Use of Digital Cameras for Pavement Surface Distress Survey

KELVIN C. P. WANG AND XUYANG LI

The categorization and quantification of the type, severity, and extent of surface distress is a primary method for assessing the condition of highway pavements. Several methodologies are reviewed that were developed to automate pavement distress surveys. Existing available applications of automated pavement surface distress surveys rely on analog video technology, which poses several limitations on the performance of the systems. Through the use of new digital, high-performance cameras, high-definition images of pavement surfaces were acquired. These images were directly captured, archived, and analyzed by microcomputers. Two types of digital cameras were used in the research: area scan and line scan. Research revealed that high-performance area scan cameras may have advantages over line scan cameras. However, line scan cameras based on the technique of time delayed integration have good potential when tight synchronization and correct timing control are fully integrated into the system. The imaging subsystem of a full digital highway data vehicle that has been developed at the University of Arkansas is also discussed.

The most widely used method to survey the surface distress of highway pavements is still human observation. This approach is extremely labor-intensive, error prone, and hazardous. An ideal automated distress detection and recognition system should find all types of cracking, spalling, and any other surface distress of any size, at any collection speed, and under any weather conditions. The automated device should be affordable and easy to operate. In recent decades, technological innovations in computer hardware and imaging recognition techniques have provided opportunities to explore new approaches to automating distress surveys in a cost-effective way. However, despite the performance improvements of new equipment over the older systems, serious problems remain in implementation costs, processing speed, and accuracy.

The objectives of this paper are to (*a*) review existing technologies of automated systems for the survey of highway pavement surface distress, and (*b*) present the use of new digital cameras to directly capture, archive, and analyze pavement surface images. Because commercial implementation of automated systems uses proprietary imaging algorithms, the description of these systems focuses primarily on the aspects of system design.

PRINCIPLES OF AUTOMATED DISTRESS SURVEY AND DEVELOPMENT DIFFICULTIES

Data Acquisition

No consensus exists on the smallest size of cracks that should be used for engineering purposes. However, if a system can detect a crack 1.5 mm wide, it would be considered adequate. Therefore, a fully automated distress collection system should be capable of detecting cracks less than 2 mm wide.

A number of crack attributes may be used for their detection. Mendelsohn (*1*) lists several possible approaches to conducting such detection. The most obvious method is through visual detection of cracks. Cracks can also be detected as abnormal depths in surface texture by measuring the profile. Additionally, vehicle tires make slapping sounds against cracks when they are crossed at high speed, suggesting another potential detection method—acoustic technology.

A profilometer is successfully applied to pavement roughness measurement. If the sampling area and resolution of the profilometer were sufficiently high, it could be an ideal means for crack detection. Unfortunately, a lane 4 m wide sampled at 2.5-mm intervals in both transverse and longitudinal directions would require 15 million readings per second at 89 km/h (55 mph). No profilometer exists with such a high-performance capability. Although the device to detect sound variations is inexpensive, the low resolution and low dynamic range of such a device prohibit it from being useful.

Therefore, collection of surface distress data through visual examination is still the method to find and classify cracks, through either human examination or a man-made vision system. The system concept for the automation of a pavement distress survey is shown in Figure 1. The system has two distinct subsystems: an image acquisition subsystem for data collection and an image display and interpretation subsystem for data processing. Image data can be collected by various means. A popular method is to record pavement surface images in analog format, through area scan cameras, line scan cameras, or laser scanning equipment. A digitizing process converts the analog images, transforming the analog data into digital format that can be read by computers. In recent years, an emerging data collection method has been the use of digital capturing devices, such as a digital camera that converts analog signals from an object into digital signals.

Much research and development has been aimed at the computerized processing of images in order to augment the computer's power with some human-like visual sensing capability. This technology, often termed computer vision or machine vision, is related to the second subsystem of image interpretation of collected pavement surface data, or data processing.

