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Deliverable D 1.1
Preliminary Report on Subsurface Defects Detection Solution for Railway Tunnels

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Table of Contents

1. Executive Summary

Periodic inspection of railway tunnels to assess changes in structural condition is critical for timely detection and remediation of problems to ensure railway user safety. Water leaks, concrete cracking, concrete spalling, concrete delamination, debonding, steel corrosion, and improper drainage are considered widespread and potentially serious tunnel structural problems. Monitoring railway tunnel condition is key to determine the right schedule of maintenance and rehabilitation activities to fix structural and safety problems.

Tunnel inspection is a challenging task. Minimizing tunnel closures and train delays must be carefully balanced with the need to conduct detailed inspections to ensure the safety of rail traffic. Nowadays many tunnel inspectors are excessively depending on visual inspection without properly utilizing novel survey methods.

This preliminary report describes non-destructive testing (NDT) methods for tunnel lining measurements with a focus on subsurface defect detection. This report is a part of a larger research project H2020, Assets4Rail. The main purpose of this study is to introduce the methods to detect defects and monitor conditions beyond the tunnel wall lining using mobile NDT technologies such as ground penetrating radar (GPR), laser scanner and thermal camera, including hardware and software solutions.

2. Abbreviations and Acronyms

Abbreviation / Acronyms	Description
NDT	Non-destructive testing
GPR	Ground penetrating radar
Lidar	Light detection and ranging

3. Research Background

The present document constitutes the Deliverable D1.1 "PRELIMINARY REPORT ON SUBSURFACE DEFECTS DETECTION SOLUTION FOR RAILWAY TUNNELS" in the framework of the TD 3.5, task 1.1 of IP 3 (please indicate to which version of the MAAP TD Gantt-chart you are referring to).

It contributes as well to TD 3.5, task 4.1 of IP 3 (please indicate to which version of the MAAP TD Gantt-chart you are referring to).

4. Objective/Aim

This document has been prepared to provide a description of a NDT measurement techniques of subsurface defects detection solution for railway tunnels.

Please describe the objective / aim of the present deliverable linked to the TDs/WAs addressed.

5. Background

5.1. General

This preliminary document presents non-destructive testing (NDT) detection methods for mapping problem locations and illustrates examples of their use in railway environment and tunnels. It also serves as a survey plan for upcoming measurements. This document is a part of WP1 Task 1.1 Subsurface tunnel defects detection in the H2020 research project Assets4Rail.

The main purpose of WP1 Task 1.1 is testing, demonstrating, and improving NDT technologies, including hardware and software, to detect and monitor defects and conditions beyond the tunnel walls. Visualization of measurement results, surface structures and conditions are also reviewed in the report. These tasks are done by utilizing state-of-the-art NDT measurement technologies and sensor fusion software for data analysis. The facilitation of proactive maintenance may be possible from the results.

5.2. Need for Inspections

Frequent inspection of railway tunnels to assess changes in structural condition over time is critical to timely detection and remediation of problems to ensure railway user safety and uninterrupted operation of trains. Different conditions and level of deterioration in structures may be caused by the age of the tunnel, construction methods, and alterations made during the years.

Tunnel linings are routinely monitored by a wide range of inspection methods, visual inspection being the most common. Maintenance and repair decisions for problem locations are based on the results of the inspections. Along with the visual inspection, modern sensors and measurement techniques utilizing NDT methods make it possible to detect problem locations and monitor tunnel deterioration over time. The methods have been proven to be fast, highly accurate, and repeatable. (Wimsatt et al. 2013, CETU 2015; Federal Highway Administration 2015).

The main stages for inspections are to detect the distress if any, evaluate the causes for the damages, to estimate the range of the defect and plan correct rehabilitation method for strengthening the structure. Many of the defects on tunnel linings are hidden beyond the surface. Water leakages, concrete cracking, concrete spalling, concrete delamination, debonding, steel corrosion, and improper drainage are tunnel structural problems considered common and potentially serious (Wimsatt et al. 2013). Monitoring rail tunnel condition and deterioration is important and key in determining the right schedule of maintenance and rehabilitation.

5.3. NDT Inspection Methods

Tunnel inspection is challenging. Inspections must be carefully planned in order to keep tunnels open during inspection or to minimize tunnel closures. Visual inspection is a typically used method, but by itself it is difficult to accurately and objectively analyse the condition of tunnel linings. Non-destructive testing methods like ground penetrating radar (GPR), laser scanner, and thermal imaging are methods for quickly evaluating rail tunnel linings on mobile platform. Other common, but stationary methods for NDT tunnel lining measurements are ultrasonic tomography, ultrasonic echo, ultrasonic surface wave analysis, and impact echo methods (Wimsatt et al. 2013).

The aforementioned technologies have been tested and used in several tunnel projects but presently they are not utilized to their fullest potential. (Wimsatt et al. 2013, Chen et al. 2015, White et al 2014, Yenwen et al. 2016). Properties of selected NDT measurement technologies for road tunnel lining measurements are presented by Wimsatt et al. (2013), RILEM State-of the Art Report (2012) and Scullion et al. (2014) and shown in Table 1. Similar methods can be applied to railway tunnels. However non-destructive testing methods like ground penetrating radar (GPR) and thermal imaging were chosen to be used in Assets4Rail project because they are methods for quickly evaluating rail tunnel linings on mobile platform compared to other non-destructive testing methods presented in Table 1. Laser scanning is used as a supporting technology for location of measurement data, detecting surface properties and for presenting results in point clouds. Figure 1 presents an illustrated example of measurement equipment in a point cloud tunnel environment.

Table 1. Properties of different NDT methods for tunnel wall lining measurements utilized in this project. (Modified from Wimsatt et al. (2013), State-of the Art Report of Rilem Technical Committee 207-INR and Scullion et al. (2014).

Method	Accuracy	Detection depth	Deterioration mechanisms detected	Tunnel lining type	Other info
Air-coupled GPR	Locates defects within 30 cm of its actual location	Does not measure depth but indicates areas of high moisture or low density (high air voids). Such areas may represent problems within or behind the tunnel lining.	Tile debonding, delamination, air-filled voids, water-filled voids, moisture intrusion	Concrete, tile lined concrete, and shotcrete	Scanning tool that can indicate where to conduct testing with in-depth devices.
Ground-coupled GPR	Can determine defect depth within 10% of the actual depth without reference cores 5% if cores are available.	Can possibly detect defects at any depth within or immediately behind tunnel linings. However, specimen testing indicates it cannot locate <0.3m2 voids in steel plates behind tunnel linings.	Delamination air-filled void water-filled voids, moisture intrusion	Concrete, tile lined concrete, and shotcrete	Experienced personnel are needed to interpret defect locations and depths from the GPR profiles.
Thermography / thermal imaging	Locates defects within 30 cm of its actual location	Does not measure depth, but indicates areas of high moisture or low density (high air voids). Such areas may represent problems within or behind the tunnel lining.	Tile debonding, delamination, air-filled voids, water-filled voids, moisture intrusion	Concrete, tile lined concrete, and shotcrete	Scanning tool that can indicate where to conduct testing with in-depth devices.

