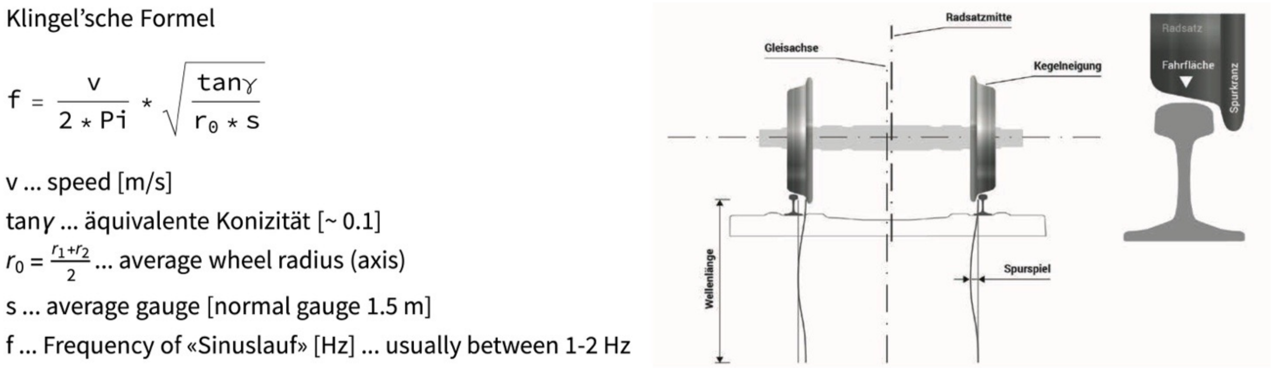
Figure 12: Availability of Location Integrity using Track Parameters on the SBB railway network

Within the GLAT PoC a wheel mounted inertial measurement device called «iRAD» was conceived and built as a prototype by iMAR Navigation GmbH. Combined with an axle generator for electrical power generation the unit is intended to provide safe and precise localization of the last vehicle of a train and thus functions as a «train integrity device» within an ETCS L3 context [6]. The purpose of iRAD prototype is to evaluate localization on the wheel axle based on the basic function GNSS, IMU and odometry.

In the context of mapping track parameters, the advantage of the mounting position on the axle is that the dynamic properties of a railway vehicle including suspension and bogies are no source of errors and don't have to be compensated. The challenge, however, is the load on the electronics, as well as the reception characteristics of GNSS on the wheel axle.

Figure 13: iMAR Navigation GmbH iRAD prototype, with axle generator (left), mounted on the Mewa12 axle (right)

iRAD was operated on the Mewa12 for about one year, 40 000km total, withstanding challenging the environment conditions without mechanical or electronic failures. GNSS localization however proved a challenge, not working reliably to due GNSS receiver characteristics. Exchanging the GNSS receiver to another model significantly improves GNSS localization. This updated version of the iRAD is to be deployed on the SBB Telekom Messwagen Mewa12 later in 2023.



Klingel'sche Formel

$$f = \frac{v}{2 * Pi} * \sqrt{\frac{\tan\gamma}{r_0 * s}}$$

v ... speed [m/s]

$\tan\gamma$ ... äquivalente Konizität [~ 0.1]

$r_0 = \frac{r_1+r_2}{2}$ ... average wheel radius (axis)

s ... average gauge [normal gauge 1.5 m]

f ... Frequency of «Sinuslauf» [Hz] ... usually between 1-2 Hz

Figure 14: Klingel'sche Equation and Gauge Play

Despite the GNSS receiver challenges some iRAD test data could be compensated for acceptable sensor-fusion performance and processed for track parameter comparison.

Using the Klingel'sche formula [10], figure 14, even «gauge play could be estimated, see figure 15.

