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Recent advances in remote coal mining machine sensing, guidance, and teleoperation

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SUMMARY

This paper presents some recent applications of sensing, guidance and telerobotic technology in the coal mining industry. Of special interest is the development of semi or fully autonomous systems to provide remote guidance and communications for coal mining equipment. We consider the use of radar and inertial based sensors in an attempt to solve the horizontal and lateral guidance problems associated with mining equipment automation. We also describe a novel teleoperated robot vehicle with unique communications capabilities, called the Numbat, which is used in underground mine safety and reconnaissance missions.

KEYWORDS: Coal mining; Machine sensing; Teleoperation; Autonomous systems; Robot vehicle

1. INTRODUCTION

Australia has excellent coal resources with a good long-term potential for wealth generation. However the Australian mining industry is currently facing a number of unique economic challenges, as well as expectations to meet increased safety requirements and strict environmental mandates. A real need therefore exists to find methods to increase coal production and improve mining efficiency while ensuring the safety of mine personnel. To this end, the CSIRO Mine Equipment Automation group is involved in developing and applying modern automation systems to coal mining machinery. Mining automation technology has significant potential to provide more accurate mining methods, incorporate sensing to improve productivity and minimise equipment damage, and to increase personnel safety by removing them from dangerous machinery and environments.[1,2]

An area in which modern automation technology can provide significant productivity and safety improvements is in the area of remote machine guidance. This requires the development of automated systems that are capable of sensing the material to be mined as well as guiding the mining machine to a designated target heading. These two underlying guidance scenarios are known as the horizon and lateral control problems.[3,4] Any practical automated system also requires integrated communication capabilities in order to transfer information on the status of the underground environment and mining equipment in real-time.

Section 2 introduces ground penetrating radar (GPR) as a coal-thickness sensor for application in the horizon control problem and describes its application to a longwall coal mining operation. In Section 3, an internal navigation system (INS) is presented as a solution for the lateral control problem. Section 4 presents a novel teleoperated field robot, called the Numbat, which is used for underground mine safety and reconnaissance activities. Numbat's real-time communication capabilities are used to convey information as to the condition of an underground mine in situations where it could be too hazardous for manual exploration.

2. GROUND PENETRATING RADAR FOR HORIZON CONTROL

This section describes the development of a GPR system for measuring coal thickness in coal mining operations. Although GPR has significant potential for depth measurement, the raw signals are frequently complicated and so 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 coal mining environment.

2.1. *Coal seam horizon sensing*

In an underground coal mining operation, there is an optimal roof and floor coal thickness that is required to provide sufficient structural support while maximising product extraction and avoiding unnecessary product waste.[5] If the remnant coal is too thick, permanently unrecoverable coal is left. If the layer remaining in the roof is too thin, it can greatly increase the risk of roof fall. Mining hard rock instead of coal also greatly increases the risk of machine damage. Figure 1 shows a cross sectional view of a typical underground mining operation, where the goal is to keep the mining machine in the coal seam by following an optimal mining horizon. In order to realise this objective, a method is required to determine the depth of coal.

2.2. *Existing coal depth sensors*

There are two main classes of coal depth sensing systems: reactive and predictive.[3] Reactive coal depth sensors are

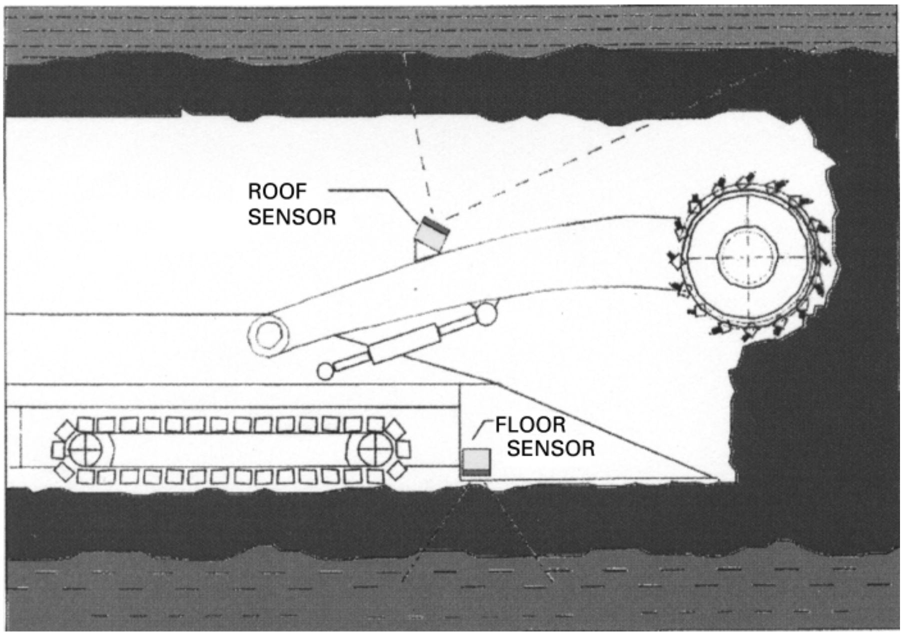


Fig. 1. The horizon control problem. Here the underlying objective is to keep the mining machine in the coal seam to in order to maximise coal recovery. The black bands represent coal and the textured zones represent tuff.

based on detecting changes in operational characteristics when a coal-rock interface is encountered. Reactive methods include monitoring cutting drum current, sensing changes in machine vibration signatures, and the use of instrumented cutting picks. The underlying limitation with reactive methods is that they rely on the actual penetration of the coalrock interface, in which case it is too late to prevent product dilution and machine damage. Unlike reactive methods, predictive sensors attempt to estimate the distance from the machine to the coal-rock interface. The most common predictive method uses a gamma radiation sensor to estimate the coal depth by exploiting the radioactivity of host strata typically found with coal deposits. The natural gamma sensors can work well in specific situations but require up to 30 seconds to obtain a reliable depth measurement. Such a delay can impact severely on coal mining operations. This limitation motivated the search for alternative predictive sensing methods.

2.3. *GPR as a depth sensor*

GPR has found special application for subsurface characterisation in civil engineering, ordinance detection, and geotechnical fields.[6–8] The central attraction of GPR is that it is non-invasive and non-destructive, and can provide instantaneous imaging of subsurface features. The basic principle of GPR involves transmitting energy into the ground and then measuring the reflections arising from the interface of materials with different dielectric values. The magnitude of the received reflection is dependent on the ground conductivity and permittivity, the size and shape of the target, and the difference between dielectric constants at a boundary. Voids, cavities, and other dielectric interfaces represent discontinuities that 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.

To date GPR has not been widely used the coal mining industry for coal depth measurement. This is largely because of the practical issues associated with making sensitive electronic equipment suitable for a rugged and hazardous coal mining environment and because of the complex nature of the radar signals returns from a GPR system. 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 utilised by non-expert personnel. Most commercial GPR systems are not suited to underground coal mining and do not provide automated real-time processing capabilities, and consequently rely on trained operators to manually interpret the raw radar data in an off-line capacity.[9]

Figure 2 shows typical raw GPR output with the sensor directed into free space. The main peak represents an antenna-air coupling characteristic. Clearly additional processing of the raw radar data is required in order to provide coal depth estimates for horizon control.

2.4. *GPR signal model and processing*

GPR-based coal thickness sensors rely on measuring the propagation delay from the sensor to the coalrock interface propagation delay and knowledge of the local coal geology. We first derive a model for the received radar signal by

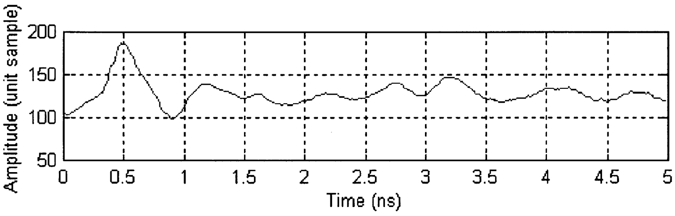


Fig. 2. Snapshot of raw GPR signal showing radar-air coupling characteristic.

considering the physical arrangement of the imaging scenario. The resulting set of equations lead to the associated processing tasks.

