APPLICATION OF GROUND PENETRATING RADAR TECHNOLOGY FOR NEAR-SURFACE INTERFACE DETERMINATION IN COAL MINING

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ABSTRACT

The use of ground penetrating radar (GPR) for detecting near-surface interfaces is a scenario of special interest to the underground coal mining industry. The problem is difficult to solve in practice because the radar echo is often dominated by unwanted components such as antenna crosstalk and ringing, ground-bounce effects, clutter, and severe attenuation. These nuisance components are also highly sensitive to subtle variations in ground conditions, rendering the application of standard signal pre-processing techniques largely ineffective in the unsupervised case. As a solution to this problem, we develop a novel algorithm which utilizes a pattern recognition-based approach using features derived from the bispectrum of the radar data. We show that, unlike traditional second order correlation based methods such as matched filtering which fail in known conditions, the new method reliably allows the determination of layer interfaces using GPR to be extended to the near surface region.

1. INTRODUCTION

1.1. The Coal Mining Industry

One of the current challenges with automating underground coal mining machinery is measuring and maintaining a coal mining horizon [1]. In underground coal mining there is an optimal remnant coal layer thickness between the roof/floor and surrounding strata which provides structural support to the roof and minimizes the recovery of impurities close to the surrounding strata. The key advantages of leaving the optimal coal thickness are the reduced risk of roof fall and improved quality of the extracted product [2].

There are two main categories of horizon control sensors in underground coal mining – reactive and predictive. Reactive sensors are based on detecting changes in the mining operational characteristics when the coal/clay interface is encountered. The reactive sensors are limited as the miner has already cut into the surrounding strata when the interface is detected which damages the machinery and dilutes the coal. Predictive approaches however sense the remnant coal thickness before it is mined and thus allow for optimal mining to improve productivity and increase safety [2]. One sensor that has shown promise as a predictive sensor for horizon control is ground penetrating radar (GPR). There are many applications that use GPR for sub-surface imaging such as buried landmine detection, pavement evaluation and forensic investigations [3]. For horizon control strategies in coal mining, it is useful to automatically present coal seam thickness information in simple forms that are readily usable. Thus the objective of this work is to process the GPR data into three classes - 0cm (no coal), between 0cm and 5cm, and greater than 5cm.

1.2. Ground Penetrating Radar

GPR is a non-intrusive technique used to determine information about media beneath the earth's surface. In impulse GPR systems a short pulse (nanoseconds) of electromagnetic energy is transmitted into the ground. A proportion of this energy is reflected back towards the surface at interfaces of media with differing electromagnetic parameters (permittivity, permeability and conductivity). The amplitude and time delay of these reflections are used to determine information about the sub-surface.

2. COAL INTERFACE RADAR PROCESSING

2.1. GPR Signal Model

The received signal of an impulse GPR system can be modeled as the superposition of attenuated and delayed replicas of a known signal $s_o(t)$ for each interface plus nuisance components such as the background signal and noise, i.e.,

$$s(t) = d(t) + \sum_{m=1}^{M} a_m s_o(t - \tau_m) + n(t), \qquad (1)$$

where $s(t)$ is the received signal, $s_o(t)$ is the transmitted signal, $d(t)$ is the background signal, $n(t)$ is additive noise, M is the total number of interfaces, a_m is the peak amplitude of the reflection from the m^{th} interface, τ_m is the time delay of the reflection from the m^{th} interface [4] and $t=0,1,\ldots,N$ where N is the discrete-time signal length.

The signal component of interest in this work is the background signal $d(t)$. The background signal includes the unwanted signal components such as ground bounce, antenna crosstalk and ringing. The ground bounce is the echo returned from the air/ground interface when the antennas are not directly in contact with the ground surface. The antenna crosstalk is the signal that propagates from the transmitter directly to the receiver when the antennas are beside each other. The antenna ringing is caused primarily by the re-radiated fields due to currents reflecting within the antenna and associated structures [5].

These nuisance components, in particular the antenna crosstalk and ringing, always dominate the start of the GPR trace which is where echoes from near-surface interfaces will be. Any processing must be invariant to the effect of these nuisance components before it is useful for practical applications.

2.2. Existing Approaches to the Problem

A common approach employed in an attempt to minimize the effect of the nuisance signal components is to keep the antennas a predetermined distance above the ground during operation. This way the ringing and crosstalk attenuate to below the system noise floor before the target reflections are received. However, only intrinsically safe GPR systems can be used in the underground coal mines as it is a hazardous and flammable environment [2], so only a low power unit can be used. Hence the antennas must be ground-coupled with the coal mine surface so the maximum amount of energy propagates into the medium.

