Use of 3D Scanning Technology for Automated Inspection of Tunnels

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ABSTRACT
Significant advances in high-speed 3D imaging technology have been made in the last decade and there are now commercial, off-the-shelf, solutions for automatically evaluating infrastructure condition at high-speed. One such device is the Laser Tunnel Scanning System developed by Pavemetrics; a "spin-off" of the National Optics Institute of Canada.

The LTSS system utilizes high-speed cameras, custom optics and laser line projectors to acquire both 2D images, and high resolution 3D profiles, of infrastructure surfaces at speeds up to 100 km/h. 3D scanners of this sort offer numerous advantages to traditional manual inspection methods including:

- Improved staff safety
- Day or night-time operation
- Reduced inspection time
- Improved accuracy and reliability of results
- A permanent visual record of the condition of 100% of the tunnel surface

Importantly, this technology can be deployed to manage multiple types of assets across different modes of transportation such as:

- Roads and Highways
- Airport Taxiways, Runways and Aprons
- Tunnels
- Rail Systems

As the same technology is deployed across different modes there is a growing opportunity for "cross-pollination" of ideas and approaches for infrastructure assessment. This sharing of information can help solve problems in one domain through the adoption of solutions from another domain.

This presentation will explore the application of 3D laser scanning technology to the activity of tunnel inspection. The discussion will include a discussion of the practical achievable levels of data precision and accuracy obtained during testing the Guadarrama and Regajal rail tunnels in Spain.

1. INTRODUCTION

The Laser Tunnel Scanning System is a 3D laser-based infrastructure assessment solution that uses sensor technology that has been continuously developed over the last 10 years by Pavemetrics (a commercial "spin-off" of Canada's National Optics Institute)[1] in close collaboration with the Ministry of Transportation of Quebec and numerous Infrastructure Management Consultants and other Departments of Transportation around the world.

The LTSS consists of high-speed cameras, custom optics and laser line projectors to acquire both 2D images and high resolution 3D profiles of infrastructure surfaces at speeds up to 100 km/h[2 3]. A high-resolution optical encoder is used as an odometer to synchronize sensor acquisition as the inspection vehicle travels across the surface being inspected.

High resolution 2D and 3D data acquired by the LTSS can be processed using either semi-automated or automated tools from the safety and comfort of an office environment for a variety of purposes including:

- Tunnel lining inspection
    - Crack detection and quantification
    - Chip detection and quantification
    - Moisture detection and quantification
    - Poor panel alignment detection and quantification
    - Etc.
- Structural evaluation
    - 3D model construction
    - Clearance analysis
- Tunnel visualization and inspection documentation
    - The ability to perform a "virtual inspection" at any point along the length of the inspected tunnel from the comfort and safety of the office environment
    - A complete, high-resolution, record of the tunnel condition and state at the time of the last inspection to serve as a permanent record

This paper describes the function of this technology and its application to the inspection of tunnel infrastructure.

2. HARDWARE CONFIGURATION

The LTSS's 3D laser profilers use high power laser line projectors, custom filters and an integrated camera as the detector. In order to inspect a surface, lasers are projected onto the surface from each sensor and the integrated camera captures an image of the projected line (Figure 1 and Figure 2).

Figure 1 - LCMS/LFOD/LTSS Sensors and Controller

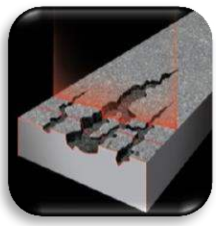

Figure 2 - Laser Profiling of Pavement

The LTSS operates on the principle of triangulation. In order to scan a tunnel surface, the LTSS projects a very precise, high-intensity, laser line which is in turn recorded by a digital camera. Laser lines are projected at high-frequencies (up to 11,200 Hz) in order to ensure maximum resolution of fine tunnel features.

The intersection between the projected laser line and the field of view of the digital camera defines the range of operation of the 3D sensor. Digital cameras are mounted at a fixed distance and on an oblique angle in relation to the projected laser line.

The recorded positions of the lighted points on the surface of the tunnel are displayed in the image obtained by the camera and the distance between points and the camera can be calculated by means of trigonometry. This permits the simultaneous capture of two data-streams: 3D "Range" (height of each pixel) and "Intensity" (the intensity of the reflected laser light for each pixel).

Images are digitized by high-speed frame grabbers and compressed in real-time using a proprietary data compression algorithm which reduces file size to just 1/40th the size of the raw images.

