DESIGNS AND IMPLEMENTATIONS OF AUTOMATED SYSTEMS FOR PAVEMENT SURFACE DISTRESS SURVEY

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ABSTRACT: The categorization and quantification of the type, severity, and extent of surface distress is a primary method for assessing the condition of highway pavements. Various methodologies were developed to automate pavement distress surveys. Significant technical advances were made during the past years. The implementations of the image capturing subsystems include conventional analog-based area-scan, analog and digital line-scan, laser scanning, and shadow Moire method. Newer implementations of image processing include artificial neural net and parallel processing. However, problems still exist in the areas of implementation costs, processing speed, repeatability, and accuracy. This paper presents some of the key developments in recent years for automating pavement distress evaluation. These new systems are described in terms of their potential and applicability. This paper also presents a modified approach to collecting and processing surface distress through the use of high-performance digital cameras for the acquisition of surface distress data.

INTRODUCTION

Large infrastructures are usually constructed with materials that exhibit distresses after construction due to various loading, environmental conditions, and aging. The large infrastructures include pavements, chimneys of nuclear power plants, skyscrapers, and pipelines. The distresses are presented in the form of surface cracking in most situations. Successful automation of surface distress survey would reduce the overall cost of performing distress surveys and provide more objective and standardized results for rehabilitation management.

For the inspection of the surface distress of highway pavements, the most widely used method to conduct such surveys is based on human observation. This approach is extremely labor-intensive, prone to errors, and poses hazards. 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 newer generation equipment over the older systems, serious problems still remain in the areas of implementation costs, processing speed, and accuracy.

The goal of this paper is to review existing technologies, designs, and implementations of automated systems for the survey of highway pavement surface distress. Potential new directions to overcome the current limitations are also discussed in the areas of applying more robust image collection and processing technologies. As commercial implementations of automated systems use proprietary imaging algorithms, the description of these systems concentrate mostly on the aspects of system design. Research efforts solely on imaging algorithms for distress analysis are not discussed in this paper. It is worth noting that Howe and Clemena (1998) published a report on using digital image processing technology for pavement distress surveys.

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Note. Associate Editor: Ken Maser. Discussion open until August 1, 2000. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publications on March 10, 1998. This paper is part of the ***Journal of Infrastructure Systems***, Vol. 6, No. 1, March, 2000. ©ASCE, ISSN 1076-0342/00/0001-0024–0032/$8.00 + $.50 per page. Paper No. 17803.

PRINCIPLES OF AUTOMATED DISTRESS SURVEY AND DEVELOPMENT DIFFICULTIES

Fig. 1 illustrates the basic system concept of an automated distress survey system, consisting of data acquisition, data storage, data display, and processing subsystems. In addition, a database system is used in Fig. 1 for archiving and retrieving the processed data.

Sensor Technique in Data Acquisition

The following factors need to be considered in the use of sensor techniques for the acquisition of pavement surface distress data:

1. Type of sensor technique to acquire and identify cracks,
2. 1D approach and 2D approach, and
3. Sizes of cracks that should and can be identified.

There are a number of crack attributes that may be used for their detection. Mendelsohn (1987) lists several possible approaches to conducting such detection. The most obvious method is through the detection of the cracks visually. Cracks can also be detected as abnormal depths in surface texture by measuring profile. Additionally, vehicle tires make slapping sounds against cracks when they are crossed at high speed, suggesting another potential detection method of using acoustic technology.

Profilometers are applied to acquire pavement roughness measurements. If the sampling area and resolution of the profilometer were sufficiently high, it could be an ideal means for crack detection. Unfortunately, a lane with 4-m width sampled at 2.5 mm intervals in transverse and longitudinal directions would require 15,000,000 readings per second at 89 km/h (55

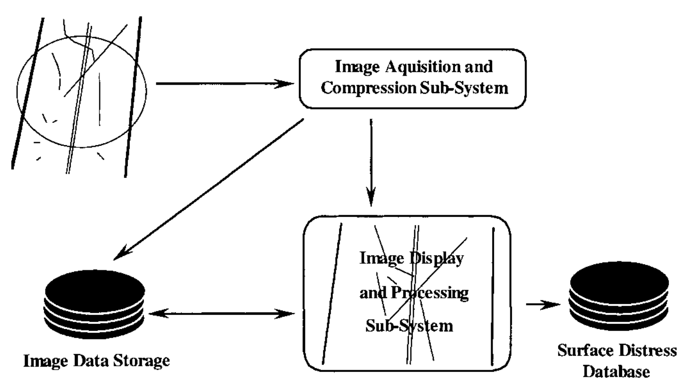

FIG. 1. System Concept in Pavement Surface Distress Survey

mi/h). No such profilometer exists. Even though 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 preferred method to find and classify cracks, either through human examination or a man-made vision system. Image data can be collected with various means, such as analog or digital, and 1D (line) scan, or 2D (area) scan. An existing popular method is to record pavement surface images in analog format through area-scan cameras. A digitizing process converts the analog-based images, where analog data is transformed into computer-understandable digital format. In recent years, an emerging data collection method is to use digital capturing devices, such as a digital camera that converts an analog signal from an object into a digital signal within the camera. The image data in digital format is then transferred to computing devices without the traditional digitizing process.

Line-scan cameras scan one line at a time, versus area-scan cameras that scan a 2D area at a single pass. The resolution of line-scan cameras can be as high as 6,000 elements or pixels per line with a data rate of 30 MHz. Captured single lines are then compiled together to form a 2D area for analysis. Line-scan cameras are widely used in manufacturing facilities to inspect product defects, while cameras are stationary and objects being inspected are moving at high speed in one uniform direction. In recent years, high-performance digital line-scan cameras are used for this type of surface inspection. Several main problems associated with analog area-scan cameras do not exist with digital line-scan cameras, such as relatively low resolution and necessary digitizing process of analog area-scan cameras. However, line-scan cameras do require higher light intensity.

Laser scanning uses different sensor technology. However, data is normally collected on a line basis with laser sensing. For instance, a highly focused small laser beam scans a surface in the lateral direction of the movement. The reflections of the laser beam on the surface are then collected and formulated as a line when one lateral scan is completed. The collected lines are then compiled into a 2D surface. Laser scanning does not require separate illumination.

