Ground Penetrating Radar Based Experimental Simulation and Signal Interpretation on Coal-Rock Interface Detection

Shuguang Miao¹,²,³, Xiaowen Liu¹,²,³*, Zhongyu Liu¹,³, Lei Zhang¹,³, Kai Zhang¹,³

¹IOT Perception Mine Research Center, China University of Mining and Technology, Xuzhou 221008, China
²School of Physics and electric information technology, Huaibei Normal University, Huaibei 235000, China
³School of Information and control Engineering, China University of Mining and Technology, Xuzhou 221008, China

* E-mail: liuxiaowencumt@163.com

Abstract. Coal-rock interface recognition is one of the key unaddressed problems in unmanned mining condition. Therefore, it is important that efforts should be made to detect coal-rock interface. In the study, Ground Penetrating Radar (GPR) has been used as a non-contacting means for coal-rock detection. We first establish three layered model of coal-rock and give the mathematical analysis of this model. Then numerical simulation and field experiment are carried out. Finally, in order to interpret radar image, an improved image segmentation algorithm is proposed. The experimental results show that it is feasible to detect coal-rock interface by GPR and the improved algorithm is well to interpret radar image of coal-rock interface.

1. Introduction
Coal-rock interface detection is one of the critical techniques associated with unmanned mining. Through coal-rock interface identification technology, the shearer drum can cut along with the coal-rock interface as far as possible, which will help to increase the extraction rate of coal resources and decrease the number of miners. At present, there are several methods for the coal-rock interface detection. Bessinger and Nelson [1] measured remnant roof coal thickness by passive gamma ray instruments in coal mines, but this method demands high radiation of roof and floor rock. A method of multi-sensor data mining and fusion technique in the coal-rock interface recognition system is presented by Ren et al. [2]. Sun and Su. [3] Introduced a coal-rock interface detection method on the basis of image texture features. Li et al. [4] proposed a hidden Markov model (HMM) memory cutting method for the shearer. Ralston and Hainsworth [5] introduced the application of GPR for coal depth measurement and presented a GPR data model.

These methods mainly focused on hardness, visual, and other physical differences between coals and rocks. Among these methods, the electromagnetic method such as ground penetrating radar has been considered to be the most feasible method and proved available to identify most coal-rock interfaces [6-9]. Ground Penetrating Radar (GPR) detects a target with electromagnetic waves, which can be used to detect coal-rock interface continuously without any collateral damage.

It can be seen from Table 1, the relative permittivity and conductivity between the coal and rock medium are different. GPR electromagnetic waves reflect well from the interface between coal and rock. Thus, coal-rock interface can be detected by GPR theoretically.
Table 1. The relative permittivity and static conductivity of common coal-rock mediums.

| Medium      | coking coal | lignite | gas coal | sandstone | limestone | Shale |
|-------------|-------------|---------|----------|-----------|-----------|-------|
| Relative permittivity | 2.1         | 4.1     | 2.4      | 4.01      | 5.7       | 7     |
| Static conductivity  | 0.027       | 0.0877  | 0.0202   | 0.04      | 1.4       | 1.01  |

In this paper, GPR was used as a non-contacting means for coal-rock detection, and the physical model of coal-rock layered media was established. Then numerical simulation and field experimentation were carried out, and finally the improved imaging segmentation algorithm of two-dimensional histogram based on traditional image segmentation algorithm was proposed.

2. Model of Coal-Rock Interface and Analysis

2.1. The mathematic model of coal-rock interface

The layered model of coal-rock interface is shown in Figure 1, the upper is hard rock and the lower is coal.

![Figure 1. Coal-rock interface model](image)

The average thickness of coal seam is \( L_1 \), relative permittivity is \( \varepsilon_1 \) conductivity is \( \sigma_1 \), rock thickness is \( L_2 \), relative permittivity is \( \varepsilon_2 \), and conductivity is \( \sigma_2 \). The emission electromagnetic wave is \( T_0 \), reflection and refraction of electromagnetic wave occurred in air and coal seam interface, reflection wave \( R_0 \) is received by receiving antenna, refracted wave \( T_1 \) through coal seam and reflection happened again in coal-rock surface, and reflected wave \( R_1 \) is refracted in coal-air interface, refracted wave \( R_2 \) is received by receiving antenna. It is well known that the time difference between \( R_0 \) and \( R_1 \) is the round-trip time of radar wave.

