Construction and Building Materials 69 (2014) 10–17

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Content-based image retrieval approaches to interpret ground penetrating radar data

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HIGHLIGHTS

- A new data processing technique for GPR data interpretation is developed to quantify fouling conditions of railroad ballast.
- The technique is based on texture retrieval of GPR images.
- Discrete wavelet transform is used to extract texture features.
- Similarity measurement is performed using different methods.
- The accuracy of quantifying ballast fouling level is high.

ARTICLE INFO

Article history:
Received 7 February 2014
Received in revised form 9 May 2014
Accepted 29 June 2014
Available online 5 August 2014

Keywords:
Ground penetrating radar
GPR
Railroad ballast
Ballast fouling
Texture retrieval

ABSTRACT

This paper presents a new data processing algorithm to interpret ground penetrating radar (GPR) data for quantification of railroad ballast fouling conditions. The algorithm is based on the observation that different fouling levels generate different textures in the GPR images. The algorithm was designed following the content-based image retrieval procedure, which includes two steps: feature extraction and similarity measurement. First, texture feature was extracted using discrete wavelet transform. Second, similarity measurement was performed. Laboratory GPR data were used to evaluate the accuracy of the algorithm. The accuracy was 93%, which demonstrated the effectiveness of the algorithm.

1. Introduction

Railroad ballast is one of the main components of the railroad track structure. It resists vertical, lateral, and longitudinal forces; supports railroad ties, reduces stress from the tie bearing area to acceptable levels at subgrade, providing resiliency and energy absorption for the track, reduces noise, provides immediate drainage, and alleviates the formation of frost [1]. Clean railroad ballast is composed of uniformly graded coarse aggregate. However, over time, ballast is gradually fouled by fine materials, which usually result from ballast breakdown and infiltration of small particles [2]. The phenomenon of fine material filling the air voids in the ballast is called fouling. Fouling may jeopardize the functions of the ballast layer. When the fouling reaches a high level, the structure's integrity can be diminished, and drainage capacity can be undermined. This can lead to track instability, loss of track support and ultimately derailments [3]. Therefore, it is critical to assess fouling condition of the railroad ballast so maintenance work can be done timely to ensure the safety of railroad transportation. Accordingly, reliable technology that can rapidly and accurately assess ballast fouling condition is needed by the rail industry.

The traditional method for assessing ballast fouling conditions is visual observation. However, in a visual survey, the conditions under the track are missed. Although drilling samples can provide reliable information about the ballast, it is time consuming and destructive and can provide information at certain discrete locations only. To overcome these disadvantages, ground penetrating radar (GPR) can be applied for railroad ballast fouling assessment.

GPR is a non-destructive technique that can assess transportation facilities rapidly and continuously. Various research studies have been conducted on the application of GPR on railroad ballast assessment. Narayanan et al. [4] compared GPR data collected using antennas with different center frequencies. Results showed that a 100-MHz antenna was better at detecting deeper water

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http://dx.doi.org/10.1016/j.conbuildmat.2014.06.060
0950-0618/

pockets than a 400-MHz antenna. The 400-MHz antenna showed better ability in estimating the depth of substructure layers. Olhoeft and Selig [5] and Sussmann [6] applied 1-GHz air-coupled antennas to assess rail track condition. Results showed that the 1-GHz antennas were able to obtain information about the thickness of ballast and subballast layers and variations in layer thickness along the track. It could also detect water pockets trapped in the ballast and soft subgrade resulting from high water content. Roberts et al. [7] and Al-Qadi et al. [8] used 2-GHz air-coupled antennas to assess fouling condition based on the scattering response of electromagnetic (EM) waves in ballast. The scattering analysis approach showed potential to distinguish fouled ballast from clean ballast. Al-Qadi et al. [9] and Leng and Al-Qadi [10] used a time-frequency approach to interpret GPR data. They found that the time-frequency approach can characterize the signal in time and frequency domains simultaneously and quantify the fouling and moisture content. A recently developed GPR data processing technique by Shangguan et al. [11] applied discrete wavelet transform (DWT) for data interpretation. In that method, the fouling level can be determined by features extracted from wavelet decompositions. The advantage of the method developed in [11], which is based on the wavelet technique, is that it can process large amounts of GPR data continuously and automatically and generate a fouling profile for an entire section of track.