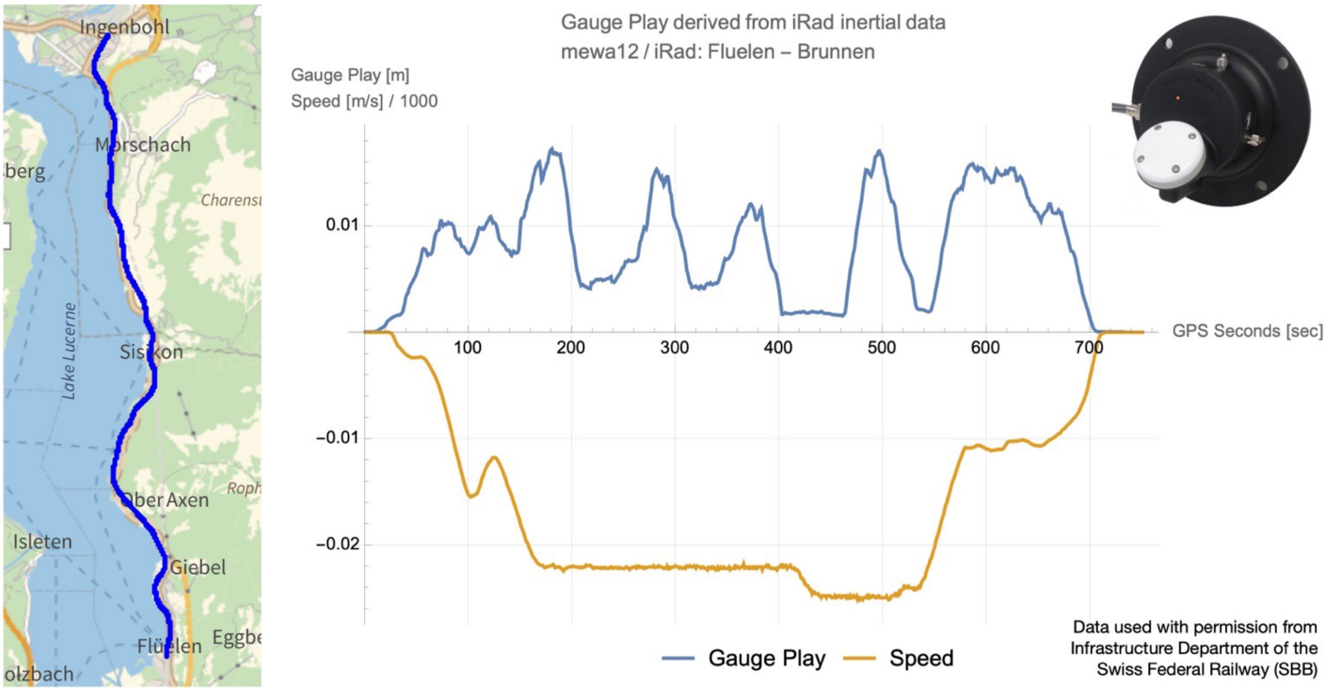


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Figure 15: iRAD based gauge play during a test champaign along Lake Lucern

Note that these are experimental, preliminary results from a rather small amount of test data. With the availability of the upgraded iRAD prototype further data will be collected for evaluation purposes.

4. Inertial Sensing and LiDAR

Combining sensor fusion with imaging LiDAR technology and automatic AI/ML processing enables even further opportunities to monitor track parameters and increase track utilization and maintenance productivity.

Recently LiDAR systems from e.g., Trimble Inc. or Riegl Laser Measurement Systems GmbH have been developed and certified by railway infrastructure managers for surveying purposes. When mounted on special vehicles (see figure 16, left) or measurement trains (see figure 16, right) they generate a very precise point cloud-based replication of the track environment i.e., a «digital twin».

Figure 16: Trimble LiDAR (left), Riegl VMX-RAIL (right)

Smaller, more flexible systems e.g., the iLIANE [11] from iMAR Navigation GmbH (figure 17) are available for a broader application field including railway, road transport and maritime applications. They have the potential to be mounted on normally operating vehicles such a locomotive, to constantly generate point cloud data for monitoring purposes.

