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Investigation of Laser Systems Used in Pavement Management Systems (PMS)

Seyed Ali Sahhaf[1], Shahriar Rahimi[2]

1- Civil Department, Engineering Faculty, Ferdowsi University of Mashhad, Iran
2- Civil Department, International Campus, Ferdowsi University of Mashhad, Iran

Shahriar.Rahimi2002@gmail.com

Abstract

The surface layer of road pavement has a particular importance in relation to the satisfaction of the primary demands of locomotion, such as security and eco-compatibility. In order to reduce road maintenance and rehabilitation costs and optimize the service condition of road networks, pavement management systems (PMS) need reliable and detailed data on the status of the highway network. Laser scanners can be used in an innovative way to obtain information on a real surface layer through a single measurement, with data representativeness and homogeneity. With the advancement of 3D sensors and information technology, high-resolution, high-speed 3D line laser imaging devices has become available for pavement surface condition data collection. This paper presents some of the key developments in recent years for laser systems automating pavement distress measurement and evaluation. These new systems are described in terms of their potential and applicability.

Keywords: PMS, Road Maintenance, Data Collection, High Speed 3D Laser, LCMS.

1. INTRODUCTION

Pavement-management systems (PMS) can work effectively only when they are constructed by organically combining all activities concerned with road pavement (planning, design, construction, maintenance, rehabilitation, evaluation, economic analysis, and research) and the database [1]. Then, the most important features are the establishment of a serviceability index, which defines pavement quality, and a prediction of performance, which is represented by the relation between the index and time (and/or traffic). Pavement quality includes two primary parameters: skid resistance and riding quality. The factors influencing riding quality are roughness and/or pavement distress. Three major factors of pavement distress are cracking, rutting, and longitudinal profile [2].

Pavement surface texture has significant effecton tire-pavement friction. Vehicle maneuvers such as cornering and braking need sufficient skid resistance to maintain vehicle stability. Furthermore, pavement skid resistance have influence on tire wear, road noise, discomfort, rolling resistance, and wear in vehicles (ISO, 1997). There are two categories of pavement textures related to skid resistance, i.e. micro texture and macro texture. The classification is generally based on specific texture wavelength range and typical peak–peak amplitude. In particular, micro texture refers to surface texture with wavelength range less than 0.5 mm and typical peak–peak amplitude less than 0.2 mm, while the corresponding ranges for macro texture are 0.5–50 mm and 0.2–10 mm.

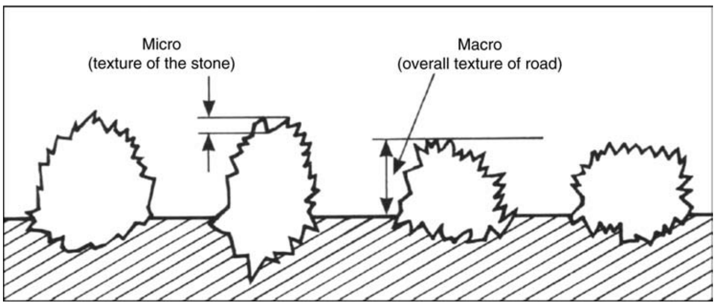

Figure 1. Micro and macro texture[3]

Micro texture defines the degree of the polishing of a pavement surface. In comparison, macro texture has a more direct impact on skid resistance. It is associated with the coarseness of road surface, which affects water drainage from the tire footprint, tire tread rubber deformation, and the friction coefficient at high speeds, as well as the friction-speed gradient. The better the macro texture is, the smaller the slope of the friction coefficient-speed function [4]. Macro texture is also a predominant contribution to wet-pavement safety and a coarse macro texture is preferred for safe wet-weather travel as the speed increases. Therefore, measuring the macro texture is one of the essential components in pavement management applications.

