Digital Image Processing in the Diagnosis of Cracks in Steel Sheet

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Abstract: The railway is an essential part of the marketing chain. If it is considered efficient, safe, and competitive, on the other hand, the railways suffer from the enormous difficulty of maintenance due not only to their great extension, dispersion and lack of financial investments. Initiatives for automatic maintenance inspection, mostly done manually, require development and consolidation. Therefore, this work presents a method for identifying defects in sleepers based on analyzing images. We will use digital image processing techniques that will allow us to extract the contours of the sleepers and therefore analyze their curvature. The development is carried out with images from laboratory tests, not previously classified but subject to noise. The method is validated through analysis with an image bank with about 20 images of defective and flawless sleepers, with an average assertiveness of 94.24%. The detection, classification, and localization of faults in train tracks are then investigated and discussed.

1 INTRODUCTION

The expansion of the use of the railway system, together with the speed, frequency, and weight per axle adopted, directly affects the structure of the railway lines, including rails, sleepers, and other components. In this context, the sleepers play an essential role in the stability of the rails, as they are responsible for transferring the efforts produced by the loads to the ballast and guaranteeing the gauge of the line (distance between the rails). (Magalhães, 2007)

However, structural problems arising from use, which begin with the appearance of cracks, can progress to the complete breakage of the sleeper. This rupture causes an overload on the adjacent sleepers, accelerating the process of structural degradation and consequently contributing to the appearance of new cracks. This process can be repeated in such a way as to result in a sequence of broken sleepers, causing an increase in the track gauge and compromising the safety of a specific section of the railway line, which can become a considerable risk for the occurrence of derailment, mainly on curves.

In addition, the position of the sleeper in a "U" shape on the rails, as seen in Figure 1, ends up increasing the possibility of corrosion of the sleepers and further increases the cost of maintenance of the railways. (Magalhães, 2007)

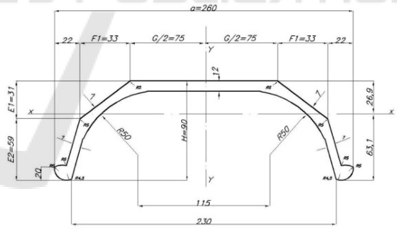

Figure 1: Shape of the steel sleeper on the train track (DNITT, 2003).

Therefore, rail wear and tear can generate financial losses and cause risks that directly affect the safety of train operators. Thus, preventive and corrective maintenance practices are essential to ensure the reliability of the railroad. However, railway maintenance has a high cost because it depends on qualified labor and an extensive and varied table of procedures to ensure safer and more efficient conditions for the operation. (Machado et al., 2009).

Therefore an automated system would be more reliable, safe, and consistent, increasing the efficiency of railway maintenance and reducing track inspection time. It would also minimize railway workers' risks

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when they are in a dangerous environment. (Malik, 2013)

For example, during maintenance, some sleepers are replaced depending on the time of use and others by the location of cracks, done manually by visual inspection. Thus, it is important to carry out this applied research, which aims to produce knowledge and generate technology to systematize, streamline and automate (when applicable) the process of diagnosing structural problems in steel sleepers. Contributing significantly to the reduction of operating costs, and losses arising from accidents, in addition to creating new business opportunities for the company, considering that other railroads also have the same needs.

Therefore, this project aims to develop applied research to diagnose structural problems in steel sleepers and identify them between flawless and defective sleepers. The work will be developed using digital image processing techniques and pattern recognition that enable the extraction of information about the geometry of the sleeper, more specifically the curvature of the sleeper edge. A system for diagnosing structural problems in steel sleepers will be implemented based on the surface geometry of the collected data, which will be divided into upper and lower geometry to compare the model's effectiveness.

2 LITERATURE REVIEW

The railways emerged during the second Industrial Revolution (17th and 19th centuries), with the need to keep up with the progress of the time, bringing even more economic and social opportunities. In this context, the railway matrix makes up an important modal within the transport sector of the world economy, providing accessibility and mobility for transporting cargo and people. It is important to note that in addition to logistics, railroads gained prominence due to some characteristics, among them: capacity of freight trains, low cost of freight over long distances, lack of delays due to traffic jams, lower incidence of thefts and accidents, low-cost energy and great sustainability, since it has low CO2 emissions in the atmosphere.

