An Industrial Application of Ground Penetrating Radar for Coal Mining Horizon Sensing

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Abstract—**Effective mining horizon sensing is an issue of major importance in the coal mining industry because it directly impacts the productivity and safety of the resource recovery process. However the development of automated mining horizon control capability has been significantly hindered by a fundamental lack of sensing that can reliably measure the coal-strata geological structure in the subsurface. In an attempt to advance practical solutions for this problem, this paper reports on the industrial application of radar technology at a production open cut coal mine. Here the use of ground penetrating radar (GPR) has been extensively evaluated through a series of extensive campaigns for detecting and discriminating subsurface geological strata boundaries. The mining scenario, experimental design, data collection, and validation processes are given in order to demonstrate the efficacy and challenges of using GPR for this horizon sensing application. This tutorial-style paper is intended to assist practical application of radar technology into industry.**

Keywords—ground penetrating radar, horizon control, coal mining, mining automation

I. INTRODUCTION

CSIRO undertakes mission-directed research to promote transformational change in the Australian mining and resource ecosystems. The vision is to secure a clean energy future in order to sustain long term benefits across environmental, economic and societal sectors. A vital component of this strategy has been the development of sensing and automated technologies to achieve safer, more productive and more environmentally sustainable coal mining systems. The coal mining ecosystem accounts for around 24% of employment and 27% of total revenue for the Australian mining sector [1]. Currently the sector is under considerable pressure and so there is a strong need to identify new ways to achieve more productive and more sustainable mining.

One fundamental area of ongoing importance for the industry is the ability to selectively identify and extract the different resources that are co-resident in a given spatial location. In the case of horizontally layered resources, as is often the case in coal mining, this particular problem is referred to as mining horizon control. Horizon control thus refers to the process of achieving a given resource extraction profile during the mining process in order to satisfy a pre-defined strata management and resource recovery strategy.

The key benefits resulting from achieving effective mining horizon control include improved safety and productivity for underground roadway development, longwall mining, and surface operations. Achieving these outcomes is linked to increased coal production rates, enhanced safety conditions for personnel, and reduced mechanical stress on mining equipment.

Realising these benefits depends on the availability of reliable resource information regarding the geometrical configuration the strata in the mining subsurface. However, there are currently very few sensing solutions that can be practically applied to this problem. This lack of sensing capability means that operations must rely on manual monitoring, which may lead to operational challenges in maintaining consistent, optimal mining extraction horizons.

In response to this problem, this paper describes the practical application of ground penetrating radar (GPR) for measuring the subsurface coal-strata geology. Section II provides a brief overview of related subsurface measurement sensors which serves to motivate the use of GPR for this application. Section III describes practical details of experimental configuration and radar deployment at the minesite. Section IV presents a discussion and analysis of the data, outlining some of the key outcomes and challenges.

II. THE SUBSURFACE IMAGING SCENARIO

A. Target Configuration

For this mining horizon sensing application, the primary targets of interest are the horizontal boundaries between the geological coal and strata in the subsurface [2,3]. Fig. 1 shows an idealised model for this subsurface imaging scenario, where distinct boundaries between the differently layer materials are shown at different vertical depths in the subsurface.

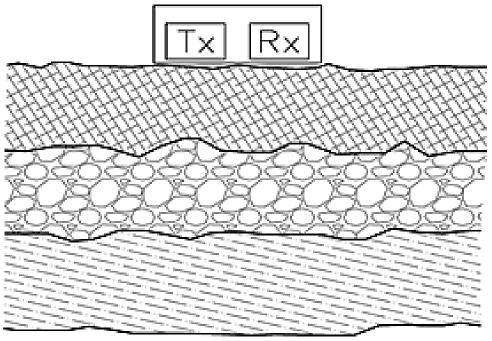

Fig 1. Side view of an idealised subsurface model for horizontally-layed coal-strata geology and sensor location.

B. *Approaches for Geological Subsurface Sensing*

Various sensing methodologies have been investigated in order to find ways to determine the vertical depth of coal-strata geological boundaries [3,4]. These methods include monitoring the mining machine's cutter drum motor current, sensing machine vibration, sensing acoustic and seismic signals, measuring cutter pick temperature with infrared cameras, measuring radioactivity with passive natural gamma sensors, various optical sensing methods, resonant frequency conductance sensing, micro-seismic methods and GPR [4]. These sensing methods can be broadly classified as either active or reactive depending on the mechanism employed to deduce the actual interface structure. GPR falls into the active sensing category as it directly transmits a signal as part of its fundamental operating method [5].

