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Feasibility Study on 3D Point Cloud Data Acquisition for Railway Structures: Evaluation of VTOL UAVs and Portable Vehicle-Mounted LiDAR

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Abstract

This paper evaluates the feasibility of utilising vertical take-off and landing unmanned aerial vehicles and portable vehicle-mounted light detection and ranging systems for the maintenance of railway structures in mountainous and heavy snowfall regions. Field demonstration tests were conducted to address labor shortages and infrastructure ageing. The vertical take-off and landing aircraft successfully captured high-resolution imagery over a twenty-kilometre section within twenty minutes under the newly established regulatory framework in Japan, enabling rapid digital twin construction and real-time situational streaming via cellular networks. Concurrently, the vehicle-mounted system demonstrated robust through-window data acquisition from an operating train under wintry conditions, achieving a dimensional accuracy within fifty millimetres. By employing a point cloud change-detection algorithm, the system successfully quantified snow overhang lengths at tunnel portals, providing a data-driven basis for prioritizing snow removal operations. The integration of these complementary technologies offers a highly efficient, multi-scale framework that bridges the gap between conventional ground-based inspections and aerial surveys, significantly enhancing operational safety and disaster resilience in railway infrastructure management.

Keywords: TOL UAV, BVLOS (Beyond Visual Line of Sight), LiDAR, 3D point cloud, railway maintenance, snow cornice

1 Introduction

East Japan Railway Company (JR East) operates an extensive railway network of approximately 6,200 km across eastern Japan. Ensuring safe and stable daily operations requires maintaining a large inventory of railway assets, including earthworks and other structures located in mountainous terrain and heavy-snowfall zones. Japan’s steep topography means that many lines run adjacent to cut slopes, embankments, and natural slopes. As climate change increases the frequency and severity of heavy rainfall, typhoons, and heavy snowfall, the risks of sediment inflow, rockfall, and avalanches are rising.
The long-term increasing trend of heavy rainfall days in Japan, which directly escalates these environmental risks, is illustrated in Figure 1. In the past, events such as embankment failures caused by concentrated heavy rainfall and the collapse of snow cornices due to heavy snow have significantly impacted train operations. Examples of recent prominent natural disasters within the Niigata Branch jurisdiction that demonstrate the critical severity of these infrastructure challenges are shown in Figure 2. Consequently, wide-area situational awareness and rapid safety verification of railway structures are increasingly vital for railway operators to ensure transport resilience and safety.

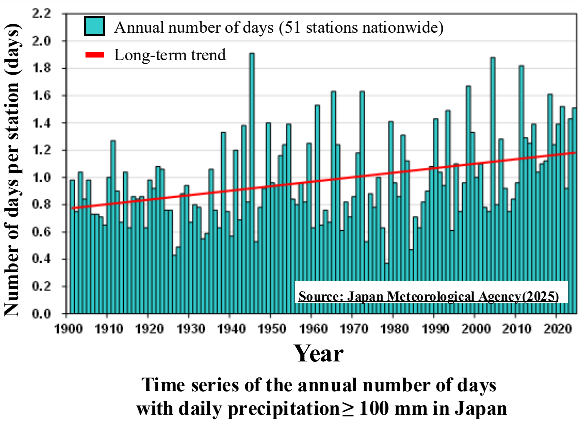

Figure1: Trends in the annual number of days with daily precipitation ≥ 100 mm in Japan.
The data is compiled from "Climate Change in Japan 2025" by the Japan Meteorological Agency (JMA), showing a long-term increase in heavy rainfall frequency.

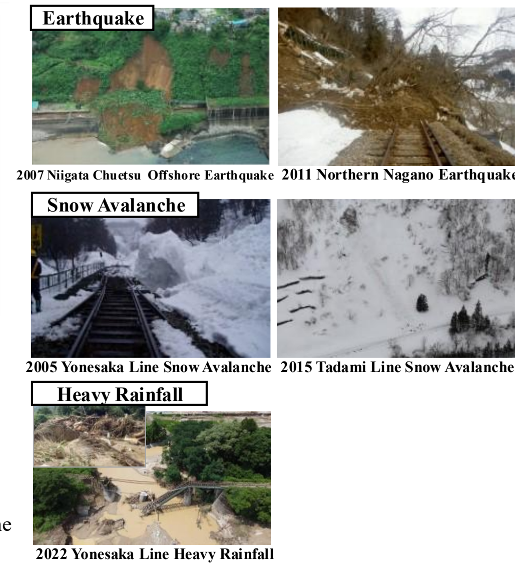

Figure 2: Recent prominent natural disasters in the JR East (Niigata Branch) jurisdiction.
Widespread damage is caused to railway structures due to heavy rainfall, earthquakes, and avalanches.