2.2. Calculation method of radar echo intensity

Electromagnetic wave energy is emitted by a directional antenna, the antenna gain is defined as \( G \), effective aperture of antenna is \( A = \frac{G \lambda^2}{4\pi} \), where \( \lambda \) is wave length. Combined the radar equation and the model of Figure 1, the power \( P_0 \) on the surface of coal seam is defined as:

\[
P_0 = \frac{P_t G^2}{4\pi L_1} \cdot A \cdot r_{0,1} = \frac{P_t G^2 \lambda^2}{64\pi^2 L_1^2} r_{0,1}
\]

Where, \( P_t \) is the transmit power of the radar antenna. The reflection and refraction of electromagnetic wave in the air layer and the coal seam conforms to principles of optics, and the reflection is caused by the difference of the electrical properties of the medium. The reflection coefficients between air and coal seam is defined as:

\[
r_{0,1} = \frac{1 - \sqrt{\varepsilon_1}}{1 + \sqrt{\varepsilon_1}}
\]

(2)

Where, \( \varepsilon_{r,1} \) is the relative permittivity of the coal seam, the power of the reflected wave (direct wave) is \( R_0 \).

\[
R_0 = \frac{P_t G^2}{4\pi (2L_1)} \times A \cdot r_{0,1} = \frac{P_t G^2 \lambda^2}{64\pi^2 L_1^2} r_{0,1}
\]

(3)

The transmission coefficient of electromagnetic wave from the air layer to the coal seam is defined as \( t_{0,1} \) (From the coal seam to the air layer is \( t_{1,0} \)):

\[
t_{0,1} = \frac{2\sqrt{\varepsilon_{r,0}}}{\sqrt{\varepsilon_{r,0} + \varepsilon_{r,1}}}
\]

(4)
Generally, σ and ε are two main parameters in GPR, the change of permeability μ of coal is very small. Assuming the medium permeability of coal seam is μ₁, the conductivity is σ₁. The expression of the attenuation coefficient of coal seam is defined as:

\[ \alpha = \omega \frac{\varepsilon_1 \mu_1}{2} \left[ \sqrt{1 + \left( \frac{\sigma_1}{\omega \varepsilon_1} \right)^2} - 1 \right] \]  

(5)

Where, ω is the angular frequency of the electromagnetic wave, \( \varepsilon_1 \) is coal seam permittivity constant and \( \varepsilon_1 = \varepsilon_0 \varepsilon_r, \varepsilon_0 \approx 8.85 \times 10^{-12} \text{F/m} \). So the power \( P_1 \) of coal-rock interface is:

\[ P_1 = \frac{P_0 G}{4\pi(L_0 + L_1)^2} t_{0,1} e^{-\alpha L_1} \]  

(6)

The reflection coefficient between the coal seam and the rock layer is defined as:

\[ r_{1,2} = \sqrt{\varepsilon_{r1} - \varepsilon_{r2}} \sqrt{\varepsilon_{r1} + \varepsilon_{r2}} \]  

(7)

where, \( \varepsilon_{r1} \) is coal seam relative permittivity, \( \varepsilon_{r2} \) is rock relative permittivity. It can reflect the difference of constant permittivity between coal and rock, and the bigger the difference is, the stronger the electromagnetic wave is reflected. The symbol \( r_{1,2} \) is also represents the propagation direction of electromagnetic wave, and reflected wave \( R_1 \) is refracted in coal-air interface, refracted wave \( R_2 \) is received by receiving antenna, and can be calculated by \( R_2 \):

\[ R_2 = \frac{P_0 G P_1}{[\pi(L_0 + L_1)]^2} e^{-2 \alpha L_1} (1 - r_{1,2})^2 r_{1,2} \]  

(8)

\( R_m \) is the minimum power of echo signal received by the radar system. When \( R_2 > R_m \), coal-rock interface can be distinguished by radar, the echo is stronger and easier to be detected usually. For a given radar, its transmit power \( P_t \), antenna gain \( G \) are fixed. Therefore, the main impact of the radar echo power is from antenna frequency, the electric parameters of coal-rock medium and the thickness of coal seam. In other words, the thickness of the coal seam can be detected by the GPR system is determined by the antenna frequency and the electrical parameters of the coal and rock medium.