2.4.1. Radar signal model. The received radar signal can be modelled as[2]

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

where $W_0(t)$ is the radar-air coupling pulse, $W(m)$ is a lumped impulse response of the radar, 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 radar stretch index $k = 0, 1, \ldots$. The sequence $N_k(t)$ includes sensor and timing jitter noise. The sequence $R_k(t)$ is given by

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

where $a_k(n)$ is the magnitude of the echo and $\tau_k(n)$ is the pulse time delay for $n = 0, \ldots, p_k - 1$. The signal $R_k(t)$ is analogous to the reflectivity series found in seismic imaging.[10] Note also that this is an approximation since the pulse shape can vary depending on the material being imaged. Equation (1) represents the convolution of the basic pulse wavelet with the (scaled) reflection coefficients. In a given radar signal observation $Z_k(t)$, there may be $0 \leq n \leq p_k$ interfaces present. The underlying goal is to estimate $\tau_k(n)$ and p_k and in particular the first reflection, from observations of $Z_k(t)$ for all k. Figure 3 shows typical raw radar data, $Z_k(t)$, arranged as a sonar-style plot for $t = 0, \ldots, 479$ and $k = 0, \ldots, 999$.

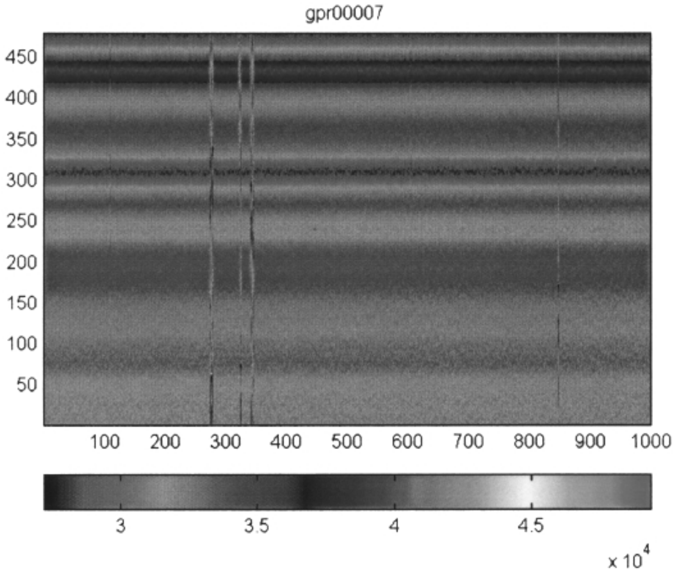


Fig. 3. Array of raw GPR data. The vertical axis represents time delay and the horizontal axis shows adjacent radar data while the sensor is held in a stationary position.

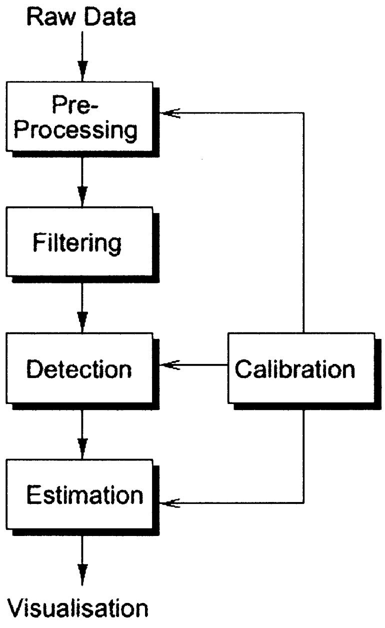


Fig. 4. Block diagram showing processing applied to the raw GPR data to provide coal depth estimates.

2.4.2. Radar signal processing. Figure 4 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.

(i) **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 radar signal attenuation characteristic 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 Equation (2). The second preprocessing step is to remove the transmitter-air/receiver coupling characteristic. An estimate of $W_0(t)$ in Equation (1) is made during initial system calibration by computing an ensemble average of $Z_k(t)$ over k assuming statistical stationarity of the raw returns over a nominated calibration interval.

(ii) **Filtering stage**

Since the movement of the mining machine is very slow with respect GPR sampling rate, Doppler effects are negligible and so

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

is a good approximation for $\nu = 10$–20 adjacent raw returns. 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 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[11] obtained from a suitable estimate of the basic radar wavelet $W(t)$. The small phase shift introduced for causality reasons is accounted for in the processed data.

(iii) **Detection stage**
The processed data is passed through a detection stage to determine potential dielectric interfaces. A time-domain sliding window energy detector 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 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 sets of peaks in a given realisation. This strategy represents a simple yet effective method for detecting the coal-tuff interface in an automatic manner, as well as being computationally efficient to facilitate real-time implementation.

(iv) **Depth estimation stage**
Given that the first echo represents the two way travel time for the coal-rock interface, an estimate of the coal depth is given by

$$d_n = \frac{c\tau_n}{2\sqrt{\varepsilon_c}}$$

for $n = 0, \ldots, p_k - 1$, where $\varepsilon_c \approx 4.5$ for coal. The processed radar data leads to a greatly simplified representation and thus acceptance of the technology to mining personnel. The data can also be meaningfully employed in more tracking and control schemes. It is important to note, however, that the radar data is subject to a wide variety of aberrations from the basic radar model: Nonlinearities, multiple reflections, heterogeneity variation, moisture variation, sensor and mining machine vibration, operator misuse, and sensor placement all contribute to measurement error.[2]

2.5. *GPR longwall application*

The GPR unit was applied to an underground coal mining machine known as a longwall shearer. The primary purpose of our tests was to establish whether the radar unit could be used as a sensor for horizon control in a coal mining scenario. To this end the GPR-based sensor was mounted on a longwall shearer at Dartbrook, NSW, Australia. The particular underground scenario had a problem that offered a long term potential for an automatic coal thickness measurement system. The floor of the seam being extracted consisted of a weathered clay layer with a high ash content (~80%). There was real benefit in cutting as close to the floor as possible as the coal immediately above the tuff layer was of high quality. However, if the tuff layer was mined, the ash content of the product increased dramatically.

The GPR processing system as a whole consists of three main components: the wideband (800 MHz) bistatic impulse radar, the data processing unit, and the visualisation system.[2] This antenna configuration produces a 5 ns data stretch, which results in high-resolution short-range (150 cm) echo data.[12] The complete GPR system was first assembled and tested on the surface. It was then transported underground and mounted on the longwall shearer as seen in Figure 5. The terms of the exemption for the operation of the GPR underground specified that the equipment could only be operated during maintenance periods.