Difficulties of Developing a Fully Automated Survey System

Humans can detect and classify pavement surface distress with ease. For instance, humans can perceive the connectivity of cracks without hesitation. Computer vision systems distinguish cracks through identifying disturbances in the brightness range of the surrounding texture and must be designed to seek connected regions through

Department of Civil Engineering, 4190 Bell Engineering, University of Arkansas, Fayetteville, AR 72701.

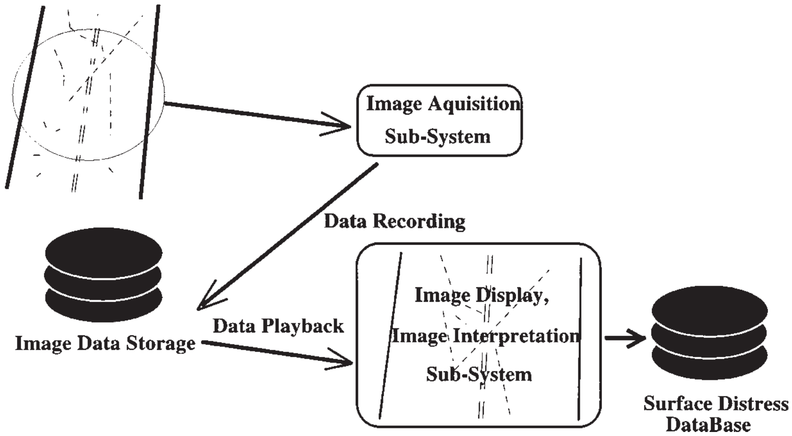

FIGURE 1 System concept in pavement surface distress survey.

mathematical algorithms. It is difficult for a computer vision system to segregate cracks from pavement surface texture, especially in the texture of bituminous materials. Even if we understood all the image processing handled by the human brain and were able to convert that knowledge so as to make the computer's performance comparable to that of humans, the amount of processing power required would be of the order of 1,012 billion floating-point operations per second (1 teraflops) (*2*). This processing power is within the reach only of today's fastest supercomputers. A workstation at a reasonable cost and augmented with a high-end imaging board can achieve only on the order of 1 billion floating-point operations per second (1 gigaflop).

Facing this tremendous challenge, many academic and industrial efforts have attempted to automate the evaluation of pavement surface distress. The developed systems include vehicles equipped with video gear traveling at or near normal travel speeds. Pavement surface images are collected into analog storage devices through cameras mounted on the vehicle. Image processing is normally conducted off-line in an office environment. It has been a frustrating period during the past two decades for developers to establish distress survey systems according to the requirements of the highway industry in the areas of real-time processing, consistency and repeatability of surveys, and accuracy. A number of reasons explain why serious problems still exist after so many years of research and development:

- Image processing for pavement surface distress survey at any practical speed requires high-performance computing equipment. When such equipment is not available or a compromise is made in performance, then data quality, processing speed, or both are affected.
- Image processing as a field of study is still evolving. Many aspects of image processing in the human brain are not yet understood.
- In the detection and recognition of pavement surface distress, a particular difficulty is related to the surface texture and foreign objects on the pavement surface, such as oil spill.
- No standard indexes quantitatively define the types, severity, and extent of pavement surface distress. However, efforts are under way to initialize a set of standards (*3,4*).
- Data collection is not standardized, especially in image resolution and collection approaches. For instance, because there is no standardized way to define a crack map of a pavement area in terms of resolution and dynamic range, images from one survey system would differ from images from another system.
- The available systems use incompatible image processing algorithms and hardware designs. From the user's perspective, it is not necessary to have compatibility of hardware and software with different vendors' systems. However, this incompatibility produces survey data from different vendors that cannot be compared.

Although the difficulties in implementing a useful survey system are many, data collection is the first step toward a fully automated system. Traditionally, analog-based area scan cameras are used in automated pavement surface distress survey. The format of the output signal is frame based according to a standard defined in the 1950s by the U.S. National Television Standard Committee. Similar formats are used in other parts of the world. There are three distinct problems with analog-based cameras. First, a digitization step is required to convert the wave signal data to digital data that can be understood by computers. Second, the highest possible digital resolution from data with analog cameras is about 400 pixels per line. Third, area scan cameras have an inherent problem in the inspection of a moving surface when the complete and exact coverage of the surface is required. The problem is surface overlapping or discontinuity of adjacent images. Additional computation is needed to have exact and complete coverage of the pavement surface, such as the use of the speed compensation encoder in the Swedish system PAVUE (*5*).

