The 6th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
Hong Kong | 9-11 December 2013

MOBILE INSPECTION SYSTEM FOR HIGH-RESOLUTION ASSESSMENT OF TUNNELS

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ABSTRACT

This paper presents a novel system for tunnel lining inspection, *Tunnelings*, which allows for high-resolution surveys at speeds up to 30km/h. This rapid tunnel condition assessment capability makes it possible to perform long tunnel inspections on a regular basis, and to assist geotechnical engineering and tunnel management, allowing for preventive and operational maintenance of large infrastructures. *Tunnelings* uses several laser-cameras units and acquires intensity images and 3D profiles with an accuracy depth of 0.5mm and a longitudinal and transverse resolution of 1 mm. The laser-cameras units can be installed on a bimodal (road-rail) all-terrain truck which provides rapid travel speeds and flexibility to cope with different types of tunnels and infrastructures. Moreover, they can also be installed on other kinds of vehicles, as well as in a standard railway wagon. A computer vision-based software helps with the evaluation of the tunnel condition, allowing for the detection of cracks and areas with missing lining or chipping, dampness and running water, areas with poorly assembled segments, protruding edges and poor workmanship, as well as the assessment of tunnel installations. The provided accurate 3D information allows for relative displacements between assembled segments (in both longitudinal and transverse direction) and deformations to be located and assessed. A comparison of several inspections over the same tunnel can be quickly carried out. Structural changes as well as the evolution of lining defects can also be assessed. This paper presents a comprehensive description of *Tunnelings*, comprising the used sensors as well as their assembly and synchronization. Several examples of damages and defects are also presented, identifying the underlying pathologies for the diagnosis of the tunnel condition. Two distinct examples of system operation are provided, a long Spanish tunnel and an old Japanese one, with different assembly and operational requirements.

KEYWORDS

Tunnel inspection; lining evaluation; defects detection; pathologies identification; sensor assembly

INTRODUCTION

Tunnelings is a high-performance inspection system that enables to carry out tunnel evaluations, by analyzing wall linings and railways with a 1mm resolution at survey speeds up to 30km/h.

Tunnelings is a solution that has been developed to assist Geotechnical engineering, tunnel project management and to turn the maintenance of tunnels operational. Both acquisition and analysis are aimed at providing solutions to the vast underground infrastructure industry, in particular the maintenance and monitoring of such infrastructure throughout its service life.

The system enables the systematic inspection of tunnels, making it possible to compare the evolution of any damages found in the linings, as well as any geometric variations (convergences, segment displacements, etcetera) on the section.

SYSTEM DESCRIPTION

Tunnelings is based on the use of high-speed cameras, custom optics and laser line projectors to acquire both 2D images and high-resolution 3D profiles of the surveyed tunnel. It can be operated under all types of lighting conditions, providing high-quality data in both illuminated and shaded areas.

The system enables to acquire both 3D and 2D images data with a 1mm resolution over 12m long arc tunnel sections at survey speeds up to 30km/h. This rapid tunnel condition assessment ability makes it possible to perform long tunnel inspections more frequently on a regular basis.
The acquired high-resolution images lighted up by laser emitters enable the analysis automation for flaws detection, so that for instance, cracks, damages, and moisture can be detected and analyzed.

The provision of 3D information facilitates the evaluation when the damage is found in the tunnel's surface, and enables relative displacements between assembled segments, in both longitudinal and transverse direction, as well as deformations to be located and assessed.

The system allows for the inspection of 12m long arc sections at survey speeds up to 30km, with a depth accuracy of 0.5mm, a longitudinal resolution of 1mm and a transverse resolution of 1mm.
It also performs a rapid tunnel condition assessment. The entire perimeter of the tunnels can be covered in two runs, giving way to an effective 15km/h survey speed, and to carry out a comparison of several inspections over the same tunnel.

