Three-dimensional infrared laser vision system for road surface features analysis

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ABSTRACT

A mobile (truck-mounted) imaging system uses laser-based technology to obtain accurate quantitative data in real time and at high speeds regarding the conditions of road and highway surfaces. Specifically, the GIE Technologies laser vision system integrates a three-dimensional laser-sensing imaging sensor array to map the cracks, ruts and roughness of road surfaces. The LaserVision System simultaneously records a three-dimensional information along with photometric data using the same set of Biris (bi-iris) sensors. These sensors were developed for this application by engineers at GIE Technologies Inc. under exclusive license from the National Research Council (Ottawa, Canada). They rely on a combination of defocusing and triangulation principles to record 3-D information about a test surface. The Biris approach, for a mobile pavement testing system, offers several performance advantages in comparison to other sensing methods. Most important, a Biris sensor uses all-solid-state components with no moving parts. This rugged design is highly resistant to misalignment and performs well in a moving, continuously vibrating vehicle. The photometric (intensity) information provides complementary data where ranging alone proves insufficient, as when detecting pavement markings, sealed road cracks or patches. In addition, the range analysis uses simple trigonometry to obtain real-time performance.

Keywords: Three-dimensional, image, range, laser, sensor, surface feature

1. INTRODUCTION

Road surface data is a critical element for quantifying the riding comfort and the real condition of a pavement surface. Since the initial pavement management development efforts in the late 1960's, pavement management engineers have relied on visual or manual pavement cracking survey procedures to determine the condition of road surface. The type, the extent and severity level of each distress are identified and recorded according to various distress classification criteria defined in distress identification manuals1,2. Manual surface distress surveys are subject to many limitations such as non-repeatability, subjectivity, and high personnel costs. Manual procedures are time consuming, and present substantial differences between evaluation of different raters (15-20%). To overcome these limitations, several automated distress survey equipment were developed in the last two decades. Previous experience showed that these equipment are able to collect quality pavement cracking data in a relative repeatable, safe, and cost-effective manner. The most used automated cracking survey is based on computerized image processing and analysis. Several computerized image processing were developed to reduce or eliminate the limitations associated with manual methods, but their application is still limited by lack of efficient image processing algorithms capable to analyze and classify cracking data collected. In addition, experience demonstrated that many external factors such as pavement texture, shadows from overhead power lines, trees and bridges, introduce major errors in image interpretation. Therefore additional equipment (high intensity strobe lighting, several cameras, control hardware, etc.) are needed to overcome this problem.

Image analysis by automated means is quite complex. The distresses can take many shapes, and complex pattern recognition algorithms must be developed to distinguish between different types of cracks. Distress evaluation on different types of pavement surfaces has proven problematic for existing systems. In the existing imaging systems, analysis is typically based on differences between the gray level of the distresses and the surrounding area. In many situations the intensity ranges in an image do not provide enough discrimination between distresses and surrounding texture. To overcome this type of difficulties, GIE Technologies developed an advanced technology, LaserVision System (LVS), able to collect three dimensional distress data of road surfaces by means of a three-line laser sensor. A laser-based vehicle-mounted imaging system simultaneously evaluates several conditions of road surface distress, such as ruts, cracks, and surface roughness, at highway speed. The three-dimensional feature extraction is done by a combination of two measuring techniques: triangulation and
defocusing. A generated pattern of transverse profiles spaced by 11 cm is used to sample the road surface. Cracking, rutting and roughness are the most critical distresses and it is important to develop a system that is able to automatically identify and classify with precision such features. Physical differences between laser beam profiles of each sensor require special signal processing and analysis techniques to reconstruct a three dimensional information that matches the reality.

As opposed to other data collection technologies that require a different technology for each collected road surface parameter (cracking, rutting, roughness), the LVS–Biris technology allows the use of data collected in a single pass for several features extraction, in other words, the same raw data provides the needed information for all major parameters of interest. This technology was originally developed by the National Research Council of Canada and further adapted and developed for road surveying applications by GIE Technologies.

In this paper it is described a road surveying system using three-line high power three-dimensional sensors. Capable of operating without regard to the ambient lighting conditions it provides accurate measurements of 0.1 mm resolution with a standard deviation of 0.7 mm. High power lasers allow high speed shuttering thus providing low image blurring at highway speeds. The highly rugged sensor packaging ensures reliable system operation in hostile environments.