The overwhelming difficulty in the automated survey of pavement surface distress is the high data rate and associated extraordinary computation needs when real-time or near real-time processing is necessary. Real-time processing is defined as processing the data as the vehicle is collecting images at highway speed, normally between 80 and 100 km/h. Off-line processing can also be done with captured images on tape or computer storage. When the processing speed is equivalent to vehicles' traveling highway speed, the off-line processing can be viewed as real-time processing.

Eight-bit gray scale (256 gray levels) images are assumed adequate for pavement surface distress survey. In addition, assume (*a*) the pavement width is 3.7 m (12 ft), (*b*) image resolution is 2048 (2k) pixels per line per lane, (*c*) uniform resolution in both directions on the 2-D surface, (*d*) vehicle speed is 100 km/h (about 60 mph). The resulting incoming raw data rate is about 31 megabytes per second. Not long ago, only supercomputers or equivalent workstations could read, process data, and generate results at this speed. Recent rapid advances in microcomputing and input-output systems provide an opportunity to explore new approaches to tackle the difficult problem of developing an automated, real-time survey system for pavement surface distress.

STATUS OF RESEARCH AND DEVELOPMENT

Since the 1980s, a number of pieces of working equipment have been produced for the automation of pavement surface distress survey. Several major efforts produced working systems with the capability of at or near real-time processing: the Japanese Komatsu system, the U.S. PCES system, the Swedish PAVUE system, and the Swiss CREHOS. Both the Komatsu and CREHOS systems were based on proprietary laser technology and are currently not available for practical use. Therefore, they are not discussed in this paper. Although the PCES system is no longer available for data collection, the research effort of PCES is interesting because it was the first attempt to apply line-scanning techniques to capture and analyze pavement surface distress. The PAVUE system is currently used for both data collection and analysis.

U.S. PCES System

Immediately after studies sponsored by the National Science Foundation in the mid-1980s, Earth Technology Corporation launched large-scale research on the automation of pavement surface distress survey, resulting in the creation of a research arm, the Pavement Condition Evaluation Services (PCES). The automated system created by PCES was the first to use line scan cameras to collect pavement data. Line scan cameras have been primarily used for surface inspection for decades in manufacturing, agriculture, and semiconductor businesses. Surface inspection is also referred to as web inspection. This type of inspection is mainly concerned with part or product defect identification. The inspected objects are traveling at high speed on the web, and the image is captured with stationary cameras through capturing one line of image at a given moment. PCES's approach was unconventional at that time because line scan cameras were never used in the field of pavement engineering. In addition, although the line scan camera's resolution and performance were better than those of the conventional area scan camera, it required many customized efforts, such as special boards and software to support the cameras.

In the PCES system, digital signal processing was used in real time, exploiting custom filter circuits, which are 3×3 neighborhood convolver boards. Each of the two 512-element line scan cameras continuously covers 1.2 m (4 ft) of pavement, for a total of 2.4 m (8 ft) of pavement width. Each camera is supported by an 8-bit analog-to-digital converter, a convolver board, and a 68020 processor. An additional 68020 processor supervises the system activity. The system was intended for daylight use throughout a normal range of highway speeds.

The PCES system also includes a VersaModule Eurocard (VME) bus–based 32-bit computer to power the image processing engine, an interrupt-driven software and proprietary pipeline hardware to accomplish real-time processing, and an imbedded operating system that was contained in read-only memory.