1.1 Conventional Inspection Methods and Faced Challenges

To guarantee the safety of railway structures, inspections are conducted during both ordinary times and emergencies using various methods. In addition to legally mandated inspections, such as the regular general inspection performed on all railway structures every two years, on-site verifications are conducted as necessary. For instance, to monitor rockfalls and heavy snowfall, patrol inspections are regularly performed by inspectors riding in the driver's cab of operating trains (train patrols). While this is crucial for detecting signs of potential disasters, it poses a challenge in lines with low train frequency, where transferring between trains requires a considerable amount of time. Furthermore, since it relies on visual confirmation from a moving train, quantitative evaluation of deformations remains difficult.

In mountainous sections with particularly heavy snowfall, the impact of snow accumulation on train operations is immense. Although snow on the tracks is mechanically removed using snowploughs, the removal of snow behind avalanche prevention fences and the clearance of snow overhangs (snow cornices) protruding above tunnel portals must be performed manually. Since it is impossible to clear all accumulated snow at once, operations are prioritised based on necessity. Additionally, when a disaster occurs, patrols using track cycles or on-foot inspections are conducted to check for collapses or fallen trees, enabling decisions on whether train operations can be resumed. However, challenges include ensuring the safety of inspectors under the risk of secondary disasters, and the prolonged duration of inspections when the affected area is extensive, which increases the downtime before resuming operations.

Furthermore, the Japanese railway industry faces a serious labour shortage driven by rapid demographic ageing and a declining birthrate, making it difficult to secure experienced technicians. Since railway structures constructed during the period of high economic growth are also ageing, there is an urgent need to sophisticatedly upgrade and streamline inspection methods by leveraging new technologies, rather than relying solely on manual labour and the skills of experienced personnel.

1.2 Challenges in the Utilisation of Point Cloud Data

In upgrading and streamlining inspection methods, three-dimensional (3D) point cloud data analysis technologies have advanced remarkably in the civil engineering field in recent years. JR East has also introduced software to generate point clouds from not only photographs but also camera videos using structure from motion (SfM) techniques, and initiatives are underway to acquire high-precision 3D point clouds of structures using handheld light detection and ranging (LiDAR) devices carried by inspectors. However, although handheld LiDAR contributes to the sophistication of inspections, its contribution to efficiency is limited because inspectors must still physically carry the equipment to the site.

Drones are also widely used as a tool for acquiring point clouds. While effective for spot investigations, conventional multi-copter drones suffer from high energy consumption and short flight ranges, leaving challenges for efficiently inspecting long, linear railway infrastructure. Furthermore, in mountainous areas, the lack of access roads for take-off and landing sites often restricts their operational use.

1.3 Research Approach

To resolve the aforementioned challenges, this study focuses on two complementary technologies. The first is a wide-area inspection method utilising a vertical take-off and landing (VTOL) unmanned aerial vehicle (UAV), which uses aerodynamic lift from fixed wings for long-distance flight and does not require a runway infrastructure. The second is a quantitative condition assessment method using a portable vehicle-mounted light detection and ranging (LiDAR) system, which can be brought into a train cabin to acquire 3D point clouds of the surrounding environment while travelling.

The conceptual flight modes of the proposed VTOL drone, which integrates efficient vertical flight mechanisms with stable horizontal cruising to overcome conventional aerial inspection limits, are clearly illustrated in Figure 3. This paper presents field demonstration tests conducted along mountainous and heavy snowfall lines characterised by harsh natural environments. Based on these tests, we evaluate the respective equipment characteristics, sort out challenges for practical application, and verify the future utilisation of these methods in infrastructure maintenance to overcome the limitations of efficiency and quantitativeness inherent in conventional inspection methods.

