Longitudinal road profile reconstruction from dual laser scans

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The article presents a practical application of lasers, for reconstruction of the road longitudinal profiles in dynamic regime. The method uses two laser sources and a video line scan camera placed at equal distance between the lasers for the contactless measurement of their height above the pavement surface. The main advantage of the proposed method is the fact that the sampling distance is equal with the distance between the two lasers, which eliminates the possible errors introduced by pitch oscillations, thus improving the calculus of the pavement quality indices.

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1. Introduction

The rapid development of the optoelectronics field has led to the improvement of laser sources and to the diversification of their range of uses. One of the many areas of laser application is the testing of road quality [1 - 3]. Differences in vertical direction, between the theoretical surface defined by the designer and the real surface of the road, can often appear. These irregularities affect the uniformity of a road, which is one of the main functional characteristics of the road structures. The studies concerning the comfort, circulation safety and the dynamic action of the loadings with which the vehicles stress the running surfaces with uniformity defects, revealed the necessity to identify the irregularities whose wavelengths are situated between 0.5 m and 50 m [4].

Road surface uniformity measuring equipment can be classified as “response” or “profilometer” type devices. The “response” type devices deliver a “uniformity note”, characterizing the dynamic behaviour on vertical direction of a vehicle or part of it, which is moving along the tested road. The response type devices do not permit the road profile reconstruction and their response varies with the nature, load and wear of the vehicle on which they are mounted. Also, the response type equipment need frequent calibration [5].

“Profilometer” type devices permit the direct or indirect reconstitution of the tested road longitudinal profile [6]. The profilometer advantages consist in their metrological qualities and in the possibility to compute a great variety of indexes, starting from the same profile acquisition. However, the road longitudinal profile sampling is conditioned mainly by the necessity to assure the correlation of the successive measurement sequences, thus the need to ensure a common reference level for all measurement points in order to reconstitute the real longitudinal profile and to compute quality indexes. According to the inertial reference used, profilometers can be grouped in two categories: profilometers which use an inertial reference or a “memory system”, at which the measurement “*i*” value depends on all previous measurement values “n”. Each of these types of profilometers has some drawbacks. Profilometers which use an inertial reference also need an accelerometer, which increases the cost of the system. Additionally, these systems are affected by the vehicle’s elastic system for suspension and damping [7]. The memory type of system favours the error propagation, as every measurement point height is a function of the previously measured points [8].

The quality of the pavement can be evaluated in terms of various road quality indices, such as the International Roughness Index – IRI and the pavement uniformity degree evaluation index. These indices are influenced not only by the road roughness, but also by the vehicle characteristics [8, 9], which can lead to erroneous calculus.

The aim of the paper is to present a new method for determining the longitudinal road profile, using two laser sources and a line scan camera placed at equal distance between them. By ensuring that the sampling distance is the same with the distance between the two lasers, the possible errors introduced by pitch oscillations are eliminated.

2. The proposed method

The proposed scheme includes two lasers and a sensor (line scan camera) for contactless measurement. The lasers are horizontally aligned in the moving direction, at a fixed distance one from the other, equal with the sampling distance imposed by the evaluation norms of the road longitudinal profile uniformity. Fig. 1 illustrates the detailed description of the measuring setup, which is based on two laser sources, used to measure the height over the pavement.

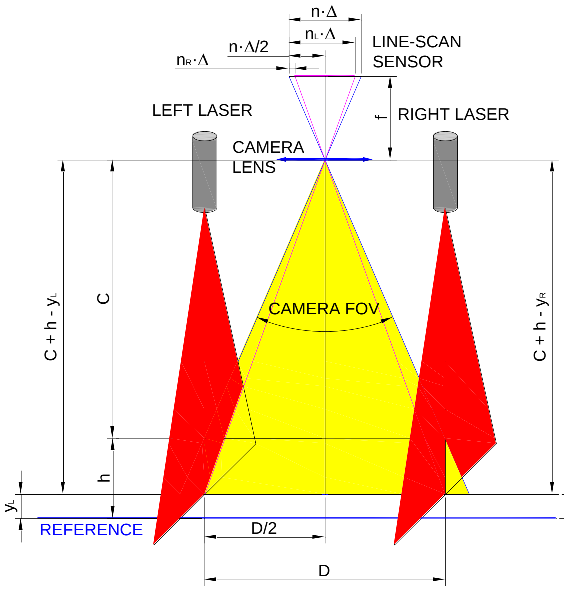

Fig. 1. The optical scheme of the system.

The lasers should be mounted close to the transversal axis passing through the centre of the ensemble (when mounted on a vehicle), in order to reduce as much as possible the magnitude of the pitch oscillations taken over by the measuring block. The line scan camera is placed in line with the laser sources, at equal distances from them, D/2. The optical axis of the camera is oriented perpendicularly to the pavement surface, while the two laser beams are oriented parallel to the optical axis of the camera. A lens, with focal distance *f*, is used to ensure the camera's field of view (FOV). The characteristics of the line scan video camera used are given in terms of number of pixels (*n)* and pixel size (Δ). Each measurement is characterized by the left and right pixel position (n_L and n_R) and by the height measured with the left and right laser (y_L and y_R). The minimal height to the camera lens is notated by *C*, and the maximum measurable height from the reference level is indicated by *h*. A prerequisite for determining the quality indices, is to ensure that distance between the two lasers, *D*, is equal to 250 mm.

