The Development of Deck Assessment by Radar and Thermography

D. G. MANNING and F. B. HOLT

ABSTRACT

A systematic approach to bridge deck rehabilitation requires considerable data on the condition of decks. In the past, data were collected using the traditional methods of visual inspection supplemented by physical testing and coring. Such methods proved tedious, expensive, and of limited accuracy. Research studies were undertaken to develop methods for the rapid and automatic collection of data on the condition of bridge decks, resulting in the deck assessment by radar and thermography (DART) system. As the acronym implies, DART utilizes two basic systems: impulse radar and infrared thermography. A prototype vehicle was equipped with both the radar and thermography equipment. The vehicle is driven slowly across the bridge deck and data are collected and stored on magnetic tape. Programs were written that would then retrieve and automatically process the data to produce a scaled plan of the bridge showing the location and type of deterioration present. DART can be used on exposed concrete decks and on concrete bridge decks covered with a bituminous wearing course.

The development of a systematic approach to bridge deck rehabilitation (1) created the need for considerable data on the condition of bridge decks in Ontario. Defects and deterioration need to be located for two principal reasons: (a) to establish priorities for rehabilitation, and (b) to determine the method of rehabilitation and prepare the contract documents.

For the first step, it is sufficient to determine only the approximate extent of any deterioration. The information is used to develop the future rehabilitation program and has traditionally been collected through a visual inspection together with a limited amount of physical testing. However, much of the deterioration can be hidden and go undetected. Second, an accurate measurement of the size and location of each type of deterioration is required. This information not only affects the selection of the method of rehabilitation, but also the quantities to be included in the repair contract. In the past, the data were collected through a detailed condition survey of the deck (2). Existing procedures require a thorough visual inspection supplemented by physical testing that includes a chain-drag survey and measurement of electrical potentials. Cores are taken and tested for chloride content, air-void analysis, strength, and sometimes, a petrographic analysis is made. The testing is expensive, and costs vary with deck size and location with an average of (Canadian) $\$12/m^2$ or about (Canadian) $6,000 for a typical bridge deck.

Despite this systematic approach, the information is sometimes of limited accuracy. This is especially true when the deck has a bituminous surfacing. Even though sections of the surfacing are removed at selected locations in the course of a detailed condition survey, it is difficult to determine the condition of an asphalt-covered concrete deck slab with any degree of confidence. A further disadvantage of the traditional methods of investigation is that the survey of a bridge deck usually takes a few days, and this results in a major disruption of traffic flow.

Research studies were undertaken to investigate improved methods of detecting defects in exposed concrete (3) and asphalt-covered bridge decks (4). The culmination of these studies was the development of the deck assessment by radar and thermography (DART) system. The results of the research studies are summarized in this paper and the prototype DART unit is described.

TYPES OF DETERIORATION

The most serious form of deterioration is that caused by corrosion of embedded reinforcement. As the reinforcing steel corrodes, it expands and creates a crack or subsurface fracture plane in the concrete at or just above the level of the reinforcement (Figure 1). The fracture plane, or delamination, may be localized or extend over a substantial area, especially if the concrete cover to the reinforcement is small. It is not uncommon for more than one delamination to occur on different planes between the concrete surface and the reinforcing steel. Delaminations are not visible on the concrete surface. However, if repairs are not made, the delaminations progress to open spalls and, with continued corrosion, eventually affect the structural integrity of the deck. Spalls on exposed concrete decks seriously impair the riding quality of the deck.

Scaling, which is the breakdown of the cement-paste matrix, is also a serious problem wherever it occurs. The disintegration of the concrete, which is caused by the freezing of concrete critically saturated with water, begins at the surface and gradually progresses so that the full depth of a deck slab may be affected. In Ontario, scaling most commonly occurs in older, asphalt-covered deck slabs built without the benefit of air entrainment or a waterproofing membrane.

On asphalt-covered decks, bond failure may occur

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FIGURE 1 Corrosion-induced delamination in a concrete core.

between the concrete deck slab and the bituminous surfacing. Debonding can result in moisture being trapped on the surface of the concrete and, where thin surfacings are used, can lead to failure of the bituminous surfacing. Although debonding is not as serious as either delamination or scaling, it can be confused with these two phenomena in surveys and, consequently, it is important to be able to identify and define debonded areas.

