Automated Survey of Pavement Distress based on 2D and 3D Laser Images

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Principal Investigator: Dr. Kelvin Wang
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ABSTRACT

Despite numerous efforts in recent decades, currently most information on pavement surface distresses cannot be obtained automatically, at high-speed, and at acceptable precision and bias levels. This research provided seed funding to produce a functional prototype developed by the research team with line lasers and 3D cameras that overcame many existing limitations, with the capability of obtaining 3D pavement surface models at true 1mm resolution with full-lane coverage, and conducting real-time analysis on rutting and cracking. In addition to the project funding, WayLink Systems Co. provided needed resources in hardware and other support to complete the research.

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INTRODUCTION

Accurate and timely information on pavement surface characteristics are critical for evaluating the performance, condition, and safety of pavement infrastructure. Both pavement design and pavement management rely on these and other information for comprehensive pavement evaluation. The research team at the University of Arkansas (UA) is recognized internationally as a leader in the automated survey of pavement infrastructure. The team has conducted research and delivered solutions to the industry for over 10 years. Starting in the mid-1990's, the Arkansas State Highway and Transportation Department (AHTD), the US DOT University Transportation Centers (UTC) program, and the National Cooperative Highway Research Program (NCHRP) provided funding support to the research team on various technology developments on highway and pavement information systems and automated condition survey.

Data collection on pavement surfaces include longitudinal profile for roughness, transverse profile for rutting, macro-texture for safety, and cracking and various surface defects for distresses. Pavement data collection technologies have improved gradually in the last few decades. Particularly after steady R&D investments in pavement profile measurements since the 1980's, roughness, rutting, and macro-texture data can be inexpensively obtained at acceptable accuracy levels. However, due to sensor and computing limitations, limited research funding, and inherent difficulties to meet stringent requirements of precision and bias, the hardware and software necessary to automatically obtain pavement cracking and other distress data at acceptable precision and bias levels have not been realized. In addition, even roughness, rutting, and macro-texture data are currently obtained through separate instrumentation on a relatively small area within a pavement lane.

Pavement engineering as an area of study has suffered from inadequate and poor quality distress data. High quality pavement distress data for the next-generation pavement design system, Darwin ME, is critically needed to facilitate the calibration of prediction models, and further validation of relevant mechanistic models. Further, many state highway agencies have been collecting pavement distress data, particularly cracking data, for years through manual, automated, or semi-automated means. However, it is believed that such data sets are of poor quality due to problems associated with consistency, repeatability, and accuracy of collected data and subsequent analyses. Despite the need to obtain pavement distress data for both management and design purposes, progress on delivering true automated survey technology for pavement distresses has been minimal.

In addition to being slow and unsafe when conducted in the field, manual survey results show wide variability (Morian et al., 2002). Therefore, automation technology for pavement survey has long been sought and tested for precision and bias (Wang 2000, 2005, and 2010; McGhee, 2004, Groeger et al., 2003; Huang, et al 2009). One product of the research team’s 10-year research effort is the Automated Distress Analyzer (ADA), which processes pavement images at 1-mm resolution for cracking information with full-lane coverage at highway speed – in other words, in real-time (Figure 1).

The current implementation of ADA is based on 1-mm 2D laser images of pavement surface, which poses challenges in terms of further improving its accuracy and consistency. Cracking, along with many other pavement surface defects, all have unique and distinctive characteristics in the 3rd dimension, which are all lost in 2D images. Therefore, developing new technology that can capture realistic pavement surface characteristics in the digital domain at sufficiently high resolution, or actual surface models of pavements, is a necessary initial step. New algorithms and software can be subsequently developed on the surface models to produce consistent, repeatable, and accurate pavement survey data. The recently developed 3D prototype system by the research team is demonstrated as being able to capture 1-mm 3D pavement surface data under adverse lighting conditions.

