3D laser road profiling for the automated measurement of road surface conditions and geometry.

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Abstract: In order to maximize road maintenance funds and optimize the condition of road networks, pavement management systems need detailed and reliable data on the status of the road network. To date, reliable crack and raveling data has proven difficult and expensive to obtain. To solve this problem, over the last 10 years Pavemetrics inc. in collaboration with INO (National Optics Institute of Canada) and the MTQ (Ministère des Transports du Québec) have been developing and testing a new 3D technology called the LCMS (Laser Crack Measurement System).

The LCMS system was tested on the network to evaluate the system's performance at the task of automatic detection and classification of cracks. The system was compared to manual results over 9000 km and found to be 95% correct in the general classification of cracks.

IMUs (accelerometers and gyroscopes) were added to the LCMS 3D sensors. This has allowed the LCMS system to be used to also measure road geometry (longitudinal profile IRI, slope and cross-slope) with a very high degree of accuracy. Results and comparison tests with standard class 1 inertial profilers show that the LCMS matches and improves upon existing technology.

Introduction

The LCMS is composed of two high performance 3D laser profilers that are able to measure complete transverse road profiles with 1mm resolution at highway speeds. The high resolution 2D and 3D data acquired by the LCMS is then processed using algorithms that were developed to automatically extract crack data including crack type (transverse, longitudinal, alligator) and severity. Also detected automatically are ruts (depth, type), macro-texture (digital sand patch) and raveling (loss of aggregates). This paper describes results obtained recently regarding road tests and validation of this technology.

Hardware Configuration

The sensors used with the LCMS system are 3D laser profilers that use high power laser line projectors, custom filters and a camera as the detector [1,2]. The light strip is projected onto the pavement and its image is captured by the camera (see figures 1 and 2). The shape of the pavement is acquired as the inspection vehicle travels along the road using a signal from an odometer to synchronize the sensor acquisition. All the images coming from the cameras are sent to the frame grabber to be digitized and then processed by the CPU. Saving the raw images would imply storing nearly 30Gb per kilometer at 100 km/h but using lossless data compression algorithms on the 3D data and fast JPEG compression on the intensity data brings the data rate down to a very manageable 20Mb/s or 720Mb/km. The critical specifications for the LCMS system can be found on table I.

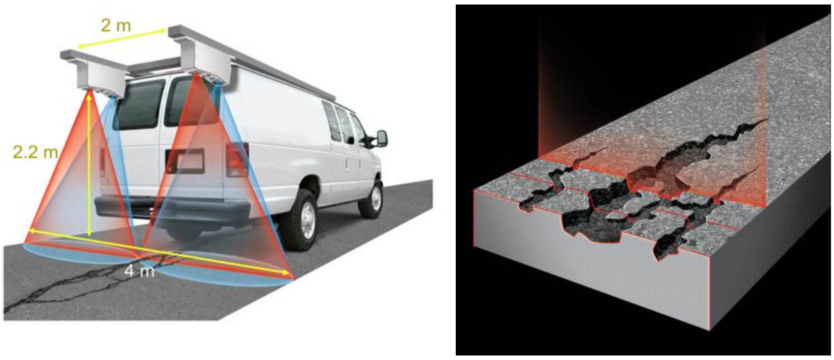

Figure 1. LCMS on an inspection vehicle (left), laser profiling of cracks (right).

Nbr. of laser profilers	2
Sampling rate (max.)	11,200 profiles/s
Vehicle speed	100 km/h (max)
Profile spacing	Adjustable
3D points per profile	4096 points
Transverse field-of-view	4 m
Depth range of operation	250 mm
Z-axis (depth) accuracy	0.5 mm
X-axis (transverse) resolution	1 mm

Table I - *LCMS Specifications.*

Figure 2. Photo of the LCMS system (sensors and controller).

The LCMS sensors simultaneously acquire both range and intensity profiles. The figure 3 illustrates how the various types of data collected by the LCMS system can be exploited to characterize many types of road features. The graph shows that the 3D data and intensity data serve different purposes. The intensity data is required for the detection of lane markings and sealed cracks whereas the 3D data is used for the detection of most of the other features.