There is no consensus on what the smallest size of cracks detected should be for engineering purposes. However, if a system can detect a crack with the width of 1.5 mm, it would be considered adequate.

Illumination, Travel Speed, and Data Storage

Except for the laser-scanning technique, both line-scan and area-scan approaches require proper illumination of the object surface to obtain a faithful replication of the surface, similar to a photographic filming of any action. However, as the data vehicle can travel at highway speed and the subject matter, cracks, can be very small, proper illumination becomes very important, as targeted objects (pavement surface) move extremely fast relative to the camera.

In the area-scan scenario, at the speed of 80 km/h (50 mi/h), or 22.35 m/s, about 6 frames are needed to cover the full length of a 3.66 m (12 ft) wide pavement if the area is square. As the smallest crack under consideration is less than 2 mm, the camera (vehicle) must not move over 2 mm distance during the exposure time to shoot one frame, which is the controlling factor in determining the exposure time. Therefore, the maximum available exposure time per frame is calculated as 0.09 ms, or 90 μs.

In the line-scan scenario, the exposure time per line is determined by the speed (80 km/h, or 50 mi/h), and the line resolution. Assume the line resolution is 2,048 pixels per 3.66 m (12-ft) lane, the total number of lines is 12,510 in 1 s. Therefore, the maximum available exposure time for one line is about 0.08 ms, or 80 μs, during which time the camera moves less than 2 mm.

These short exposure times require high illumination intensity to obtain the needed images of pavement surface. As it is cost-prohibitive to obtain a continuous-illuminating device at such high intensity, strobe-illuminating devices are cost-effective for area-scan cameras. However, illumination of a narrow line surface of pavement for a line-scan camera is difficult. First of all, there are over 10,000 lines per second to be captured. There is no strobe-illuminating device that can have this high frequency. Therefore, a continuous-illuminating device is needed. In order to have uniform and focused high intensity, such a device must be placed close to the inspected surface, such as less than 30 cm (1-ft) from the surface. The required lighting intensity can be so strong that asphalt pavement may get burned when exposed to such lighting for a long period of time.

The data rate at highway speed is very high. For example, 8-bit gray scale (256 gray levels) images are assumed adequate for pavement surface distress surveys. Also, assume: (1) the pavement width is 3.66 m (12-ft); (2) image resolution is 2,048 (2 k) pixels per-line-per-lane; (3) uniform resolution exists in both directions on the 2D surface; and (4) vehicle speed is 80 km/h (50 m/h). The resulting in-coming raw data rate is about 26MB/s. Recent rapid advances in microcomputing and I/O systems provide an opportunity to explore new approaches to tackle the problem of streaming this high data rate into a microcomputer-based storage device.

Data Processing and Difficulties of Automation

The source visual data has to be normalized into a continuous 2D surface, representing the pavement surface. In the case of line-based source data, collected lines have to be digitized if the source is not digital, then integrated into a uniform 2D surface based on speed. In the case of area-based source data, also based on speed information of the data vehicle, overlaps of adjacent images need to be cut off to form a continuous pavement surface.

Much research and development have been aimed at the computerized processing of the normalized pavement 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 in Fig. 1.

Humans can detect and classify pavement surface distress with ease. 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 mathematical algorithms. Even if all the imaging processing handled by the human brain were understood, it was possible to implement that knowledge into a computer to make its performance comparable to a human's performance, the amount of processing power required is of the order of 1,012 billion floating point operations per second (1 teraflops) (Crevier 1997). A workstation at a reasonable cost and augmented with a high-end imaging board can only achieve the order of 1 billion float point operations per second (gigaflop).

The highway industry would like to apply automated distress survey equipment with real-time processing capability, and acceptable consistency, repeatability, and accuracy. It has been a frustrating period in the past two decades for developers to implement distress survey systems based on these requirements.

1. Image processing for pavement surface distress survey at any practical speed requires very high performance computing equipment. When a compromise is made in respect to computing performance, data quality, processing speed, or both, are affected.
2. Image processing as a field of study is still evolving. There are many aspects of image processing in the human brain that are not yet understood.
3. 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 spoil.
4. There are no standard indexes to quantitatively define the types, severity, and extent of pavement surface distress. However, efforts are underway to initialize a set of standards (Paterson 1994; FHWA 1997).
5. The dominant data collection format today is based on an analog standard defined in the 1950s by the U.S. National Television Standard Committee (NTSC). The visual data collected with this method needs to be digitized for processing and be of low resolution.
6. It is not necessary to have compatibility of hardware and software with different vendors' systems. However, this incompatibility introduces noncomparable survey data from different vendors.

The overwhelming difficulty in the automated survey of pavement surface distress is the high rate and associated extraordinary computation needs when real-time or near real-time processing is necessary.

CURRENT STATUS OF RESEARCH AND DEVELOPMENT

In the early 1990s, the Texas Department of Transportation and U.S. Federal Highway Administration organized a trial test of existing automated systems. Vendors in the highway data collection business were invited to conduct surveys with their automated equipment. There was not much agreement among the results from different vendors and the trial test did not produce a comparison evaluation of the various devices. Smith et al. (1998) led a team and conducted a study on the existing survey equipment on pavement surface distress. Four vendors were invited and participated in the study. Most of the four vendors only have capabilities of collecting pavement surface images. The analyses of surface distresses were conducted manually, or with the assistance of a vision system under manual control.

Since the 1980s, five major efforts that produced working systems with the capability of at, or near, real-time processing are described in this paper: (1) the Japanese Komatsu system; (2) the U.S. Pavement Condition Evaluation Services (PCES) system; (3) the Swedish PAVUE system; (4) the Swiss Crack Recognition Holographic System (CREHOS); and (5) the Illinois Automated Road Inspection system. Several other efforts are discussed in less detail in this paper, primarily due to the lack of documentation.

