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AUTOMATED PAVEMENT CRACK DETECTION: AN ASSESSMENT OF LEADING TECHNOLOGIES

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AUTOMATED PAVEMENT CRACK DETECTION: AN ASSESSMENT OF LEADING TECHNOLOGIES

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Current products and development efforts for automated pavement crack detection equipment are reviewed in light of their relative technologies. The technologies are characterized by the data collection and processing systems, grouped into optical processing, analog electronic processing, digital electronic processing, and hybrid approaches. Each technology is described with reference to equipment currently available or nearing final development, and each is assessed for merits, limitations, and relative costs in light of pavement management requirements.

Keywords: automation, crack detection, image processing, instrumentation, pavement management, video.

Introduction

In the face of decaying road surfaces and limited maintenance budgets, fresh technologies are being applied more vigorously to collect, compile, and process information about new and aging highways, for the purpose of improved pavement management. Instrumentation has been applied to measurements of surface roughness, skid resistance, texture, delamination, and other measurable attributes. To date, surface distress, particularly cracking, has not been well characterized by any automated means[1]. As surface distress is a critical indicator of overall pavement condition[2], a good deal of effort has recently been applied to this area of research.

An automated crack detection system should ideally detect all types of cracking, spalling, and other surface distress, of any size and at any collection speed. It should be affordable, easy to operate, and capable of daylight operation. Although research programs may require great accuracy from such devices, locating crack positions and dimensions with detail, pavement management programs would be very adequately served by devices which give meaningful, repeatable distress ratings to sections of pavement, providing the critical information for informed maintenance decisions.

In states which currently attempt to take inventory of surface distress, almost all rely on sampled data from diverse techniques of human observation[1], with productivity, accuracy, and sampling intervals closely related to the inspectors' speed. While human observers are far more versatile and clever than automated counterparts, machines are fast, objective, tireless, and generally consistent. Given the speed and remote sensing nature of automated devices, far safer data collection conditions may be provided for the operators who run them.

Several technologies for the automated detection of surface cracking have been investigated in the last few years, and they will be compared in the remainder of this paper. The general concepts and approaches will be presented, to be followed by a summary of some particular projects.

Data Acquisition

There are a number of crack attributes which could be appropriate to their detection. Table I lists several of these. The most obvious is their visible location, as this is the method to which we are most accustomed. Cracks could also be detected as abnormal depths in surface texture by measuring profile. Also, vehicle tires often make slapping sounds against cracks as they are crossed at high speed, suggesting yet another potential detection method.

TABLE I: Data Collection Technologies for Automated Pavement Crack Detection

Data Collection Approaches	Merits	Limitations
Rangefinding Methods		
Acoustic (e.g.,ultrasonic)	- inexpensive	- resolution too low (both range and breadth)
Optical (e.g.,laser)	- very accurate - ideal measurement (fewer artifacts)	- expensive - too slow to scan imagery (i.e., limited mainly to transverse cracks)
Reflective Optical Methods		
Photolog	- very mature technology - inexpensive hardware - very high resolution - historical record	- automated image processing would require scanning; - post-process only - non-reusable media
Short-Exposure Video Capture	- mature technology - inexpensive hardware - reusable media (videotape, if post-process) - readily digitized - historical record	- requires shuttered system or phased array of strobe lights - limited resolution - complex processing often required
Line Scan	- less light field uniformity required - real-time signal processing possible - medium-high resolution	- custom hardware design - complex processing & interface
Flying Spot Laser Scanner	- high transverse resolution - superior illumination uniformity	- low longitudinal resolution - may fail to find transverse cracks at highway speeds - custom hardware design; moving parts
Directed Light Meter (Slit Integration)	- helps to distinguish cracks from texture - well suited to real-time processing - inexpensive hardware	- custom hardware design - limited versatility - finds only transverse and longitudinal cracks
Acoustic Pickup Methods (e.g., microphonic)	- very inexpensive	- generally poor performance anticipated - very susceptible to artifacts

Profile

Profilometry has been applied for roughness measurements for some time. If the sampling area and resolution of profile measurements were sufficiently high, profilometry would make an ideal means for crack detection as well. First, even a single point significantly below the surrounding average texture height could be inferred as distress, so that a precise rangefinding system could be very sensitive. Second, depth information may give a great deal of insight into the causes and implications of the distress. Third, roughness and three-dimensional texture measurements could probably be derived from the same data. Finally, there is less chance that such a system would be confounded by visual artifacts such as oil spots, tire tracks, and paint lines, as they have no appreciable three-dimensional profile.