On the other hand, its computer vision-based software for the automatic evaluation of tunnel condition offers the following advantages:

- Tunnel linings: detection of cracks and areas with missing or chipping lining, dampness and running water, areas with poorly assembled segments, protruding edges and poor workmanship, as well as tunnel installation assessment.
- Railway evaluation: includes the assessment of the transverse section by means of 3D geometry and rail flaws detection such as: lack of fixing elements, corrosion, cracks on sleepers or on slab tracks.
- Structure evaluation: 3D reconstruction and clearance analysis.

In addition of the above mentioned it can operate under all types of lighting conditions, it is immune to shadows, has low power consumption and includes data compression algorithms to minimize storage.

Principles of the Inspection System

Tunnelings extracts 3D information using the principle of triangulation. A pattern of known lighting, a line in this case, is projected from the laser into the object to be inspected. The line is recorded by a digital camera positioned away at a fixed distance, at an oblique angle relative to the projected light. The intersection between the pattern of emitted light and the field of view of the digital camera defines the range of operation of the 3D sensor. The positions of the lighted points on the surface of the object are displayed in the image obtained by the camera and the distance between these points and the camera can be calculated by means of trigonometry. This technique enables high-quality digital images and superimposed 3D information to be obtained in a single capture, as it can be seen in Figure 1.

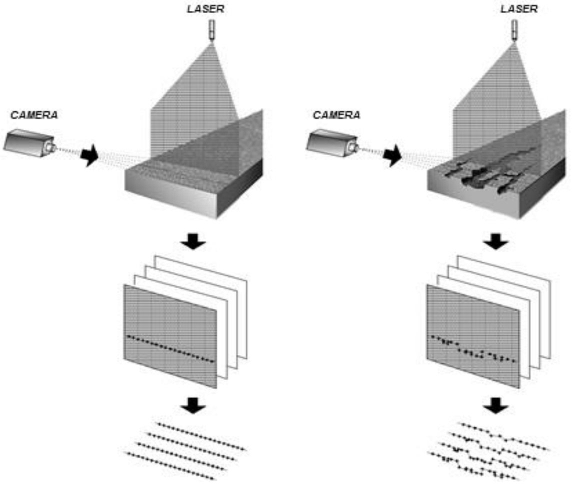

Figure 1. Triangulation measurement principle for high-speed acquisition of 3D information.

SENSORS ASSEMBLY

The laser-cameras units used for the survey can be for example installed on a bimodal (road-rail) all-terrain truck which provides rapid travel speeds and flexibility to cope with different types of tunnels and infrastructures. They can also be installed on other kinds of vehicles or in a standard railway wagon. Figure 2 shows both examples.

Figure 2. Examples of vehicles used for the tunnel inspection task.

The structure that carries the laser cameras used for the inspection is fitted on the truck or wagon bed and a mechanical system is used to position its arms so that the system constantly matches the geometry of the tunnel, as Figure 3 shows.

Figure 3. Mechanical installation of an inspection arm holding six sensors.

With the most comprehensive configuration the vehicle can normally hold up to six laser cameras. Each laser camera unit carries out the inspection using the most common setting –a 2m wide section with an accuracy of 1mm. By using the six cameras, 9m diameter tunnels can be inspected at the system’s maximum resolution of 1mm, scanning an arc of 12m which is equivalent to virtually half the perimeter of the tunnel (sidewall and keystone). The entire perimeter of the tunnel can be covered in two runs, one on each side.
Moreover, a high-resolution odometer (20,000 pulses per revolution, approximately 0.1mm.) is also installed in it (see Figure 4), as well as a monitoring and control system, composed of an industrial computer for the sensors’ synchronization and a monitor for control and monitoring tasks.

Figure 4. High-resolution odometer installed on the wagon’s wheel.

The cameras position can be modified for the inspection of the railway, as it can be seen in Figure 5 below.