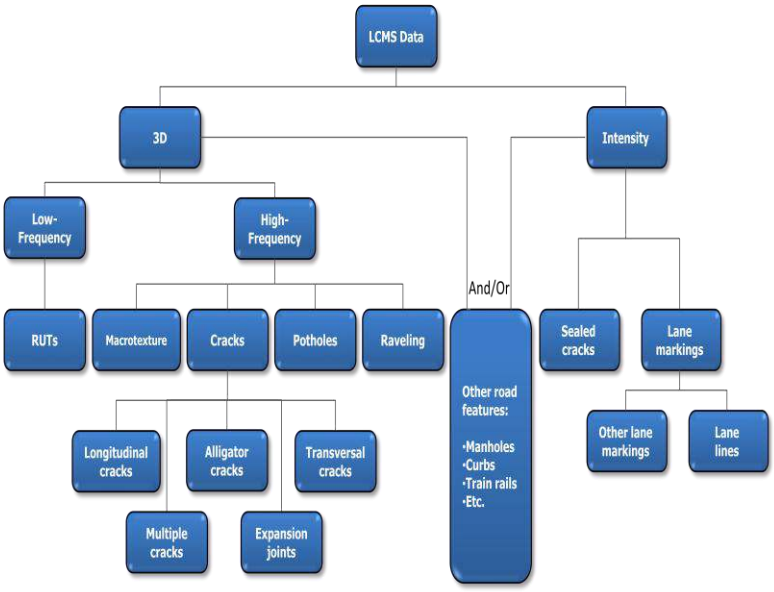

Figure 3. Data analysis library diagram.

Intensity Data

Intensity profiles provided by the LCMS are used to form a continuous image of the road surface. The first role of the intensity information is for the detection of road limits. This algorithm relies on the detection of the painted lines used as lane markings to determine the width and position of the road lane in order to compensate for driver wander. The lane position data is then used by the other detection algorithms to circumscribe the analysis within this region of interest in order to avoid surveying defects outside the lane. Highly reflective painted landmarks are much easier to detect in 2D since they generally appear highly contrasted in the intensity images. With the proper pattern recognition algorithms, various markings can be identified and surveyed. Figure 4 shows the results of the different types of images (intensity, range, and 3D merged image) that can be produced from the LCMS data.

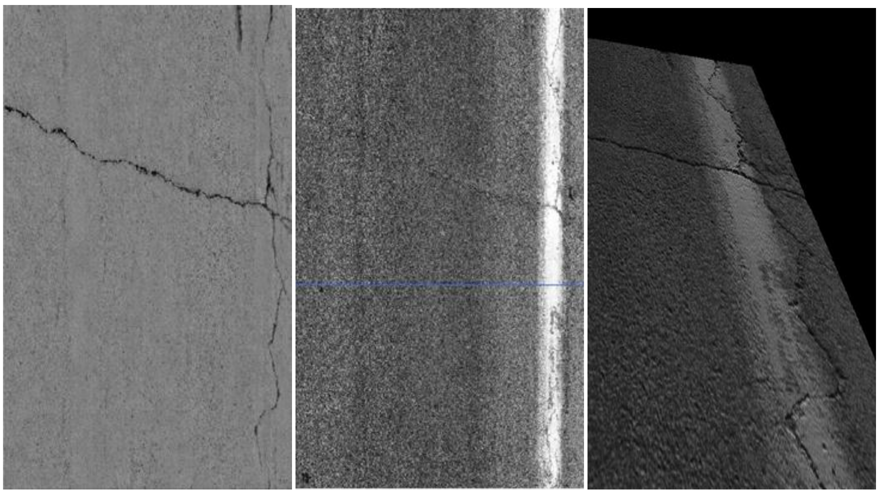

Figure 4. LCMS data type – Range (left) – Intensity (center) – 3D merged (right).

3D Range Data

The 3D data acquired by the LCMS system measures the distance from the sensor to the surface for every sampled point on the road. The previous image (above left) shows a range data image acquired by the sensors. In this image, elevation has been converted to a gray level. The darker the point, the lower is the surface. In a range image the height can vary along the cross section of the road. The areas in the wheel path can be deeper than the sides and thus appear darker this would correspond to the presence of ruts. Height variations can also be observed in the longitudinal direction due to variations in longitudinal profiles of the road causing movements in the suspension of the vehicle holding the sensors. These large-scale height variations correspond to the low-spatial frequency content of the range information in the longitudinal direction. Most features that need to be detected are located in the high-spatial frequency portion of the range data. The figure 5 shows a 2m (half lane) 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 point and the height variations (in blue) around the red line correspond to the macro-texture of the road surface.

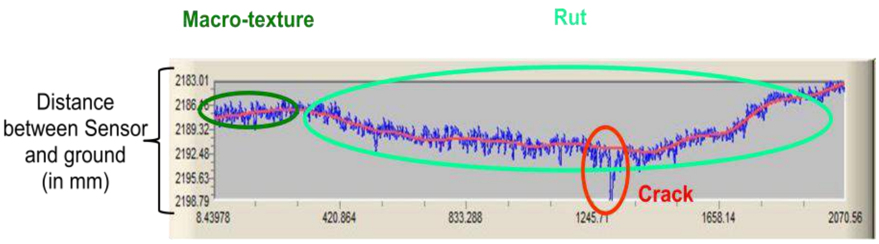

Figure 5. LCMS (half lane) 2 m transverse profile showing ruts, cracks and texture.