For tunnel inspection, multiple pairs of synchronized sensors are combined and installed on a rail inspection car, or a road/rail all-terrain vehicle, in order to scan the large surface area of a tunnel quickly. In addition to laser scanners, high-speed industrial computers are utilized to store 3D profiles in real-time for subsequent automated and semi-automated image processing. The resulting system is known as the "Laser Tunnel Scanning System" or LTSS (Figure 3).

Figure 3 - LTSS Mounted on an All-terrain Vehicle

A high-resolution optical encoder (20,000 pulses per revolution) is mounted on one of the wheels of the inspection vehicle in order to accurately location reference 3D data scans by translating wheel rotations into linear distance traveled through the tunnel.

By combining high vertical accuracy, intense artificial illumination, and rapid scanning rates (Figure 4), the LTSS is capable of collecting extremely precise and detailed data, day or night, on a wide variety of surface types.

Parameter	Specification
# of laser profilers	6
Sampling rate (max.)	11,200 profiles/s
Vehicle speed	30 km/h
Profile spacing	1mm
3D points per profile	12,288 points
Transverse field-of-view	12 m
Depth range of operation	250 mm
Z-axis (depth) accuracy	0.5 mm
X-axis (transverse) resolution	1 mm

Figure 4 – LTSS Sensor Specifications

The LTSS multi-sensor array allows a 9m diameter tunnel to be inspected in just two passes; the first in one direction of travel and the other in the opposite direction of travel (Figure 5).

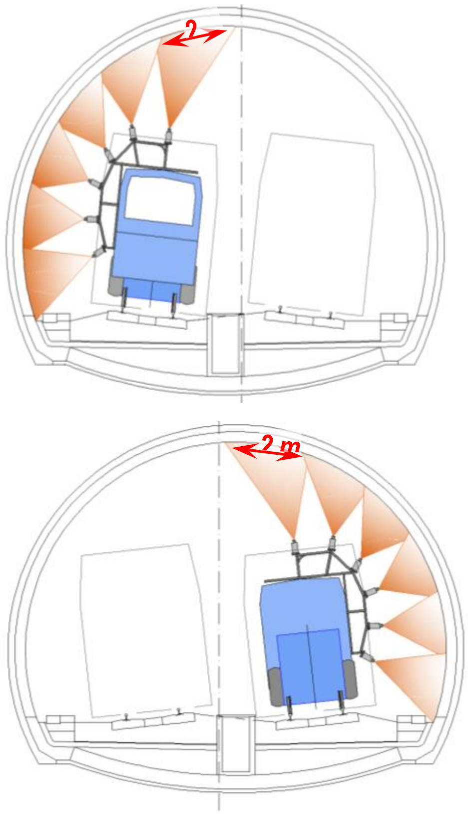

Figure 5 – Tunnel Scanning Sensor Deployment

Images from each pair of sensors are subsequently merged to produce a complete 24m long image of the tunnel surface (12m from each pass) and to permit condition rating across the entire surface (Figure 6).

Figure 6 - Merged 24m Image of Tunnel Wall

Data collection can be performed at speeds up to 100 km/h, but for more detailed inspections a traveling speed of 30 km/h is utilized (Figure 7).