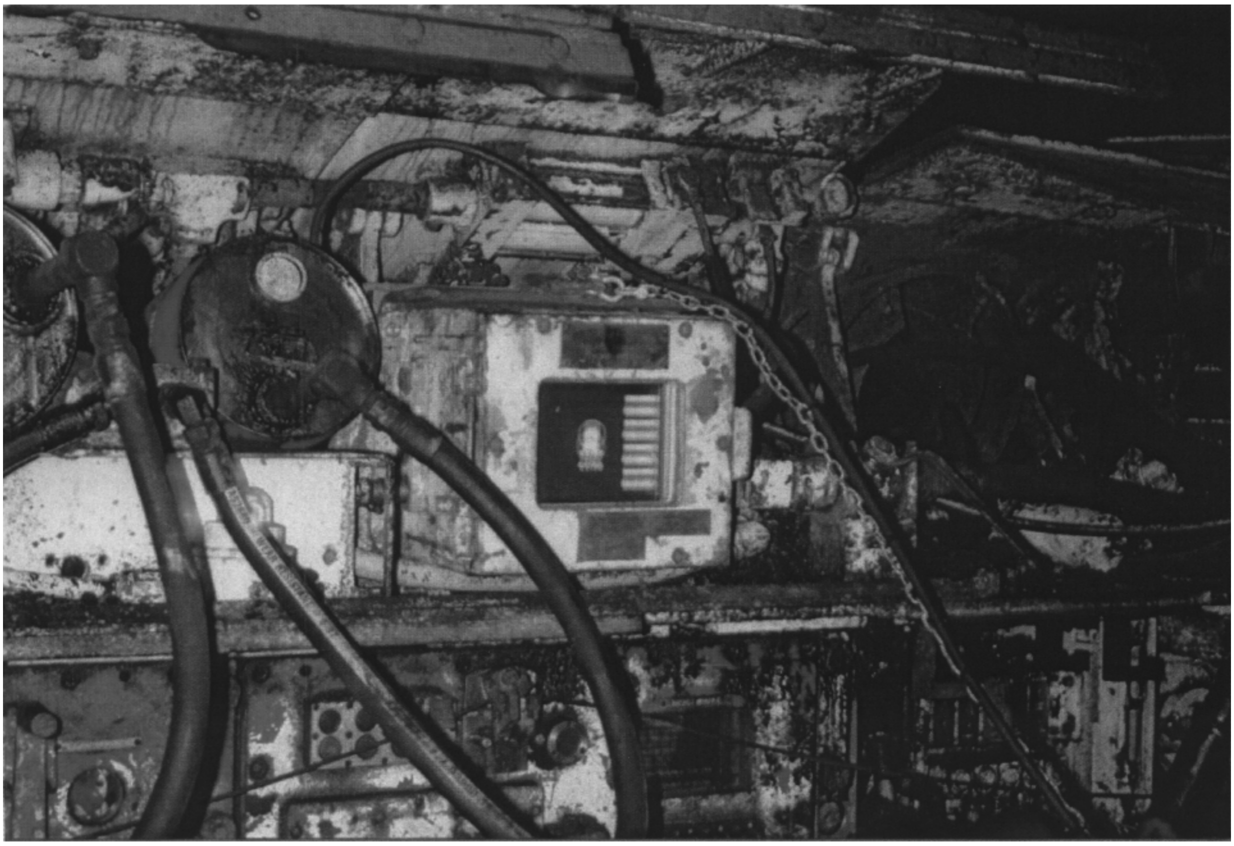


Fig. 5. The GPR processing and display unit mounted on the longwall shearer.

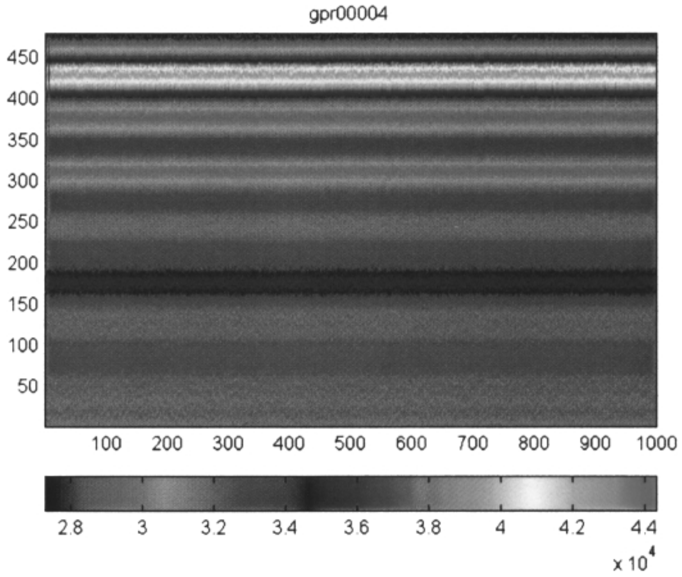


Fig. 6. Raw radar output display in the case where the coal-rock interface is out of the range of the radar. No reflection is observed.

2.5.1. Test procedure. Testing involved making coal thickness measurements in the area between the horizontal push rams of adjacent roof supports. The longwall shearer was moved to a position on the face where the remnant coal thickness exceeded the radar's nominal penetration depth. The radar unit was placed directly on the surface of the coal and the returns recorded. Figure 6 shows GPR echoes from an undisturbed region where the coal-rock interface was out of the GPR range (greater than 300 mm).

A test bench was constructed to manually establish a local floor horizon within the range of the instrument. Figure 7 shows the raw radar data at 100 mm coal thickness with the horizontal axis representing the coal-rock interface. The coal-tuff interface can be clearly seen in where the coal thickness is within the range of the sensor.

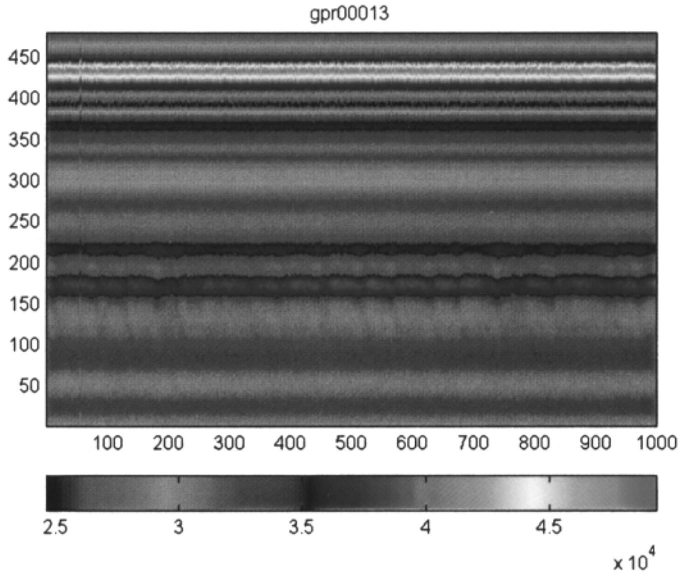


Fig. 7. Output from the GPR display unit in the presence of a coal-rock interface approximately 100 mm below the surface.

2.6. Considerations for underground use

Special design and construction corisiderations were necessary in order to make the radar processing system suitable for use in the harsh coal mining environment. In addition, the system need 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 8. Of special interest is the use of a non-metallic flameproof enclosure for the radar transmitter-receiver assembly. Clearly this was necessary as the use of a metallic enclosure would not permit transmission of the radar signals. The radar enclosure is made of a ruggedised carbon-based alloy of a sufficiently low dielectric constant so that the radar signals are not adversely attenuated, and is interconnected with the main flameproof via an armoured cable.

The GPR system must operate with as little operator intervention as possible (ideally none), be physically robust, comply to strict intrinsically 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.

2.6. GPR summary

GPR has the potential to solve an important coal depth estimation problem in the mining industry. A GPR processing system for coal depth measurement has been designed, built, and evaluated on a coal 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. Experiments conducted show that there exists a positive correlation between the coal-rock interface and known geology. The continued development of radar signal processing techniques is the key to improving the reliability and utility of the measurement system.

3. INERTIAL NAVIGATION SYSTEMS FOR HIGHWALL MINING

Highwall mining is an important method of coal mining in which a remotely controlled mining machine is driven into a coal seam that has been exposed by previous open cut operation. A continuous haulage system is use to carry the coal from the miner to an open-air installation for stockpiling and transport. The highwall mining process forms a series of nominally parallel, unsupported drives. Figure 9 shows a highwall mining machine in operation.

