Fusion of Ground-Based and UAV Data for Rail Infrastructure Monitoring – a conceptual example at the Port of Brunswick (Braunschweig, Germany)

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Introduction: The integrity of railway tracks and their immediate surroundings is crucial for safe and efficient rail operation. Current practices of inspection especially for branch lines and industrial networks heavily rely on regular visual inspections by foot, supported by trolly-based measurements at long time intervals. This is labor-intensive, safety-critical and time-consuming. And in far most cases, it is not sufficient to introduce schemes of predictive maintenance for proactively identifying and solve potential issues.

This study presents a concept to investigate the integration of in-service ground-based/terrestrial and unmanned aerial vehicle (UAV)-based monitoring systems to enhance inspection of railway track and surrounding areas. By combining data from embedded terrestrial sensors with UAV-mounted sensors such as RGB cameras and LiDAR, we aim to develop a comprehensive monitoring system capable of detecting track anomalies, vegetation encroachment and infrastructure degradation with greater accuracy and efficiency. The potential benefits include reduced inspection and maintenance costs, improved safety, comprehensive monitoring of peripheral areas, minimized service disruptions, increased objectivity and a shift towards predictive maintenance strategies, especially for smaller railway infrastructure operators.

State-of-the-Art: For decades, visual inspections and ground-based inspection systems (especially for track geometry) have been the pillar of railway inspection. Established regulations, which have been in place for decades, serve to ensure safe railway operations. Regarding the main line considerable efforts are being made in the last 15 years to improve inspections by enhanced multi-purpose inspection vehicles (e. g. Samson et al., 2025), broader application of wayside monitoring systems (e. g. Reetz et al., 2023), utilization of drones for specific monitoring tasks (e.g. Andert et al., 2020) as well as improved exploitation of existing data through data fusion/holistic monitoring (e.g. Neumann et al., 2026 and simulations/digital twins (e.g. Heckmann et al., 2025). Most of these innovations are easier accessible for large main line infrastructure operators due to better scalability. Regular visual inspections by foot (typically every four to six weeks) with supplementary trolly-based track geometry measurements (typically every two years) remain state of the art for smaller infrastructure operators instead.

In recent years, approaches utilizing comparable low-cost monitoring systems with accelerometers and cameras embedded on in-service rail vehicles proved their potential for track and rail condition monitoring with several demonstrations in the operational environment (e.g. Niebling et al, 2020; Heusel et al, 2021).

At the same time, UAV have emerged as a cost-effective and flexible supplement for data acquisition. Equipped with high-resolution cameras, UAV can rapidly survey tracks, identifying surface defects like rail cracks, deteriorated isolators (e.g. Andert et al., 2020) ballast degradation, and vegetation encroachment (Aela, P., 2024). Photogrammetry and LiDAR mounted on UAV enable the creation of detailed 3D-models (Dietenberger et al., 2023) of the track and surrounding environment, facilitating accurate track measurements for numerous monitoring tasks. Utilizing UAV for acquisition campaigns by pay-per-use or as-a-service is getting more and more available at reasonable cost.

Objectives and research questions: The combination of terrestrial and UAV data offers the potential for a more comprehensive and robust inspection solution at reasonable cost especially for operators of smaller networks (less than 300 km of tracks). Main objective is to enhance (and on the long term replace) visual inspections by combining condition information from embedded terrestrial sensors (e.g. on the operating rail vehicles) with condition information from UAV sensors. The desired benefits are:

- High level of automation and reduced personnel in the tracks

- Complete documentation of condition development with high spatial and temporal resolution at reasonable cost
- Monitoring of the loaded track
- Enabling the application of AI for further automation / improved decision support

Based on past research activities on embedded railway monitoring solutions as well as UAV and AI technologies, the German Aerospace Center (DLR) is currently establishing an experimental setup in the operational environment of an industrial rail network to further research and demonstrate this approach. Main focus is to combine and fuse already available research data sets from ground based embedded monitoring system with UAV image data and to prepare future joint measurement campaigns. Based on these joined data sets the following research questions are addressed:

(1) What level of detail regarding railway inspection parameters (e.g., defect size, type) can be reliably retrieved from UAV imagery matching or exceeding results from visual inspection?

(2) Which sensor modalities (spectral properties, flight configuration) are best suited for identifying different defect types typically addressed by visual inspections?

(3) How to solve remaining challenges in georeferencing to join terrestrial and UAV data?

(4) What synergistic benefits can be achieved through the combination of terrestrial and UAV-based sensors?

This work presents a preliminary concept developed within an ongoing project at DLR. We outline a methodological framework for data acquisition, processing, and fusion, focusing on establishing correlations between sensor characteristics, flight parameters, and the detectability of relevant track and rail defects.