2. OPERATING PRINCIPLE

The basic concept used in this 3D sensing technology is a unique combination of two measuring techniques: triangulation and defocusing. A laser beam is line formatted by means of an optical system. This line is projected on a surface in the field of view of a CCD camera. The image position of the projected line on the CCD detector depends upon the distance between the camera and the projection surface. Simple trigonometry calculations yield the relationship for the range (z) and the image position on the detector (p). This method is well known as the triangulation measuring technique. The range accuracy computed this way is proportional to the triangulation basis (D), the focal length of the optical system (f) used to form the image on the CCD and inversely proportional to the square of the range itself (z²). So, one can see that high precision measurements are limited by their scope and also by a reasonable size of the triangulation basis.

\[
Z = \alpha(l^{-1}+\frac{b}{dl'})^{-1}+(1-\alpha)(Dl'/p+ltg\theta))
\]

\[
\frac{\Delta p}{\Delta Z} = \frac{Df}{Z^2}
\]

The second measuring technique employed is defocusing. Using the approximation for thin lenses, in a well tuned optical system, the image of an object point from a reference plane is also a point in the image plane (the detector’s plane). Assuming that the first point moves from the reference plane, the image will correspondingly change to a spot in the detector plane because the system is no longer tuned and the image point is located elsewhere out from this plane. The size

![Figure 1: The sensor operating principle](image-url)
of the spot on the detector is related to the distance (range) that the object point moved from the reference plane. Accurate measurement demands a precise detection of the edges of the spot, a rather difficult task especially due to diffraction phenomena. If, in front of the collection lens, is installed a mask with two circular apertures spaced by a small distance (d), the spot on the detector becomes two little spots on the edges of the ancient spot. Measurement of the distance between these new spots (b) is easier to do and provides the relationship with the change in position of the object point. Now, if the object point is replaced by a line (a laser projected line) the image of this line in a well tuned system will be also a line. Installing again the same mask with the axis connecting the two holes perpendicular to the projected laser line and bringing the system out of the tuned situation, one will obtain a pair of lines on the detector (instead of the pair of spots). The spacing of these two lines on the detector is a measure of the distance of the object line from the reference plane.

Combination of both these measuring techniques led to the Biris technology development. The triangulation method provides the range by measuring the exact position of the pair of lines on the detector and the defocusing method provides the range by measuring the space between the lines imaged on the detector. The result is a linear combination of both methods. The combination coefficient has a typical value of 0.15. The use of both techniques allows a cross validation of both results and provides a higher signal-to-noise ratio. A ray tracing diagram of both methods is given in figure 1.

Each laser projection is seen by the CCD detector as a pair of lines due to the Biris mask aperture. Moving the Biris sensor closer to or farther from the measured surface changes not only the position of the line pair on the detector but also the spacing between the two lines. Measuring the exact position and spacing of the laser peaks in the image allows not only the range to be computed but also the measurement to be validated. Every image is transposed and scanned line by line to detect and compute the position of each peak on each video line with a resolution of 1/64 of a pixel.

Figure 2 shows two images seen by the detector at two different distances: at 700mm (left) and at 1000mm (right). The images were truncated at 390 pixels to show only the difference between the two positions. As can be seen, a change in the position of the imaged projections occurs in addition to a change in the spacing of each pair of lines. The change in position of each line depends on the triangulation base of each laser projector.

Figure 2. Images (390x256 pixels) of laser profiles at 700mm (left) and 1000mm (right).

3. SENSOR SPECIFICATIONS AND EXPERIMENTAL RESULTS

The simplicity and the flexibility in using one or more identical sensors was of great importance. Previous developments showed the potential of this technology with no moving parts in a hostile environment (shocks, vibration, dirt, etc.) and its capacity to provide requested performances in acquiring data. The use of three laser line projectors for each sensor improved data density by providing three measured profiles in each frame. Basically, the sensor is intended for use in an array to provide transverse and longitudinal road profiles at highway speed. A first generation system engineered at G.I.E. Technologies, showed some limitations that had to be overcome. The first weakness came from the laser power that was insufficient: the main effects of that were a low signal-to-noise ratio at high shutter speed and a high sensitivity to ambient lighting conditions. The lack of power forced the use of reduced shutter speed (1/500s) which resulted in high image blurring (40mm at 72km/h) or low vehicle speed (maximum of 36km/h). The use of a narrow band filter at the detector level
was also limited by the insufficient power availability which led to a low signal-to-noise ratio. These situations were corrected as soon as much higher power laser diodes became available. By increasing the laser power (up to 2w at 810nm), the sensor can operate in any lighting conditions and with shutter speeds up to 0.1ms. This new configuration reduced the image blurring as low as 2mm at 72km/h.

The sensors were designed with a solid sealed aluminum housing. Three high power laser line projectors (2w each) are used to project three lines in the field of view of a CCD camera used as detector. In front of the camera, an optical system ensures laser light collection and filtering. Figure 3 shows a picture of the assembled sensor installed on vehicle.

