Mining complex geology, mitigating float dust, and developing autonomous machine capability using horizon sensing technology for coal seam boundary detection

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Long before the environmental movement, coal miners were experiencing occupational diseases that became apparent in the later years of service and especially during the retirement years. Mine dust affects coal miners due to chronic inhalation of micro-fine dust in the respirable range, i.e. ‘float’ dust. The various lung diseases associated with this dust are referred to as ‘coal mine dust lung disease’. In the USA alone, 76 000 miners have died of coal mine dust lung disease since early legislation recognized the issue in 1969. There is belief among researchers that merely reducing float dust exposure limits will not reverse the negative trend in coal mine dust lung disease observable in the present generation of miners. The thin boundary layers of coal seams also contain concentrations of trace and radioactive metals. Thus ‘float’ dust includes silica and toxic trace metals. The production and quality of coal is also significantly impacted by the presence of these contaminants. In the combustion process, these trace metals are oxidized, becoming components of the fly ash and flue gas, and are extremely water-soluble, representing a significant health and environmental danger. Coal preparation plants and power stations need to mitigate these contaminants as much as practical, but the simple fact is that most contaminants should have been left unmined.

This paper describes an innovative coal cutting solution to the long-standing technology gap in mining – the ability to measure uncut coal layer thickness to the boundary rock layer. Because of constant changes in geology, seam thickness, and seam undulation, the horizon sensor must be located in the bit-block of the rotating cutter drum of the continuous mining machine. The reduction of contaminants in ROM coal must be minimized at its source, that is, at the rock/coal crushing cone directly under the bit-tips of the cutting drum. The distance from the bit-tip to the rock boundary layer must be automatically controlled in real time when mining in a complex and undulating coal bed. Horizon sensing (HS) technology enables the coal mining machine’s cutting ‘picks’ to stop at a specified distance from undulating horizons of the boundary rock. The thin contaminated coal layer can be left behind in the mine and the toxicity of ‘float’ dust significantly reduced. By preventing the metal picks from striking quartz-containing boundary rock, the very commonly occurring and oftentimes unreported methane ignitions are prevented. The horizon sensor equipped with pick force vector sensing can allow optimization of the cutting pick lacing pattern for minimum coal and rock crushing, thereby reducing ‘float’ dust. This technology may enable the mining industry to convert from automated to autonomous machine control during coal cutting and loading.

Introduction

The 1999 vision statement developed by the Chief Executive Officers of the National Mining Association (NMA) for the Mine of the Future (MOF) and their prioritized Technology Development Road Map, and a 2010 Section 11 National Research Council/National Engineering Academy Study, confirmed that boundary detection in coal and metal/non-metal mining remains a mining technology gap. The National Aeronautical and Space Administration (NASA) Automated Coal Extraction (ACE) programme also determined in 1971 that a horizon sensor (HS) installed on a rotating coal cutting drum and geological vision ahead of mining technologies were beyond-the-state-art.
Remote control of mining machines assisted by ‘last cut’ machine-control algorithms has enabled machine operation from a distance. The technology, when augmented with helmet-mounted air breathing filters, has significantly improved machine operators’ health and safety. The Upper Big Branch Mine accident investigation autopsy report surprised legislators, regulators, and researchers when most of the 29 victims were found to be suffering from varying degrees of lung disease.

In ideal coal deposits without meandering palaeochannels, faults, and many other types of anomalous seam geology, the prevailing state-of-the-art is highly useful. In the real world of sedimentary deposits, meandering palaeochannels, and differential compaction cause seam roles, floor ‘horse backs’, rapidly-thinning coal, and fractured roof rock. Palaeochannels, faults, and dykes cause very high nonlinear stress fields in the seam and boundary rock. The thin boundary layers of a coal seam are commonly contaminated by heavy metals and radioactive elements precipitated by biochemical reduction during the deltaic or strandline peat-coal forming processes. Gradational deposition is partly responsible for the higher density, sulphur, and ash contents observed in the thin boundary layer. Researchers now believe that heavy metals in the cutting dust plume are a contributing factor in lung disease. These considerations are drivers for leaving the thin contaminated boundary layers behind in the mine. Additional arguments can be made that the horizon sensing hardware must be mounted on the rotating coal cutting drum to look up and forward for abandoned hydrocarbon well casings (the cause of the Farmington Mine explosion), loss of hydraulic pressure in roof support canopy (the cause of the San Juan Mine fire), and abandon mine entries (the cause of the Quecreek Mine water inundation).

