ANALYSIS ON THE DETERIORATION OF ROAD PAVEMENTS THROUGH LASER SCANNING TECHNOLOGY

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ABSTRACT

The need to organise and rationalise maintenance interventions on road pavements, through management systems that are cost-effective and functional, has led to the setting up of Pavement Management Systems (PMS).

These systems consider the objectives of transportation-related policies, as well as budget limitations of road infrastructure Management Authorities. They also provide for the arrangement of urgent maintenance works, when the paving deterioration is particularly harsh. In addition, there is a need to adjust a PMS according to the actual situations and to plan outlay, times and feasibility.

This paper presents a method to survey the deterioration state of road paving and to manage the maintenance intervention through a non-destructive system based on terrestrial laser scanners. The images related to the deterioration state have been acquired by different resolution sensors; segmentation, extraction and classification operations have also been done. The images have been compressed at different levels, in order to extract the deterioration state information, through edge extraction, smoothing, and quality enhancement operators.

The deteriorated road surface is acquired as a dense point cloud, for producing metrically correct 3-D models. The geometric three-dimensional information, acquired by the laser scanner sensor, is integrated with the real radiometric information of the object in order to obtain truly photorealistic digital 3-D objects.

It is therefore possible to extract metrical information relative to the deteriorated state from a quantitative point of view, defining the deterioration severity level.

The data, related metadata, images and 3-D global models can be managed by a database, which allows both technicians and managers to evaluate the deterioration evolution over time and to plan the most suitable maintenance for the pavement restoration.

Keywords: pavement management system, laser scanner, digital image processing.

1. INTRODUCTION: REASONS FOR THE RESEARCH

The global functionality of a road pavement, intended as its capability to fulfil the functions for which it was built, in terms of both structural resistance and roadway evenness and safety, can only be guaranteed during its working life if a series of tasks are performed to:

- check that the performance corresponds to that planned, during the building stage;
- preserve, or restore in the case of deterioration, its functional characteristics;
- adapt the performance to any new requirements (e.g. unexpected increases in traffic volumes), with reinforcement operations that could increase the lifespan of the pavement with respect to that foreseen at the design stage.

The hope is that the management authorities of the road networks, through their technical-administrative bodies, consider the planning, construction, service and maintenance as inseparable phases of the same general pattern, to be carried out with public funds, as it is a duty to provide the public with functionality, comfort and safety.

The execution of all the operations and activities suitable to preserve the functional and structural characteristics of a pavement throughout its working life requires the a priori evaluation of the deterioration state of the road pavement. To be able to define its behaviour, it is necessary to have as much information available as possible about the formation of the road, its history, the factors that have influenced its behaviour over time, the composition and distribution of traffic and weather conditions. Continuous and planned monitoring allows all the information on the state of the pavement to be surveyed with precision and, as a consequence, to programme interventions in advance.

The fundamental phases for the correct management of the maintenance process are:

- evaluation of the structure;
- analysis of the maintenance works carried out;
- examination of the types of deterioration and their evolution over time.

With reference to this last point, through the combined use of suitable threshold level indices, it is possible to evaluate the level of deterioration of a road pavement, forecast the evolution and identify the most opportune moment to intervene, in order to restore skid resistance, evenness and functionality, at the lowest possible cost.

This paper describes a system for evaluating the deterioration of a road pavement. Two different but complementary types of analysis have been used. The first, which is qualitative, involved the acquisition of images of deteriorated pavements by means of CCD sensors at different resolution; these images were processed to evaluate the state of deterioration and, having more than one image available for the same observation point referring to different time intervals, it is possible to identify the speed at which the deterioration has evolved.

The second, of quantitative type, involved the evaluation of the instability in metric terms through laser scanner technology; having the metric dimensions of the crack available, the PCI index could be calculated. This is a computerised procedure which offers the undisputed advantage of evaluating the severity of the cracks using a standardized index.