A batch of 250 consecutive acquired profiles of 256 points each was used to generate a three dimensional surface, which is represented in figure 4. Profile sampling was limited to 236 points in order to provide a good figure readability. Range (z) is represented on the vertical axis.

The nominal standoff of the sensor is 900mm. The horizontal field of view of the sensor covers 52° which corresponds to a 900mm laser line length at the ground level. The laser projections are equally spaced in the detector’s field of view by about 11cm at the nominal standoff. In one frame each sensor is capable of acquiring three profiles of 256 points each at a rate of 60 frames per second. The measurements provided are the range (z), the position within the profile (x) and the intensity (the
photometric information) of each point. The third dimension (y) is obtained by the sensor’s translation. The range resolution is of 0.1mm and the position resolution within the profile is of 3.5mm at the nominal standoff distance. On the y axis, the resolution depends upon the sensor’s traveling speed. At speeds over 72km/h gaps over 11cm can occur between subsequent frames of three profiles. For the sensors used at a closer range (600mm), the position resolution within the profile is reduced to 2.5mm. These lower sensors are built with only two laser projectors and provide a larger depth of field. The short integration time (1/10000s) avoids image blur during the acquisition. The sensors can operate in normal exterior lighting conditions during day or night. The sensors’ characteristics were verified under laboratory as well as in field conditions. Each measurement is provided in two bytes format for a total of 270kB/s.

A graphical representation of the standard deviations of all profiles shows slight variations around the value of 0.7mm (figure 5).

Figure 5: Standard deviation for measured profiles

Standard deviation is in this case a measure of the sensor’s accuracy because the specific application that uses this sensor (road surface distress survey), does not address the absolute range value which is discarded by a real time processing system. If absolute range values are required the accuracy must be evaluated and expressed as relative range measurement error.

4. FEATURE EXTRACTION BY FUZZY TECHNIQUES

The fuzzy system developed for the identification and classification of all of road surface cracks is designed by extracting knowledge from available distress identification manuals and by transforming them into linguistic rules and membership functions. LVS technology is used to provide collected data. Then, dispersed events generated by LVS are used to analyze road surface distresses. The basic idea is to transform all possible combinations of the variables that characterize road cracking into linguistic fuzzy implications to describe the type, the extent and the severity of road surface cracks. To this end, it is important to select the input variables first and then to design the fuzzy reasoning that evaluates the detected distresses. The input variables should be chosen on the basis of LVS operating principle. Therefore, the four transverse three line laser sensors and the two longitudinal sensors are used to detect respectively longitudinal and transverse events in the pavement surface, characterized by three main parameters: Severity level, Density of events and their Repartition on the pavement. The calculation of these variables is based on the analysis and filtering of the digital data provided by every laser sensor. This step is essential to automatically evaluate the road surface cracking. A special filter was developed and used to avoid the noise generated by LVS. The numerical filter uses an adaptive width mobile window. The width is self-adjusting according to a quality index computed for the data provided by LVS laser sensors.

Once the input variables are computed, they are used in a fuzzy reasoning that takes into account the vagueness and the subjectivity of the identification process provided by human experts and distress identification manuals in the formulation of the classification criteria. The severity level of the detected events is measured depending on the width of the event. A simple comparison between the numerical profile and the filtered one permits a fast and accurate calculation of the width of every event. This parameter is used to approximate the severity level. The top of figure 6 shows three membership functions.
used to calculate the severity level of cracks. Three symmetrical triangular membership functions are selected to resolve this problem in order to take into account the non-linear dependence of severity level and the crack width. For this example was assumed that low severity cracks are characterized by a crack width lower than 5mm and high severity level by crack width over 40mm. Between 5mm and 40mm the crack has a medium severity level. This classical approach of calculating severity level is found to be inefficient because the limits between two successive severity levels is limited to a single value. For example, if the width crack is equal to 4,99 mm, the severity level should be considered as low. However, if the crack width is equal to 5,00 mm the severity level is medium. Membership functions used in fuzzy systems allow to overcome these situations by considering a degree of membership to each severity level class. A numerical value will be transformed into a fuzzy term with a well defined degree of membership that varies between 0 (does not belong to the fuzzy subset) and 1 (full membership).