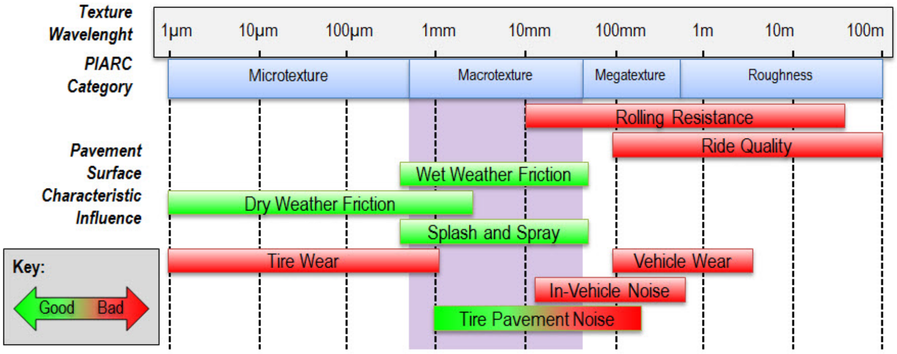

Figure 2. Relationship between texture and characteristics of the pavement surface[5]

The requirements for acquiring these parameters are the following: (1) That data-acquisition cost is as low as possible; (2) that data analysis can be done in a short time; and (3) that data acquisition doesn't affect the speed of other traveling vehicles, in particular on roads with heavy traffic [2].

Pavement surface distress measurement is a necessary part of a pavement management system (PMS) for determining cost-effective maintenance and rehabilitation strategies. Visual surveys conducted by engineers in the field are still the most widely used means to inspect and evaluate pavement's conditions, although such evaluations involve high degrees of hazardous exposure, low production, and subjectivity rates. Consequently, automated distress identification systems are gaining wide popularity among highway and transportation agencies [6]. With the advancement of 3D sensor and information technology, a high-resolution, high-speed 3D line laser imaging system has been developed for pavement surface condition data collection. With the advances in sensor technology, a 3D line-laser-imaging-based pavement surface data acquisition system has become available. The Laser Crack Measurement System (LCMS) [7] can collect high-resolution 3D continuous pavement profiles for constructing pavement surfaces. The purpose of this paper is to validate the capability of 3D laser pavement data to detect cracks in support of subsequent crack classification [6].

Another application of laser systems in highway management and maintenance is tunnel vault scanning. The Laser Tunnel Scanning System (LTSS) uses multiple high speed laser scanners to acquire both 2D images and high resolution 3D profiles of tunnel linings. This system can scan a full tunnel vault (24m) at 1mm resolution image and 3D data at acquisition speeds up to 20km/h. Once digitized the tunnel data can be viewed and analyzed offline by operators using multi-resolution 3D viewing and analysis software that allow the high precision measurement of virtually any tunnel feature. Automatic analysis software is available to detect and rate the condition of joints, faulting, cracks, degraded concrete, wet as well as wet and humid area tunnel linings. The LTSS is one hundred times faster and 10 times more accurate than typical LIDAR technology [8].

The paper is organized as follows. This section reviews related research on automated pavement crack surveying and identifies the objective of this study. Methods and materials briefly introduce the 3D line-laser-imaging system for pavement data collection. It is then followed by the description of systems and its features. Discussion is then provided and finally conclusions are drawn.

2. METHODOLOGY

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 distress data including crack type (transverse, longitudinal, alligator, etc) and severity. Also, these laser systems can automatically detect ruts (depth, type), macro-texture (digital sand patch) and raveling (loss of aggregates).

The sensors used in the LCMS system are 3D laser profilers that use high power laser line projectors, custom filters and a camera as the detector. The light stripe is projected onto the pavement and its image is captured by the camera. 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.