Therefore, in the world's major economies, railways represent the basic means of high-density infrastructure and highly connected networks in the transport system. For example, according to data obtained from (ANTT, 2021), railroads represent the main way of transportation for Russia (81%), Canada (46%), Australia and the US (43%), and China (37%). That is, countries with a developed economy have rail logistics that are very participatory within the transport sector; this causes mobility to advance the connection between the main cities in the country and facilitate the flow of goods.

Given the importance of railroads for the global economic sector, the improvement of their management has been the subject of several studies to automate and facilitate inspections of railroad components since it is still a very human-dependent process, making it exhaustive and slow. (Rubinsztejn, 2011), for example, proposed an automatic system based on the Viola-Jones algorithm for the automatic detection of the presence or absence of parts of interest on railroad tracks using real images acquired by a digital camera installed under a train.

Other innovative works in the area can be cited, (Rong et al., 2016) use a camera that captures images of the rails and a vibration sensor and present a system to detect irregularities on the track and the wagon wheels through computer vision and analysis of the rail vibration signal (SVD). (Yokoyama and Matsumoto, 2017) uses an algorithm based on Adaboost for crack detection in images of concrete sleepers. It is trained using crack and non-crack characteristics.

(Srinivasan, 2020) uses visual perception and image processing techniques for railway inspection and anomaly detection. All work is developed in LabView and the images used are extracted through a webcam, which runs along the entire length of the railway. Here, edge detection and image convolution, performed by changing pixels, are sufficient to detect loose or bent screws and cracks on the sleeper surface. (Franca and Vassallo, 2021) present a method to inventory and identify the types and defects of sleepers through real images obtained on railways and subject to various noises. For this, it uses image processing, heuristics, and feature fusion, all in an unsupervised way and through Matlab. Haar transform, integral imaging, edge detection, entropy calculation, and topology aspects are applied. Furthermore, (Passos et al., 2022) use convolutional neural networks (CNN) to automatically detect defects on the rail surface. In this work, a comparison is made between 10 (ten) CNN models in order to find the one that performs better results and accuracy.

The works presented so far have become similar in that they use image processing techniques to assess and inspect the conditions of the railways. But unlike what has been exposed so far, the sleeper's object of analysis in this work will be analyzed not by their surface, but by their curvature. The next topic will describe in detail the methods used to create a practical and efficient framework for automatic rail inspection.

3 METHODOLOGY

Image analysis and its representation play an important role in applications related to computer vision and the construction of visual inspection systems. This process is characterized as an area where systems are built to identify, classify, and interpret objects in a scene. Thus, as it is an iterative software, which includes a programming language for technical and scientific computing and toolboxes, allowing problem-solving with high versatility (Demuth and Beale, 2001), Matlab was the software chosen as the platform for the development of this research.

The flowchart that represents the methodology of the information control systems used in this work has 5 (five) main phases and is adapted in the sequential pattern of (Gonzalez, 2015), which is divided into: digital image acquisition, digital image processing(PDI), and digital image analysis (ADI). The flowchart represented in Figure 2 describes the steps of this work, starting from the representation in pixels and advancing toward the regions and data.

Figure 2: Flowchart of the methodology steps.

3.1 Image Acquisition

Building a database with real images of defective and non-defective sleepers is challenging, as it depends on numerous factors related to companies and the protection of their data and information. Thus, our proof of concept uses images of sleepers obtained in the laboratory for further testing in the field.

The image acquisition process was carried out through laboratory experiments. All sleepers are placed exactly in the same place and at the same distance so that the only variant in the image collection is the sleeper itself. Thus, the position of the camera allows for obtaining an image of the sleeper from the front and above, where it is possible to view the entire edge of the sleeper. Therefore, the database comprises a total of 20 (twenty) images, 10 (ten) images of sleepers with apparent defects, and 10 (ten) images of sleepers without defects. Figure 3 illustrates one of the database images.

Therefore, as the images obtained have a lot of noise, pre-processing becomes essential for a cleaner image. That is, the manipulations were performed properly to eliminate useless information or impair the analysis. We also use techniques to improve

Figure 3: Database image example, faulty sleeper.

lighting, define the region of interest, and extract attributes.