Cracking is the most common defect in concrete. However, with the exception of delaminations, cracks are usually easy to identify and were, therefore, not included in the research studies.

INVESTIGATIONS ON EXPOSED CONCRETE DECKS

The first studies were conducted on exposed concrete decks during the period 1977-1979 and were designed specifically to investigate methods of detecting delamination.

Most methods, including the use of a hammer or a chain, rely on the fact that a delaminated area produces a characteristic dull sound when the surface of the concrete is struck. These methods are tedious and depend on the skill of the operator. They can be difficult to use when a bridge deck is only partially closed to traffic and there is noise from vehicles in adjacent lanes. A machine was developed to eliminate the subjective judgment of the operator (5). It consists of three basic components: a tapping device, a sonic receiver, and a system of signal interpretation. However, the machine has only limited accuracy (3).

The detection of delaminations by infrared thermography is based on the difference in surface temperature that exists between delaminated and sound concrete under certain atmospheric conditions. The delaminations interrupt the transfer of heat into and out of the deck. Consequently, in periods of

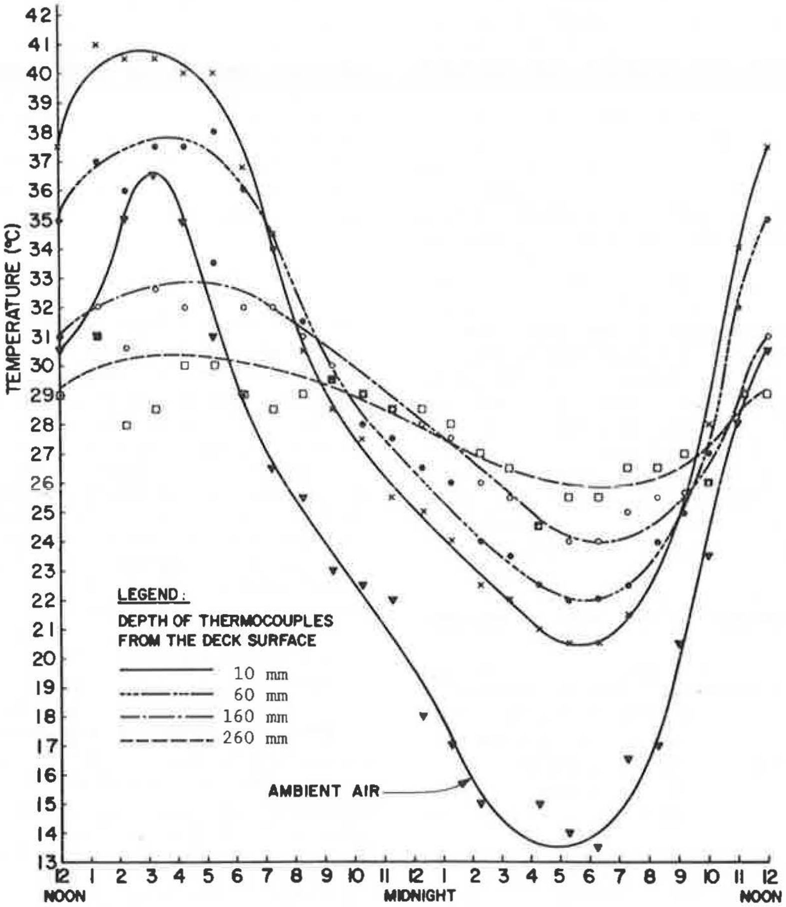

FIGURE 2 Typical diurnal temperature distribution in a thick slab deck in summer.

heating, the delaminated concrete heats more rapidly than surrounding areas of sound concrete and a difference in surface temperature develops. The reverse situation occurs during periods of cooling, usually during the night. Figure 2 shows a typical temperature variation during a 24-hr period in the top 240 mm of a thick slab deck with an exposed concrete surface on a summer day under clear skies. A substantial temperature gradient was recorded in the top 65 mm of the deck where delaminations occur most frequently. During the hottest part of the day, the concrete temperature decreased with the depth below the deck surface and at night the situation was reversed. Similar temperature distributions have been recorded on thin slab decks in both summer and winter, although the temperature gradient is less in winter.

Figure 3 shows the temperature variation in sound and delaminated concrete measured by thermocouples installed 6 mm below the surface. During the test period the difference in surface temperature between the solid and the delaminated concrete reached 3°C.