Macrotexture

Macrotexture is important for several reasons, for example it can help estimate the tire/road friction level, water runoff and aquaplaning conditions and tire/road noise levels produced just to name a few. Macrotexture can be evaluated by applying the ASTM 1845-01 norm [3]. This standard requires the calculation of the mean profile depth (MPD). To calculate the MPD, the profile is divided into small (10cm) segments and for each segment a linear regression is performed on the data. The MPD is then computed as the difference between the highest point on the profile and the average fitted line for the considered portion. MPD is the only way possible to evaluate texture using standard single point (64 kHz) laser sensors. The LCMS however acquires sufficiently dense 3D data to not only measure standard MPD but also to evaluate texture using a digital model of the sand patch method (ASTM E965) [4] as shown on figure 6.

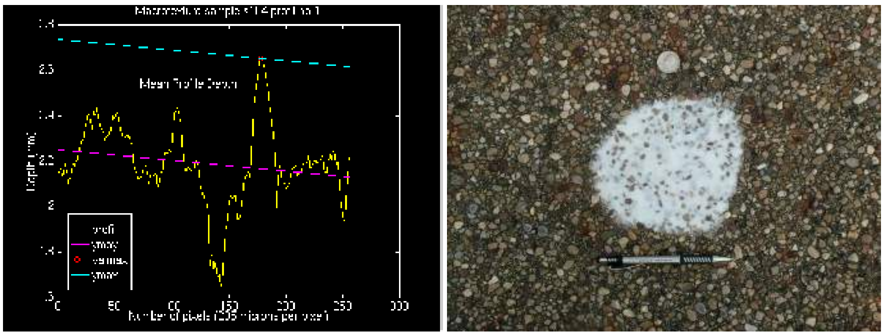

Figure 6. MPD vs sand patch.

The digital sand patch model is calculated using the following proposed Road Porosity Index (RPI). The RPI index is defined as the volume of the voids in the road surface that would be occupied by the sand (from the sand patch method) divided by a surface area. The digital sand patch method implemented allows texture to be evaluated continuously over the complete road surface instead of measuring only a single point inside a wheel path. The RPI can be calculated over any user definable surface area but LCMS reports by default the macro-texture values within the 5 standard AASHTO bands as illustrated on figure 7 (center, right and left wheel paths and outside bands).

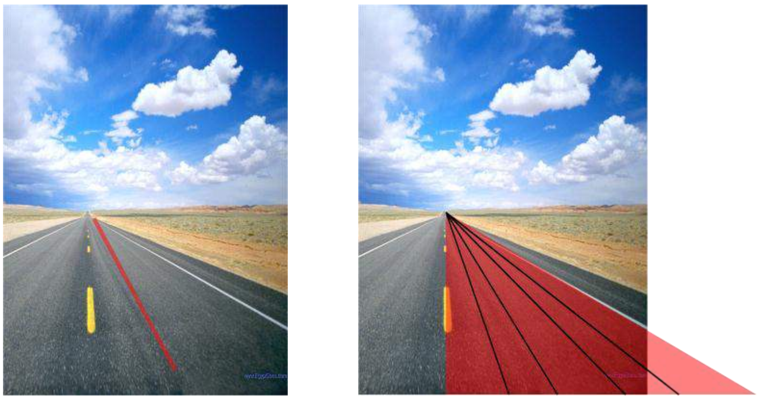

Figure 7. MPD vs digital sand patch (RPI).

Results show (see figure 8) that RPI measurements using the LCMS are highly repeatable as shown by road tests on several Alabama test sections and that RPI closely matches MPD measurements collected by standard texture lasers over a wide range of texture values.

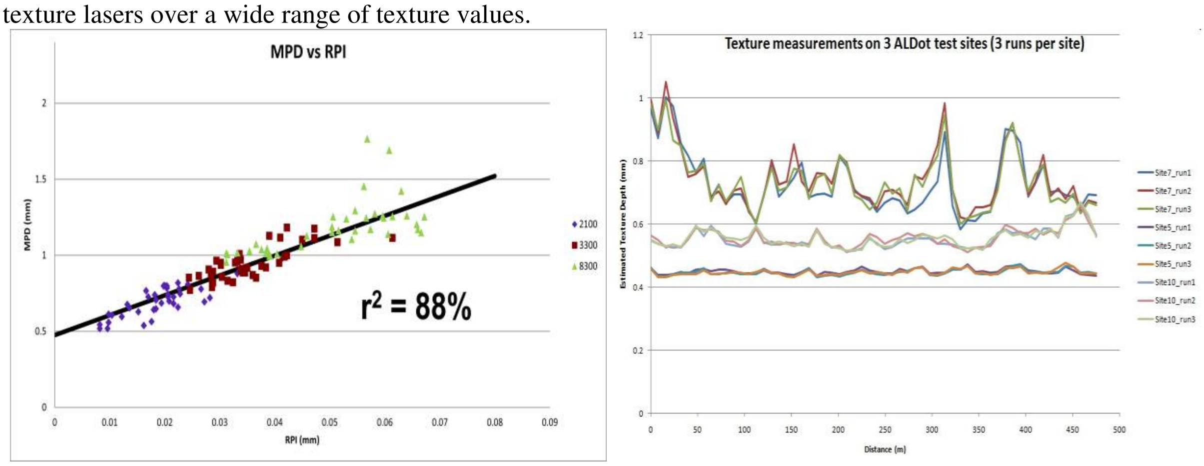

Figure 8. Digital sand patch (RPI) accuracy and repeatability results (Alabama tests).

