Networked Sensor System for Automated Data Collection and Analysis

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Abstract: *This research describes the development of a real-time multi-functional system for roadway data acquisition and analysis with multiple sensors. This system, Digital Highway Data Vehicle (DHDV), combined the technologies of laser illumination based digital imaging, inertial profiling and GPS mapping into an integrated system to accomplish the multiple tasks of survey and management for roadway data. It can capture the pavement surface images, the right-of-way (ROW) color images, the roughness and rutting data at a driving speed over 100km/h (60 mph). The resolution of the pavement images is 1-mm in both longitudinal and transverse directions with the use of high resolution gray-scale line cameras. The image covers 4-meter full lane width. ROW color images are acquired with multiple high resolution color frame cameras. The pavement distress analysis and road sign inventory can be conducted in real time. The system provides a comprehensive database engine which streams various imaging and location data into the on-board computer system as the data sets become available. This research presents the designs of this comprehensive data acquisition and analysis platform with respect to multi-function, integration and automation. The reliability and efficiency of DHDV have been demonstrated in different agencies with thousands of running miles.*

1 INTRODUCTION

Efficient transportation system depends on the well maintained transportation facilities. Pavement is the infrastructure element that costs the most capital in terms of initial investment and maintenance needs among all roadway structures. Each year, substantial amounts of money are spent for the inspection of road networks to provide decision makers valuable information about status of their pavement network. Therefore, condition and serviceability of the pavement has to be monitored regularly through an efficient survey system. In recent years, an increasing number of highway agencies started collecting inventory and condition data of roadside structures, such as sings, guardrails, bridges, and, tunnels, for comprehensive asset management purposes. Reliable and cost-effective inspection and condition assessment technologies for the various infrastructure elements are becoming a critical component in the decision making system.

Since the monumental AASHO Road Test in the late 1950's and early 1960's, highway agencies in developed countries started gathering performance and condition data on pavements on regular basis, so that proper maintenance and rehabilitation can be made based on field information. For example, Response Type Road Roughness Measurement System (RTRRMS) (Haas et al, 1993) was widely used to measure pavement roughness, which was used to correlate with pavement performance through the use of Pavement Serviceability Index (PSI). Right-of-Way (ROW) imagery was initially collected using 16-mm or 35-mm color films for general asset management purpose. In the 1980's and 1990's, analog tapes and laser disks were used for ROW imagery. Pavement condition survey was conducted with manual labor by visual observation in the field. This practice is still widely used today all around the world, which is hazardous, slow, prone to errors, and expensive.

Throughout the 1990's, various efforts in public and private industries were made to integrate several functions of data collection into one vehicular platform (Wang 2000). In 1999, the team at the University of Arkansas constructed and demonstrated the first full digital highway data vehicle, later referred to as the DHDV for Digital Highway Data Vehicle shown in Figure 1.

Fig.1. The original Digital Highway Data Vehicle (DHDV)

Recent advances in technology for field data acquisition, computer processing, and storage improved the data acquisition process and the quality of the data. Roadway data survey using digital imaging techniques are becoming increasingly popular due to many advantages. Other testing technologies such as laser are widely employed for data acquisition as well (McGhee, 2004). At the same time, the development of the Global Positioning System (GPS) allows an accurate satellite positioning for geo-referencing collected data sets. Many semi-automated and automated highway survey vehicles are emerging (Wang, 2000).

However, the existing system platforms share common limitations in terms of multi-function and automation of the analysis of the collected data. For instance, integration of sub-systems with high real-time data rates has been a challenge to many agencies, particularly on time-critical items such as positioning, and database streaming. Most of the platforms are capable of collecting data sets automatically, but limited in data processing to produce end-user results. For example, except for rutting measurement, distress surveys of all other types are mostly conducted with manual process. This current status has given rise to the need for a comprehensive real time multi functional survey platform.

Effective implementation of such an integrated survey system requires consideration of hardware, software, and procedures. The research provides an overview of the overall configuration of the developed system and focuses primarily on hardware integration and system design. The framework, which is designed to manage the needs of multiple components of the survey needs, is based on the use of imaging technique, laser profiling and GPS mapping to serve as an integration platform, as well as multiple task objective interfaces.

The immediate application of this system is pavement condition survey and road sign inventory. It can be extended to the survey of other facilities along the road. The proposed system is expected to save significant amounts of time and money to municipalities in carrying out inspection. It eliminates the cost of human inspectors that amounts to a large part of the total inspection cost. It also provides an incentive for checking road way conditions more regularly, thus helping survey engineers plan preventive maintenance programs in advance. Moreover, integrated management systems allow for optimizing budget allocation, as well as for coordinating work schedules for maintaining the different components of the system.

The DHDV also has well-established, user-friendly software, with advance data management and analysis capabilities. The architecture which exploits the parallel computing resources of multiple devices to achieve a computation speed of real time processing will be addressed in another report.

