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EVALUATION OF MOBILE PLATFORMS FOR AUTOMATION OF METRO TUNNEL INSPECTIONS

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Abstract

Metro tunnel inspections face growing demands from urbanization and tight maintenance windows, yet manual and time-consuming inspection methods remain. While rail-bound vehicles, wheeled and tracked robots, quadruped robots, and Unmanned Aerial Vehicles (UAVs) show promise for inspection tasks, no systematic evaluation addresses metro tunnel-specific constraints like track geometries, tunnel access and inspection windows for mobile platform choice. This paper reviews inspection platforms, derives evaluation criteria from literature, operator interviews, and observations, and quantitatively compares platforms across sensing, payload, speed, runtime, deployment, and locomotion. Results identify optimal use-cases for each system, guiding deployment strategies for automated metro tunnel inspections.

Introduction

Motivation

Tunnel infrastructure, including road tunnels, railway tunnels, utility corridors and metro systems, plays a crucial role in modern transportation networks, particularly in regions with complex topography or high population density. Urbanization and the resulting densification of cities are driving the need to maintain and expand this underground infrastructure. In the past 75 years, the urban population has increased from 20% of the global population (500 million people) in 1950 to 45% of the population in 2025 (3.69 billion people) (United Nations, 2025). During a similar period of time, from 1950 to 2015, the cumulative global length of metro systems has increased more than tenfold from 1250 km to 13000 km through a combination of extending old networks and the construction of new metro lines (Bono et al., 2022). As such, metro systems have established themselves as a substantial contributor to inner-city passenger transport with a total annual ridership count of 58 billion in 2023 (International Association of Public Transport, 2024), accounting for up to 33% of the modal share in major cities like Tokyo (Le et al., 2022).

Like other infrastructure buildings, tunnels inevitably deteriorate over time due to the influence of material aging, heavy loads, environmental conditions, and irregular events such as earthquakes. In combination with an increasing average service life of tunnels due to the demand for underground infrastructure, structural damage can occur in the form of cracks, leakages and cross-section deformations (Bao et al., 2026). From a safety perspective, defects in tunnel linings and surfaces, such as water ingress and spalling, pose a potential threat to passengers and workers within them. Regular building inspections are thus required to ensure the safe, fully-functional operation of tunnels. Currently, manual on-site inspections are performed by certified inspectors and structural engineers at regular inspection intervals (routine inspection) or after unforeseeable events (post-disaster inspection). These inspections are used to assess and predict future building conditions, plan investments and allocate maintenance and repair resources, however the manual inspection process is time-consuming and often suffers from poor visibility and subjective judgment, expressing the demand for more intelligent and automated approaches (Bao et al., 2026).

Metro tunnels impose particularly stringent operational constraints that further demonstrate the need for automated inspections. As metro services operate throughout the day, maintenance windows are timely restricted and typically limited to a maximum of 4-6 hours, including time required for safety checks, resulting in an effective inspection window of approximately 3 hours during nightly shutdowns (Chen et al., 2023). Moreover, the metro-specific environment, including central rails, ballast, crossties, and frequent stations create fundamentally different requirements for automated inspection systems compared to road tunnels. Given the unique combination of metro tunnel-specific inspection constraints, a comparative assessment of mobile inspection platforms is necessary to guide future developments of inspection systems and inform metro operators looking to automate their inspection processes.

Contributions and Outline

While previous work mainly focused on the design and development of individual inspection systems for tunnel environments, this work contributes by evaluating different mobile platforms for automated metro tunnel inspections, specifically focusing on the requirements and operating conditions therein. By doing so, this paper addresses the research gap of systematically evaluating mobile inspection platforms such as rail-bound vehicles, wheeled and tracked robots, quadruped robots and Unmanned Aerial Vehicles (UAVs) against metro tunnel-specific environments and operating constraints.