Unfortunately, to provide the coverage areas and resolutions required, very high sampling rates would be needed at highway speeds. For example, a 13 foot (4.0 m) lane width sampled at 0.1 inch (2.5 mm) intervals in both transverse and longitudinal axes would require 15 million readings per second at 55 mph (89 km/h). This is more than 100 times the sampling rate of laser rangefinders which have been applied to the problem to date. Also, it would be necessary to scan such devices, and many rangefinders are not well suited to rastered application. Inexpensive ultrasonic rangefinders could be arrayed for full coverage, but do not have sufficient spatial resolution for crack detection. This very attractive method is simply limited by the technology of available rangefinder response and scanning difficulties.

Visible Images

State-of-the-art computer technologies have introduced rudimentary forms of machine vision. There are many vision tasks in which machines may already outperform human beings, but complex problems of perception still present a very significant challenge to designers of automated equipment. Although cracks are often readily observable, there are several properties which allow humans to distinguish them. In particular, the eye-brain combination readily perceives the connectivity of the cracks. Image processing systems "perceive" cracks mostly as disturbances in the brightness range of the surrounding texture, and must be designed to seek connected regions. It is quite difficult to segregate cracks from texture, particularly for the more open textures of bituminous pavements. However, various methods have been developed, based on several image input methods.

Photologging

The oldest image capture method is the photolog[3]. In some cases, this uses a through-the-windshield perspective to assist human observers in the rating of distress from the safety of the office. Technology has been applied in offices such as the Connecticut DOT to present these images in a fashion that is convenient and aids mensuration, but still requires a human observer for estimates of distress. The French GERPHO system and Japanese PASCO[4] systems provide highly resolved, continuous photographic records of pavement from a normal perspective (i.e., from directly above). Although these night-collected images are of very creditable quality and value (potentially facilitating rut depth measurements as well), the resultant images are not in suitable form for **automated** inspection. A post-processed crack detection system would have to be based on an automatic film transport, with digitization of the films before digital image processing could commence. Handling of films is often difficult, and the film media are obviously not reusable.

A novel photolog technique was studied by the University of Texas in 1983, in which aerial photos were taken from an airplane as wet pavements were in the process of drying after a rainstorm. The cracked areas were visibly amplified by their surrounding water marks, and could be seen in the resultant imagery. However, the resolution was found to be inadequate, and the data reduction was still not automated.

Video Imagery

Another mature technology for image capture is the video camera. Although standard video equipment has much inferior resolution to most photographic records, it serves as a high-speed, off-the-shelf, recordable image capture system, with reusable media (videotape). Further, there is a great deal of hardware available for the purpose of translating analog video image frames into digital codes which are suitable for digital image processing. Video cameras may be very sensitive, allowing their use with shutters or strobe lamps to reduce the "smear" associated with high-speed vehicle motion. To limit smear to less than 0.1 inch (2.5 mm) at 55 mph (89 km/h), an exposure time of less than 100 microseconds is required. Consequently, strobe lights or shutters are required for sharp images.

The chief limitation of video image capture is the resolution of both intensity and spatial definition. Very high quality cameras, particularly the newest CCD array types, have much improved intensity and spatial resolutions in rugged packages, but are very expensive and generally incompatible with more standard tape recorders and digitizing hardware. Thus, two or more video cameras of more standard specifications are generally recommended to increase spatial resolution.

As with the photographic case, uniform illumination in the cameras' fields of view is very important to most automated detection algorithms. In particular, shadows from objects such as trees may be very difficult for an automated system to reject.