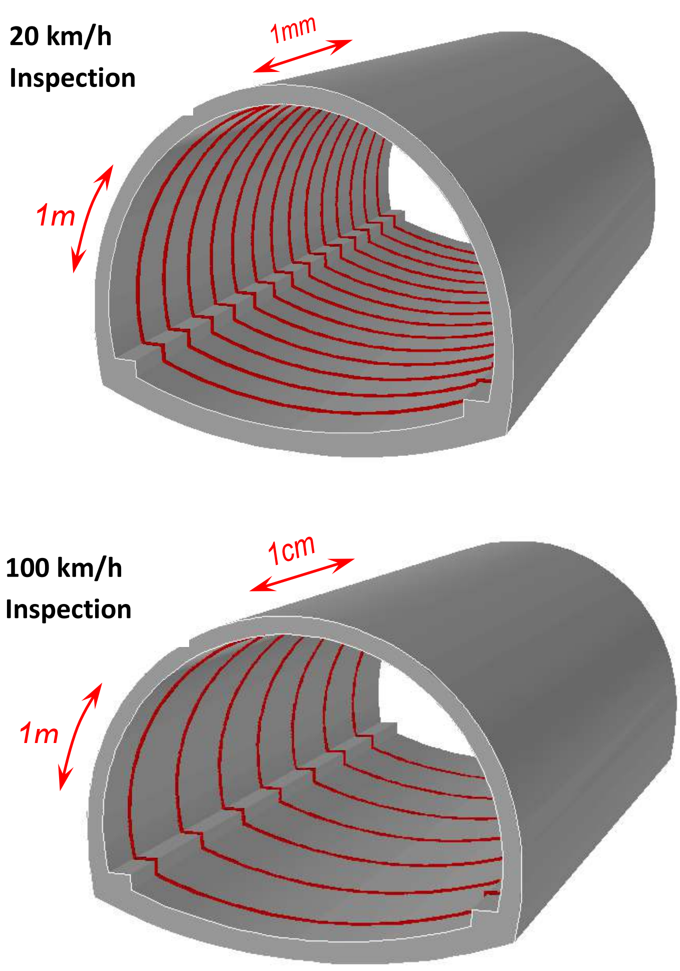

Figure 7 – Resolution vs. Inspection Speed

3. DATA ANALYSIS

Automatic algorithms can be used to analyze each data stream in order to extract different data elements; for example, the presence of dark moist areas can be detected from intensity images and the presence of cracking can be detected from range data. Results from data processing are stored using the open XML data format, and Range, Intensity and Merged 3D images can be output as standard JPEG images to facilitate sharing and viewing.

3.1 *Intensity Data*

Intensity profiles provided by the LTSS are used to form a continuous image of the scanned surface. Intensity images can be used to for a variety of purposes such as the detection of flaws or moisture on a tunnel wall (Figure 8).

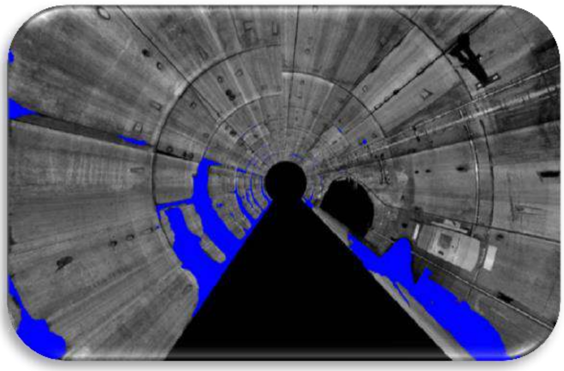

Figure 8 - Example Intensity Image Showing Detected Moisture on Tunnel Wall

3.2 *3D Range Data*

The LTSS system acquires 3D data by measuring the distance from the sensor to the surface for every sampled point. Figure 9 shows range data converted to a gray scale image; wherein portions of the wall which are relatively speaking farther away from the sensor (e.g., concrete seams and hollow portions) are shown using white or light gray shades. Uniform surface areas of the tunnel wall are represented in darker shades of gray.

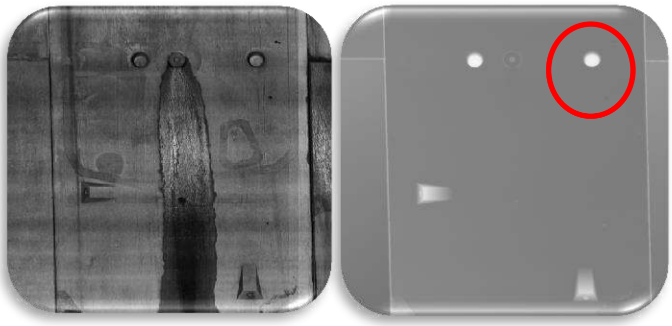

Figure 9 - Intensity and Corresponding Grayscale Range Image

3.3 *Benefits Over Manual Field Inspection*

One of the key benefits of LTTS technology is the fact that data analysis can be performed through the use of semi-automated and fully-automated image/data processing algorithms from the comfort and safety of an office environment as opposed to in the field (Figure 10).

Figure 10 - Manual Measurement of a Joint

For example, using range data, a wide variety of tunnel lining defects can be quickly and safely detected and measured including: faulting between adjacent concrete segments, cracking and chipping (Figure 11, Figure 12, Figure 13).