Including the Abstract and Introduction, the paper is structured into seven sections. Section 3 presents the methodology for deriving metro tunnel-specific evaluation criteria from literature, operator interviews, and in-tunnel observations. Section 4 reviews literature on developed mobile inspection systems for tunnel environments and identifies the main platform classes analyzed in this study. Section 5 provides the core contribution, an evaluation of mobile platforms including rail-bound vehicles, wheeled and tracked robots, quadruped robots, and UAVs. Sections 6 and 7 discuss the implications of the findings and present the conclusions, with recommendations for future work.

Methodology

The evaluation of mobile platforms presented in this paper is based on a mixed-method approach combining a literature review, semi-structured interviews with German metro tunnel operating companies, and qualitative in-tunnel observations. The following section explains how these three data sources were collected and analyzed, and how they informed metro tunnel-specific evaluation criteria.

First, a literature review was conducted to identify existing mobile inspection systems for tunnel environments and to extract key technical parameters. The review focused on robotic and automated inspection systems used in road tunnels, railway tunnels, and metro systems. Relevant publications were identified through the Scopus and Google Scholar databases using a keyword-based search approach, with combinations of terms related to automated tunnel and subway tunnel inspections. From the resulting set of publications, studies were selected based on their relevance to tunnel inspection tasks and the maturity of the described systems. For each platform class, typical performance ranges of key system characteristics were consolidated.

Semi-structured interviews were carried out with multiple representatives from German metro tunnel operating companies. In total, six participants from maintenance and infrastructure departments participated, covering a range of responsibilities from planning and scheduling to on-site inspection and asset management. The main focus of the interviews was on existing maintenance approaches for metro tunnels and the derivation of requirements for a digital, predictive maintenance system. The interview guideline addresses several thematic blocks, including the organizational processes of tunnel inspections from planning to execution, current maintenance strategies, handling of inspection data and reports, and operational constraints in the maintenance process.

The interviews were recorded and transcribed, and the textual data were analyzed using qualitative content analysis according to Mayring's approach. The analysis aimed to identify recurring themes and explicitly stated operational constraints relevant to metro tunnel inspections, such as the duration of night-time inspection windows, track-related access restrictions, and safety procedures. The main outcome for this paper was the extraction of key operational constraints that later served as core criteria in the platform evaluation.

Third, qualitative in-tunnel observations were conducted inside a German metro tunnel during regular inspection and maintenance windows. These observations focused on the physical environment and infrastructural conditions inside metro tunnels. The observations were documented through photos and videos, and the collected material was subsequently analyzed to identify requirements that were not explicitly mentioned in academic literature. The resulting insights were translated into additional evaluation criteria and integrated into the final comparison of mobile platforms.

Tunnel inspection systems

The following section presents existing mobile systems developed for tunnel infrastructure inspections. Since the focus of this work is on the mobile platform of inspection systems, they are categorized according to four main locomotion types: rail-bound vehicles, wheeled and tracked robots, quadruped robots and UAVs. These platforms were selected as they represent the largest share of used platforms for developed systems, including the most mature commercial technologies, balancing trade-offs in characteristics such as payload and terrain adaptability. Figure 1 shows an inspection system based on each locomotion type.

Rail-bound vehicles

Rail-bound inspection vehicles represent an established approach for railway and metro tunnel maintenance, leveraging existing rail infrastructure for stable, high-capacity operation. The Metro Tunnel Surface Inspection System (MTSIS) (Li et al., 2021) deploys a rail-mounted platform equipped with eight high-resolution line-scan cameras and linear lights, capturing tunnel lining images at speeds up to 15 km/h with 0.15 mm/pixel resolution during 3-hour nightly windows. Covering 280° of the tunnel circumference, MTSIS enables automated defect detection via deep learning, achieving 88.5% mean average precision while reducing inspection time by 40% compared to manual methods, which has been evaluated in a series of experiments within different metro tunnels (Li et al., 2021).