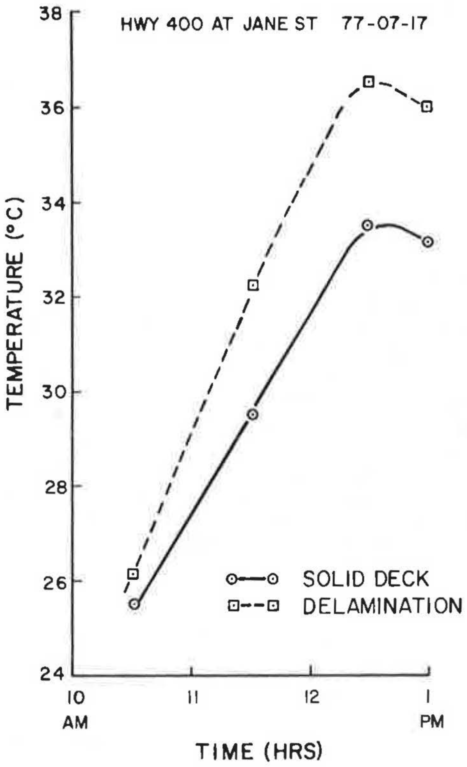

FIGURE 3 Difference in temperature between solid and delaminated concrete on a thin slab deck.

Infrared detection systems are used for the remote measurement of the surface temperature of an object. A typical system consists of an infrared sensitive scanner, a display monitor, and a power source. The typical temperature differences shown in Figure 2 are well within the capabilities of many scanners with a sensitivity of better than 0.2°C. The image from the scanner is displayed on a cathode ray tube and indicates the surface temperature of the object being viewed in a continuous range of gray tones from black to white. During daytime hours, when the delaminated areas are hotter than the surrounding solid deck surface, they appear as white areas against a dark background. A permanent record of the image can be made using an instant camera or a video recorder. Color monitors are also available but are not well suited to bridge deck applications because of the difficulty of recognizing the physical features on the deck (e.g., oil spots, debris in the curb area, or pavement markings) in the image. Furthermore, the types of deterioration present are generally not associated with a single color level.

The first series of tests was made at ground level using targets to locate the position of the image (Figure 4). Although the delaminations were easily identified, the method was impractical because of the limited field of view and the difficulty of constructing a plan of the deck from photographs taken at an oblique angle.

FIGURE 4 Infrared thermovision equipment being operated at ground level.

Airborne testing was undertaken using a scanner mounted in a helicopter. Although this method had the advantage of not requiring lane closures, the quality of the image was substantially reduced. The use of the helicopter was also complicated by the requirement to obtain a waiver of air regulations to fly at low altitude over the bridge decks. The best compromise between these two extremes was the use of a vehicle-mounted scanner, which resulted in an acceptable field of view and good definition of the delaminations.

INVESTIGATIONS ON ASPHALT-COVERED DECKS

During the period 1980-1982, the work on exposed concrete bridge decks was extended to a much more detailed evaluation of methods for investigating the condition of asphalt-covered decks. The objective of this research was to identify reliable methods of defining the type and extent of defects and deterioration. It was also desirable that the methods be rapid, inexpensive, noncontact, and capable of having the data transcribed to a scale plan of the bridge deck using automated equipment.

A test site was created by selecting a typical bridge that exhibited corrosion-induced distress. This deck was surveyed and then paved with two 40-mm thick lifts of bituminous surfacing without first making repairs. Areas of scaling and debonding were simulated before paving (4). Consequently, the locations and type of deterioration were known and the capabilities of different test methods could be evaluated under controlled conditions.

Eight tests methods were investigated (4) and the results obtained are summarized in Table 1. The most promising techniques were found to be infrared thermography and impulse radar.

Thermography

Several commercial infrared systems were tested at ground level from a boom truck and, in some cases, from a helicopter. This work confirmed that the truck was the most practical platform in terms of accuracy, cost, and speed. The optimum height above the deck was in the 4- to 6-m-range to provide the best definition of delaminated areas with the least interference from reflected radiation, and to enable the full width of the traffic lane to be investigated during a single pass.