3.1. The need for lateral guidance

It is vital that the coal pillars remaining between adjacent drives are capable of supporting the overburden structure. This mining method is totally reliant on effective remote control. Straight, parallel openings at the tightest separation consistent with geotechnical design can only be achieved if the mining machine's position and heading can be deter-

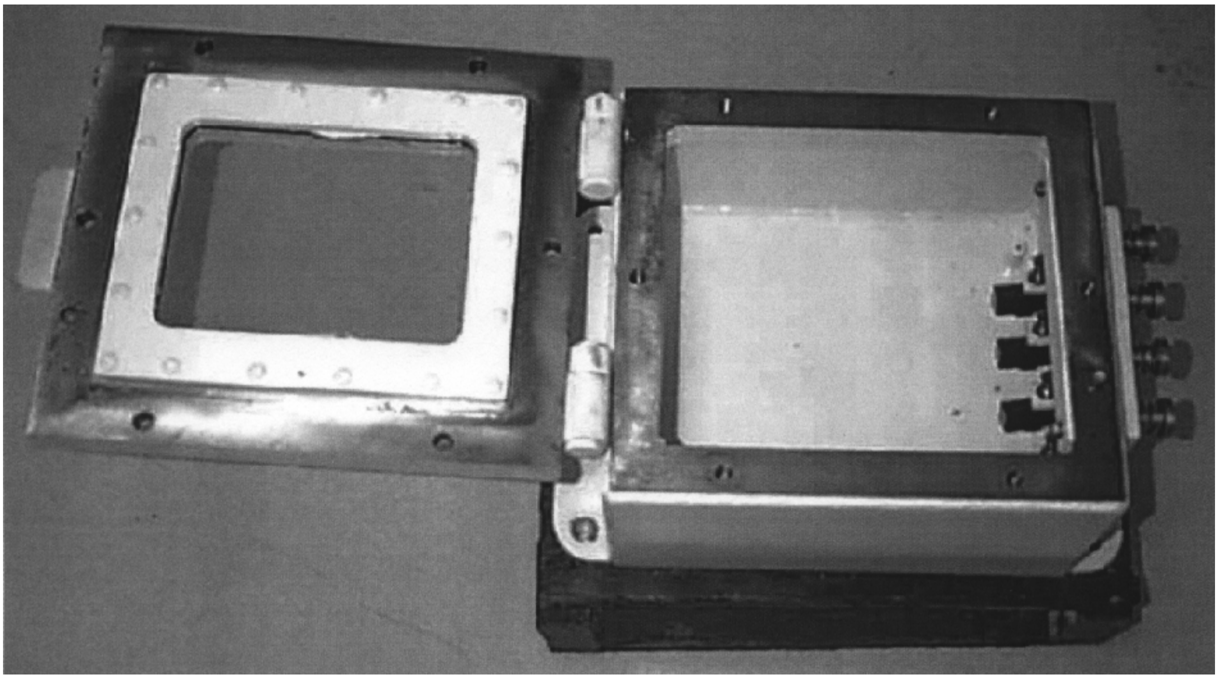


Fig. 8. Flameproof enclosure to house the signal processing and display components of the GPR system.

mined and controlled remotely. Figure 10 shows a plan view highlighting the lateral guidance problem associated with highwall coal mining.

A number of methods have been proposed for lateral guidance of highwall mining machines. Laser surveying offers the potential for accurate longwall machine position determination but site dependent issues such as visibility and line of sight mean that a general approach is not possible. Some opto/mechanical borehole-type surveying methods have been considered but also suffer from practical implementation difficulties because of the need for high accuracy angle measurements in a very inhospitable environment. Special purpose triangulation systems using radio propagation cannot achieve the required machine positional accuracy using the low frequencies required to penetrate the overburden. The limitations associated with the existing methods strongly suggest the need for a positional sensing system that requires only a minimal external infrastructure.

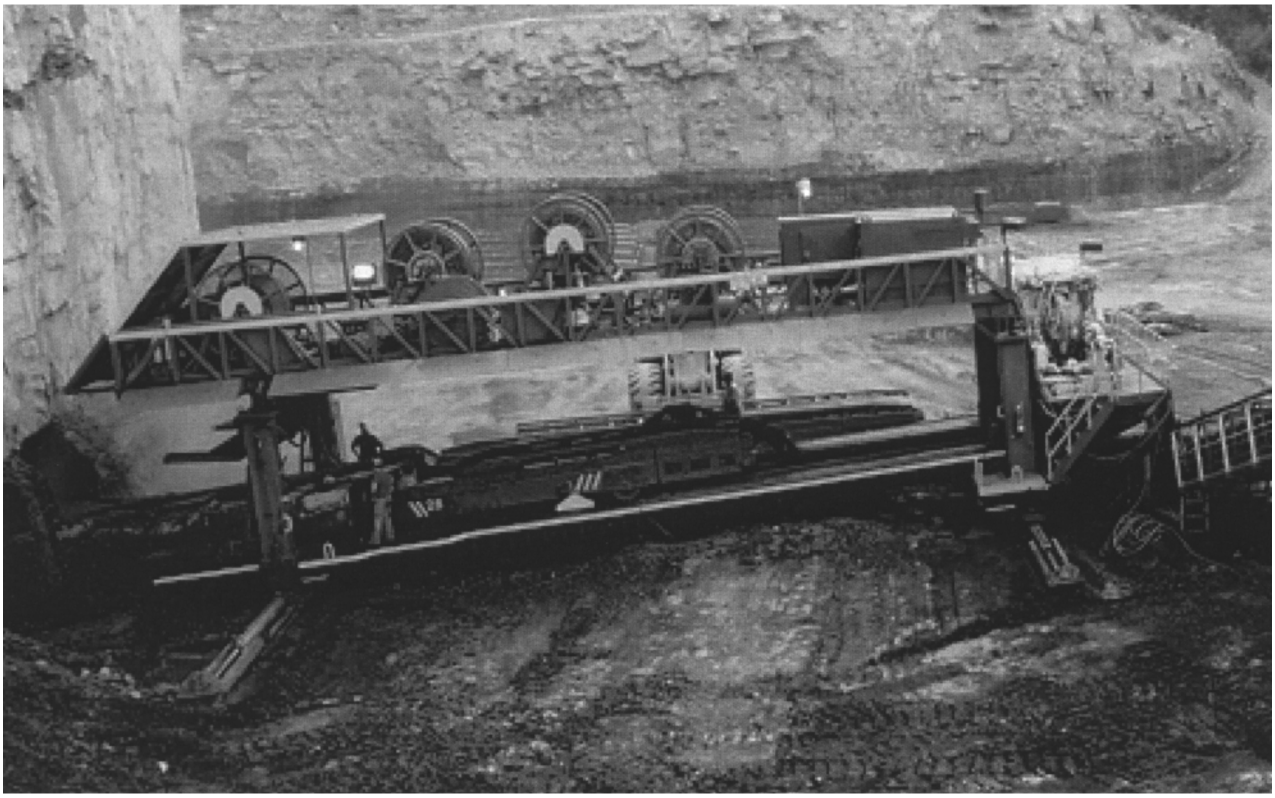


Fig. 9. A highwall mining machine creating a drive into an exposed coal seam.

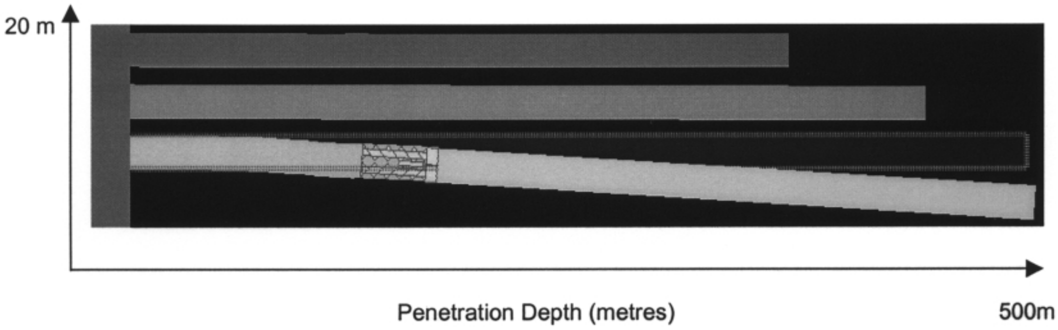


Fig. 10. The lateral control scenario encountered in highwall mining. The goal is to maintain a target heading in order to optimise coal recovery and ensure pillar integrity.