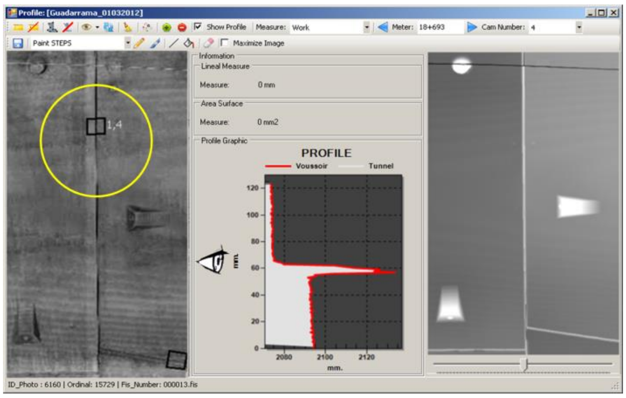

Figure 11 – Gap Between Joints

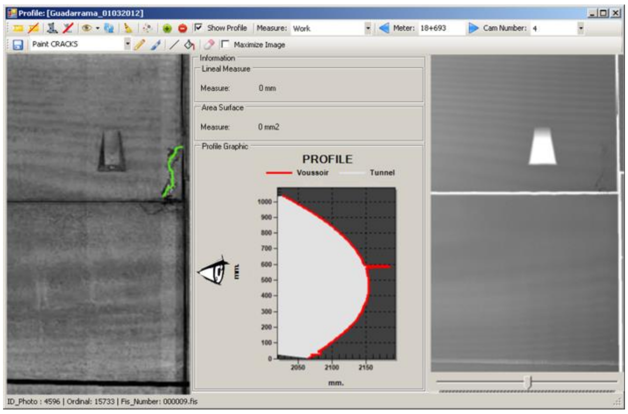

Figure 12 – Liner Cracking

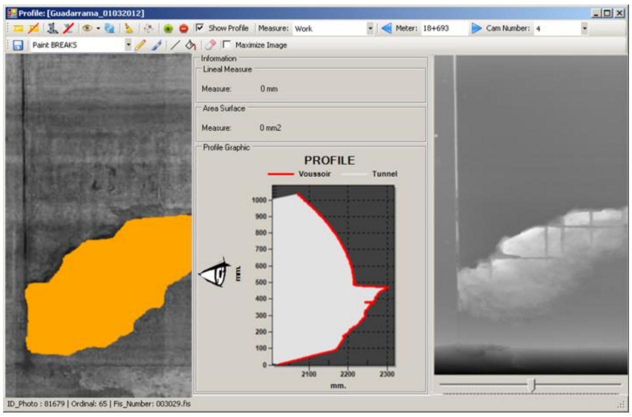

Figure 13 – Chipping/Exposed Reinforcement

4. SAMPLE PROJECT WORK

The LTSS has been deployed to scan a variety of tunnels in Europe and Asia including: segment or slab-based TBM tunnels, mass concrete tunnels, cut and cover precast tunnels, diaphragm walls, sprayed-concrete tunnels and more.

Of particular interest is work done by Euroconsult in Spring of 2012 in order to scan the Guadarrama and Regajal tunnels in Spain. The Guadarrama (Figure 14) is a TBM railway tunnel with an interior diameter of 8.50m which spans the Sierra de Guadarrama in Spain between Madrid and Valladolid. With 28,407m long western and 28,418m long eastern tubes the Guadarrama is the 5th longest tunnel in the world. The Regajal tunnel shares an interior diameter of 8.50m but is a much shorter tunnel with a length of 2,200 m.

Figure 14 - Guadarrama Tunnel

The entire length of both tunnels, as well as rail surfaces, were scanned using the LTSS, with 1 pass in each direction of each tunnel for a total of 4 passes at a speed of 20 km/h. Scanning time for the Guadarrama tunnel was approximately 6-8 hours and approximately 1-2 hours for the Regajal (Figure 15); thus minimizing tunnel downtime. 1mm resolution (longitudinally and transverse) 3D scans were collected for each tunnel with a vertical accuracy of 0.5mm.

Figure 15 - LTSS Inspection Vehicle Deployed in Regajal Tunnel

Figure 16 presents an intensity data image of the Guadarrama tunnel where there significant amounts of moisture are present on the walls (visible as darker areas in the intensity image).

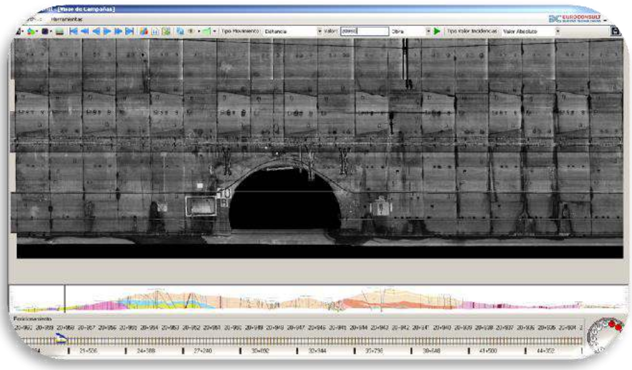

Figure 16: Merged Intensity Image of Tunnel Wall

Figure 17 shows the capabilities of automated algorithms for detecting flaws such as excess moisture (shown in blue) and loss of concrete (shown in orange).