2. THE DIGITAL IMAGE

An image can be defined as a two-dimensional function f(x,y), where x and y are the spatial coordinates (lying on one level), and f, for each pair of (x,y), is termed "intensity". The intensity can be represented through the product of two terms, illumination i(x,y) and reflectance r(x,y):

$$f(x,y) = i(x,y) \cdot r(x,y) \qquad \text{(Eq. 1)}$$

being $0 < f(x,y) < \infty$, $0 < i(x,y) < \infty$, $0 < r(x,y) < 1$.

The image is thus composed of a component due to the light coming directly from the light source and a component due to the light reflected from the objects present in the scene. The illumination component is responsible for the slow variations of luminosity (low spatial frequencies), while the component of reflectance causes brusque variations of luminosity, for example at the edges of objects (high spatial frequencies). It can therefore be assumed that $L_{Min} \leq f(x,y) \leq L_{Max}$ where reasonable values for L_{Min} and L_{Max} are:

$$L_{Min} \approx 0.005 \quad L_{Max} \approx 100 \text{ (indoors)} \qquad \text{(Eq. 2)}$$

For a monochrome image, the interval [L_{Min}, L_{Max}] takes the name of the grey scale, whereas the intensity f(x,y) is also called the shade of grey of the image at the point of the coordinates (x,y). In practice, a grey scale is conventionally used of [0, L-1], in which 0 corresponds to black and L-1 represents white. L are considered as discrete levels of grey to take into account the digital nature of the f(x,y) after quantizing of intensity. Typically $L=2^k$, where k is the number of bits used to encode each pixel. For example, with 8 bits it is possible to represent a number of levels (256) that, in the majority of applications, provides an acceptable discrimination of the greys, in that it is very close to that of the human eye.

Computers cannot handle continuous images but only series of numbers, so the images are represented as a two-dimensional matrix where the grid point represents the pixel. A digital image contains *m* x *n* pixels, and can be represented by the matrix *m* x *n* where the index *n* varies from *0* to *N-1*, while the index *m* varies from *0* to *M-1*.

Given the original image, it is necessary to process it to be able to extract the desired information. The processes involved in the images of deteriorated pavements are the following:

- equalizing the shades of grey;
- smoothing;
- sharpening;
- erosion;
- thinning.

Given the normalized histogram of the shades of grey of a digital image, i.e. the discrete function:

$$p(r_k) = \frac{n_k}{n} \quad \text{per } k = 0,1,\ldots,L-1 \qquad \text{(Eq. 3)}$$

where n_k is the number of pixels of the image with the shade of grey r_k and n is the total number of pixels. This represents an *a posteriori* estimate of the probability of occurrence of the shades of grey in the image, which is useful because it provides a global description of the so-called "appearance" of the image.

The equalizing of an image is an operation that allows the density function of distribution of the shades of grey (histogram) to be altered in order to obtain a distribution of constant density. This operation allows the quality to be improved of an image with poor contrast.

Unwanted effects can be added to the consequent increase in contrast, such as “graining” of the image, or the appearance of “false” regions, etc., especially when the contrast of the original image is very low. The appearance of the image can also be improved with other techniques that modify the contrast, but the equalizing of the histogram has the advantage of being completely automatic.

The smoothing filters eliminate brusque transitions and noise; this corresponds in the dominion of the frequency to attenuate the high-frequency components; for this reason the filters for the smoothing are all of the “low-pass” type. Of the different types of smoothing filters, the Gaussian one acts so that the new value of the pixel is the weighted average of the values nearby (figure 1).