Raveling

Raveling is the wearing away of the pavement surface caused by the dislodging of aggregate particles and loss of asphalt binder that ultimately leads to a very rough and pitted surface with obvious loss of aggregates. In order to detect and quantify raveling conditions a Raveling Index (RI) indicator is proposed. The RI is calculated by measuring the volume of aggregate loss (holes due to missing aggregates) per unit of surface area (square meter). With the LCMS the high resolution of the 3D data allows for the detection of missing aggregates. Algorithms designed to specifically detect aggregate loss were developed in order to evaluate the RI index automatically. The figures 9 demonstrate the results of aggregate detection (in blue) on range images. Figure 10 show an example of a high RI rated road section measured on porous asphalt roads in the Netherlands. Finally, the results of a repeatability test (3 passes) also on road sections in the Netherlands are shown on figure 11.

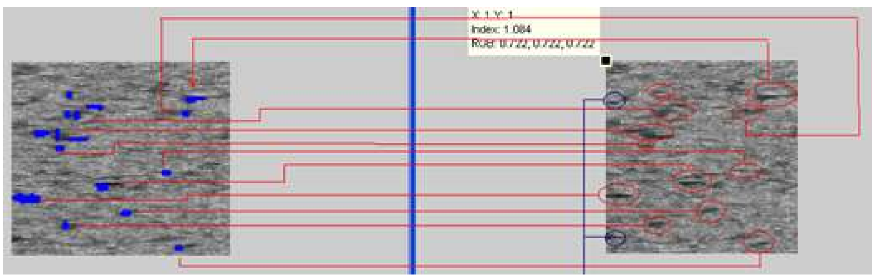

Figure 9. Example of the automatic detection of aggregate loss in range images.

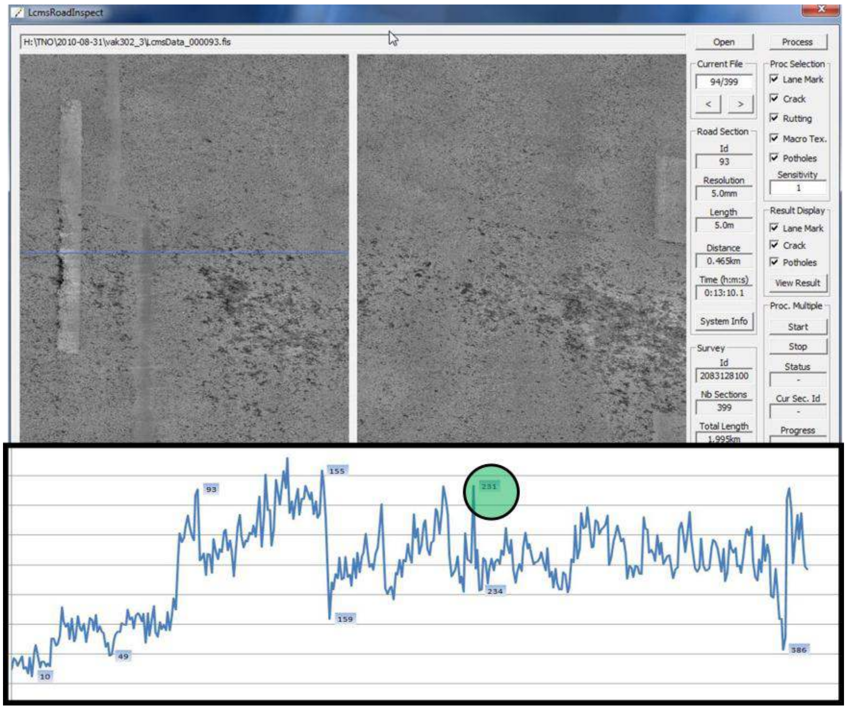

Figure 10. Example of high RI road section on porous asphalt roads in the Netherlands.

