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Digital image analysis technique for measuring railway track defects and ballast gradation

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ABSTRACT

In order to guarantee safety and driving comfort and to maintain an efficient railway infrastructure, the first step is to carefully monitor the track geometry and wear level of the materials constituting the superstructure. To that end diagnostic trains are widely used on main lines, in that they can detect several geometric track parameters and rail wear, but under no circumstances they can yet detect ballast gradation.

Due to the practical implications for the planning of maintenance operations on the railway network, this article presents a "DIP" digital image processing technique for measuring the transverse profile and corrugations of the rails as well as ballast gradation. The research was carried out in the laboratory on samples of worn-out rails taken from operational railway lines and in situ in the case of ballast analyses. For the latter, the reliability of the results obtained was assessed by comparison with available results yielded by traditional testing methods. It is shown that the proposed technique can be used not only for laboratory analyses, but most conveniently for high-efficiency in situ surveys, along with the methods traditionally adopted by the railway managing authorities thus contributing to lowering the maintenance cost associated with rail inspection.

1. Introduction

Railway track wear is a primary source of both user discomfort and safety problems. Above all, the rail-head wear can be a concomitant cause of derailment following train wheels climbing on the track. This case occurs when the forward motion of the axle combines with an excessive ratio of Q/P (wheel/rail contact forces), usually just when reduced vertical force and increased lateral force act on the wheel flange so that it rolls onto the top of the rail head. The climb condition may be temporary, with wheel and rail returning to normal contact, or it may result in the wheel climbing fully over the rail [1]. By denoting the transverse load, the wheel load, the flange angle and the friction coefficient with Q, P, α and f respectively, the limit value of the ratio Q/P which avoids derailment can be obtained with Nadal's well-known formula [2]:

$$\frac{Q}{P} = \frac{\tan(\alpha)-f}{1+f\tan(\alpha)} \tag{1}$$

Relation (1) shows that when the flange angle increases, the ratio Q/P decreases, thus maximizing the derailment risk. This circumstance arises as an effect of rail wear (α increment).

On the other hand, the different types of irregularity of the rail rolling surface and especially of the corrugation due to the wheel/rail parametric excitation [2–4] lead to N increase in dynamic load [5] to which the track is subjected, with a consequent rapid functional decay of the railway superstructure (so called "railway track") and an increase in rolling noise (prevailing over the other railway noise sources in the speed range 40–200 km/h).

Rail reclamation and removal of transverse and longitudinal wear faults are achieved with "rail grinding machines" (e.g. the Plasser GWM 250 rail-grinding machine [5]).

In order to keep the infrastructure efficient, reduce derailment risk and limit noise emission, maintenance activities need to be adequately planned after proper monitoring of the railway superstructure and identification of primary distresses in track components [6,7]. The same happens for road infrastructures or in civil concrete structures and image processing is becoming an extremely useful tool for this kind of applications [8–10]. Distress detection and monitoring for railways (mainly focusing on rail profile and level as well as overall geometry and ondulation) is typically based on mechanical devices in contact with the track, or via innovative approaches based on laser scanning and image analysis [11–13]. Amongst the contact methods it is worth mentioning:

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- the so-called low-efficiency tools (e.g. MiniProf device, continuous track and switch recording trolley, etc.) [14];
- diagnostic trains which perform a track laser and/or ultrasonic scan during monitoring train journeys, e.g. the italian diagnostic trains Archimede, Dia.man.Te, etc. [5].

Currently this equipment makes it possible to take precise measurements of track wear and geometry, yet it does not make it possible to quantitatively estimate ballast decay and especially ballast size distribution.

In light of what has been briefly described, an alternative technique is proposed to monitor the railway superstructure in order to gather useful information for defining maintenance and rehabilitation strategies for both network and project levels. This technique is based on image analyses (with a mono- and stereoscopic approach) and allows one to determine the following features of interest:

- vertical, horizontal and 45° rail wear [11,15];
- defective transverse profile of the rail-head;
- longitudinal track corrugation;
- ballast gradation;
- perimeters and "roundness" of ballast grains.

In order to detect the gradation of the ballast, the experiment was carried out in situ on a newly constructed Italian railway line since for this line a useful comparison can be made with the analyses performed by an accredited laboratory and considered in conformity with the Technical Specifications of the Italian Railway Authority. As regards the rail analyses, these were carried out in a laboratory, on sections from Italian railway lines under maintenance. The laboratory analyses were performed by using 3D cameras (Samsung NX300, equipped with NX45–F 1.8 3D lenses) and specific numerical formulations in a MATLAB environment.

2. Theory

2.1. Monoscopic approach

Image processing makes it possible to use the information content of a given image depending on the nature of the application of interest [16]. The segmentation methods allow to process an image with specific algorithms which subdivide the image into distinct and homogeneous regions according to a set characteristic. This is the first step that allows to distinguish the region containing the object of interest (*region of interest, ROI*) from the others, i.e. from the background. This process of image partition must not eliminate the most valuable information of the object contour, which is greatly important in this study for detecting:

- the transverse rail profile to estimate the wear also at specific points of interest (e.g. vertical, horizontal and 45° rail-head wear);
- the shape and dimension of ballast grains to estimate their gradation.

The segmentation procedure used in this research detects the contour or "edge" of the image through Canny's algorithm [17]. The phase of *image edge detection* is necessary because some pixels could be affected by "noise" (very rough light scatterings located at the rail image contour), thus making the detection of the edge of the object of interest (rail or ballast grains) less accurate. Canny's algorithm examines the behaviour of the gradient operator applied to a noisy contour.

On the plane of the image A (i,j,p), the pixel located at (i,j) is considered on the generic chromatic plane p (p = 1 Red plane, p = 2 Green plane, p = 3 Blue plane) as a contour pixel according to Canny if, compared to the adjacent pixels, its intensity is higher than the set threshold values as established by Canny [17]. The algorithm leading to this detection is called *hysteresis thresholding and non-maximum suppression*.

Fig. 1a. Rail image.

It has been observed that an edge detection, if done separately on the three chromatic planes (RGB), provides a great number of details on object contours [15,18]. The contour points of the elements of interest (ballast grains and rail profile), denoted with C, are illustrated only for the rail in the binary image of Fig. 1b, which is an enlargement of a part of the original image (see Fig. 1a).

For every point [17] of the contour we proceed to distinguish some groups of clearer pixels near the rail edge which do not belong to rail micro corrugations. For each chromatic image plane a moving average filter is applied; its kernel is:

$$B = 1/9 \cdot \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \quad (2)$$

or:

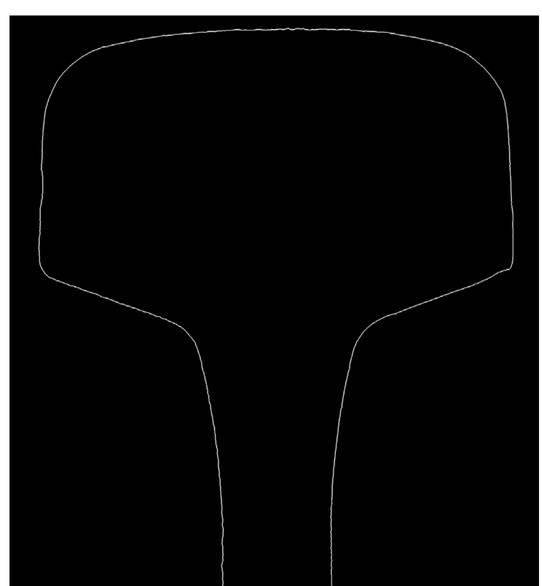

Fig. 1b. Binary image.