Komatsu System

In the late 1980s, the Japanese consortium Komatsu built an automated-pavement-distress-survey system (Fukuhara et al. 1990), shown in Fig. 2, comprising a survey vehicle and data-processing system on board to simultaneously measure cracking, rutting, and longitudinal profile. Maximum resolution of $2{,}048 \times 2{,}048$ is obtained at the speed of 10 km/h. The Komatsu system works only at night to control lighting conditions. When the survey is conducted with the moving vehicle, the road surface is illuminated with argon laser light through the laser scanner in the lateral direction. The deflected light from the road surface is detected at an angle by a photomultiplier tube (PMT) and a video camera that are attached to the front bumper of the vehicle. When cracks are present on the surface, the quantity of received light by the PMT is reduced. Therefore, the change of output from the PMT indicates the existence of cracks at the scanning position. The video cameras are used to capture rutting, as the scanning line observed from an oblique angle is curvy when rutting is present. The integration of the collected information over time presents cracking and rutting data on the 2D road surface. The longitudinal profile is measured based on the distance between the survey vehicle and the road surface. The profile is calculated based on three sets of data collected at three locations in the vehicle: the first being the rutting measurements, and the two others being measurements collected by the two line sensors under the body of the vehicle. Tape-based data storage devices are used for data archiving. Digital image processing techniques are applied to crack image data in a postprocessing mode. Parallel processing is used at two stages to determine cracking parameters such as the number, width, and length of cracks.

In the first processing stage (image segmentation), 64 MC68020 parallel microprocessors, also called the extracting processors, are used. In segment extraction, the image is divided into 32-pixel $\times$ 32-pixel square areas, called slits. Pro-

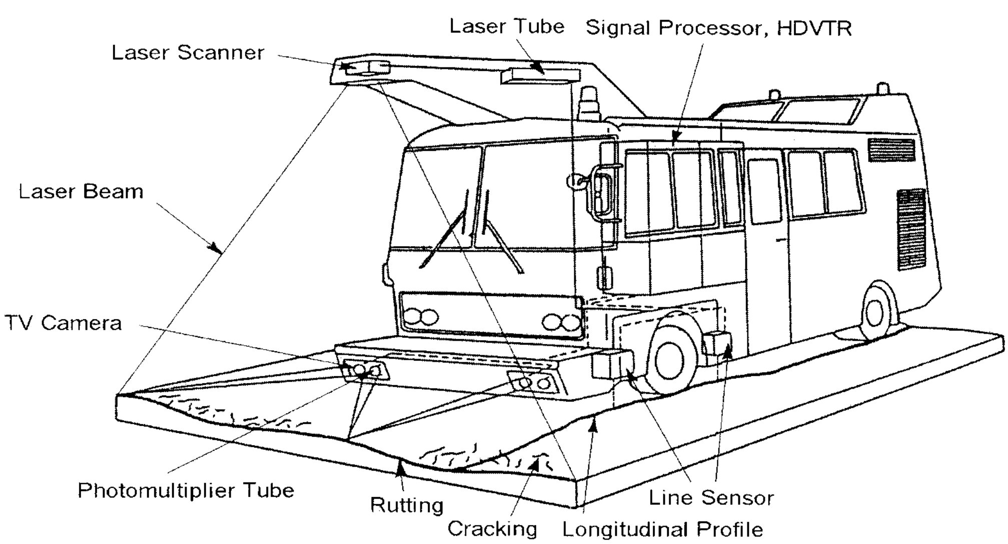

FIG. 2. Komatsu Survey Vehicle

jection curves for the two orthogonal directions along the sides of the slits are calculated as shown in Fig. 3. In order to determine the angle, length, and width of the crack in a slit, it is necessary to rotate the projection directions in the image until a peak of the crack appears, indicating that the actual width of the crack is found. The portion of the crack that is contained in the slit is represented by a rectangular element. Each of the MC86020 processors is used to process one slit at a time in parallel with all other processors. After the processing, all of the cracks found are represented by segmented slits.

In the second stage (crack connectivity), seven T800 transputers are used in parallel to determine the connectivity among the extracted segments, and to eliminate noises. The connectivity is determined by the relative positions of cracks in neighboring segments. The transputers produce a line image of the pavement surface, or a crack map.

The Komatsu system represents an implementation of the most sophisticated hardware technologies at that time. However, it does not output the types of cracking and only works during the night.

U.S. PCES System

From the late 1980s to early 1990s, Earth Technology Corporation launched a large-scale research on the automation of pavement surface distress survey and created the PCES research unit. The automated system created by PCES was the first to use line-scan cameras to collect pavement data. The inspected objects (pavements) are traveling at high speed and the image is captured with cameras through capturing one line of image at a given moment. PCES's approach was unconventional at that time. Even though the line-scan camera's resolution and performance were better than the conventional area-scan camera's, it required many customized efforts, such as special boards and software to support the cameras and high intensity illumination.

In the PCES system, digital signal processing was used in real-time, using custom-made filter circuits, which are 3×3 neighborhood convolver boards. The boards contain special processors with built-in imaging algorithms to filter images quickly. Each of the two 512-element line-scan cameras continuously covers 4 ft of pavement, for a total of 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 VME bus-based 32-bit computer to power the image processing engine with interrupt-driven software and proprietary pipeline hardware to accomplish real-time processing, an imbedded operating system that was contained in read-only-memory (ROM).

The developed vehicle shown in Fig. 4 is a 21-ft Grumman truck. Two 15-k·w diesel generators power the computer, lighting, and other equipment. It should be noted that in order to obtain lines of images at required speed, line-scan cameras need much higher intensity lighting than conventional area-scan cameras

Earth Technology Corporation did not continue to fund the research after the first operational PCES system was built. One important factor for this decision is that the necessary technologies associated with the image capturing and processing were not mature enough. In addition, PCES designed, produced their own processing boards, and made their own system level software, which were not only costly, but also limited the research team from obtaining higher performance equipment from third parties at a later time.