3.2. *INS for lateral guidance*

The use of an INS-based sensor can be used to provide absolute position of the mining machine without the need for any external positional information. A complete review of INS operational principles is outside the scope of this paper.[13,14] Modern inertial sensors have no moving parts and use solid state optical gyroscopes and accelerometers. This results in an inertial sensor that is highly resistant to vibration but internally requires more computation to produce heading and position data. By mounting the INS on the mining machine it would be theoretically feasible to follow a given target heading taken from a mine plan.

Most inertial units are used in one of two modes to provide either a full three-dimensional position survey or an azimuth-heading reference system (AHRS). The disadvantage of operating the INS survey mode is that it is necessary to frequently stop the unit to perform a zero velocity update (ZUPT) to allow the INS to trim accumulated accelerometer errors.[15,16] Even if the ZUPT requirement is stringently observed, the accumulation of residual errors will cause the position accuracy to degrade with time. All inertial-based systems drift because position is obtained by doubly integrating accelerometer outputs to provide a position estimate. These operations produce errors that increase with time. Figure 11 shows the magnitude of two-dimensional positioning error caused by INS drift characteristics over a 12-hour test period. The data was obtained while the INS was executing oscillatory motion about a fixed point on a gimble table. The large positional errors represent uncertainty in heading information which serves to limit the maximum allowable drive penetration depth. Figure 12 shows the direct penalty in terms of loss of recoverable coal that is incurred as a result of INS heading/azimuth uncertainty. The loss of potential coal recovery, coupled with production delays arising from INS ZUPT requirements, mean that no practical systems currently use guidance based solely on INS derived position.

3.3. *Navigation using INS and odometry*

An alternative approach is to combine INS heading information with an external along track distance measurement in order to derive relative machine position. In this mode of operation, the INS does not require ZUPTing and heading accuracy can be maintained over extended periods. Since heading information is obtained by a single integration of the angular velocity output of the high accuracy ring laser gyros, it is therefore more accurate than surveyed position and much less susceptible to drift. This method

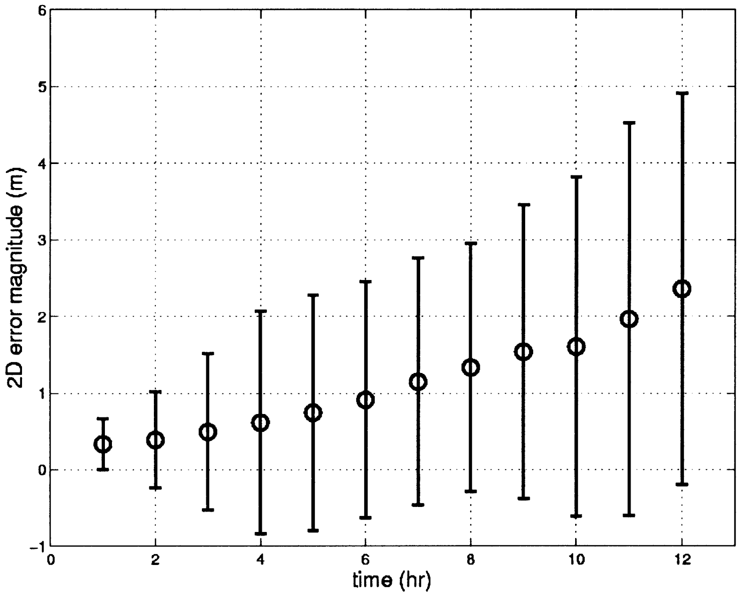


Fig. 11. Results of an experiment demonstrating the 2D positional error arising from INS. The gimble-mounted INS unit was executing oscillatory motion about a fixed point over a 12-hour period.

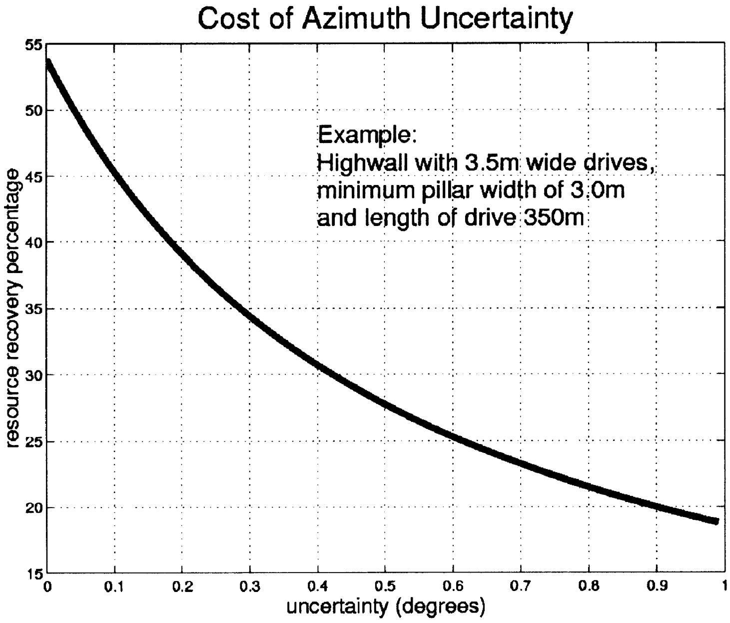


Fig. 12. Impact on recoverable coal as a result of INS heading uncertainty.

facilitates periodic corrections of the INS indicated position by zeroing accumulated errors using independent position fixes.

Work has been carried out using an INS in AHRS mode in highwall mining guidance using an odometer as the external along track distance sensor. Heading deviation is defined as the difference between the designed or desired heading for a particular highwall entry and the miner heading, which in this case is provided by an INS. The miner heading, and therefore heading deviation, is a function of along track distance which in this application can be measured by sensors external to, and independent of, the INS. The miner progressive cross track deviation can be calculated as the integral of the sine of heading deviation with respect to along track distance. The progressive cross track distance describes the path of the miner relative to the designed path. If the cross track deviation, designed heading and entry separation are known for two adjacent entries, it is a simple matter to compute pillar thickness at any point along the entries.

3.4. *Guided continuous miner application*

The combined INS and odometry lateral guidance system has been used on a production highwall mining system at the Moura mine, Queensland, Australia. The system allows the position and path of the highwall miner to be displayed graphically and numerically in real-time to an operator. The thicknesses of adjacent pillars are inferred from the mapping software. The operator has access to instantaneous values of along track, heading deviation, cross track deviation and pillar thickness. Figure 13 is a plan view of the lateral guidance software, which shows both mined and planned drives. The desired drive headings are shown as a dotted lines and cross-hatched region represents drives that have been mined.

The introduction of the lateral guidance system has increased resource recovery by 40% and virtually eliminated the incidence of unplanned drive intersections. Drive penetration depths over 500 meters are now routinely and reliably obtained, as compared with previous drive depths of less than (an inconsistent) 300 metres. Cross track errors in drive entries of the order of 500mm after 500m penetrations have been achieved using the system.

