Use of 3D Scanning Technology for Automated Inspection of Multi-modal Transportation Infrastructure

Richard Habel, Pavemetrics Systems Inc.
John Laurent, Chief Technical Officer, Pavemetrics Systems Inc.
Jean-Francois, Product Manager, Pavemetrics Systems Inc.
Richard Fox-Ivey, Principal Consultant, Pavemetrics Systems Inc.

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. The technology deployed includes 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.

Interestingly, new multi-functional 3D scanners can now 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.

As well, they offer numerous advantages to the traditional manual inspection including:

- Improved safety to staff
- Day or night operation
- Improved speed of operation
- Improved accuracy and reliability of results

These new technologies allow the quality control of thousands of meters of runways, highways, rail and tunnels in a matter of minutes; thus helping to maximize facility uptime.

This paper will explore the state-of-the-art with regard to the development of automated condition assessment algorithms across different modes of transportation including highways and roads, airport runways, tunnels and rail. The discussion will include some of the advances in algorithm development that have been possible through adopting ideas and concepts from one mode to the problems of another. Real-world examples will be used for discussion of achievable levels of data precision and accuracy, along with data formats.
INTRODUCTION
The LCMS/LFOD/LTSS is a 3D laser-based infrastructure assessment technology that has been continuously developed over the last 10 years through the close collaboration between Pavemetrics (a spin-off of Canada’s National Optics Institute), the Ministry of Transportation of Quebec, and numerous Infrastructure Management Consultants and other Departments of Transportation around the world.

The LCMS/LFOD/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.

High resolution 2D and 3D data acquired is then processed using algorithms that automatically extract feature and defect information such as: cracking quantity, severity and location on roads, FOD location and volume on runways and the presence of moisture in tunnel linings.

This paper describes the function of this technology and its application to the inspection of a wide variety of Transportation Infrastructure.
HARDWARE CONFIGURATION
The LCMS/LFOD/LTSS system consists of 2 or more fully synchronized 3D laser profilers mounted on an inspection vehicle (Figure 1), high-speed industrial computers, and sophisticated image processing algorithms.

The LCMS/LFOD/LTSS’s 3D laser profilers use high power laser line projectors, custom filters and a camera as the detector. Lasers are projected onto the surface to be inspected and its image is captured by the camera (Figure 2 and Figure 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.

By combining high vertical accuracy, intense artificial illumination, and rapid scanning rates (Figure 4), the LCMS/LFOD/LTSS is capable of collecting extremely precise and detailed data at speeds up to 100 km/h, day or night, on a wide variety of surface types.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td># of laser profilers</td>
<td>2 or more</td>
</tr>
<tr>
<td>Sampling rate (max.)</td>
<td>11,200 profiles/s</td>
</tr>
<tr>
<td>Vehicle speed</td>
<td>100 km/h (max)</td>
</tr>
<tr>
<td>Profile spacing</td>
<td>Adjustable</td>
</tr>
<tr>
<td>3D points per profile</td>
<td>4,096 points</td>
</tr>
<tr>
<td>Transverse field-of-view</td>
<td>4 m</td>
</tr>
<tr>
<td>Depth range of operation</td>
<td>250 mm</td>
</tr>
<tr>
<td>Z-axis (depth) accuracy</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>X-axis (transverse) resolution</td>
<td>1 mm</td>
</tr>
</tbody>
</table>

Sensors simultaneously acquire both 3D “Range” (height of each pixel) and “Intensity” (the intensity of the reflected laser light for each pixel) images of the scanned surfaces (Figure 5). 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.

Automatic algorithms are then used to analyze each data stream in order to extract different data elements; for example, the presence of pavement markings can be detected from intensity images and the presence of FOD or pavement 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.

INTENSITY DATA

Intensity profiles provided by the LCMS/LFOD/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 identifying the type and number of Foreign Object Debris (FOD) on a runway, the message contained in a pavement marking or the configuration of rail components on a railway track (Figure 6, Figure 7, Figure 8, Figure 9).

Figure 6 - Example FOD Intensity Images (Wrench, Screwdriver and Keys)

Figure 7 - Example Pavement Intensity Image Showing Cracking
Intensity images can also be used to detect highly reflective painted surfaces such as pavement striping and informational messages due to the fact that markings are highly contrasted against the surrounding pavement. With the proper pattern recognition algorithms, various markings can be identified and surveyed.
3D RANGE DATA

The LCMS/LFOD/LTSS system acquires 3D data by measuring the distance from the sensor to the surface for every sampled point on the road. Figure 10, Figure 11 and Figure 12 show range data image acquired by the sensors. In these images, elevation has been converted to a gray scale; allowing 3D features contained in the images to be easily distinguished.

Figure 10 - Range Image Showing FOD on a Runway

Figure 11 - Example Range Image Showing Cracking
In these images, the lighter the point, the higher the surface is; so features sitting on top of the surface being scanned (e.g. FOD on a runway) or near the surface (the top of a runway spike) appear light grey or white in range images whereas features whose depth extends beneath the top surface of the runway (e.g., cracks, raveling, rutting, potholes, etc.) appear as dark grey or black in colour.

**AUTOMATED DATA ANALYSIS ALGORITHMS**

One of the key benefits of this technology is the fact that data analysis can be performed through the use of automated image/data processing algorithms. Both Range and Intensity algorithms can be used to detect features/defects of interest.