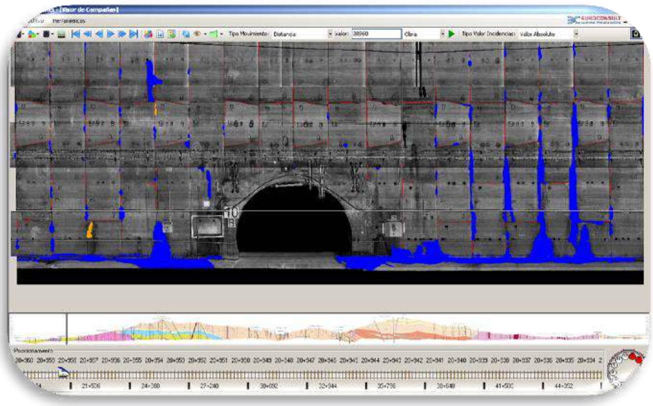

Figure 17 – Merged Image Showing Results of Automated Analysis (Cracking, Moisture and Voids)

Results of the semi-automated and automated inspection were then tabulated and reported to the client as detailed in Figure 18, Figure 19 and Figure 20.

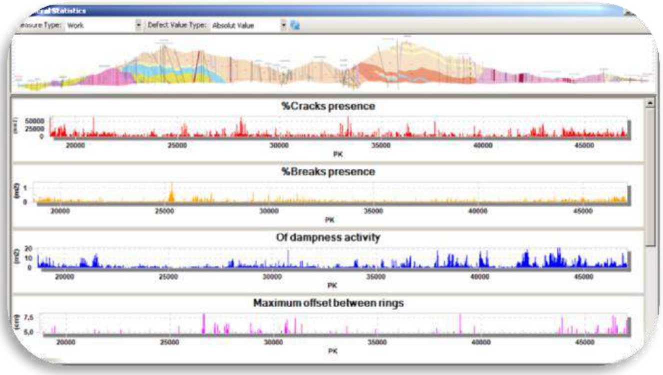

Figure 18 - Tunnel Defect Summary Data

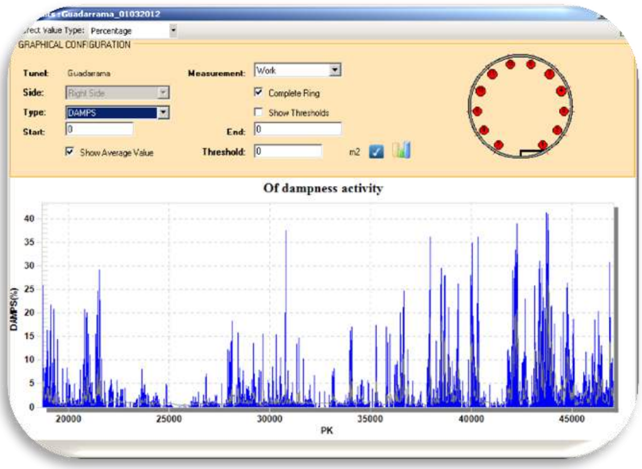

Figure 19 - Tunnel Moisture Report

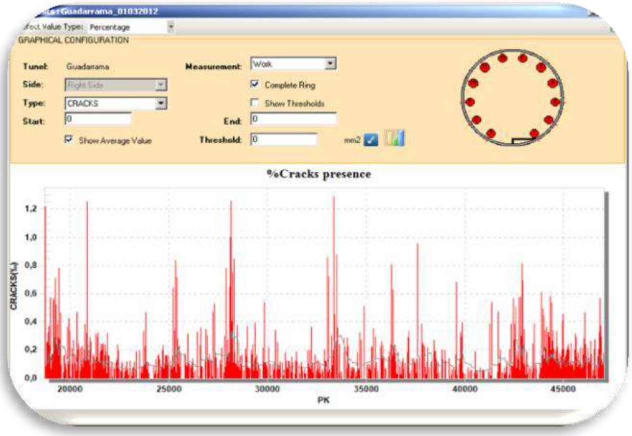

Figure 20 - Tunnel Cracking Report

5. CONCLUSION

The LTSS is a versatile laser-based 3D scanning technology that can provide value to infrastructure managers across numerous modes of transportation.

The key advantages to this technology are:

- The ability to scan surfaces day or night (maximizing productive uptime)
- The ability to scan at traveling speeds up to 30 km/h; making the device efficient for the collection of large infrastructures and suitable for use in high-pressure operational environments (e.g., between train and metro normal down times)
- The ability to view, identify and measure defects and features of interest; saving tunnel down time compared to manual on-site inspections and improving the repeatability and objectivity of results.
- The ability to provide a permanent detailed 3D record of the tunnel for future reference and to follow the evolution of the tunnels condition over time.

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