2 TECHNICAL BACKGROUND

2.1 Other systems

In the past two decades, the development of the data acquisition and analysis system has had a revolutionary change on civil engineering infrastructure management. Conducting a highway survey by a moving vehicle is a technology driven idea. The cost of the digital camera being reduced, the advance development of the non-destructive data acquisition techniques, the more powerful computing ability and storage ability in computer processors, and the development of the GPS satellite network all contributed to the possibility of building up a comprehensive highway survey system in a moving vehicle.

The earliest system reported is the consortium Komatsu which was built in the late 1980s by the Japanese (Wang, 2000). The system consisted of a survey vehicle and an onboard data processing unit to simultaneously measure cracking, rutting, and longitudinal profile. Maximum resolution of 2,048 by 2,048 pixels was obtained at a speed of 10 km/h (6 mph). The Komatsu system worked only at night to control lighting conditions and represented the most sophisticated hardware technologies at that time. After that, several other systems emerged such as U.S PCES system, Swedish PAVUE system, Swiss CREHOS, Illinois Automated Road Inspection System, Roadware’s WISECRAX (Wang, 2000) and WayLink’s earlier DHDV (Wang, 2003). The configurations of these systems are similar to the Japanese system. The variations are mainly on the camera types, the number of cameras, the lighting types, the resolution of the images and the increasing speed.

The following are some of the current available automated/semi-automated systems on the market: ARAN (Canada), HARRIS (UK), uniAMS (USA), RoadCrack (CSIRO), DHDV(WayLink). ARAN equipment is the most widely employed system for automatic crack identification in the USA. It employs digital frame cameras and synchronized strobe lighting and stores the images digitally for post-processing by the WiseCrax software. WiseCrax can operate in either a real-time or in a full intervention after the processing parameters have been set-up. In semi-automatic mode the user can revisit the results overlaid on the images and augment the output by visual assessment. HARRIS applied three line scan cameras and halogen lighting. The pixel resolution is about 2 mm and can operate at up to 80 km/h with a covering width 2.9m. uniAMS is a pavement image collection system developed by Adhara systems. It employs no lighting. There is an automated crack identification software (uniANALYZE) works with uniAMS. The performance is not consistent in the network level survey. RoadCrack uses four lines scan cameras and continuous lighting. It can obtain real-time processing resolution is about 1mm and survey width is 2.25m.

Several vendors on the market provide Right-Of-Way (ROW) inventory system. GPSVision (USA) and Trident-3D (Canada) are among them. Both of these have the capability to capture the ROW images by a GPS/INS equipped vehicle. The ROW images stamped with the GPS information are obtained. The interested features on the images are extracted by software mostly by human intervention. The features are then mapped with their GPS position and inventory is accomplished.

2.2 System Components

The following sections will introduce the basic sensors and technology in the survey systems for pavement and other roadway data.

2.2.1 Sensors

The key part in the imaging system is the camera. The major methods of pavement imaging are generically termed “analog” and “digital.” Analog refers to the process wherein images are physically imposed on film or another medium through chemical, mechanical, or magnetic changes in the surface of the medium. Digital imaging refers to the process wherein images are captured as streams of electronic bits and stored on electronic medium. The digital bits can be read electronically for processing or reproduction purposes.

Although much of the earlier work has been done with analog photographs or videotapes, digital imaging is fast becoming the most popular method, owing to the quality of images that can be produced, the ease of data manipulation, and the applicability to automated data reduction. Two types of digital cameras are normally used in the data acquisition system in highway surveys: line scan cameras and area scan cameras. 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. It is analogous to scanners and fax machines. 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 speeds in one uniform direction. In recent years, high-performance digital line-scan cameras were 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.

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 Figure 1. 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.

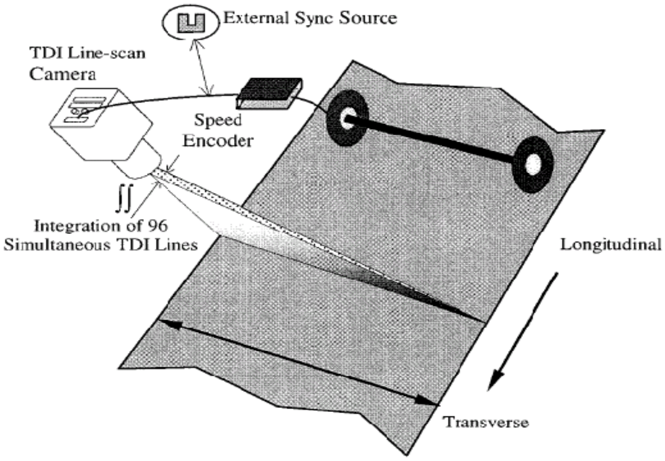
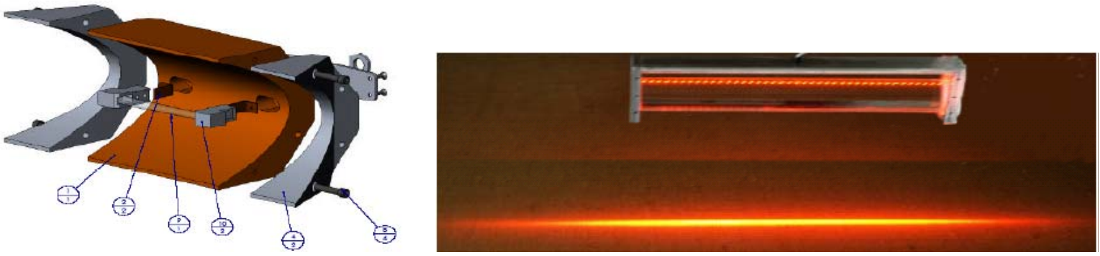