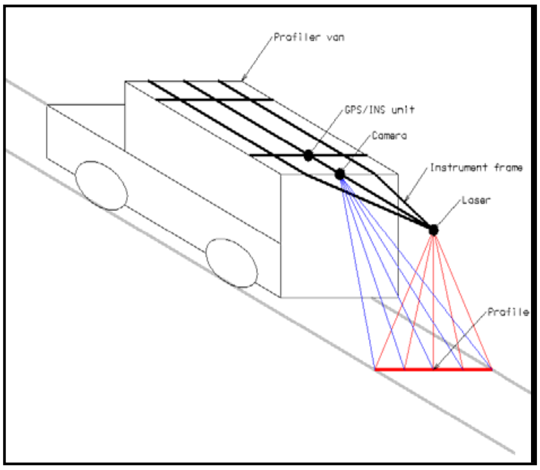

Figure 3. The concept of LCMS's components

The LCMS sensors simultaneously acquire both range and intensity profiles. The figure below 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.

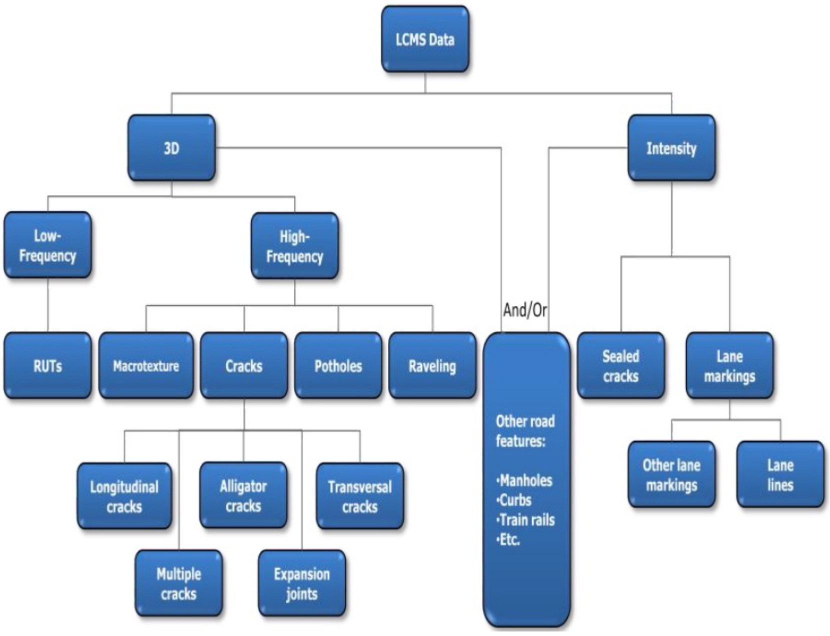

Figure 4. Data analysis diagram [9]

The idea behind Laser detection system is measuring height in a single image by profile detection. If a straight line is projected on a smooth surface and an image is taken from oblique camera position, the line appears straight on the image (see Figure 5).

In case of height change (an object or pothole, for example), the image of the line seems straight only from top view, but it's broken from any oblique view point. Based on similar triangles clear correspondence can be defined between *y* and *x*, which is a quadratic equation. For *x* the function is the following:

$$x = f(h, t, c, y) \quad (3)$$

During the calibration, the camera focal length is considered as constant. So the only inputs of calibration are the *h* and *t* values [10].

The laser triangulation is an active stereoscopic method that, based on the principle of the topographic forward intersection, is able to indicate the position of a point in the space defined by the instrumental reference system. According to the outline in Figure 5, the laser emitter produces a beam of energy that comes from the instrument at an angle (α), which is known due to a prior calibration of the rotating mirror. It hits the surface of the object (in this case pavement) at the point (A) that is being measured. The laser beam undergoes a reflection, where the magnitude of the reflection depends on the type of pavement surface targeted; a part of the reflected signal hits the receiving sensor (usually a CCD or CMOS) positioned at a known distance, called the baseline (b), from the emitter. The angle (β) of the incoming ray is unknown, but it is possible to calculate it by applying the trigonometric formulas (1), and through the knowledge of the focal length (c) and the position of the laser spot (P_x, P_y) recorded by the sensor array. By repeating this technique for all the points (in which it is possible to discretize the surface of the object), it is possible to indicate their coordinates according to the relations (2), and then discretize the surface through a three-dimensional point cloud [5].