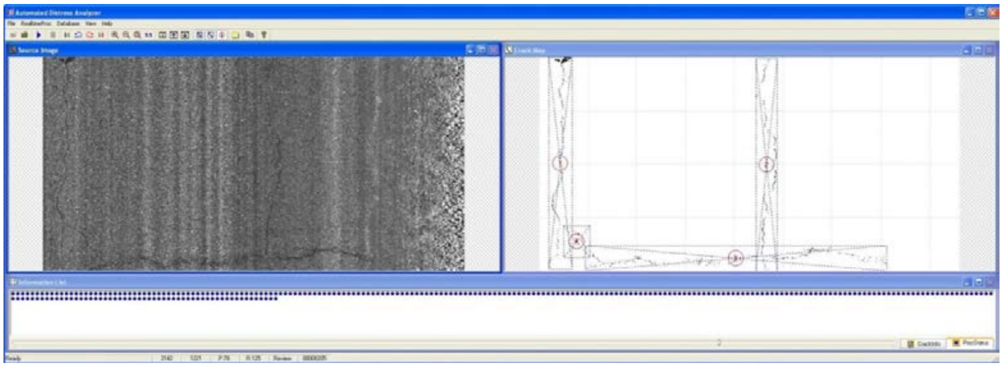


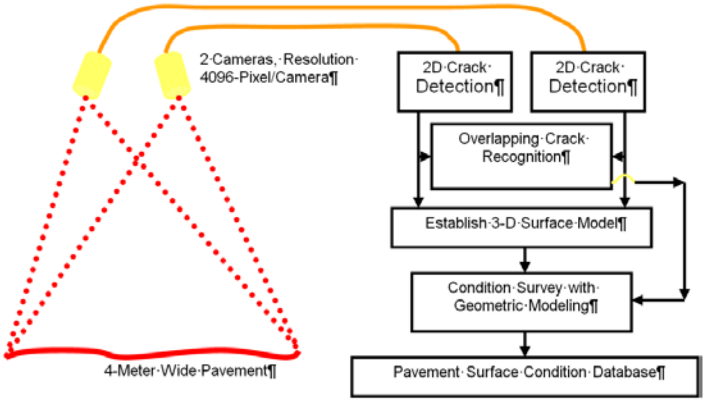
Figure 1. The Real-Time Automated Distress Analyzer (ADA)

The objectives of the proposed research are to leverage the expertise on automated distress survey developed by the research team in the last 10 years to (1) develop a vehicular platform, including laser based sensors, that can capture true 1-mm resolution 3D representation of pavement surface and in adverse lighting conditions, (2) develop algorithms and software to produce results on pavement distresses.

BASIS OF 3D DATA COLLECTION TECHNOLOGY

3D surface features of pavements have been studied closely for years for various data analysis needs. However, true 3D surface measurements of pavements obtained for computer analysis at high resolution and at highway speed have not been obtainable for production purposes. Rather, for decades, 2D images have been used by pavement engineers to estimate pavement distress, with less-than-desirable results. It was therefore natural to conclude that in order to have better solutions to pavement surface evaluation, obtaining pavement surface information in its original format, or a 3D representation, at sufficient resolution such as 1-mm, represents a new research frontier. However, this development heavily relies on advancement of sensor and computing technologies due to the need of high resolution, complete coverage of pavement lane, sustained high data rates of acquisition and analysis, and overcoming adverse influences of sun light and ambient light during data acquisition.

There are several techniques to collect 3D surface data. A conventional method is based on the photogrammetric principle, which has been widely used in highway engineering dating to the use of analog film. From 2005 to 2007, the NCHRP IDEA program funded the team to use the photogrammetric principle to establish 3D pavement surfaces in the project NCHRP-88, “Automated Pavement Distress Survey through Stereovision”. The research produced good results. However, the critical limitation of this technique is the lighting requirement for the paired cameras to obtain high fidelity 2D images of the pavement surface. Even today, the illumination of a pavement surface to the required intensity level under direct sunlight for a full-lane area is nearly impossible, which is required for photogrammetric image acquisition in order to have high-quality 2D visuals to establish common points in the paired images. Figure 2 illustrates the photogrammetric principle used in the NCHRP IDEA project and the resulting software to match a pair of 2D images with common points to generate a 3D surface model of pavement.