2 Wide-Area Condition Assessment Method Using VTOL Drones

VTOL drones are unmanned aircraft that lift and descend vertically like a multi-copter during take-off and landing, and transition to horizontal flight as a fixed-wing aircraft once aloft. By utilising the lift generated by the wings, they achieve better energy efficiency than multi-copter drones, enabling long-distance inspections of up to approximately 70 km per flight. This offers a significant advantage for inspecting long linear infrastructure like railway structures. The conceptual flight modes of the VTOL drone, combining vertical flight mechanisms with efficient horizontal cruising, are illustrated in Figure 3.

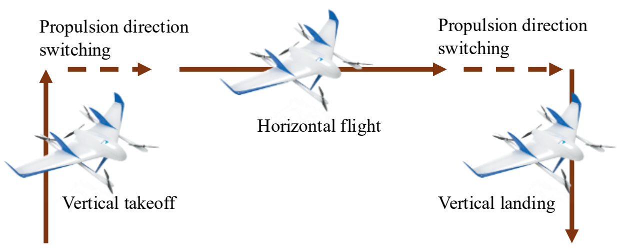

Figure 3: Flight modes of the VTOL drone.
The diagram illustrates the vertical takeoff and landing capabilities combined with efficient, long-range horizontal flight utilizing aerodynamic lift.

Item	AeroboWing (AS-VT01K)	AeroboWing (AS-VT02K)
Wingspan	2.2 m	2.1 m
Length	1.4 m	1.2 m
Height	0.4 m	0.4 m
Airframe weight	9.2 kg	10 kg
Maximum payload	1.0 kg	1.6 kg
Maximum flight time	40 min	59 min
Maximum flight range	50 km	70 km
Maximum speed	100 km/h	100 km/h
Cruising speed	65 km/h	72 km/h
Communication method	LTE	LTE

Table 1: Specifications of the utilized VTOL drones.
The technical parameters and performance characteristics are shown for the Aerobo Wing AS-VT01K and AS-VT02K models.

In this study, field verifications were performed using the Aerobo Wing (AS-VT01K and AS-VT02K models) manufactured by Aerosense Inc. The key technical parameters and performance characteristics of the utilised aircraft are detailed in Table 1. In particular, the successor model, AS-VT02K, features an extended flight range and a newly implemented waterproof specification. Since it can operate under adverse weather conditions such as light rain, it is expected to improve operational adaptability during disaster responses. Both aircraft were equipped with a gimbal camera for high-quality video recording and a vertical camera capable of continuous vertical photography to generate orthomosaics and 3D point cloud data via structure from motion (SfM) processing. The outward appearance of the UAV and the actual scene of the flight demonstration test conducted at Echigo-Yuzawa Station are presented in Figure 4.

Figure 4: Appearance and flight demonstration of the VTOL drone. The photographs show the aircraft configuration and the verification test conducted at Echigo-Yuzawa Station.

2.1 Regulations on Unmanned Aerial Vehicles in Japan and Application of "Level 3.5 Flight"

In implementing railway structure inspections using UAVs, regulations surrounding beyond visual line of sight (BVLOS) flights represent a common challenge globally. Under the Japanese Civil Aeronautics Act, regulations are structured based on risk classification (Categories) and operational methods (Levels), as summarised in Table 2.

Item	Level 3 (Conventional)	**Level 3.5 (Digitalized)**	Level 4 (Advanced)
Flight Category	Category II	Category II	Category III
Flight over Third Parties	No	No	Yes
Deployment of Assistants (Spotters)	Required	**Not required (Replaced by digital technology)**	Required (Strict safety measures)
Primary Requirements	Standard permission and approval	National Remote Pilot Certificate + Liability Insurance + Onboard Camera	Class 1 Type Certification + First -class National Certificate
Practical Benefits	Conventional BVLOS flight	Efficient inspection with minimum personnel	Flight over urban / populated areas

Table 2: Drone operation categories classified by the Japan Civil Aviation Bureau (JCAB). Beyond visual line of sight (BVLOS) flights without assistants are permitted under the Level 3.5 framework.