The problem – coal boundary geology impacts health, safety, and productivity

Most likely, coal seams were lenticular deposits with smoothly changing thickness at the time of their formation. However, the seams have been affected by tectonic events over time and have been deformed considerably from their original forms. The common deformations of coal seams induced by such earth movements include severe undulations, sandstone intrusions, faults, and sudden thinning, which change the shape and locations of the boundaries between the coal seam and the roof and/or floor rocks. Geological exploration in advance of mine development can identify some of the deformations, but the large spacing between the exploration drill-holes or data points makes detection of localized and very often more severe deformations impossible. These undiscovered deformations frequently cause significant operational difficulties and economic losses. There are numerous cases where such localized and severe deformations have forced the abandonment of large underground coal reserves and developed longwall panels. To avoid cutting into the seam boundary rock caused by a meandering palaeochannel seam roll, the automated cut algorithm of the continuous mining machine must begin with the downward floor cut ahead of the palaeochannel margin to safely mine through a differentially compacted seam anomaly. The ‘last cut memory’ horizon control algorithms are not useful in automated control of shearers in an undulating seam environment. In geologically disturbed environments, the shearer operator needs to be in visual range of the machine.

Complex geology and stratified contaminants

The red dashed line in Figure 1 illustrates extracted coal roof and floor horizons where the machine operator controls the vertical cut by observation of the bedding planes ‘marker bands’. On approach to seam disturbances caused by a palaeochannel, marker bands vanish and the machine cuts through the contaminated coal layer and sandstone intrusion. The yellow dashed line in Figure 1 illustrates the cut when the machine automation includes horizon sensing. Because of microbial processes occurring during the seam deposition (strandline, fluvial, or deltaic), the thin boundary coal layer is contaminated with the biochemically reduced forms of heavy metals. Figure 2 illustrates the physical, chemical, and thermal properties of a typical stratigraphic section within a coal seam and provides a layered breakdown of contaminants such as mercury, ash, and sulphur.
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Figure 1. Cross-section of the high-energy cutbank region of a palaeochannel

Figure 2. Stratigraphic cross-section illustrating contamination in a coal bed

Heavy metal contamination and quartz in respirable dust are drivers in lung disease. Researchers now realize lung disease causes may include the heavy metals, as well as silica dust reactions, that diminish lung tissue oxygen transfer into the blood stream.

A serious environmental threat to the mining industry is the promulgation of legislation declaring boiler fly ash toxic because of the re-oxidation of heavy metals in the combustion process. From a health and safety point of view, thin contaminated boundary coal layers should be left behind in the mine.
Coal workers’ pneumoconiosis (CWP) is one of the worst diseases among coal miners. The recent increase in CWP cases in the US coal industry makes dust control in underground coal mines a very challenging task. Preventing the cutting bits of the mining machine mining into quartz-containing hard rocks is one of the most important dust control strategies employed in coal mining operations. The avoidance of cutting into hard roof and floor rocks in coal mining operations can greatly benefit miners’ health and safety. Real-time detection of the shape and location of the boundary between the coal seam and the hard rock roof and floor of the localized deformations in advance of the mining machines is the most effective way to eliminate sparks and quartz dust.

More immediate to miners’ safety, cutting the severely deformed coal seams without detailed knowledge of the deformation boundaries could affect roof conditions and the explosiveness of the mining environment. For example, cutting into unexpected hard roof or floor rocks, such as sandstone, by mining machines can produce incendiary sparks with more than 0.25 millijoules of energy, capable of igniting methane and then coal dust. The ignition source for the Upper Big Branch (UBB) Mine explosion was longwall shearer bits cutting into hard rock. Sparks induced by cutting into quartz-containing hard rock in US coal mines have caused numerous unreported short-duration methane flames, which did not develop into mine explosions or large mine fires due to insufficient methane and coal dust present in the working space. However, the most important way to prevent mine fires and explosions in underground coal mines is to eliminate the ignition sources, among which cutting sparks are the most difficult ones to prevent. Avoidance of cutting quartz-containing hard roof and floor rock is an effective way to prevent cutting sparks.

