APPLICATION OF GROUND PENETRATING RADAR FOR COAL DEPTH MEASUREMENT

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ABSTRACT

This paper describes the development of a new ground penetrating radar system for measuring coal thickness in underground mining operations. Although subsurface radar exhibits significant potential for depth measurement, the raw signals are complicated and cannot be readily interpreted by mining personnel. We show how real-time digital signal processing plays a key role in transforming the raw radar signals into a form that can be readily understood. We also indicate some of the unique challenges encountered when implementing a radar processing system in a harsh underground mining environment.

1. INTRODUCTION

One of the common problems encountered in underground coal mining operations is measuring and maintaining a coal mining horizon [1, 2]. For a given mining task, there is an optimal remnant coal thickness between the roof/floor and surrounding strata which provides sufficient structural support while avoiding unnecessary product waste. If the remnant coal is too thick, permanently unrecoverable is left. If the layer near the roof is too thin, it can greatly increase the risk of roof fall [3]. Consequently there exists a real need for a reliable coal depth measurement system.

Ground penetrating radar (GPR) has recently found application for subsurface characterisation in civil engineering, ordnance detection, and geotechnical fields [4]. The central attraction of GPR is that it is non-invasive and non-destructive, and can provide instantaneous imaging of subsurface features [5]. There are currently no commercially available radar-based measurement systems for use in underground mining. In addition, most GPR systems do not provide automated real-time processing capabilities, and so rely on trained operators to manually interpret the raw radar data in an off-line capacity.

Therefore a key requirement in the successful implementation of a coal measurement system is the use of signal processing to transform the raw radar data into a form that can immediately be utilised by non-expert personnel.

In Section 2 we describe the coal depth estimation problem using subsurface radar. Section 3 focuses on data processing issues, where we present a GPR data model and highlight the steps required in obtaining coal depth estimates. Section 4 describes the GPR system as a whole and highlights some of the practical issues associated with the development and implementation of the GPR processing system in the coal mining industry.

2. THE GPR BASED MEASUREMENT SYSTEM

2.1. Coal Strata Configuration

Figure 1 shows a typical scenario encountered in underground coal mining, where mining is carried out above a layer of weathered clay, called *tuff*. Here our goal is to estimate the depth of the remaining coal using a GPR system. The coal floor measurement scenario is illustrated here, but the concept equally applies to roof thickness determination.

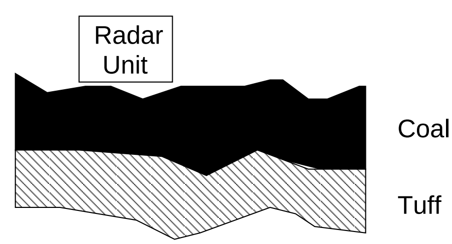

Figure 1: Typical coal strata configuration encountered in underground mining. The black upper band represents coal and the lower band represents tuff. The radar unit is in contact with the coal floor.

2.2. Radar Imaging Principle

In GPR, electromagnetic waves propagate downward from the radar transmitter into the ground and then scatter/reflect at dielectric boundaries. The magnitude of the received reflection is dependent on the ground conductivity and permittivity, the size and shape of the target, and the degree of discontinuity at the reflecting boundary. Voids, cavities, and other dielectric interfaces represent discontinuities which can give rise to pulse echoes. The geological features typically found in coal-bearing strata are particularly amenable to radar imaging. This is because coal has a relatively low conductivity and high dielectric constant with respect to its host strata.

The GPR sensor itself is moved over the coal surface either manually for a "snapshot", or mounted on the mining machine for a continuous display. This latter configuration results in a characteristic 2D array of time/delay verses radar displacement, as shown in Figure 2. Clearly additional processing of the raw returns is required in order to extract coal depth information for monitoring, guidance, and control.

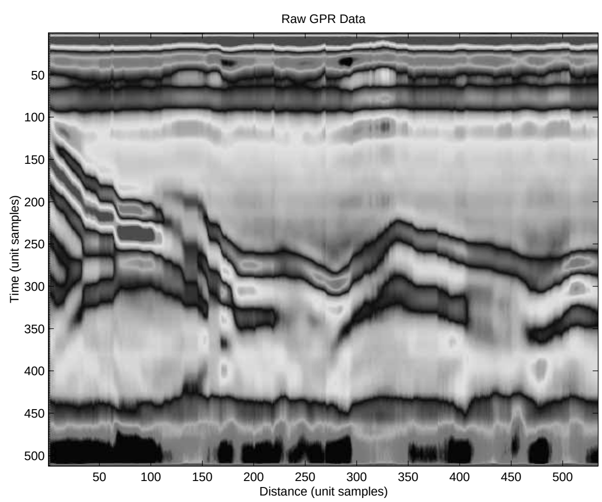

Figure 2: Raw GPR signals. The vertical axis is time delay, and the horizontal axis is distance.