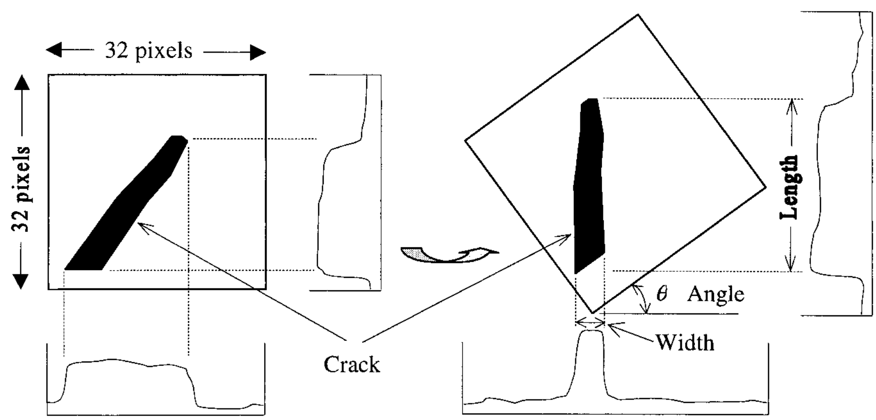

FIG. 3. Understanding of Rotation of Projection Curves for Slit

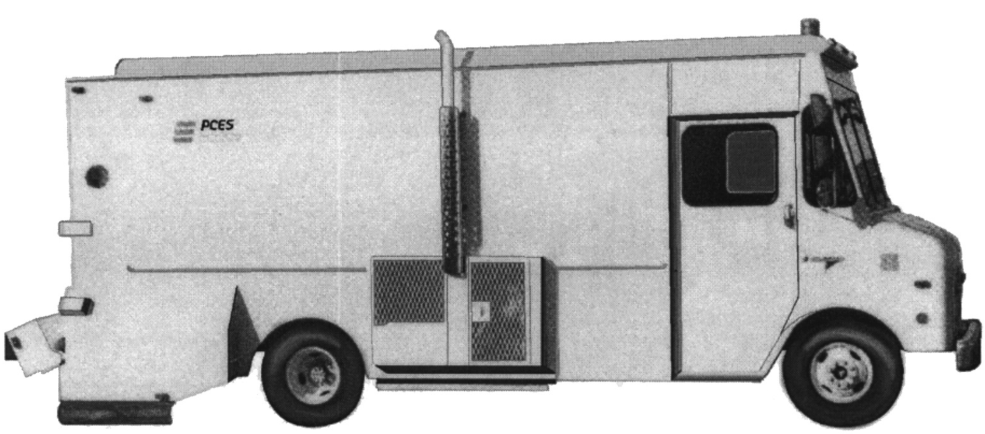

FIG. 4. PCES Survey Vehicle

Swedish PAVUE System

The Swedish PAVUE 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 is based on a set of custom designed processor boards in one cabinet to analyze continuous pavement data from the recorded video images.

In Fig. 5, each of the four video cameras cover about one-fourth of the pavement surface, or about 2,000 pixels per lane. The speed compensation device allows the van to drive at any speed between 5–55 mi/h to ensure that the video image is continuous. The detectable size crack is about 2.0 mm. The unique feature of the PAVUE system is with its image processor boards. A total of 12 VME-based boards were developed to form the core of the image processing. Image processing algorithms were coded in hardware to speed up the processing.

The image processing technique used in the PAVUE is referred to as pipeline processing, where image data is piped through series on-board computational elements, or chips, which contain algorithms in hardware. The elements perform a broad 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 at the aggregate speed of up to 55 mi/h. Surface images are stored on S-VHS tapes in analog format. The pipeline analyzer in the PAVUE system performs the following functions.

Initial Filtering and Thresholding

The initial filtering removes noises (oil drips, shadows from trees, power lines, surface texture, and discolored stones, etc.) from the image to only have larger distress patterns in the image. The filtered image is then ‘‘adaptively thresholded’’ to a binary image, where any pixels in an image are determined by either cracks or background. The output of the thresholding contains tiny dots, holes within larger distress ‘‘blobs,’’ and gaps in distress boundaries.

Morphological Operations and Final Filtering

The output from the thresholding process is cleaned up with several stages of morphological operations to reduce or increase the sizes of the distress blobs in a fixed sequence that results in the removal of small noncrack-like objects and the joining of crack-like objects into single cracks. At this point in the pipeline, the objects in the image represent regions of surface distress. A connectivity algorithm determines which objects are separate and which are branches of other objects. The image has therefore been converted to a vector format consisting only of the outline of cracks with coordinates of the crack boundaries.

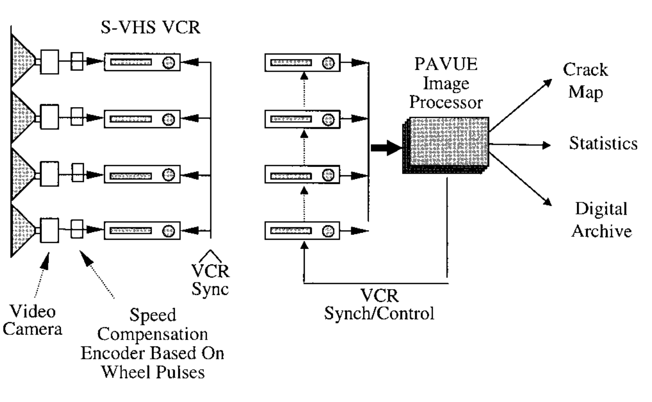

FIG. 5. Data Flow in IMS's PAVUE System [Based on IMS (1996)]

The PAVUE system uses a software module, the crack pattern classifier, to classify distress information into crack types, severity, and extent through performing feature extractions. Each crack in the image so far is described only by its location and outline. The pattern classifier calculates a number of statistics for each individual crack, based on the geometry of the crack, such as area, perimeter, and average width, as well as more complex features such as orientation and convexity.

Once the feature extraction is complete, the classifier follows a method based on decision tree analysis to assign each crack a particular type and severity. The cracks are then accumulated for a given pavement segment to derive the values for extents. Cracks of the same type are combined in close proximity, removing gaps that might have been created due to previous processing. The final output involves the creation of crack indices.