The vehicle developed is shown in Figure 2. The vehicle is a 6.4-m (21-ft) Grumman truck body, which contains space for all system hardware, an operating console, and an observer station. Two 15-kW diesel generators power the computer, lighting, and other equipment. It should be noted that in order to obtain lines of

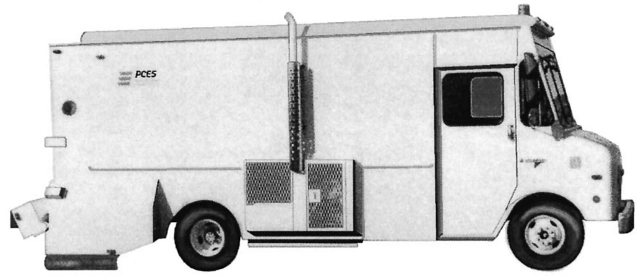

FIGURE 2 PCES survey vehicle.

images at required speed, line scan cameras need much higher intensity lighting than conventional area scan cameras. The lighting from the PCES system could burn the asphalt surface if it were directed at the same areas for a few minutes.

Earth Technology Corporation did not continue to fund the research after the first operational PCES system was built. Several factors contributed to the decision. One important factor is that the necessary technologies associated with the image capturing and processing were not sufficiently mature. For instance, a high-performance line scan camera contained only 512 elements in the linear array. Today's line scan cameras can exceed 4,096 elements, with a much higher frequency. In addition, PCES designed and produced its own processing boards and made its own system-level software, which were not only costly but also constrained the research team from obtaining higher performance equipment from third parties because of incompatibility.

Swedish PAVUE System

Infrastructure Management Services (IMS) primarily markets its service with the PAVUE system, which consists of the acquisition equipment to collect pavement distress data and the off-line analysis workstation to diagnose the gathered images. The acquisition equipment includes four video cameras, a proprietary lighting system, four S-VHS videocassette recorders, and the speed-compensation module. This image collection subsystem is integrated into a Laser RST van that also collects other pavement information. The off-line workstation uses a set of proprietary and custom-designed processor boards to analyze continuous pavement data from the recorded video images.

Figure 3 illustrates the data flow of the PAVUE system. Each of the four video cameras covers about one-fourth of the pavement surface, resulting in a resolution of about 1,400 pixels per lane. The speed compensation device allows the van to travel at highway speed to ensure that the video image is continuous with uniform resolution in both longitudinal and lateral directions. The detectable size crack is about 2.5 mm ($\frac{1}{8}$ in.). A strobe lighting system compensates for irregular lighting of the pavement surface.

The unique feature of the PAVUE system is its image processor boards. A total of 12 different VME-based boards were developed by IMS to form the core of the image processing. A total of 80 boards is used in a full PAVUE processor system. The boards were constructed with a combination of various customized and off-the-shelf circuits. Image processing algorithms were also coded in hardware to speed the processing.

The image processing technique used in PAVUE is generally referred to as pipeline processing, in which image data are piped

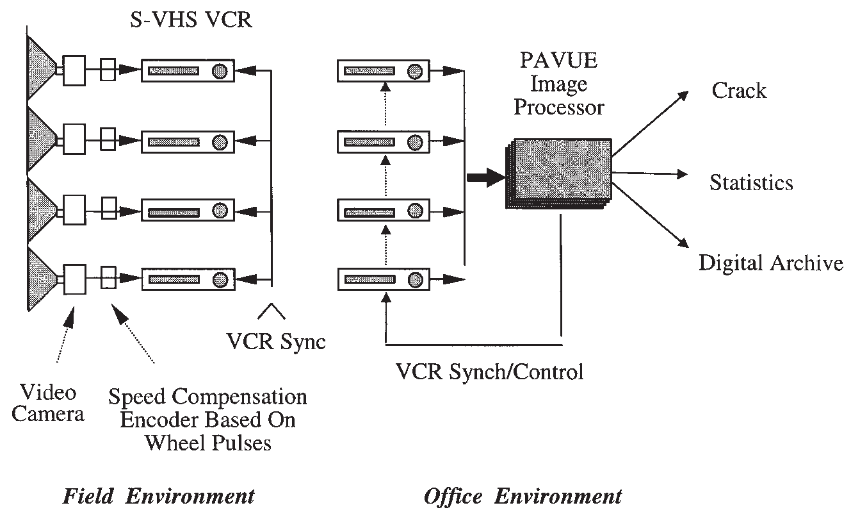

FIGURE 3 Data flow in IMS's PAVUE system (*5*).

through a series of on-board computational elements, or chips, that contain algorithms in hardware. The elements perform a range of image processing tasks and are connected through a tight on-board and among-board communication network. Images are processed at various stages in the pipeline simultaneously. The high-performance hardware allows the PAVUE system to process pavement images up to 86 km/h (55 mph) at a high resolution. However, images of surface distress are stored on S-VHS tapes in analog format.