C. *GPR for Subsurface Imaging*

Of these various geophysical sensing techniques, GPR emerges as strong candidate based on its fundamental operating characteristics, subsurface imaging capability, spatial and time resolution, physical size, electromagnetic safety, and functional range. GPR has also been used for a wide variety of applications such as archaeology, civil engineering, hydrology and defence.

GPR utilises the same fundamental time-of-flight measurement principle as in conventional through-air radar, however the radar antennas are placed such that the electromagnetic energy is radiated directly into the ground. When this wave energy interacts with an interface boundary, some of the wave energy may be reflected or scattered. By measuring the (two-way) time period between the transmitted and received waves, and knowing the wave propagation velocity, the distance between the radar and the object can be computed [2,5]. This basic radar distance measurement principle is shown in Fig 2.

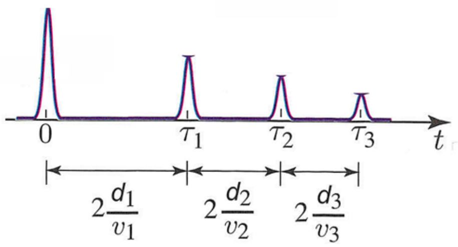

Fig 2. Idealised radar returns corresponding to reflections at the bounaries of horizontally-layed coal-strata geology at spatial positions at d1, d2 and d3.

The specific depth to the target subsurface interface can be determined using GPR as follows

$$d = \sqrt{\left[\left(\frac{vt}{2}\right)^2 - \left(\frac{x}{2}\right)^2\right]} \tag{1}$$

where *d* is the depth to underlying interface, *v* is the wave propagation velocity through the transmission medium, *t* is the two-way travel time of the received electromagnetic signal, and *x* is the distance between the transmit and receive antennas.

The electromagnetic wave propagation velocity in the coal layer can be determined using the fundamental relationship [3]:

$$v = \frac{c}{\sqrt{\varepsilon_r}} \tag{2}$$

where *c* is the speed of light in a vacuum and ε_r is the relative dielectric constant of the host media. The relative dielectric constant can be computed using a range of EM modelling techniques, however in practice it is best determined using either a separate dielectric sensor or via a calibration routine, e.g., using a subsurface target at a known depth. Equations (1) and (2) are then applied to determine an approximate spatial depth of the interface.

A subsurface profile is generated by physically moving the GPR across the ground surface, resulting in a sequence of spatial interface signal returns (ref Fig 2). This idealized subsurface profile is shown in Fig 3 which is often referred to as a radar B-scan image. In practice, however, it should be noted that the returned radar signal tends to be more complicated and the associated interface reflections are not always distinctly identifiable.

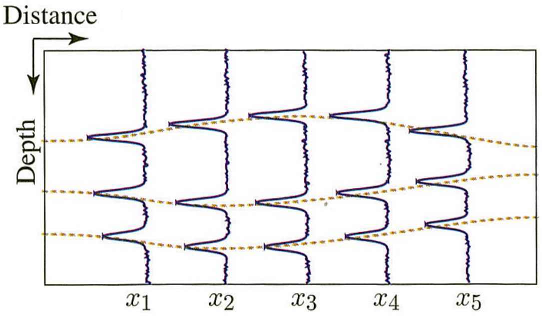

Fig 3. Idealised profile showing a sequence of radar returns generated as the GPR is moved across the ground surface.

D. *GPR System Used for Field Surveys*

For this minesite application, a commercial available cart-mounted GPR system was used as it provided a very convenient means to acquire raw subsurface radar data. This effectively provided an UWB (or impulse) radar with a bistatic bow-tie antenna configuration deployed in ground contact mode. This system was manually pushed along a series of grid lines to cover a given survey area. Fig. 4 shows an operator using a commercial GPR system for the minesite surveys.

Typically the GPR system acquires and displays the radar data with minimal processing and thus separate steps consisting of post-processing and interpretation must be later conducted in order to generate meaningful subsurface information.

