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A combined strategy for landmine detection and identification using synthetic GPR responses

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ABSTRACT

Synthetic Ground Penetrating Radar (GPR) target responses may be successfully used for buried landmine classification purposes. This paper demonstrates that accurately simulated one-dimensional temporal signatures can be employed as reference waveforms for efficient clutter suppression and improved target detection/recognition. The proposed methodology is a combined approach consisting of a cross-correlation based identification algorithm and an energy based detection algorithm. The former can be implemented before conducting the detection as an additional filtering step in the form of a similarity constraint between measured and synthetic scattered signals. The application of the combined method to experimental data yields a clear gain in the detection sensitivity, particularly for those mines which are most difficult to detect through scattered energy considerations alone. Moreover, an adapted Inverse Distance Weighted (IDW) averaging has been incorporated to enhance the quality of the imaging and to rise the Signal-to-Clutter ratio (SCR) of the resulting maps. This strategy can help to substantially reduce the number of false alarms and speed up the clearance labors.

1. Introduction

Antipersonnel mines (APM) represent one of the worst kinds of global pollution. The use of conventional metal-detectors in demining operations may become particularly slow and inefficient because of the low-metal content of several modern landmines and the presence of abundant metallic scrap in battlefields. Therefore, alternative methods have been intensively investigated in the past years. The Ground Penetrating Radar (GPR), which is a very popular tool for underground noninvasive imaging, has demonstrated good potential for the detection of all types of landmines due to its sensitivity to any contrast in the electromagnetic properties of the soil (Daniels, 2007). Nevertheless, the detection of plastic landmines with GPR remains a challenging task: the weak responses produced by the low-contrast small mines are frequently obscured by other undesirable effects (clutter) from antenna coupling, system ringing and rough surface/inhomogeneous soil reflections.

There are different processing techniques to overcome the problem of landmine detection and identification in realistic scenarios. For target detection a model of the background can be defined and all the reflections that clearly differ from the estimated background signal are declared as targets (Gader et al., 2004). Some methods that have shown good potential to take the target/background decision and reduce the clutter are for example a statistical binary hypothesis testing (Uschkerat, 2000), wavelet transform (Carevic, 2000) or independent component analysis (Karlsen et al., 2002). Another strategy, which is the one followed in this paper, is to establish a clutter level according to the average amount of scattered energy at each depth, and the detection is called when a cluster or a single pixel supersedes sufficiently this level. However, it must be noted that all these approaches are not capable of discriminating between a landmine and other reflectors present in soil (such as munition fragments, roots, stones), hence the false alarm rate increases and additional processing becomes necessary to identify anomalies. Regarding target classification, the common approach relies on defining a target model given by a target feature vector which is searched in the GPR data (Potin et al., 2006; Shao et al., 2013). These vectors may be based on single one-dimensional (1D) target echoes or on characteristic 2D or 3D target traces spread along the scans. The search of scattering features in the data can be implemented in different ways, including Fuzzy Logic approaches (Wilson et al., 2007), Neural Networks (Yang and Bose, 2005), Markov Models (Gader et al., 2001) or Support Vector Machines (Massa et al., 2005; Shao and Bouzerdoum, 2011).

This work presents a signal processing procedure which involves target models based on the shape of the scattered 1D signals (A-scans) in a first recognition phase, and an energy-based detection algorithm which takes into account the amplitude information in a second phase. The outputs from both algorithms have been improved by IDW averaging where the attribute value of each individual pixel is substituted by a properly weighted average value of the information contained in it and within its surrounding area.

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The organization of the paper is as follows. Section 2 is a brief introduction to some GPR modeling issues concerning the software and the GPR model utilized to synthesize the radar responses. Section 3 contains the measurement details regarding the test site characteristics, the buried targets and the acquisition parameters. Section 4 describes the recognition and detection algorithms as well as the combined processing strategy together with the achieved results. Finally, the conclusions are presented in Section 5.

2. GPR modeling

Since analytical solutions of the GPR problem are restricted, numerical forward modeling is crucial to compute synthetic responses. A reliable estimation of the radar echoes and performance in general (especially in near field conditions), requires to model simultaneously all the elements in the GPR scene, i.e. antennas, soil and targets, in an accurate way. Only then, a direct comparison between simulated and measured signals is possible.

The synthetic signatures for this work were obtained using COMSOL, a finite element method based commercial tool for multiphysics modeling which is suitable for solving complex GPR scenarios. The equipment employed for the experimental investigation is an impulse GPR system built by ERA Technology and 2 GHz emission bandwidth.