Swiss CREHOS

Considering the limitations of systems in the early 1990s, Dr. Max Monti of the Swiss Federal Institute of Technology (EPFL), Laboratory of Stress Analysis (IMAC), completed his PhD work with the goal to design and implement a new pavement imaging system ‘‘in a complete and lasting way’’ (Monti 1995). The developed system is CREHOS. With CREHOS, the pavement surface is scanned with a focused laser beam along a straight line in the lateral direction, while the longitudinal scan is conducted with the movement of the vehicle. The reflected light from the surface is collected with a collector, which was a customized holographic element. When the laser light falls into a crack, the strength of the signal collected by the holographic element decreases. This signal is filtered and binarized to obtain sets of binary pulses representing the crack. These sets of data are then formatted, preprocessed, and stored at real-time with a parallel processor.

A major advantage of this laser solution is the elimination of illumination of a large and rough surface of pavement. Fig. 6 shows the basic configuration of CREHOS mounted on a trailer. There are three subsystems: (1) the scanning device; (2) the holographic light-collection system; and (3) the image processing system. The scanning device emits laser light to pavement through a rotating polygonal mirror. A 4-m long line can be scanned in 83 μs. To have square millimeters for the pavement surface, the vehicle can travel at the maximum speed of 43.2 km/h. Higher speed can be achieved when longitudinal resolution is relaxed to over 1 mm. Two multifacet holographic collectors (MFHOE) are placed on both sides of the scan line at 10 cm from the pavement surface. Each MFHOE is composed of thousands of HOEs of 5×5-mm size. One photodetector is positioned 60 cm above each of the two MFHOEs. The photodetectors convert the light signals from the MFHOEs into analog signals, which are usually noisy. The preprocessing unit transforms the analog signals into binary pulses, indicating the probability of the presence of a crack. Therefore, CREHOS does not work on an ‘‘image,’’ but on a continuous temporal, 1D signal. An image is obtained through illuminating point-by-point and integrating the points over space. The output signal is analog pulses, which is thresholded adaptively into a binary format before entering the digital-processing unit.

The processing unit, a parallel processor, was built for CREHOS to further filter noise, recognize cracks, and vectorize their shapes at real-time. The parallel processor consists of a number of tracking units, or processing units, each of which works on a single crack-representing pulse at one time. The processing units are not the same as conventional digital microprocessors. They are simple electronic devices based on analog technology with the capability of identifying crack-representing pulses. Each tracking unit can complete processing in every 80 μs, about the same as the duration of scanning one line. CREHOS applies analog approaches to data collection and preprocessing. The parallel processing is also unique in that no traditional digital microprocessors were used.

Illinois Automated Road Inspection System

A team headed by Professor Sidney Guralnick at the Illinois Institute of Technology produced an Automated Road Inspection Vehicle (Guralnick and Suen 1995). The system was developed using the shadow Moire optical interference method. The vehicle can acquire out-of-plane road surface distress information at highway speed. The image resolution is about 512 × 480 pixels for a one-lane pavement surface.

The shadow Moire method is demonstrated in Fig. 7. The light source and the camera are placed at the same observing plane and at a distance of d from each other. The grating plane is parallel to the observing plane. The distance between both planes is H. The spacing of the black grating lines is p. Contour planes, h_n, are generated by the intersection of the projected lines from the light source and the sight lines from the camera's position. The contour interval, Δh, can be approximately expressed as

$$\Delta h = p\frac{H}{d} \tag{1}$$

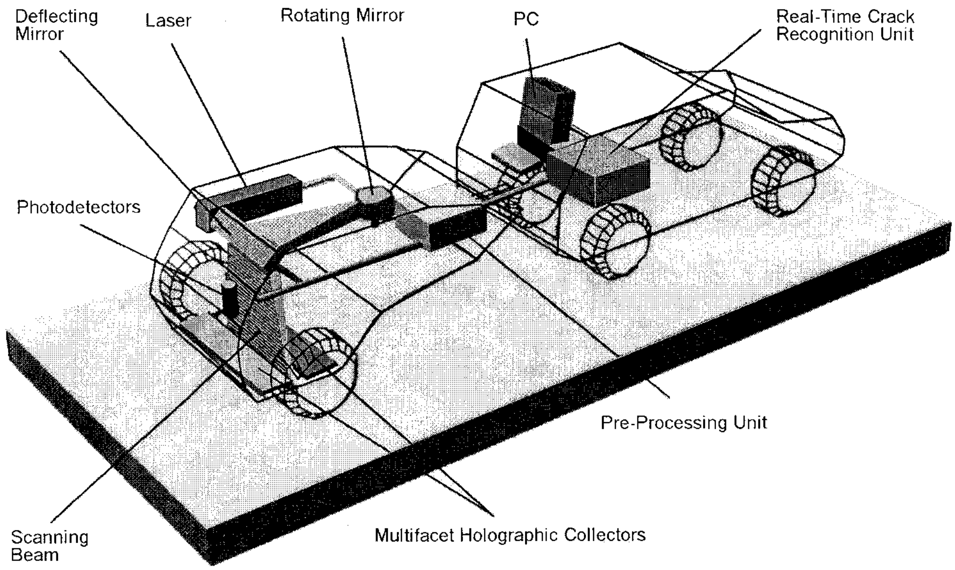

FIG. 6. CREHOS Survey Vehicle [Based on Monti (1995)]