For the post-processed scenario (most common to video capture approaches), a system must be devised to accurately play videotaped frames or fields back to a digitizing circuit under computer control. This adds further complexity to the processing system.

Other Optical Methods

Originating from NSF-supported studies by AMI Consultants[5],[6],[7], Earth Technology Corporation's Pavement Condition Evaluation Services (PCES) system uses linear arrays to collect pavement data in line scan or "pushbroom" fashion. An image is built up by reading consecutive one-dimensional lines of imagery. These provide relatively high resolution, and the vehicle motion facilitates the rapid collection of consecutive lines to form an image. This exploitation of rugged CCD technology provides fast, sensitive readings continuously, much in the fashion of "slit cameras," which continuously expose a slit of a long moving roll of film.

Komatsu, Ltd., builds up images via flying spot scanning. A small, bright spot of light is continuously scanned across the pavement in the transverse direction. A photocell (or two in the Komatsu system) stares at a broad area which is dark except for the flying spot. Hence, the photocell output represents the reflectivity of the pavement at the instantaneous position of the illumination spot. As with the PCES system, vehicle motion provides scanning in the longitudinal axis, so that the moving system can create images from consecutive scan or "raster" lines. Flying spot scanning may offer more uniform lighting than broadly illuminated techniques, but is limited in speed or resolution, due to raster speed. While the Komatsu system works only at night, flying spot scanners employing lasers might be used in daylight by using a narrow bandpass optical detector filter, selected to match the monochromatic output of the laser radiation.

Another optical exploitation is the "slit integrator," currently under development at EKTRON Applied Imaging, Inc. This method uses a set of directed light meters for optical preprocessing, to reduce the data reduction complexity. The details of its approach will be deferred to a later part of this discussion. In both the PCES and EKTRON approaches, the restrictions on illumination field uniformity are very significant, but considerably less difficult than "snapshot" data collection techniques.

Sonic Detectors

One last technology worthy of mention is the application of a microphonic system to infer crack locations by the sound of tire slap. Representatives from Highway Products International, manufacturers of the PURD and ARAN systems, have investigated such an idea for the characterization of special road textures in Italy, but did not foresee a favorable application of this simple technology to accurate crack detection.

Data Reduction

The automated treatment of pavement data for detection of cracks may take several forms, with digital image processing most common. Image processing may be applied to profile-based "range images" or to visible images, as derived from any number of instruments, cameras, electronically scanned photographs, or tape recorders. In almost all cases, the image information must be transformed to a digital code pattern for further treatment. The most common approach is the digital interpretation of video imagery. If the data is processed on board, immediately or shortly after it is acquired, the system is said to use "real-time" processing. If the imagery is recorded for later interpretation in a laboratory or office, it is "post-processed." Naturally, it is preferable to have results instantly, as this reduces effort and allows verification that the data collected were correct.

Image processing draws on many electronic technologies. Although video signals may be preprocessed through analog electronics, they will generally be digitized at frame grabbers for subsequent digital processing. This allows powerful, software-driven manipulation of the data at high speeds. Still, because there is so much data (typically 1/4 million image points for a single video frame), the sophisticated digital treatment may take several seconds per image. As standard video images are presented at 1/60 second per field, a real-time processor must be capable of completing its detection in 1/30 second per frame to maintain constant sampling. (A video "field" has one half the image points of a video "frame.")

Even with the aid of special video-processing hardware, this requires a very fast computer. Consequently, most of the studies have centered about the concept of post-processing of video recordings, allowing each video field to be digitized by the computer system and analyzed over one or more seconds.

The post-process time of a fully sampled system is generally much greater than the data collection time. If, for example, video images were gathered at 60 fields per second each on two cameras, a 24-hour automated processing operation which required only one second per image frame would require 20 days to process 100% of the data collected in one eight-hour shift! Fortunately, it is often not necessary to analyze every image frame to properly characterize distress.

Other studies have included the development of extremely fast, custom-designed hardware to alleviate the speed burden from the computer system. This may be applied to effective real-time processing, but requires significant development and specialized system components.