In particular, the antenna unit consists of two identical bowtie–dipole antennas placed side-by-side and enclosed in a shielding case filled with absorbing material. In order to introduce the real illumination in the COMSOL simulations, the radar antenna model was optimized and validated by means of laboratory measurements (in free space) until a satisfactory agreement between measured and synthetic responses was reached (Gonzalez-Huici and Uschkerat, 2010). Together with a precise antenna model, exact CAD representations of the targets and realistic soil characteristics were included in the GPR model.

3. Measurements

3.1. Test site description

To assess the performance of the proposed approach in realistic conditions, a measurement campaign was carried out in a prepared test field of the Leibniz Institute for Applied Geophysics (LIAG) in Hannover (Germany). A picture of the field is shown in Fig. 1 where arrows point to the lane where the targets were buried. In the left side of the figure, there is a detailed layout of the test area. Here the red squares correspond to 1 × 1 m survey areas scanned in every measurement. The targets in the left line (red points with odd numbers) are buried approx. 5 cm depth and the targets in the right line (red points with even numbers) lie approx. 10 cm depth. The bold lines with numbers starting in 200 and 300 respectively, designate the plastic rails at the borders of the test lane and the reference positions for the measurements in centimeters. The zero point of the coordinates is located on the right corner of the left rail and it is indicated with a red circle.

The grassy surface presented moderate roughness and the soil texture was sandy and highly inhomogeneous due to the presence of organic material, stones, etc. Hence, the resulting non constant moisture content and irregular upper subsurface, led to a notorious variability of the electrical parameters (in particular the permittivity), elevating significantly the clutter contributions in our radar data.

The dielectric constant was measured at three different days in August and September with a Time Domain Reflectometer (TDR) along a 12 m long line every 10 cm. The average value oscillated between 4.6 in August and 10.1 in September with ~15% standard deviation and correlation length of ~20 cm. The days of the campaign the average permittivity was around 7.

3.2. Acquisition parameters

The main acquisition parameters during the LIAG campaign are summarized in Table 1.

3.3. Test targets

In the referred test field, there were four different buried targets: three landmine simulants (PMN, PMA-2 and Type-72) and a Standard Test Target (ERA test target). In this study the focus is especially on three of them: the PMN simulant, the Type-72 simulant and the ERA test target, whose pictures and the corresponding CAD models used for the simulations are illustrated in Fig. 2.

4. Methodology and results

The proposed approach is a processing methodology consisting of a target recognition technique and an energy based detection technique which can be applied separately or in combination (see Fig. 3). More specifically, the recognition algorithm incorporates a similitude constraint that sets equal to zero those traces which locally deviate from the target model in a relevant manner; in this way, the significant data volume is reduced and several undesired echoes (clutter) are suppressed. On the other hand, the detection algorithm determines the average energy value for every depth slice (C-scan) and then, those pixels whose amplitudes are not sufficiently above this value are set to zero. Thus, the contributions which may be associated to noise even if they present a high correlation degree with a reference target, are eliminated. The last step is to perform the sum of all the resulting C-scans over a certain time interval in order to get the final detection maps.

Additionally, a weighted averaging is applied to the data in order to improve the performance of the strategy.

4.1. Recognition

In order to simplify and accelerate the target recognition procedure, the proposed algorithm uses single one-dimensional (1D) scattered signals. These waveforms are employed in the similarity assessment.

4.1.1. Cross-correlation

A measure of the similarity between a given signal $u(t)$ and a reference $v(t)$ is well-known by means of their cross-correlation function,

$$R_{uv}(\tau) = \int u(t-\tau)v(t)dt = u(-t) * v. \tag{1}$$

This function determines the analogy between two non-identical waveforms as a function of the time shift τ between them and can reveal similarities undetectable by other techniques. The cross-correlation can be approximated via the sampling method:

$$R_{uv}(\tau) = \frac{1}{N}\sum_{n=1}^{N} u(n\Delta t-\tau)v(n\Delta t). \tag{2}$$

Table 1
GPR system acquisition parameters.

GPR type	Impulse radar
Central frequency	2 GHz
PRF	1 MHz
Pulse length	0.5 ns
Sampling time	25 ps
Spatial sampling in X/Y	1 cm/4 cm
Antenna height	5–9 cm
Antenna configuration	Perpendicular broadside
Samples/scan	512/A-scan