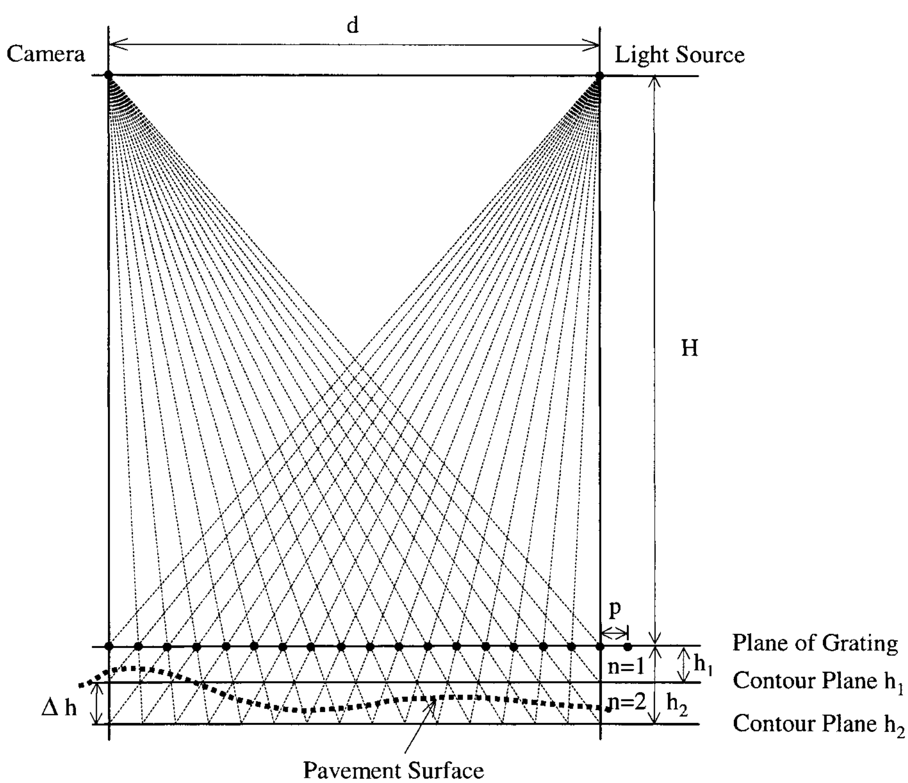

FIG. 7. Demonstration of Shadow Moire Method

Based on the known Δh and the contour map created by casting the shadow with the light source through the grating lines on the pavement surface, a digital terrain surface of the pavement is established. However, pavement condition survey with this method does not allow the detection of surface cracks on the same plane. The developers believe that the system can be built with $60,000 worth of materials.

Several Other Efforts

Triple Vision's NCHRP Project

In the Triple Vision project that was sponsored by the National Cooperative Highway Research Program and completed in 1991, sample video data from PASCO 35 mm films were transferred to a video disk (Fundakowski et al. 1991). The video image processing were distributed across two computer systems. The bulk of the image processing operations (i.e., image preprocessing and segmentation) was performed in a DSP-1000 image processing system (a product of Datacube, Inc., Peabody, Massachusetts). The feature extraction and classification stages of the video image processing system were implemented in a 386 PC. The DSP-1000 incorporates several image processing boards, a digitizer/frame grabber and a display board. The comparison of the machine generated cracking recognition, and the data based on the two experts on pavement engineering was poor (Fundakowski et al. 1991). An upgraded system with a 33 MHz 486 computer and the Data Cube processor can only process 1 frame of image per minute, equivalent to 29 h of processing time per 1 lane-mile.

ADAPT and RoadWare's WISECRAX

From 1995, the U.S. Federal Highway Administration awarded contracts to LORAL Defense Systems in Arizona, now a unit of Lockheed-Martin, to provide an Automated Distress Analysis for Pavement (ADAPT) (FHWA 1995). The researchers used techniques based on an artificial neural net (ANN) developed for military purposes. The data source is digitized images from PASCO's 35-mm film with the digitized resolution at about 4,000 pixels per 12/ft/lane, or about 1 mm per pixel. ADAPT was written in MATHALB and is not being used in any operating products.

Since late 1996, RoadWare Corporation has been actively using a new product, WiseCrax, for automated survey of pavement surface. Initially, RoadWare attempted to apply the ADAPT technology to WiseCrax. Subsequently, RoadWare developed its own algorithms. The data collection uses two analog cameras synchronized with a strobe illumination system, with each camera covering about a half-width of a pavement lane. The image processing is done in the off-line office environment relying on the host CPUs to conduct image processing.

University of Waterloo Effort

While studying at the University of Waterloo, Carl Haas (Haas et al. 1985a,b; Mendelsohn 1987) designed and implemented an image processing system based on an IBM PC for the Ontario Ministry of Transportation and Communication. This effort was prior to the following high-profile developments during the period from the middle 1980s to the present. The system used field video logs collected at 15 km/h. The postprocessing required ~5 s per frame. The precision of the system was reported to be ~95% for identification of the cracked images, most of which were images from bituminous pavements. Dr. Carl Haas used edge detection and traditional pattern recognition techniques for the development of the system.

Table 1 presents a feature comparison of six vendors' automated systems for pavement distress survey. The information in Table 1 is not an exhaustive list of systems in pavement surface distress survey. However, in the U.S. market, WiseCrax of RoadWare and PAVUE of IMS were dominant in automated or near-automated systems for pavement distress survey.

NEW LOOK AT THE APPROACH OF USING LINE-SCAN CAMERA

The Time Delayed Integration (TDI) camera is a new type of high-performance line-scan camera used for high speed and relatively low lighting applications. TDI makes use of synchronous motion to take multiple pictures of the same line image and add them up to get an amplified image. The high sensitivity of TDI cameras is due to image integration over multiple stages as shown in Fig. 8. Compared with a regular line-scan camera, a TDI camera can have 96 stages, resulting in 96 times the integration period. The overall sensitivity is improved by a factor of 80, due to added noise sources in the TDI sensors.

Basis of Applicability

In any line-scan application, the system designer must consider both the resolution across the object's movement (transverse resolution) and the resolution along the path of the object's movement (longitudinal resolution), as demonstrated in Fig. 9. In the design of line-scanning-based data vehicle, the transverse resolution is limited only by the number of line pixels in the camera. Longitudinal resolution is a function of the speed of movement, or the data vehicle's speed, and the scan rate of the camera. The inspection with the line-scan camera can be 100% coverage of the surface at one predetermined resolution at longitudinal and transverse directions. The speed encoder in the figure generates and sends the speed data to the camera at real-time. With the speed known and the resolution fixed, scan rate of the camera can be dynamically adjusted to

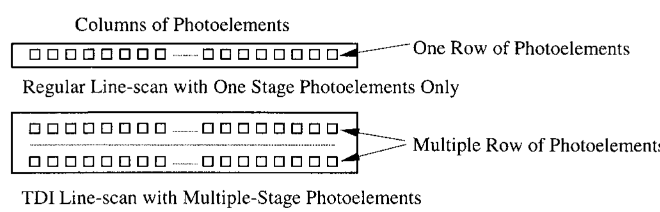

FIG. 8. Photoelement Layout for Line-Scan and TDI Cameras

TABLE 1. System Features of Six Automated or Near-Automated Systems for Pavement Distress Survey