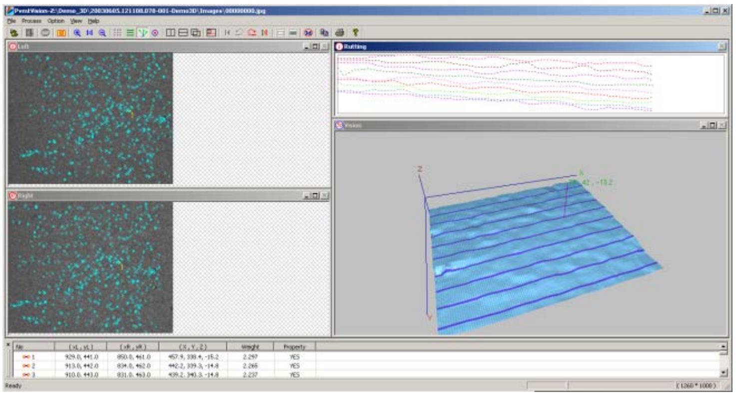
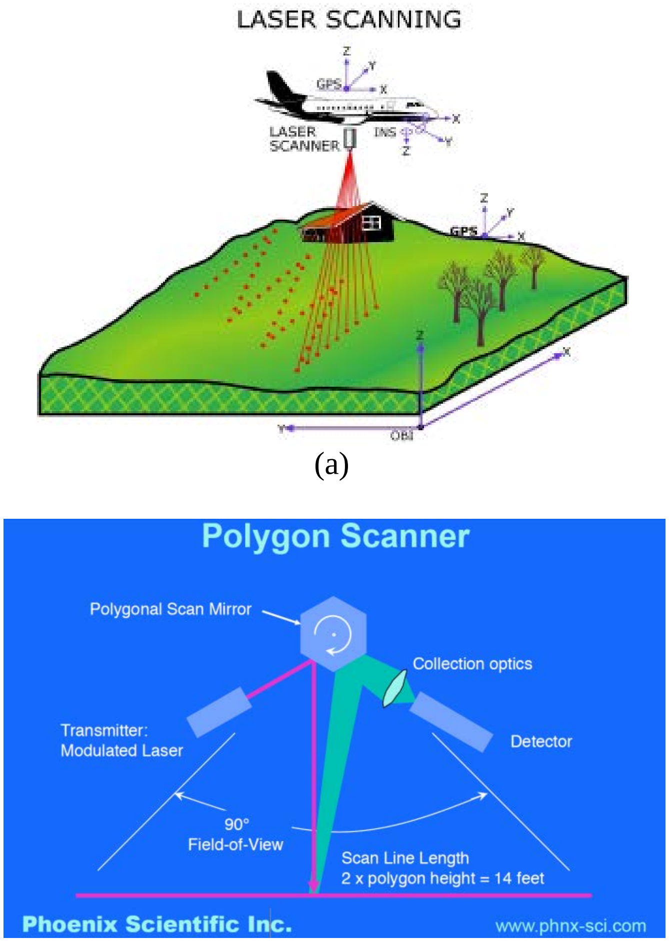


Figure 2. Basis of stereovision for condition survey and the 3-D reconstruction software (Wang, 2007)

Another technique for 3D surface modeling is Light Detection And Ranging (LIDAR), which was initially used to geo-reference terrain features. In some literature LIDAR is referred to as laser altimetry. A LIDAR system shown in Figure 3(a) is composed of a laser scanning system, GPS receiver, and an IMU (Burtch, 2002). The laser scan data is collected using a scanning mirror that rotates transverse to the direction of flight or motion. LIDAR signal is not a point but rather is an area beam. The beam is very narrow, but it does get larger as it moves away from the source.



(a)

(b)

Figure 3. LIDAR Principle (a) (Burtch, 2002) and Rotating laser system for pavement survey (b) (Herr, 2001)

Moreover, the laser beam also becomes distorted, taking on an ellipsoidal shape, as it travels along the scan (Burtch, 2002). Based on LIDAR principle, Figure 3 (b) shows a rotating laser system for pavement survey developed in the 1990's by Phoenix

Scientific (Herr, 2001 and 2009). Devices based on the rotating laser principle received widespread attention and enthusiasm early on. Due to difficulties in making significant improvements to the resolution of the system in the last decade, and the popularity of laser based 2D imaging system introduced several years ago, the usage of the technique based on the rotating laser principle has been limited to niche applications.