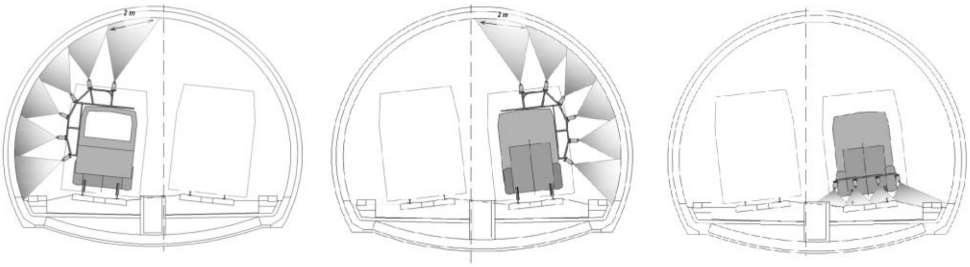

Figure 5. Diagram of the cameras' installation for wall and railway inspection

Apart from the information described above, the system also includes a panoramic image of the complete scene. Figure 6 shows the position of the camera on the structure and a panoramic image of a tunnel being monitored. The image is synchronized with the odometer's measurements.

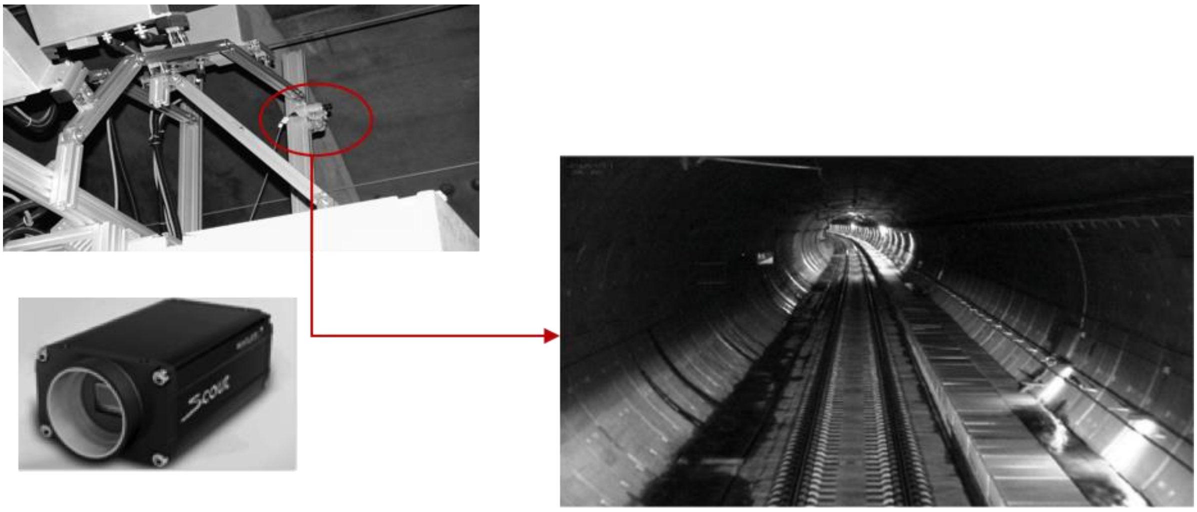

Figure 6. High-resolution panoramic images taken from a camera positioned on top of the vehicle and looking forward. This camera is synchronized with the data collection from the laser sensors.

Tunnelings Recorder performs control and synchronization tasks. An industrial computer is used to ensure the synchronization of the six laser-camera units and the panoramic camera. The acquisition spacing can be set by the system operator to obtain the most convenient trade-off between speed and resolution. The signal received from the odometer is used to trigger all the sensors at the precise same instance.

SENSORS

As Figure 8 shows, the sensors used are laser cameras from the manufacturer *Pavemetrics Systems Inc*. composed of a laser line projector and a digital scanning camera, which are monitored by a control unit. The following are the main features of the cameras:

- Depth accuracy: 0.5mm.
- Sampling rate: at least 2,800 profiles/second
- Longitudinal resolution (profile spacing): usually 1mm (adjustable)
- Transverse resolution: 2,048 points/profile. The suggested trade-off between transverse accuracy and transverse field of view is 1mm – 2m.