From a theoretical point of view, the ‘float’ dust associated with the bit tip crushing of coal and rock must have been the ‘technical root cause’ of the UBB Mine accident. When reading the UBB accident report from an engineering and applied science, rather than a regulatory, point of view, the following questions arise: (1) where did the ‘float coal’ fines come from; (2) why did the autopsy report that the victims were experiencing various stages of lung disease; (3) why were the pick and bit blocks excessively worn; and (4) why was there an ignition of methane on the face? To combat the ‘float’ coal dust problem, the bit tip vector force and bit-block lacing pattern can be optimized for ‘minimum coal dust generation’ only if horizon sensing (HS) and vector force data are captured and analysed by the mining machine in real time. All of these questions, when discussed in an engineering and applied science-based forum, define the design specifications for coal seam boundary detection that will significantly improve mining health and safety.

Formation and alteration of coal deposits

Advancement in mine health and safety depends on knowledge of the geochemistry, biology, and the radio-geophysics of the peat-coal forming environment. Coal beds are formed in different sedimentary environments. The most common are deltaic and strandline deposits of a transgressing sea. Lagoons form behind sea barriers and inland lakes contain nutritious floor sediments (i.e. ‘fire clay’) that support vegetation. The marine and littoral environments contain large quantities of sodium, chlorine, magnesium, potassium, and sulphur, which are incorporated into the peat. Magnesium, iron, and calcium may be trapped in coal as carbonates, although generally seawater does not introduce much iron or calcium. Much of the liquid contamination is expelled as the coal it is compacted and the rank increases. Peat-coal deposits form in the delta swamp regions of river systems. The upper floodplain, mud-water flow, and the subsiding delta regions of a river system are illustrated in Figure 3 (upper diagram).

Frequently, sequences of dry and wet periods during burial create a gradational coal seam boundary layer with higher ash density increasing from a mid-seam value of 1.3 to 1.4. Continuing argillaceous mudflow forms shale and mudstone roof-rock layers, which are relatively impermeable. In deltaic deposits, flooding through breaches in the levees creates porous sandstone palaeochannels that meander in the sedimentary layers surrounding the coal layer. Deltaic deposits typically have a contaminated layer at the top of the coal layer. Often, the high-energy ‘cutbank’ or erosional component of a palaeochannel scours into the coal layer, replacing coal with porous quartzite sandstone palaeochannels as illustrated in the lower diagram in Figure 3.
Upper floodplain argillaceous mud-water flows into the peat-coal swamp carrying oxides of trace elements. Vegetation grows in the swamp region of the delta forming peat-coal. During the time sequences of mudflow, deposition, and subsidence of the delta region peat-coal swamp, the environment of the upper layer of peat-coal changes to an oxygen-deficient, abiotic condition. Accumulation of anaerobic bacteria creates a reducing (oxygen-reduction reaction) environment. Some elements precipitate when encountering a reducing environment in the swamp, contaminating the upper peat-coal layer. Pyrite (FeS$_2$) in coal typically forms from hydrogen sulphide (H$_2$S) and iron (Fe) and involves the bacterial reduction of sulphates (SO$_4$) to H$_2$S at pH values of 7 to 4.5 followed by combining of H$_2$S, elemental sulphur, and ferrous oxide (FeO) to form pyrite and water. The SO$_4$ source may be seawater or vegetation. Subsequent burial and greater than 5:1 compaction forms a thin boundary layer of coal contaminated with pyrite, sulphur, and heavy metals such as mercury, uranium, arsenic, and radioactive potassium ($^{40}$K). The assemblage of these contaminants is called ash.
Coal seam microstructure and gas flow

Differential compaction occurs in the stratified rock and coal layers due to incompressible sandstone palaeochannels creating fracturing, rolls, and rapid thinning (compaction) in the coal bed. The coal layers illustrated in Figure 4 exhibit face and butt cleat structures, which significantly impact gas flow permeability and differential stress within the coal seam. This anisotropy in the physical microstructure of the coal translates into an equally anisotropic nature of its electrical properties such as dielectric constant, an important variable in remote sensing and radiowave imaging.

