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A GPR Signal Processing Procedure for Detecting Rail Ballast Conditions by an Entropy-Based Approach

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Ballasted railroads are among the most common construction types in railway engineering due to the effective drainage capability and load-bearing capacity achieved at relatively low construction costs. Rail ballast is usually made of uniformly-graded coarse aggregates derived from crushed rocks of differing geological nature, mostly granite, basalt and limestone. According to Selig and Waters [1], several categories can be identified as principal source mechanisms of fouling, namely, the breakdown of ballast, the infiltration from ballast surface (downward migration of coal dust from commercial trains) and the upward migration of clay fines from the subgrade, are the major causes of fouling. Notwithstanding the increased costs of maintenance, fouling occurrence may dramatically impact on the safety and operation of railways [2]. In view of this, effective health monitoring and early-stage detection of fouling is mandatory to allow significant reduction of both unsafe events and maintenance costs. Within this context, non-destructive testing (NDT) techniques are becoming more important in the health monitoring of railways. In particular, fouling inspection of ballasted railroads have been carried out using infrared imaging, electrical resistivity tomography, seismic surveys and, mostly, ground penetrating radar (GPR). The GPR sends an electromagnetic (EM) wave into the ground using a transmitting antenna and receiving the back-reflected signal by a receiver antenna in a given frequency band. Overall, interfaces between different materials within the railway track bed and the inhomogeneities within materials with different EM properties cause changes in signal peak positions and amplitudes, such that the information on the layer thicknesses and properties of the materials can be obtained.

The idea behind our work is to investigate the presence of fouling in railway ballast by means of an entropy-based analysis [3]. Entropy is a concept initially borrowed from the classical mechanics, and later from the information theory. In mechanics, the entropy is used to quantify the disorder and the uncertainty of dynamical systems, or in other words, it is an expression of the randomness of a system [4]. On the other hand, the entropy in information theory is considered as a measure of the information content of the series under investigation [5]. In particular, Shannon [5] has also related the concepts of entropy and uncertainty in his pivotal work. He argued that the information is a measure of the degree of uncertainty exercised by the source in the phase of selecting the message to transmit (i.e. the presence of a regular pattern in the ballast/assessing good as-built conditions, herein). In practical terms, information is the removal of the uncertainty: high values of the Shannon entropy are relevant of an increasingly polluted ballast (by fouling intrusion), whereas lower values mean less uncertainty, hence a more regular and unpolluted ballast. The entropy has been used in several fields of application such as the biomedical engineering, speech, information data mining, front-wall clutter rejection, financial signal processing, and color image enhancement. To the best of our knowledge, there is only one paper applying the entropy analysis to GPR systems by the use of 2-D entropy of GPR images for detection of sporadically distributed features [6].

The rationale of our approach is as follows: if the ballast is a "regular one" (i.e. without intrusions of fines), its structure should be characterized by repetitive patterns, hence its entropy should tend to small values. Conversely, if the ballast is fouled (i.e. it is a "polluted" ballast), its structure becomes irregular, and the entropy of the system should reach higher values. Thereby, if the ballast is clean, its structure is repetitive (the same pattern repeated in the structure), and it can be represented (or "encoded", speaking in terms of information) by a few bits (low values of entropy). On the contrary, if the ballast is polluted, its structure contains more information, hence it should be encoded with a higher number of bits (i.e. higher entropy value than before).

A laboratory set-up was built and both cleaned and fouled ballast scenarios were manufactured. In order to simulate a real-life scenario within the context of railway structures, four different ballast/pollutant mixes were introduced from clean to highly-fouled ballast. Limestone aggregate particles used for the construction of railway track beds and a silty soil material were utilized for testing purposes. The experimental tests were carried out using GPR systems equipped

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with different ground-coupled (600 and 1600 MHz) and air-coupled antennas (1000 and 2000 MHz). With regard to the 2000 MHz radar systems, one ordinary (i.e., 2 GHz EU) and one low-powered (i.e., 2 GHz NA) version of the horn antenna for the European (EU) and the North-American (NA) markets, respectively, were utilized. A binary hypothesis testing method that automatically discriminates between the presence and absence of fouled ballast has been proposed. The performance of this method has been evaluated in terms of the receiver's operating characteristic (ROC) (i.e. the detection probability versus the false alarm rate) by calibrating the optimal threshold in laboratory tests. The agreement between the theoretically-based and empirically-based results obtained confirms the validity of the proposed approach in rapidly identifying distinctive areas of interest related to fouling (e.g., see Fig. 1). Thereby, the computational costs traditionally related to more sophisticated data post-processing could be considerably lowered. On a comparable (multi-frequency) GPR system with ground-coupled antennas, the low-frequency antenna (i.e. 600 MHz) turned out to provide a lower detection performance than the higher frequency (i.e. 1600 MHz). Such an outcome was confirmed by the application of the proposed entropy-based approach to the data collected using the air-coupled GPR systems. Both the 2000 MHz systems have returned detection probability values higher than the 1000 MHz. In particular, the 2 GHz EU version of the antenna has proved to be the most effective within the context of the entropy-based analyses here proposed, showing a detection probability always higher than 95%, even with a relevant false alarm rate less than 5%. Such results prove how frequencies of investigation greater than 1600 MHz are suited for the inspection of ballast using the proposed entropy-based methodology. Resolution powers with dimensions consistent to the voids sizes allow to detect the thinner clean layers of the top ballast as well as to distinguish these from the underlying fouled layers.

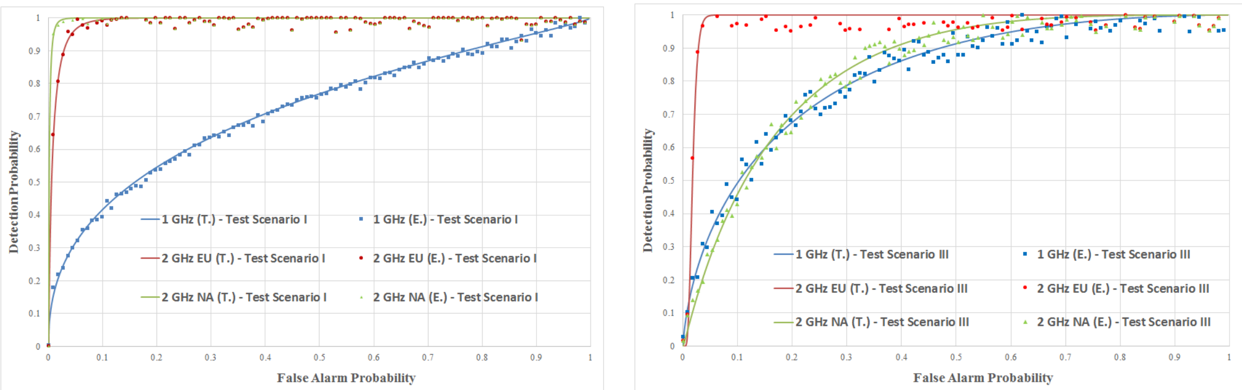

Fig. 1. Theoretical (T.) and Empirical (E.) ROC of the air-coupled GPR, equipped with 1 GHz, 2 GHZ EU, and 2 GHz NA monostatic antenna frequencies, for: *left*) 38 cm clean ballast over 10 cm fouled ballast; *right*) 18 cm clean ballast over 30 cm fouled ballast.

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