First, under the risk classification, BVLOS flights and night flights are defined as "Specific Flights", which in principle require permission and approval from the government. Among these Specific Flights, flying over unpopulated areas is defined as "Category II", while flying over populated areas (above third parties) is defined as "Category III", representing the highest risk. The automated patrols in mountainous areas targeted in this study fall under Category II BVLOS flight.

Next, under the operational classification, flights are divided into Levels 1 to 4 depending on whether they are within or beyond the visual line of sight. BVLOS flight corresponds to Level 3 or higher. Under the conventional "Level 3" framework, to reduce ground risks, it was mandatory to deploy assistants (spotters) at intersections with roads along the flight path and temporarily halt the drone when crossing roads. However, deploying personnel at all intersections over a patrol route spanning tens of kilometres is impractical.

To resolve this issue, a new framework called "Level 3.5 Flight" was introduced in December 2023. By satisfying conditions such as the pilot holding a national licence and utilising an onboard camera for forward monitoring, safety management via digital technology is recognised, thereby eliminating the requirements for deploying spotters and pausing at road crossings. For reference, "Level 4" flight, which involves BVLOS flight over populated areas under Category III, requires even stricter airframe certification and a first-class national licence.

This demonstration represents the first case within JR East where "Level 3.5 Flight" has been applied to railway structure inspections. By utilising this regulatory relaxation optimised for mountainous fields, long-distance BVLOS flights involving road crossings were achieved without imposing the excessive requirements of Level 4 flight.

2.2 Verification Test Results for VTOL Drones

2.2.1 Field Setting and Existing Measures

The field tests were conducted along sections of the Tadami Line (between Ōshirakawa Station and Kamijō Station, approx. 20 km) and the Jōetsu Line (between Tsuchitaru Station and Echigo-Yuzawa Station, approx. 20 km), both of which traverse mountainous areas and face high natural disaster risks. These areas have historically suffered from avalanche and sediment disasters. Currently, safety is maintained through structural measures alongside non-structural measures such as regular patrol inspections and aerial surveillance using disaster-prevention helicopters.

2.2.2 Operational Mobility and Data Acquisition Efficiency

Regarding the application for Level 3.5 Flight, operational experience confirmed that permissions could be obtained within a few days if the flight plan matched the conditions of a previously approved plan, verifying high operational mobility.

During the flight on the Jōetsu Line, autonomous navigation was executed at a relative altitude of approximately 140 m and a flight speed of approximately 70 km/h. While a conventional multi-copter would require significant time due to the lack of access roads and the need to move between multiple takeoff sites, the VTOL drone completed the vertical photography required for point cloud generation across the entire 10 km single-way section in approximately 20 minutes from a single takeoff. Following the flight, SfM analysis was executed on the acquired data, successfully generating high-definition orthomosaics and 3D point cloud data for the entire target section within a few hours, demonstrating that a digital twin can be rapidly

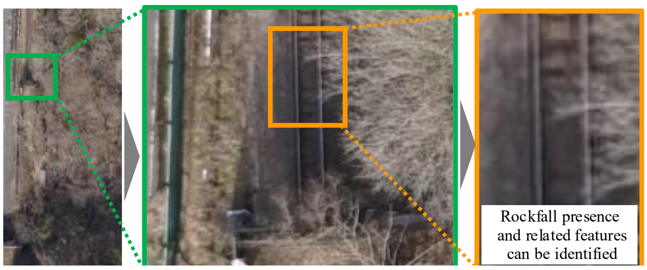

Figure 5: High-resolution aerial imagery used for slope condition assessment.
High-resolution magnification enables post-flight identification of small-scale slope features.

constructed. An example of the high-resolution aerial imagery acquired during this efficient operation is presented in Figure 5.

2.2.3 Condition Assessment Using Gimbal Cameras

In the 4K video captured by the gimbal camera on the lower part of the airframe, deformations of railway structures—such as fallen trees or rockfalls around the track, signs of slope failure, and structural damage to earthwork facilities—were sufficiently visible. Furthermore, a comparative verification with aerial surveillance images conventionally taken from helicopters on the Tadami Line confirmed that the footage from the VTOL drone secured an equivalent angle of view and field of vision while providing higher-resolution imagery owing to stable, close-proximity flight, as shown in Figure 6. Based on these observations, the applicability of the VTOL drone-acquired datasets was comprehensively evaluated across various railway structures, the results of which are summarised in Table 3.