Each pair of cameras is controlled by a control electronics device to ensure the synchronized acquisition of a pair of laser cameras.

Figure 7. LCMS cameras and control electronics devices.

RESULTS PROVIDED BY THE SENSORS

The data provided by *Tunnelings* comprises 3D images which contain information in a radial direction relative to the direction of the condition's survey, and 2D images with greyscale intensity information. Figure 9 shows a 2D image, a profile and a 3D image.
Examples of the type of result obtained by using the system for tunnel inspections are shown below:

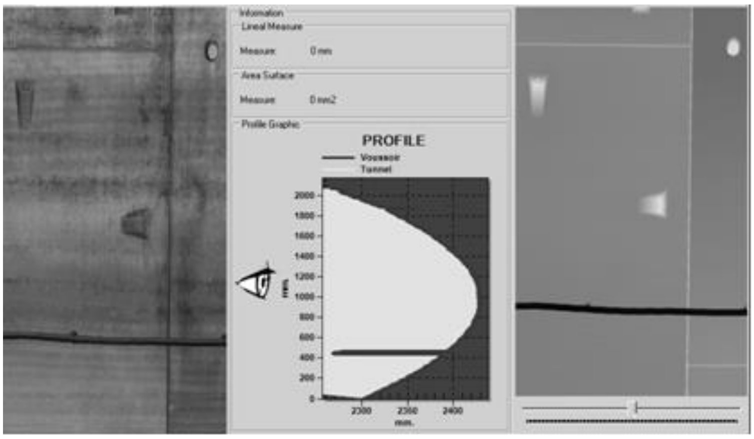

Figure 8. Transverse sections of the lining (in the case of assembled segments image) obtained from the 3D data information available. The middle one is the profile, right one is 2D and left one is 3D.

High-quality digital images and a 3D reconstruction of the inspected area can be obtained from the captured data, as the following Figure 10 clearly shows.

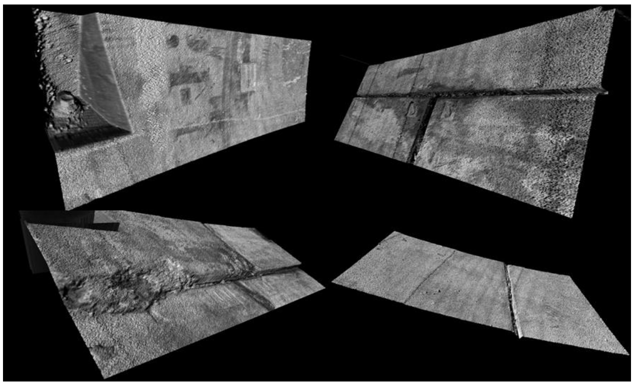

Figure 9. 3D reconstruction.

DEFECTS ANALYSIS AND GEOMETRIC MONITORING

For the automatic analysis of lining damages a software application has been developed which detects any given defects as well as a geometry evaluation of the tunnel lining.

Lining Evaluation

A comprehensive set of defects can be automatically detected and evaluated. Most common defects in tunnels are shown as examples in this section, but an extensive number of options are available for detecting other defects or measuring different tunnel condition indicators.
The Figures 10 and 11 shows examples of the most common defects in a lining segment tunnel.