There are several standard means for deriving information from images via digital processes. Most systems have a series of steps: filtering, segmentation, and feature extraction. The first step is often the most difficult, as it must quickly separate the signal from the noise. Segmentation allows the system to identify distinct objects in the scene. Finally, the features of interest are characterized and logged.

The most common means of segmentation is based on an intensity threshold, generally derived from histogram information. The histogram represents the number of image points which have a given intensity. Typically, intensities will range from 0 to 255. A typical histogram is shown in Figure 1. In the case of a black crack on a white background,

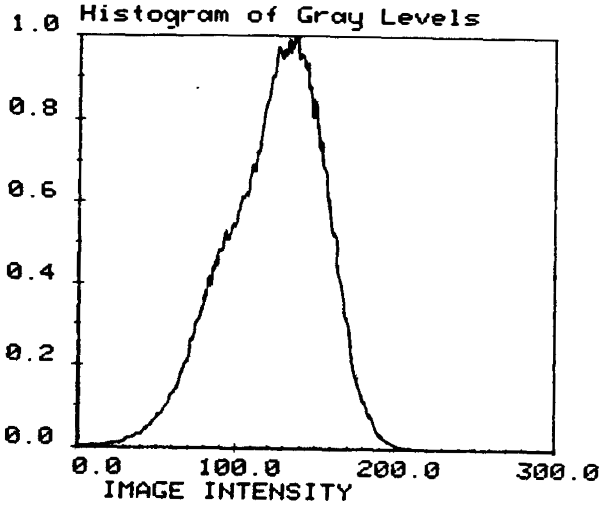

Figure 1. Histogram of an Image of Bituminous Pavement with Cracking

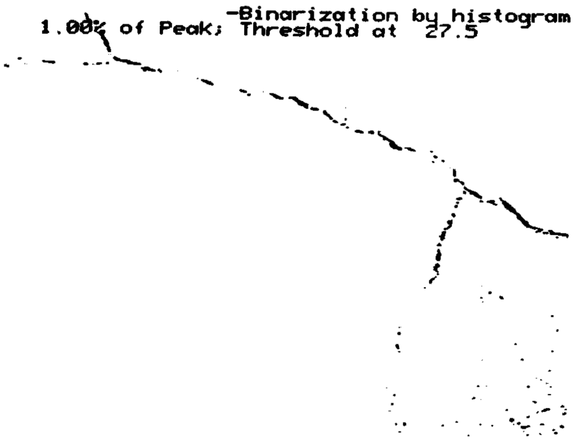

Figure 2. Binary Image of Detected Distress of Image Represented in Figure 1. Note Cracking and Some Texture.

the histogram will readily reveal the information; the black crack will form a weak peak in the lower intensity region of the histogram, and the background texture will form a large peak in the lighter region. This is called a bimodal histogram, but is rarely seen in the practice of pavement data reduction. The lower intensity tails of histograms may be used to threshold images and draw out crack information, but there are some limits. The illumination field must be very uniform and free of shadows when the image is captured, or its effects filtered electronically. Also, texture in bituminous pavements often has a sufficiently broad contrast range to include some areas of the lower end of the histogram. Thus, the histogram techniques will generally identify some texture as well as cracks, particularly in scenes which have no cracks. Figure 2 shows the application of a successful threshold (derived from the histogram of Figure 1) to indicate a crack in flexible pavement.

There are some methods to improve upon these limits, and these mostly center on the preprocess filtering. Clever applications of digital filters may be applied to smooth out the texture variations without losing the crack information. An analysis of the Fourier power spectra of bituminous pavements reveals, however, that the spatial frequency content of flexible pavement aggregates is quite similar to the width of typical cracks. That is, most of the standard image filters will have very limited success. For example, a wide filter will average a lot of texture, but will also greatly reduce the contrast of the crack. Various studies have produced hardware or software filters which seem to be effective in these cases, but the basic physics suggests that these filters must have some sophistication, adding to system complexity.