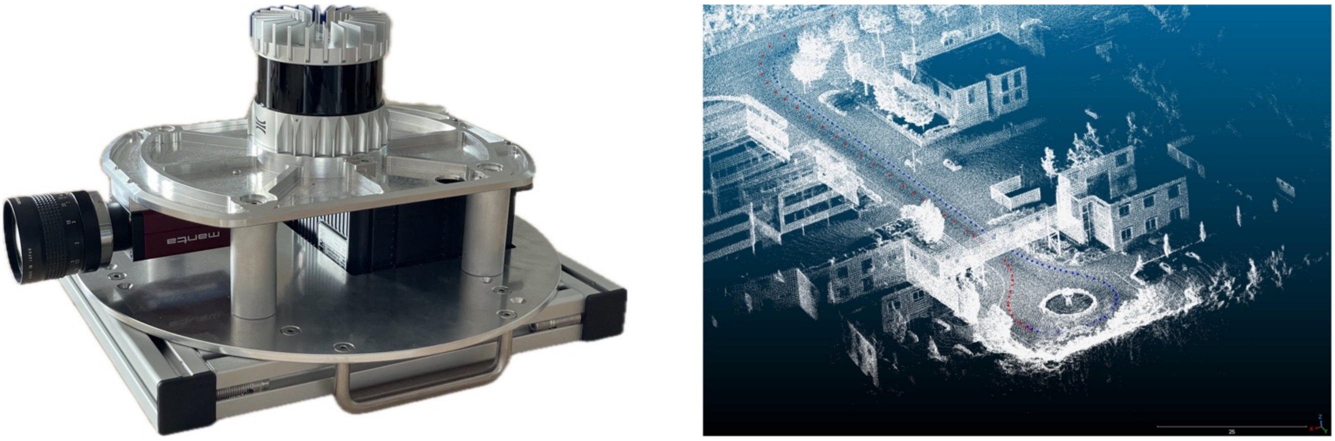

Figure 17: iMAR Navigation iLIANE prototype (left), iLIANE test data (right)

With companies such as The Cross Product (TCP) developing and providing automatic AI and ML processing technology [12], see figure 18, these vast amounts of point cloud data can efficiently be processed into track information, supporting the infrastructure manager's maintenance plans.

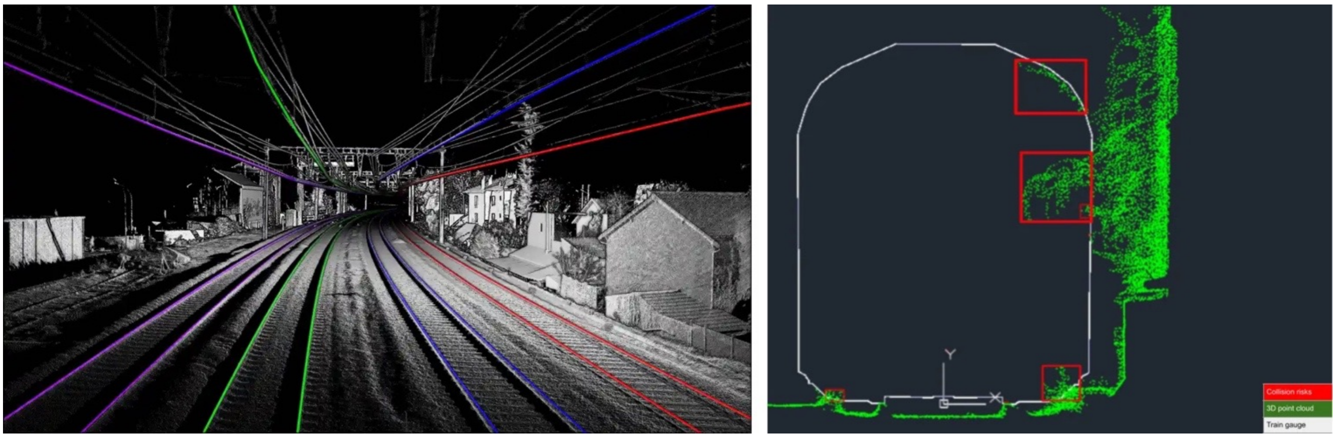

Figure 18: The Cross Product AI/ML based point cloud processing examples, track classification (left), Minimum Clearance Outline Processing (right)

5. Conclusion

Inertial Sensing is likely to be part of the technology stack in advanced railway location for future ETCS L3 systems.

Depending on the design of advanced railway location systems inertial sensing may be used to improve track maintenance by measuring and processing track parameters during normal operations, in addition to manual surveying and special purpose measurements vehicles.

Inertial Sensing and imaging LiDAR systems further improve data collection options. When combined with advanced AI/ML based processing these systems provide even more timely insight into the condition of the track infrastructure. Track deterioration would be detected at earlier stages and track health could be preserved though light rather than corrective maintenance.

However, as shown in the iMAR Navigation iRAD example much research & development remains to be undertaken to develop prototypes into robust and affordable products. This requires extensive collaboration with Rail Infrastructure Management Companies to collect and process large amounts of (inertial) sensor data.

References

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network: 1.4 billion Swiss francs for the renewal of the facilities after their service life has expired (e.g. replacing rails), 700 million Swiss francs for maintenance during their service life (e.g. grinding rails).»

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