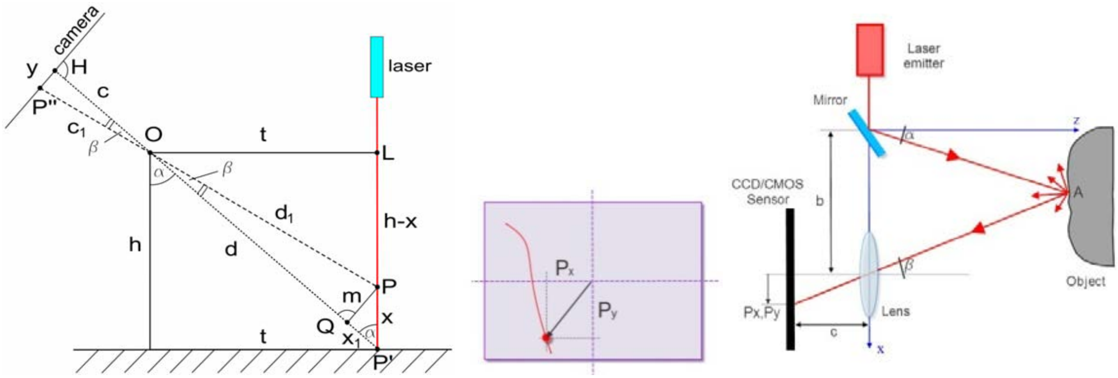

Figure 5. Triangulation laser scanner outline

$$tan\beta = \frac{P_x}{c} \qquad tan\gamma = \frac{P_y}{c} \quad (1)$$

$$x_A = \frac{b}{1+\frac{tan\beta}{tan\alpha}} \quad y_A = \frac{b}{\frac{tan\alpha}{tan\gamma}+\frac{tan\beta}{tan\gamma}} \quad x_A = \frac{b}{tan\alpha+tan\beta} \quad (2)$$

Following a process of triangulation, the point clouds can be converted into a mesh of triangles, which constitute the 3D surface of the pavement. According to the technology adopted by the manufacturing tools and the type of footprint projected on the pavement's surface, the lasers can be categorized as "single spot", "line" or "multi-line" systems. One acquisition is generally not enough to recover the entire surface for freeform objects. For this reason, in order to describe the surface in the best way, other scan positions from different point of view are employed.

3. DISCUSSION

Laser Crack Measurement System (LCMS) allows the automatic detection of cracks and the evaluation of rutting, macro-texture and other road surface features (such as IRI, slope, pot holes, raveling, sealed cracks, joints in concrete, tinning, etc). Distress analysis outputs combined with a Pavement Management System (PMS) can be used to prioritize rehabilitation work in order to optimize road maintenance costs and to monitor the process of the road-network condition over time. The Laser Crack Measurement System (LCMS) has adjustable sampling rate between 5600 to 11200 profiles per second. Also LCMS has operational speed of 0 to 100 Km/hr which enable it to acquire data with ongoing traffic stream. Therefore, there is no need of closing the lane while the road inspection is going on and this fact, results in massive time and cost reduction.

Intensity profiles provided by the LCMS are used to form a continuous image of the road surface. The first role of the intensity data is for the detection of road limits. This algorithm relies on the detection of the painted lines used as lane markings to specify the width and position of the road lane in order to compensate for driver wander. The lane position information 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. The following figure (see Figure 6) indicates the results of the different types of distresses that can be concluded from the LCMS data.

The 3D data acquired by the LCMS system measures the distance from the sensor to the surface for every sampled spot on the road and elevation can be converted to a gray level. The darker the point, the lower is the surface and 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 differences 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 differences correspond to the low-spatial frequency content of the range information in the longitudinal direction. Most characteristics that need to be detected are located in the high-spatial frequency portion of the range data. The figure below (Figure 6) 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 differences (in blue) around the red line correspond to the macro-texture of the road pavement surface.