Fig.1. Line scan camera

2.2.2 Illumination

Once the camera is used, no matter whether it is a line scan camera or an area scan camera, the lighting is necessary. The imaging system won't be able to obtain high quality images without good lighting devices.

The current lighting sources used in the pavement imaging system include natural light, strobe light, halogen lamp, LED, and laser. Natural light is the simplest light source but the drawbacks are obvious. The image taken under different weather conditions will not be consistent and the shadow from the vehicle and other devices will exist. Strobe lights are cost effective lighting source for area scan cameras. But it wouldn't have high enough frequency for line scan cameras as line scan cameras might capture over 10000 lines per second. A halogen light is a lamp in which a tungsten filament is sealed into a small envelope filled with a halogen gas such as iodine or bromine. It is simple but inefficient. Halogen lights consume high energy (300 watts per unit) (Xu, 2005) which puts a heavy power burden on the vehicle. LED, Light Emitting Diode, has better power efficiency (30 watts per unit) and much longer lamp life than traditional light bulbs. It is a promising light source for pavement imaging. The most successful lighting device for line scan cameras applied in the industry is the laser lighting in INO's Laser Road Imaging System (LRIS). Laser shows its advantages of being stable, compact, and power-efficient (10W) in the LRIS system. But it needs high quality manufacturing to align it with the line scan camera properly and to be safe.



Halogen LED

Fig. 2. Halogen and LED used in pavement imaging system

2.2.3 Profiler

Pavement profile or smoothness has been identified nationally as a good measure of highway user satisfaction. Older profiling devices are usually contact systems, while the more recently manufactured devices used non-contact sensors. High-speed road profiling is a technology that began in the 1960s at the General Motors Research Laboratory. The number of states that have adopted high-speed profilers to collect roughness data on their highway networks has shown a dramatic increase in the past decade (McGhee, 2004). Inertial profilers collect pavement profile data at highway speeds, and generate the true profile of a roadway. The principal components of an inertial profiler are height sensors, accelerometers, and a distance measuring system. The height sensors record the height to the pavement surface from the vehicle. The accelerometers, located on top of the height sensors, record the vertical acceleration of the vehicle that can be integrated twice to obtain the vehicle vertical displacement. The difference between the measurements of the height sensors and accelerometers is the surface profile. The distance measuring system refers the measurements with respect to a reference starting point.

The non-contact height sensors currently used in profilers are either laser, ultrasonic, optical, or infrared. Ultrasonic sensors were the most common type of sensors used in the 1980s. However, because of the effect of environmental conditions on this type of sensor, their use has declined over the past several years (Perera, 1995). The ultrasonic, optical and infrared work on the basis of a simple concept that the distance from the reference plane to the road surface is directly related to the time it takes for the signal to travel from a transducer to the road and back. Now lasers are the principal means of profile measurement. Lasers work on the basis of a phase shift of the refracted laser beam in a process beyond the scope of this synthesis. In the application of a laser profiler, very high-speed and high-capacity electronic components are required to capture the large volumes of data generated.

Figure 3 shows the working principle of a laser profiler. The laser line is projected onto the ground as a probe. The reflected light is collected and focused into a photodiode array by an optical system.

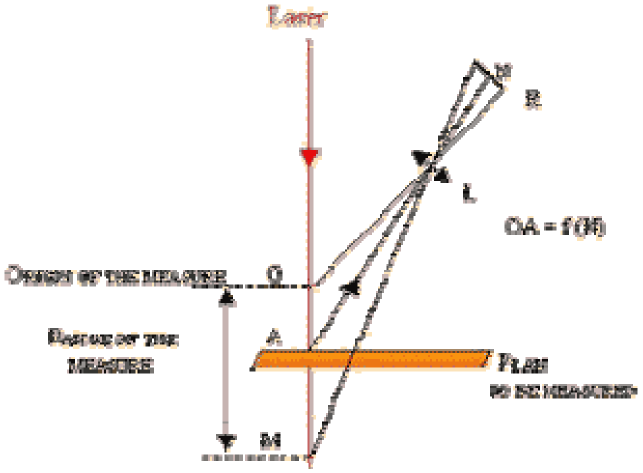


Fig. 3. Laser projector triangulation

2.2.4 GPS mobile mapping

The GPS system has developed by the United State Department of Defense. Its official name is NAVSTAR GPS (Navigation Signal Timing and Ranging Global Positioning System). It is the only fully-functional satellite navigation system. More than two dozen GPS satellites orbit the Earth, transmitting radio signals which allow GPS receivers to determine their location, speed, and direction. The first experimental satellite was launched in 1978. During the past three decades, the systems have been improved again and again. The current GPS accuracy is within 2 meters (6ft). It can be improved further, to about 1 cm (half an inch) over short distances, using techniques such as Differential GPS (DGPS).

