REASSESS Project - Executive Summary

Project Title

REASSESS - Early Detection and Assessment of Railway Substructure Moisture Problems at National to Local Scale Using Spaceborne, Airborne and Train-Based Remote Sensing Systems

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Background

A highly available and affordable railway infrastructure relies on development of innovative solutions in infrastructure monitoring. The use of remote sensing systems operating from satellites, drones, and mobile mapping platforms offers tremendous potential for preventive and automated monitoring of the railway infrastructure. One of the most common causes for deterioration of the tracks is water intrusion leading to subsurface ballast moisture/wetness. This type of damage results in significant costs for mitigation and repair.

Goals

REASSESS envisions a remote-sensing-based approach to efficiently and timely detect railway track anomalies that serve as a proxy for subsurface ballast moisture. Detection methods based on three remote sensing systems 1) satellite imaging radar (synthetic aperture radar - SAR), 2) (airborne) laser scanning, and 3) train-based ground penetrating radar (GPR) are investigated and assessed using reference data provided by SBB AG.

Three Remote Sensing Approaches Investigated

Satellite imaging radar for proxy-based anomaly detection In this study, we investigated a new approach to detect track anomalies based on surface displacements retrieved from interferometric time series of satellite radar data (TerraSAR-X). The performance of the satellite-based detection method is compared to chord-based measurements, which are obtained from survey trains and which are currently used by SBB as a proxy for track anomalies on a network-wide scale. Inspired by the chord-based method's use of vertical undulations of the track geometry, our proposed approach employs statistics derived from variations of surface displacements along the railway track retrieved with persistent scatterer interferometry (PSI) as proxies for railway track anomalies.

Laser scanning for deformation and moisture proxies We investigated the detection and quantification of ballast moisture proxies in airborne LiDAR point clouds. The first focus was on optimally extracting surface deformations. We compared (i) approaches sensitive only to displacements perpendicular to the surface and (ii) machine-learning-based approaches exploiting the structure of the ballast to derive 3d displacements. The other focus was on more direct moisture proxies, like clay fouling or vegetation changes. While we could not find a benefit of the LiDAR data for these proxies, the sensitivity for deformation analysis could be increased substantially through spatial filtering with and without exploiting rails and sleepers within the point clouds.

Ground penetrating radar for ballast assessment We investigated the use of train-based Ground Penetrating Radar (GPR), as a promising solution for early and accurate detection of moisture accumulation in the ballast. We have conducted both simulated and experimental analyses, with the latter carried out on a controlled railway track section, established in collaboration with SBB AG. Our findings demonstrate that GPR systems can effectively detect moisture infiltration in railway tracks, albeit certain challenges still need to be addressed for ensuring accurate and automated assessment. Toward such automation, we will be coupling the GPR-derived condition indicators with a reinforcement learning based decision support tool for optimizing maintenance policies.

Key Takeaways

Satellite imaging radar: Detection of railway track anomalies using time series of satellite radar data

- Both, the satellite-based and chord-based methods to detect track anomalies are proxy-based indicators.
- Both approaches lead to qualitatively similar but not identical detections. Validation remains challenging.
- We see our satellite-radar-based detection approach as a useful additional source of information that complements chord-based techniques used for an expert-driven identification of anomalies in railway tracks.
- In the future, high-resolution wide-swath (HRWS) imaging radars will provide high spatial resolution and large spatial coverage at the same time, which is needed for a network-wide satellite-based detection.
- Scientific publications and outreach: Bernhard et al. 2024 [1], Bernhard et al. 2023a/b [2] [3].

Laser scanning for deformation and moisture proxies

- Non-deformation moisture proxies can be better determined using images instead of point clouds.
- Estimating moisture from monochromatic LiDAR intensities is only possible under very restrictive conditions.
- Direct estimation of 3d displacements of the ballast from point clouds is challenging because the structure is not unique and salient enough.
- Height changes on the order of a few cm can be resolved by spatially averaging over areas of at least about $1\ \mathrm{m}^2$; using only the points on sleepers improves the sensitivity to better than $1\ \mathrm{cm}$.
- Scientific publications and outreach: Gojcic et al. 2021[4], Laasch et al. 2023 [5], Meyer 2024 [6]

Ground penetrating radar for ballast assessment

- The experimental results demonstrate the potential of adoption of GPR technology for moisture assessment in the track substructure.
- Assessing the water content of the track substructure from a single GPR measurement is a challenging task.
- The intention is to capitalise on more observations over time, enabling robust detection and dense spatial tracking of moisture content.
- Early detection of moisture accumulation in the substructure can form a potent tool for supporting preventive maintenance actions.
- Scientific publications and outreach: Arcieri et al. 2023 [7], Hoelzl et al. 2023 [8], Arcieri et al. 2023 [9], Arcieri et al. 2024 [10]