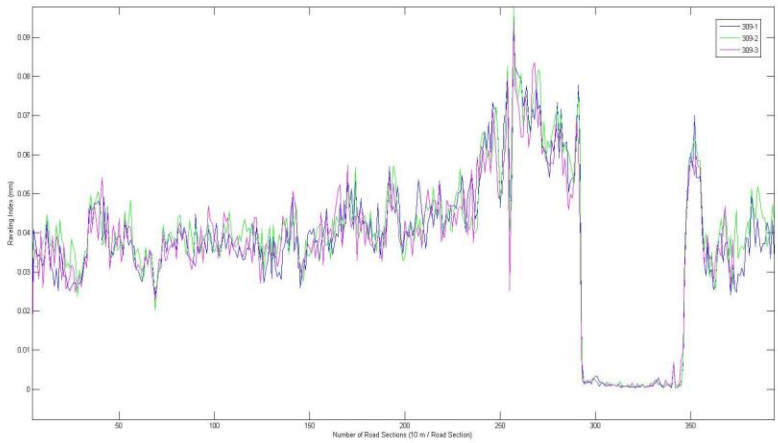

Figure 11. Repeatability of RI measurements (3 passes) on road sections in the Netherlands.

Cracking

Detecting cracks reliably is far more complex than applying a threshold on a range image. As mentioned previously the 3D profile data needs to be detrended from the effects of rutting and vehicle movements. Macrotexture is also a problem; road surfaces have very variable macrotexture from one section to the next and even from one side of the lane to the other. For example, on roads with weak macrotexture we can hope to detect very small cracks which will be harder to detect on more highly textured surfaces. It is thus necessary to evaluate and to adapt the processing operations based on the texture and type of road surface. Once the detection operation is performed, a binary image is obtained where the remaining active pixels are potential cracks. This binary image is then filtered to remove many of the false detections which are caused by asperities and other features in the road surface which are not cracks on the pavement. At this point in the processing, most of the remaining pixels can correctly be identified to existing cracks, however many of these crack segments need to be joined together to avoid multiple detections of the same crack. After the detection process, the next step consists in the characterization of the cracks. The severity level of a crack is determined by evaluating its width (opening) typically cracks will be separated in low, medium and high severity levels. The cracks also need to be grouped into two main categories: Longitudinal and transverse cracks. Furthermore, transverse cracks are further divided into complete and incomplete types and joints need to be classified separately. Longitudinal cracks are further refined into three sub-categories: simple, multiple and alligator.

The LCMS system was used by the MTQ to survey nearly10,000km of its road network. In order to validate the system an independent 3rd party under the supervision of the MTQ was mandated to manually qualify the crack detection results of the LCMS system over the entire survey. To do this each 10m section was visually analyzed and the results were categorized in 3 classes (Good, Average and Bad). A forth class (NA) was used when for when it was not possible to correctly evaluate a section. Figure 12 shows an example of crack detection results on a 10m pavement section. Transverse cracks are identified with a bounding box. Regions in red indicate high severity cracks (15mm+) and light blue and green represent low severities (less than 5mm). Table II shows the results of the compilation of the manual evaluation. The final results are deemed excellent by the MTQ as the overall ‘Good’ rating reaches 96.5%. Repeatability tests were also conducted on several MTQ test sections and the results shown on the figure 13 also demonstrate very repeatable crack detection results on these sections.

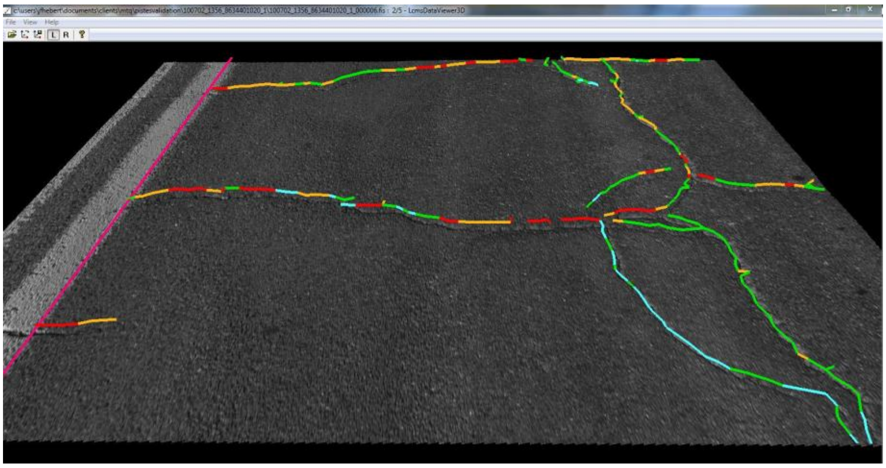

Figure 12. Example crack detection results (severity = color code).

District #	Total (10 m sections)	Results (manual classification)							
		Number of images (10 m sections)				Proportion (%)			
		Good	Average	Bad	NA	Good	Average	Bad	NA
84	35288	34144	310	144	690	96,8	0,9	0,4	2,0
85	4243	4101	53	51	38	96,7	1,2	1,2	0,9
86	147903	144040	516	1520	1827	97,4	0,3	1,0	1,2
87	149926	138453	1170	5728	4575	92,3	0,8	3,8	3,1
88	189097	183010	1064	2002	3021	96,8	0,6	1,1	1,6
89	125003	121835	442	2015	711	97,5	0,4	1,6	0,6
90	123653	116930	2980	2434	1309	94,6	2,4	2,0	1,1
91 & 92	215513	213142	197	956	1218	98,9	0,1	0,4	0,6
Total	**990626**	**955655**	**6732**	**14850**	**13389**	**96,5**	**0,7**	**1,5**	**1,4**

Table II - 10,000 km automatic vs manual survey results.