Similarly, Zhou et al.'s mobile laser scanning rail trolley (Zhou et al., 2021) uses a Z+F PROFILER 9012 laser scanner on a motorized rail cart, generating intensity/depth point clouds at 0.5 m/s (100 Hz scan rate) for 3D spalling quantification in railway tunnels. The SIDNet model segments defects with 92.5% mean intersection over union (MIoU), enabling volume calculation of spalling via depth analysis. The system was experimentally tested in several railway tunnels in China, proving the validity and feasibility (Zhou et al., 2021).

Specifically targeting crack detection, Liu et al. (Liu et al., 2022) present a system mounted on a Metro Intelligence Inspection Vehicle (MIIV) for subway tunnels. The MIIV

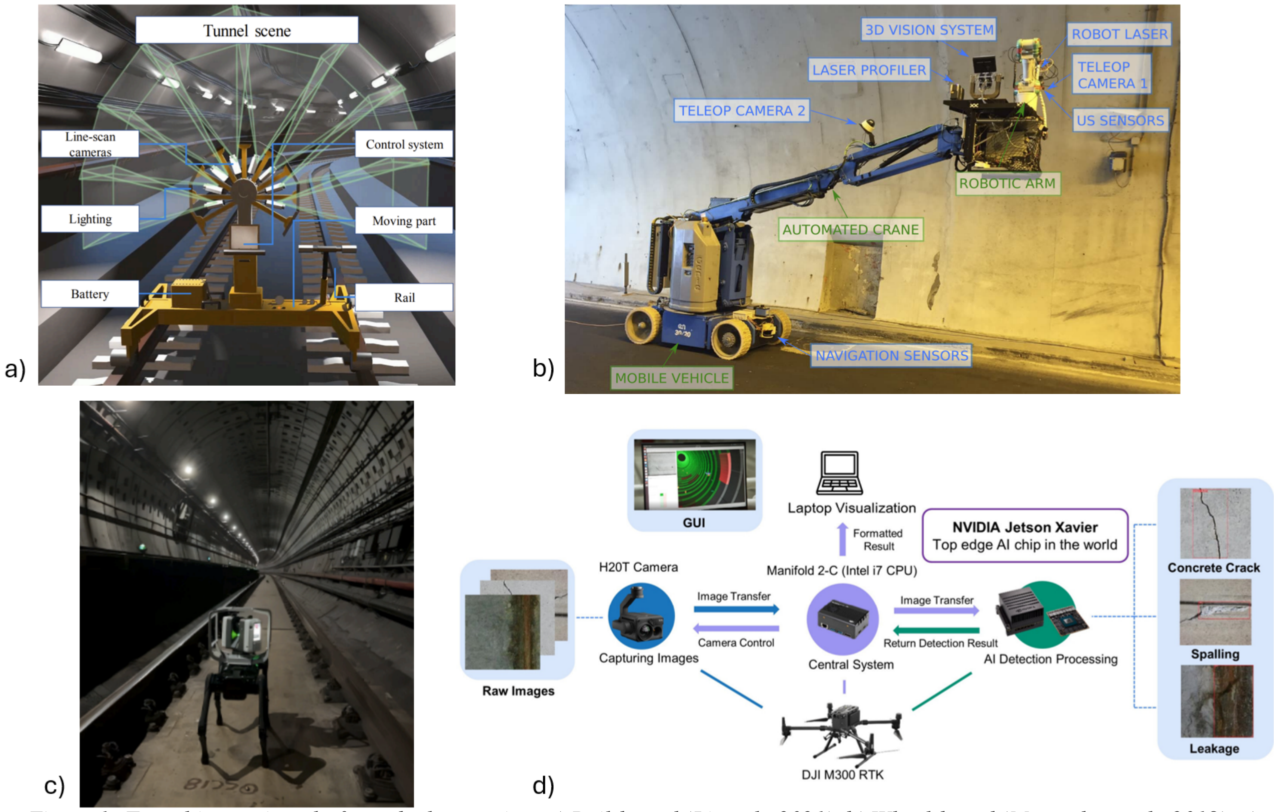

Figure 1: Tunnel inspection platforms by locomotion, a) Rail-bound (Li et al., 2021), b) Wheel-based (Menendez et al., 2018), c) Quadruped-based (Feng et al., 2026) d) UAV-based (Yang et al., 2022)