The GPS system has been a great tool for the development of highway survey vehicles. Earlier experiments were conducted by a number of Canadian provinces and some US states in 1983 (Schwarz, 1993). It used gyroscopes, accelerometers, and a wheel odometer to locate and document the features in the highway images taken by the cameras in the van. The positioning accuracy of this survey van was rather poor and the video images were not digitized for measurement purposes. However, it provided a good visual record of highway features and their approximate location. In 1988, differential GPS started to be used to improve the positioning accuracy. The results of these tests obtained an accuracy of 0.2 m to 0.3m while moving at 50-70 km/hour (Schwarz, 1993). Later, the information contained in the video images was itself incorporated into the measurement process. This idea is basic to the highway van developed by the Ohio State University's Center of Mapping and the GEOVAN system operated by GEOSPAN Corp. (Schwarz, 1993). Both systems work with an array of video cameras. The video information is stored and individual images are digitized post-mission.

3 SYSTEM DESIGN

The Digital Highway Data Vehicle (DHDV) is a highway survey system built by the researchers at the University of Arkansas since the 1990s. Figure 4 shows the system in schematic form. The whole system can be divided into three subsystems in terms of their functions: pavement imaging subsystem, Right-Of-Way imaging subsystem, and rutting/roughness measuring subsystem. The survey van is equipped with a GPS receiver, a cluster of CCD cameras on the top of the van for Right-Of-Way imaging subsystem, two line scan cameras and laser sensors (LRIS) mounted at the rear of the van for pavement imaging subsystem, and a laser profiler mounted on the bumper for rutting and roughness measuring subsystem. The hardware also includes power supply equipment, control board for system control, the computer workstations inside of the van, and the Distance Measurement Instrument (DMI) connected to the wheel.

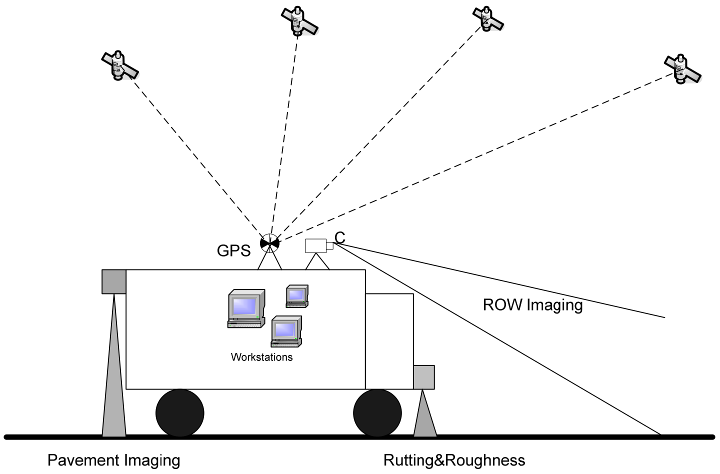


Fig. 4. Concept of the DHDV system

Figure 5 shows the data flow of the system. The sensors collect the ROW image, the pavement image, and the road profile while the vehicle drives along the road. The GPS information is integrated into the collected data. The images are stored in the hard disks of the in-car computers. Corresponding software is used to process data in real time or to do post-processing. The last step is to save all the collected information and the post processing information into a comprehensive database. This database can be read by the utility software to review the collected data or review the analysis result.