USE OF DIGITAL CAMERAS

Advantages of Digital Cameras

Digitization is conducted inside digital cameras, eliminating the need for a separate digitization step. The output images of digital cameras can be processed directly by computers in real time. The images captured by digital cameras can be of high resolution, which is higher than normal analog area scan cameras. Digital cameras offer a variety of practical features. These features include externally selected high-speed electronic full-frame shuttering, asynchronous (random) shuttering, extended integration, built-in video enhancement, electronic exposure to eliminate auto iris lenses, area of interest scanning, intensifiers and gated intensifiers, remote imagers, fiber optic faceplates, and external pixel clocking.

Principles and Properties of Digital Area Scan and Line Scan Cameras

Charge-coupled devices (CCDs) have many applications. The most important one is in imaging. The basic operation of the sensor is to convert light into electrons. When light is incident on the active area of the image sensor, it interacts with the atoms that make up the silicon crystal. The energy transmitted by the light is used to enable an electron to escape from the tight control of one atom to roam more freely about the device as "condition" electrons, leaving behind an atom short of one electron. The more photons incident on the sensor, the more electron-hole pairs generated. The intensity of light can be obtained by measuring the amount of electrons activated by light. The process of collecting electrons by the CCD sensor is called integration. Digital area scan cameras use CCDs to digitize images formed from the lenses. At each pixel location, the brightness of the image is sampled and quantized. For gray-scale (i.e., monochrome) area scan cameras, this step generates an integer for each pixel representing the brightness or darkness of the image at that point. When this has been done for all of the pixels, the image is represented by a rectangular array of integers. Digital area scan cameras send this array of integers to computers connected to them through signal cables.

Progressive scanning is a method of scanning image information out of the CCD sequentially, line by line. This allows full-frame, full-resolution images to be captured in extremely short duration. Some progressive scan cameras use interline transfer CCDs as opposed to full-frame transfer CCDs. This format allows for high-speed electronic shuttering. The actual horizontal lines of video can be scanned out in one of two modes. The standard operation is the interlace mode, in which the odd field is scanned first, followed by the even field. For noninterlace mode, the camera scans the same field repeatedly. The shutter speed of a digital camera is controlled by electronic shuttering. Images are electronically shuttered by scanning out only a portion of the charge that has accumulated over one field time. Varying the portion of the charge retained yields specific shutter speeds. The electronic shutters of some area scan cameras have speeds selectable from 1/50 to 1/39,000 s. They can be asynchronously reset by external pulse control.

There are three modes to control the asynchronous reset and the shutter speed:

- Internal shutter speed mode. The video signal starts with internal V-reset timing related to shutter speed. A built-in frame memory can maintain the asynchronously captured full-frame image until the next external pulse comes in.
- Direct shutter mode. It is selectable from a large range (e.g., from 1/39,000 to 1/12 s), in increments of one horizontal scan time.
- Asynchronous reset with no shutter. Video images are acquired at a constant speed (e.g., 1/12 s), with no electronic shutter.

Line scan cameras scan one line at a time, unlike area scan cameras that scan a 2-D area at a single pass. The resolution of line scan cameras can be as high as 6000 elements or pixels per line with a data rate of 30 MHz. In recent years, high-performance digital line scan cameras have been widely used for surface inspection. The many problems associated with analog area scan cameras do not exist with digital line scan cameras. However, line scan cameras do require higher light intensity and do not have shutter to control exposure.