![Figure 4. Anisotropic dielectric constant and gas flow permeability](image)

One of the important features of coal is its microporous and highly fractured nature, which plays an important part in many of its physiochemical properties, such as methane gas retention capacity and highly adsorbing and absorbing properties. Trapped methane gas is released during the mining process when the coal is fractured and the micropores open allowing transport of gas to the atmosphere, and chemically adsorbed gas becomes available for liberation into the microporous structure or fracture system. The flow of gas stored in the microporous structure is governed by Flick’s Law. The free gas in the fracture system flows according to Darcy’s Law. These two modes of transport are interdependent. The physics of gas in coal during mining is complex and conventional gasfield methods of reservoir engineering analysis are not applicable.

The internal surface area of coal can be as high as 1.5 million square feet per pound of coal, and 0.34 standard cubic feet of methane per pound of coal can be adsorbed on the internal surface area at the saturation pressure of 1500 pounds per square inch (psi). Depending on the rank of the coal and integrity of the overburden, the amount of methane adsorbed and absorbed can reach as high as 28 times the volume of coal. Each pound of coal fuels the generation of one kilowatt-hour (kWh) of electric power in a typical coal-fired power plant.

At atmospheric pressure, the most explosive concentration of methane in air is 9.5% by volume. Methane also has a tendency to stratify and form horizontal layers near the roof of mine workings where the ventilation velocities are insufficiently high to prevent layering. This phenomenon occurs because the density of methane is only 0.55 that of air. In many instances, a ventilation air velocity of 1.6 feet per second will prevent layering, but in some circumstances this air velocity will be insufficient as barometric pressure decreases. These changes are created by passing storm fronts decreasing barometric pressure.

Charles McIntosh of Eastern Illinois University conducted the earliest detailed study of methane gas in coal seams in the late 1950s. The rate of gas liberation from coal mining depends upon age, depth, and the structure of the coal seam; the mining technique; and the rank of the coal (the higher the fixed carbon content of the coal, the higher the methane
liberation). Geologically induced nonlinear stress fields create fractures, which along with the cleats, form gas and water pathways through the coal matrix. Cutting machines are oriented to cut (fracture the coal) at an angle to the butt cleats to maximize roof-rock stability. The anisotropic gas-flow permeability is maximized when horizontal production wells are drilled such that long face cleats drain gas and water into a well.

Adsorbed (bound to the matrix, approx. 67%), absorbed (pressurized cleat volume, approx. 27%), and micro-fracture (free, approx. 6%) methane gas concentrations range up to 1000 cubic feet per ton, with a typical value being about 360 cubic feet per ton. The coal seam water content resides in fractures and the cleat structure. During degassing, water is pumped from the well to reduce pressure and facilitate gas flow. There is a thermodynamic mass transfer problem that suggests acoustic stimulation may increase the gas flow permeability. Frequently, argillaceous cuttings or drilling mud ‘cake’ the walls of the drill-hole, decreasing gas flow permeability. Acoustic stimulations within degasification boreholes increases gas flow permeability by a factor up to three. Acoustic stimulation ahead of high-production-rate longwalls will increase the degassing rate and reduce methane ignition potential, especially if water is injected into the acoustically enhanced permeability of the borehole walls. The shale and mudstone layer bounding the coal seam seals the coal bed from nearby porous sandstone freshwater aquifers. The sealing layer of a coal bed is often scoured by an overlying sandstone palaeochannel, which creates a dangerous margin of weak rock.

