Automation in Construction 45 (2014) 42–49

Contents lists available at ScienceDirect

Automation in Construction

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

A semi-automatic processing and visualisation tool for ground-penetrating radar pavement thickness data

María Varela-González [a], Mercedes Solla [b,*], Joaquín Martínez-Sánchez [a], Pedro Arias [a]

[a] Department of Natural Resources & Environmental Engineering, University of Vigo, School of Mining Engineering, Maxwell s/n, 36310 Vigo, Spain
[b] Defense University Center, Spanish Naval Academy, Plaza de España 2, 36920, Marin, Spain

ARTICLE INFO

Article history:
Received 26 August 2013
Revised 4 February 2014
Accepted 2 May 2014
Available online 21 May 2014

Keywords:
Ground-penetrating radar
Pavement
Civil engineering
Processing
Visualisation

ABSTRACT

Ground-penetrating radar (GPR) is a recommendable and cost-effective non-destructive technique for measuring the thickness of pavement layers because data acquisition can take place at normal traffic speeds. On the other hand, the large amount of data collected is difficult to process. Given that processing is conducted by qualified practitioners, it is a key to obtain software tools that allow for accurate thickness measurements and fast processing times. This paper presents a new semi-automatic program for the processing and visualisation of GPR data to measure pavement thicknesses. The results showed that an optimisation in the execution time allowed for a near-immediate response in data processing even when dealing with large data sets. Different data set lengths, ranging from 100 m to 20 km, were analysed, and the processing times required to complete the entire process were examined taking into account three different hardware configurations (i3, i5 and i7 processors). In all cases, the processing times did not exceed 30 s. An additional test was performed to evaluate the reproducibility of the algorithm on a well-defined and preconditioned concrete asphalt course. Furthermore, the visualisation application allows for the georeferencing of the field GPR data by using additional GPS data.

1. Introduction

The preservation and maintenance of transportation infrastructure is a global concern that affects social and economic development in all countries. The pavement is an essential part of the road that directly contributes to improving safety and vehicle comfort and reduces fuel consumption. The pavement life-cycle is not only affected by the number of heavy loads but also by the layer thickness, which is a vital factor defining pavement quality. Thickness deficiencies reduce life-cycle, and periodical rehabilitation is therefore necessary in any country's road management program to maintain optimal road conditions of use or to monitor quality control on new asphalt overlays [1].

Pavement thickness has traditionally been determined by drilling and extracting cores, which is a considerably slow and expensive method that greatly damages the road structure. The use of non-destructive techniques (NDT) and near-surface remote sensing is now demanded for road subsurface inspection, such as pavement thickness estimation, which is important for reducing deterioration and for providing an accurate overall analysis in a relatively short time to reduce maintenance costs [1]. In this sense, ground-penetrating radar (GPR) is one of the most frequently recommended NDT methods for the measurement of pavement thickness [2–4]. GPR technology is rapid, cost effective, and allows field surveys to be conducted without disturbing the pavement structure and the normal traffic flow [5,6]. Thickness measurements using GPR are typically accurate to within ±10% [7]. In fact, some studies have shown that with proper field methodologies and data processing techniques, thickness measurements of newly built pavement with layers thinner than 250 mm are typically accurate to within 73% with the use of GPR [8,9].

Due to the greater amount of high capacity roads built in Europe during the last decades, and the constant maintenance requirements for these roads, developing cost-effective inspection methods has therefore become a high priority to reduce economic infrastructure investments. In road inspections, the GPR systems are most commonly mounted on a moving vehicle [10,11], but the large amount of data collected makes it difficult to process and manage in a reasonable amount of time. Currently, only some specific software are designed for this application, but most of them were developed from manufacturing companies of GPR devices, and they are not only expensive but also implement user interface designed for user who specializes in the GPR methods. This work aims to develop semi-automatic software for the processing and visualisation of GPR data to be used by any non-experienced user to optimise the time and resources invested for road management and maintenance. An innovative approach is therefore presented in this work to provide a more powerful, functional and versatile tool, which is efficient in terms of operability, to be applied in road inspections and, particularly, for thickness estimation. The software was developed to determine the thicknesses from GPR data collected by using either the core calibration or amplitude methodologies [12].

* Corresponding author. Tel.: +34 986 814052.
E-mail address: merchisolla@uvigo.es (M. Solla).

http://dx.doi.org/10.1016/j.autcon.2014.05.004
0926-5805/

Exploiting the power of the C++ programming language and the Qt framework allows for the development of applications with graphical interfaces, which provides a simple and intuitive tool for a qualified worker, and thus was implemented to reduce the processing times and to give information at the earliest possible moment. To verify the optimisation process provided by the software developed, a test battery was performed for this tool using certain execution cases. For an exhaustive analysis, the software was evaluated by taking into account different hardware configurations. Furthermore, the software developed provides a visualisation application for the georeferencing of GPR data by using additional GPS (Global Positioning System) data. Both GPR and GPS data are therefore spatially related to a common trajectory, which allows for the integration of additional data generated from other sensors such as laser scanners, profilometers or video cameras, all of which can be installed on a moving vehicle. Thus, by geopositioning, all the data acquired from different sensors can be accessed simultaneously for a particular geographic location, which has a clear application in road management systems [13–15].