Ultrasonic tomography	In concrete can detect voids within 1-2 cm, shallow delaminations within 2 cm. In shotcrete can detect air-filled voids within 2 cm.	Can detect defects up to 20 cm deep according to specimen tests. Tunnel tests indicate it can detect possible defects up to 0.5 meters deep.	void detection, delamination, micro-cracking	concrete, tile lined concrete and shotcrete	Experienced personnel needed; many bias factors exist. Cannot see defects that are 5 cm or less from the lining surface. Measurement speed is low.
Ultrasonic echo	Comparable to the ultrasonic tomography. Can measure tunnel lining thickness within 3% of the actual thickness.	Comparable to the ultrasonic tomography method.	delaminations and voids	concrete and shotcrete	May not be effective for measuring defects that are 5 cm or less from the lining surface. It may not be accurate enough for measuring defect depths in shotcrete. Measurement speed is low.
Ultrasonic surface wave analysis	About 15% of the actual depth for defects up to 15 cm deep	Up to 15 cm deep	delamination and voids	concrete, tile lined concrete and shotcrete	The accuracy of thickness estimate is not as reliable as provided with other methods. The surface conditions may adversely affect the results. Results collected from tunnels with cast iron liners may not accurately characterize the properties of the substrata. Measurement speed is low.
Impact Echo	10% for deep delaminations greater than 15 cm deep.	Thickness measurement from 10 cm to about 1 m. The minimum depth at which discontinuity can be detected is assumed to be equal to half the minimum input wavelength.	voids, honeycombing, delamination, debonding areas, grouting defects	concrete, tile lined concrete and shotcrete	Experienced personnel are needed to interpret defect locations. Essential to ensure that the impact frequency is sufficiently high to identify existing defects. Measurement speed is low.

Figure 1. 3D GPR and thermal camera survey illustration in point cloud model from 2D laser scanner.

6. Ground Penetrating Radar Technique

6.1. General

Ground penetrating radar (GPR) is widely used in railway maintenance planning for structural condition monitoring, structure thickness assessment, and root cause identification of subsurface defects at both project and network levels (Silvast et al., 2012, Silvast et al., 2013). Some benefits that GPR provides are as follows: determining railway structures layer thickness, evaluating degree of ballast quality, calculating moisture condition in structures, and identifying subgrade soil types. Combined analysis with other datasets, such as track geometry and track stiffness, offers tools for determining root causes of defects (Silvast et al. 2013).

This study focuses on how GPR can be applied in railway tunnel wall investigations. Railway tunnel wall lining measurements differ from railway bottom structure surveys in that the GPR antenna needs to be positioned vertically towards the tunnel walls, which typically results in a slower measurement speed. Detection of anomalies beyond the wall surface such as moisture defects, air-voids, and delamination is examined through GPR signal analysis. The lining thickness itself may be interpreted from the GPR data and depending on the materials used, anomalies in bedrock can possibly be investigated. For example, steel fibres in a concrete lining cause interference in the GPR data, which can decrease the quality of the collected data.

This chapter describes principles of the GPR method, types of equipment typically used in railway and tunnel surveys, data collection, processing, and analysis methods.

6.2. GPR Principle

A GPR antenna consists of a transmitter and receiver and transmits an electromagnetic pulse of radio frequency into the medium. Typical GPR frequencies range between 100 MHz to 3 GHz. When the transmitted wave reaches an interface of different material properties, part of the energy is reflected while the remaining energy continues its passage beyond the interface. The radar system will measure the time elapsed between wave transmission from the transmitter and reflections back to the receiver as well as the reflection strength aka amplitude. Figure 2 illustrates how a pulse travels from the transmitter through the medium and to the receiver. This is repeated at specified intervals while the antenna moves along the measurement line and the output (scans) are displayed consecutively in order to produce a continuous profile of the changes in material properties (reflections) in the medium (**¡Error! No se encuentra el origen de la referencia.**).

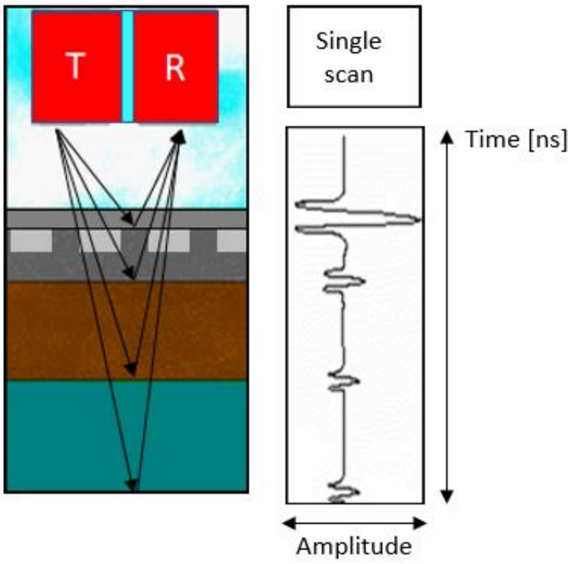

Figure 2. GPR principle. Electromagnetic wave is transmitted to the medium from the transmitter (T) and the receiver (R) records reflected signal travel time and amplitude.

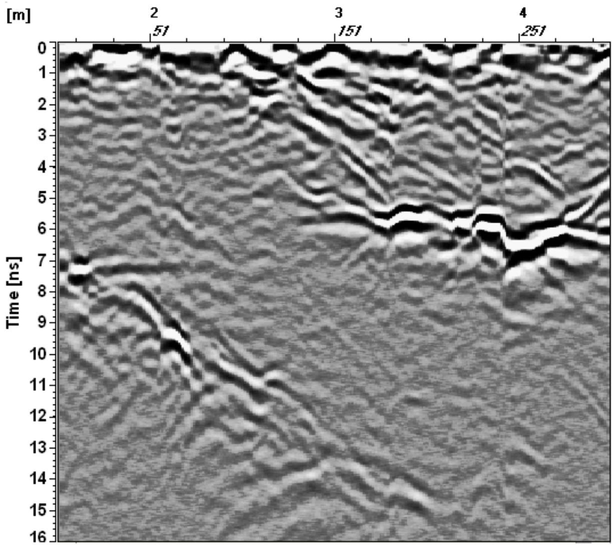

Figure 3. Example of longitudinal GPR profile from tunnel wall constructed from individual scans (Modified from Heikkinen et al. 2010).