**Layered coal deposits form natural electromagnetic and seismic waveguides**

Increasing moisture in the coal cleats increases both the dielectric constant and electrical conductivity of the coal layer. The anisotropic dielectric constant of the cleated coal depends on the molecular polarization of ions, absorbed from the argillaceous minerals into the pores of the cleat. The electric field component of an electromagnetic (EM) wave may cause differing polarization of asymmetrically charged molecules in place between the face and butt cleat structure, creating an anisotropic dielectric constant. The bedding (partings) plane is orthogonal to both the face and butt cleat structure. The relative dielectric constant of mid-seam coal is near 4. The relative dielectric constant is in the vertical direction and is also near 4 except near the seam boundary. The thin boundary layer often has a higher ash content, which increases the relative dielectric constant towards 9.

The bedding planes are often observable in the ribs of recently cut coal and are used as visual ‘marker bands’. Machine operators use the ‘marker bands’ in an attempt to visually control the advancing machine roof and floor cutting horizon. Visual guidance prevents cutting through the contaminated boundary layer and into quartz-containing boundary rock. The ‘marker bands’ often vanish on approach to a geologic disturbance, such as a palaeochannel or fault zone, or are obscured by cutting ‘float’ dust plumes. The bedding plane can form because of ash plumes from volcanic eruptions settling over the peat-coal region and alterations in the peat-coal depositional environment. The mudstone and shale sealing layer has an electronic charge density and electrical conductivity that is several orders of magnitude greater than the mid-seam coal layer. The conductivity and dielectric contrast form a natural waveguide for transmission of quasi-transverse (quasi-TEM) electromagnetic waves. One of the EM wave theory boundary conditions requires that the electric field ($E$) components of the traveling quasi-TEM wave be vertically polarized and terminate on the mobile negative charge in the roof boundary rock and begin on the positive charge in the floor rock, as illustrated in Figure 5.

The quasi-transverse EM seam wave (quasi-TEM) electric field component, $E$, is polarized in the vertical direction and the magnetic field component ($H$) is polarized horizontally in the seam. The energy in this part of the EM wave travels laterally in the seam from the transmitter to a companion receiver. There is a horizontally polarized electric field component ($E_x$) that has zero value in the centre of the seam and reaches a maximum value at the interface between the sedimentary rock and the coal. Because of the boundary charge illustrated in Figure 5, the $E_x$ and $H_y$ components are responsible for transmission of the EM wave signal into the boundary rock layer. The energy in this part of the EM wave travels vertically and out of the coal bed (i.e. the coal seam is a leaky waveguide). However, the transmission of low- and medium-band frequencies ‘trapped’ within the coal seam waveguide has been used to detect and image geologic disturbances like those seen in Figure 5.
Energy in the EM wave 'leaks' into the fractured rock overlying the seam, increasing the absorption rate. Thus, weaker roof rock can be detected by mapping rapid increases in attenuation rate (i.e. gradient) across the plan view of the seam, including the developed entries. Fractures in the boundary layer will increase the roof fall hazard (see Figure 1).

Due to the EM waveguide behaviour, the magnitude of the seam radiowave decreases due to absorption because of two different factors; namely, the attenuation rate and cylindrical spreading of wave energy in the coal seam. The cylindrically spreading factor is independent of the conductivity of coal and is mathematically expressed by $10 \log r$, where $r$ is the distance in metres from the transmitting to the receiving antenna. This factor compares with the non-waveguide far-field spherically spreading factor of $20 \log r$. Thus, at 100 m, the magnitude of the EM wave within the coal seam decreases by a factor of only 10 in the waveguide and by a factor of 100 in an unbounded medium. An advantage of the seam waveguide is greater travel distance. Another advantage is that the traveling EM wave remains predominantly within the coal seam waveguide (i.e. the coal bed), except when the sealing mudstone or shale laver is fractured by an overlying palaeochannel. Because energy transmission is primarily within the coal bed, seam anomalies can be detected with radio imaging method (RIM) reconnaissance (i.e. cross-panel direct ray) and tomography scans.