This research selects cooking coal-shale combination, lignite-sandstone combination, gas coal-sandstone combination, and the cooking coal-limestone combination. So as to ensure the validity and authenticity of the simulation results, we choose parameters of LTD-2100 GPR which are developed by China Research Institute of Radar Wave Propagation as simulation data. Transmit power of LTD-2100 is 144.5W, antenna gain is 4.7dB, antenna frequency is 400MHz and 900MHz respectively.

![Figure 2. The max detectable depth of 400MHz and 900MHz antenna](image)

The simulation results are shown in Figure 2, it is not difficult to know that the detectable depth of 400MHz antenna is greater than 900MHz antenna. For 400MHz antenna, the detectable depth of cooking coal-shale is close to 5.8 meters and cooking gas coal-sandstone is about 3.6 meter. According to the current mining technology, the thickness of coal seam can be divided into three categories in china: thin coal seam < 1.3 m; the range of medium-thickness is 1.3-3.5m, and thick of coal seam is more than 3.5m. Therefore, the 400MHz antenna can meet the need of applications in theoretically.
3. Experiment

3.1. Numerical Simulation Experiment

In our study, we used the GprMax software for 2D forward numerical simulation of coal-rock interface detection by GPR. GprMax is a software tool that can be used to model GPR responses from arbitrarily complex targets.

GprMax [10] is electromagnetic wave simulators for GPR model. It is based on the Finite-Difference Time-Domain numerical method. GprMax is available free of charge for both academic and commercial use and has been successfully employed in situations where a deeper understanding of the operation and detection mechanism of GPR was required.

The geometric model of coal-rock interface is shown in Figure 1. In order to improve the simulation speed, the parameters of the geometric model are set as: \( L_1 = 0.2 \text{ m} \), \( L_2 = 0.4 \text{ m} \). The size of coal medium is 0.2 m×2.5 m and the size of rock medium is 0.4 m×2.5 m. The relative permittivity and conductivity of the coal and rock are shown in Table 1. The size of the numerical forward simulation grid is 0.0025 m×0.0025 m, the antenna distance is 0.05 m, the time window is 12 ns, the acquisition step size is 0.02 m, the acquisition tract number is 115, and the center frequency is 400 MHz.

The purpose of the numerical simulation is to study the GPR system’s detection capacity in different coal and rock combination. The coal-rock combination are lignite-sandstone, gas coal-sandstone, coking coal-limestone and coking coal-shale. The simulation results are shown in Figure 3, the reflection of the coal-rock interface gets better and the resolution becomes higher as the relative permittivity and conductivity of the medium difference increase. We can also get the same conclusion that the 400MHz antenna can meet the most requirements.

Figure 3. Detection results of different Coal and rock combination. a Detection result with lignite-sandstone interface. b Detection result with gas coal-sandstone interface. c Detection result with coking coal-limestone interface. d Detection result with coking coal-shale interface.

3.2. Field Experiment with LTD-2100 GPR

3.2.1 Experimental Coal Mine Survey and Scene

As shown in Figure 4, the test site is chosen in GuoZhuang coal mine, the fault is visible partly, the rest of the oblique extension. The test point is gas coal and sandstone boundary and the thickness of coal seam is from 1.3m~1.8m.
3.2.2. Field Test using 400MHz Antenna
As shown in Figure 5, the field test data with 400M antenna.