The wave velocity and its reflection amplitude are affected by the dielectric permittivity, electrical conductivity (or resistivity) and magnetic susceptibility of the medium. In cases where the medium is a rock or mineral based material, properties vary according to rock type, presence of conductive minerals, presence of porosity or fracturing, and the alteration and mineralogy of fracture fillings.

The signal wavelength or antenna frequency affects the ability of the system to identify objects of different sizes. For example, high frequency antennas have a better resolution of smaller particle sizes, but a shallow penetration depth, while low frequency antennas have a coarser resolution, but penetrate deeper into the medium. The degree of saturation with water, the salinity of water, and variations in porosity or fracturing intensity will also affect the net propagation of radar waves The increase of water content in the medium will increase dielectric permittivity (and decrease wave velocity) as well as decrease resistivity (increase wave attenuation).

6.2.1. Basic Equations of GPR Theory

The electromagnetic pulse transmitted by GPR antenna travels in resistive material with the speed v, which depends on dielectric permittivity εr and magnetic susceptibility μr (~1) (Formula 2.1) (Ulriksen, 1982).

$$v = \frac{c}{\sqrt{\mu_r \varepsilon_r}} = \frac{c}{\sqrt{\varepsilon_r}} \qquad (2.1)$$

where v is propagation speed of the wave in medium [m/ns], c is speed of light in a vacuum (0.3 m/ns).

The depth of the interface can be calculated using formula 2.2 (Ulriksen, 1982).

$$s = \frac{vt}{2} = \frac{ct}{2\sqrt{\varepsilon_r}} \qquad (2.2)$$

where s is depth of the interface [m] and t is the two-way travel time of the signal [ns].

The dielectric value can be calculated using formula 2.3, when the travel time t, speed of light c and depth of the reflector s are known (Hänninen, 2000).

$$\varepsilon_r = \left(\frac{2ct}{s}\right)^2 \qquad (2.3)$$

The wavelength of the received signal is affected by the antenna central frequency and the dielectric permittivity of the material. The wavelength can be calculated using formula 2.4 (Hänninen, 1991).

$$\lambda = \frac{c}{f\sqrt{\varepsilon_r}} \tag{2.4}$$

where λ is wavelength of the signal [m] and f is central frequency of the GPR antenna [MHz].

6.2.2. Dielectric Values of Rock and Concrete

¡Error! No se encuentra el origen de la referencia. presents dielectric values of common rock types. Dielectric values of common rocks vary between 4.5-15. For example, the average value for granite is approximately 7. Table 3 presents typical values of dry and water saturated concrete.

Table 2. Dielectric values of different rock types. (Maijala, 1991).

Rock type	**Dielectric value** εr
Metamorfic rocks	
Amfibolite	7,9 - 8,9
Gneiss	8,0 - 15
Quartzite	4,3 - 7,0
Sediment rocks	
Dolomite	7,8 - 8,6
Quarz	4,7 - 5,1
Limestone	7,3 - 12,0
Plutonic rocks	
Granite	4,5 - 9,0
Diorite	5,9 - 11,5
Gabro	8,8 -13
Diabase	9,0 - 13

Table 3. Dielectric values of dry and water saturated concrete (Davis et al, 2013).

Material type	**Dielectric value** εr
dry concrete	6
saturated concrete	12

6.2.3.Limitations of GPR method

The GPR antennas are sensitive to electromagnetic radio noise especially on high frequency spectrums. Tunnel wall reflections, reflections from ventilation pipes and electricity installations, etc., are isolated noise sources, possibly causing anomalies in the data in a certain time window, having a certain frequency band or varying in frequency and time. These sources of noise have to be taken into consideration when processing and analysing data. (Saksa et al., 2005).

6.3. GPR Equipment

GPR systems use discrete pulses of radar energy. These systems typically have the following four components (Saarenketo & Scullion, 2000):

1) a pulse generator which generates a single pulse of a given frequency and power
2) a transmitter, which transmits the pulse into the medium to be measured
3) a receiver, which collects the reflected signals and amplifies the signal
4) a sampler which captures and stores the information from receiver antenna.

There are two main types of GPR systems: traditional time-domain pulse systems and SFCW (stepped-frequency continuous-wave) frequency-domain systems.

Figure 4 shows GPR method principles for stepped-frequency continuous wave and pulse radar systems. The frequency spectrum of the time-domain system is bell-shaped with the center frequency of antenna. In contrast, the stepped frequency-domain system transmits same power and time of each frequency step (e.g. 100-2000 MHz with 2 MHz steps) which produces a more regular frequency spectrum. The time-domain signal is then calculated from frequency information using the inverse Fourier-transformation. The antenna consists of antenna array of several (up to 63) transmitter-receiver dipoles.

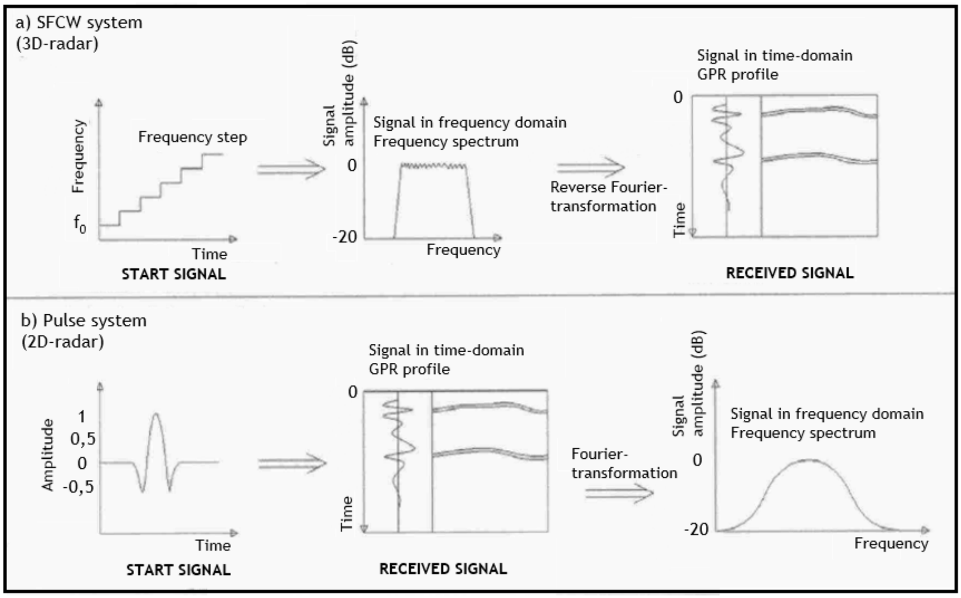

Figure 4. a) SFCW and b) pulse radar system principles (Modified from Passi, 2007).