Tomographic mapping of palaeochannels ahead of mining can locate where ground control should be intensified by roofbolting and installing screening and/or trusses. The roof rock fails often when entries are driven under the margins of palaeochannels. Roof-fall injuries will be reduced significantly when images of margins are mapped and ground control measures are intensified. Measuring the $H_y$ field component will increase mine safety by locating palaeochannels crossing an entry. Over 500 longwalls have safely mined through these anomalies with the assistance of RIM transmission tomography.

Detection of acoustic and seismic waves

The acoustical (i.e. pressure wave) resonance of the coal seam depends on seam thickness and is typically near 760 Hz. High nonlinear stress fields in the coal bed and surrounding rock can be measured with suitable instrumentation, providing additional information for mining safety purposes. Double-sideband acoustic waves are heterodyned (generate sum and difference frequencies) when transmitted through nonlinear stress fields. Detection of the heterodyne frequencies can be useful in the in-situ mapping of stress fields when pulling pillars in the coal extraction process.
Seismic wave reflection and transmission in the coal seam waveguide have been used to detect and image anomalous geologic structures. The wave velocity is near 4000 m/s in the seam-bounding rock layers, decreasing to 2500 m/s in the coal seam. The reflection method has proven to be effective in detecting full-seam faults ahead of mining.

Seismic imaging was developed to detect and map geologic structure in coal beds. A seismic source applied on the rib initiates both pressure (P) and shear (S) waves that propagate in the coal seam because of contrasting acoustic impedance between the boundary rock and coal. The propagation velocity is approximately 4000 m/s in rock and 2500 m/s in coal. Most of energy propagates in the rock layers, and not in the seam as in the EM case. Seismic imaging is based on reflections from boundaries of contrasting acoustic impedance. The detection and imaging method is highly successful in detecting full-seam vertical faults but is problematic in detection of partial seam disturbances, such as scouring palaeochannels.

**Gamma and electronic charge emissions from floor and roof rock**

The river argillaceous mud-flow contains radioactive potassium ($^{34}$K). Higher concentrations are found in shale, mudstone, and slate seam boundary rock. There are 40 to 60 emissions per second in boundary rock and less than 20 emissions per second in the coal bed. Because of absorption in coal, the boundary detection distance is limited. Bursts of gamma emissions occur when the boundary rock is crushed by a pick. Gamma emissions from sandstone palaeochannels are very low, causing an automated mining machine to lose horizon control when most needed. Quartz crystals are piezoelectric and generate bursts of electrical charge with changes in pressure along their axis. Crushing piezoelectric quartz-containing hard rock generates electromagnetic radiation.

**The solution - a smart coal cutting drum**

**Historical horizon sensor development**

Driven by many observations made at the Miners’ Colfax Medical Center in Raton, New Mexico, of coal miners retiring from service and then being rewarded with a slow smothering death, a revolutionary horizon sensor development programme and in-mine demonstration program was initiated in 1960. The 53-year R&D phase of the horizon sensor (HS) product life cycle began with the National Aeronautics and Space Administration (NASA) Johnson Space Center funding to develop a sensor to measure, in real time, the thin ice layer thickness build-up on the liquid fuel tanks on the space shuttle booster rocket prior to launch, which was the ‘technical root cause’ of the Columbia shuttle re-entry disaster. The US Department of Energy (DOE) Mine of the Future (MOF) programme, responding to the technology road mapping work undertaken by the National Mining Association (NMA) achieved prototype validation of the HS technology at a cost of approximately $1 million. Internal corporate funding totalling nearly $10 million achieved prototype demonstrations of the HS technology in a mining environment.