III. MINESITE GPR SURVEY CAMPAIGN

A field survey at a production mine was conducted at the New Acland site operated by New Hope Group which is located north-west of Oakey, Queensland. The coal deposit at the New Acland site is in the Acland-Sabine sequence, located within the Clarence Moreton Basin.

The particular coal deposit contains six seam groups designated A-F, with up to ten plies in each group. The coal is banded and the average thickness of the individual plies is 0.23 metres [6], providing an ideal opportunity GPR performance evaluation in a practical mining context.

Fig 4. Deployment of commercial cart-mounted GPR antenna and controller system at an open-cut coal mining operation.

A. Goals and Methodology

The primary goal of the field evaluation at the New Acland site were conduct a series of extensive surveys using GPR and to then validate through ground truth information gained by visually inspecting exposed benches of the survey area.

The specific experimental methodology for this site campaign involved the following key steps:

1. Identify a survey area consisting of typical coal geology away from immediate production mining for safety and convenience.
2. Prepare a series of tiered benches at the survey area to enable visual inspection of the subsurface geology.
3. Scan along identified sections and estimate surface permittivity using a dielectric sensor.
4. Manually excavate small areas and insert metallic targets into the scanning area to validate echo detection methods with known targets.

B. Experimental Design Approach

For the GPR subsurface data validation task, a tiered bench design concept was proposed for the survey area (see Fig. 5). This provided an ideal way to visually inspect the otherwise non-visible subsurface seam structure to gain critical ground truth information necessary for GPR signal validation.

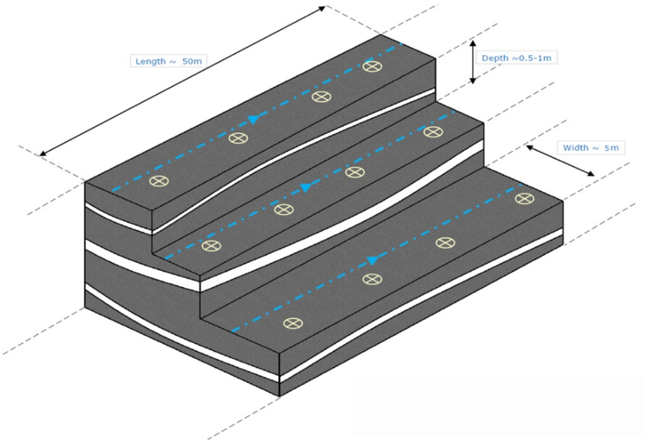

Fig 5. Concept drawing of tiered benches for the survey area designed to enable visual inspection of the subsurface geology.

C. GPR Survey Process

The survey area prepared at the New Acland minesite consisted of four benches located within the B seam group. These benches are referred to as Bench #1, Bench #2, Bench #3 and Bench #4, respectively, labelled in order of increasing elevation. Each bench was approximately 70m long and 5m wide. This allowed for scanning sections on each bench of 50m in length. Fig. 6 shows the actual constructed testing configuration on site (compare with idealised Fig. 5).

Fig 6. Photo of multi-tier configuration excavated for the GPR evaluation.

GPR data was collected through a series of detailed surveys of each of the four tiers of the bench configuration. The geology of each bench was obtained through manual inspection and site core logs. A photo of the side profile of Benches #1 to #4 (obtained from a nearby highwall) is shown in Fig. 7. Note that the thickness values given here are approximate and vary throughout different sections of the seam. The subsurface of Bench #1 was not exposed, however, a small section of the coal surface and underlying stone band was excavated manually to obtain a ground truth measurement at that location. The thickness of the coal layer beneath the stone band of Bench #1 was inferred from core logs of the seam.

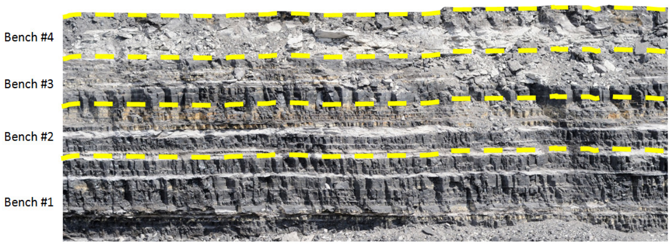

Fig 7. Photo of a highwall in close proximity to the survey area showing the layered geological structural profile of the surveyed benches. The yellow dashed lines represent the approximate ground surfaces scanned by the radar equipment.