Antennas are categorized to air-coupled horn antennas and ground-coupled dipole antennas (Figure 5). Ground-coupled antennas tend to use low frequencies while air-coupled are typically using higher frequencies in pulse radar systems. SFCW radars are exception and for example the 3D antenna used in this project uses a wide frequency range of 200 MHz to 3 GHz. One benefit of 3D systems is that they can measure simultaneously up to 41 horizontal profiles. This can be used to create 3D-models including information in both longitudinal and transversal directions. Compared to pulse radar systems, SFCW radars emit electromagnetic waves differently. This is illustrated in Figure 6. The benefits of ground-couple antennas are increased depth penetration and vertical resolution. Air-coupled antennas on the other hand, can be positioned further from measured surface, which allows higher survey speeds without risk of damaging the antenna.

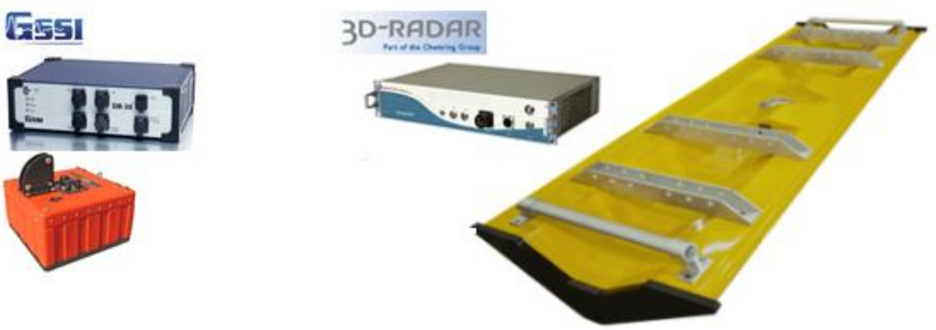

Figure 5. Example of 400MHz ground-coupled antenna (left) and 3D DX1821 air-coupled antenna (right).

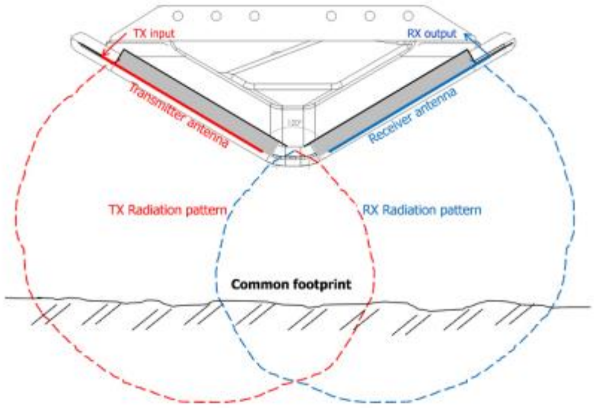

Figure 6. 3D-radar emission principle (picture from 3D-RADAR AS).

6.4. System Installation and Data Acquisition

GPR measurement are done with a mobile platform to maximize the amount of collected data and minimize the tunnel closure time. For tunnel wall lining measurements, a special vertical antenna setup is required. The ground penetrating radar used in this project is Geoscope MK IV + DX1821, which is 1.8-meter-wide 21-channel step-frequency radar. The manufacturer is 3D-radar AS from Norway. GPR antenna needs to be at about 0.5 meters from the wall lining surface when collecting data to avoid damaging the antenna. Distance between tunnel wall and rail is not constant, so distance between wall and antenna will not stay constant either which needs to be considered when handling and analysing the GPR data. In tunnel measurements, the survey speed in normal conditions can be up to 10 km/h depending on the sampling density of the data points. Figure 7 and **¡Error! No se encuentra el origen de la referencia.**8 show example configuration for tunnel lining measurements from both mobile and manual measurements.

Figure 7. Equipment are mounted to cherry picker (left), then antennas are lifted near tunnel wall (middle) while driving through survey line. Distance is measured with survey wheel (right).

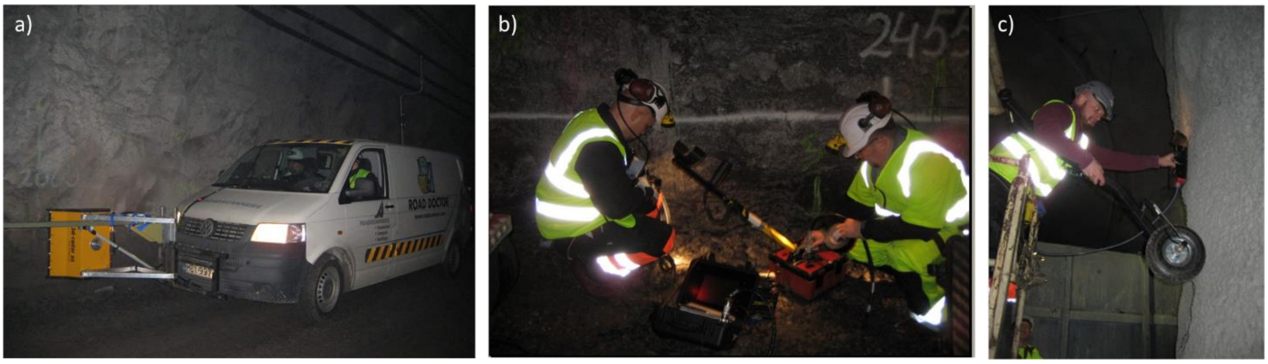

Figure 8. The different GPR survey systems on tunnel wall measurements: a) 3D-Radar Geoscope with 7-channel antenna, b) GSSI SIR-2000 with 400 MHz antenna and with c) 1500MHz antenna.

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6.5. GPR Data Processing and Visualization

In this project Rail Doctor software v. 3.4 will be used for data analysis. The software enables the user to simultaneously view, process, interpret and analyse multiple datasets that use the same co-ordinates, e.g. GPR data from different antennas, digital video, rock databases and other reference measurements. This kind of data combination allows the user to conduct an integrated analysis of all the available datasets on a single screen. Figure 10 presents a data view of the Rail Doctor software from railway tunnel measurement.