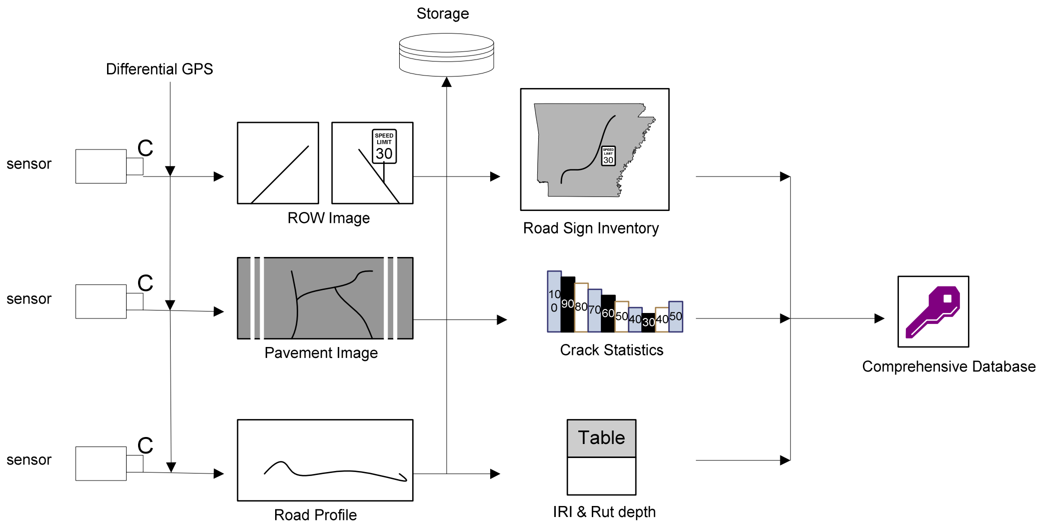


Fig. 5. Dataflow of the DHDV system

The following sections will describe the subsystems in detail.

3.1 Laser Road Imaging System (LRIS)

A major step forward was made in the pavement imaging technology when lasers were used as a lighting source and combined with a high quality line scan camera by INO (Canada). The LRIS system is composed of two high resolution line-scan cameras and lasers that are configured to image full 4m transverse road sections with 1mm resolution at speeds that can surpass 100 km/h. This imaging system was designed to increase the contrast and visibility of both small longitudinal and lateral road cracks. Using high power laser line projectors and special collection optics, the LRIS system can operate in full daylight because it is immune to variations in outside lighting conditions and shadows cast by roadside objects, viaducts, and the inspection vehicle itself.

The image size obtained in LRIS is 4096 pixels/line and 28000 lines/second which allows 1mm resolution at 100km/h driving speed. The LRIS system uses both high speed/high resolution line-scan cameras in conjunction with high power laser line projectors that are aligned in the same plane in a symmetrically crossed optical configuration (Figure 6). The laser used in LRIS has a wavelength of 800nm to 580nm which belongs to classIIIb. These lasers will produce an eye hazard if viewed directly. The line scan camera is triggered as distance to fix the longitudinal 1 mm resolution. This particular configuration offers several advantages as compared to more traditional imaging techniques. It is compact (20 kg total weight), power efficient (250W), and immune to shade and illumination change. The most important feature of the system is that this optical configuration increases the visibility of even the smallest cracks by using the incident illumination angle of the laser to cause the cracks to project shadows.

The cameras need to be calibrated before using. Special treatment has to be made to solve the offset between the left camera and right camera, the strip pattern unevenness in the image and the contrast difference between the left camera and the right camera.

A Real-time distress analyzer, Automated Distress Analyzer (ADA), was developed which provides the real time analysis of the longitudinal, transverse, alligator, and block crack. The detected cracks in the images are highlighted in a bounding box in the crack map. The length, width, direction, type, and other information of the cracks are imported to utility software, ReportWriter. The crack statistics of the target road is provided in a graph or in an Excel file.

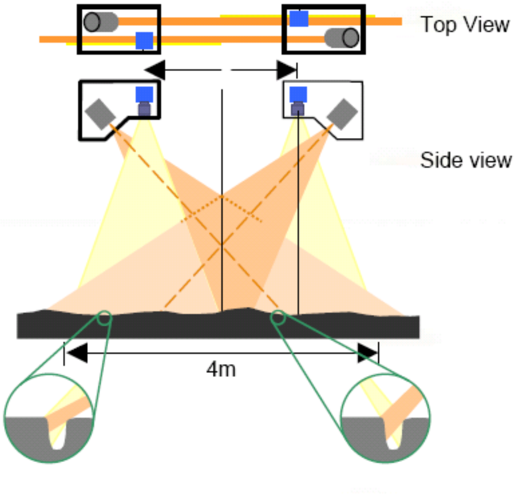


Fig. 6. Configuration of the LRIS sensors

3.2 ROW

The Right-Of-Way system provides georeferenced digital images and the transportation infrastructures of the road environment. This system uses the Navstar Global Positioning System (GPS) in combination with two high-speed digital stereo cameras. The integrated GPS system provides the position of the ROW system, and the cameras take images of the road environment while traveling at normal driving speeds. Two CCD cameras are mounted on the top of the vehicle and wired with in-car computers. They are positioned and oriented at any instant of time. The cameras feature a progressive scan 1228800 pixels CCD (1280*960) or higher resolution CCD. They incorporate an external trigger with exposure range from 1/20000 to 2 seconds, allowing them to capture fast moving objects clearly or still objects in low light.

The cameras capture the images based on the triggering signal from the control board. The cameras can be triggered up to 15 frames per second or triggered based on the distance traveled by the vehicle. The images cover up to 180° field of view.

The images captured from the cameras can be used in different task based on different camera set ups. Pointing the camera into the same object enables the stereovision and accomplishes 3D positioning. Aligning the two cameras with a narrow strip of overlapping can form the panorama view.

Visible objects such as road sign along the highway can be precisely surveyed by processing the digital image information. A software SignAnalyzer was developed for this purpose. The system uses GPS and DMI to fix the location of the vehicle and video camera to document features in the highway corridor.