Since severity level of road surface cracks depends on distress identification manuals from agencies interested in developing such surveys, it is important to mention that the interval fixed between 0 mm and 40 mm in figure 6 can be changed by users. \( \mu \) (Severity) is the membership degree of the severity level of the detected crack to the corresponding fuzzy severity subsets, namely “Low”, “Medium”, and “High”. The density of events per each sensor is the number of the detected defects on each sampled profile. This number varies between zero and twenty so that the highest number of events that will be detected by each laser sensor is limited to twenty. The repartition of the identified events is measured by a simple evaluation of the continuity of the detected events. This variable serves to locate the events and their dispersion on each profile. The repartition of the detected events vary between zero (events are not regularly dispersed) and one if they are regularly dispersed. The density and repartition of the detected events are described by respectively four and two linguistic terms (Low, medium, High and Very High density) and (Regular and Irregular repartition). The membership functions used to digitize these terms are symmetric with a trapezoidal shape. The trapezoidal shape is based on the observed influence of the number of events per sensor on the fuzzification process. These observations showed that for example, if a sensor detects from 4 to 7 events, the density should be considered as Medium. Also, the system is insensible to the variation of the density if it belongs to this interval. The same remarks are applied to the rest of fuzzy terms and as consequence the four membership function are sufficient to describe the density in linguistic terms. The membership degrees, \( \mu \) (Density) and \( \mu \) (Repartition), serve to calculate the degree of membership of the density and the repartition of the detected events to mentioned fuzzy terms.

As stated above, the three-line laser ranging sensors are sampling the road surface at intervals of 11cm. Each sampled profile contains 1024 measured points for a lane width of 3.6m (12ft.). This provides a transverse resolution of 3-4mm. The
obtained sampled pattern is enough representative to accurately assess the surface cracking in terms of type, severity level and extent, but not always sufficient to accurately build a comprehensible image to match the reality. Validation methods sometimes implies visual comparison of data collection equipment results with digital images, photographic pictures or drawn crack maps. To this purpose, be able to provide such an image becomes an important issue. Several tests were conducted to assess and validate the new technique.

Figure 7. Alligator cracking site. Scales shapes in the reconstructed image match those in the video image.

In the first step an alligator cracked site was selected. Data collected with LVS at speed as low as 15Km/h was simply pasted together, every profile to next one, in order to obtain a simple bitmap. Only one projected profile from each sensor was used. At such a low speed, due to the high data density, the obtained bitmap approximates very well the reality and may be used for validation purposes. In the next step, the same site was surveyed at highway speed (70Km/h) and the results displayed also as a bitmap. This time the comparison was no longer possible. The collected data is in this case constituted from several points distributed in a random manner on the road surface. At this point the above described fuzzy technique was used. The results correspond to a traveling speed of 70Km/h and reproduce very well the real aspect of the sampled road surface. This technique was further extended to some other types of defects such as edge cracking, transverse and longitudinal cracking. In every case, a specific, easy to identify pattern, was searched in order to facilitate recognition and validation processes. The data was selected from previous data collection campaigns. Super VHS video imaging equipment allowed visual validation of results. The above images (figure7) present the bitmap of LVS collected data, the fuzzy reconstructed image and the corresponding digitized video image. Image scales were adapted to fit this paper.

5. IMPLEMENTATION

The six sensors used on the data acquisition system are mounted between the front axle and the rear axle of the surveying vehicle. Up-to 6 sensors are mounted on the vehicle and data processed in real-time, illustrating the importance of real-time, low cost, and low power consumption issues associated with this application.

Figure 8 shows the vehicle which has been equipped with six sensors and the necessary data acquisition and processing equipment to extract, at normal highway speed, the parameters of interest describing the road conditions: cracks pattern, rut depth, and longitudinal profiles in the wheel paths. The full transversal profiles for a lane width of 3.6 m are collected by four sensors. These four sensors are currently positioned at a height of 90 cm and are used for longitudinal crack detection, rut depth measurement and cross section analysis of the road. Each lane profile is acquired with a total resolution of 1024 points (256 points per sensor-profile) which corresponds to 3.5 mm of transversal resolution. The longitudinal profiles are collected in both wheel paths by two sensors closer to the road surface (60 cm) providing a total of six profiles of 256 points each with a resolution better than 3 mm. They are used for transverse crack detection and longitudinal profile retrieving. Range resolution (elevation) better than 1 mm are obtained. The configuration of the sensors on the vehicle and the footprints of the laser profiles on the surface under inspection are shown in figure 8. This acquisition geometry and the number of sensors can be adapted to meet various specific requirements.
6. CONCLUSION

In this paper, a three-dimensional infrared laser vision system for road surface features data acquisition and analysis was presented. The three-dimensional sensor array along with the parallel processing system architecture developed for this application provide reliable range and photometric data that are processed in real-time. Post-processing data retrieval and automatic analysis of the information allow defects identification and classification. Both acquisition and interpretation of the data are fully automated and objective. Fuzzy methods were particularly well suited for this kind of application.

The use of multiple features data extraction methods based on a single technology is of major importance in terms of reliability, versatility, data registration and analysis, and costs. The high resolution of the system allows detection and identification of most major types of pavement defects.

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