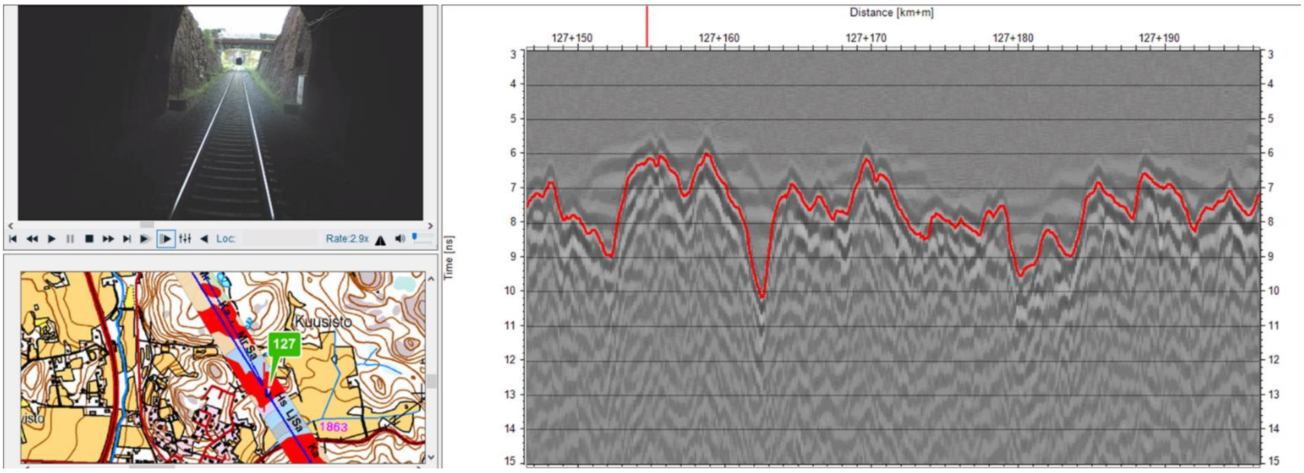

Figure 7. A data view from Rail Doctor software, showing a GPR profile with surface interpretation on the right side. The digital video and map is shown on left side.

6.6. GPR Analysis

GPR provides continuous information about the structure thickness along the measurement line. During interpretation, the drilling information can be used as reference data. GPR distribute information also on subsurface material quality and moisture condition. Special structures such as cables and drainage pipes as well as structural failures can be identified from the measurement data. When digital video, laser scanner and thermal data are used in the interpretation, other tunnel assets in the GPR data are easy to locate. GPR data analysis consists of structure layer interpretations and moisture condition analysis. Layer thickness and moisture analysis are shown in the following Figures 11 and 12.

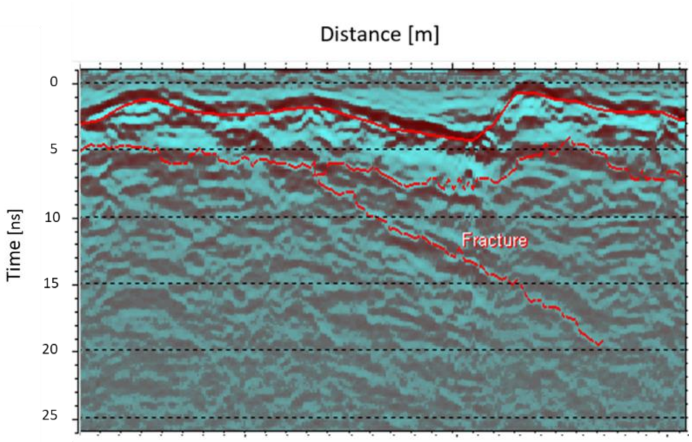

Figure 8. Interpreted layer interfaces in GPR profile.

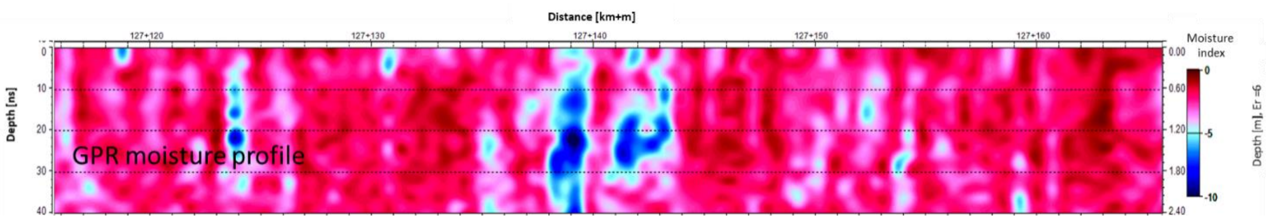

Figure 9. Example of GPR moisture analysis profile. Detected moisture anomalies shown as blue areas inside tunnel wall structure.

7. Thermal Camera

7.1. Basics

Thermal camera is an NDT device which acquires infrared radiation emitted by objects. The intensity of the infrared radiation emitted by objects is mainly a function of its temperature; the higher the temperature, the greater the intensity of the emitted infrared energy. The main use is to record surface temperature differences of objects, but it can also be used to make interpretations about moisture anomalies and such, only a few centimetres beyond surface. It does not measure depth, but can indicate tile debonding, delamination, air filled, water filled voids and moisture intrusion. Figure 13 shows a thermal camera which will be used in this project. While thermal cameras are not widely used in railway surveys, it does have some applications. Besides tunnel lining investigations, thermal cameras have been used in drainage analysis and during night surveys to replace digital cameras when light source is insufficient for camera lenses.

The goal for thermal imaging in this project is to test and demonstrate the method's suitability for tunnel lining investigations in detecting anomalies near lining surface. This chapter describes thermal camera technology's main principle, different usages in railways, data collection at field and processing and displaying of results.

Figure 13. FLIR Thermovision camera.

7.2. System Installation and Data Acquisition

This project will use FLIR A325 which operates in infrared wavelength range, 8-12 µm. The camera takes 60 images per second and can detect temperatures changes with 0,07 °C accuracy. Mounting is done on a train engine or cherry picker and is connected to the distance measuring unit (DMI). Figure shows thermal camera survey with Road Doctor Camlink software in tunnel. In addition to thermal camera, digital video and laser scanner can be connected to this software simultaneously.

Figure 14. Thermal surveys in Finnish tunnel 2018.

7.3. Thermal Camera Results

Temperature data is visually inspected to find defects and possible moisture anomalies from a tunnel lining surface up to a few centimetres' depth. The best results are achieved by combining and analysing thermal results with other inspection methods. Below are two examples of data where anomalies were detected in left side's tunnel wall (Figure). Anomalies are darker spots in the views.

This project has received funding from the Shift2Rail Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement no. 826250 Assets4Rail).

Often, temperature changes do not describe anomalies but rather special structures inside the tunnel. These should not be misinterpreted as defects.