3.2 Segmentation

In this context, specifically, image analysis involves processes based on regions, thus requiring segmentation and processes based on transforming the image into the domain of spatial frequencies. Both allow the extraction of attributes used for pattern recognition, whether geometric or related to the power spectrum. Here, segmentation was used with the delimitation of the object (sleeper) in the region of interest (ROI) to define a contour of the two-dimensional geometry of the edge, the main object of the study.

The main segmentation approaches may involve linear methods, which act uniformly throughout the image and are fast and simple but cause loss of information and image details, as occurs with thresholding methods. Non-linear methods require more complex implementations to preserve more information about image details. The main interpretations involving non-linear segmentation cases are the variational approach. A technique where an energy functional is defined (cost function) and whose solution is found when this functional is minimized. Nonlinear partial differential equations are used to represent the contour, and the contour evolution is expressed as some function of invariant properties of the image. In Figure 4 we see the segmented sleeper and the (x,y) points representing the sleeper segmentation. X determines the column's position, and y is the line's position in the image where the contour is located.

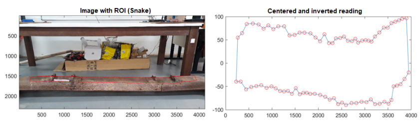

Figure 4: Segmented sleeper and referent chart.

The functional energy minimization problem is characterized by being ill-conditioned, where different solutions can lead to the same minimized function; i.e. the solution is not unique. There are several techniques for the solution of the functional. However, it strongly depends on the type of parameter used in its definition. In this context, we will investigate the segmentation using *snakes*: active contour. This technique allows us to segment the image from energy functionals defined by the image. From an initial curve in the image, it is deformed towards the edge region. This curve deformation is then accomplished by minimizing the total functional energy. Therefore, as it is an effective method for detecting edges of images with little contrast, presence of noise, and texture, this technique was used to delimit the edge and consequently obtain the extraction of points from the desired contour. (Kass et al., 1988)

3.3 Data Analysis

Thus, once the sleeper edge is detected using snakes, the delimited edge is transformed into a set of points x and y, allowing a detailed analysis of the curvature that forms the sleeper edge.

These data will be pre-processed through point interpolation. Interpolation is a technique used to estimate values of functions at intermediate points of intervals; this determination is made from functions calculated at the extremes of these intervals. (Knott, 2000).

This technique is necessary so that all points have the same distance along the axis and consequently form an edge curvature. Even so, the technique known as spline was chosen for the curve to be interpolated as smoothly as possible. Considered an approximation technique, spline interpolation consists of dividing the interval of interest into several subintervals and interpolating these subintervals with low-degree polynomials, causing the curve to be smoothed.(Knott, 2000)

Thus, for better analysis and representation of information about the outline of the sleepers, we separated the points that form the outline into upper and lower parts. We can see this in figure 5.

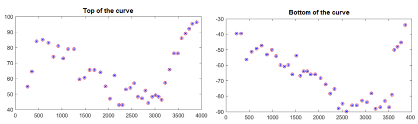

Figure 5: Upper and lower contour sleeper points.

After defining the contour points, we calculate each curve's curvature (κ) using Fourier Transform properties proposed by (Estrozi et al., 2003). It is well accepted that curvature provides an essential representation of salient shape points and is invariant to rigid-body transformations (Estrozi et al., 2003). Once the one-dimensional signal y was obtained, a numerical curvature κ was calculated through Equation 1.

$$\kappa = \frac{|y''|}{\sqrt{(1+y'^2)^3}} \tag{1}$$

where y' is the first and y'' the second derivatives of one-dimensional signal. After all this process, the curvature is stored in a matrix to classify the sleeper as defective or flawless.

The developed algorithm uses the second frequency component of the Fourier transform. Thus, for this second frequency component, there is a tendency for the spectrum of the curve extracted from damaged sleepers to assume higher values when compared to flawless sleepers. This frequency limit is then defined from the mean of the flawless sleeper data chosen for training, which tended to assume the Gaussian parameters.