3. GPR SIGNAL MODEL AND PROCESSING

The GPR-based measuring concept assumes that the coal thickness can be inferred by estimating the coal–host rock propagation delay. We first derive a model for the received radar signal by considering the physical arrangement of the imaging scenario. The resulting equations lead to the associated processing tasks.

3.1. Radar Signal Model

The received radar signal can be modelled as

$$Z_k(t) = W_0(t) + \sum_{m=-M}^{M-1} W(m) R_k(t-m) + N_k(t)\,, \quad (1)$$

where $W_0(t)$ is the radar-air coupling pulse, $W(m)$ is a lumped impulse response of the radar wavelet[1], M specifies the temporal support of the (two-sided) wavelet, and $N_k(t)$ is an independent noise process for time $t = 0, \ldots, T-1$, and realisation index $k = 0, 1, \ldots$. The sequence $N_k(t)$ includes sensor and timing jitter noise. $R_k(t)$ is given by

$$R_k(t) = \sum_{n=0}^{p_k-1} a_k(n) \delta(t - \tau_k(n))\,, \quad (2)$$

where $a_k(n)$ is the magnitude of the echo and $\tau_k(n)$ is the pulse echo time delay for $n = 0, \ldots, p_k - 1$. Equation (1) therefore represents the convolution of the basic pulse wavelet with the (scaled) reflection coefficients. Note that $R_k(t)$ is analogous to the reflectivity series found in seismic imaging [5, 6]. In a given radar signal observation $Z_k(t)$, there may be $0 \leq k \leq p_k$ interfaces present. The underlying goal is to estimate $\tau_k(n)$ and p_k, and in particular the first reflection, from observations of $Z_k(t)\ \forall\ k$.

[1] This is an approximation since the pulse shape can vary depending on the material being imaged [5].

3.2. Radar Signal Processing

Figure 3 shows the four basic stages involved in processing the raw radar data: preprocessing, filtering, detection, and estimation. This includes time-varying gain for path loss compensation, suppression of radar-air coupling characteristic, wavelet deconvolution, delay and displacement domain filtering, short-term ensemble averaging, energy detection and peak location.

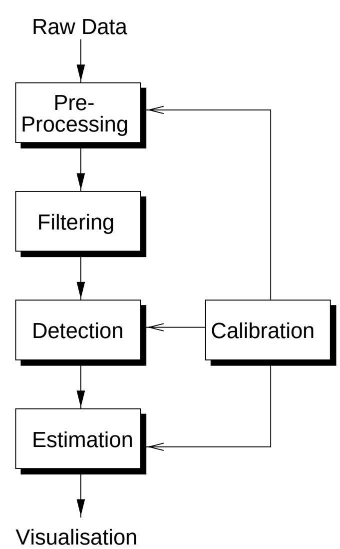

Figure 3: A block diagram showing processing applied to the raw radar data to provide coal depth estimates.

3.2.1. *Preprocessing Stage*

There are two preprocessing steps used. The first step is to apply an exponential gain to the received signal to compensate for the basic radar attenuation characteristics through earth material. This time-varying gain considerably extends the dynamic range of the system and has the effect of removing the time dependency of $a_k(t)$ in (2), i.e, $a_k(t) \approx a_k$, $\forall t$. Although this transformation results in a noise process with time-dependent variance, the worst case SNR is still relatively high.

The second processing step is to remove the transmitter–air/receiver coupling characteristic. Figure 4 shows a typical free-air coupling characteristic from the impulse radar. An estimate of $W_0(t)$ in (1) is made during initial system calibration by computing an ensemble average of $Z_k(t)$ over k assuming stationarity over the calibration interval.

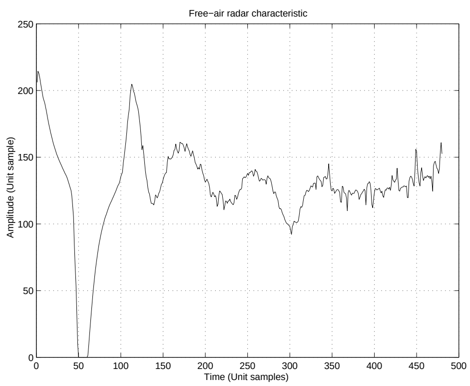

Figure 4: Typical radar–air coupling characteristic of the impulse radar directed into free space.

3.2.2. Filtering Stage

Since the motion of the mining machine is physically constrained, it follows that

$$Z_{k+\nu}(t) \approx Z_k(t) \tag{3}$$

is a good approximation for small ν. This property permits lowpass filtering in the displacement domain, which serves to suppress artifacts arising from radar timing jitter. Lowpass filtering in the time/delay domain over a filter support $\leq M/2$ also proves particularly effective in suppressing the effects of sensor noise and machine vibration.

To improve the detection power, the radar data is deconvolved with a regularised inverse [7] obtained from a suitable estimate of the basic radar wavelet $W(t)$. Note that the small phase shift due to causality considerations is accounted for in the final time-delay estimate.