This study is going to focus on the following parameters, comparing UAV sensors (RGB cameras, LIDAR) accuracy to existing terrestrial vehicle-borne and wayside sensors (cameras, vehicle-track-interaction):

- Rail defects: defects of the rail surface (e. g. wheel burns, squat-like defects, corrugation, …), rail profile (e. g. burr formation) and at joints detectable through high-resolution imagery and potentially advanced image processing techniques enhanced with spectral analysis and/or in combination with vehicle-track-interaction;
- Track defects: defects at the superstructure regarding track geometry, sleepers (e. g. cracks), missing clamps, etc. assessable via visual inspection and potentially enhanced with spectral analysis and/or vehicle-track-interaction;
- Ballast degradation: e. g. the accumulation of debris or development of mud spots within the ballast layer, identifiable through changes in surface texture and 3D point cloud analysis;
- Railway crossing: e. g. monitoring of distances between the tracks, analysis of crossing profile and changes thereof;
- Vegetation encroachment: growth of plants near or in the track detectable using RGB imagery and enabling proactive vegetation management.

Study site: The inland port of Braunschweig (Brunswick), Germany, has been selected as study area. The port is an important regional intermodal hub for water-borne, rail and road transport (bulk goods and containers). The railway network comprises about 19 km of tracks with 34 switches. Two shunter locomotives are operating to compose and decompose freight trains.

Existing datasets: The port railway network and shunter locomotives are utilized for research on vehicle localization and railway condition monitoring in operational environment for about one decade. Several years of vehicle track interaction measurements as well as vehicle trajectories (e.g. Niebling et al, 2020; Heusel et al, 2021) are available for research as well as comprehensive image data from several measurement campaigns with vehicle-borne cameras (e.g. Jahan et al. 2021a+b). Several campaigns with state-of-the-art inspection systems (track geometry and longitudinal rail profile) as well as visual track inspections were conducted. Furthermore, prototypes of wayside condition monitoring systems are tested. First footage captured by a UAV including annotations for a semantic segmentation are available as well (Figure 1). Additionally, there exists a 3D model of the port based on geodata from the city of Braunschweig.

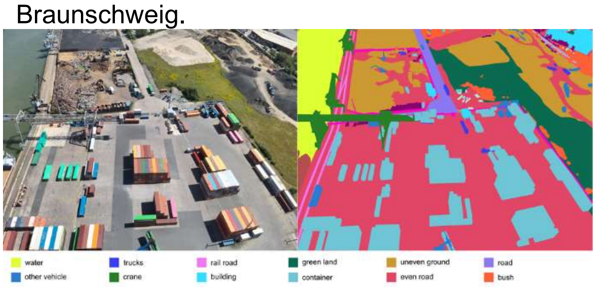

Fig. 1. Annotations for *AI-based image segmentation of the harbor area of Braunschweig. Credit: DLR (CC BY-NC-ND 3.0)*

Methodology:

Terrestrial methods: Condition monitoring with embedded vehicle-borne and wayside sensors is focusing on capturing the vehicle-track-interaction by accelerometers (vehicle-borne and wayside) and utilizing robust RGB cameras (vehicle-borne). The AI supported analysis of the vehicle-borne vehicle-track-interaction (Axle-Box Accelerations, ABA) is capable to map entire networks regarding unusual vehicle reactions (Figure 2) due to track defects (Niebling et al., 2020; Baasch et al., 2025) as well as the mapping of specific track characteristics such as track and rail longitudinal profile. With respect to shunting operations the derived longitudinal level can be utilized to map rail corrugation (Heusel et al., 2021) as well as the monitoring of the railway switch transition geometry (Heusel et al.,2023*)*. Regarding camera-based monitoring, there are deep learning approaches to utilize driver-perspective (Jahan et al., 2021a+b) as well as top-down perspective (Jahan et al., 2023; Leich et al., 2023) images to detect relevant assets and several types of defects. The transfer of the existing models for vehicle-borne cameras to UAV-borne cameras is promising ongoing research. Wayside acceleration measurements are utilized especially for railway switch monitoring (e.g. Reetz et al., 2024). Recent research is focusing as well on low-power wireless edge-AI-capable devices to scale wayside acceleration measurements. The joint visualization of condition information derived from vehicle-track-interaction and images upon available high-res footage will enable safe visual track inspections in the future.