Over time and through exposure to the analysis of images from a wide variety of infrastructure asset types a robust library of algorithms has been developed (Figure 13).
Through the application of this technology to different surfaces; e.g. a highway compared to a runway, algorithms developed for one application area can serve as the starting point for the development and refinement of an algorithm for another application area. For example, the initial development of a FOD detection algorithm was first based on the hybridization of an algorithm for detecting potholes. To detect FOD, the pothole detection algorithm was more-or-less turned on its head to look for 3D objects sitting on top of the paved surface (rather than extending below it).
Following automated analysis, results are stored using the open data format; XML, or “Extensible Markup Language” which can be readily imported into all major data formats including spreadsheet programs like Excel as well as various Relational Database technologies such as Microsoft Access and SQL and Oracle. For each detected feature or defect records typically include information such as date and time of detection, location of detection, and physical dimensions (Figure 14).

Figure 14 - XML Data Record
Results of data analysis can also be overlaid on Intensity, Range or Merged 3D images captured by the system and output as JPEG images to facilitate visualization of the detected feature or defect (Figure 15).

![Merged 3D Image Overlaid with Detected Cracking from XML File](image)

Figure 15 - Merged 3D Image Overlaid with Detected Cracking from XML File
APPLICATIONS OF DATA FOR PAVEMENT MANAGEMENT (AIRPORT OR HIGHWAY)
The LCMS/LFOD/LTSS processing library contains an extensive set of algorithms related to pavement condition rating including:

- Longitudinal profile and/or roughness
- Transverse profile and rutting
- Potholes
- Longitudinal cracking
- Transverse cracking
- Pattern cracking
- Crack and/or joint seal failure
- Concrete slab faulting
- Macro Texture
- Bleeding
- Raveling

From a pavement condition inspection perspective, most features are located in the high-spatial frequency portion of the range data. Figure 17 shows a 2 meter wide transverse profile where the
general depression of the profile corresponds to the presence of a rut, the sharp drop in the center of the profile corresponds to a crack and the height variations around the red line correspond to the macro-texture of the pavement surface.

Figure 17 - Analysis of Range Data to Extract Pavement Condition Data

These data items can be used to support a full pavement management program for a DOTs/City’s/Airport’s paved surfaces using MicroPAVER™ or other Pavement Management System software applications.

Figure 18 - Pavement Deterioration Curve
APPLICATION IN AN AIRPORT ENVIRONMENT
REALTIME FOD DETECTION

When deployed for automatic FOD detection, the LCMS/LFOD/LTSS is mounted on an inspection vehicle which is driven along the airfield surface at high-speed. As the inspection vehicle is being driven, 3D data scans are transferred in real-time to an onboard processing computer.

FOD detection algorithms scan the 3D profiles for presence of debris which exceed operator-specified thresholds for minimum height and area. Features meeting the minimum height and area criteria are recorded as FOD and their position as well as height, area and an actual image of the object are recorded for each (Figure 19).

![Figure 19 - Detected FOD (a wrench)]

A “severity rating” can be given to each detected FOD based upon its height and area with the operator being able to configure the height and area ranges according to 3 levels of severity: high, medium and low (Figure 20). High severity FOD are marked in images using a red color, Medium severity are marked using an orange colour and Low severity FOD are marked using a green colour.

![Figure 20 - Automatic FOD Severity Rating]

Audio alarms can be set by the operator to trigger only upon the detection of FOD of a minimum
height and area. This is particularly useful considering the high sensitivity of the system and its ability to detect FOD down to a size of a few millimetres. The GPS coordinates, dimensions and images of small FOD which do not meet the airport-set criteria for immediate retrieval can be stored and used to create a targeted work program for weekly runway sweeping or vacuuming.

**FOD REPORTS**

A number of different data elements are available as outputs from the system so as to allow the user to better manage their risk due to FOD. For each detected FOD the system records the following:

- FOD location (linear as well as latitude, longitude and elevation),
- FOD height (max, min and average),
- FOD area,
- Images of the FOD (range, intensity and 3D),
- FOD “severity rating” (High, Medium, Low).

Additionally, a report can be generated using Google Earth (Figure 21) such that the locations of detected FOD are highlighted on a satellite or aerial photo in Google along with a data file for each item detailing the FOD’s key characteristics.

![Figure 21 - Google Map Report of Detected FOD](image)

Over time, a database of detected FOD can be created documenting the date and time, locations, sizes and types of FOD detected at the airport. This information can serve as a valuable input into an airport’s Safety Management System.
APPLICATION OF LCMS/LFOD/LTSS for TUNNEL AND RAIL INSPECTION

A multi-sensor array is deployed for a tunnel scanning application which allows a 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 22).

Figure 22 – Tunnel Scanning Sensor Deployment
Data collection can be performed at speeds up to 100 km/h, but for more detailed inspections a traveling speed of 20 km/h is utilized (Figure 23).

Images from each pair of sensors are subsequently merged to produce a complete image of the tunnel surface and to permit condition rating (Figure 24).
Rail can also be inspected using either a single pair of sensors or two pairs of sensors simultaneously depending on the desired field of view of the rail (Figure 26).

Figure 26 – Sensor Deployment for Rail Inspection
CONCLUSIONS
The LCMS/LFOD/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 100 km/h; making the device efficient for the collection of large networks and suitable for use in high-pressure operational environments (e.g., between plane departures and arrivals)
- The ability to automatically detect features of interest; saving time and labour associated with data processing and improving the repeatability and objectivity of results