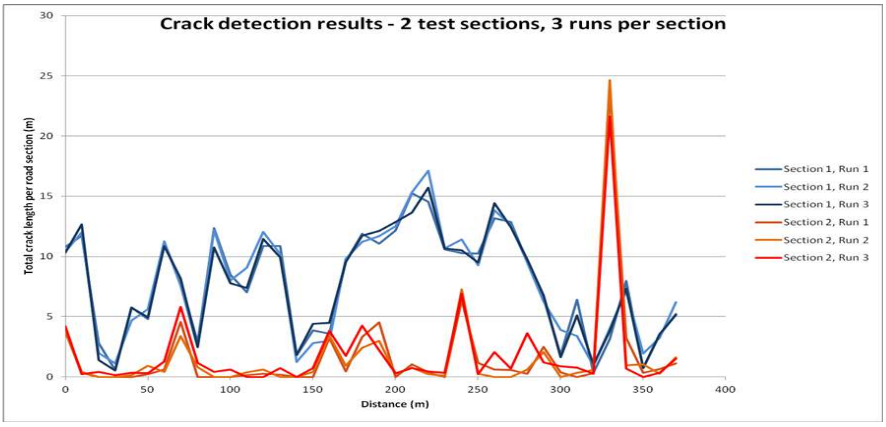

Figure 13. Repeatability results (3 passes) on two MTQ road sections.

Road Geometry

In order to measure road geometry (longitudinal profile IRI, slope and crossfall) with a very high degree of accuracy IMUs (inertial measurement units) were added to the LCMS sensors (Figure 14). The IMUs are composed of three axis accelerometers and gyroscopes where the vertical axis of the IMUs (gravity) are carefully aligned in the same plane as the lasers from the 3D sensors. This alignment allows for a direct referencing of the coordinate system of the IMUs with the 3D sensors allowing the fusion of the data from both types of sensors.

Figure 14. IMUs (gold) added to the LCMS sensors.

Longitudinal profile is measured by integrating the vertical (G) accelerometer (z-axis) signal in order to measure the total vertical displacement of both the vehicle and the road profile while subtracting the distance variations between the vehicle and the road as measured directly by the 3D sensors. The 3D sensors thus allow the removal of the variations in the longitudinal profile that are caused by the vehicle suspension as the vehicle hits bumps in the road. The 3D sensors and the IMUs must also be carefully synchronised for the whole process to work with precision.

The following charts (Figure 15) compare the results obtained while measuring longitudinal profiles (IRI) on multiple runs at tests sites in Utah by the LCMS versus another Class 1 profiler (Dynatest Mark IV - RSP). The tests and graphs show very comparable results in both accuracy and repeatability between the two systems.

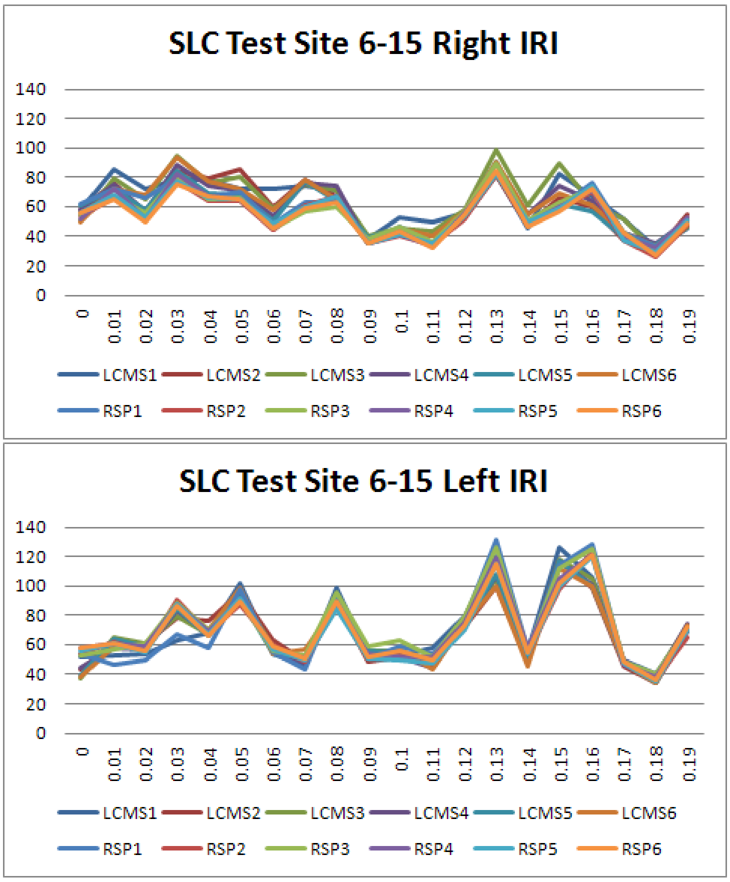

Figure 15. IRI test results LCMS vs RSP at Utah DOT test sites.