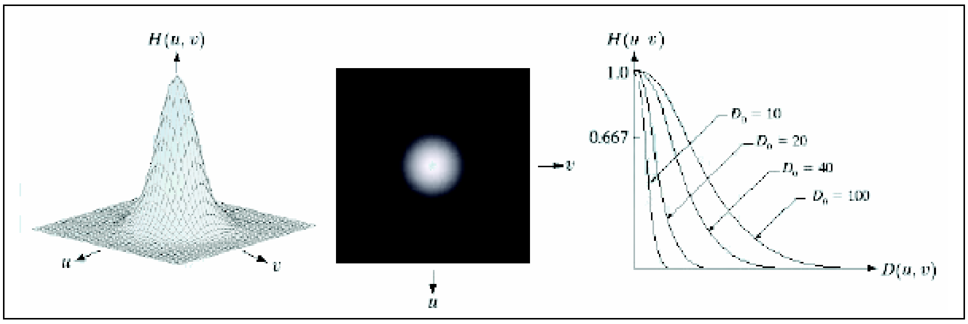

Figure 1 Smoothing filter

The use of masks of this type, instead of to a simple calculation of the average, is because the weighted sum with the discretized Gaussian coefficients preserves the real trends (in correspondence to the transitions between background and object) much better. The result remains anyway that of a “high-cut” filter, which filters the noise at high frequencies with maximum efficiency.

The aim of the sharpening filters is to restore the clarity of the original image, which may have deteriorated during the acquisition process or following other previous elaborations. The aim of the restoration of clarity is to accentuate the spatial high frequencies, increasing the local contrast (figure 2). The fine details and edge regions are consequently emphasized (the contrary of the smoothing filters), increasing the difference between the values of adjacent pixels. These filters act like “high-pass” filters with respect to the frequency and are produced by means of operations of spatial differentiation.

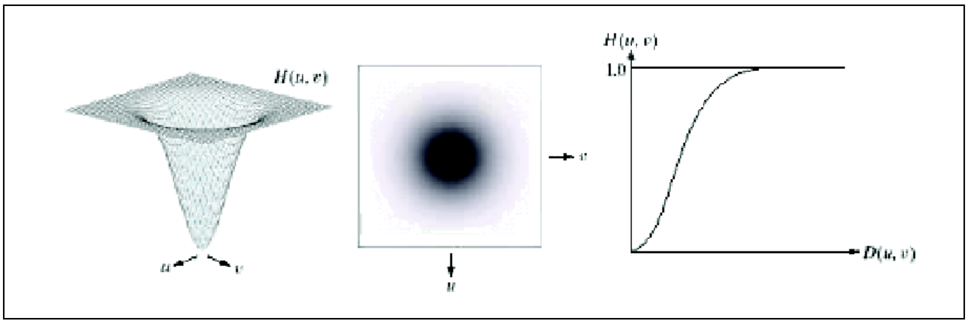

Figure 2 Sharpening filter

The aim of mathematical morphology is to extract topological and geometric information from a binary image A⊆E, where E indicates the set of all the possible images of known dimension, through the use of a smaller image B, called the “structuring element”; this is obtained by applying operators that act on every point h∈A. The elementary operations of mathematical morphology include that of erosion. Given two sets A and B, the erosion of A by B, indicated with A Θ B is defined as:

$$A \Theta B = \{r,c | (B)_{r,c} \subseteq A\} \quad \text{(Eq. 4)}$$

This equation indicates that the erosion of A by B is the set of all the shifts r,c of the centre of B, so that B results as totally contained in A. The erosion irrevocably eliminates some parts of the object (figure 3).

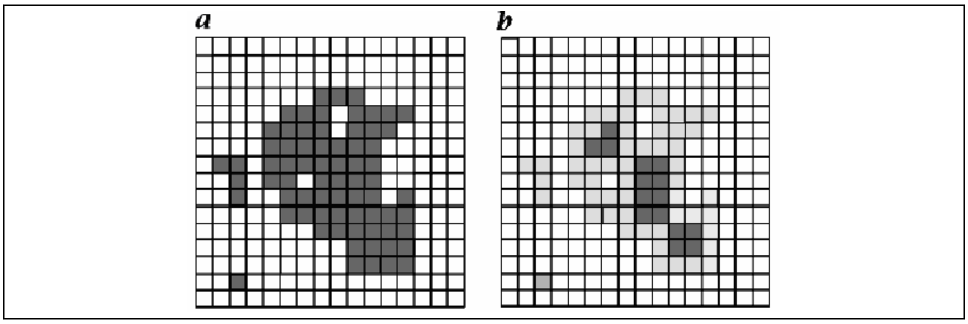

Figure 3 Erosion (b) of the binary object in (a) with a 3x3 mask. The pixels removed are indicated in a lighter colour