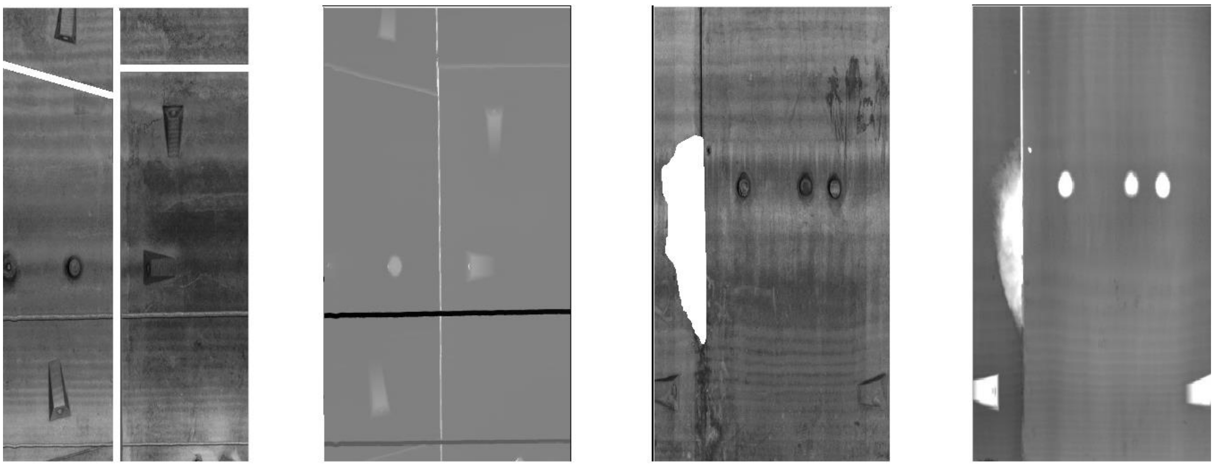

Figure 10. Common defects (I). The first two pictures show joints between assembled segments and the second two show surface chipping.

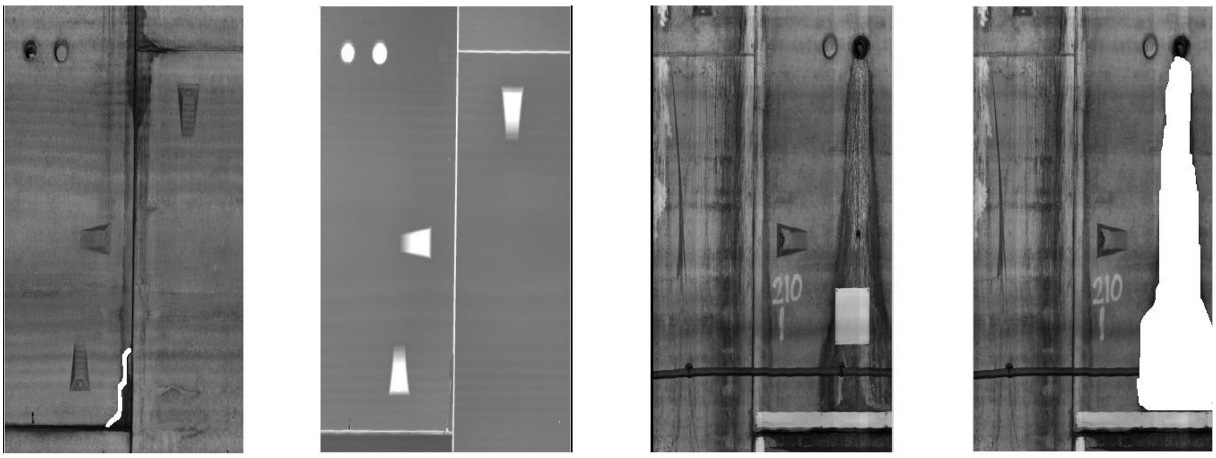

Figure 11. Common defects (II).The first two pictures show fissures and cracks and the second two show dampness.

The system also performs measurement of different tunnel condition indicators such as computing the measurement of joints opening and the gap or offset between assembled segments, allowing for the detection of protruding edges, as the following Figure 12 shows.