The measured left (y_L) and right (y_R) heights of a frame, in terms of brightest left (n_L) and right (n_R) pixels, can be calculated as follows:

$$y_L = h - C\frac{n - n_L}{n_L - \frac{n}{2}} \qquad (1)$$

$$y_R = h - C\frac{n_R}{\frac{n}{2} - n_R} \qquad (2)$$

When the left (y_L) and right (y_R) measured heights are equal, the pixel positions, (n_L and n_R), will be symmetrically placed around $n/2$: $n = n_L + n_R$.

The minimal height, *C*, is a function of the distance between the two lasers, the focal length of the lens and the video line scan camera characteristics, as indicated by eq. (3):

$$C = \frac{D \cdot f}{n \cdot \Delta} \qquad (3)$$

The camera field of view (FOV), $2 \cdot \theta$, is given by:

$$\tan(\theta) = \frac{n \cdot \Delta}{2 \cdot f} \qquad (4)$$

Taking into account that the distance between the two lasers, *D*, must be 250 mm, and that a typical camera lens has the FOV of 45°, the minimal height to the camera lens can be approximated using eq. (5):

$$C = \frac{D}{2 \cdot \tan(\theta)} = \frac{D}{2 \cdot \tan(45°/2)} \approx 1.2 \cdot D \approx 300 \text{ mm} \qquad (5)$$

The accuracy of the measurements is given by the derivatives $\frac{\partial y_L}{\partial n_L}$ and $\frac{\partial y_R}{\partial n_R}$, which can be estimated from equations (1) and (2), as follows:

$$\left|\frac{\partial y_L}{\partial n_L}\right| = \frac{C}{\frac{n}{2} \cdot \left(1 - \frac{2 \cdot n_L}{n}\right)^2} \qquad (6)$$

$$\left|\frac{\partial y_R}{\partial n_R}\right| = \frac{C}{\frac{n}{2} \cdot \left(1 - \frac{2 \cdot n_R}{n}\right)^2} \qquad (7)$$

The accuracy will be minimal for n_L = n or n_R = 0, when $y_L = y_R = h$:

$$\left|\frac{\partial y_L}{\partial n_L}\right|_{\min} = \left|\frac{\partial y_R}{\partial n_R}\right|_{\min} = \frac{C}{n/2} \qquad (8)$$

The accuracy will be maximal when $y_L = y_R = -h$:

$$\left|\frac{\partial y_L}{\partial n_L}\right|_{\max} = \left|\frac{\partial y_R}{\partial n_R}\right|_{\max} = \frac{C}{n/2} \cdot \left(1 + \frac{2 \cdot h}{C}\right)^2 = \left|\frac{\partial y_L}{\partial n_L}\right|_{\min} \cdot \left(1 + \frac{2 \cdot h}{C}\right)^2 = \left|\frac{\partial y_R}{\partial n_R}\right|_{\min} \cdot \left(1 + \frac{2 \cdot h}{C}\right)^2 \qquad (9)$$

Equation (8) suggests that the only way to improve the accuracy is to use a sensor with a high resolution (large *n*). Obviously, this means a more expensive camera, but equation (9) gives us a hint about how large *n* should be:

the maximal value for $\left|\frac{\partial y_L}{\partial n_L}\right|_{\max}$ and $\left|\frac{\partial y_R}{\partial n_R}\right|_{\max}$ and h are required by application so $\left|\frac{\partial y_L}{\partial n_L}\right|_{\min}$ and $\left|\frac{\partial y_R}{\partial n_R}\right|_{\min}$ can be determined from (9) and n can be determined from (8).

The real longitudinal profile (y_i) can be determined from the right (y_{Ri}) and left (y_{Li}) measured heights. As can be seen in Fig. 2, each pair (y_{Li},y_{Ri}) of measured heights differs from the real profile values (y_i,y_{i+1}) by the error e_i.

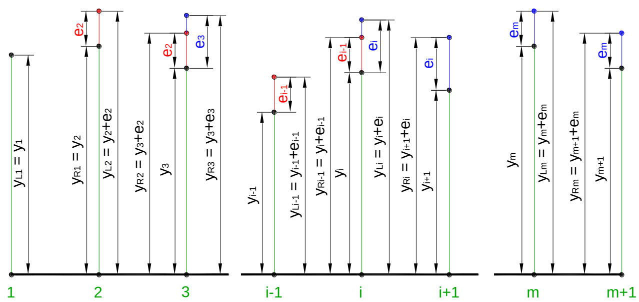

Fig. 2. True profile (y_i) and measurements (y_{Ri} – right and y_{Li} – left).