carries three high-speed cameras on a circular frame, synchronized to capture 150° of inspection range at an optimal inspection speed of 18 km/h. An improved image processing pipeline, including illumination correction, adaptive thresholding, structural noise removal and pixel-level crack width estimation, achieves a crack recognition rate of 91.15%, evaluated in railway tunnel environments (Liu et al., 2022).

Wheeled and tracked robots

The ROBO-SPECT project presents a highly integrated road-tunnel inspection robot composed of a self-navigating mobile vehicle, an automated crane, a 7-degree of freedom (DOF) robotic arm carrying an ultrasonic sensor, stereo cameras, and a 3D laser profiler. The wheeled platform autonomously follows the tunnel wall using laser-based navigation and Simultaneous Localization and Mapping (SLAM) with reflective beacons, performs visual inspection for cracks and other defects, and when a crack is detected, repositions the crane and arm to place the ultrasonic sensor on the lining for width and depth measurements, while the laser profiler captures 3D deformation with 2 mm accuracy. Field trials in motorway tunnels demonstrate the complete inspection workflow and show reduced inspection times compared to manual methods while delivering comparable inspection quality (Menendez et al., 2018).

Earlier work by Yu et al. in 2007 presents a mobile robot-based crack inspection system for concrete tunnels that combines a two-wheel differential-drive platform with a line-scan camera, high-power illumination, and an image-processing pipeline for semi-automatic crack detection and measurement. The robot maintains a constant distance to the tunnel wall, acquires line-scan imagery at up to 5 km/h with a spatial resolution of 0.3 mm/pixel, and applies contrast enhancement, edge detection, graph-based crack tracing, and feature extraction to estimate crack length, orientation, and width, yielding measurement errors below 10%. Although the system focuses on 2D vision rather than full 3D evaluation, it demonstrates the feasibility of wheel-based tunnel inspection with higher speed and more objective results than manual inspections (Yu et al., 2007).

Quadruped robots

Quadruped robots are emerging as a promising mobile platform for autonomous tunnel inspection because they decouple the inspection system from the rail infrastructure while maintaining high mobility on uneven terrain. Feng et al. integrate a laser scanner with a legged inspection robot to realize rail-independent deformation inspection of metro tunnels, enabling dense point cloud acquisition in sections where trolley-based mobile laser scanners are impractical due to track layout. In their system, the quadruped robot carries a laser scanner through the tunnel and, together with terrestrial laser scanners, provides a point cloud dataset containing more than 574 million points to support segmentation of tunnel components and deformation analysis. The approach achieves sub-millimeter accuracy (average error 0.60 mm) comparable to total stations while overcoming the low efficiency of static terrestrial laser scanning and was tested in various metro tunnel sites in Shanghai, China. (Feng et al., 2026).

Beyond pure defect inspections, quadruped robots are also being used as carriers in heterogeneous inspection approaches that combine legged mobility with aerial close-up sensing. Chu et al. propose a collaborative system composed of a quadruped robot and a collision-resilient micro-UAV for crack inspection in road tunnels, explicitly addressing GPS-denied navigation, poor lighting, and wet, obstacle-rich road surfaces that challenge wheeled or tracked platforms. The quadruped robot is equipped with stereo and panoramic cameras plus a VLP-16 LiDAR scanner to autonomously follow a pre-planned path to perform global scanning and patch-based CNN crack localization, while serving as a mobile helipad and communication relay for the UAV. Once potential damage regions are detected, the caged UAV is launched to perform detailed crack segmentation, allowing tiny cracks to be identified with over 93% segmentation accuracy in field tests (Chu et al., 2023).

