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An Embedded System Methodology for Real-Time Analysis of Railways Track Profile

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Abstract: ***Inspecting railway status is decisive to assure high operating safety, appropriate maintenance schedule, low maintenance and operating costs. This operation consists of the analysis of the rail profile, overall geometry and ondulation. Embedded image processing systems based on laser scanning and image analysis, are the key to achieve the complete track profile measurement during ordinary service of a rail convoy. This paper presents a methodology to design an embedded composite system, regarding the tradeoff between the accuracy and the computational complexity.***

Keywords: ***laser scanner, profile measurement, real-time embedded systems, accuracy complexity trade-off.***

I. INTRODUCTION

Public transportation companies surely consider safety in railways and tramways one of the key issues. The condition of the tracks is relevant in this perspective, in particular when high-speed trains are foreseen. Detection of wear and deformation of tracks at an early stage allows for better scheduling of the maintenance, avoiding the need of immediate action when dangerous conditions are observed.

In [9] a more complete literature analysis of the state of the art is present, including brief description of: automatic maintenance using multirobot system [1], genetic techniques to improve the planning of the railways tracks maintenance work [2] by sampled profile mechanical measurement, real-time inspecting systems measuring the railway track geometry [3] detecting vertical and horizontal accelerations, checking shifts from the ideal geometry in curves of the tracks, using a compensated accelerometer [4], differences between the inertial, mechanical and optical techniques [9]. Principal drawbacks of the tactile/mechanical techniques are: components are subject to wear, rail carriages must run at low speed, achieving low accuracy and high costs of acquisition. Present optical systems partially overcome the drawbacks but have insufficient accuracy for early global detection of incipient deformations. (e.g., grooved track is not allowed), work at low speed, and the track must be kept out of normal service until a special vehicle terminate the measurement.

In [9] we presented an innovative approach based on image analysis and processing to reconstruct the whole track profile. At prototype level, we showed the possibility of the real-time functioning with good accuracy, using algorithmic pre-processing and a neural processing [6-8]. In this paper we present a methodology to optimize the processing system regarding the tradeoff between the accuracy and computational complexity. The methodology shows how to integrate all the available high level information and "a priori" assumption in a proper decomposition of modules. The presented decomposition leads the designer to flexible choices to match different accuracy/complexity requirements. The presented methodology is general and not only related to the described application, enlightening how a strong modular analysis at system level be effective to maintaining a complex overall system behavior with simple functionality in the modules.

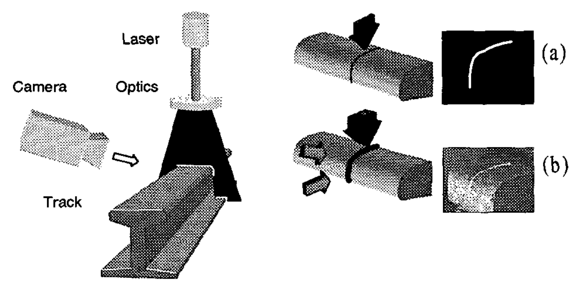

Fig.1. Left: the detection system. Right: the CCD images of the upper left part of the track: (a) ideal, (b) real

II. THE DETECTION SYSTEM

The detection system consists of a laser source, whose beam is collimated by a suited optic lens into a light plane, two 512x512-pixel CCD cameras for complete optimum observation of the track, a digital processing system per camera, and a supervision system (Fig. 1). Each digital processing system performs real-time profile filtering and extraction from images of the corresponding CCD camera. The detailed description is given in [9]. Real-time operation is needed since 200 track sections per second must be captured and processed to guarantee a sufficient accuracy of deformation localization at a normal convoy speed. In this condition and using the minimum number of cameras the system generates a bit-rate of 1,7 Gbit/s at least.

Identification of the profile is made complex by the presence of noise and environmental disturbances that modify the ideal profile reflection to be observed by the camera (fig.1a). Real images (e.g., fig.1b) are affected by environmental light, multiple reflections, track oxidation, greasy track, speckle effect due to track roughness, non-infinitesimal thickness of the laser plane scanning the track, optic aberrations, CCD sensor saturation, and image distortions due to vibrations. The detection system ideally have in input the real image (fig.1b) and produces the 2D-line of the profile as similar as possible to the line detected in the "ideal case" (fig.1a) where only a infinitesimal thickness laser plane enlightens the profile line and any kind of noises are not present.