A new type of high-performance line scan camera used for high-speed and low-lighting applications is the time-delayed integration (TDI) camera. TDI makes use of synchronous motion to take multiple pictures of the same image and add them to get an amplified image. The high sensitivity of TDI cameras is caused by image integration over multiple stages, as shown in Figure 4. A TDI camera has many times the integration period of a regular line scan camera if the line rate is constant. For instance, compared with a regular line scan camera, a typical TDI camera has 96 stages, resulting in 96 times the integration period and 96 times the amount of signal for a given light input. After the last TDI stage, the sensor transfers its collected charge to one or more readout registers. These registers serially shift each pixel's charge from the shift register to an output node that uses a sense diffusion to convert the charges into voltages. After this transfer and conversion, the voltages are amplified. Then the camera's analog-to-digital board converts voltages to digital numbers. The frame grabber gets these digital numbers through the connecting signal cable. The overall sensitivity is improved by a factor of 80, as a result of added noise sources in the TDI sensors.

A crucial matter in operating a TDI line scan camera is the synchronization of the scanning speed and the TDI stage shifts. TDI line scan cameras usually offer a hardware interface to accept a synchronization signal from a controller. In the application of highway pavement image collection, the controller is linked to a speed encoder mounted on the transmission of the vehicle that houses the camera.

Data Collection with the Two Types of Cameras

The first camera that was tested in a data collection vehicle is an area scan camera. With the vehicle traveling at 97 km/h (60 mph) and the shutter speed of the area scan camera set to 1/10,000 s, the images captured under normal sunlight are quite clear. An example image is shown in Figure 5.

A TDI line scan camera was also tested in the same vehicle. Before a line scan camera can be set up, several parameters need to be calculated. Assume that the width of the pavement to be captured is 12 ft (3658 mm). One pixel on the final image represents less than 1 mm on the pavement surface. Each scan line should contain at least 3658 pixels. Suppose the vehicle's speed is 48 km/h (30 mph or 13 408 mm/s). The camera should operate at a speed of at least 1/13,408 s per scan line. In other words, the external synchronization signal frequency should be about 13.4 kHz.

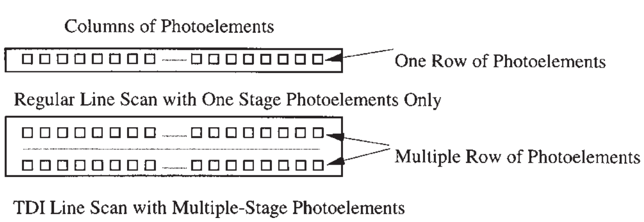

FIGURE 4 Photoelement layout for both line scan and TDI cameras.

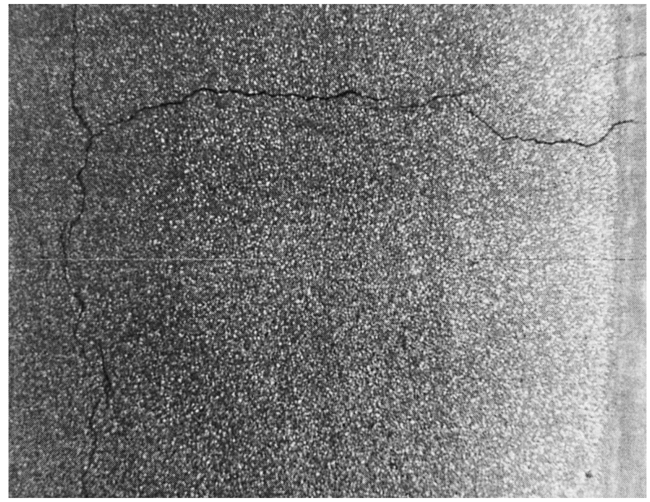

FIGURE 5 Image captured with area scan camera at speed of 1/10,000 s on vehicle traveling 97 km/h (60 mph).

TDI sensors must be aligned perpendicularly (normal) to the direction of object movement. As an object's image is focused on the TDI sensor's pixels, the image should not drift laterally more than one pixel relative to the sensor over the TDI scan distance or the image scanned may be blurred or smeared. The position and stability of the camera mounting are therefore vital. A TDI line scan camera was tested at a travel speed of 48 km/h (30 mph). The captured image is shown in Figure 6.