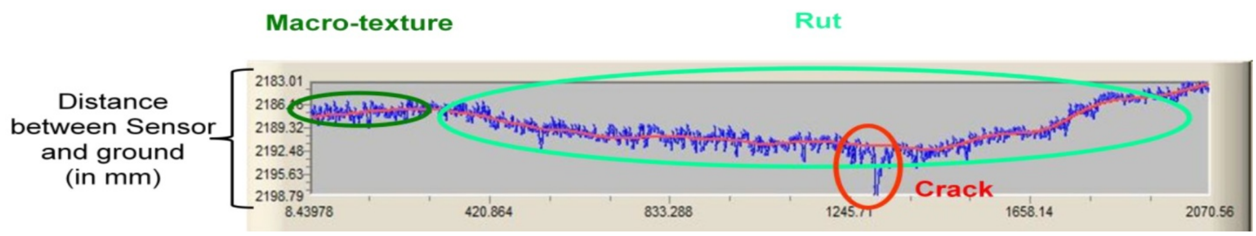

Figure 6. 2m transverse profile showing ruts, cracks and texture.

The Texture is calculated using the proposed Road Porosity Index (RPI). The RPI index is determined 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 Laser Crack Measurement implemented method allows texture to be evaluated continuously over the complete pavement surface instead of measuring only a single point inside a wheel path.

$$RPI = \frac{Vol_{air\ void} - Vol_{ravelling} - Vol_{cracks}}{Surface\ Area} \quad (4)$$

In order to compare the accuracy of the RPI model several tests were done on various test sections on several pavements and comparing the results with MPD (Mean Profile Depth) measurements collected by a standard 64kHz texture laser. Figure 7 shows a high degree of correlation (88%) between the RPI – LCMS method as compared to the MPD measurements for this range of asphalt textures.

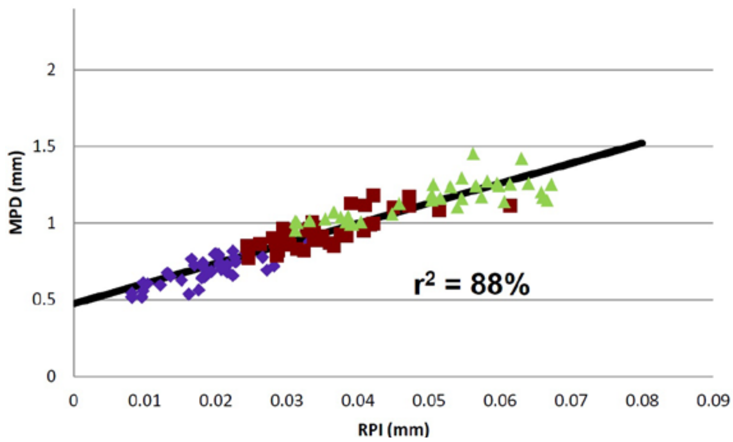

Figure 7. LCMS texture measurement correlation and repeatability [9]

The LCMS system can also determine raveling of asphalt pavement. 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 pitted and rough surface with obvious loss of aggregates. Raveling index is calculated by measuring the volume of aggregate loss (holes due to missing aggregates) per unit of surface area (square meter).

Figure 8 demonstrates a roadway image with a low intensity contrast between a crack, approximately 1 to 6 mm wide, and pavement background. The low intensity contrast makes the crack difficult to detect, even with the human eye. However, the data collected using the 3D laser technology from the same area indicate a more distinct contrast between the pavement background and the crack. Figure 8 shows the potential of the 3D laser technology for detecting cracks under low intensity contrast conditions and also evaluates the consistency of using the proposed system in detecting cracks under three different lighting conditions: nighttime (a), daytime with shadows(b), and daytime no shadows(c).