Another means to aid the problem is an electronic post-process step such as erosion and dilation. By this method, the thresholding identifies texture, as well as cracks, but the connectivity of the cracks are exploited to eliminate the islands of texture after the fact. This is reasonably effective, but requires a great deal of computation, suitable only to post-processing (given affordable computer equipment).

Analog Signal Processing

Other means of signal processing deserve attention as well. Analog electronics (such as that found in radios) are extremely fast and may be very accurate, but have little of the flexibility available in computer-based digital electronics (such as that found in calculators). Image processing requires extremely fast data manipulation, but is generally not well suited to analog means. If optical preprocessing could be used, analog reduction systems might then take over. This would be an attractive system for a fast, affordable, real-time detector. This theory was the basis for the "slit integrator," under development at EKTRON Applied Imaging. It is intended to be a simpler alternative to image processors, forming an affordable, real-time system of limited but useful accuracy.

Slit Integration

As the most difficult processing step is the discrimination of cracks from texture, the slit integrator exploits the linear connectivity of the cracks to simplify the collection and reduction system. There are two detectors proposed, as shown in Figures 3 and 4: a transverse crack detector, based on a simple, slit-shaped light meter, and a longitudinal crack detector, based on a linear photocell array. In the first case, the light meter views a slit of pavement perpendicular to the direction of travel. In the absence of cracks, the light meter provides an electronic signal which represents an average of texture in the slit. As the vehicle moves over a transverse crack, the light meter signal will drop (or possibly rise if the crack is sand-filled). This drop (or rise) may be interpreted by analog processing circuitry.

A similar method is employed for the detection of longitudinal cracks. A linear array is used to integrate 2048 narrow slits by exposing the photocells while in motion. This is a deliberate use of smear for texture averaging, as opposed to the fully imaged application of linear arrays in the PCES system. Again, this preprocessing greatly simplifies the data reduction. However, this system can only detect transverse and longitudinal components of cracks, and will not generally detect diagonal ones.

Current Projects for Automated Systems

Table II lists several manufacturers and research teams studying automated crack detection. The table is not intended to be an exhaustive list of activities in the field, but includes several firms and organizations which have drawn note for their recent progress in the field. In addition to those listed, interesting work has taken place at KLD Associates[8], Penn State[9], the Arizona DOT[10], MHM Associates[11], and other agencies and corporations.

Swedish Laser RST

The Swedish Laser Road Surface Tester device uses 11 laser rangefinders, including four capable of reading 32,000 samples per second. These fixed 32 kHz lasers are capable of picking up transverse cracks which cross their paths, so that