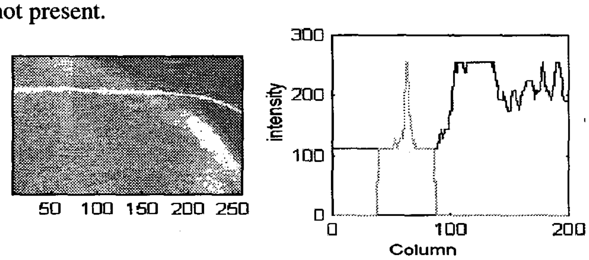

Fig.2. Identifying the laser reflex in a noise affected image column. The plot shows the intensity in column n° 225.

In each column of the image, localizing the position of the track profile means to find the position of the maximum laser reflection intensity. In the ideal case the laser intensity distribution along the column is Gaussian. Localizing the maximum implies therefore detect the position of the expected Gaussian profile with the maximum likelihood.

III. THE METHODOLOGY

In the present paragraph is described the methodology to design the embedded image processing system. The methodology proceeds from higher level of abstraction to lowers ones, integrating all the "a priori" information as possible, identifying a structure composed by modules. The goal of the methodology is indeed to solve the nontrivial application problem using a suitable composition of simplest functional modules.

The previous description of the detection system enlightens that some "a priori" information is helpful to the design of the system and that directly impact on computational complexity and maximum throughput:

a) The "signal" -the laser enlightened profile- is confined in a small area in the total image. The possibility to select the area where the information is contained and to discard the remaining part of the image where only "noise" is present is critical. Subsequent processing can enhance the profile extraction, working on a smaller dataset (less than 10% of the image contains the "signal").
b) The profile is approximately laying in a linear direction, i.e., cutting the image in stripes only one point of the profile belongs to each stripe. This characteristic allows parallel processing since each stripe can be analyzed independently to reach 10ms image processing time without affecting the profile accuracy.
c) The track profile can be considered continuous, as following from reasonable hypothesis regard as the roughness of the surface compared to the discriminating capability of the optic system. It allows to discard the "outlier" profile points (incorrect positions whit respect the continuous hypothesis due to error in the processing).

The designing of the processing system by a can be divided in two conceptual phases: the identification of the area of interest (phase A) and the finer localization of the profile using the reduced dataset contained in the area of interest (phase B). The best situation is when phase A is implemented at low computational complexity (to allow phase B to interpolate the final profile with maximum accuracy using the remaining processing time), but at the same time the behavior is kept robust with respect the variation of the environmental condition of the input image.

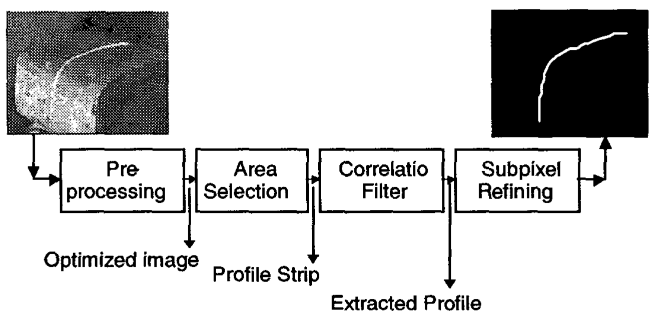

Fig.3. Methodology principal phases.

The sequence of processing phase (fig.3) can be summarized as following:

- phase A:
  1. *preprocessing sub-phase;*
  2. *area of interest selection;*
- phase B:
  3. *correlation filtering* (working on single column) to extract the profile using the information concerning the typical gaussian intensity pattern of the laser reflection as described in the introduction;
  4. *sub pixel profile refining* (using the continuity hypothesis *b*);

The preprocessing sub-phase should be present only if it indispensable to reduce noise to maintain a reasonable behavior of the processing system. The results show that the processing system present good accuracy performance over the required range of different input image condition, without any preprocessing filtering.

A suitable rotation of the principal camera axis allows to satisfies the b) hypothesis. In particular, phase 2) can be seen as a chain of subsequent area reduction sub-phases: horizontal and vertical. It is important to note that if the area reduction sub-phases have different computational complexity, the lower complexity ones must be positioned at the beginning of the chain, allowing the higher complexity ones to process narrow areas. Since identifying the presence or not of the laser reflection in a column image is less complex than locate the position of the reflection in the column image, the operation of cutting lateral blank parts of the image (horizontal area reduction) must be previous located in the processing chain than the more complex phases.

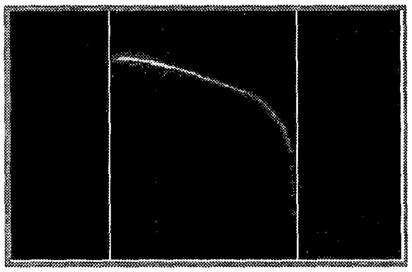

Fig.4. Horizontal area reduction, cutting lateral blank parts of the image

The horizontal area reduction (fig.4) can be implemented by iterating the "cutting" action from the outer columns to the inner ones, controlling if the maximum intensity in the considered column is lower than an minimum laser intensity threshold. The interaction must continue independently on left and right edges. The left and right loops must stop when a candidate column (whatever containing the laser reflection or external reflection) is encountered.