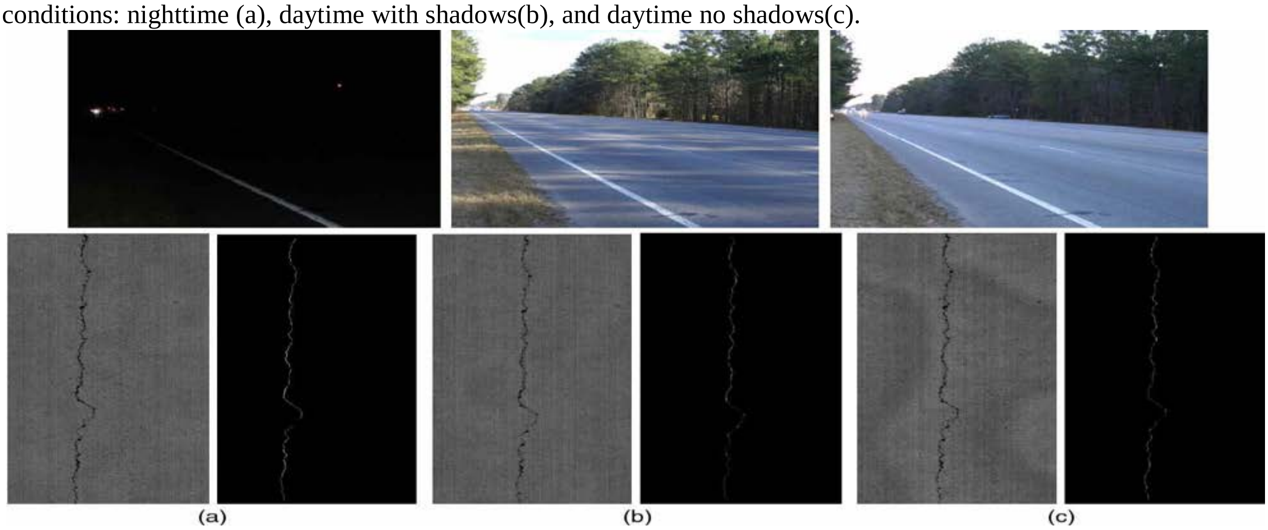

Figure 8. 3D laser data and corresponding crack detection results for three lighting conditions

Also, the 3D laser pavement data have the capability to remove the interference of contaminants on pavement surface, such as oil stains, tire marks, discoloration caused by the camera lens, incomplete lane marking, etc [11].

4. SUGGESTIONS

Laser system's application in pavement management is a developing area and it needs further studies (e.g. reliability and localization) into the matter, especially a Cost-Benefit Analysis is required to determine the cost effectiveness of laser devices and economical comparison between them and regular data acquiring methods.

5. CONCLUSIONS

Automated analysis of pavement images requires the use of image processing and pattern recognition techniques. New technologies of laser scanning overcome some weaknesses of common visual inspections and early systems in resolution and dynamic range. The method proves to be immune from noise. This paper 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 facing downward in such a way as to scan the entire 4m width of the pavement surface with 1mm resolution. This configuration enables the direct measurement of many various types of surface distresses by simultaneously acquiring high resolution 3D and intensity data. Laser Crack Measurement System (LCMS) is able to work with traffic flow (speed up to 100 Km/hr) that cause massive time and accident reduction (due to not closing the road lane through inspection period) and LCMS can determine the following pavement characteristics: rutting (rut depth, rut type), Macro-texture measurements over 100 % of the lane width, 3D and 2D data to characterize cracks, pot holes, raveling, sealed cracks, joints in concrete, tinning, etc, Day and night operation, IRI and longitudinal profile, Slope and cross fall. Also, it can be concluded that Laser Devices outputs are accurate and repeatable. These laser systems will be used by the transportation authorities and intended to replace the existing road measurement technologies.

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