Figure 4 illustrates a 3D laser imaging technique that has been widely used for object inspection on conveyor belts in the recent decade. By illuminating a surface using a line laser and shooting 2D images using an area camera from the side (an angle) targeting at the narrow area of the laser line, the surface variation in the vertical direction can be analyzed by examining the laser line features in the captured 2D picture. When 2D images are captured in a sequence, the laser lines in the sequential 2D pictures can be extracted and combined sequentially to form a digital 3D surface.

Figure 4 Laser Line based 3D Imaging Technique on a Conveyer Belt

(http://www.adept.net.au/news/newsletter/200810-oct/3D_Camera.shtml)

This technique has been used by the research team to develop a 3D prototype system for pavement surface data collection to produce 1-mm resolution 3D images of pavement surfaces, including the sample 3D images shown in the proposal. It should be noted that the cameras used with this technique are commonly referred to as 3D cameras, despite the fact that they are specialized 2D cameras that have dedicated processors inside the cameras to extract the laser lines from the captured 2D images.

The same technique is also used recently by the Quebec company INO for its new LCMS product, which licensed the technology to Pavemetrics. However, the proposed system, PaveVision3D, has substantially better performance due to higher specifications and more features than the LCMS in terms of 3D line rate, 2D visual data, and other technical capabilities.

3D cameras based the line laser principle can only produce height information at pixel points. Laser intensity information on pavement surface from 3D cameras is generally of poor visual quality. As pavement surface imagery is important supplementary information to the 1-mm 3D surface models for both purposes of visualization and automation algorithm for distresses, the proposed research will integrate a 1-mm resolution 2D laser imaging sub-system into the PaveVision3D, resulting in a hybrid 2D/3D data acquisition system.

THE ALGORITHM OF 3D LASER SENSOR IN PAVEVISION3D

Figure 5 shows a basic relationship for determining the distance from the camera to the pavement based on the laser point. *C* and *T* represent two reference points (e.g., camera and laser), while *T stands for* a target point. The length *L* is determined with the baseline separation B and the angles α and β:

$$L = \frac{B}{\sin(\alpha+\beta)}\sin(\alpha) \qquad (1)$$

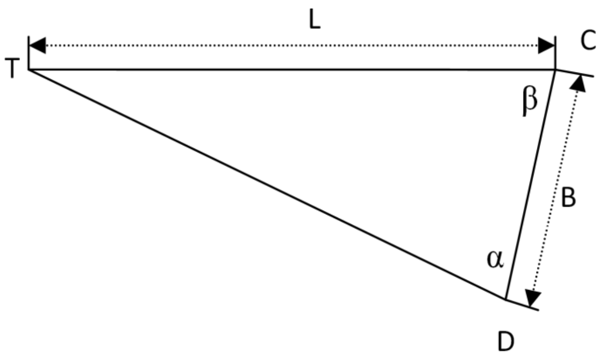


Figure 5. Simple Triangulation Principle

It is not possible to measure the baseline separation and angles accurately in the field during driving. A different technique in Figure 6 for obtaining depth information is used even if the two angles (α and β) and one separation length *B* are not known.