Compared to the GPR data collected on pavements, the data collected from ballast are much more complex. This is because pavement layers can usually be considered homogeneous medium, whereas ballast cannot be considered homogeneous medium due to relatively larger size of ballast particles compared to the wavelength of GPR wave. EM wave encounters significant scattering within the ballast which increases the difficulty of data interpretation. An effective and efficient data interpretation algorithm which can process the data automatically and rapidly is urgently needed. With the aim of developing such an algorithm, this study proposes a new data processing technique.

This study is inspired by the content-based image retrieval (CBIR) system. CBIR utilizes computer vision techniques to solve image retrieval problems. By extracting features from query images, the most similar images in an image database can be found based on the ranking of similarities [12,13]. There are different features to represent an image in CBIR system such as color, texture, and shape [14]. Findings in previous studies have shown that GPR data collected from railroad ballast with different fouling levels have different scattering patterns [5,8,9,11]. And different scattering patterns result in different textures in GPR images. Therefore, texture can be used as a good feature to correlate fouling levels. In this paper, a texture retrieval approach was developed for GPR data interpretation. Laboratory experiments were conducted to collect GPR data on ballast with different fouling levels. Different feature extraction and similarity measurement methods were then performed, and texture retrieval rates for all the approaches were calculated and compared.

2. GPR principles

GPR has a transmitting antenna and a receiving antenna. The transmitting antenna emits EM waves, and the receiving antenna receives the reflected signal scattered back from the interfaces and inhomogeneities having different EM properties within the materials. There are two types of GPR antennas: ground-coupled and air-coupled. For the application of railroad ballast assessment, an air-coupled antenna is preferred because it can be installed at a specific distance above the ballast, allowing rapid collection of data. Typical setup of GPR antenna above railroad can be found in [8–10,15,16]. Fig. 1 illustrates the travel path of EM waves using

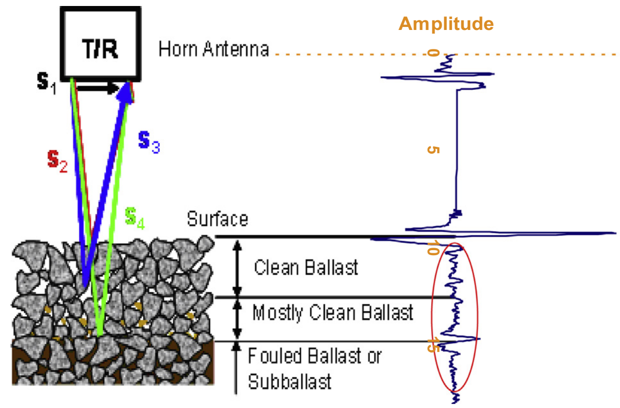

Fig. 1. Travel path of the GPR signals.

an air-coupled GPR antenna. S_1 represents the EM wave propagating directly from transmitter to receiver. This part of the signal is called the coupling pulse; it is usually removed. S_2 is the wave reflected by the surface of the ballast. S_3 represents the EM wave scattered by the ballast/air-fouling interfaces. This part of the signal (see the circled portion on the right side of Fig. 1) propagates within the ballast and thus contains most of the fouling information. S_4 represents the interface between clean ballast and fouled ballast or subballast. S_4 might not be observed if the interface is not clear.

3. GPR data processing techniques

Researchers have developed different approaches to interpret GPR data collected on railroad ballast. This section summarizes the main data interpretation approaches. The advantages and disadvantages of each approach are included.

3.1. Traditional approach

The traditional approach to interpreting GPR data is to identify reflections at interfaces, such as the ballast surface and the interface between ballast and subgrade, in time domain GPR images. The depth of the interface can be calculated based on the dielectric constant value of the ballast and the two-way travel time. Fig. 2 shows an example of GPR data interpretation using the traditional approach. A clear interface between ballast and subgrade is observed. The result is validated by ground truth data.

However, it is difficult to assess fouling condition using the traditional approach. The gradation of fouled ballast usually changes gradually, and no clear interface is present between clean and fouled ballast, which makes it difficult to find the fouling location from GPR images.

3.2. Time-frequency analysis

The traditional approach interprets the GPR data in the time domain. By using time-frequency analysis, the GPR signal can be viewed in both the time and frequency domains. The basic form of time-frequency analysis is short-time Fourier transform. A more sophisticated technique is wavelet transform. Both have been applied in the analysis of GPR data for assessment of ballast fouling conditions.

Short-time Fourier transform (STFT) is a method that can track frequency spectrum change with time [17]. It has been applied in GPR data interpretation [8,9,16]. The STFT spectrum can be obtained from Eq. (1).