2.3. Existing Processing Techniques

Traditional techniques for interface detection and depth estimation using GPR involve matched filtering and layer stripping [6]. This is a straightforward task when the targets are well separated spatially relative to the wavelength of the transmitted signal and deep enough that the echoes are not masked by the antenna crosstalk and ringing. However, for near-surface interface determination the typical time support for radar signals is of the order of 2ns. This translates into a return propagation distance of 15cm in a medium with relative permittivity of 4 (typical for coal). This is a measure of how shallow an interface can be before a matched filter detector begins to fail. Depending on site conditions, the optimal remnant coal thickness is of the order of 3cm to 5cm for longwall underground coal mining. Thus the standard matched filter technique will fail to provide a satisfactory solution to the problem.

3. BISPECTRAL FEATURE EXTRACTION

The power spectrum is often used as an analysis tool for GPR data [7] because it is simple to apply. However, important information contained in the phase of the radar signal is lost because power spectral representation is a second order measure. This limitation motivates the exploration of higher order spectral processing for this radar processing task as the phase information is retained [8].

The bispectrum has been used as a feature vector to classify one-dimensional shapes [8]. Balan and Azimi-Sadjadi [9] have investigated the use of the bispectrum to detect and classify buried landmines with two-dimensional GPR data. This paper presents a new technique to detect the presence of an interface close to the earth's surface using bispectral features of one-dimensional GPR data.

The bispectrum $B(f_1,f_2)$ of the background discrete-time sequence, $d(t)$, is defined as

$$B(f_1, f_2) = D(f_1)D(f_2)D^*(f_1 + f_2), \qquad (2)$$

where $D(f)$ is the discrete-time Fourier transform of $d(t)$ and * is the complex conjugate operator. Due to symmetry, the bispectrum is defined in the triangular region, $0 \le f_2 \le f_1 \le f_1 + f_2 \le 1$, provided there is no bispectral aliasing [8].

To obtain a feature that is invariant to translation, amplification, scaling, and DC offset, the bispectrum must be integrated. The phase $P(a)$ of the integration having these invariant properties is integrated along lines with slope *'a'* as shown in Figure 1. To obtain the feature values of the parameter, the values of *'a'* are chosen to be evenly spread between 0 and 1. In practice, the value of *'a'* which provides the most discrimination between the two classes is the best choice for a single feature. If multiple features are used (including the use of both magnitude and phase), the problem of choosing the optimal combination requires an effective measure of discriminability or error statistics on data used to determine this. In this work an examination of the bispectrum and its variations on the bifrequency plane for the different classes was used to choose *'a'* = 1. However, for most data there may not be significant difference in results obtained for other values of *'a'* less than 1.

The time domain data has N=500 samples, of which the first 128 samples were windowed using a Hamming window. This segment contains the main component of the crosstalk and ringing, and the shape of this segment varies when targets are close to the surface. The bispectrum is computed and the integration is performed. The result of this integration is complex whose phase parameter, $P(a)$, with its invariant properties is generally chosen as the feature vector [8], [9]. To achieve better class separation, the magnitude of the integrated bispectrum was also chosen as a feature.

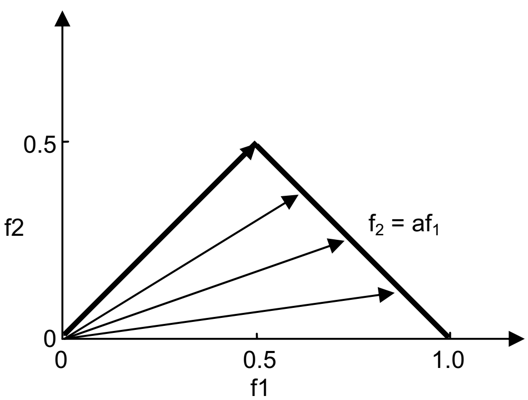

Figure 1. The bispectrum is integrated along lines with slope 'a' chosen to be spread evenly between 0 and 1. When four parameters are computed, the values for *'a'* are 0.25, 0.5, 0.75 and 1.

4. EXPERIMENT

The unit used for the experiment was custom built by CSIRO for coal mining applications [10]. It is an approved intrinsically safe impulse GPR system with pulse duration of 1-2ns. The bi-static antenna module consists of two bow-tie antennas with centre frequency of 1.4GHz. A typical raw waveform from this GPR is shown in Figure 2.

A testbed with layers of coal, shale and clay was constructed to obtain real GPR data. The testbed dimensions are 2.4m × 2.25m × 0.8m deep with three layers of various thicknesses and depths. The coal surface is relatively flat whereas the clay layer has 14 steps at different depths. The shale was put in 8 of the 14 regions as a thin layer of slight contrast to the coal.