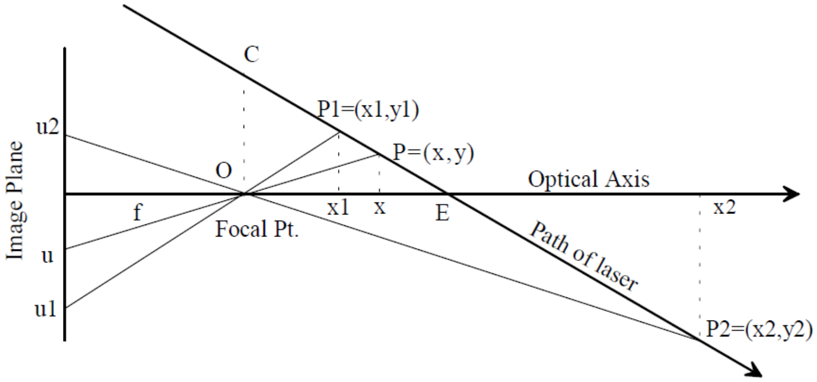


Figure 6. Field Triangulation Principle

The camera is represented by the *Image Plane, Focal Point* and *Optical Axis*. The laser light is represented by line *CE* and *P* is the target of interest. The unknown is the distance of *x*, the projection of point *P* on the optical axis. *u* is the vertical projection of point *P* on the image plane . P_1 and P_2 are two points used in the calibration and x_1, x_2,

u_1, and u_2 are known after the calibration. *E* is the point where the path of the laser intersects the optical axis. Two equations are based on geometry of similar triangles:

$$\frac{y_1}{x_1} = \frac{u_1}{f} \text{ and } \frac{y_2}{x_2} = \frac{u_2}{f} \qquad (2)$$

By moving the origin of the coordinate system at the focal point, the slope (*m*) of the laser path and the y-intercept (*c*, the height of point *C*) are:

$$m = \frac{y_2 - y_1}{x_2 - x_1} \text{ and } c = y_2 - m * x_2 \qquad (3)$$

By substituting (2) into (3) to eliminate y_1 and y_2, two new equations will be:

$$m = \frac{u_2 x_2 - u_1 x_1}{f(x_2 - x_1)} \text{ and } c = \frac{u_2 x_2}{f} - \mathrm{m} x_2 \qquad (4)$$

The point *C* can be found given measurements of y_1 and y_2 or knowledge of the focal length. This point can be used as the location of a "virtual" laser source, and the length *OC* becomes the "virtual" baseline distance. The line *uP* passing through *O can* be represented by Equation (5) and the laser path is represented by Equation (6). Equation 7 is developed based on Equation 4, 5, and 6. N, d and k are obtained after the calibration in Equation (8) (Based on Blackburn, 1994 and Wu, 2007):

$$y = \frac{u}{f} x \qquad (5)$$

$$y = mx + c \qquad (6)$$

$$x = \frac{N}{ud - k} \qquad (7)$$

$$d = x_2 - x_1, k = u_2 x_2 - u_1 x_1, N = (u_1 - u_2) x_1 x_2 \qquad (8)$$

THE RESEARCH APPROACH AND RESULTS

The proposed system collectively called PaveVision3D will have four major capabilities integrated into a single vehicular surveying platform: surface distresses, profiling (transverse for rutting and longitudinal for roughness), macro-texture, and roadway geometry. All data sets in the survey vehicle will be obtained at highway speed and processed in real-time. Software solutions for the four capabilities are among the key contributions of the proposed research that no other research teams have demonstrated with 3D data to date. It is anticipated that efforts will be made in the proposed research to conduct precision and bias analyses based on various ASTM and AASHTO protocols against widely accepted and certified measurement devices for macro-texture and longitudinal profile, and manual surveys of pavement surface distresses.

The proposed PaveVision3D will be based on a single vehicular platform (Digital Highway Data Vehicle, DHDV) shown in Figure 7 with entire-lane area coverage for all collected surface data sets. The research tasks include designing and constructing the hybrid 2D/3D laser imaging system with the following unique characteristics:

1. Integrated arrays of 3D cameras, lasers, accelerometers, multi-CPU and multi-core computing devices, and differential GPS receivers and one high-precision IMU.
2. Software algorithms to provide the four automated capabilities: surface distresses, profiling (transverse for rutting and longitudinal for roughness), and macro-texture, and roadway geometry.

3. 3D data for entire surface of pavement lane at 1-mm resolution in transverse (x), longitudinal (y), and height (z) directions at the data collection speed of 60 MPH (100 KPH).
4. A sub-system to acquire 1mm 2D laser images of surface imagery. 3D and 2D data streams are synchronized for location accuracy.