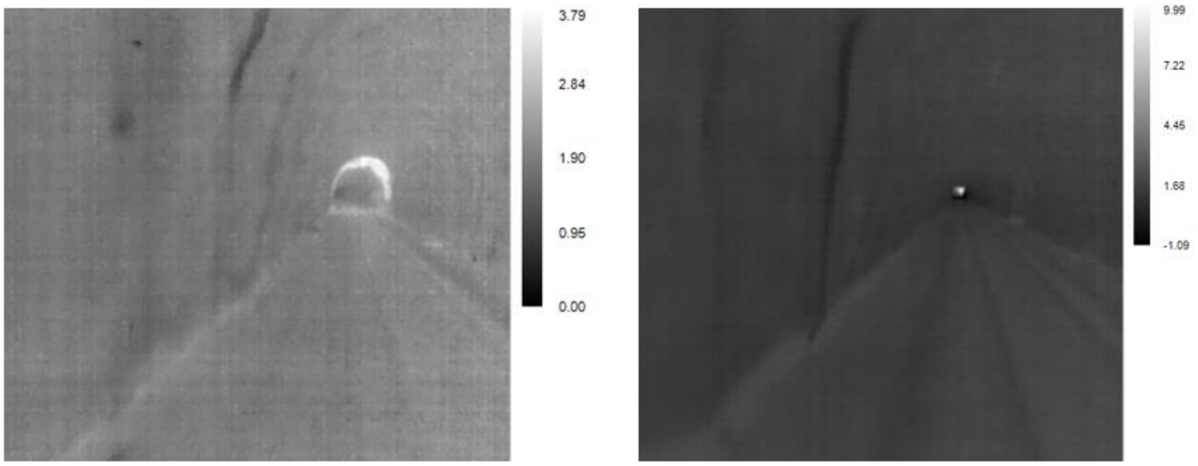

Figure 15. Darker areas indicate possible moisture anomalies.

Thermal data can be analysed in other ways as well. Images can be calculated and transformed to plain surface view as

Figure **10** demonstrates. This kind of transformation is especially practical when doing integrated analysis and it also allows temperature data to be projected in point clouds.

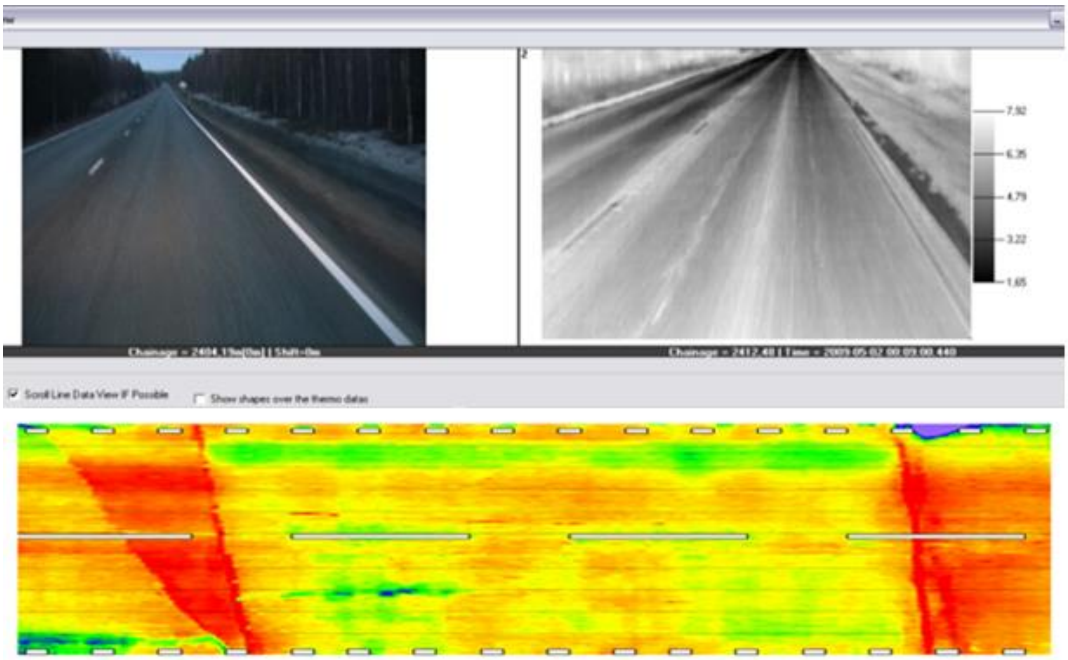

Figure 10. Example from road survey how thermal data can be calculated to surface image.

8. Laser Scanner

8.1. General

Laser scanner technology is a widely used technique in infrastructure condition monitoring projects. It serves also railway line and tunnel maintenance planning. It is not a subsurface detection technique like GPR and Thermal Camera but is used for to calculate various parameters and to create environmental point cloud models for survey area surfaces. The goal of this project with respect to laser scanner surveys is to demonstrate its suitability to locate assets and to create point cloud models where results of the GPR and thermal camera surveys can be integrated. This report will also describe how laser scanner, also known as LIDAR (Light Detection and Ranging) could further be used to benefit tunnel owners.

This section describes laser scanner technology's main principle, equipment, different usages in railways and how data collection is done. Data processing tools and different output possibilities for LIDAR results are presented in the following sub-sections.

8.2. Laser Scanner Principle

Laser scanner consists of three parts, namely a laser canon that generates the laser beam, a scanner that circulates the beam and a receiver that measures the reflected signal. It is a non-contact distance measurement device which measures the surroundings in relation to the measurement point. The scanner itself is the origin or the zero point in distance which emits a laser beam that hits the non-cooperative target and bounces back. Once the re-bound signal is detected by the receiver, it calculates the time of flight (TOF) and divides it by a factor of two which gives the distance in meters from the target. TOF measurement is based on the speed of electromagnetic radiation, which is a constant.

Since vertical and horizontal angles of each generated laser beam as well as the distance to each measured point are known, coordinates for every measured point can be calculated. Based on the strength of the return signal, the system also records intensity values of each point.

As laser scanner technologies have developed fast in recent years, both at hardware and software level, processing software has incorporated point cloud model capabilities. Moreover, point clouds have become a very popular way of displaying laser data (see Figure 7).