The vibration of the camera when mounted on a vehicle traveling at high speeds poses serious problems because the alignment requirement for the camera cannot be satisfied. In the conducted test, the scan speed of the camera was fixed. The synchronization was achieved by adjusting the vehicle speed. Because this synchronization

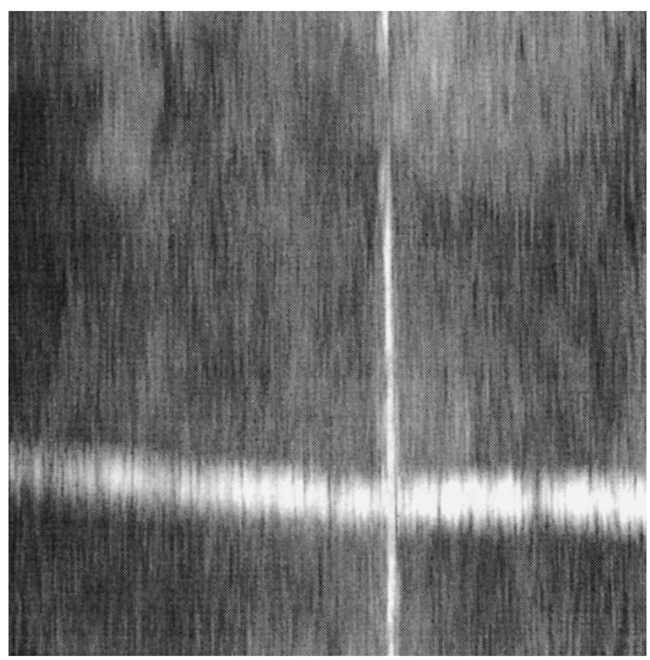

FIGURE 6 Image captured with line scan camera on vehicle traveling 48 km/h (30 mph).

is not sufficiently accurate, and the alignment problem exists, the resulting images are blurry. The vibration problems can be eliminated by using a shock absorber with the camera. With a wheel encoder mounted on the transmission of the vehicle linked with the camera, the synchronization problem can also be solved.

The camera and illumination structure is shown in Figure 7 as a part of a highway data vehicle that has been developed at the University of Arkansas. The camera is housed in an aluminum cylinder in the middle. Four strobe lights are placed at the four corners surrounding the camera. The digital area camera captures 12 frames per second in progressive mode. The strobe lights are synchronized with the camera shutter. In normal operation mode, the shutter speed is set at 1/40,000 s. Images were taken when the vehicle was still, at 96 km/h (60 mph) and 129 km/h (80 mph). No visual difference exists among the images taken at still and varying speeds because of the fast shutter speed. This imaging subsystem is able to archive complete pavement surface images through a process of patching adjacent images on the basis of the vehicle's traveling speed.

APPROACHES TO IMAGE PROCESSING

Image processing techniques can be used in finding distresses from pavement images and classifying them. This normally involves two phases: (*a*) image segmentation and (*b*) pattern recognition, classification, and estimation. In image segmentation, distress in the image is found and isolated from the rest of the scene (i.e., the background). In pattern recognition, features are extracted from the isolated distress image. The distress objects are measured on some quantifiable property such as the orientation of the cracks, the length and width of the cracks, and so forth. In the classification and estimation phase, decisions are made on the class in which each distress object belongs. All possible distress classes are preestablished. The classification is based solely on the result of the first phase.

Most portions of a highway are good or intact pavement areas. Distress occurs only on a small percentage of surveyed highways. Therefore, a considerable amount of processing time can be saved if the intact pavement area of an image is excluded from further processing.

The image segmentation process can be defined as one that partitions a digital image into disjoint (nonoverlapping) regions (*6*). A region is a connected set of pixels—that is, a set in which all the pixels are adjacent or touching (*7*). Connectedness is defined as follows: between any two pixels in a connected set, there exists a connected path wholly within the set, where a connected path is a path that always moves between neighboring pixels. Thus, in a connected set, any two pixels can be linked by a connected path (*8*).