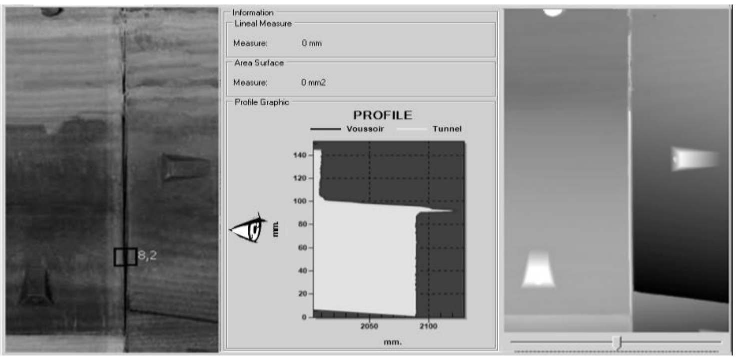

Figure 12. High gap (> 50mm) between dislocated and uplifted segments.

In addition to this, figure 13 below shows the tunnel installations assessment

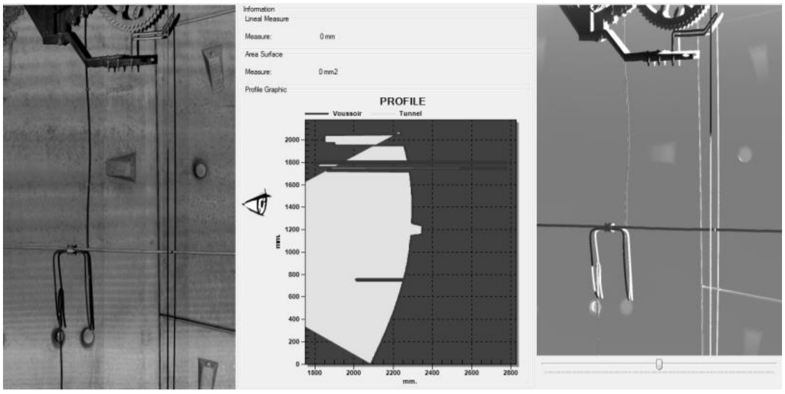

Figure 13. Tunnel Installation Assessment.

Clearance analysis

The high-accuracy profile recordings of the tunnel enable to review the overhead clearance and to check the structure gauge of railway tunnels. Free space dimensions are computed and critical areas can be highlighted for user awareness and evaluation.

Convergence analysis

Tunnel converge monitoring provides important information about tunnel behavior and helps anticipate tunnel deformations. *Tunnelings* software provides tools for comparing several surveys along the tunnel life and performing an accurate convergence analysis. Figure 14 shows an animated 3D reconstruction of the tunnel lining.

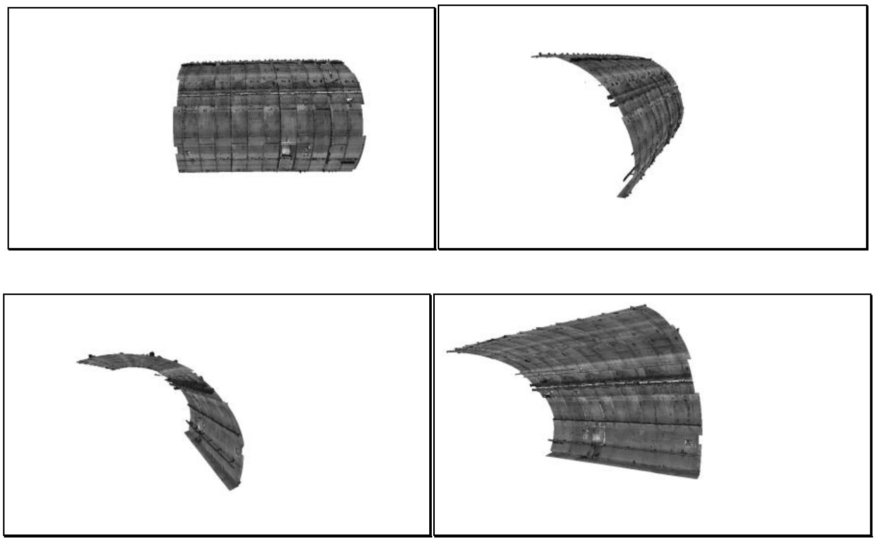

Figure 14. 3D Reconstruction of the tunnel linning.