Figure 7. The Prototype DHDV with Two 2D/3D Hybrid Sensor Cases of PaveVision3D

Current Research with the Prototype

Figure 8 shows the sensor system configuration of PaveVision3D in a DHDV. Each sensor case covers half of a lane and contains two sensor assemblies: 2D laser imaging for 1mm visual images, and 3D laser imaging for 1mm surface information. Figure 9 illustrates an actual data set obtained from the prototype DHDV equipped with PaveVision3D hybrid sensors: the gray-scale visual imagery on the left from the 2D laser assembly, and rainbow 3D imagery on the right from the 3D laser assembly. The bar of red line on the 3D surface in Figure 9 is the virtual measurement tool of transverse profile.

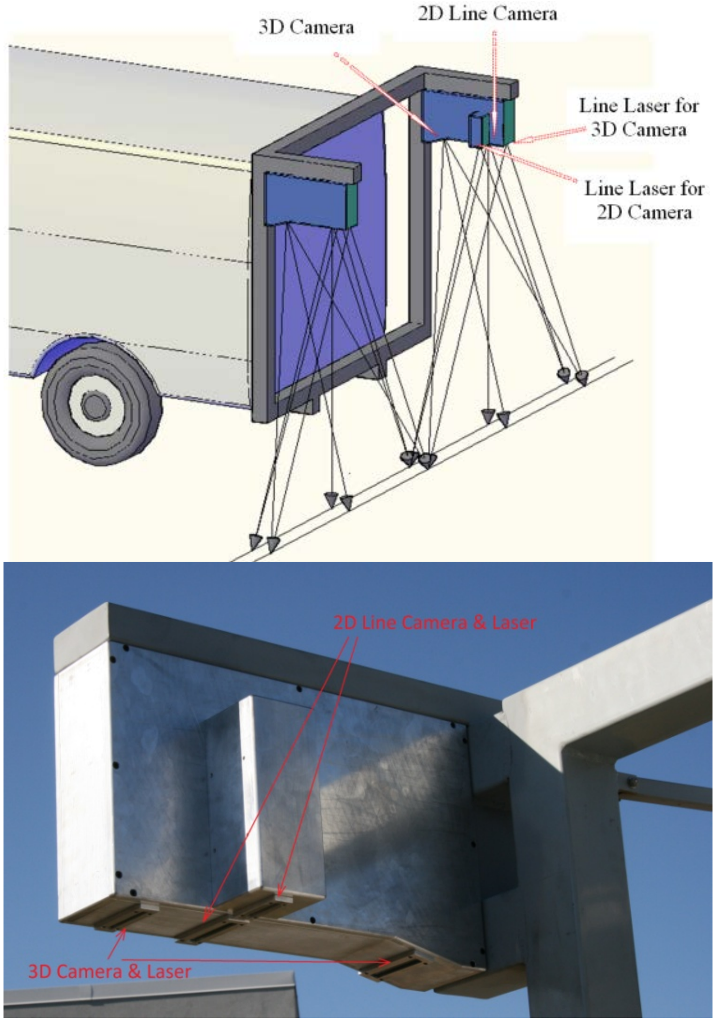


Figure 8. Sensor System Configuration (top) & a Laser Imaging Sensor (bottom)