Currently, ROW imaging as a separate system is available on the market. The advantage of this system is that the integration of the imaging system and the automated feature extraction software developed for this system.

3.3 Laser roughness and rutting

The Roughness measurement subsystem is composed of several internal and external system components. Two laser profilers are responsible for the acquisition of the left and right side transverse profiles. Each profile is composed of a high-power laser line projector, and a special camera to measure deformations. The longitudinal profile measurement is based on the "South Dakota" method. An accelerometer is used to obtain vertical vehicle body movement, and a laser sensor is used for measuring the displacement between the vehicle body and the pavement. Road profile measurements are then obtained by summing the body movement with the appropriate body-road displacements. IRI is calculated in accordance with World Bank Specifications. The measured longitudinal profile meets the Class 1 precision and bias specifications as defined by ASTM E-950 and also meets the TxDOT TEX-10001-S. ASTM Standard E-950 is currently widely used for rating the repeatability and accuracy of profilers. The Standard includes a classification system for profiler that is based on the requirement of precision (standard deviation) among repeated elevation measurements and bias (absolute difference) in elevation compared to a reference measurement. Texas Specification TEX-1001-S uses a method similar to ASTM E-950, but it has additional IRI accuracy (bias) and precision criteria. Transverse profile and rut depth are based on a minimum of 3 lasers.

4 SYSTEM INTEGRATION

Synchronization of the subsystems is made by the triggering signals sent from the control board of the system. In order to acquire the proper amount of imaging data, it is necessary to generate accurate trigger signals for the cameras. Since the triggering signal from the installed DMI is at about 1,024 pulses per 1.34 meters for the DHDV, it is straightforward to properly trigger the area scan camera in the ROW imaging subsystem, as there are only a dozen or so image frames to be captured every second. However, the necessary line scan trigger pulse rate for the pavement imaging has to be synchronized with traveling speed at one pulse per one millimeter. For instance, the default pulse rate is about one pulse every 1.325 millimeter of traveling distance. Since this triggering rate is greater than the necessary 1-mm width, an interpolation method is needed to generate approximately 1.325 trigger pulses per input pulse.

A counting device in a computer measures the incoming pulse frequency at a programmable interval (generally 1 to 10 ms). The measured frequency is then multiplied by a calibration factor which results in the correct trigger output frequency. A frequency synthesizer then generates the required trigger pulses. This solution requires negligible processing resources. Also this method may introduce errors of inaccurate pulse rate in the line scan measurement during rapid acceleration and deceleration of the DHDV. However, based on tests that were conducted with the DHDV, the error is below the resolution of the camera. Particularly, in actual data acquisition, the data vehicle normally is driven at relatively uniform speed with small variations, which further diminishes the issue of pulse errors. Figure 7 shows the use of pulse triggering for both area scan and line scan approaches.

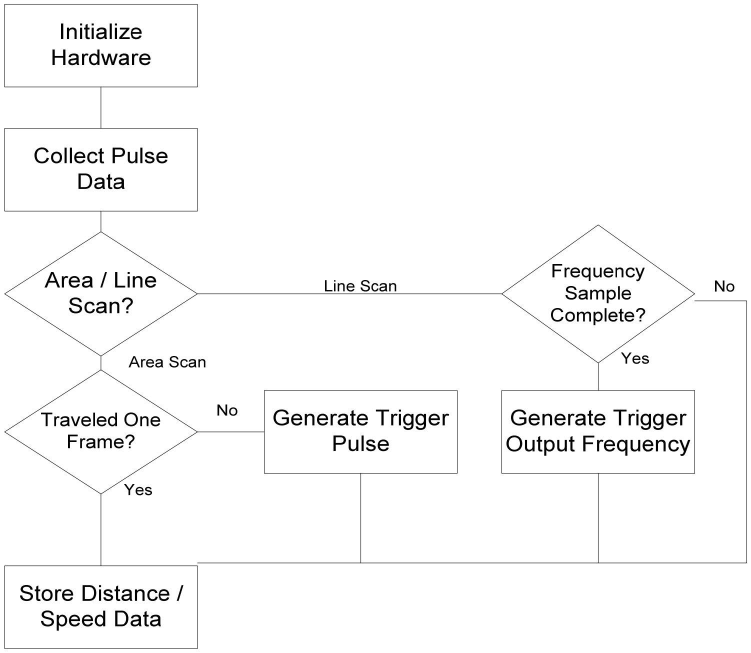


Fig. 7. Generation of DMI Trigger

DMI is the important part in the triggering function. DMI is like an odometer. It is connected to the wheel and provides a linear reference tag for each capturing point. Since the subsystems are triggered based on DMI distance, every single data captured in the subsystems are stamped with a certain DMI distance number. This number is the knot of the synchronization of the data and becomes the primary key for the database formation.