Unmanned Aerial Vehicles (UAVs)

UAV tunnel inspection is increasingly defined by full-stack, field-tested systems that tightly couple navigation, sensing, and defect analytics in Global Navigation Satellite System (GNSS)-denied, low-light environments. Zhang et al. propose a Proximity-Pause-Photo for Surface Defect Inspection (PMPP-SDI) method, which uses a DJI Mavic 2 Enterprise with onboard lighting and omnidirectional obstacle sensing to execute a reactive grid-scan of tunnel walls. Instead of relying on pre-built maps, the UAV regulates lateral position via vision, height via infrared ranging, and axial motion via front/back obstacle distances, moving in short steps (1 m - 1.5 m) and pausing to acquire high-overlap image strips that later feed a structure-from-motion photogrammetry pipeline. A field test in a railway tunnel demonstrates stable navigation in darkness, high-resolution 3D reconstruction, and accurate surface defect localization, while highlighting remaining needs in higher-level autonomy, data quality control and integrated computer-vision-based defect analysis (Zhang et al., 2024).

Yang et al. developed a real-time tunnel lining inspection system that embeds an edge-AI stack and a dual RGB/infrared payload on a DJI Matrice 300 RTK platform to detect cracks, spalling, and leakages in TBM-driven tunnels. Positioning and tunnel coverage are enforced by AprilTag-based relative pose estimation, with an automated routine that captures 12 RGB and 12 infrared images per tunnel segment. Subsequently, the on-board YOLOv3-inference evaluates the data and returns the defect results, achieving the highest precision when combining RGB and thermal channels during field tests (Yang et al., 2022).

Evaluation of Mobile Platforms

Metro tunnel operating constraints

While robotic tunnel inspection literature often assumes highway or generic underground conditions, metro tunnels present distinct operational challenges that fundamentally constrain mobile platform selection. The following aspects are derived from the three complementary data sources (literature, interviews, observations) and later serve as an underlying basis for the evaluation of different mobile platforms.

Literature-based constraints:

- **GNSS-denied environment:** Absence of GPS demands robust onboard localization, while tunnel feature scarcity and repetitive geometries challenge SLAM performance (Schichler et al., 2025).
- **Low illumination:** Low-light tunnel environment requires the addition of external light sources for sufficient illumination and high quality data acquisition (Liao et al., 2022).
- **Dust pollution:** Metro tunnels show increased particulate matter concentrations (Smith et al., 2020), demanding sealed electronics, filtered intakes and protective covers for reliable sensor operation.

For the low illumination and dust pollution constraints, while they are derived from literature, in-tunnel observations confirmed the presence and operational impacts of these conditions.

Interview-based constraints:

- **Limited inspection time:** Interviewed metro operators in Germany reported that daily inspection windows during nighttime shutdowns are limited to approximately 3 hours of effective inspection time.
- **Railway track maintenance:** Major maintenance and repairs of railway tracks require temporary track closures, resulting in sections periodically unavailable for continuous track access (Dao et al., 2018). Interviewed metro operators confirmed that individual track sections are regularly unavailable for maintenance.

Observation-based constraints:

- **Railway track geometry:** Tracks, ballast and crossties require obstacle-straddling capability for non rail-bound platforms, ensuring reliable navigation and freedom of movement.
- **Metro tunnel access:** Entry and exit to metro tunnels can involve overcoming elevation changes such as stairs.

Platform Evaluation

Building on the general constraints of tunnel environments and the metro-specific constraints outlined previously, Table 1 evaluates four mobile platforms against criteria including payload capacity, speed, system runtime, deployment time, locomotion, and general considerations, derived from inspection requirements.

Payload Capacity

Payload capacity directly determines sensor quality and availability in metro tunnel inspection. Rail-bound platforms excel with high possible payloads, supporting extensive sensor suites for data collection. Depending on the system size, wheeled and tracked platforms can achieve around 20 - 100 kg of payload capacity, offering potential for comprehensive multi-sensor setups, while quadruped robots are usually limited to around 10 - 40 kg. UAVs remain with the lowest payload capabilities of up to 2.7 kg for commercial drone systems, usually restricting them to camera setups.