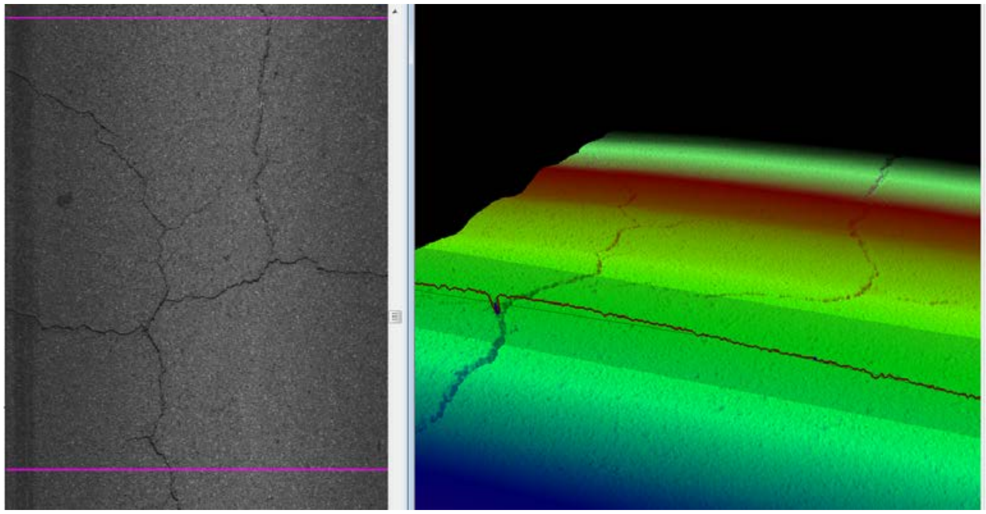


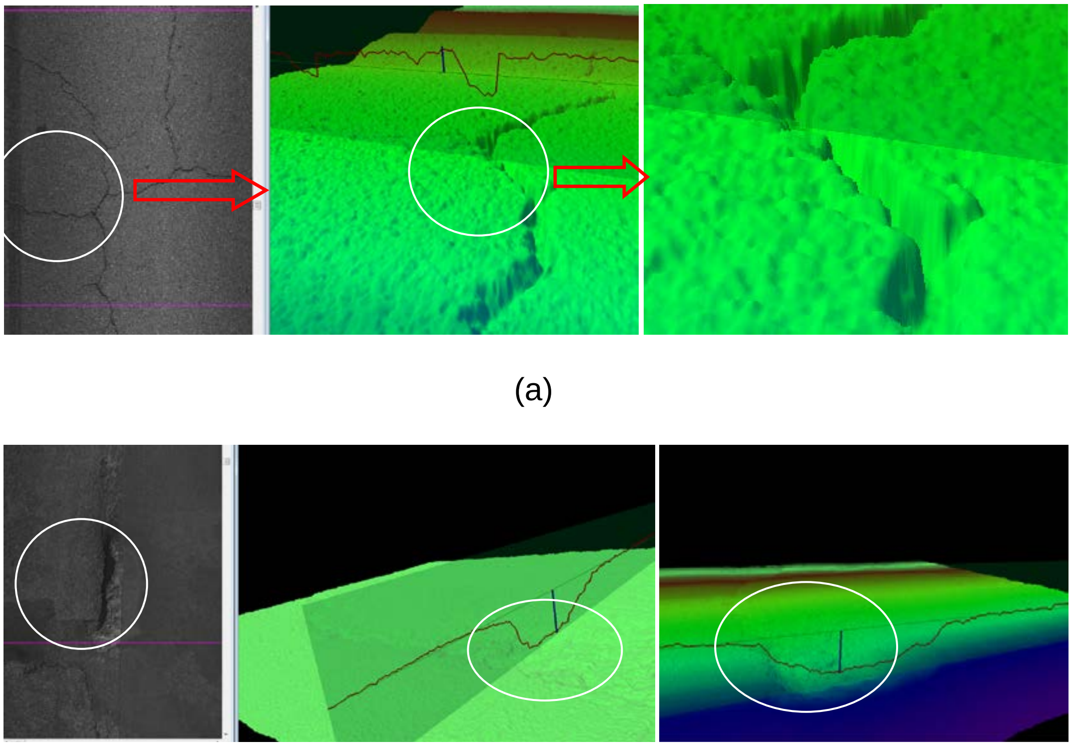
Figure 9. Sample 2D and 3D Data of an Actual Pavement Area

Currently, the design and engineering for building two prototyping sensor cases has been completed shown in Figures 7 and 8, including laser assembly, cameras, lenses, filters, trigonometry relationships, and geometric dimensions to construct the cases. 2D line cameras at 2048 pixels are used to capture surface imagery of pavement at 1-mm resolution in both transverse and longitudinal directions. A 2D line camera covers about half lane or 2-meter wide area. A 3D camera at the resolution of more than 2000 pixels in the transverse direction is used to cover half-lane as well with 3D profile rate at 6,000 per second.