The thinning is a morphological operator that corrodes an object but does not break it except into the different parts. With this operator, the topology of the object is preserved and the structures with similar lines can be reduced to the thickness of a pixel. The thinning of a set *A* by a structuring element *B*, indicated with A⊗B, can be defined in terms of the transformed hit-or-miss:

$$A \otimes B = A - (A * B) = A \cap \overline{(A * B)} \quad \text{(Eq. 5)}$$

Once again, the interest is in matching the pattern of structuring elements and the image. A more useful formula for the thinning of *A* is based on a sequence of structural elements:

$$\{B\} = \{B^1, B^2, B^3, ..., B^n\} \quad \text{(Eq. 6)}$$

where B^i is the rotated version of B^{i-1}. Utilising this concept the thinning can be defined by a sequence of structural elements like:

$$A \otimes \{B\} = ((...((A \otimes B^1) \otimes B^2)...) \otimes B^n) \quad \text{(Eq. 7)}$$

The process is that of thinning *A* by means of a pass with B^1, the result is then thinned with a pass of B^2 and so on until no more changes are obtained.

3. IMAGE COMPRESSION

The notable progress registered in many aspects of digital technology, in particular in the field of tools for image acquisition, data storage, printing and graphic display by points, have led to many applications regarding digital images. A big obstacle for the development of many of these applications is the enormous amount of memory required to directly represent a digital image. This therefore involves problems linked to the high costs of data storage and transmission. Modern compression techniques offer a solution to these problems by drastically reducing that amount of data necessary to represent a given quantity of information.

The basic principle is that of exploiting different compression factors (CF) to display the edge of the objects surveyed and to extract the required information from them (figure 4).

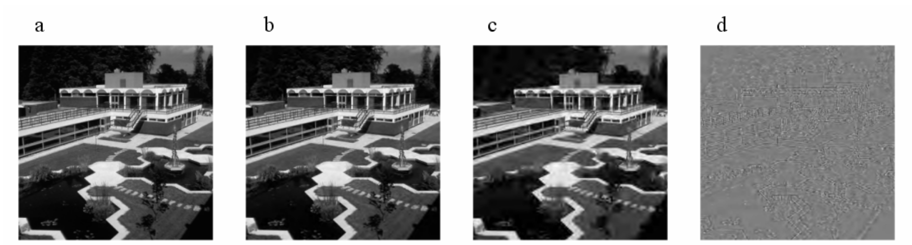

Figure 4 Original image (a) - Compressed image (b, CF: 0.5) - Compressed image (c, CF: 0.1) - Edge extraction (d)

4. LASER SCANNING TECHNOLOGY

The diffusion of instruments based on laser scanner technology is quite recent and will probably expand rapidly in the near future. The high density of sampled points allows a geometric survey to be made of objects with a remarkable level of detail and completeness. No universally recognised definition exists regarding scansion instruments: from the point of view of “the user” a laser scanner is any instrument that yields 3-D coordinates of the surface of an object.

Laser scanners are instruments that can provide digital models of any object in the form of a very dense cloud of points. However, a point model is not very legible and it is often not easy to extract useful information. So that the model can be more readily understood it is usual to conduct three-dimensional modelling, which consists of transforming the set of points on one or more surfaces by means of suitable methodologies.

One of the simplest models of 3-D representation is the *wireframe*. An object represented by a wireframe model consists of a finite number of points and sides that connect them two by two, thus aiding the visualisation of the object. The advantage of this model is its computing simplicity, while its limitation is sometimes in the quality of the final representation. The sampled image is represented through model “shading”, which offers the advantage of giving a photorealistic effect and model “texture” to the virtual image, which displays the structure of the surveyed object.