The integration of the subsystems requires powerful computing storage ability and processing ability. A pair of ROW images are 2*1280*960 in color image (3 byte per pixel), a pair of pavement images are 2*2048*2048 in gray scale (1 byte per pixel). If the trigger interval for ROW imaging is set as 5 meters, at a speed of 60 mph (100 km/h), the ROW imaging system capture 6 frames and the pavement imaging capture about 14 frames. Which means the ROW subsystem generates about 36 Megabytes of data and the pavement imaging subsystem generates about 120 Megabytes of data. And for 100km of road, the computer needs a space of 58 Gigabytes to store the collected data.

Since the introduction of 32-bit microprocessor, the technique of threading has been used frequently to exploit the resources of the microprocessor. The realization of the 32-bit operating system in Windows environment made this technique even more popular among resource hungry applications. The ability to divide a task into multiple threads of execution, each executing in parallel on separate processors has a number of advantages. First and foremost, the system potentially can get twice the processing power for a dual-CPU system. For example, by dividing image compression task into multiple threads, individual images can be compressed alternatively on a separate processor. Therefore, efficiency in image compression can be potentially doubled. Another advantage is a thread’s ability to interrupt or preempt another thread in execution on the same processor.

The operating system gives each thread on the same processor a limited time slice during which it can execute. Depending upon configuration parameters, this is generally about 20 milliseconds. Threads are executed in a round robin fashion with each preempting the previous thread. The current state of any thread that has been preempted is saved so that when it is that thread’s turn to execute another time slice it can be restored to its previous task. A thread can also preempt another thread before a given time slice has elapsed if an event that the other thread has been programmed to respond to occurs.

For instance, if image data becomes available a thread assigned to that input can be activated to insure that it is handled in a timely fashion. After the data has been consumed; in the case of image data, another thread will be created for compression and storage. The thread that was activated by its availability will be placed on hold until another event occurs. In this fashion each thread only utilizes the resources that it needs and does not consume excessive processor time otherwise. By carefully dividing task into various threads of execution we can balance the simultaneous constraints of maximum processing resource usage and timely responses to system events.

In Figure 8, Thread 1 monitors the DMI and activates a trigger when the vehicle position has changed enough to require the acquisition of a new image. Thread 2 then reads in the image data and spawns thread 3 and eventually thread 4 to compress and store it. Notice that by the fourth iteration all four threads have a task. Ideally all threads have processor time when they need it, and the processor itself always has a thread to execute when it becomes available.

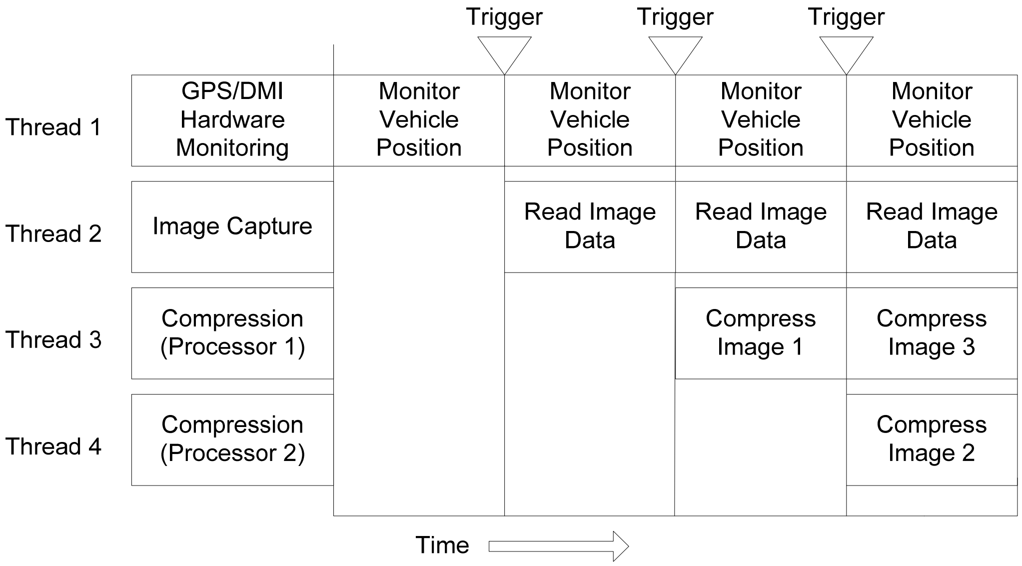


Fig. 8. A Typical Example of Multithreading in DHDV

The standard of Joint Picture Expert Group (JPEG) was chosen as the Compression and Decompression (CODEC) method for all image compressions for both the area scan and line scan cameras. The JPEG CODEC used in DHDV provides about 10:1 compression ratios, resulting in image quality level that is sufficiently faithful to the quality of raw images, and storage requirements that are easily met. The challenge was to compress the images at real-time, so that when the DHDV travels at 100 kilometers per hour, the image stream from acquisition to storage is maintained at any point of time.