The chosen threshold value can be a fixed or adaptively calculated considering the distribution of intensity present in N equally spaced column (N must be greater enough to guarantee that at least one column containing the laser reflection is present in the extracted set). The adaptive threshold cans maintain a correct behavior with respect to variation of maximum intensity of the laser (e.g. when the camera automatically adapts the exposition time to enhance the contrast once the background intensity shifts).

The subsequent phase lead to extract from each column of the previously reduced image, only M pixels where the laser intensity is present. Usually the reflection is no wider than 10-15 pixel, depending on the zoom level and the laser lenses. The M pixels from each column form a strip in the image where the enlighten profile lays (fig.5).

The centre of the strip should be the central point of the laser reflection. The positioning of the strip can be done with different methods. The most robust method with respect the described noises consists of the convolution the column intensity with a Gaussian pattern [5].

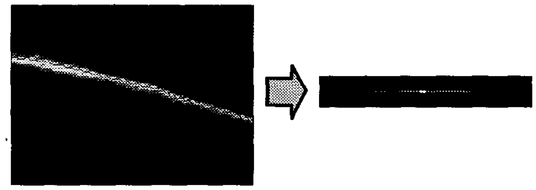

Fig.5. Vertical area reduction: extracting the strip containing the profile. In the left image, the darker line show the point identified likely to be the centre of the laser reflection. On the right: the extracted strip.

The convolution is repeated by positioning the maximum value of the Gaussian profile in each pixel of the column. The maximum value of the convolution corresponds to the position in which the light intensity is more similar to the expected Gaussian distribution (likely the center of the laser reflection). To reduce complexity, the same operation can be done using down-sampled vectors, and scaling the results. The laser reflection can be identified in less noise corrupted input image using simple convolution matrix such as:

$$\begin{bmatrix}0&1&0\\0&1&0\\0&1&0\end{bmatrix}\quad\begin{bmatrix}0&0&0\\1&1&1\\0&0&0\end{bmatrix}\quad\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}\quad\begin{bmatrix}0&0&1\\0&1&0\\1&0&0\end{bmatrix}$$

The first on the left matrix uses only values coming from the column in analysis. It allows maximum parallelism, and it achieves good performance with only three sums. Error can be corrected after, using *c* hypothesis.

Phase B (profile localization) must be designed exploiting the residual processing time in the frame. Many postprocessings are available:

- *Gaussian convolution* (optional): Since the pixels number to be analyzed in one column is strongly reduced, it is possible to refine the localization using the previously described convolution method (using all pixel values, without down-sampling). The location of the maximum value of the convolution function is the "single column sub-pixel interpolation" of the profile point. The maximum value can be subsequently exploited to gain more information (see Reflex identification). A method that can be called "*Optimum Path*" (and can be applied subsequently both after simple matrix or convolution pattern techniques) selects from a set of the N point in each column the one that maximize the profile continuity. The N point must be the ones with highest convolution function values because they are the N points with the highest probability to be the center of laser reflection. It can be implemented using dynamic programming.

A similar -but reduced in complexity method- can be called "*Outlier Removal*": identification and removal from the profile of the selected points with a not permitted offset from the "local continuity".

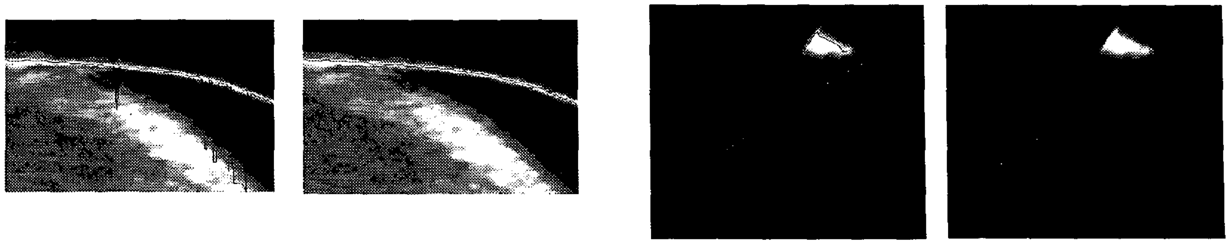

Fig.6. Discarding the outlier using "a priori" knowledge with "Outlier Removal" (left images) and "Optimum Path" methods (right images). In spite the simplicity of the algorithm, results are very effective in presence of external reflex.