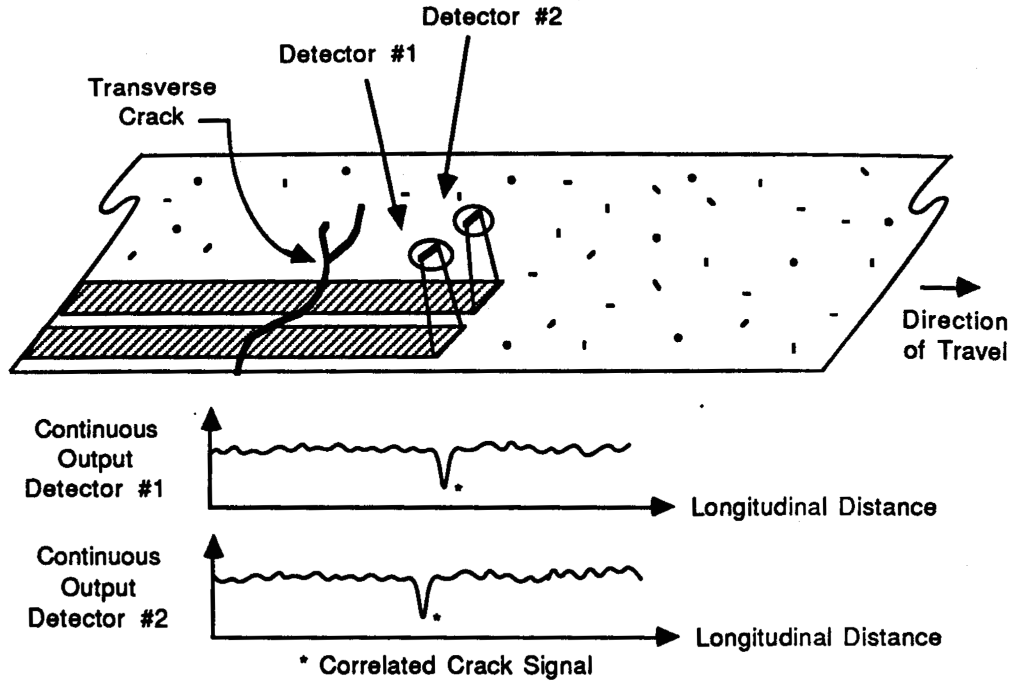

Figure 3. Principles of EKTRON's Slit Integration, as Applied to Transverse Cracks

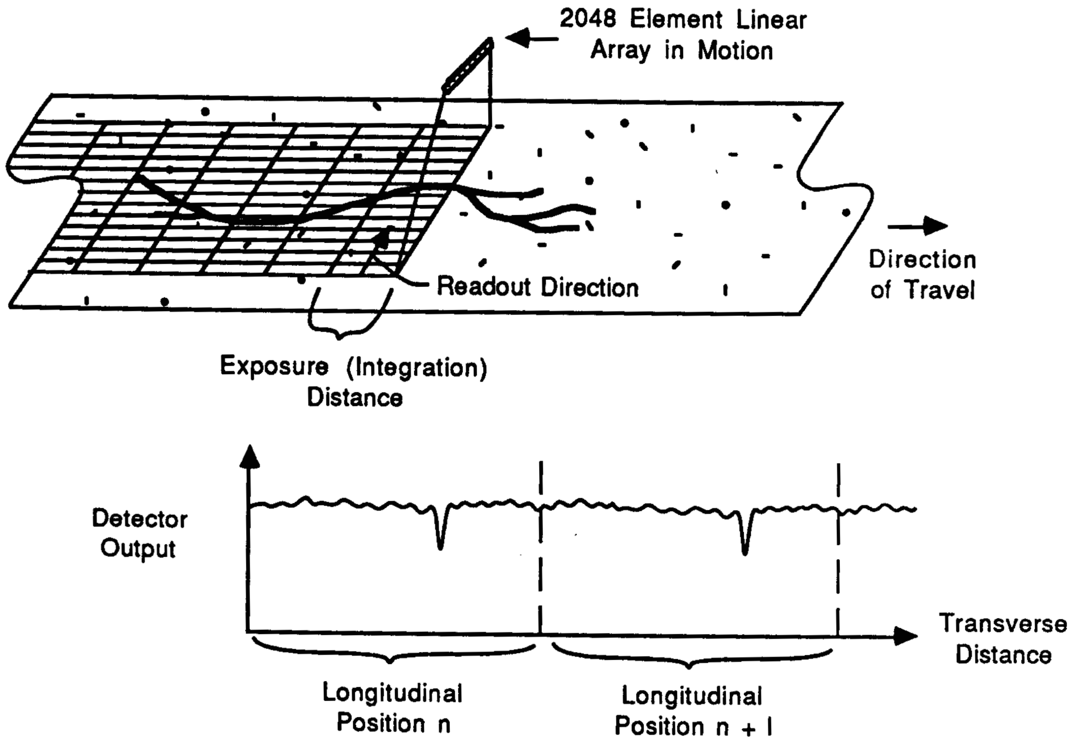

Figure 4. Principles of EKTRON's Slit Integration, as Applied to Longitudinal Cracks