Company/system (1)	Basic data collection method (2)	Data storage (3)	Data analysis (4)	Method of marketing (5)
RoadWare/WiseCrax	Analog video, area coverage	Analog tape	Host CPU-based processing	Equipment sale or service
IMS/PAVUE	Analog video, area coverage	Analog tape	Real-time, proprietary parallel processing	Service only
Komatsu system	Laser scanning	Hi-Den tape	Proprietary parallel processing	No
PCES	Line scanning	Hard disk	Proprietary parallel processing	No
SWISS CREHOS	Laser scanning	Hard disk	Proprietary analog-based parallel processing	No
Illinois' Moire system	Analog video, area coverage	Analog tape	N/A	Unknown

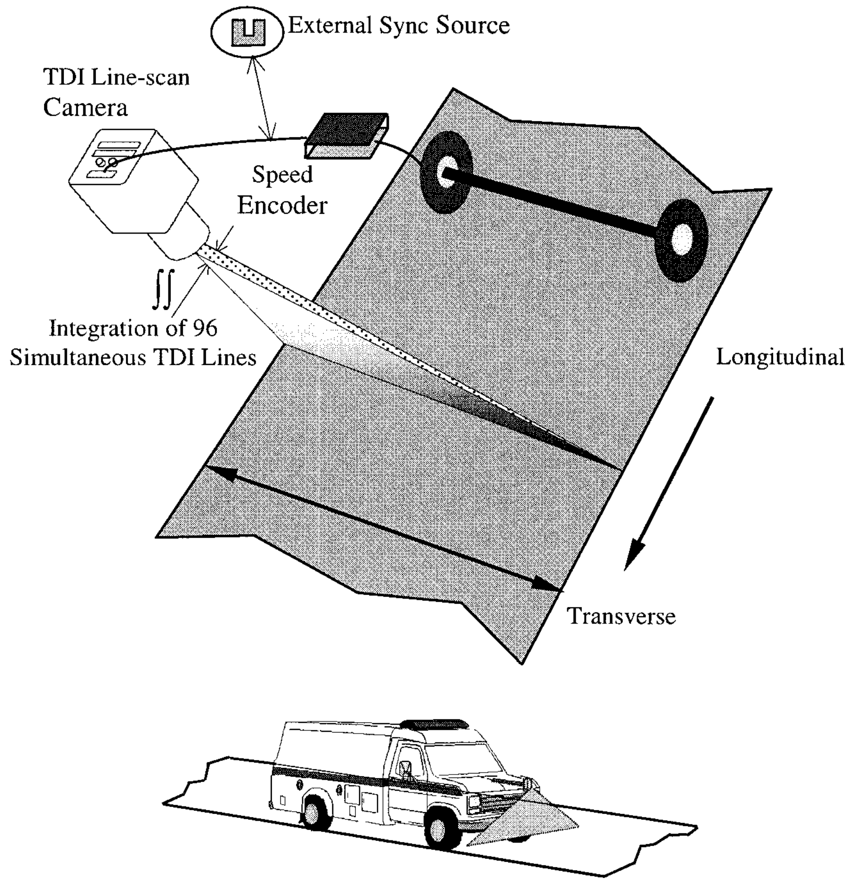

FIG. 9. Line-Scan Camera-Based Pavement Surface Inspection Vehicle

satisfy the requirement of uniform resolution for both transverse and longitudinal directions. At 100 km/h, a scan rate of 1.5 kHz is needed. The performance of a high-end TDI camera exceeds this specification, with line rate over 40 kHz. The principle to establish a 2D image of the pavement surface is as follows:

$$\text{pavement surface image} = \iint f(\text{raw TDI lines})\, dl\, dx \qquad (2)$$

where l = image lines before integration; and x = distance of traveling.

In order to capture clean images with a TDI camera, tight synchronization with the moving vehicle is required. Barbe (1976) presents the modulation transfer function (MTF), relating to the effect on image quality by speed variation

$$\text{MTF(TDI)} = M \cdot \Delta V/V \qquad (3)$$

where M = number of stages; and $\Delta V/V$ = ratio of change in velocity to the average velocity during the integration period for the photoelements of all stages.

Barbe also shows that when MTF is less than 2, there is no effect on image quality. For instance, when $M = 96$, $\Delta V/V$ can be as high as 2%. It is possible to control the speed variation of the data vehicle within this range. If the variation is over 2%, for instance, when $\Delta V/V = 5\%$, the number of stages can be reduced accordingly so that MTF is always less than 2. Certain TDI cameras may allow the dynamic adjustment of stage number.

Side-to-side motion can also affect the image uniformity when photoelements in the same column may capture unnecessary pixels. Sideways velocity must be limited to 1/96th of the vehicle speed to limit the effect. The total stage number is 96 in the TDI camera. Based on integration needs, the number of stages may be adjusted or selected for certain TDI cameras. The effect of side-to-side motion on image quality can also be controlled through adjusting the number of stages.

In addition, acquiring any visual data requires proper lighting. In the case of high-speed surface inspection of pavements, this requirement becomes even more important, despite the fact that TDI cameras already provide high sensitivity. Another problem is ''blooming.'' TDI cameras are usually used in light-starved applications. However, if the target area has a bright region, the pixels may be filled up with signal and bloom into adjacent photoelements.