3.2.3. Detector Stage

The processed data is passed through a detection stage to determine potential dielectric interfaces. A time-domain sliding window energy detector of support $< M$ is implemented at each instant k. The output of the energy detector is then compared to a threshold previously determined empirically from field tests and calibration. If the detector output exceeds the given threshold, an estimate of the average two-way travel time $\tau_k(n)$ is then made by computing the median of the resulting set of (sequentially ranked) indices within the domain of the energy window. An estimate of p_k is obtained by noting the number of distinct grouping of peaks in a given realisation.

This strategy represents a simple yet effective method for detecting the coal–rock interface in an automatic manner, as well as being computationally efficient to facilitate real-time implementation.

3.2.4. Depth Estimation Stage

Given that the depth of the first echo can be approximated via the average two-way travel time for known site conditions ($\epsilon \approx 4.5$ for coal), an estimate of the coal depth can be given by

$$d_n = \frac{c\,\tau_n}{2\sqrt{\epsilon}}, \tag{4}$$

for $n = 0, \ldots, p_k - 1$. Confidence bounds on the estimate are easily derived empirically following the property in (3). Equation (4) is subsequently used to produce a graphical representation much like Figure 1. Presenting the measurement data in this simplified form greatly increases the acceptance of the technology to mining personnel. The data can also be meaningfully employed in more sophisticated tracking and control schemes.

The efficacy of the basic depth estimation procedure has been corroborated with actual coal depth measurements. It is important to note, however, that the radar data is subject to a wide variety of abberations from the model in (1): Nonlinearities, multiple reflections, heterogeneity variation, moisture variation, sensor and mining machine vibration, operator misuse, and sensor placement all contribute to measurement error.

4. DISCUSSION

4.1. GPR System Configuration

The GPR processing system as a whole consists of three main components: the bistatic radar assembly, the data processing unit, and the visualisation module as shown in Figure 5. A purpose-built wideband (800 MHz) bistatic impulse radar is used to produce a 1-2 ns pulse, which results in high resolution short-range (100 cm) echo data [8]. The system also furnishes a communications link to facilitate remote data access. The radar system uses $T = 500$ data points acquired at 30 kHz (12-bit ADC) at a rate of 50 Hz.

4.2. Flameproof Enclosures

Special design and construction considerations were necessary in order to make the radar processing system suitable for use in the harsh underground mining environment. In

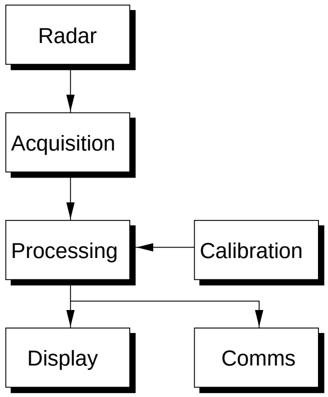

Figure 5: A block diagram showing the main components of the ground penetrating radar system.

particular the system needs to safely operate in the presence of potentially explosive gases.

The signal processing module and display screen are housed in a ruggedised flameproof enclosure with a viewable window as shown in Figure 6. Of special interest is the use of a non-metallic flameproof enclosure for the radar transmitter–receiver assembly. This was obviously required as the use of a metallic enclosure would not permit transmission of the radar signals. The radar enclosure is made of ruggedised epoxy and is interconnected with the main flameproof via an armoured cable.

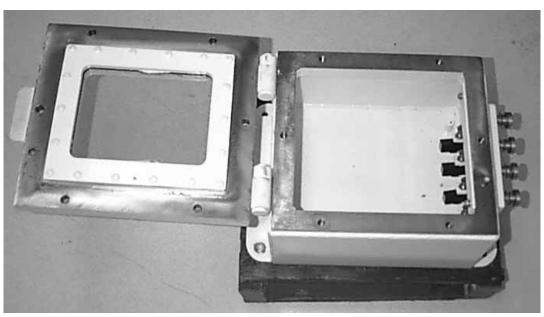

Figure 6: Flameproof enclosure which houses the signal processing and display components of the GPR system. The operator push-button controls are shown on the right.

4.3. Operating Requirements

The GPR system must operate with as little operator intervention as possible (ideally none), be physically robust, comply to intrinsic safety requirements, and facilitate remote software maintenance and data retrieval. As a result, the operator "interface" is limited to four ruggedised push buttons to select calibration and other control functions as shown in Figure 6.

5. SUMMARY

Ground penetrating radar has the potential to solve a range of coal depth estimation problems in the mining industry. A GPR processing system for coal depth measurement has been designed, built, and implemented on an underground mining machine. The first generation radar measurement system developed provides data acquisition, processing, and visualisation of coal thickness estimates in real-time, as well as remote data communication facilities. The continued development of radar signal processing techniques is the key to improving the reliability and utility of the measurement system. Future work includes the integration of GPR with existing predictive and reactive sensors to solve a range of monitoring, guidance and control problems in the underground mining industry.

6. REFERENCES

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