Ways Forward

Radar remote sensing

- Consolidation of the proposed satellite-based detection and inclusion of lower radar frequencies (L/S-band).
- Quad-copter drone-based radar interferometry at L-band and S-band is technically feasible and accessible by Q1/2025 providing a spatial resolution better than 0.5m at S-Band. This overcomes the spatial resolution limitations of current satellite imaging radars, but comes at the cost of reduced coverage and additional effort.
- Explore synergies of radar-interferometry-based measurement of surface displacements with other applications (earth works, geohazards, e.g. land slides) and technologies.

Laser scanning

- Extend the deformation analysis software DeSpAn, developed within this project, to include sleeper-based height monitoring and more advanced spatial filtering.
- Explore extraction of non-deformation moisture proxies from train-based, drone-based, and satellite-based hyperspectral images.

Ground penetrating radar

- Refinement of the physics-based modeling framework for simulation of the track-substructure system under various fouling and moisture conditions.
- Development of a Reinforcement Learning framework for decision support.

Scientific Publications and Outreach

[1] P. Bernhard, D. Haener, and O. Frey, "Detection of railway track anomalies using interferometric time series of TerraSAR-X satellite radar data," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, pp. 1–11, 2024, Early Access. DOI: 10.1109/JSTARS.2024.3405019.

[2] P. Bernhard, D. Haener, and O. Frey, "Persistent scatterer interferometry to detect railway track anomalies using TerraSAR-X observations," in *Proc. IEEE Int. Geosci. Remote Sens. Symp.*, Pasadena, CA, USA: IEEE, Jul. 2023, pp. 1838–1841. DOI: 10.1109/IGARSS52108.2023.10283221.

[3] P. Bernhard, D. Haener, and O. Frey, "Persistent scatterer interferometry to assess railway track conditions using TerraSAR-X observations," in *Abstract Volume 21th Swiss Geoscience Meeting*, Mendrisio, Switzerland: Swiss Academy of Science (SCNAT), Nov. 2023, pp. 565–566. [Online]. Available: https://geoscience-meeting.ch/sgm2023.

[4] Z. Gojcic, L. Schmid, and A. Wieser, "Dense 3d displacement vector fields for point cloud-based landslide monitoring," *Landslides*, vol. 18, no. 12, pp. 3821–3832, 2021-12, ISSN: 1612-510X. DOI: 10.3929/ethz-b-000507673.

[5] H. Laasch, T. Medic, and A. Wieser, "Towards assessing sandstone surface moisture and degradation level from radiometrically corrected TLS intensity data," in *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. X-1/W1-2023, 2023-12-13, pp. 567–574. DOI: 10.3929/ethz-b-000651281.

[6] N. Meyer, *Despan–Deformation spotter and analysis workflow for elongated point clouds*, version 1.0, Jun. 25, 2024. [Online]. Available: https://github.com/gseg-ethz/despan.

[7] G. Arcieri, C. Hoelzl, O. Schwery, D. Straub, K. G. Papakonstantinou, and E. Chatzi, "Bridging POMDPs and Bayesian decision making for robust maintenance planning under model uncertainty: An application to railway systems," *Reliability Engineering System Safety*, vol. 239, p. 109 496, 2023. DOI: 10.1016/j.ress.2023.109496.

[8] C. Hoelzl, G. Arcieri, L. Ancu, *et al.*, "Fusing expert knowledge with monitoring data for condition assessment of railway welds," *Sensors*, vol. 23, no. 5, 2023. DOI: 10.3390/s23052672.

[9] G. Arcieri, C. Hoelzl, O. Schwery, D. Straub, K. G. Papakonstantinou, and E. Chatzi, *POMDP inference and robust solution via deep reinforcement learning: An application to railway optimal maintenance*, arXiv:2307.08082, 2023. DOI: 10.48550/arXiv.2307.08082.

[10] G. Arcieri, C. Hoelzl, O. Schwery, D. Straub, K. G. Papakonstantinou, and E. Chatzi, "POMDP inference and robust solution via deep reinforcement learning: An application to railway optimal maintenance," *Machine Learning*, 2024, ISSN: 1573-0565. DOI: 10.1007/s10994-024-06559-2. [Online]. Available: https://doi.org/10.1007/s10994-024-06559-2.