System Design

The principle of all systems that inspect moving objects is to achieve stop action within the resolution of the smallest point of interest. New TDI cameras overcome limitations of area-scan, laser-scan and regular line-scan cameras with high resolution, a high line rate and a magnitude higher sensitivity to light. Fig. 10 illustrates a system design for an inspection system for pavement surface distress with a TDI camera. The

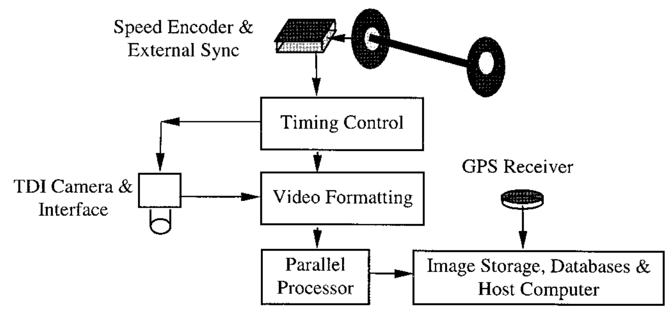

FIG. 10. Elements of TDI-based Surface Inspection System

speed of the data vehicle is monitored in the encoder to determine the synchronization with the camera. The timing control unit generates necessary camera clock signals based on the data from the encoder. Lines from the camera are formatted in the video formatting step in the camera interface device. The formatted digital lines are then fed into a parallel processor for image processing. All the interfacing devices and the parallel processor are housed in the host computer. The host computer also controls disk array for the storage of the images and related data sets. In addition, a GPS receiver is connected to the host computer to log location data for the collected images.

Parallel Processing for Image Archiving and Processing

At a speed of 50 mi/h (80 km/h), the processing of 28MB/s data at real-time can only be handled with a dedicated computation device and robust image-processing algorithms. This device should have the following characteristics:

1. High parallelism and highly expandable.
2. Low-cost and commericially available.
3. High-speed communication with the system memory, storage, and camer(s).

Processing chips with the power of over 2G instructions per second are available today at a reasonable cost. The structure of these boards is based on multiple processing units in one chip, each of which can execute instructions independently and communicate with other units via a tight on-chip network.

A critical task is the identification and classification of the distresses on the pavement surface. However, a board-travel system that supports multiple parallel processors is available, which may be used in the two levels of parallel environment. The first level of parallelism is conducted within each processor. The second level of parallelism is conducted among the processors.

As archiving of pavement surface images is beneficial for later examination and analysis, another task is to compress the processing results at real-time into the host disk array. Assume that a binary crack map is established after the final image processing. The crack map can be immediately saved into storage at the rate of 0.4MB/s after 10:1 compression in sync as the gray-scale raw image comes into the system from the camera at 31MBP/s. Therefore, for a 6,000-lane-mile pavement, the storage for the complete coverage of the pavement surface is about 144,000MB or 144GB. A single disk drive with over 50GB capacity could be obtained inexpensively in 1999.

A common issue in using a high performance parallel processor is the comparison of real-world data throughput with the theoretical data rate. To achieve high throughput, all other I/O bandwidths must remain optimal within the chip and surrounding peripherals, which may not be the case for most scenarios. It is most likely that a combination of multiple chips/boards is to be used in this newly designed system.

CONCLUSION

New technologies of laser scanning overcome some weaknesses of early systems in resolution and dynamic range. However, TDI-based line-scan design has advantages over laser implementation. Laser devices are more costly, as light collectors and analog-to-digital converters need to be customized. Hardware and software development kits for the TDI line-scan-based system are widely available from multiple sources at reasonable system cost. Based on initial investigations on parallel processing boards and interfacing devices, it is determined economically and technologically feasible to implement a TDI line-scan system. Challenges remain in the areas of effectively utilizing the TDI camera's performance, developing efficient parallel algorithms, and providing powerful enough continuous line light. It must also be pointed out that resolution and frame-rate of new digital area-scan cameras are also competitive. It is also possible that hardware costs for digital area-scan cameras and strobe-illumination are lower than those of TDI designs. This factor cannot be ignored in system design and implementation.

APPENDIX. REFERENCES

Barbe, D. F. (1976). ''Time delay and integration image sensors.'' *Solid state imaging*, Jespers, Wiele, and White, eds., Nordhoff International, Leyden, The Netherlands, 659–671.

Crevier, D. (1997). ''Computer vision and artificial intelligence.'' *Advanced imaging*, May, Melville, N.Y., 60–63.

FHWA. (1995). ''Defense technology adapted for pavement distress analysis.'' *Focus Newsletter*, May, U.S. Federal Highway Administration, Washington, D.C.

FHWA. (1997). ''Protocol for distress.'' U.S. Federal Highway Administration and TRDF, Washington, D.C.

Fukuhara, T., Terado, K., Nagao, M., Kasahara, A., and Ichihashi, S., (1990). ''Automatic pavement-distress-survey system.'' *J. Transp. Engrg.*, ASCE, 116(3), 280–286.

Fundakowski, R. A. et al. (1991). ''Video image processing for evaluating pavement surface distress.'' *Final Rep., National Cooperative Highway Research Program 1-27*, September, Washington, D.C.

Guralnick, S. A., and Suen, E. S. (1995). ''Advanced testing of an automated NDE system for highway pavement surface condition assessment.'' *Proj. Rep. of the Idea Program*. Transportation Research Board, Washington, D.C.

Haas, C. et al. (1985a). ''An expert system for automation of pavement condition inventory data.'' *North American Pavement Management Conf.*, March, Ontario.

Haas, C. et al. (1985b). ''Application of image analysis technology of automation of pavement condition survey.'' *Rep. to the Canadian Ministry of Transportation*.

Howe, R., and Clemena, G. G. (1998). ''An assessment of the feasibility of developing and implementing an automated pavement distress survey system incorporating digital image processing.'' *Rep. No. VTRC 98-R1*, Virginia Transportation Research Council.

IMS. (1996). ''An overview of the PAVUE fully automated surface distress image processing system.''

Mendelsohn, D. H. (1987). ''Automated pavement crack detection: An assessment of leading technologies.'' *Proc., 2nd North Am. Conf. on Managing Pavements*, Vol. 3, Toronto. 3.297–2.314.

Monti, M. (1995). ''Large-area laser scanner with holographic detector optics for real-time recognition of cracks in road surface.'' *Optical Engrg.*, 34(7), 2017–2023.

Paterson, W. D. (1994). ''Proposal of universal cracking indicator for pavements.'' *Transp. Res. Rec. 1455*, Transportation Research Board, Washington, D.C., 69–76.

Smith, R. E., Freeman, T. J., and Pendleton, O. J. (1998). ''Evaluation of automated pavement distress data collection procedures for local agency pavement management.'' *Proc., 4th Int. Conf. on Managing Pavements*, 269–286.