RESULTS VIEWER SOFTWARE, STATISTICAL ANALYSIS AND REPORT TOOLS

Together with the aforementioned acquisition and synchronization software, different software packages have also been developed to provide a complete solution for the tunnel inspection task:

Data Display Software

This software application comprises tools and utilities to combine images along both longitudinal and transverse ways, and display in a superimposed manner tunnel sections together with any different defects or information of interest regarding the analyzed section.

The following Figure 15 shows one of the halves of a 100m long tunnel section. The bottom image depicts the upwelling areas within the section.

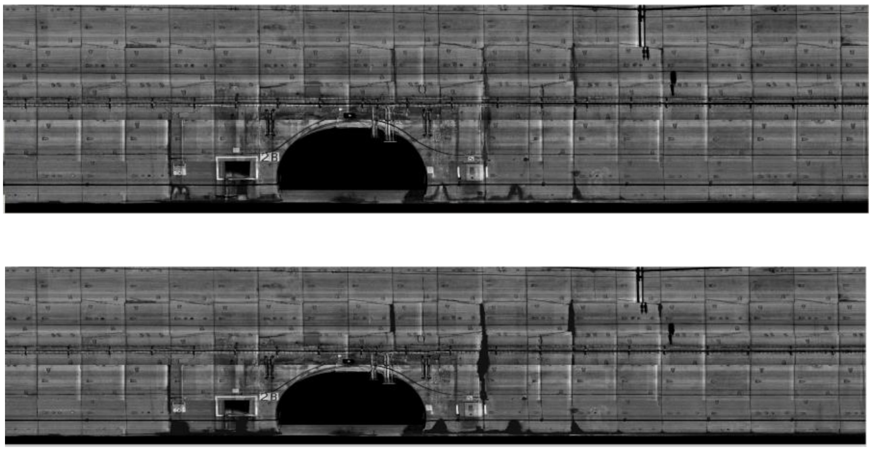

Figure 15. Image showing half of a tunnel with highlighted upwelling areas.

All the analysis data are stored in databases which can be quickly referred to by means of relative coordinates, kilometer point or user-defined reference points.

Expert Annotation and Marking Tools

The application also provides tools for the manual marking of defects as well as expert annotations. It also enables the engineer in charge of the inspection to automatically check or verify the previously analyzed defects.

Tunnelings Stats provides an easy-to-use tool aimed at performing statistical analysis and generating tunnel assessment reports. Statistics can be extracted and displayed for the inspected tunnel as a whole or in individual sections, which can be subsequently used to draw conclusions about the overall condition of the tunnel. Results can be shown through graphs or reports. The results presentation can be set by the user. Two inspections carried out on different days can be displayed and compared as captured images or analyzed results. The provided information can be used for the management and planning of repairing actions for the observed defects.

The following Figure 16 shows an example with a summary of several statistics in the entire cross-section along the tunnel with distance related to the site's kilometric point references.

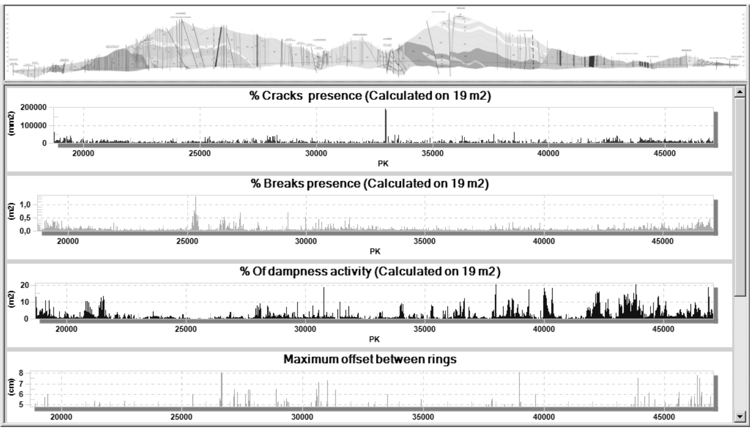

Figure 16. Statistics graph.