Figure 6: Comparison of aerial observations used for slope avalanche surveys.
The left panel shows an aerial photograph taken from a helicopter on March 2, 2025, while the right panel shows imagery acquired by a VTOL-type drone on April 1, 2025. These aerial observations are used to identify key indicators of slope instability, including surface cracks, snow wrinkles, snowball-like features, and the development of snow cornices.

Evaluation Item	Earthwork Structures	Bridges	Station Yard Facilities
Macro View			
Detailed View			
Evaluation	• External shapes and dimensions can be captured. • High point cloud accuracy due to abundant feature points from retaining walls, tracks, etc.	• External shapes and dimensions can be captured. • High point cloud accuracy due to abundant feature points from bridges, abutments, etc.	• External shapes can be captured. • Point cloud accuracy is lower due to fewer feature points in predominantly flat structures.

Table 3: Verification of the applicability of VTOL drone-acquired point cloud data to various railway structures.
The results demonstrate the feasibility of identifying medium- or larger-scale deformations such as structural damage.

2.2.4 3D Data Generation and Accuracy via SfM Analysis of Vertical Camera

SfM analysis was performed using continuous still images from the vertical camera to generate 3D point cloud data. Regarding the resolution under these flight conditions, when flying at a relative altitude of 110 m, the ground sample distance (GSD) was 2.9 cm/pixel, confirming that it is possible to capture facility dimensions, verify access routes, and understand the spatial relationships of structures texturally. An illustrative example of a continuous 3D point cloud model generated through this methodology is depicted in Figure 7. Conversely, it was also confirmed that the SfM approach has limitations in acquiring ground surface data in vegetation-covered areas and in detecting micro-displacements on the order of a few centimetres.

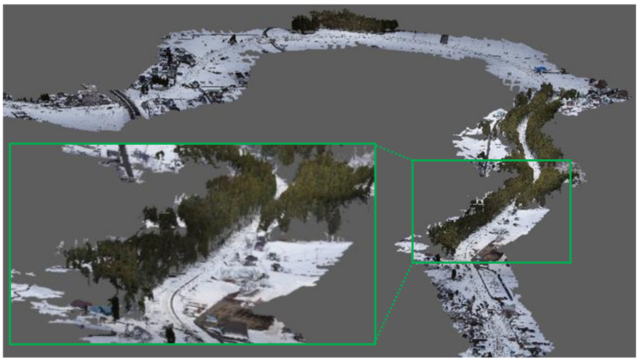

Figure 7: Example of a continuous 3D point cloud acquired by the VTOL drone.
Although a continuous 10 km section was successfully captured, centimeter-order displacement detection remains challenging compared to macro-deformation checks.

2.2.5 Realisation of Real-Time Information Sharing

During the flight, the VTOL drone transmitted its telemetric data, including flight positions, and forward camera imagery to a control PC via an LTE network. By outputting this display through a capture board into a web conferencing system, the team successfully streamed the real-time flight status and camera footage to a remote location. This verified that a system can be established enabling specialised technicians to evaluate disaster conditions from an office and rapidly make decisions for initial responses.

3 Quantitative Condition Assessment Method Using Portable Vehicle-Mounted LiDAR

LiDAR is a technology that emits laser pulses at target objects and measures the time taken for the light to reflect back, thereby acquiring the distance to the target as a three-dimensional (3D) point cloud. Aiming for a "portable" system that can be easily installed on regularly scheduled commercial trains, this study positioned the equipment "inside" the cab of the front vehicle.

3.1 System Configuration and Equipment Installation

To evaluate the practicality of this approach, the validation focused on whether environmental factors expected during through-window measurement—such as laser attenuation and refraction when passing through the windscreen, window contamination, raindrops, and windscreen wiper operation—would affect data acquisition. Furthermore, from a practical standpoint, we prototyped and verified a tool capable of easily comparing and extracting differences between two datasets collected at different times, based on the railway's absolute positional framework, the "kilo-post" (chainage). The layout and component configuration of the onboard equipment secured behind the windscreen are illustrated in Figure 8. The detailed technical specifications of the utilised compact LiDAR sensor are summarised in Table4.