Therefore, the established threshold will define an expected pattern in which, above the threshold, it will consider a defective sleeper and below the threshold a flawless sleeper and will save this performance. This whole process will be repeated 110 times, and at the end, we will have a ranking result based on the average of this performance. The methodology used to develop the classification system was to test different combinations between feature extractions, classifiers, and classifier parameters to find the attribute sequence that achieves the best performance for the situation.

3.4 Data Classification

To classify the curvature and to separate the defective sleepers from the healthy ones, the 2nd component of the Fourier derivative will be used. This approach was chosen because, in addition to Fourier adequately analyzing non-periodic functions, there is greater applicability to problems related to signal processing. (Junior and Costa, 1996) That is, in the Fourier Transform, the global or semi-local frequency information is captured along an entire signal or in processing windows, not oscillating in short intervals.

Thus, according to (Silva et al., 2022) the geometry of the sleepers associated with the spatial signs of the permanent way, have information that helps us to characterize the railway superstructure. In this sense, the discrete Fourier transform (DFT), which is a function composed of samples that can have pixel values altered along a row or column, is one of the tools that will help us in digital image processing. It is used because it is a mathematical technique based on the decomposition of signals into sinusoids, these sinusoids enter a linear system and come out as sinusoids that can change amplitude and phase, maintaining the original frequency, thus knowing if the sleeper has a fracture or not, let's visualize the change in amplitude of this sinusoid.

Thus, Fourier's second-order derivative method can be applied to estimate the curvature along the entire isopotential, curves defined by a surface (x and y), taking the contour of the original shape as one of its curve levels. In addition, it provides more excellent curvature enhancement, which would contribute to the greater accuracy of our analysis. (Estrozi et al., 2003) and (Junior and Costa, 1996)

Finally, after applying the second derivative, a frequency threshold will be established to define a classification region in the image. From this limit, all frequency components that are below this limit, reflecting the amplitude of the curve, will be classified as defective sleepers and above as healthy sleepers. Given the difficulty of establishing a threshold, an automatic global thresholding method was proposed to efficiently establish a threshold and minimize the error rate. (Gonzalez, 2015)

3.5 Performance Evaluation

Considering the proposed method for defect detection, its evaluation is based on three known pattern recognition metrics: Precision, Recall, and F1 Score. These metrics measure how well the method's detection is performed. Precision and recall are metrics useful for measuring relevance since they show the amount of data obtained that are relevant (precision), and the amount of relevant data obtained (recall). The Equations 2 and 3 describe precision and recall, respectively

$$\text{Precision} = \frac{TP}{TP+FP} \quad (2)$$

$$\text{Recall} = \frac{TP}{TP+FN} \quad (3)$$

where TP is the true positive rate, corresponding to defect sleepers that were correctly detected, FP, the false positive rate, a defect sleeper that was detected incorrectly, and FN, the false negative rate, indicating no detection when it does.

Using precision and recall, we can calculate the F1 Score, which represents the balance between the two metrics, and can be described by Equation 4.

$$F1 = 2 * \frac{\text{Precision} * \text{Recall}}{\text{Precision} + \text{Recall}} \quad (4)$$

4 RESULTS

From obtaining the curvature points with the snake, these are divided between the upper points of the sleeper and the lower points, but to define equal and consistent regions along the contour, we calculate a midpoint of the sleeper in such a way that values greater than the midpoint are treated as the top and lower values as the bottom of the tie.

In the next step, after separating the points, the data obtained from the sleeper geometry are interpolated with the spline function, using a distance of 1 *cm*. In this case, the interpolation aims to make evaluating the upper and lower curvatures efficient and equal. This is because the edge points that form the curvature of the sleeper that will be analyzed later, when extracted, are not obtained equally spaced. Therefore, the interpolation will calculate the internal points not given, allowing the (approximate) reconstitution of an occupation. In Figures 6 and 8, we can see the curve before and after interpolating the points.

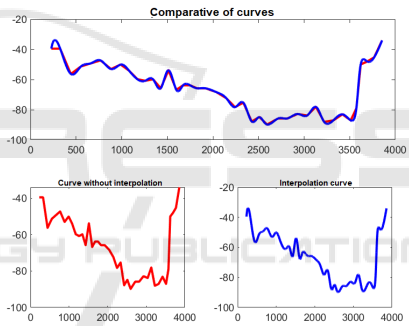

Figure 6: Lower curve before and after interpolation.