In the proposed scheme, the variation of the road profile elevation can be obtained from the difference between the height values from the two lasers, for every measurement sequence. The position of each image, for i from 1 to m, can be calculated using the measured heights:

$$y_{Li} = y_i + e_i ; y_{Ri} = y_{i+1} + e_i \qquad (11)$$

Taking into account that for the first measurement sequence, there is no vibration or other source of errors (e_1 is zero), the first set of coordinates is:

$$y_{L1} = y_1 ; y_{R1} = y_2 \qquad (12)$$

The process is iterative, so a value y_{i+1} can be derived from the previous value y_i and the pair (y_{Li},y_{Ri}) of the current frame:

$$y_{i+1} = y_i + y_{R_i} - y_{L_i} \qquad (13)$$

By replacing y_{Li} and y_{Ri} from equation (12) in (13) the current frame's error, e_i, is annulled and the profile is accurately reconstructed, without any error. This annulment of the errors (caused by vertical oscillations during the travel) represents a major improvement in the calculus of the road longitudinal profile.

In Fig. 3 an imagine obtained with the proposed system is illustrated (zoomed in). Camera acquired frames at every 250 mm over all the analysed distance, generating images that contain the signals from the left and the right laser.

Fig. 3. Acquired image of a frame.

From each frame, the positions of the brightest left and right pixels are extracted and two laser profiles are generated (Fig. 4.a-b). Fig. 4-c presents the difference between the two generated profiles, which is approximately ± 0.2 mm.

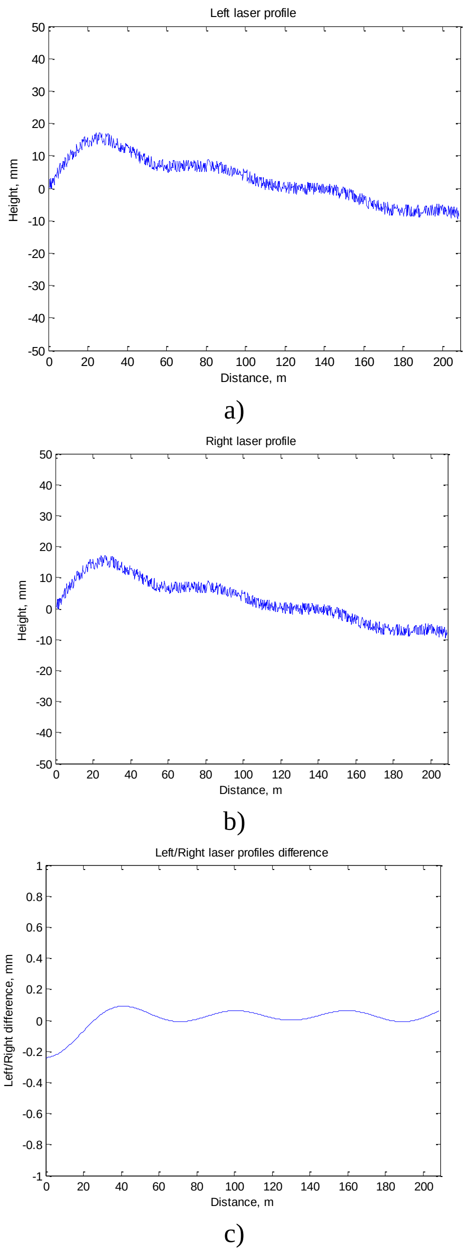

Fig. 4. The a) left, b) right laser profile, and c) the difference between them.

Using the algorithm presented in equations (11) – (13) and the left and right laser profiles, the real profile is accurately reconstructed, as it can be seen in Fig. 5.

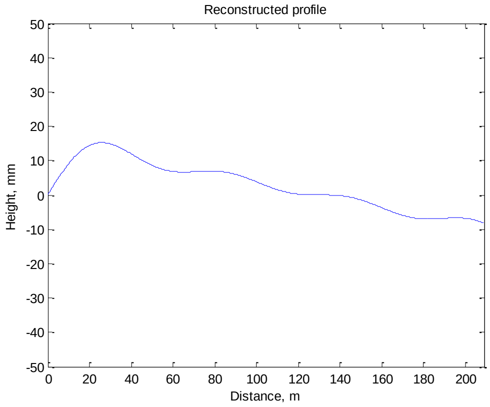

Fig. 5. Real profile, reconstructed from left and right profiles.

Due to the proposed calculation method, the real profile does not contain the influence of the possible pitch oscillation errors, and can lead to an improved characterization of the pavement quality. This profiling method has the important advantage to avoid expensive solutions that use accelerometers or GPS by a simple and effective device.

3. Conclusions

The new setup for longitudinal route profile, based on two laser sources and a line scan camera, was developed with the aim to eliminate the possible errors introduced by pitch oscillations, thus improving the calculus of the pavement quality indices. The orientation on vertical direction of the video camera axis ensures that the laser markings are always visible in the camera field of view and are not affected by the slopes of the terrain elevations. The variation of the road profile elevation can be obtained from the difference between the height values from the two sensors, for every measurement sequence. Using the reconstructed profiles of the left and right lasers, the real profile of the pavement is determined with high accuracy.

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