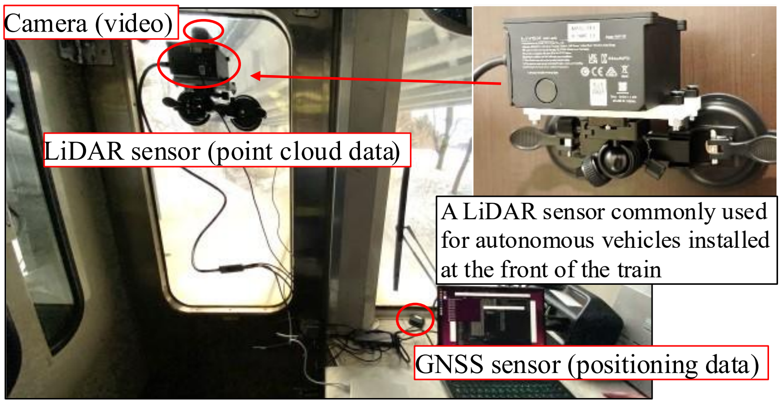

Figure 8: Onboard equipment installation for data acquisition.
The system components, including the LiDAR, camera, and GNSS sensor connected to a PC, were secured to the front windshield using a suction-cup mount.

Item	Specification
Model	HAP (T1) / HAP (TX)
Laser wavelength	905 nm
Laser safety class	Class 1 (IEC 60825-1:2014)
Detection range	150 m (at 10% reflectivity, 100 klx)
Field of view (FOV)	120° (horizontal) × 25° (vertical)
Distance random error	< 2 cm (1σ at 20 m)
Angular random error	< 0.1° (1σ)
Angular resolution	0.23° (vertical) × 0.18° (horizontal, ROI)
Beam divergence	0.28° (vertical) × 0.03° (horizontal)
Point rate	452,000 points/s (first or strongest return)
Data interface	Automotive Ethernet (100BASE-T1 / 100BASE-TX)
Time synchronization	gPTP

Table 4 :Technical specifications of the utilized LiDAR sensor.
The performance data outlines the key operational capabilities of the Livox HAP sensor.

3.2 Verification Results of Through-Window Measurement and Obstacle Impacts

During the field test, snowfall of up to approximately 2 mm/h was experienced. However, due to the high transmittance of the laser wavelength, a reflected signal of sufficient intensity for practical use was obtained even through the window glass, enabling point cloud generation without issues. Measurements were also conducted under conditions involving rain, wiper operation, and window contamination. Examples of the forward railway views captured under these varied atmospheric and imaging conditions are compared in Figure 9. In all cases, no significant impact hindering the comprehension of point cloud shapes was observed, demonstrating that practical-level point cloud data can be acquired from within an operating commercial train, even in snowy environments.

Figure9: Comparison of railway images acquired under different imaging conditions.
The figure demonstrates that window contamination and rainfall
with windshield wiper operation do not significantly affect image interpretation.

3.3 Quantitative Evaluation of Snow Accumulation and Snow Cornices Using a Two-Period Comparison Tool

To verify practical applicability, a comparative analysis was performed on multi-temporal data collected during different snowy periods. The 3D point cloud processing software "CloudCompare" was utilised for the analysis, applying the "Compute cloud/cloud distance" (cloud-to-cloud distance calculation) function, which is effective for detecting shape changes between point clouds.
Through this analysis, precise numerical values were successfully extracted: for example, the overhang length of a snow cornice was quantified as 1.1 m at one tunnel portal (Tunnel A) and 0.25 m at another location (Tunnel B), as visualised in Figure 10. These geometric variations were extremely difficult to distinguish or measure from visual camera images alone. Conventionally, the prioritisation of snow removal operations depended heavily on the subjective judgment of experienced technicians. However, the proposed method enables robust, objective decisions based on quantitative cross-sectional numerical data. The dedicated user interface developed for this multi-temporal imagery and point cloud data comparison is shown in Figure 11. Consequently, human resources can be intensively deployed to high-priority locations, which is expected to contribute significantly to early service resumption and the securing of stable train operations.