5. THE STUDY

The research involved the monitoring of a small urban road network and the identification of pavement points considered particularly significant because of high levels of deterioration.

The types of deterioration identified differ in nature (longitudinal and transverse crackings, patches, crazing); the surface deterioration was analysed as a function of the specific operating conditions (presence or otherwise of road markings and road signs, presence of manhole covers, road with heavy or light traffic).

For each degraded pavement point, two types of analysis were conducted: qualitative and quantitative.

The quality analysis allowed the identification of the outline of the deterioration. CCD sensors with different levels of resolution were used for these analyses:

- 640x480 pixels (0.3 Mpixel) - compression factor of 1:8;
- 2048x1536 pixels (3 Mpixel) – compression factor of 1:8;
- 2592x1944 pixels (5 Mpixel) – compression factor of 1:4.

Although various types of CCD sensors are available on the market with different levels of resolution and at relatively low cost even with a quite high resolution, the research also aimed to verify if, having only a low resolution available, it was anyway possible to display the deterioration without suffering an excessive loss of information.

The availability of images at low resolution with a sufficient level of detail for requirements allows the image processing times to be drastically reduced. This has undoubted advantages - especially if the technology has to be mounted on a moving vehicle for the pavement monitoring.

Two different approaches were used for the quality analysis: the first involved the processing of the images using MATLAB® (MathWorks, USA), the second included image compression with the software VcDEMO (TU-Delft, NL).

With reference to the quality analysis - approach I, given the original image, extracted the image in a scale of grey and subsequently the histogram of the original image and the equalized image (figure 5).

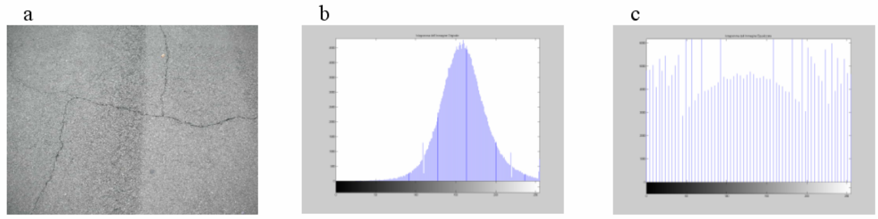

Figure 5 Original image (a) - Original and equalized histogram image (b, c)

The histogram of the shades of grey of the original image is markedly unimodal, but this characteristic is common to all images of road pavements. It is difficult that images of this type can present a bimodal trend: the equally distributed component of the histogram is substantially due to the noise, while the peak dispersion can instead be attributed to the effects of light, shadows or the limited resolving power of the entire system of acquisition. The equalizing of the histogram completely alters the distribution density function of the shades of grey, obtaining a distribution at constant density.

The operators of smoothing and sharpening were then applied to the equalized image, and lastly those of erosion and thinning (figure 6). The conversion into binary image allows at this point to eliminate all the information considered irrelevant.

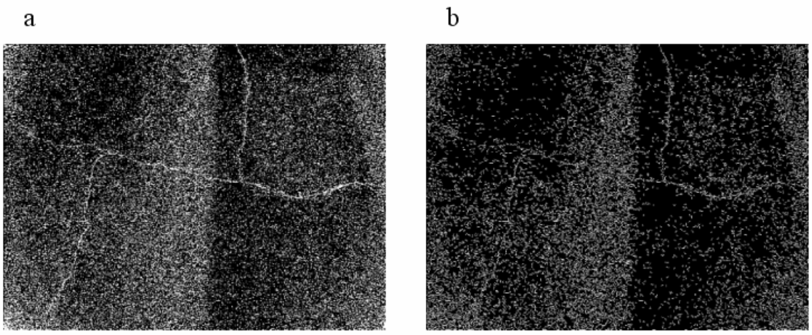

Figure 6 Smoothing+sharpening (a) - Final result (b)

The same procedure was conducted for all three specified resolutions. It was established that, even with a low resolution (0.3 Mpixel) the result, intended as the identification of the deterioration, is anyway guaranteed; there is a minor loss of information and the result is satisfactory with minimal computational effort (figure 7).