2. Materials and methods

The main objective is to create an effective desktop application that provides, in a reasonable amount of time, a graphical depiction of the thicknesses obtained for the different layers that compose the pavement structure. In addition, another desktop application was created to display the obtained layer thicknesses in greater detail.

2.1. Technical description of the software

To develop competitive software in comparison to other existing commercial tools, a series of initial requirements were established. The main requirement was the use of a powerful programming language that is capable of developing graphical user interface (GUI) applications with support for graph implementations. Graphs are needed to represent the traces obtained by the radar pulses and the final layer thicknesses of the pavement. A review of available resources was carried out by taking into account the initial requirements and the C++ programming language along with the Qt libraries were selected as the most appropriate.

C++ is a general purpose programming language created by Bjarne Stroustrup and designed for object oriented programming. C++ is, essentially, a superset of the C programming language. In addition to the resources provided by C, C++ provides flexible and efficient facilities for defining new data types [16]. A complete library in the C++ language was created for raw data processing. This library can be used in different programming environments even without any graphical interface.

Qt is a multi-platform set of libraries for software development with a graphical user interface. It is released under the "GNU Lesser General Public License" and uses C++ language [17], which ensures the compatibility with our raw data processing library. There exists a library named Qwt, which is usable in Qt environments. This library contains GUI components and utility classes that enable the creation of spectrograms and curve plots [18], which are capable of building radargrams and profiles, respectively. Using the integrated Qt and Qwt libraries, two desktop applications were created: one for GPR data processing and another for results visualisation.

The development environment consists of versions 4.8.0 of Qt and 5.2.2 of Qwt, and these were installed on the Qt Creator IDE. This environment was built making use of the MinGW compiler in 64 bits, which is an implementation of Linux GCC compilers that facilitate the migration to a Windows environment [19].

2.2. C++ processing library

The processing tool considers two different methods commonly used during data acquisition for the calculation of layer thicknesses: velocity or core calibration [20] (for ground-coupled systems) and amplitude [21] (for air-coupled or launched systems). To do this, a library in C ++ has been built to be reused in future developments.

To conduct the thickness measurements for ground-coupled systems, the longitudinal profiles corresponding to the reflections generated at the interfaces between different layers are extracted. With this procedure, the thickness is obtained for all the traces in the GPR profile in terms of the wave travel-time distance between two different reflectors or layers. Knowing the propagation velocity of the radar-wave (v) and the travel-time distance (Δt) to and from the target, the thickness can be derived using Eq. (1):

$$d = v \times \frac{\Delta t}{2} \tag{1}$$

where the thickness is coincident with the distance travelled by the radar-wave (*d*).

The calculation method explained above has been included to the library as reflected in Algorithm 1:

Algorithm 1.

```
for(int i = 0; i < layers - 1; i ++){
    for(int j = 0; j < traces; j ++)
        thicknessMatrix->at(i).at(j) = speed.at(i) * posDiffMatrix.at(i).at(j) / 2;
}
```

The same longitudinal profiles extracted in time can also be exported in terms of amplitudes, which are created by following the location of the maximum signal peaks thorough the entire GPR profile. By knowing the amplitudes at the interfaces and the travel-time distances between reflections, it is possible to estimate the layer dielectric constants and thicknesses. The first step in the process is determining the dielectric constants for each layer. The amplitude of the incident GPR signal and the amplitudes of the layer returns are necessary for the calculations (Eqs. (2) and (3)). In particular, the amplitude of the incident GPR signal is determined by collecting GPR data over a large flat metal plate placed on the pavement surface either at the beginning or at the end of the GPR survey [22]. Because metal is a good conductor, it can be considered as a perfect reflector.

$$\varepsilon_a = \left[\frac{1 + \frac{A_1}{A_m}}{1 - \frac{A_1}{A_m}}\right]^2 \tag{2}$$

where;

ε_a dielectric constant of the first layer
A_1 amplitude of the reflection from the surface
A_m amplitude of the reflection from a large metal plate.

$$\varepsilon_b = \varepsilon_\alpha * \left[\frac{1 - \left(\frac{A_1}{A_m}\right)^2 + \frac{A_2}{A_m}}{1 - \left(\frac{A_1}{A_m}\right)^2 - \frac{A_2}{A_m}}\right]^2 \tag{3}$$

where;

ε_b dielectric constant of the base layer
A_2 amplitude of the reflection from the base.

Next, the amplitude profiles are transformed into layer thickness profiles as follows:

$$d = \frac{c \times \Delta}{\sqrt{\varepsilon}} \tag{4}$$