Temperature measurements showed that a delamination in the concrete deck slab produced a difference in the surface temperature of the bituminous surfacing during periods of heating. As with the exposed concrete decks, this occurs because the delamination interferes with heat flow through the deck and a higher surface temperature is associated with areas of delamination. However, the maximum difference in surface temperature recorded was 2°C at 2 p.m. and the time of day when delaminations could be identified was limited to 11 a.m. to 6 p.m. The ability to detect delaminations on asphalt-covered decks was also found to be much more sensitive to atmospheric conditions such as wind, humidity, and cloud cover than on exposed concrete decks.

Despite the dependence on weather conditions, the results using thermography to detect delaminations were very encouraging. The system detected more than 90 percent of the known delaminations, some of which were less than 150 mm in diameter. Debonding was not detected because it did not produce a thermal discontinuity. The inability to detect scaling was ascribed to the fact that the areas of simulated scaling were all adjacent to the curbs and any difference in surface temperature was masked by the difference in emissivity between the asphalt deck surface and the concrete curbs. The major technical problem to be overcome was identified as the production of scaled hard copy from the image stored on videotape.

Radar

The use of low-power, high-resolution, ground-penetrating radar for detecting deterioration in concrete bridge decks is a relatively new technique first reported in 1977 (6). The equipment consists of a monostatic antenna, a control console containing a transmitter and receiver, and an oscilloscope. A 1-nanosecond pulse of low-power, radio-frequency energy is directed into the bridge deck. A portion of the energy is reflected from each interface between different materials including the asphalt-concrete interface, the surface of reinforcing bars, and air-filled or water-filled voids associated with defects such as delamination, scaling, and debonding. These echoes are received by the antenna and displayed on the oscilloscope.

For the purposes of the investigation described here, the equipment was mounted on a cart pushed by hand along the deck. The waveforms were recorded at grid points using an instant camera. Figure 5a shows a typical radar signal for a sound portion of the deck and Figure 5b shows the signal for a section known to be delaminated. In areas where the concrete is deteriorated or the character of the interface changes, the amplitude and time of the echo also change.

Using a simple visual assessment of the waveforms, 51 percent of the grid points located over delaminations and the simulated scaling were identified. The areas of debonding were not identified and false indications of delamination at several grid points were made. Despite these results, the radar was found to have considerable potential if the interpretation of the waveforms could be improved. The hand-operated cart was rather crude and it was apparent that the next step in the development of the radar system should be vehicle-mounted equipment in which the signal is recorded continuously on magnetic tape for off-line processing, using software specifically developed for the purpose. A useful feature of the radar is that it permits an accurate measurement of the thickness of the asphalt surfacing because of the well-defined echoes from the surface of the asphalt and from the asphalt-concrete interface. Except for the presence of moisture on the deck, the radar is independent of constraints by the weather.

THE DART SYSTEM

Following the completion of the research studies described earlier, development work concentrated on the construction of a prototype unit and automated data processing techniques. The prototype unit was to have the following operational characteristics: (a) be self contained, (b) produce real-time results, and (c) be simple to operate and offer safeguards to ensure that data are useable before the unit leaves the bridge.

TABLE 1 Summary of Results of Procedures Evaluated on Asphalt-Covered Decks

Test Procedure	Evaluation Summary
Chain drag	Only a small percentage of delaminations identified, but no false results. Independent of weather and inexpensive. Useful screening device in conjunction with other procedures.
Sonic reflection	Very low accuracy.
Ultrasonic transmission	Impractical.
Microseismic refraction	Identified anomalies but interpretation difficult. Procedure is very slow.
Resistivity	Results did not correlate with area of deterioration.
Potential survey	Useful indication of corrosion activity. Does not identify other forms of deterioration. Requires drilling through asphalt.
Radar	Good correlation with known deterioration. Many false results but accuracy could be improved by better methods of signal interpretation. Offers potential for rapid, noncontact procedure independent of weather.
Thermography	Excellent correlation with areas of deterioration with no false results. Main disadvantage is dependence on weather.