Results and comparison tests using Proval software and Surpro reference profiles for evaluating ground truth show that the LCMS generates longitudinal profiles that match standard class 1 inertial profiler requirements. However the fact that the LCMS covers the entire 4m width of a road lane allows the system to detect local IRI variations that can be missed by single point profilers. Figure 16 shows an IRI map of 2x30 meters of road surface that demonstrate that road surfaces are not uniform in IRI along both the transverse and longitudinal directions. Such an IRI map helps identify local problems with the road surfaces that would be invisible to standard profilers thus improving upon existing profiling technology.

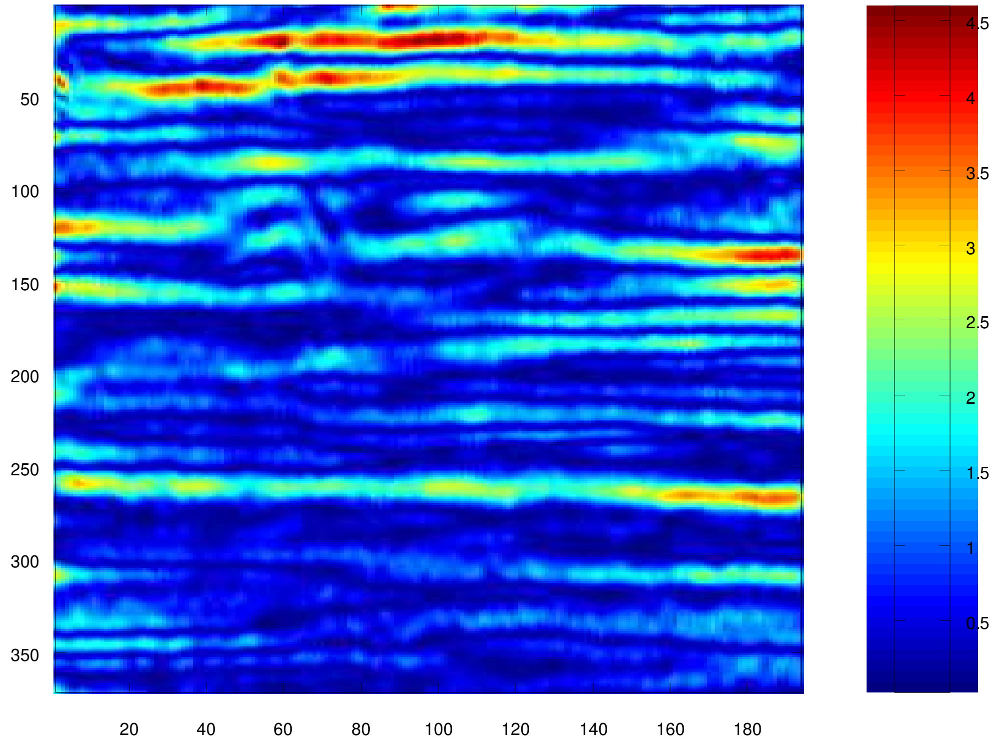

Figure 16. IRI map of 2 x 30m road section show local IRI problems (red)

Slope and cross-slope is measured in a similar way as the longitudinal profile. In these cases however it is the signals coming from the IMU's gyroscopes that are integrated in order to determine the pitch and roll of the vehicle. The 3D sensors are again used to measure the variations in the position of the vehicle versus the road to compensate for the pitch, roll and yaw of the vehicle as it sways over non-uniformities in the road and by accelerations caused by changes in vehicle speed. Figure 17 below show that the LCMS geometry measurements match closely with other standard methods (point lasers and Applanix POS-LV GNSS system) as measured on roads in France.