3.5. *INS summary*

The use of INS for lateral guidance of a mining machine was investigated. It is concluded that drift, accuracy, and operational limitations mean that it is unlikely that miner guidance can be based on INS alone. However, heading information combined with along track measurement (odometry) can give accurate guidance and control. The need for guidance is well appreciated by the industry. Heading information, and in general orientation, can be combined with along track measurements to derive cross track

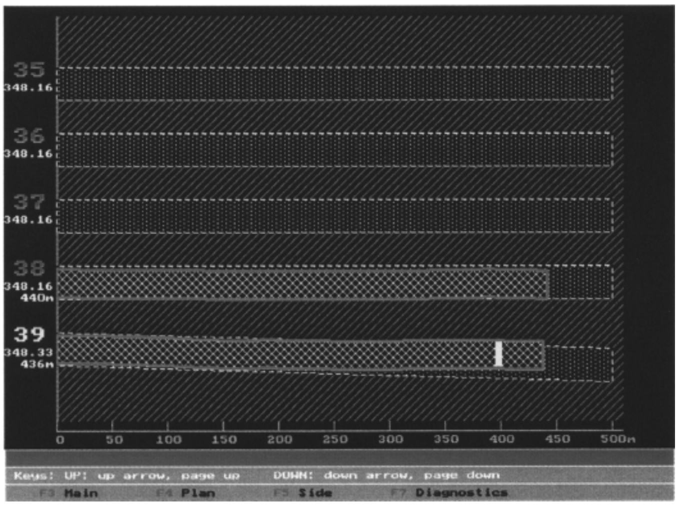


Fig. 13. Highwall miner operator's display screen showing the actual path of the mining machine (cross hatched region) compared with the designed path (dotted region) for adjacent drives.

deviation, and therefore the lateral position and path of the miner. The path of the miner in the vertical plane can be derived from pitch information in a similar manner. Applications of the INS-based lateral control system on three separate production highwall mining operates have proven the validity of the approach. Significant improvements in productivity and safety have resulted from the application of the INS-based lateral guidance system.

4. THE NUMBAT MINE SAFETY VEHICLE

One of the most significant problems following a mine incident is a lack of knowledge regarding the geological integrity and environmental condition of the mine. This uncertainty, coupled with a reluctance to compromise personnel safety, invariably leads to losses in mining productivity and may even cost lives.[17,18]

The Numbat mine emergency response vehicle was developed by the CSIRO following the Moura mine explosion in 1986.[19,20] It is a remotely controlled vehicle used to convey information on the condition of underground mines in situations where it is too hazardous for manual exploration. The primary purpose of the Numbat project is to provide rescue teams with immediate information on underground mine conditions after an emergency incident. Sending the Numbat vehicle into hazardous areas instead/ahead of mining rescue teams not only minimises risk to personnel, but also provides an invaluable source of information regarding the mine's environmental state.[21]

The Numbat integrates a diverse range of communications, actuation, mobility, power, control and software technologies. The Numbat system consists of a mobile surface control station and a remotely controlled mine emergency surveying vehicle. Recent upgrades and improvements to the Numbat's hardware, software, and mechanical design have been made to enhance the capabilities of the vehicle. A special emphasis has been placed on increased system modularity, re-configurability, and ease of maintenance.

Figure 14 shows the configuration and interconnectivity of the Numbat vehicle and surface station core functionality. The vehicle computers act as slaves with respect to the surface computer. All computers are ruggedised to withstand vibration and harsh treatment. An optical fibre link provides bi-directional communications between the surface station and the Numbat. Three x86-based computers running real-time UNIX are used for real-time control and processing; one in the surface control station and two mounted in the Numbat vehicle.

4.1. *Surface control station*

The Numbat is remotely controlled in real-time from a portable control station located near the mine entry. The air-conditioned control station houses all of the computers, communication racks, video display units, and monitoring equipment required in teleoperating the Numbat vehicle. Figure 15 shows an inside view of the control station, which readily accommodates 3-4 people and maintenance equipment.

An operator controls the Numbat through the use of video cameras, joystick, control panel, and graphic user interface located in the control station. The surface station is used to remotely control all aspects of the vehicle. It is also