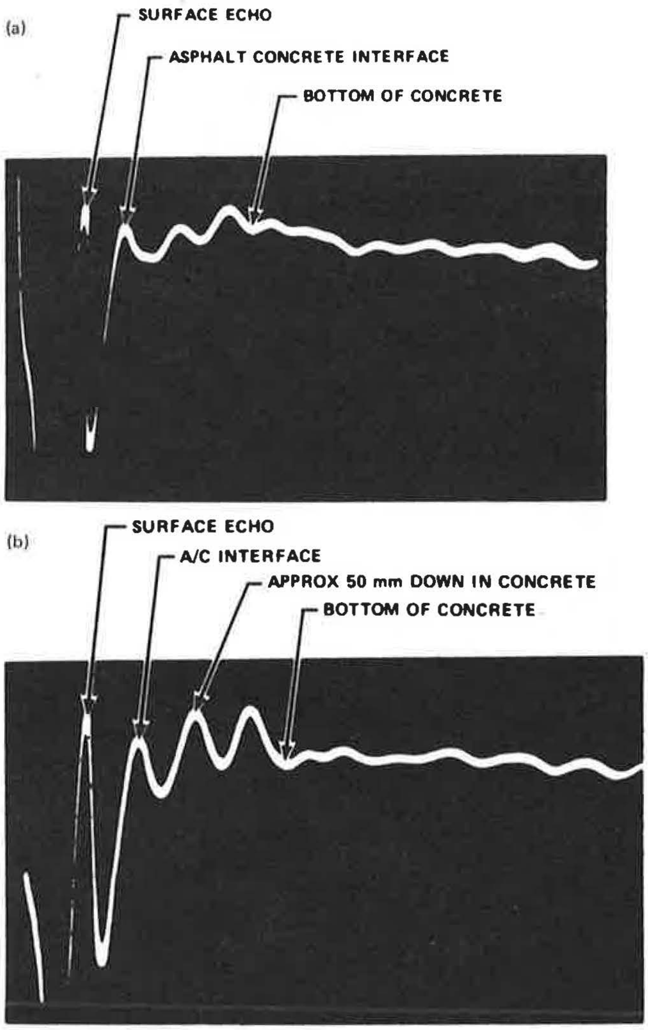

FIGURE 5 Typical radar waveforms: (a) radar output for sound concrete, and (b) radar output for delaminated concrete.

Prototype Unit

The prototype unit was designed to incorporate both the radar system and the infrared system with their respective peripherals. The vehicle dedicated to the system was equipped as follows:

1. A rail was attached to the front of the vehicle so that the radar antenna could be positioned 150 mm over the deck anywhere within the width of the vehicle. Note that the antenna is normally mounted 150 mm over the deck surface and can be mounted as high as 600 mm over the deck. The 150-mm position gives a 300-mm wide survey of the surface, combined with good penetration and resolution of the radar. The rail also allows for the future addition of antennas to scan additional areas of the deck at a single pass.
2. A hydraulically lifted rack for mounting the infrared scanner approximately 5 m above the deck surface was added to the front of the vehicle. A standard video camera to view the real-life condition of the pavement surface can also be mounted on the rack. The rack also ensures the repeatability of the height and angle of view of the scanner and video camera.
3. Vibration-controlled racks were mounted in the vehicle. Although the radar system and the infrared scanner were designed for use in the field, the peripheral equipment and the computer were not. In order to protect the equipment, instrumentation racks were installed in the vehicle. A series of vibration tests was carried out to evaluate the vibration characteristics of the vehicle. Isolation mounts were installed for each of the racks to minimize the vibrations being transferred to the equipment.
4. Two air-conditioning units were added to the vehicle to help keep the environment stable and prevent the breakdown, as a result of excessive heat, of the electronic equipment.
5. A fifth wheel was added to the vehicle. The fifth wheel gives accurate information on the speed and the distance traveled. An interface was built to produce distance pulses to the recording devices for both the radar and the infrared systems.
6. A trailer was built to house a generator to supply electrical power to the instrumentation on board the vehicle. In addition to the generator, the trailer can also carry such equipment as safety signs and a core drill.

Figure 6 shows the exterior of the vehicle with the radar antenna and the infrared scanner in position. A schematic representation of the infrared and radar components is shown in Figure 7.

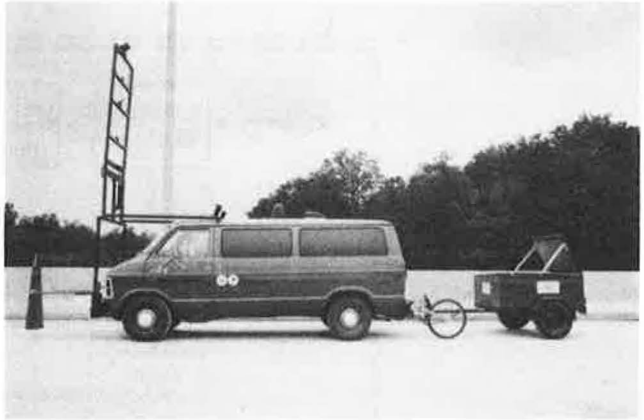

FIGURE 6 DART system with radar antenna and infrared camera mounted on the front of the vehicle.