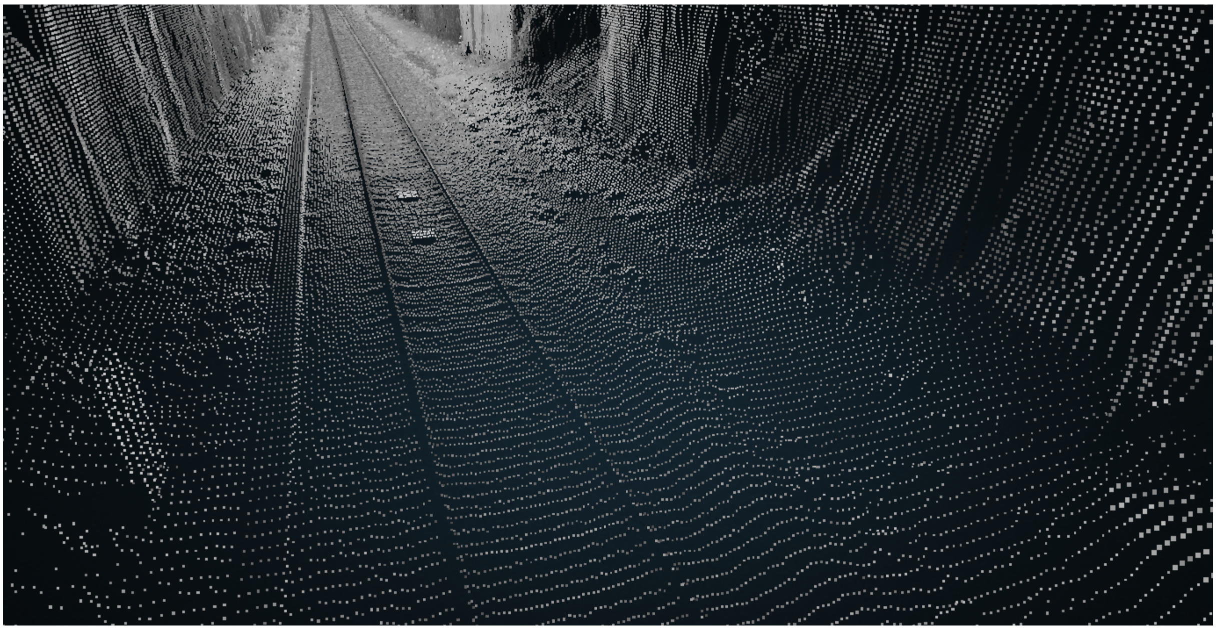

Figure 17. Point cloud from start of tunnel with 2D Lidar LMS511.

8.3. System Installation and Data Acquisition

In this project, mobile laser scanner LMS151/LMS511 will be used to measure the tunnel profile. **Figure** 8 shows a mounting system used in a railway tunnel roof project where scanner was pointed upwards. In Figure 19 scanner is pointed downwards. Downwards mounting is typical for railway line surveys.

Figure 18. Laser scanner configured upwards for tunnel roof measurement.

Figure 119. Typical railway line survey has laser scanner mounted high and pointed downwards.

For this project it is decided to setup double laser scanner system where one laser is pointed up while the other one is pointed down (Figure). This will enable a full 360-degree point cloud model, with all angles covered. Afterwards, data will be processed and combined in Rail Doctor software. Figure 21 presents the 3D model made using the previously explained configuration.

Figure 20. LMS511 double mounting system for 360-degree point cloud models.

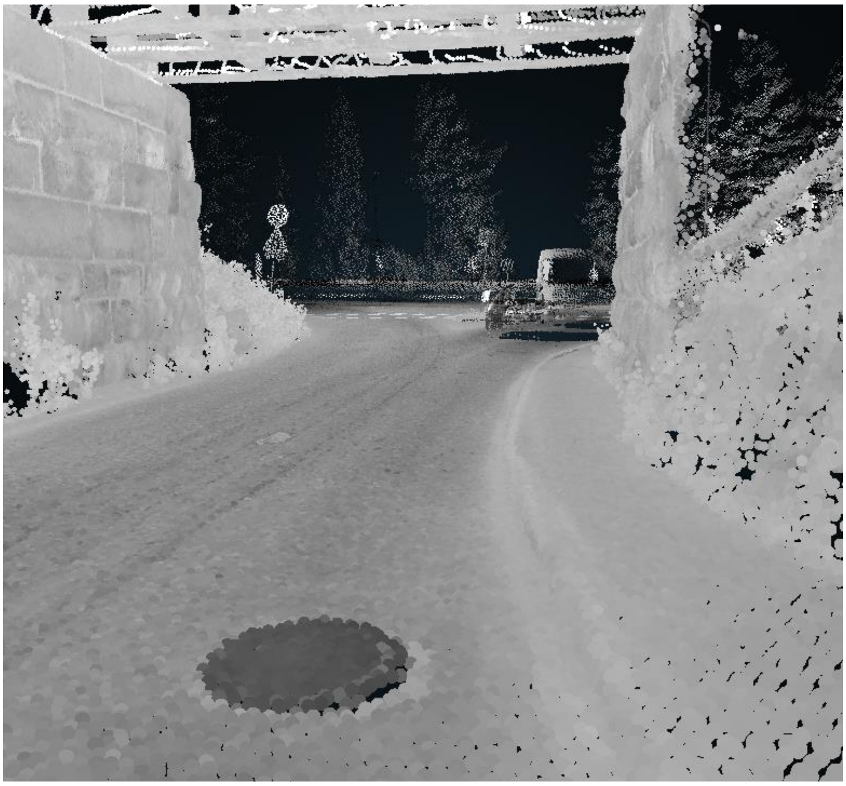

Figure 21. 360-degree point cloud video from double laser scanner setup by Roadscanners Oy's Road division.

8.4. Laser Scanner Results

Laser scanner data is constructed of numeric values describing location of reflections (xyz) and their remission (reflectivity) information. Laser scanner data can be visualized in different output formats as seen in **¡Error! No se encuentra el origen de la referencia.**22 a-d.