TABLE II: Partial List of Developers of Automated Crack Detection Technologies

Manufacturer or Researcher	Data Collection Technology	Data Reduction Technology	State of Development	Cost Category**	Comments
Swedish Laser RST	laser rangefinder	real-time; analog & digital	available	H,S	- makes several other measurements as well - may fail to detect some longitudinal cracks
PCES/Earth Technology	continuous line scan	real-time; digital	version 1.0 nearing completion	H,S	- makes several other measurements as well
EKTRON Slit Integration	directed light meter & integrated line scan	real-time; analog; digital logging	version 1.0 nearing completion	L	- statistical device; will not detect diagonal cracks - future versions to retrofit vehicles already in use
VideoComp (Idaho DOT)	short-exposure video	post-process; digital image processing	version 1.0 nearing completion	M,S	- videologs done for Idaho & Arizona DOTs - software nearing completion
Univ. of Waterloo	video	post-process; digital image processing	study phase	n/a	- "accurate" processing PC-based software delivered to Ministry
Komatsu, Ltd.	flying spot laser scanner	post-process; digital image processing	n/a	n/a; probably H	- limited speed for detection of transverse cracks - night use only - also measures rut depth and slope variance
MHM Assoc.s	short-exposure video	post-process; digital image processing	study phase	n/a	- study phase
KLD Assoc.s	short-exposure video	post-process; digital image processing	currently inactive	n/a	- study phase

**Relative Cost Category: L=Lower ($40,000-80,000), M=Moderate ($80,000-150,000), H= Higher (>$150,000), S=Available as a Service; n/a= data not availabale; NOTE: Most costs are estimated.

they will count most transverse and diagonal cracks, but will detect longitudinal cracks only as the cracks cross one of the four rangefinder's field of view. The system operates in daylight at varied speeds up to full highway limits. It is sold as a service only, and is also capable of measuring roughness, relative transverse profile (with rut depth), macrotexture, and possibly friction. The data reduction is in real time, using digital means to combine laser data with accelerometer data and other instrument readings.

Representatives of the RST report that the newer capabilities of crack detection are operating well[12], but quantitative measures of performance were not found during research for this report. Although the cost of services for the RST may be higher than many system designers anticipate for applications of their upcoming products, the RST is the only system currently delivering automated crack measurement.

PCES/Earth Technology

As mentioned above, the PCES (Pavement Condition Evaluation Services) system employs linear arrays to form a pushbroom scanner[13]. Digital signal processing is employed in real time, exploiting custom filter circuits (3 x 3 neighborhood "convolver boards"). Each of the two 512-element CCD arrays continuously covers four feet of pavement, for a total of eight feet of lane width (which may eventually be increased to 12 feet with the addition of a third linear array). Each is supported by an 8-bit analog-to-digital converter, a convolver board, and a powerful 68020 microprocessor. An additional 68020 supervises the system activity. It is intended for daylight use throughout a normal range of highway speeds.

The PCES system is also intended to make roughness and rutting measurements in addition to crack detection. PCES plans to offer its product mainly in the form of services. The system has undergone some field testing, but is not yet available. A two-camera system will be demonstrated by the end of the year, with processing speeds allowing 30% pavement coverage at 60 mph. As appropriate, PCES may later increase coverage to higher percentages, while retaining real-time performance.

EKTRON Slit Integration

With FHWA support, EKTRON Applied Imaging (a subsidiary of Eastman Kodak Company[14]) has been developing a lower cost/lower precision alternative system via slit integration and analog processing. The principles were presented above, in which a slit-shaped light meter is used to detect transverse cracks, and a linear array is used with a deliberate motion smear to detect longitudinal cracks. Most diagonal cracks and cracks narrower than 1/8" will not be detected. The EKTRON system is intended to be used during daylight, and to operate from 20 to 55 mph (32 to 89 km/hr). (The prototype under development runs only at 40 mph.) It is intended to sample continuously, but to detect only a statistical (but repeatable) fraction of all cracks. Signals from the detectors are analyzed in analog hardware, counted in digital circuitry, and reported and logged via portable computer. The system is designed primarily to report crack density (extent) in raw index form, but may also provide severity information in the future. Statistics of preliminary field tests forecast an estimated 85% confidence of "heavy," "medium," or "light," crack extent categorizations for 1/4 mile sections.