Image segmentation can be approached from three philosophical perspectives. A region approach assigns each pixel to a particular object or region. A boundary approach attempts only to locate the boundaries that exist between the regions. In the edge approach, one seeks to identify edge pixels and then link them together to form the required boundaries. Most research efforts to date concentrate on the region approach in distress recognition.

Experiments were conducted on the images collected by the area scan camera. Global thresholding was used in the segmentation process. Important in using thresholding is the correct selection of the threshold. Using different thresholds, the resulting images for the image shown in Figure 5 are shown in Figures 8–10.

The segmented images can be indirectly used as inputs for pattern recognition, sometimes with neural networks. There are many ways to transfer the segmented images into the inputs of neural networks. Further experiments need to be done in this area.

FIGURE 7 Imaging subsystem of full digital highway data vehicle at University of Arkansas.

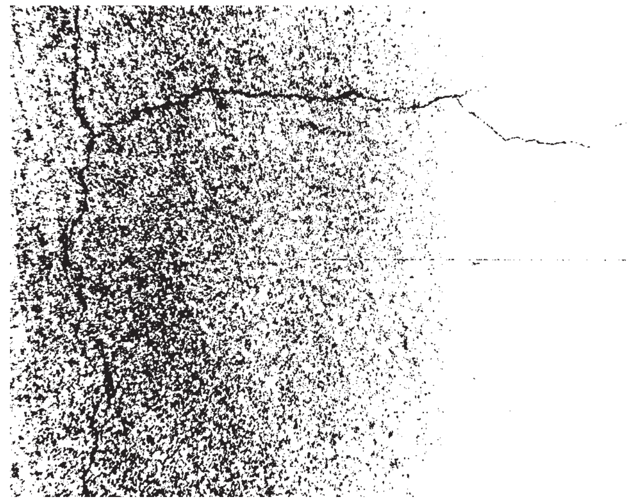

FIGURE 8 Results of thresholding with threshold 90.

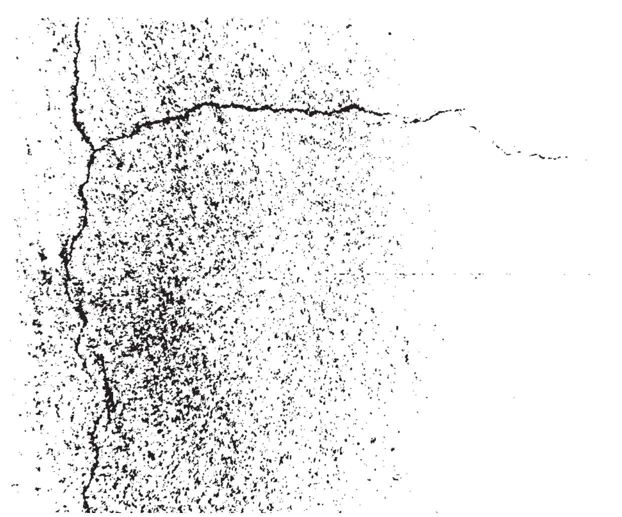

FIGURE 9 Results of thresholding with threshold 85.

FIGURE 10 Results of thresholding with threshold 81.

CONCLUSIONS

Different system design, hardware performance, recognition algorithms, and implementation were used in existing survey systems for pavement surface distress. New cameras and imaging technologies overcome most, if not all, limitations of existing systems. The advantages of using digital area scan and line scan cameras in pavement surface distress surveys were discussed in the paper. Some crucial problems still need to be solved in the use of TDI line scan cameras because the alignment and synchronization requirements are quite high. New digital area scan cameras have high resolutions and use sensitive CCDs with fast electronic shutters. This allows high-speed image capturing because traveling at highway speed is a requirement for modern data collection vehicles. The data collection conducted in a testing vehicle showed that collecting clear images at 97 km/h (60 mph) is feasible. Preliminary image processing results were presented in this paper. Further studies can be done in the areas of new segmentation methods and crack identification and classification using statistical methods and neural networks.

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Publication of this paper sponsored by Committee on Applications of Emerging Technology.