Inspection Speed

Inspection speed reflects the traversal efficiency across tunnel geometries. Rail-bound platforms can achieve fast inspection speeds of up to 4.2 m/s due to their ease of locomotion in subway environments, while wheeled and tracked platforms reach a velocity of 2 m/s in non-track areas, further limiting the resulting inspection speed due to track-crossing and ballast navigation. Quadruped systems can maintain a speed of 0.75 - 1.6 m/s in non-track environments, however they are able to maintain more of that speed due to their obstacle avoidance capabilities. UAVs attain up to 20 - 23 m/s in ideal outdoor conditions, but tunnel constraints reduce practical speeds significantly.

System Runtime

System runtime depends on energy capacity and operational demands in tunnel conditions. Since inspection windows are usually limited to around 3 hours per day, this reflects the target system runtime for inspection operations without battery changes. As such, rail-bound platforms, wheeled and tracked systems and quadruped robots can reach system runtimes of up to 4 - 8 hours depending on the installed sensor systems, resulting in sufficient operation time for metro tunnel inspection windows. UAVs are usually limited to a shorter runtime due to limited battery-to-weight ratios, leading to required battery changes and inspection stops.

Deployment Time

Deployment time critically impacts the 3-hour inspection window. Developed rail-bound platforms require 3 - 5 minutes for assembly and disassembly tasks on tracks. Wheeled and tracked systems are estimated for around 10 - 15 minutes for deployment due to their bulky nature and difficult tunnel access. Quadruped robots, usually lighter and more flexible in motion capabilities, are estimated to require around 5 - 10 minutes, while UAVs excel with the fastest deployment due to their low size and weight.

Locomotion

Locomotion determines the access to diverse tunnel locations, while considering the complexity of system control. Rail-bound platforms use available rail systems with no possible deviation from the track layout, however they require very simple control to move along the tunnel. Wheeled and tracked platforms feature medium control complexity, while being able to navigate floors effectively but struggling with track straddling and poor object avoidance. Quadruped robots depend on complex system control, but reward high flexibility, being able to efficiently navigate around obstacles and provide large tunnel access including side tunnels not connected by tracks. UAVs require complex control due to aerial collision avoidance, but benefit by being able to inspect hard-to-reach locations that would be inaccessible by other systems.

General Considerations

General considerations highlight platform-specific limitations for metro tunnel operations. Rail-bound systems depend entirely on available tracks, excluding any areas currently under track maintenance. Wheeled and tracked systems suffer from poor obstacle avoidance and track-straddling features in complex metro environments. Quadruped robots benefit from stair-walking capabilities, while large UAVs face the risk of propeller-induced dust swirling, reducing visibility and damage detection potential.

Discussion

The comparative evaluation of mobile platforms reveals distinct strengths and weaknesses emerging from metro tunnel-specific inspection conditions, guiding deployment decision based on environment, access, data requirements and mission duration. Each platform benefits in particular aspects, which promotes scenario-specific deployment strategies rather than generic platform recommendations.

Rail-bound platforms excel in linear inspection with substantial payload capacity for comprehensive sensor suites, achieving fast traversal and extended runtime on established rails. They therefore perform well in long, straight sections with uninterrupted track access and limited track maintenance activity. Thus, their ideal use case involves track-maintenance free tunnels with uninterrupted track access, where large amounts of the tunnel surface can be inspected rapidly once the system is established.

Wheeled and tracked platforms offer balanced performance across payload, speed, and runtime, with robust sensor integration but limitations in obstacle avoidance and reliable track straddling. They perform best in relatively flat metro tunnel areas, where the ground surface is continuous and track-crossing poses minimal issues. In such scenarios, their locomotion simplicity supports efficient coverage of extensive tunnel sections, prioritizing horizontal mapping and data acquisition over vertical or complex geometries. However, they lag in environments with frequent ballast sections, crossties, and stations, where their limited obstacle-navigation reduces inspection capability.