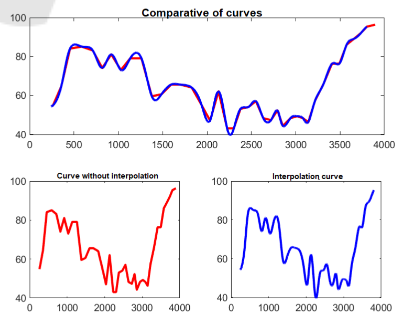

Figure 7: Upper curve before and after interpolation.

The treatment of all these data is part of the result that will allow us to save these points in a matrix that will be applied to the curvature for its classification. Thus, in the algorithm developed for this work, based on the calculation of the Fourier transform on the curve obtained from each sleeper, the data, but specifically, the curvature of the sleepers, are randomly separated, that is, 70% of these curvatures are separated for training the model and the other 30% for validation/testing.

In this way, this separation of training and test data is done 110 times, and each time the code is executed, the result is saved and the final result is an average performance of these 110 draws. We emphasize that making this result repeated 110 times was the way we found so that our result is not biased in a specific database, increasing the reliability of the model, considering that the final result is based on an average of these 110 times the algorithm runs differently. In addition, the limit automatically defined by our model was an adjustment based on training data from healthy sleepers as mean plus standard deviation, assuming that the data distribution of the chosen parameter is Gaussian.

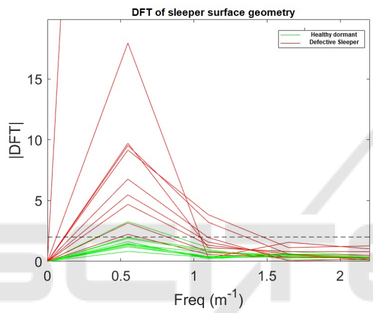

Figure 8: DFT of sleeper surface geometry.

In the graph shown in 8 we have the coincidence of the Fourier transform in the turned curve of each sleeper. Thus, we can observe, for visual and qualitative purposes, that for this second frequency component, there is a tendency for the curve spectrum extracted from damaged sleepers to assume higher values when compared to the frequency spectrum recovered from healthy sleepers.

In 1 we have the final performance result of our model. Therefore, we have the overall average hit rate, the general value of the classification of sleepers. We have the average index in the location of defective sleepers and we have the false positives, which represent healthy sleepers that are being classified as damaged. There is a better performance of the points extracted from the upper part of the sleeper, with 100% in the location of the sleepers; that is, all defective sleepers were detected, contrary to the points extracted from the lower part of the sleeper, where 81.82 % of defective sleepers were detected. Also, the false positives at the top are 11.51% as opposed to the false positives at the bottom.

Therefore, the average performance of the points

Table 1: Results.

Data	**Precision**	**Defective**	**False Posit**
Upper	94,24%	100%	11,51%
Lower	83,03%	81,82%	15,72%

that form the upper curvature of the sleeper edge has a better global average classification performance, 94.24%, than the points that form the lower curvature of the sleeper edge, 83.03%.

5 CONCLUSIONS

This work proposed applying a pattern recognition modeling for automatic railway defects investigation using digital image processing. Its main contribution is analyzing and classifying sleepers and the consequent rail maintenance management. This innovative process extracts information from the curvature of the surface of sleepers, aiming to optimize the maintenance of railways, which is fundamental in preventing accidents and reducing costs.

The classification based on the extraction of the sleeper surface curvature showed good performance when we analyzed the upper curvature, the model correctly classified 94.24% of the validation data, having found all the defective sleepers, contrary to the classification carried out with the points below, here the average hit rate for damaged sleepers was 81.82%. Thus, the system presents a user-friendly and easy-to-use interface. However, the validation dataset needs to be bigger, limiting our study, and it is important to analyze the architecture's performance in the face of a greater challenge.

A larger database is proposed for future work, varying the training parameters. Furthermore, we suggest that the extraction of the points that form the curvature of the sleeper be fully automated. In this work, this was not possible, as the snakes, the method used, needed help to demarcate points around the object of study. We also suggest comparing different defect detection techniques; these techniques can be better exploited if we get a bigger image bank.

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