Radar

The radar signal passes from the control unit inside the vehicle through the transmitter/receiver mounted on the front of the vehicle, through the antenna, and into the bridge deck. The return echoes are received by the antenna and returned to the control unit inside the vehicle. The waveform is simultaneously displayed on an oscilloscope and recorded on a seven-channel FM tape recorder. The operator can monitor the signal from the control unit and from the tape recorder, thus permitting a check of the quality of the signal before and after recording. As well as recording the raw waveform, the trigger pulse for the system, a gated version of the waveform, and three sets of distance information are recorded for analysis using a microcomputer. The radar itself is battery powered and has an operating time of approximately 6 hr on a charge.

The output of the fifth-wheel distance device is put through an interface to produce three sets of distance pulses; the raw 214 counts per revolution,

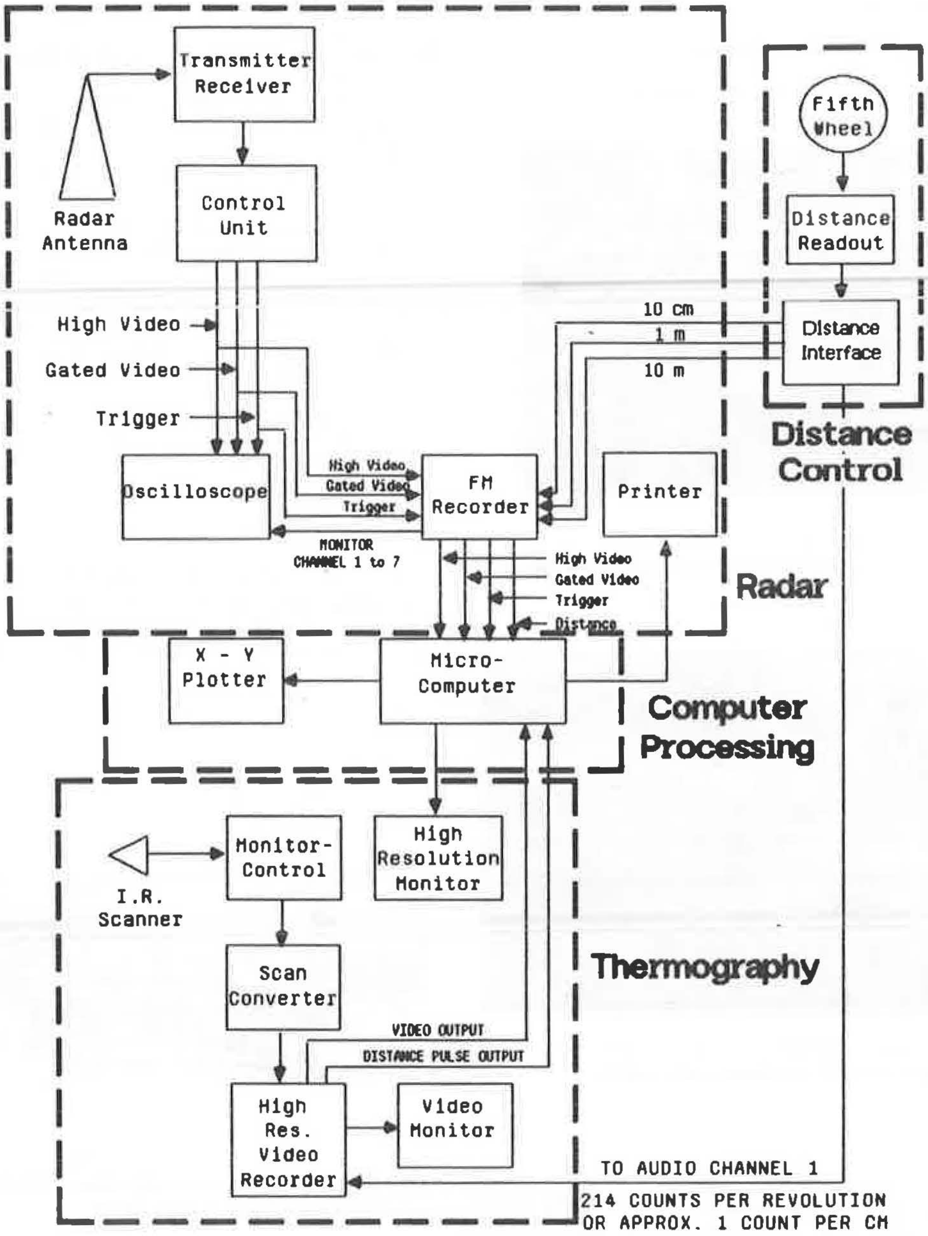

FIGURE 7 Schematic representation of the DART system.

a pulse every meter, and a pulse every 10 m. Each of these is used in the processing of the radar data for various program options.

Initially, the radar system is mounted with the antenna positioned within 1 m of the curb or the right-hand edge of the lane. A second pass is made with the antenna positioned between the wheel tracks, and a third pass is made with the antenna positioned adjacent to the left-hand edge of the lane. The maximum speed for the collection of data is 5 km/hr.

The monitoring checks built into the system allow the operator to verify the data collected before leaving the bridge. Should the operator observe problems with the data or observe significant deterioration in the bridge deck, a pass can be repeated or additional passes can be made over the deck.

Infrared System

The infrared system used on the DART prototype senses in the 3.5- to 5.6-μm range using an indium antomonide (InSb) detector. It has a sensitivity of approximately 0.1°C. Using a 20 degree lens, the system is capable of scanning an entire traffic lane width in a single pass. The scanner is connected through the scanner control unit to a proprietary interface unit to convert the scanner signal to a standard North American Television Standard Color (NTSC) video signal. The output of the interface is then fed to a high resolution videotape recorder.

The operator monitors the raw infrared image on the scanner control unit, on a monitor from the interface output, and from the output side of the video recorder. This enables the operator to ensure that the quality of the data collected is adequate and that the scanner is functioning properly.

The output of the fifth wheel is recorded on one of the audio channels on the video recorder. This enables the microcomputer to process the data and identify the longitudinal position on the deck. Data can be collected at speeds up to 6 km/hr, which is compatible with the maximum speed for collection of the radar data.