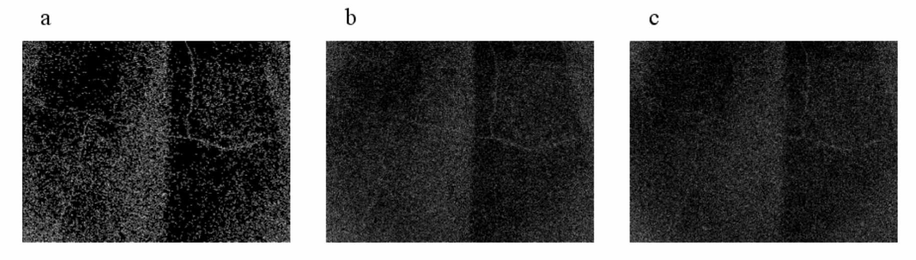

Figure 7 Final result after the processing for 0.3, 3, 5 Mpixel resolution respectively (a, b, c)

The average times obtained for the three resolutions, 0.3 Mpixel, 3 Mpixel and 5 Mpixel, provided the following processing times: 9s, 245s and 546s, respectively (figure 8). It is clear that the lowest resolution allows the processing times of the image to be slashed.

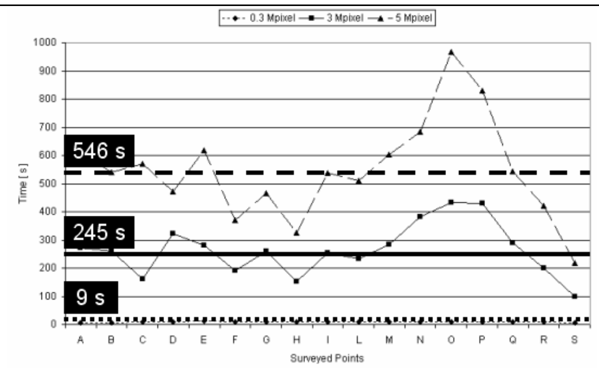

Figure 8 Average processing times of images at different resolution

The quality analysis – approach II exploited the different compression factors of the images. The compressions of the original image used were 0.5 (average compression factor) and 0.1 (high compression factor). The result was identical to that obtained with the first approach, i.e. identification of the outline of the deterioration, only following a pre-processing of the original image with MATLAB® (figure 9).

The quantitative analysis instead allowed a metric analysis of the road pavement deterioration and was done using laser scanner technology. The operative phases involved acquisition of the real surface, generation of the virtual surface and identification of the state of deterioration. For the acquisition phase it was considered appropriate to conduct the surveys utilising the lens with average focal distance (14.5 mm) and maximum resolution of 0.068 mm. The use of lenses with lower focal distances involves a consistent loss of information on the cracking state and the use of lenses at higher focal distance markedly reduces the size of the surveyed surface.

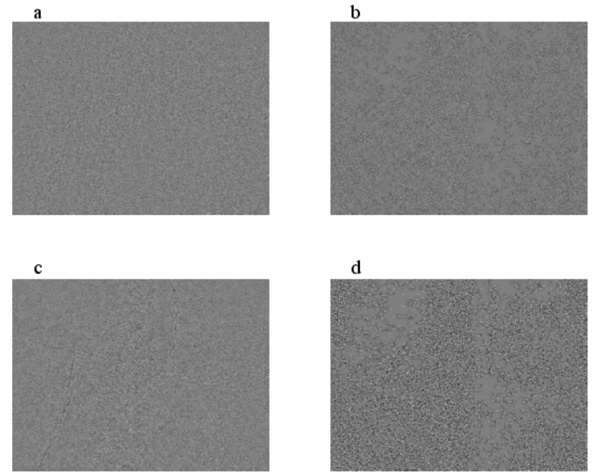

Figure 9 Final original image compression result with CF 0.5 and 0.1 (a, c) - Final pre-processed image compression result with MATLAB with CF 0.5 and 0.1 (b, d)

Once the operations of wireframing, shading and texture had been done on the original scansion (figure 10), the software RAPID FORM (INUS, ROK) was used to conduct an analysis of the deterioration.