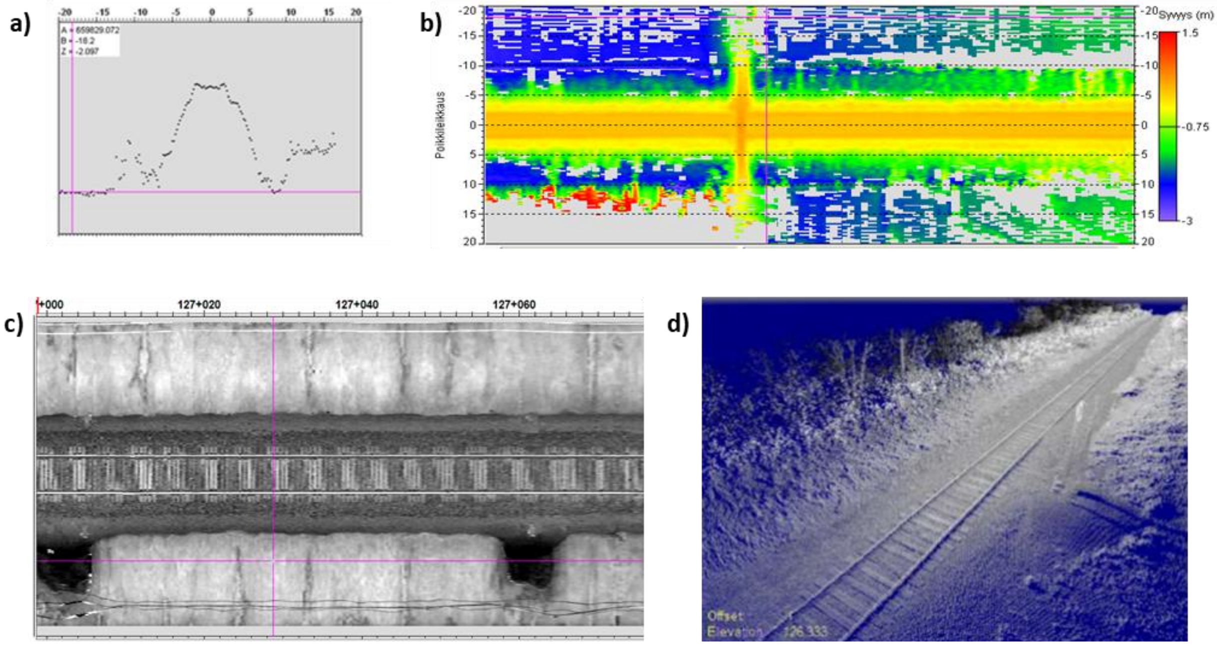

Figure 22. Examples of different laser scanner data presentation formats: a) cross-section view, b) height plan view, c) remission plan view and point-cloud view.

Sequential laser scanner survey results can also be compared with each other to detect and monitor changes in areas of interest. Comparison analysis can be done with high accuracy and visualized in point cloud. Figure 3 shows laser data comparison in point cloud. Red area shows expanded section in wall, meaning that tunnel lining has moved closer to rails due to frost action behind the lining. The method makes possible to identify areas under excessive stress which are subject to cracking and where other forms of defects are more likely to start forming. For monitoring changes, at least two surveys of the same section need to be done at different times or seasons.

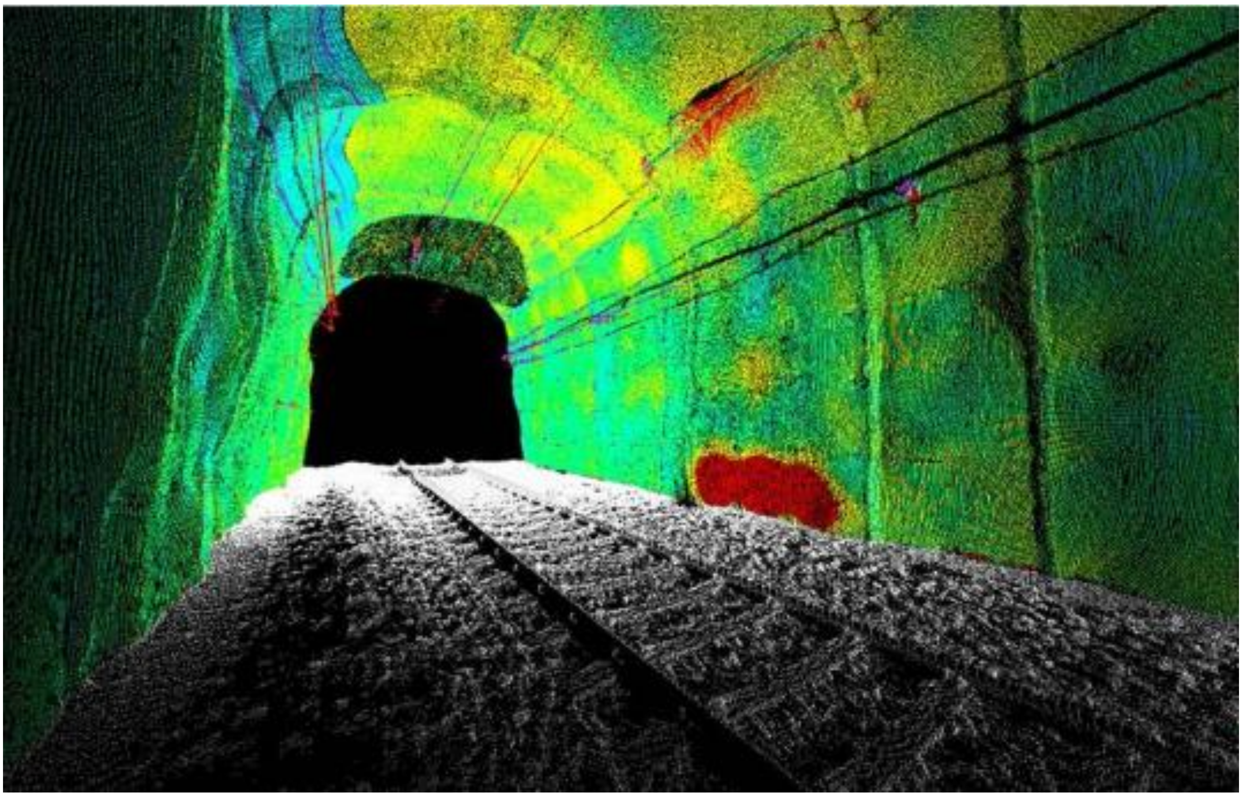

Figure 23. Comparing temporal changes between two laser measurements. Deviations are marked as red areas. (Cronvall 2014).

9. Integrated Results

This chapter will be added during the project get actual measurement results.

10. Conclusions

Goals of this research are to select tunnel lining survey techniques with a focus on subsurface defect detection, validate them, present software solutions for analysis, and produce a deliverable to share knowledge of the results. Selected methods are ground penetrating radar (GPR), laser scanner, and thermal camera. GPR and thermal imaging methods have been researched as separate techniques for subsurface defect detection purposes in tunnel environments, but this project will focus on the integration of the measurement results. Lidar technology was chosen for visualization of results in point cloud and to produce information of the lining surface. These techniques have several desirable features. First, surveys for long or multiple tunnels can be done fast, keeping traffic disruptions caused by inspection work minimal. Second, they are cost-effective and commercially available. Third, the methods provide comprehensive and repeatable results for tunnel monitoring and therefore assist in maintenance planning.

Conclusions will be supplemented after actual measurement results.

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12. Appendices