The transverse crack detector has been built and field tested. It is undergoing enhancements to improve weak detectability under some conditions, but has demonstrated an ability to repeatably detect cracks under realistic conditions. The longitudinal crack detector is in the design phase. The system has been designed to be affordable for purchase for retrofit to existing pavement test vehicles (approximately $50,000 estimated, excluding the vehicle and power source). The current system draws 3000 watts of power for its illumination system, impeding such retrofit efforts. However, future versions are expected to reduce the power requirement.

VideoComp

A high-speed video capture system is employed by VideoComp to provide a tape recorded photolog for subsequent post-process[15]. The collection system may be used at any time of day, at varied speeds up to 65 mph (105 km/h). Working closely with the Idaho DOT, past systems have used pairs of cameras to cover eight foot (2.4 m) lane widths, with shrouding to protect the imagery from extraneous shadows. Future systems will incorporate three cameras (to cover a 12 foot (3.7 m) width), with methods to avoid using such shrouds. VideoComp has already prepared many videotapes of photolog information for the Idaho DOT and Arizona DOT.

The methods of post-processing are proprietary, and are said to be at least 90% complete as of this writing. Representatives of VideoComp report that automated crack detection performance has been quite good, based on data gathered from SHRP long-term monitoring pavements. Although most testing has been on rigid pavements, early tests of the system on flexible pavements were reportedly successful.

Once completed, VideoComp plans to offer the use of their equipment as a service, but would primarily seek to sell systems. System costs, including all collection and processing equipment, might be anticipated to fall in the range of $100,000, but precise cost estimates would be premature at this time. "Version 1.0" is expected to be complete within one year.

University of Waterloo

Under the direction of Mr. Carl and Dr. Ralph Haas, an image processing system based on an IBM^R PC AT was delivered to the Ontario Ministry of Transportation and Communication[16],[17]. The system relied on field videologs gathered at relatively low speeds of approximately 9 mph (15 km/h). The post-processing required approximately five seconds per frame, and the images were gathered at that rate from free running video playback. Given the collection rate, this reportedly provided coverage of roughly 20%. The precision of the system has been reported to be approximately 95% for identification of cracked images, mostly using images of bituminous pavement.

Researchers feel that the processing time might be reduced to one second per frame or less, and that collection quality and speed could be increased significantly by the application of shuttered cameras. (Note, however, that a 60 mph (89 km/h) collection would outweigh the faster 1 second processing, reducing total coverage.) Shadows would be compensated in future systems by strong illumination. Unfortunately, the project has not been very active since delivery, and its architects have not had sufficient opportunity to try these enhancements.

Komatsu, Ltd.

Komatsu, Ltd. has recently reported on their ZR04LY-1 bus-carriage type vehicle, capable of measuring cracks, rut depth, and slope variance[18]. The crack detection is based on a flying laser spot scanner, which uses a rastered, water-cooled argon ion laser. This Japanese device is used at night only, and records the pavement images via special high-density video tape recordings for post-process. The algorithms for tape image interpretation are not clear from the published information, but seem to be based on straightforward digital image processing.

The ZR04LY-1 can be set to measure pavement widths between eight and 13 feet (2.5 and 4.0 m). Komatsu claims to resolve 1 mm cracks at 12 mph (20 km/h). Higher speeds (up to 37 mph or 60 km/h) are available, with correspondingly lower resolution and detectivity of transverse cracks anticipated.

Conclusion

Several technologies are being applied to the task of automated crack detection. While many of these technologies are appropriate to the requirements, there has been little Quantitative performance data published for existing or developing systems. At the root of the issue is a simple truth; the "superior" technology will be that which performs best and provides the highest overall value to end users. The purpose of this paper has been to provide a comparative explanation of technical approaches, but the pavement management community must ultimately select an approach based on documented performance, reliability, and value. All of the projects listed above are now ready, or should shortly be ready, to bear quantitative results, and pavement managers may (and should) then compare the technologies in light of pavement survey requirements.

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