Ground truth layer depths were obtained by measuring the interface profiles at 20cm intervals and at region boundaries. The coal layer thicknesses in the testbed range from 0cm to 37cm while the shale layer varies between 2cm to 7cm.

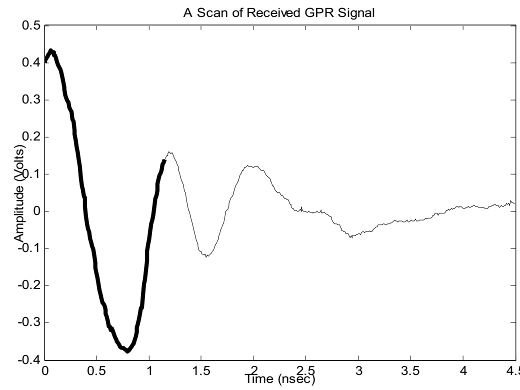

Figure 2. Typical raw signal obtained using the GPR system. The first segment of this signal consists of the antenna crosstalk and ringing. The thick line represents the segment used for bispectral feature extraction.

The coal and clay were wet, which represents a typical coal mine in Australia. This increases the electrical permittivity and conductivity of the media reducing the probing depth due to signal attenuation. In the underground coal mine, the water content in the coal arises from the longwall coal mining process where water is sprayed onto the coal face and longwall shearer drum to cool the picks and suppress dust.

5. RESULTS

The experimental results can be broadly classified into three classes according to the coal layer thickness (coal/clay interface depth): 0cm (no coal present); between 0cm and 5cm (thin coal layer); and greater than 5cm. The significance of these classes is related to what action the longwall coal miner should take. If there is no coal remaining, the miner has mined too far and the surrounding strata has been hit. If the coal is between 0cm and 5cm, the optimal amount of extracted coal has been reached. If the coal thickness is greater than 5cm, more coal can be extracted. Figure 3 shows the integrated bispectral magnitude versus phase for these classes.

In Figure 3, the cluster of asterisks on the left side is the feature values obtained from the clay interface (no coal present). The cluster of squares at the top right is the feature values obtained from a coal depth of on average 40mm. This cluster would be classified in the "remnant coal thickness between 0cm and 5cm" class. The two clusters in the center from right to left (triangles and circles) were from an average coal depth of 60mm and 100mm respectively. These two clusters would be classified in the "remnant coal thickness greater than 5cm" class. The separation of these clusters indicates the technique shows promise as a near-surface interface detector.

The wet clay has higher conductivity than coal resulting in higher signal attenuation of both nuisance components and echoes. This is why the magnitude of the left cluster is closer to zero than the other clusters where the attenuation is not as significant.

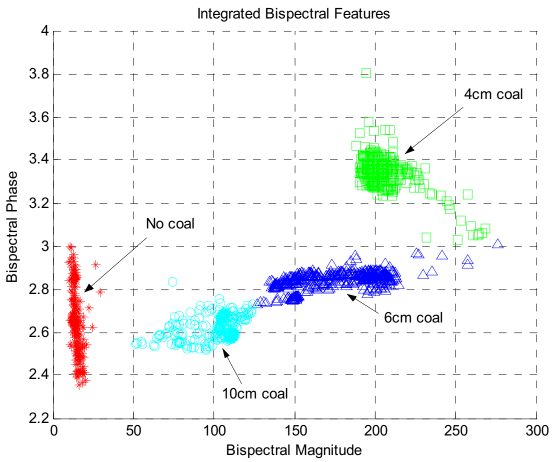

Figure 3. The bispectral feature values for varying coal layer thicknesses with a coal/clay interface. The four clusters relate to remnant coal thicknesses of 0cm (no coal), 4cm, 6cm and 10cm.

At the commencement of the mining operation, the coal/clay interface should not be within range. As mining progresses the coal thickness will decrease and reflections from the interface should alter the shape of the signal segment from which the feature value is being computed. It is during this time that the feature values should approach a decision boundary according to the desired depth at which mining is stopped. This is to prevent the cutting of the clay.

6. CONCLUSION

This paper has presented a novel algorithm for classifying near-surface interface features using GPR. This scenario is of special interest to the underground coal mining industry for automating horizon control systems. The bispectral-based method works in situations where traditional second order matched filter techniques fail. The results have been validated with real data obtained from a testbed with layers of coal, shale and clay, with features successfully classified into three well separated clusters of coal thicknesses of 0cm, 0cm to 5cm, and greater than 5cm. This outcome is of practical interest to the underground coal mining industry as it allows for the reliable, in-situ monitoring of subsurface features. It also represents an important enabling technology for improving safety and productivity for both personnel and plant.

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