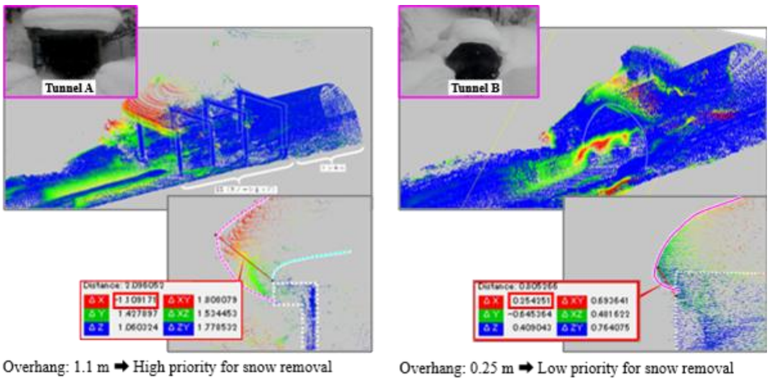

Figure 10: Evaluation of snow overhang at tunnel portals based on LiDAR data.
While visual images alone make it difficult to distinguish differences between the two tunnels, LiDAR measurements clearly show a significant difference in overhang length (1.1 m vs. 0.25 m).

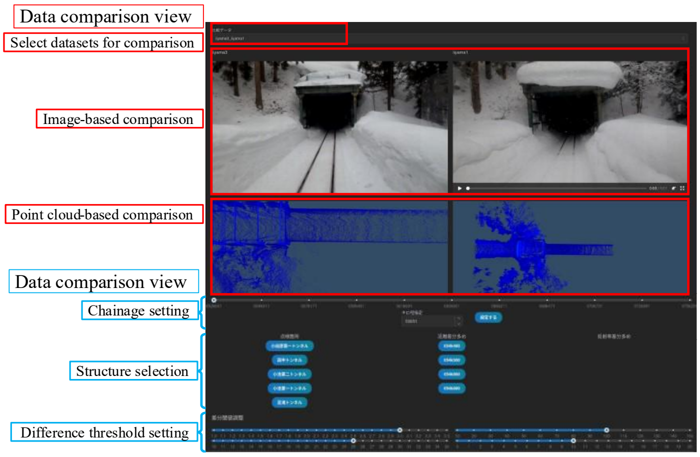

Figure 11: User interface for comparing multi-temporal image and point cloud data.
Functions required for practical operation, including dataset selection, visual comparison, and difference-based navigation, were evaluated

3.4 Accuracy Verification of Point Cloud Data

To verify the measurement accuracy of the acquired point cloud data, three types of styrofoam samples mimicking snow cornices (500 mm, 300 mm, and 100 mm cubes) were installed above the tracks, and data was collected from a commercial train travelling at approximately 45 km/h. The physical setup of these installed targets and the corresponding point cloud visualisation are presented in Figure 12.The quantitative verification and visibility results for each sample size are summarised in Table 5. Regarding detection via the two-period point cloud comparison, target objects with a size of 300 mm or larger could be easily and reliably detected, whereas the 100 mm cube presented a practical challenge for interpretation due to low point cloud density. For operational snow cornice management, although it depends on weather conditions, a protrusion length of approximately 1 m is generally used as a threshold guideline for deploying snow removal teams. In this experiment, since difference extraction of 300 mm or larger was fully successful, it can be stated that the system satisfies the structural accuracy required for practical operations. The dimensional error relative to actual hand-measured values was well within ±50 mm, indicating that the system holds promise not only for civil engineering structure inspections but also for utilisation in power and track facility maintenance.

