Integral system for the auscultation, diagnosis and predictive maintenance of railway tracks based on inertial techniques and GNSS georeferencing

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1 Introduction

In recent years, rail transport has become the most important strategic mode of transport for both freight and passengers [1]. In this context, the maintenance of track quality, as well as the rapid intervention of its defects, is one of the challenges on which railway administrations focus their efforts. Predictive rail maintenance, based on non-invasive auscultation technology, massively reduces the risk of an incident occurring, as operators can both implement preventive maintenance actions and strategically plan maintenance through accumulated data sets [2].

Today, there are many state-of-the-art track monitoring systems, but they are inefficient systems, which lead to road occupancy and traffic interruptions, the need for special vehicles and skilled manpower, among other things. This is why the need has arisen to develop a track monitoring system that works on the track maintenance equipment itself: the draisine.

The general objective of this work is to develop a product that, integrated in any light rail vehicle (draisine), can characterise the state of the track, listening to all the geometric parameters as the vehicle is in circulation, and to carry out the georeferencing of the route of the track axis. All of this with the aim of performing a statistical treatment of the data and applying a predictive maintenance philosophy to the railway track.

2 Methods

This new system aims to develop a new auscultation system based on inertial methods and GNSS georeferencing systems, with the use of sensors located on light rail vehicles called draisines, capable of providing track condition data, from which predictive maintenance can be implemented.

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2.1 Data acquisition

In this regard, the time history of accelerations is registered on the vehicle body by means of tri-axial accelerometers, while its position on the track is constantly recorded with two GPS systems. All of this is connected to a data acquisition system that records and transmits the information.

On the one hand, the inertial system is used to obtain the geometrical parameters of the railway track indirectly, i.e. the starting point is the accelerations generated at the wheel-rail contact. For this purpose, the inertial system has two triaxial accelerometers placed on both sides of one of the draisine axles and connected to the data acquisition system.

On the other hand, the shape of the track axis and its position in the global coordinate system are essential in defining the design parameters of the track. The correct reconstruction of these quantities is vital both for verifying the conformity of the actual track parameters with the design and for diagnosis since all track deformations can also be defined as deviations of the actual parameters from their design values. The georeferencing system has two modules. Each of them will be located on the symmetry axis of the draisine, just above the axis of the wheels.

2.2 Data processing

The data processing is based on two key points: i) georeferencing and track layout algorithm; and, ii) mathematical model of the track-draisine system to obtain the geometrical parameters of the track.

Firstly, the algorithm for georeferencing and track layout starts by pre-processing the GPS signal to unify it with the (much higher) sampling frequency of the inertial system through an interpolation process.

To improve the accuracy of the GPS data, the uncertainty of the measurements is evaluated using the standard deviation [3], given that the distance between the two GPS antennas is known. After this, the algorithm to compensate for the dynamic movements of the draisine uses an inclinometer to adjust longitudinally and laterally the measurements [4]. Finally, the route is obtained by joining the points of the GPS coordinates, which are transformed into the UTM global coordinate system [5].

Secondly, the mathematical model of the track-draisine system to obtain the geometrical parameters of the track is composed by an algorithm following the Figure 1 scheme.

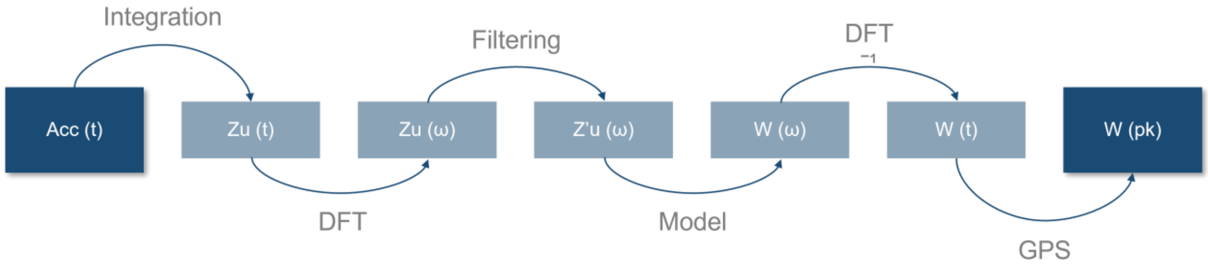

Figure 1 Scheme of the data processing algorithm.