A standard color video camera mounted on the rack below the infrared scanner is used to record the visual defects in the deck surface. This information is recorded on a separate video recorder, along with the distance pulses, so that surface defects also visible to the infrared scanner can be interpreted properly during the analysis of the data.

Data Analysis Using Computer Processing

As noted, one of the main objectives of the DART system was to have the ability to produce an accurate and rapid evaluation of the deck condition. During the development phases of the work, it was apparent that the use of a computer would enable the operator to make rapid judgments as to the condition of the deck. In addition, it was apparent that the massive amounts of data produced by the radar system would require the use of computer processing to produce timely and accurate results. Two research contracts with McMaster University in Hamilton, Ontario, resulted in the development of software that processes the radar waveforms automatically (7). The program retrieves the following data from the radar waveforms: (a) location of delaminations, (b) location of debonded areas, (c) location of scaled areas, and (d) thickness of the asphalt overlays. Each of these is presented in the computer printout in the form of a deck plan with the type and extent of the deterioration along each grid line. The thickness measurements are tabulated and also averaged for each grid line, and an average for the entire deck is given.

The initial programs were written for use on a mainframe computer. Although this satisfied the goal of computer processing, there was a need for inexpensive data processing and real-time processing in the field. The second of the McMaster contracts involved the use of a microcomputer and investigated the effects of parameters not included in the first study. For this purpose, a microcomputer was equipped with a 10-megabyte hard disk, 640-K RAM, a single floppy disk drive, and a high-speed analog-to-digital interface. The original software was reconfigured to run on the microcomputer and the processing improved to the point that, with the computer on board the vehicle, some real-time processing was achieved.

Software has also been developed to utilize the microcomputer to analyze the infrared image. First, the videotape is digitized and then sampled so that the oblique angle to view and other distortions of the image are eliminated. Defects are identified through a combination of operator and machine interpretation. The software produces a scaled image of the deck showing the areas of delamination and scaling. Debonding can only be predicted with certainty if it covers large areas of the deck. If the debonded areas are small in area, then their infrared signature is very similar to that of delaminations.