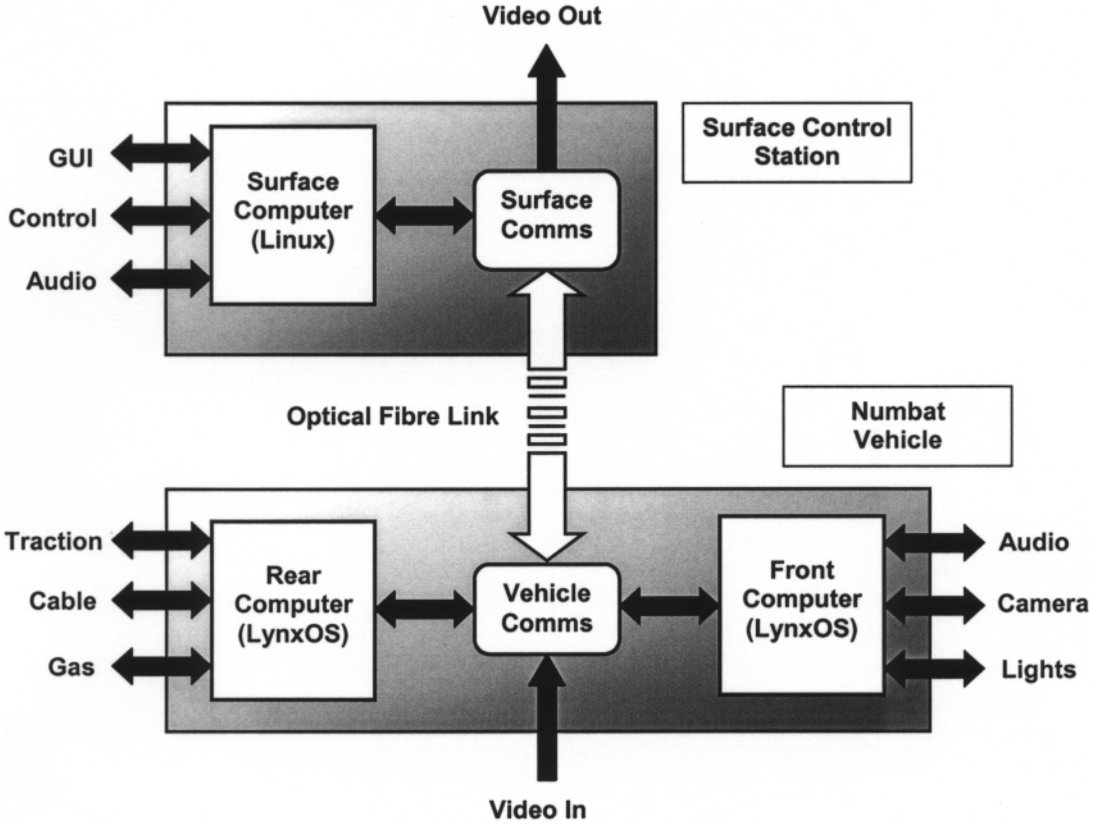


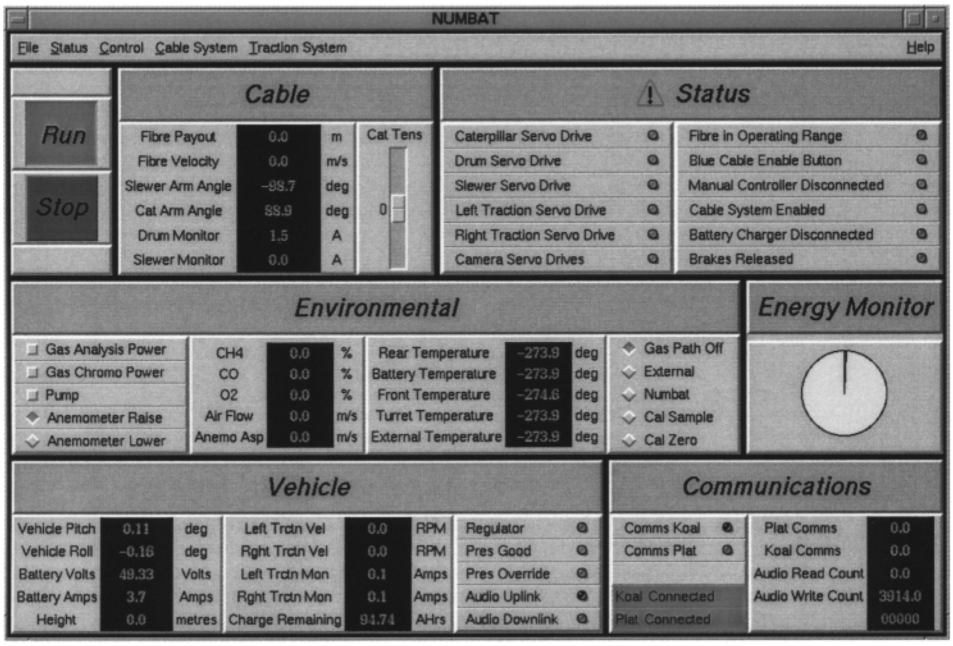
Fig. 14. Architectural overview of the functionality and interconnections of the Numbat surface station and vehicle.

Fig. 15. An inside view of the Numbat surface control station.

responsible for the management of the graphic user interface (GUI) and a real-time audio uplink/downlink to the vehicle. The main operator GUI is shown in Figure 16. The environmental conditions of the mine, telemetry data, two-way audio, system status, and video information are constantly relayed from the vehicle to the surface station. Normal navigation uses four video cameras mounted on the Numbat vehicle. The Numbat can also be controlled directly via a plug-in control module on the vehicle.

4.2. *The Numbat vehicle*

The Numbat is an eight-wheeled vehicle with a base measuring 2.5 × 1.65 metres. It is designed to traverse rough terrain and operate in extremely harsh underground mining



Fibre Payout 0.0 m
Fibre Velocity 0.0 m/s
Slewer Arm Angle −98.7 deg
Cat Arm Angle 88.9 deg
Drum Monitor 1.5 A
Slewer Monitor 0.0 A
Cat Tens 0

☐ Gas Analysis Power
☐ Gas Chromo Power
☐ Pump
◆ Anemometer Raise
◇ Anemometer Lower

CH4 0.0 %
CO 0.0 %
O2 0.0 %
Air Flow 0.0 m/s
Anemo Asp 0.0 m/s

Rear Temperature −273.9 deg
Battery Temperature −273.9 deg
Front Temperature −274.6 deg
Turret Temperature −273.9 deg
External Temperature −273.9 deg

◆ Gas Path Off
◇ External
◇ Numbat
◇ Cal Sample
◇ Cal Zero

Vehicle Pitch 0.11 deg
Vehicle Roll −0.16 deg
Battery Volts 49.33 Volts
Battery Amps 3.7 Amps
Height 0.0 metres

Left Trctn Vel 0.0 RPM
Rght Trctn Vel 0.0 RPM
Left Trctn Mon 0.1 Amps
Rght Trctn Mon 0.1 Amps
Charge Remaining 94.74 AHrs

Plat Comms 0.0
Koal Comms 0.0
Audio Read Count 0.0
Audio Write Count 3914.0
00000

Fig. 16. The main operator GUI for Numbat teleoperation.

environments. A picture of the Numbat vehicle is shown in Figure 17. Pairs of wheels mounted on rocker arms move independently over rough surfaces. Vehicle direction is achieved through skid steering. This configuration serves to keep all wheels on the ground while the vehicle is traversing rough terrain. The vehicle is designed so that it can propel itself across water obstacles and flooded roadways.

There are a number of gases encountered in underground mines which, in certain concentrations, will explode if given a source of ignition. As a result, all components of the Numbat are internally isolated and enclosed in a sealed body that is pressurised with nitrogen.

The control and functionality of the Numbat is distributed across two computers located in the front and rear of the vehicle. The rear computer is responsible for the cable reeling control system, the mobility and steering (traction) control system, and for controlling the environmental monitoring package. The front computer is responsible for activating emergency breakers, system power management, lights, real-time audio communications, and camera pan and tilt movement.

The traction control system uses two velocity control systems to provide steering and mobility for the Numbat. The control systems are distributed to separately control the left and right hand pairs of wheels. The vehicle has considerable traction that enables it to traverse rough terrain. Failsafe braking is achieved through the use of energise- to-release braking mechanisms.

4.3. *Onboard sensing equipment*

The Numbat uses two main classes of sensors to survey the environmental condition and infrastructure of the mine, namely atmospheric transducers and video cameras. The Numbat also has a number of other onboard sensors for monitoring vehicle attitude, hardware status, power supply condition, and so on.

The Numbat has an onboard gas analysis package to provide information on the environmental condition of the mine. The gas analysis package constantly performs analyses to determine concentrations of methane, oxygen, carbon monoxide, carbon dioxide, and hydrogen in the vicinity of the vehicle. Other important environmental parameters such as internal and external temperature, atmospheric pressure, and ventilation air speed are also monitored. This information is then relayed and displayed to operators in the surface control station. The Numbat vehicle has four video cameras mounted for remote guidance. Two of the cameras are fixed and permanently face the front and rear of the vehicle. The rear camera proves to be particularly useful for monitoring the status of the cable reeling system. The two other cameras are mounted in a turret that is remotely panned and tilted as required for guidance by the operator.

An active thermography (infrared) system is also being evaluated to enable the Numbat to see through smoke and dust. Airborne disturbances in underground mines frequently obscure conventional camera images, making remote navigation and guidance extremely difficult. The need for an active thermography system arises because the surfaces in underground mines do not always exhibit sufficient thermal differentiation to permit sufficient terrain perception.

A non-contact proximity laser scanner (PLS) was used with the Numbat to evaluate the possibility of autonomous or semi-autonomous navigation capability. The laser range finder was mounted onto the Numbat's turret and evaluated at underground mine test track at CSIRO in clear conditions. Figure 18 shows the laser range finder data as the Numbat approached a junction in the test track. The range sensor provided a navigation headlight range of approximately 50 meters The white region of the image represents open area ahead of the vehicle that is scanned by the laser. The clarity of the returned data clearly indicates the potential for

Fig. 17. The Numbat mine emergency response vehicle.

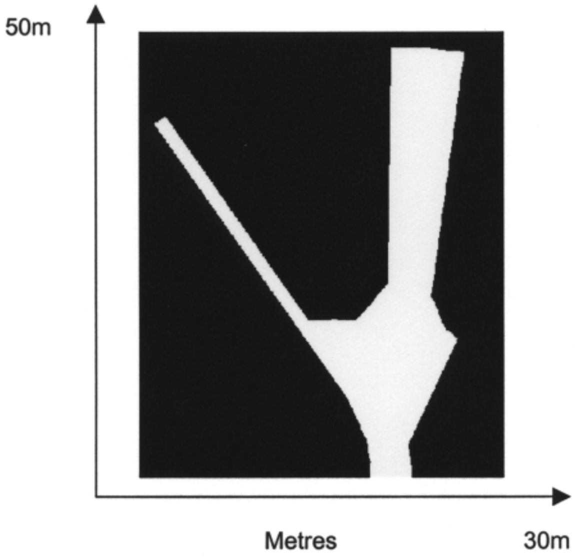


Fig. 18. Returned laser range finder data as the Numbat negotiates a junction. The data can readily be used for navigation and path finding.

autonomous navigation and path finding. The Numbat was always intended to be a teleoperated vehicle to assist mines rescue teams as distinct from a fully autonomous robot. It should be noted, however, that partial autonomy is not technically inconceivable given current mapping and collision avoidance technologies.[22]

4.4. *Optical fibre communications link*

One of the more interesting aspects of the Numbat is the form of communications link. The Numbat frequently needs to drive several kilometers into the mine in order to reach the incident site. This need, coupled with strict intrinsically safe equipment requirements, essentially precludes the use of conventional trailing-type communication cables or radio beacons. To meet these link requirements, the Numbat communication system employs optical fibre technology.