IV. RESULTS AND INTERPRETATION

A. Data Processing and Inference

The GPR survey data was collected on Bench #1 with 900, 400 and 270 MHz antennas with the aim to estimate the thickness of the 15cm coal layer above the 5cm stone band. Fig. 8 summarised a single bench scan and shows the raw, processed, interpreted data collected a 900 MHz antenna along with thickness estimates and uncertainty levels. The top layer thickness was estimated to be close to 15cm at the point of excavation (6m) indicated by the red point, which is in good agreement with the measured thickness of 15cm at that location.

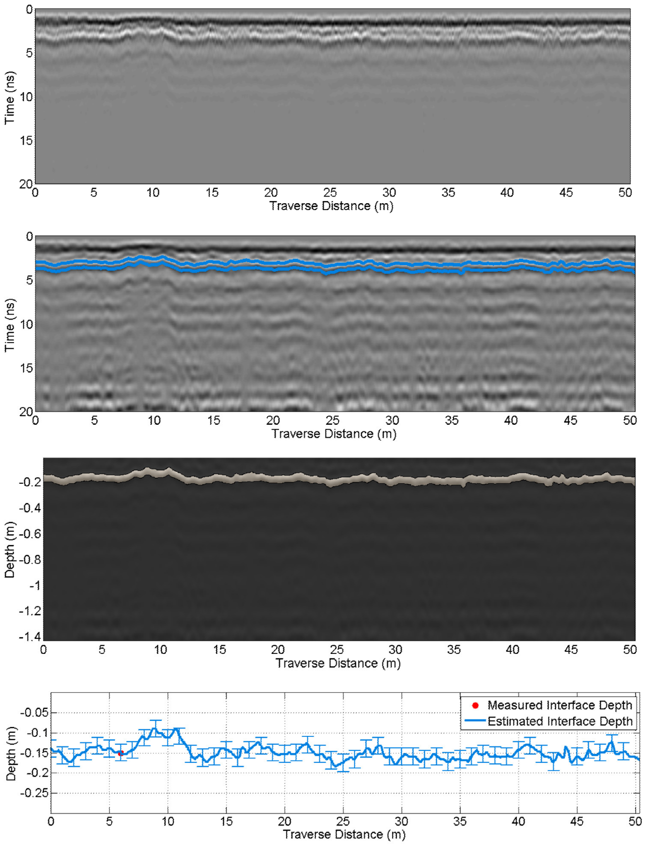

Fig. 8. Images of GPR data collected along Bench #1 using a 900 MHz antenna. The first image shows the raw data, the second image shows the processed data with blue lines representing the detected interfaces, the third image shows a simplied view after interpetation, and the fourth image shows the estimated and measured top layer thickness with error bars representing estimate uncertainty.

B. Key Observations and Outcomes

After completing the field evaluation at New Acland, it was clear that the best subsurface penetration performance was achieved when the antennas were used in direct contact with the ground, even when lower frequency antennas were used in the air-coupled configuration. Of the GPR equipment evaluated, the 900 MHz bow-tie, ground coupled system provided the best results for this geology when the coal-stone interface was in the order of 15cm deep [6,7].

Note that the depth estimate produced by the sensor corresponds to the distance between the radar antenna and the subsurface feature. Therefore, if the radar antenna's vertical position is displaced due to surface profile changes (e.g., roughness), then the change in radar-to-interface depth will result in a change of estimated top layer thickness. This aspect was identified in the error sources table but was not evaluated in this survey.

With regards to the estimated seam depth, it should be noted that any changes in dielectric constant of the top layer will result in a change in signal time-of-flight and thus the depth estimate [2]. For these data processing steps, an average of the surface dielectric has been used. However, this potential variability in dielectric has been accounted for in the uncertainty metric and expressed through the error-bar confidence intervals on the estimated seam thickness.

V. SUMMARY

This paper has presented practical outcomes from field radar research conducted to improve the performance subsurface sensing capabilities for towards the development of automated coal mining horizon control systems. Here the use of radar technology has provided an important means to sense geological target. GPR has provided ways to better characterise performance by understanding the dominant factors governing performance. These factors involved a broad range of technical, operational, and geological impact factors. GPR research continues to refine and improve the approach for mining applications.

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