As can be seen from Figure 5, the maximum thickness of coal seam is about 1.8 meters and the minimum thickness of about 1 meters, the coal-rock interface can be approximately described, but the interface of coal-rock is not clear enough, the radar image is not very readable. Therefore, in order to achieve an accurate image of coal-rock interface, an improved image segmentation algorithm of two dimensional histogram based on traditional image segmentation algorithm is proposed.

4. Experiment Result Interpretation
In this paper, the improved image segmentation algorithm was used to interpret radar image [11-13]. As shown in Figure 6, the definition of 2D histogram, a threshold combination \((s, t)\) is chosen, and \(S\) is gray scale segmentation threshold, \(t\) is neighbor gray-scale segmentation threshold, so the definition domain is divided into four parts: region 0, region 1, region 2 and region 3. It is general considered that region 0 is the background, and region 1 corresponds with the target, while the region 2 and region 3 represent the boundary points and noise.

In Figure 6, we can know that there are two kinds of region in the two dimensional histogram. One is that corresponds with the background and the other is that corresponds with the target (represented by \(w_0\) and \(w_1\), respectively). The two kinds of regions have different probability distributions. If the image is segmented by arbitrary threshold vector \((s, t)\) in the two dimensional histogram \((0 \leq s, t < L)\). The probability distribution of these two kinds of regions can be expressed as:

\[
w_i = P(W_i) = \sum_{s=0}^{L-1} \sum_{t=0}^{L-1} \eta_i = w_i(s, t)
\]
\[ w_i = P(W_i) = \sum_{i=1}^{k} \sum_{j=1}^{l} p_{ij} = w_i(x, t) \]  

(10)

Where \( w_i \) represents the probability the background, and \( w_t \) represents the probability of the target, and the corresponding average value of the background and the target can be expressed as:

\[ u_0 = (u_{0i}, u_{0j}) = \left[ \sum_{i=1}^{k} \sum_{j=1}^{l} p_{0i} / w_0(x, t), \sum_{i=1}^{k} \sum_{j=1}^{l} p_{0j} / w_0(x, t) \right] \]  

(11)

\[ u_t = (u_{ti}, u_{tj}) = \left[ \sum_{i=1}^{k} \sum_{j=1}^{l} p_{ij} / w_t(x, t), \sum_{i=1}^{k} \sum_{j=1}^{l} p_{ij} / w_t(x, t) \right] \]  

(12)

Because of the assumption, all values in the region 2 and region 3 are negligible, so \( w_0 + w_t = 1 \) and the overall average value can be expressed as:

\[ u = (u_0, u_t) = \left[ \sum_{i=1}^{k} \sum_{j=1}^{l} p_{ij} \right] = w_0 u_0 + w_t u_t \]  

(13)

In the 2D Otsu method, the trace \( \psi_{st} \) of sample matrix \( \psi \) is the inter class distance measure function of the background and the target.

\[ t_{\psi_s} = w_s \left[ (u_0 - u_t) + (u_0 - u_t) \right] + w_t \left[ (u_t - u_0) + (u_t - u_0) \right] \]  

(14)

Where,

\[ u_0 = \frac{1}{k} \sum_{i=1}^{k} p_{0i} u_i, \quad u_t = \frac{1}{l} \sum_{j=1}^{l} p_{0j} u_j \]

From the formula (14), the calculation of distance measure function is only related with three parameters which are \( w_0(x, t) \), \( u_0(x, t) \) and \( u_t(x, t) \).

The maximum value of distance measure function \( t_{\psi_s} \) can be obtained by changing the two dimensional gray threshold \((s, t)\). At the same time, the threshold vector \( (s_0, t_0) \) is:

\[ t_{\psi_s} (s_0, t_0) = \max_{0 \leq s \leq 1} t_{\psi_s} (s, t) \]  

(15)

The traditional Otsu threshold segmentation method only takes into account the variance between foreground and background classes, and the classification information contained in each category is not considered. In order to achieve accurate segmentation, this paper introduces a class of discrete measures, to improve the threshold recognition function, then a new threshold segmentation method is proposed. The minimum within-cluster variance \( \lambda_s \) can be expressed as:

\[ \lambda_s = w_0 d_0 + w_t d_t \]  

(16)

Where \( d_0 = \sum_{i=1}^{k} \sum_{j=1}^{l} \left[ (u_0 - u_t)^2 + (u_0 - u_t)^2 \right] / p_{ij} \), \( d_t = \sum_{i=1}^{k} \sum_{j=1}^{l} \left[ (u_t - u_0)^2 + (u_t - u_0)^2 \right] / p_{ij} \). It is easy to get, in order to achieve the within cluster variance, the smaller \( \lambda_s \) is the better of cohesion.