Quadruped robots provide versatile and flexible locomotion with good stair-climbing and obstacle avoidance.

Table 1: Comparison of mobile platforms for automated metro tunnel inspection.

Criteria	**Rail-bound** (Huang et al., 2017) (Zhou et al., 2021) (Li et al., 2021)	**Wheeled and tracked** (Clearpath Robotics, 2020) (Clearpath Robotics, 2024)	**Quadruped** (ANYbotics AG, 2022) (Boston Dynamics, 2024) (Unitree Robotics, 2023)	**UAV** (DJI, 2021) (DJI, 2024)
Payload Capacity	high (total system weight 65 - 140 kg)	20 - 100 kg	10 - 40 kg	<0.2 - 2.7 kg
Speed	0.5 - 4.2 m/s	~ 2.0 m/s, in non-track environment	0.75 - 1.6 m/s, in non-track environment	20 - 23 m/s, outdoor and no-wind conditions
System Runtime	3 - 4 hours	2 - 8 hours	1.5 - 4 hours	30 - 55 min
Deployment Time	3 - 5 min, for each assembly and disassembly	10 - 15 min, bulky and difficult tunnel access	5 - 10 min, fast tunnel access and mid-range weight	<3 min, fast setup due to small size and weight
Locomotion	simple, no deviation from track possible	medium complexity, struggles with crossing tracks	complex, high flexibility	complex, able to inspect hard-to-reach locations
General Considerations	dependent on available tracks	poor 3D obstacle avoidance	stair-walking capability	risk of dust swirling from large drone propellers

They support comprehensive sensor configurations with sufficient system runtime for typical inspection windows available for metro tunnels, while excelling in complex-geometry environments such as station-adjacent tunnels, cross-passages, and elevated areas reachable by stairs. Their main drawbacks are slower inspection speeds compared with rail-bound platforms and higher control complexity. Nevertheless, they benefit in complex-geometry environments such as direct track proximity and inspection routes that require climbing stairs or navigating uneven terrain.

UAVs deliver fast deployment and unique aerial reach for otherwise inaccessible locations such as overhead and ceiling inspections, despite short runtime and payload constraints that are mostly limited to camera setups. They are therefore superior in confined, vertical, or hard-to-reach areas where ground-based access is limited. As such, they pose most valuable for quick vertical scans in confined areas or for temporary assessments and spot checks in areas not reachable by other platforms.

Conclusions and Outlook

This work evaluates mobile platforms for metro tunnel inspections, demonstrating how rail-bound, wheeled and tracked, quadruped, and UAV systems address distinct operational constraints through tailored strengths in system payload, mobility and deployment. The analysis identifies optimal deployment strategies matching platform capabilities to tunnel geometries, access challenges and time windows, advancing automated inspection and monitoring of metro tunnel infrastructure. In summary, the evaluation confirms rail-bound platforms suit long linear rail surveys, aiming to cover large portions of the tunnel surface, while wheeled and tracked systems excel in flat-floor mapping due to their balanced performance and ease of control. Additionally, quadruped robots enable access to complex areas with their high locomotive flexibility and stair-climbing ability, while UAVs offer quick system deployment, targeting short overhead inspections in hard-to-reach areas.

Future research can be conducted into hybrid inspection fleets combining multiple platforms for entire metro tunnel coverage under efficient system usage. Thus, the benefits and drawbacks of single systems can be compensated to allow for comprehensive metro tunnel inspections under varying conditions. Additional emerging research fields include multi-platform sensor fusion, enabling the data of different platforms and sensors to merge into single evaluation models, which could leverage complementary strengths such as UAV overhead imagery with quadruped ground-level LiDAR for advanced defect mapping.

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