- *Gaussian interpolation*: sub-pixel gaussian interpolation. The center of the laser reflection is sub-pixel interpolated using an ideal gaussian function (each column separately). An interpolation using only 3 points showed good performances.

- *Reflex identification* (optional): the shape of the intensity around the points selected by the gaussian correlation filter is checked. If the shape is not suitably similar to the gaussian laser reflection the point is unmarked (it probable corresponds to a non-laser external reflection). It is important to note the value of the normalized convolution of the pixel intensity is itself a "gaussianity" index, because the maximum value is obtained when the gaussian standard pattern match a perfect gaussian laser reflection (it is possible to derivate the two input vector of the convolution to better manage some flat-pattern external reflex, using the convolution function in the same described manner).

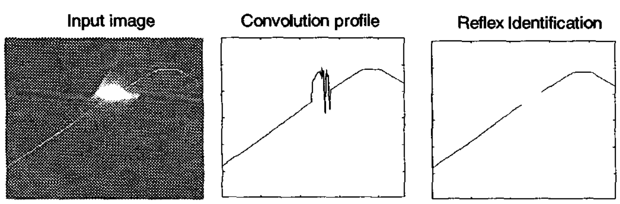

Fig.7. Effect of an external reflex in the profile regularization phase using the *Reflex identification* method (right), and without (center). The plots shows the point in input of the Regularization phase.

Fig.7 shows how the reflex identification method can give the possibility to exclude from the subsequent processing the points not linked to the laser reflection, but coming from the external reflexes.

It is important to note that the profile extracted using the convolution method (fig. 7, center) is intrinsically correct, because the algorithm chooses the point in the column that are more similar to the reference gaussian pattern. The external reflex completely saturated the intensity of the laser reflection (white spot), and indeed the border of the saturated area is the more similar part to the reference gaussian pattern. The *Reflex identification* method, combined to the *optimum path* method (or the equivalent previously proposed), allows the effective facing of the external reflex occurrences.

- *Profile regularization*: -using only the marked points if the *Reflex identification* phase has been used- a regularized reconstruction of the final profile is made using a linear/quadratic interpolation

The proposed modules can be different combined in order to contain the accuracy/complexity in the requirement. Opposite situation are the simplest processing chain (minimum chain) and the more robust one (complete chain). Minimum chain is composed by: area selection horizontal and vertical, gaussian interpolation and quadratic interpolation. Complete processing chain is composed by: adaptive horizontal area selection, vertical area reduction by correlation filtering, optimum path method to remove outliers, gaussian convolution to interpolate the profile in each column, reflex identification and quadratic profile regularization.

If the input images are not strongly corrupted by noise (i.e.: strong external reflexes are not present), the minimum processing chain can be used: *area reduction* (no *optimum path* method), *gaussian interpolation* using three points and profile regularization (white modules in fig.8). If the level of noise contained in the input image is considerably higher and strong external reflections can be present, the complete chain should be implemented

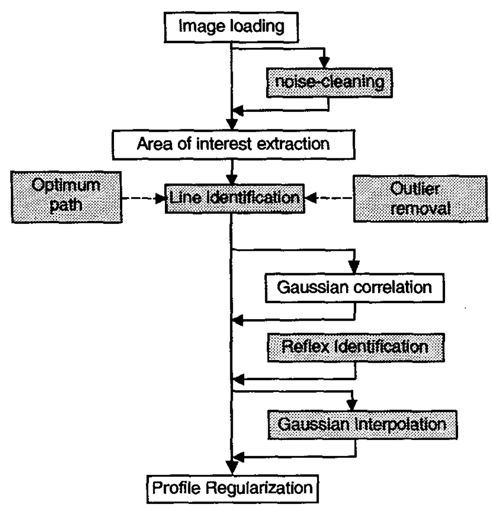

Fig.8. The complete processing chain

IV. EXPERIMENTAL RESULTS AND CONCLUSIONS

The paper presented an embedded system methodology for real-time analysis of railways track profile. The given methodology allows the designer to effectively balance the computational-complexity/accuracy trade-off of the solution with respect the input image noise and external conditions.

The experimental results show an accuracy close to 20 μm (in laboratory), using 9 flops per pixel for the case of images with low noise. This processing chain is suitable for underground or overnight scanning campaigns. In the cases when external reflex are present and the images are strongly corrupted by the noise, the complete chain provides maximum robustness.

The complete sequence of modules uses only 12 flops per pixel. The accuracy has been measured equal to 20 μm in every input image considered (in laboratory). This processing chain is suitable for be utilized in "all purpose" situation (mounted in normal train convoy, traveling by day, in presence of any sunlight condition and wheatear). A more extensive on-field experimentation is required to verify the accuracy with respect to the real effects of vibrations, dust and external light conditions.

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