Many mining companies participated in the installation, demonstration, and assessment of HS performance on 20 coal cutting drums, six of which were high production rate longwall mining systems. Shock and vibration levels were measured in real time and found to average 26 Gs and to reach peak 100-G force levels. Sandia National Laboratories (SNL) assisted in the development of high-, low-, and band-pass mechanical filters installed in the Mine Safety and Health Administration (MSHA) approved flameproof enclosure. The enclosure endurance of more than 18 months was validated at a maximum shock and vibration level by SNL. The mining company's in-mine demonstration expenses were not accurately determined; however, a conservative estimate is on the order of $200 000 per installation. The Consol in-mine HS demonstration on the Robertson Run Coal Mine longwall shearer was directed and independently evaluated by Consol’s technical team. In-mine demonstrations were also conducted by Interwest Mining and Blue Mountain Energy at the Deserado Mine, which confirmed that rotating shearer drum pick dust, ignition control water spray, and pick fracturing changed the dielectric constant of the thin fractured coal layer, creating coal thickness calibration problems. The HS development and evaluation team determined that a technical solution was well beyond the state-of-the-art for ground penetrating radar (GPR) technology. At that time, the HS programme was halted and the research phase investment continued with a goal of solving the calibration problem caused by the varying relative dielectric constant of the bit-fractured coal layer. During the development of these various sensor platforms, a number of patents were issued to horizon sensor instrumentation and methods of operation. Photos of various horizon sensor installations are shown in Figures 6A and 6B (continuous miner and longwall shearer, respectively).
Figure 6A – Horizon sensor on continuous miner drums

Figure 6B. Horizon sensor on a longwall shearer drum
Advanced horizon sensor capabilities

To combat the state-of-the-art interface varying dielectric calibration problem, revolutionary radar technology was developed and demonstrated in Consol and Oxbow coal mines. This work solved the problematic geologic clutter (i.e. rapid spatial change in dielectric constant) and very high reflection in the ‘early arrival time’ EM field components that engulf the ‘late arrival time’ EM field components reflected from the coal-rock interface, air- or water-filled abandoned entries.

The double-sideband gradiometer (DSBg) GPR technology was developed initially under the NMA/DOE MOF programme. Initial trials on a highwall mining machine and horizontal drill string navigation collar enabled distance determination relative to the seam boundary. With internal and demonstration funding from DOE, the DSBg GPR resulted in a validated prototype in the mining environment. The DSBg GPR was successfully developed for detection of abandoned mine entries with funding provided by the Mine Safety and Health Administration (MSHA). The six-year DSBg GPR development of a spatial clutter and reflection elimination (SCARE) functionality may have overcome the horizon sensor calibration issue observed in most of the HS demonstrations. A detailed discussion of this radar theory and the break-through science of the DSBg GPR are provided in Appendix 2.

The SCARE functionally was developed to suppress the ‘early arrival time’ (EAT) cluttering reflection from the pick-fractured coal layer and to detect the late arrival time’ (LAT) EM field components reflected from the coal-rock interface and even a gradational boundary. The DSBg GPR with SCARE functionality suppresses the EAT EM wave field components ($E_{R1}$) by up to 70 dB relative the LAT field components ($E_{R2}$) from the coal-rock boundary interface (see Figure 7).

![Figure 7. Electromagnetic wave energy flow in the detection of buried objects by a double-sideband gradiometric radar with spatial clutter and reflection elimination functionality](image)

The suppression depth can be selected by the adjusting the modulation frequency, which is one-half of the double-sideband frequency separation. The fracture suppression depth is approximately the pick length. By including a bit force vector sensor in the bit block, the interface pick-rock boundary intersection can be determined to provide the calibration needed in an automated machine to control rock cutting depth and to acquire data for bit lacing to minimize the production of fines. The $^{256}K$ gamma emission burst, when the pick strikes the argillaceous boundary, can be detected by
a gamma radiation sensor built into the electronics. Quartz radiation emitted when boundary rock is crushed may also be used to detect the boundary rock interface.

It is often necessary to cut through the contaminated coal layer and into boundary rock to allow machine clearance. Bit blocks with piezoelectric sensors have been designed to measure the bit tip force vector and can determine bit intersection with the rock interface. The rock cut depth can be accurately controlled in the automation of the machine.

Dust produced by cutting drums is generated from rock and coal that is crushed directly under the individual bits on a rotating cutter head. The pick tip angle of attack, bit penetration, and drum lacing pattern affect the generation of fines and dust. A pick bit block, instrumented with piezoelectric sensors, was developed in the NMA/DOE/MOF programme in partnership with Colorado School of Mines (CSM) engineers and trialled in their pick cutting force measuring apparatus. The objective of the work was to measure the pick vector force angle in real time. The CSM work suggested that reducing the number of picks on the drum and increasing the spacing of the picks on the bit block would reduce the production of fines and dust.