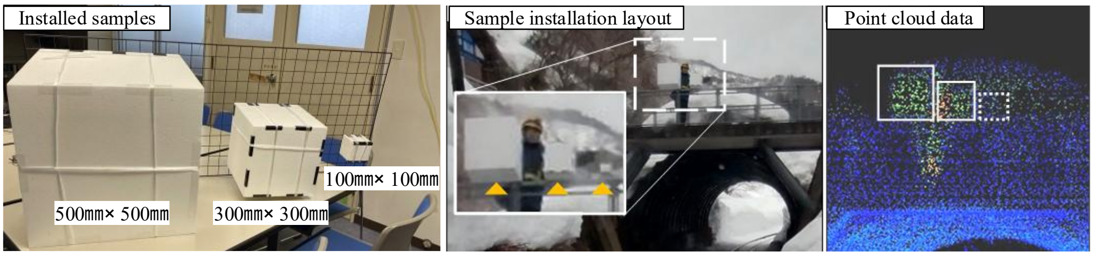

Figure 12: Styrofoam samples and their installation layout for resolution verification.
Three different sizes (500 mm, 300 mm, and 100 mm cubes) were placed above the track to evaluate point cloud visibility from a moving train.

Sample size	Data readability	Measured value	Measured value from point cloud data	Error
50mm×500mm	○	500mm	452mm	△48mm
300mm×300mm	○	299mm	249mm	△50mm
100mm×100mm	△	98mm	116mm	18mm

Table 5: Accuracy and visibility verification results for the target samples.
The dimensional errors were within ±50 mm; targets ≥ 300 mm were clearly identified, while the 100 mm sample was difficult to discern due to low point density.

4 Conclusions & Contributions

This study demonstrated the efficacy of VTOL drones and portable vehicle-mounted LiDAR systems across safety, efficiency, and sophistication metrics for railway maintenance.

For wide-area surveys, the VTOL drone overcame the spatial and temporal limitations of conventional multi-copters or on-foot patrols in rugged terrain. Its capacity to rapidly digitise extensive post-disaster conditions complements manual inspections and bridges the gap left by disaster-prevention helicopters within mid-range sectors under 20 km. While not replacing millimetre-order inspections, it offers sufficient value for identifying affected locations and planning restoration. A comprehensive operational comparison between conventional methods, VTOL drones, and manned helicopters is presented in Table 6.

Evaluation Items	Conventional Method (Walking / Track Cycle) 	VTOL Drone 	Manned Helicopter 
Patrol Speed	Approx. 20 km/h	Approx. 100 km/h	Approx. 200 km/h
Risk	Risk of secondary disasters, etc.	Low (Remote / Unmanned flight)	Low (Remote)
Labor Efficiency	2 persons / team (Disadvantageous for long sections)	2 persons / day (Advantageous for long sections)	Outsourced to specialized organizations
Data Accuracy	Primarily visual/photographs (Additional time for detailed surveys)	Medium to High (High-resolution images , Point clouds)	Low to Medium (Depending on altitude)
Operational Constraints	None (Immediate inspection possible)	Strong wind, Heavy rain, LTE disconnection	Strong wind

Table 6: Comparison of inspection methods.
VTOL drones overcome the safety and speed limitations of conventional methods. By enabling autonomous, high-precision flight at lower altitudes than manned helicopters, VTOL serves as a new, efficient alternative bridging the gap between ground-based and aerial inspections.

For the second challenge—quantitative evaluation during train patrols—the vehicle-mounted LiDAR demonstrated resilient data acquisition capabilities under snowy, adverse weather, and enclosed in-cabin constraints. Deformations that previously relied on subjective human judgment can now be quantified within a few centimetres. This numerical framework enables data-driven snow removal decisions, contributing to enhanced transport safety and advanced maintenance via accumulated historical point clouds.

These two complementary methods address distinct operational phases: rapid situational awareness during emergencies, and efficient quantitative evaluation during routine or alert periods. JR East has already implemented these data collection workflows, such as monitoring avalanche-prone slopes during snowmelt seasons, and intends to expand their operational scope going forward.

As a future outlook, JR East aims to further promote the multi-purpose utilisation of the acquired datasets based on this established framework. Specifically, by applying image analysis algorithms to the orthomosaics captured by VTOL drones, the company plans to automatically evaluate tree mortality and fallen tree risks in adjacent forests. Horizontally deploying a single flight's dataset into diverse disaster prevention and maintenance analytics will achieve a higher dimension of efficiency, ultimately contributing to safer and more resilient railway infrastructure management.

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