The DART system represents a significant investment. The value of the major items is summarized next; however, because of duties, fluctuations in exchange rates, and volatility in the price of electronic components, the following costs (in 1985 U.S. dollars) should be regarded as approximate: radar $40,000, thermal scanner and converter $40,000, microcomputer and peripherals $16,000 (including extra circuit boards), FM recorder $10,000, industrial VCR $4,000, fifth wheel $5,000, oscilloscope $1,400, and generator $1,300. Adding the cost of the vehicle, trailer, external and interior racks, and numerous smaller items such as cables, filters, and interface devices would make the replacement cost of the fully equipped DART vehicle approximately U.S. $135,000. It should be noted that the Ontario Ministry of Transportation and Communications did not purchase the thermal scanner and converter, but rented the equipment during the summer months for (Canadian) $2,400 per month. In addition, the cost of developing the software was (Canadian) $62,000 for the radar, and (Canadian) $20,000 for processing the thermal images.

Summary

The DART system combines the use of radar and infrared thermography to take advantage of the complementary nature of the two technologies. It also provides a useful check on the validity of the data from two different techniques.

The advantages of the radar system are that it is virtually independent of weather conditions, is well suited to use on asphalt-covered decks, and can identify some defects undetectable by infrared thermography. It is less well suited to use on exposed concrete decks because of interference between the waveform reflected from the deck surface and any delamination just below the surface. This is not a problem on most asphalt-covered decks in Ontario because the standard asphalt thickness is 80 mm. The major disadvantage of radar is that it only produces data along the grid lines traversed by the antenna and, unless several passes are made, areas of deterioration can be missed. Conversely, thermography can be used wherever differences in surface temperature exist to produce information on the entire deck surface and not just along grid lines. Its major disadvantage is dependence on the weather, especially for asphalt-covered decks. Clearly, the two systems complement each other extremely well.

FUTURE RESEARCH

The next stage in the development of this system is to operate the prototype unit under field conditions in 1986 to assess its accuracy and reliability. Initially, it will be used to investigate a large number of bridge decks in order to assess priorities for rehabilitation. The unit may be particularly well suited to this application because only limited accuracy of the data is required. As experience is gained in the use of the equipment, it is expected that a number of the activities now included in detailed condition surveys can be eliminated. The potential exists to carry out detailed surveys using the DART system supplemented by a small amount of physical testing and sampling. This is expected to lead to improvements in the accuracy of the data, reduction in survey costs, and less disruption to traffic.

Other studies will be undertaken to identify other applications for the DART system such as the condition of joints in pavements, voids under bridge approach slabs, and the moisture content and degree of consolidation in subgrade materials.

ACKNOWLEDGMENT

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Considerations for Administering Underwater Contracts

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ABSTRACT

The objective of this study was to identify the considerations for administering an underwater inspection program to be conducted by contractors. Issues include identifying and assigning a priority to structures for periodic inspection, establishing inspection procedures, selecting a contractor, formatting the contract, and estimating contract costs.

National bridge inspection standards require that all bridges located on public roads be inspected at least once every 2 years. The inspections are to be conducted in accordance with the AASHTO standards stated in the Manual for Maintenance Inspection of Bridges (1). In general, highway and transportation departments nationwide comply with these standards; however, many states do not have a program for routinely conducting underwater inspections (2). The Virginia Department of Highways and Transportation is attempting to strengthen its underwater inspection program through the efficient use of contractors.

The objective of the research reported here was to identify those aspects of underwater inspections that are necessary for an efficiently administered underwater inspection program, and can be specifically stated in a contract.

Meetings and interviews were conducted with personnel responsible for bridge inspections in the Virginia Department of Highways and Transportation, other states and federal agencies, and with contractors. The issues identified for consideration in administering contracts for underwater inspections are discussed here in a general manner, and it is anticipated that they will be modified, specifically by traffic engineers, structural engineers, economists, and those experienced in bridge inspections.

IDENTIFYING AND ASSIGNING A PRIORITY TO STRUCTURES FOR UNDERWATER INSPECTIONS

Based on information available on their maps, many states appear to have responsibility for more bridges with substructures underwater than can be inspected in a short time; therefore a system of assigning priorities to upgrade inspection programs to include structures underwater is needed. The system would not be used to decide what bridges would be inspected, but to determine the order in which all bridges would be inspected during a given time period. Some of the variables that appear to be essential to such a system are discussed.

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