Taking into account the class of discrete measures and the inter class variance, combined the maximum between cluster variance with the minimum within-cluster variance, a new threshold recognition function is proposed:

\[ \Phi_s(x, t) = w_s (1 - w_0) + 1 / \lambda_s \]  

(17)

To contrast the segmentation effect, we use the traditional algorithm and the improved algorithm to process the field GPR image. The results are shown in Figure 7 and Figure 8.
Figure 7 is the radar image segmentation with traditional Otsu algorithm, corresponding to the segmentation threshold vector $(s, t)$ is $(115, 108)$, Figure 8 is the radar image segmentation with improved Otsu algorithm, corresponding to the segmentation threshold vector $(s, t)$ is $(103, 105)$. It can be seen that coal-rock interface is divided more detailed and more accurately, which compared with traditional segmentation algorithm. Therefore, in practical application, it is not only need to consider the geological conditions, but also need to deal with the radar image by advanced digital image processing methods.

5. Conclusions
The paper verifies, through both numerical simulation and field experiment, the feasibility of using GPR detection on coal-rock interface. We also interpret detection signals by image segmentation. The research results provide a new and effective means for detecting coal-rock interface using GPR technology.

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References
[1] Bessinger, S. L., Nelson, M. G. (1993). Remnant roof coal thickness measurement with passive gamma ray instruments in coal mines. IEEE Transactions on Industry Applications, 29(3), 562-565.
[2] Ren, F., Yang, Z. J, Xiong, S.B. (2003). Study on the coal-rock interface recognition method based on multi-sensor data fusion technique. Chinese Journal of Mechanical Engineering, 16(3), 321-324.
[3] Sun, J., Bo, S. (2013). Coal-rock interface detection on the basis of image texture features. International Journal of Mining Science and Technology, 23(5), 681-687.
[4] Li, W., Luo, C., Yang, H., Fan, Q. (2014). Memory cutting of adjacent coal seams based on a hidden markov model. Arabian Journal of Geosciences, 7(12), 5051-5060.
[5] Ralston, J. C., Hainsworth, D. W. (1999). Application of ground penetrating radar for coal depth measurement. , 4, 2275-2278 vol.4.
[6] Strange, A. D., Ralston, J. C., Chandran, V. (2005). Near-surface interface detection for coal mining applications using bispectral features and gpr. Subsurface Sensing Technologies & Applications, 6(2), 125-149.
[7] Francke, J. (2012). A review of selected ground penetrating radar applications to mineral resource evaluations. Journal of Applied Geophysics, 81(6), 29-37.
[8] Xie, J. L., Xu, J. L. (2015). Ground penetrating radar-based experimental simulation and signal interpretation on roadway roof separation detection. Arabian Journal of Geosciences, 8(3), 1273-1280.
[9] Xin, W., Ding, E., Kexiang, H. U., Duan, Z. (2016). Effects of coal-rock scattering characteristics on the gpr detection of coal-rock interface. Journal of China University of Mining & Technology.
[10] G. Antonis, (2005). User’s manual of GprMax2D version 2.0, Edinburgh University Press, Edinburgh, pp. 4–26, 2005.
[11] Otsu, N. (1979). A threshold selection method from gray-level histograms. IEEE Trans.syst.man.cybern, 9(1), 62-66.
[12] Abutableb, A.S. (1989). Automatic thresholding of gray-level pictures using two-dimensional entropy. Computer Vision Graphics & Image Processing, 47(1), 22-32.
[13] Zhu, W. (1999). 2d gray level histogram thresholding based on distance measure. Journal of Southeast University.