There are a number of patents that claim dust and fines reduction methods (e.g., very smooth drum surfaces and shaped picks). Coal fracturing is dependent on the cleat geometry and micro-fractures induced by horizontal stresses relative to the vector pick force angle and propagating fracture angle. Reduction in coal fines occurs when the next pick intersects the propagating fracture. Measurement of vector pick angle and uncut coal thickness can be transmitted by radio modem to the shearer.

The DSBg GPR with SCARE functionality will have the capability of looking up through uncut coal to detect longwall roof supports that have lost hydraulic pressure and of looking forward to detect abandoned hydrocarbon well casings. The multiple-mode smart coal cutting drum data can be transmitted from the rotating drum to the mining machine and processed. The acquired data enables optimization of coal cutting for minimum fines generation.

**Practical horizon sensor requirements**

State-of-the-art advancement in the automation of coal cutting machines will benefit miner health and safety. Figure 8 shows the integration of the RMPA sensor into the bit block. The rotating cutting drums of continuous and longwall shearsers rotate at one revolution per second. The RMPA bit block sensor has a 17 millisecond window to measure the thickness of uncut roof and floor coal. The bit tip fractured zone illustrated in Figure 7 exhibits a varying relative dielectric constant, which causes the cluttering reflected EM wave field components to vary in magnitude.
Data processing software for determining the bit block lacing pattern will require bit pick vector force measurement and filtering, (i.e. Fourier and Laplace transform analysis) between the time and frequency domains of the pick force sensing signal. The nonlinear stress fields and fractures in the coal layer cause the ‘strained’ pick to instantaneously release energy, creating heterodyne acoustic band frequencies that must be processed to determine the direction cosines of the pick vector force. The pick intersection with the coal-rock interface must be determined to achieve self-calibration of the uncut coal layer thickness measured by the HS, and the required depth of cut into the rock for machine clearance.

The RMPA sensing and DSBg GPR with SCARE functionality enables automation of the machine cut so that the operator can be out of the ‘float’ dust plume. The DSBg GPR with SCARE provides a signal-to-clutter (S/C) ratio of 13 dB. Conventional GPR cannot provide an S/C above -11 dB. Therefore to solve the technology gap that exists in horizon sensing technology, conventional RMPA and GPR technology needs to be replaced with DSBg with SCARE functionality, as well as the implementation of smart pick sensors.

Concluding remarks
Coal fuelled the industrial revolutions in the UK and the USA and is doing so in the rapidly developing countries. World coal production is currently approximately 10 billion tons per year. Environmental regulations have caused a rapid decline in US coal demand, resulting in domestic production falling below one billion tons per year. China is increasing coal production above four billion tons per year, taking economic advantage of lower energy costs while creating enormous manufacturing wealth. Coal beds exhibit stratified layers of reduced forms of heavy metals that when burned become oxidized in the fly ash. Even though the modern Chinese boilers produce far less gaseous emissions and ash than boilers manufactured decades ago, the oxidized forms of heavy metals are toxic and soluble, making them mobile in the environment. The heavy metals found in fish suggest that the world’s oceans and river systems are being contaminated in the process of wealth creation. Even if US coal production is shut down, worldwide environmental contamination will not change as world demand for coal-fired energy is increasing faster than the US shutdown rate.

There are 500 underground coal mines in the USA. Assuming there are three continuous mining (CM) machines in each mine, there would be a total of 1500 CM machines with cutting drums operating in the USA. Assuming that the market in the rest of the world is twice the size of the US market, the worldwide total is 4500 cutting drums requiring advanced HS functionality. This advanced horizon sensing technology must be an advanced radar device (HS-Radar) to combat the known limitations of the current technology. The HS-Radar will have a dramatic and positive impact on the health and safety issues associated with dust, contaminants, and ground control hazards for all coal miners.
The Author