CASE STUDIES

The system has been applied to different types of tunnels: segment or slabs TBM tunnels, mass concrete tunnels, cut and cover precast tunnels, diaphragm walls, sprayed-concrete tunnels, etcetera.
The most significant examples of tunnels in which *Tunnelings* has been employed are the following:

Guadarrama Tunnel (Spain)

The Guadarrama Tunnel is a TBM railway tunnel across the Sierra de Guadarrama, along the high-speed railway Madrid–Valladolid in Spain.
The tunnel has two tubes with a circular inner diameter of 8.50m. The western tube is 28,407m long and the eastern tube is 28,418m long. It is the longest tunnel in Spain and the sixth longest in the world.
The Guadarrama Tunnel was inspected at night with a resolution of 1mm measurement. The results from the different inspections are compared on a regular basis in order to ensure its appropriate service condition.

Tokyo Metro (Japan)

A section from the Ginza Line in Tokyo was inspected with the *Tunnelings*. This line is the first underground railway in the OrientProject. It is an old tunnel composed of vertical diaphragm walls with a square section. This is an example of an old mass concrete tunnel that has undergone a large number of restorations and repairs, about which *Tunnelings* was able to provide detailed data from the lining as well as from the rail on plate.

In addition to the above two, other mass concrete and cut and cover tunnels have been monitored for the Spanish High-Speed Railway Administration and Madrid Underground.

OTHER APPLICATIONS AND CONCLUSIONS

Railway Evaluation

Tunnelings also offers an automatic railway evaluation. This module, which is aimed at the inspection of the track's slabs, provides an assessment of the transverse section by means of 3D geometry analysis and rail flaws detection such as: lack of fixing elements, corrosion, cracks on sleepers or on slab tracks. Figure 17 shows a representative example of one of the many railway evaluation options, such as rail corrosion.

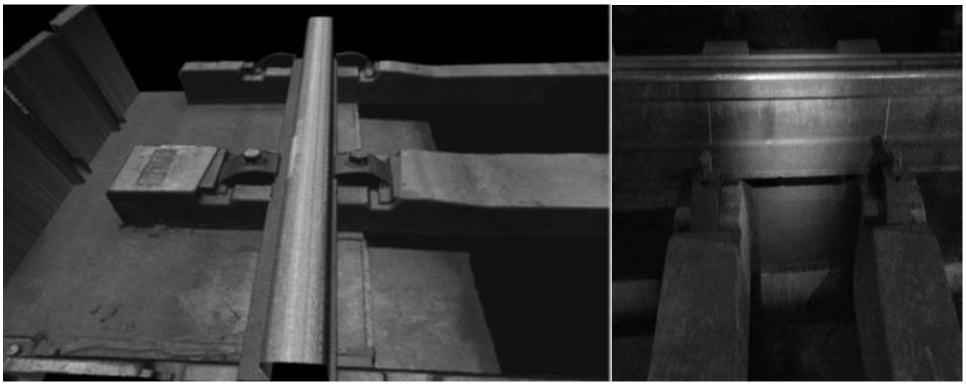

Figure 17. Rail corrosion example.

Tunnelings is a high-performance inspection system that enables to carry out tunnel evaluations, by analyzing wall linings and railways with a 1mm resolution at survey speeds up to 30km/h.

The system enables the systematic survey of tunnels, and makes it possible to compare the evolution of any damages found in the lining, and the geometric variations (convergences, segment displacement, etcetera) on the section.

Having a high-performance tunnel inspection system such as *Tunnelings* represents a tool that enables to perform a detailed structural monitoring of the behavior of great-length tunnels or tunnel networks in which the inspection times are very reduced. Moreover, the detection and damages analysis automation through algorithms makes it possible for the condition analysis and tunnel behavior to be objective, thus alarm thresholds with respect to the service condition can be established.