The assembled prototype system can operate during any weather condition as long as pavement surface is dry. Due to the effective use of wavelength filters and line laser emitters in the prototyping system, sun light does not influence data quality for both 2D imagery and 3D surface data. The prototype system can operate at night or in day time to collect both 2D and 3D data at the same quality levels.

Cracking, Rutting, and Other Surface Distresses

The proposed PaveVision3D hybrid system can present surface defects in a visual and realistic format as shown in Figure 10. Figure 10(a) illustrates a 2D 1mm image of pavement section on the left produced with the 2D 1-mm laser imaging sub-system, a corresponding 1-mm 3D model in the middle, and close-up of the 1-mm 3D surface on the right at 1:1 zoom ratio for the zoomed-in surface. Figure 10(b) shows a different pavement section with both rutting and pothole problems. Image data in Figure 10 was generated by the research team with the prototype PaveVision3D.



(a)

(b)

Figure 10. Cracking and Rutting/Pothole on 2D and 3D Imageries

As 3D surface models of pavements clearly show surface defects as they are in the field, the process then becomes clearer than using 2D images only to develop algorithms to capture the relevant information and to produce analysis results on pavement surface characteristics. In addition, rutting data from the proposed 3D system will have more than 4000 reference points across a pavement lane, exceeding the number of measurement points in any rutting instruments in use today. In Figures 10(a) and 10(b), a dynamic rutting line or bar in red is visible, which is essentially an extracted surface profile in the transverse direction at the point of reference. This feature has been implemented in software in the current prototyping system.

In using 2D images for cracking survey with ADA, thin cracks, cracks on open-graded pavements, and certain types of alligator cracks can be missed or miss-identified. Per preliminary tests, 3D surface data along with matched 2D laser images can be used together to improve the processing accuracy. Algorithm development to accomplish this capability will be a major thrust of research to be conducted in the proposed project.

MERIT OF THE TECHNOLOGY

Data collection and evaluation of pavements are integral processes in pavement engineering. Their importance is similar to portfolio and asset management of a mutual fund: getting critical data to evaluate the performance of the investments. However, despite decades of research and to a certain degree, frustration resulting from slow technological progress, the automation level of data collection and analysis remains limited. In addition, data collection on the same pavement must be conducted separately for different purposes with different types of equipment.

The research team has constructed a prototype system for 3D data collection on pavements with complete lane coverage and at 1-mm resolution. The logical next step is to overcome certain limitations of the new 3D technology and produce a production-worthy platform for true 1-mm resolution in all three directions (x, y, and z) at the data collection speed of 60MPH.

In addition, data analysis with the true 1-mm resolution 3D pavement surface data is a critical component of the proposed research. It is anticipated that transverse and longitudinal profiling, pavement surface cracking and other distresses, and macro-texturing will become standard outputs from the proposed PaveVision3D technology in a single vehicular platform. This platform of hardware and software shall have real-time processing capabilities to generate these data outputs. As safety relating to pavement friction is important for the driving public, the researchers will establish statistical correlations if there are any among pavement macro-texture data from PaveVision3D, macro-texture data from point laser ranger, and standard friction testers.

The PaveVision3D technology has the potential to replace several types of pavement data collection devices with a single vehicle, including transverse and longitudinal profilers, pavement distress imaging system, and macro-texture measurement device. These traditional devices and technologies could easily constitute over $2 million in investment for a highway agency. A complete vehicular platform with PaveVision3D technology may cost less than $1 million. In addition, users have additional advantages with the proposed research, such as positioning data integration, which is automatically conducted during data collection among all collected data sets, and accessibility to true 1-mm pavement surface data and 1-mm 2D visual data through an integrated database system. Additional labor savings from using single two-person crew for a PaveVision3D based vehicle versus using several two-person crews operating the different devices are significant over a period of five years.

CONCLUSION

Despite the limited funding of this project, the research team produced a prototype that can obtain 2D and 3D laser images of pavements, and developed basic algorithms for measuring rutting and cracking distresses. The long-term objectives of the proposed research are presented in the report. However, funding from both private and public sectors are sought to continue the research to establish virtual pavements at 1mm resolution and at highway speed. WayLink Systems Co provided much needed hardware, vehicular platform, and other resources to complete the described research.

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