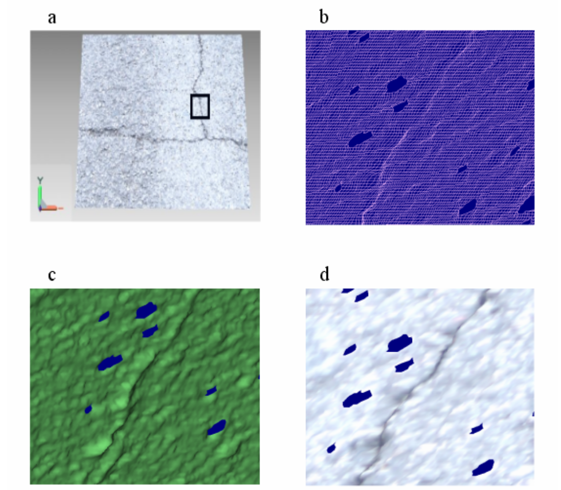

Figure 10 Image surveyed with the laser scanner (a) – Wireframe, shading, texture of the particular indicated in a) (b, c, d)

Having identified the crack, it is possible not only to measure the linear distance between each end, but also to know the length of the profile that supports the depth of the crack (figure 11).

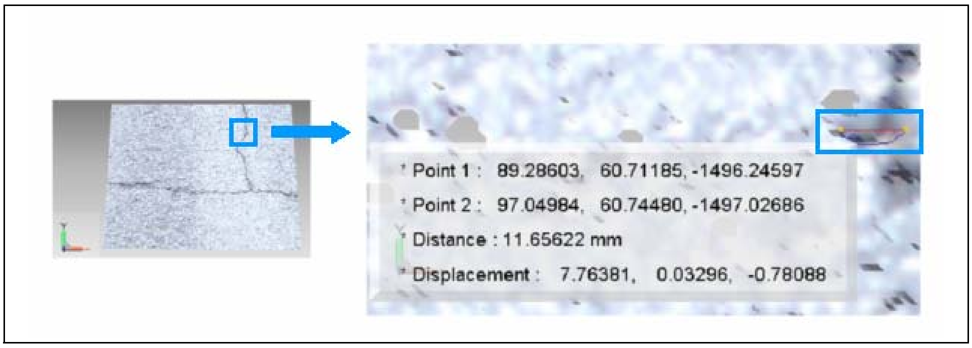

Figure 11 Measurement of the cracking

The deterioration index PCI (pavement condition index – ASTM D6433) was then determined. The PCI is a numerical indicator that:

- takes into account the type of deterioration, its extent and severity;
- provides an objective and rational basis for the maintenance process favouring the determination of intervention priorities.

It varies from 0 (completely deteriorated pavements) to 100 (pavements in perfect condition). When the road section is divided in survey units and the width of the crack defined using the laser scanner technology, the PCI is determined. For the examined pavement the PCI index was equal to 52.

On the basis of what is prescribed by the regulation, a PCI=52 identifies an unsatisfactory pavement, which urgently requires maintenance to restore the good adhesion and regularity of the road surface.

6. CONCLUSIONS

The proposed methodology allows the state of deterioration of a road pavement to be evaluated based on an automatic analysis, not just on a visual evaluation.

The CCD sensors allow rapid and sufficiently precise acquisitions even at low resolution, when processing times of the images are particularly rapid. The laser scanner allows an objective evaluation of the state of deterioration of the road pavement, permitting the determination of the depth and layout of the deterioration profile.

The integration of the two procedures allows an exhaustive analysis of the deterioration state of a road pavement.

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