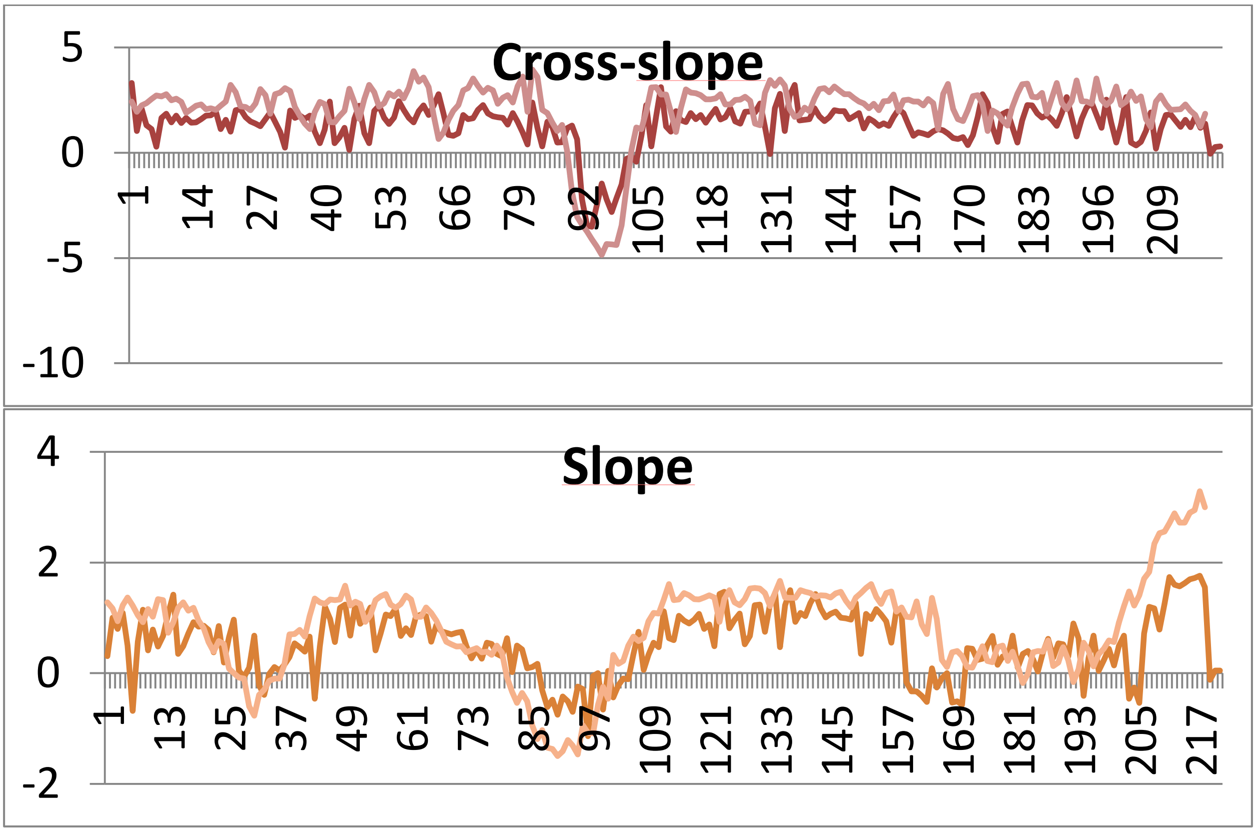

Figure 17. Slope and cross-slope results (degrees vs km) LCMS (bold) Applanix+3 point lasers (non-bold)

Conclusions

We have presented a road surveying system that is based on two high performance transverse 3D laser profilers that are placed at the rear of an inspection vehicle looking down in such a way as to scan the entire 4m width of the road surface with 1mm resolution. This configuration allows the direct measurement of many different types of surface defects by simultaneously acquiring high resolution 3D and intensity data. Examples of different algorithms and results were shown using the 3D data to detect cracks, ruts, evaluate macro-texture and to detect raveling while the intensity data was used for the detection of lane markings.

The LCMS system was tested at the network level (10000 km) to evaluate the system's performance at the task of automatic detection and classification of cracks. The system was evaluated to be over 95% correct in the general classification of cracks.

A Road Porosity Index (RPI) was proposed as a model to measure the equivalent of a digital sand patch. The digital sand patch (RPI) method implemented allows texture to be evaluated continuously over the complete road surface and within each of the five AASHTO bands.

A Raveling Index (RI) indicator calculated by measuring the volume of aggregate loss (holes due to missing aggregates) per unit of surface area (square meter) was proposed. This indicator was shown to allow the quantification of the amount of raveling present and was shown to be highly repeatable.

The addition of IMUs to the LCMS 3D sensors has been demonstrated to allow the system to be used to measure road geometry (longitudinal profile IRI, slope and cross-slope) with a very high degree of accuracy. Results and comparison tests with standard class 1 inertial profilers show that the LCMS matches and improves upon existing technology.

References

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[2] Laurent, J., Hébert JF. (2002). *High Performance 3D Sensors for the Characterization of Road Surface Defects.* Proceedings of the IAPR Workshop on Machine Vision Applications, Nara, Japan.

[3] ASTM E1845 - 09 *Standard Practice for Calculating Pavement Macrotexture Mean Profile* Depth, Active Standard ASTM E1845 Developed by Subcommittee: E17.23.

[4] ASTM E965 - 96 *(2006) Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique,* Active Standard ASTM E965 Developed by Subcommittee : E17.23