The figure above shows the different transformations that occur throughout the process, which must be coupled together within the same algorithm. The stages or phases that make up this process are as follows:

- Integration of accelerations
- Discrete Fourier transformation
- Filtering of recorded data
- Solving the model equations
- Discrete inverse Fourier transform
- Space domain shift

The recorded time history of accelerations is double integrated over time through Equation 1 to obtain the time history of vehicle displacements.

$$Z_u(t) = W_0 + V_0 t + \int \int_0^t Acc(t)\ dt\, dt$$

Equation 1

Where x(t) and v(t) are the displacement and acceleration time histories, respectively; and x0, v0 are the initial values of vehicle displacements and velocities. Once the vehicle displacements have been calculated in the time domain, they shall be transformed into the frequency domain to allow a subsequent filtering of the data. This process is carried out by means of the Fourier transform in a discrete form (DFT, (Equation 2)).

$$Z_u(w) = \sum_{r=1}^{n} Z_u(t) \cdot e^{\frac{2\pi i (r-1)(s-1)}{n}}$$

Equation 2

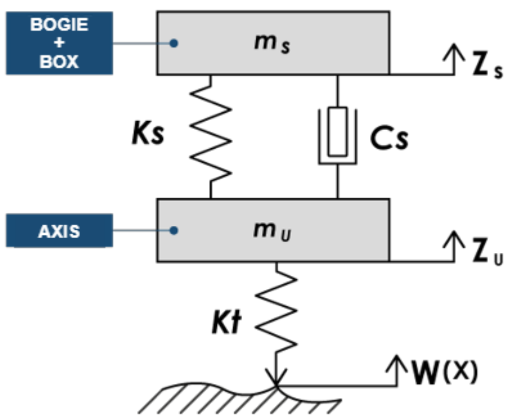

Figure 2. Quarter bogie model.

Where coefficients r and s vary from 1 to n; and n is the total number of points in the data series. A high pass filtering of the signal is then performed with the aim of removing low frequencies (i.e., long wavelength components), since they do not correspond to rail irregularities or alignment defects, but to track geometry regular variations, such as cant and slope changes.

The fourth step of the algorithm deals with the vehicle-track interaction as shown in Figure 2. In this phase, the displacements on the wheel-rail interface are calculated by solving the system of differential equations provided by the two-masses model of the vehicle - Equation 3 -. The model explicitly accounts for the effect of the unsprung mass (i.e., wheelset) and a combination of sprung (i.e., car body) and semi-sprung (i.e., bogie) masses.

$$m_s\ddot{Z}_s + C_s\left(\dot{Z}_s - \dot{Z}_u\right) + K_s(Z_s - Z_u) = 0\backslash$$
$$m_u\ddot{Z}_1 - C_s\dot{Z}_s + C_s\dot{Z}_u - K_sZ_s + (K_t + K_s)Z_u - K_tW = 0\backslash$$
$$W = Z_u + \frac{m_s\ddot{Z}_s + m_u\ddot{Z}_u}{K_t}$$

Equation 3

Where m_u is the unsprung mass; m_s is the combination of sprung and semi-sprung masses; k1 is the track stiffness; and $(K_s), (C_s)$ are the stiffness and damping coefficients of the primary suspension, respectively. The recorded data have been transformed in the previous step into the frequency domain for filtering; and thus, Equation 3 is transformed into Equation 4 by means of the Fourier transform properties [6] and solved in such domain.

$$-m_sw^2Z_s + iC_sw(Z_s - Z_u) + K_s(Z_s - Z_u) = 0\backslash$$
$$-m_uw^2Z_u - iC_swZ_s + iC_swZ_u - K_sZ_s + (K_t + K_s)Z_u - K_tW = 0$$

Equation 4

Once the rail geometry is known in the frequency domain, the results shall be transformed back to the time domain, which is performed by means of the inverse discrete Fourier transform shown in Equation 5.

$$W(t) = \frac{1}{n}\sum_{r=1}^{n} W(w) \cdot e^{-2\pi i \frac{(r-1)(s-1)}{n}}$$

Equation 5

Finally, the rail geometry dataset in the time domain is transformed into the space domain by correlating its values with the locations provided by the GPS. In this way, the position W for each rail point is obtained, which can be analysed and compared with the standard and track geometry defects can be discovered through its geometrical parameters: levelling, alignment, superelevation, track gauge and warping.