As today's off-the-shelf storage devices do not have sustained throughput rate of over 20 Megabytes per second and disk drive capacities still cannot accommodate the storage of raw images of pavements over extended length, this image data stream must be compressed at real time to maintain the operation of the vehicle. First the data compression task is to be divided across two processors in a dual-CPU computer. This lowers the requirement of processing per processor per second. When new image data becomes available, a new thread of execution is generated to process and compress it. Each new thread is scheduled according to processor availability to make maximum use of processor resources shown in Figure 9, which illustrates the command flow for image acquisition and compression.

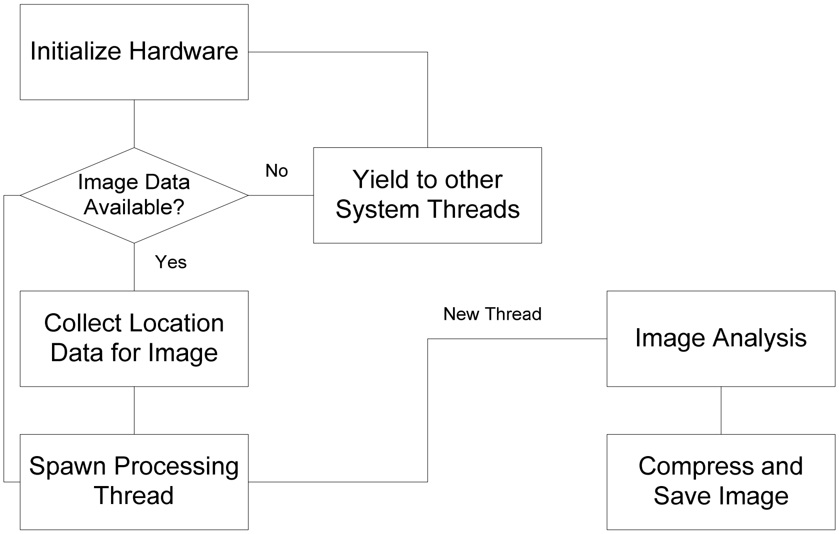


Fig. 9. Command Flow of Image Capture and Processing

However, based on the test of using the standard implementation of JPEG (CODEC) for this application, it is not able to accommodate the required data rate. The Independent JPEG Group's reference implementation (1991-1996) compresses data on our hardware architecture at about 8 megabytes per second per processor, which is far lower than the necessary speed. A special implementation was therefore required. The basic JPEG algorithm divides the image into 8x8 pixel blocks and performs a transform which moves the image data into the frequency domain. The transform used is the Discrete Cosine Transform (DCT). The resulting coefficients are then quantized according to the compression ratio desired. Quantization is the process of reducing the bits needed to store an integer value by reducing its precision. After quantization, the coefficients are then further reduced in size using a lossless compression method such as Run Length Encoding (RLE) and Huffman Compression.

Profiling of a reference implementation showed that the majority of processing time (>60%) is spent in the DCT stage of the compression sequence. Several fast implementations of the transform have been produced. The Loeffler-Ligtenberg-Moschytz (LLM) (1989) integer based algorithm was chosen for the DHDV implementation, due to its effectiveness in parallelizing DCT algorithm and its use of integer operations, which is a magnitude faster than float-point operations. Newer processors from Intel and AMD support Single Instruction Multiple Data (SIMD) instructions (Intel 1997), which allow multiple addition and multiplication operations to proceed simultaneously. Through hand coding the algorithm in assembly we were able to reduce the time required to perform an 8x8 pixel transform to 249 clock cycles from greater than 10,000 clock cycles based on a standard C language implementation. On the DHDV hardware with dual 2.4 GHz CPUs, a 4096x2048 pixel image can be compressed in 13 milliseconds, equivalent to the compression speed of 600 MB per second.

The remaining bottleneck is streaming the compressed data to the hard disk. Unfortunately this is a physical bottleneck that is beyond our research capability. However, based on tests conducted during the research, an off-the-shelf state-of-the-art storage sub-system can sustain over 15 Megabytes per second compressed data stream, equivalent to 136 Megabytes of uncompressed data per second. This result is sufficient for the necessary 114 Megabyte per second image stream at 100 kilometers per hour.

A comprehensive database is generated right after the capturing process starts. The database includes the collection information such as the time, weather, operator, road name, the pavement image information, the ROW image information, GPS information, the IRI and rutting information, the analysis result of the ROW image and pavement distress. The utility software can revisit the database and let the user review the collection result at anytime or do further statistical analysis of the result.

5 CONCLUSION

The multi-functional highway survey system, Digital Highway Data Vehicle (DHDV), presented in this report represents a distinct improvement for the automation and integration of the systems. Real time survey and analysis can be conducted at a speed over 100km/h. A comprehensive database is obtained after the survey which include pavement images, ROW images, pavement roughness and rutting. The resolution of the pavement image is 1mm at a driving speed over 100km/h.GPS information etc. In particular, the real-time distress analyzer has a remarkable feature of automatically detecting the cracks in the pavement images. The automated road sign recognition software shows its superiority over other products.

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