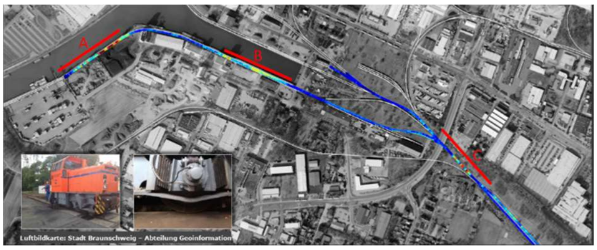

Fig. 2. *Strength of vehicle reactions in the port of Braunschweig with anomalies in the area of coal loading (A), bulk goods loading (B) and a very heavily loaded central section (C). Credit: DLR (CC BY-NC-ND 3.0)*

UAV Methodology: To optimize parameter retrieval with UAVs, we will test varying flight configurations (Mueller et al., 2023) with a particular focus on flight altitude. The goal is to identify an optimal altitude for each defect category, balancing external constraints – such as overhead wires, locomotive clearances, and airspace regulations – with internal requirements like defect detection accuracy and tolerance. Following data acquisition, RGB data will undergo photogrammetric processing to generate a 3D point cloud, geometrically corrected orthomosaics, and high-resolution digital surface models (Dietenberger et al., 2025). These datasets will serve as input for both rule-based and deep-learning methods designed to extract the desired parameters. For example, U-Net classification will enable vegetation type detection and 3D segmentation for accurate delineation of encroachment extent (Adam et al., 2025). Height information will be used to verify track and crossing profiles, while pre-trained deep-learning networks will be employed for defect detection and potential categorization. Furthermore, 3D reconstruction from the point cloud will facilitate assessment of ballast granularity and identification of areas indicative of ballast degradation.

As the full methodology is yet to be implemented with data from the Port of Braunschweig, we present preliminary analyses conducted on comparable infrastructure, demonstrating expected transferability. We will showcase deep learning-based crack detection on asphalt, highlighting the potential for further crack categorization (e.g., open, sealed) and object segmentation. We will illustrate vegetation encroachment on a roadway. Utilizing both spectral and height difference information allows for the geographically exact delineation of encroachment areas and volumes. Figure 3 presents a profile of a bicycle path, demonstrating the granularity of detectable defects achievable with a ground sampling distance (GSD) of 0.3 cm obtained through a 5 m flight altitude.

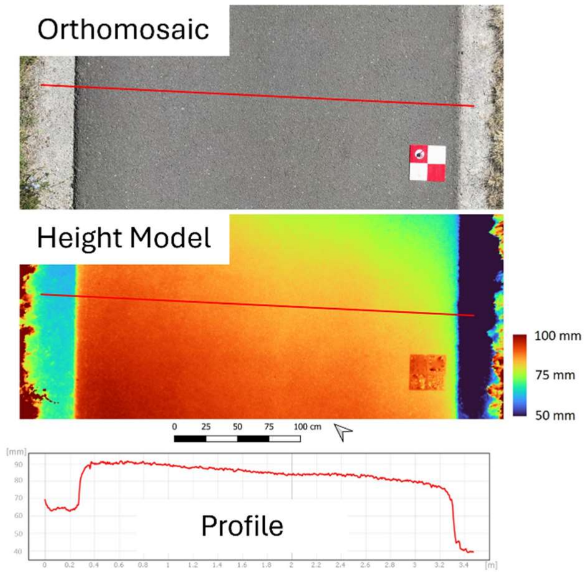

Fig. 3: *Orthomosaic, digital surface model and height profile of a bicycle way. Credit: DLR (CC BY-NC-ND 3.0)*

*Complementarity and Limitation*s: The ultimate aim of this study is to establish a meaningful integration of terrestrial and UAV-derived data, investigating their synergies to optimize railway inspection practices. To this end, detection results from both systems will be analyzed and compared based on key criteria including observation frequency, accuracy, spatial coverage, and cost-effectiveness. We will publish recommendations regarding the optimal deployment of either system individually or in combination. Specifically, the areas of use and limitations of each sensor type will be highlighted, with potential recommendations for alternative or route-specific sensor combinations provided. While UAV-based systems offer advantages in speed and accessibility, current limitations – including flight endurance, payload capacity, and operational challenges in complex environments like tunnels or areas with signal interference – necessitate a combined approach leveraging the complementary strengths of both terrestrial and aerial inspection methods.

Conclusion and Outlook: This study outlines a concept for UAV-based railtrack inspection, focusing on optimized parameter retrieval and synergistic data fusion with existing embedded terrestrial monitoring approaches. The Port of Brunswick provides a perfect test case to validate this approach in a real-world operational environment.

Looking ahead, our immediate focus is the implementation of this framework with field data from Brunswick, allowing for quantitative assessment of retrieval accuracy and performance. Future work is going to concentrate on developing automated data fusion algorithms, refining defect classification models, and exploring the integration of additional sensor modalities (e.g., LiDAR and thermal imaging). Finally, we aim to provide data and methods to better support optimal inspection strategies, balancing cost, efficiency, and data quality for various railway infrastructure scenarios, ultimately contributing to safer and more sustainable rail operations.

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