3 Statistical analysis algorithm and representation

The statistical evaluation of track geometric parameters is developed through three processes: i) systematic sampling of the data; ii) statistical distribution fitting and calculation of optimal pitch; iii) calculation of queuing probabilities and temporal analysis; and iv) maintenance planning and prioritisation.

The data series is obtained from the system's pass history to which systematic sampling is applied [7]. The objective of this technique is to create several sub-samples from a single larger sample.

Once the track has been segmented, for each specific section, the probability distribution that best fits the data series must be selected. Among the most appropriate statistical distributions for the geometric parameters of the track are the Normal distribution, the Weibull distribution, the Gamma distribution, or the Pareto distribution. The fit and selection of such a distribution is performed using the Kolmogorov-Smirnov (K-S) and Chi-Square (C-2) goodness-of-fit tests. These tests indicate whether a probability distribution fits a set of data, and indicate how well it fits them, i.e. by performing these goodness-of-fit tests for all samples fitted to each distribution, the optimal probability distribution and measurement step to perform the analysis can be obtained.

Once an admissible probability P [8] is set, it is compared with the calculated probability P0. According to the maintenance criterion stated above, conservation work is necessary if P0 > P.

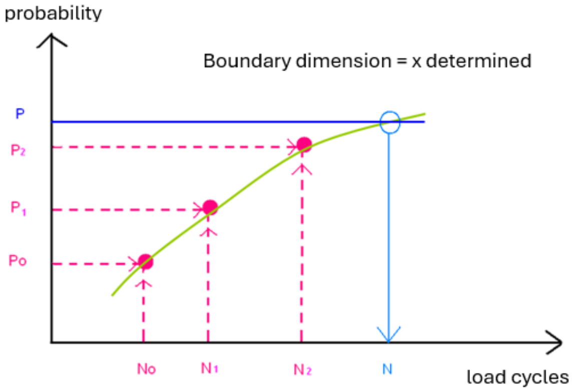

Figure 3. Graph probability - load cycles.

The two previous steps can be represented in a probability-time graph, or if instead of time, we work with load cycles (N0), the graph will be probability-load cycles. A function can be fitted to the points represented on it, and as shown in the following figure, once the admissible probability P has been set, it is possible to determine the time at which track maintenance will be required. Once the queue probability trends are obtained for each segment, finally, the maintenance planning and prioritisation algorithm takes as inputs the calculated queue probabilities, the available maintenance schedules, the costs of performing track repairs and the available maintenance budget.

References

[1] A. Elkhoury, N., Hitihamillage, L., Moridpour, S., & Robert, D. (2018). Degradation prediction of rail tracks: A review of the existing literature. The Open Transportation Journal, 12(1).

[2] Editor. (n.d.). Railway Maintenance: the New Frontier of Wireless Monitoring. Worldsensing. Retrieved May 1, 2024

[3] Parkinson, B. W. (1996). Global Positioning System: Theory and Applications II. Progress in Astronautics and Aeronautics, 164, 3–50.

[4] Grewal, M. S., Weill, L. R., & Andrews, A. P. (2007). Global Positioning Systems, Inertial Navigation, and Integration. Wiley.

[5] Hofmann-Wellenhof, B., Lichtenegger, H., & Collins, J. (2003). Global Positioning System: Theory and Practice (5th ed.). Springer-Verlag.

[6] Melis, M., Apuntes de Introducción a la Dinámica Vertical de la Vía y a las Señales Digitales en Ferrocarriles. Madrid, INGENIERÍA DE FERROCARRILES, METROS Y TÚNELES, 2008.

[7] Review of Probability. (n.d.). Retrieved May 1, 2024.

[8] Casal, J., & Mateu, E. (2003). TIPOS DE MUESTREO. Rev. Epidem. Med. Prev, 1, 3–7.