The Numbat communication system uses an umbilical-based communications system consisting of 10 Kilometre length of Teflon strengthened optical fibre. Optical fibre communication racks and protocol converters are located in the surface control station and the Numbat vehicle. This link provides an independent, high bandwidth, low-latency communications system. The optical fibre is surprisingly robust and has proven to be reliable media for communications. The Numbat communications system currently uses four independent colour video channels and one T1 (1.54 Mbits/sec) data channel. The communications system has sufficient bandwidth to support up to 32 colour video channels.

The data communication channel provides the backbone for system message passing and audio services between the surface and vehicle computers. To maximise connectivity and modularity, the communications are configured to provide a UTP Ethernet port-to-port network. This arrangement also permits ease of system maintenance and makes the addition of devices such as inertial navigation units, laser imaging systems, or manipulators possible.

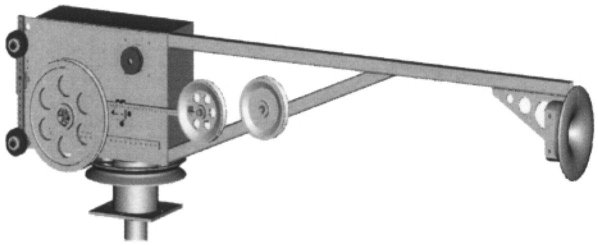


Fig. 19. The fibre payout arm located at the rear of the vehicle.

4.5. *Optical fibre payout system*

The optical fibre payout control system is responsible for feeding out and feeding in a trailing optical fibre. Figure 19 shows the cable payout arm, which is mounted at the rear of the vehicle.

The control system maintains the correct tension on the optical fibre when the vehicle is in motion and at rest. The payout system uses a cascade of two separate control systems: one for control at the payout arm and the other for management at the reeler drum. This is required as the fibre tension at the payout arm is much less than that required for winding on the reeler drum. The caterpillar wheel mounted on the fibre payout arm provides the necessary tension conversion between the two systems.

The payout control system infers fibre tension via the angle of tension arms, which are mounted on the payout arm and near the internal drum assembly. The fibre payout system must also account for a nonlinear relationship between the fibre tension and the measured tension arm angle. The cable payout distance is transduced via an encoder mounted on the caterpillar drive. The payout arm uses an independent control system for angular position.

Figure 20 shows the drum assembly located in the centre of the Numbat vehicle. The fibre tension is maintained by the drum and tension arm control systems. In order to allow the transfer of optical signals across the rotational interface between the drum and the internal communications network, the Numbat uses a novel fibre optic rotary joint.

4.6. *Software system*

Figure 21 shows an overview of the software model employed in the Numbat project. Considerable effort has been made to make software as modular and reliable as possible. The software system utilises the concept of a centralised system executive to control and coordinate the activities of the various system tasks, called workers. The point of a mission critical system is to recognize that software failures might occur and design the system as much as possible to survive them in some intelligent way. For reasons of robustness and safety, the Numbat software uses a number of integrity monitors and watchdog functions.

The central executive. The central executive is responsible for the flow control and management of the system. All requests are submitted to the central executive via a message queue structure, which mediates to resolve the appropriate response. While all requests must go through the central executive, the underlying implementation of this function is quite efficient and therefore does not result in the bottleneck

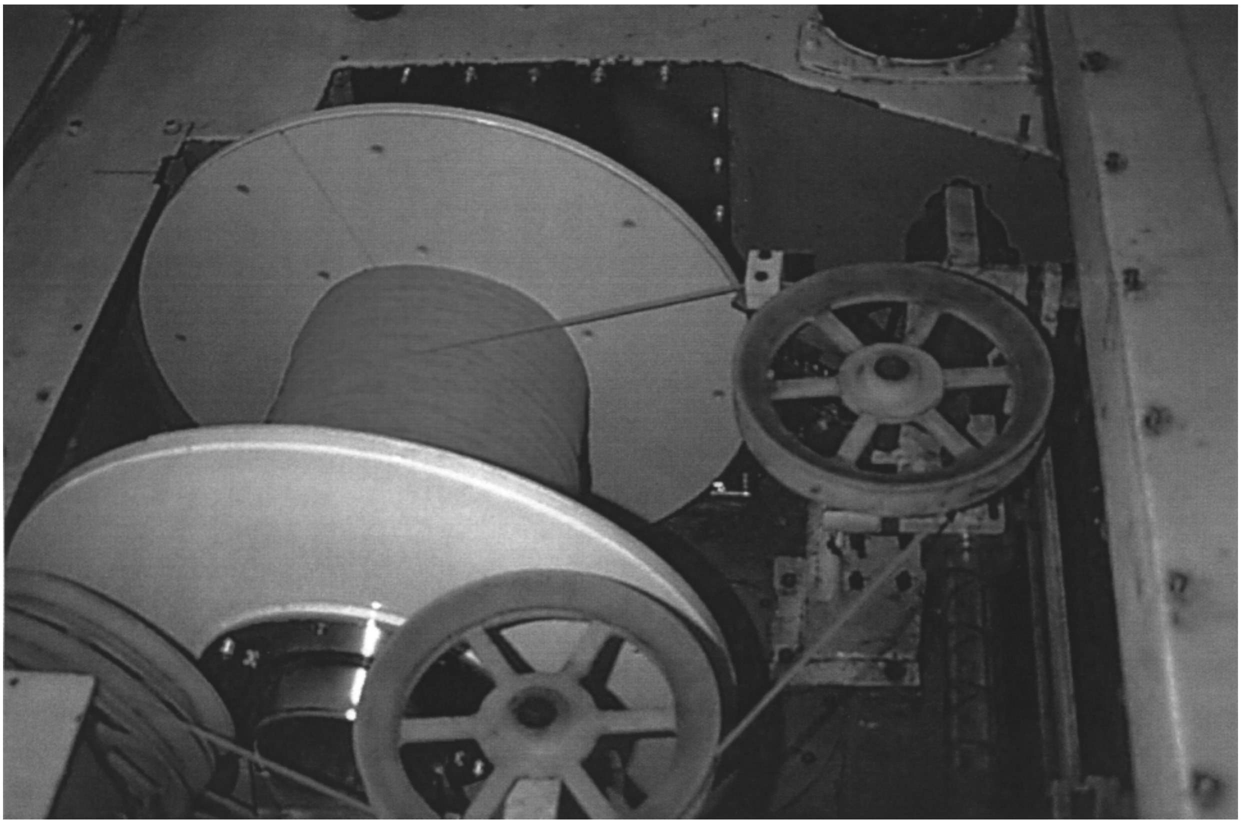


Fig. 20. The automatic optical fibre reeling system showing the drum assembly and diamond bar reeving mechanism.

found on some centralised control systems. The advantages of this control paradigm are that it is simple, highly deterministic, and easy to reconfigure as necessary.

The worker. A number of tasks need to be simultaneously performed by the computer systems: Servicing of socket oriented communications, reading from and writing to a variety of hardware devices, integrity monitoring, updating control algorithms and so on. Many of these functions may delay or block awaiting data, and so the use of traditional cyclic executives or polling would require additional timing, synchronisation and scheduling mechanisms in order to achieve the desired result. Instead, the Numbat software uses a multithreaded approach, scheduled via a real-time UNIX operating system. While the central executive has complete access to all worker resources, individual workers are restricted to use to their own resources. Each worker is therefore acts as an independent thread of execution with a preassigned execution priority.

Message queuing and control. The message queue approach provides a powerful priority based mechanism for

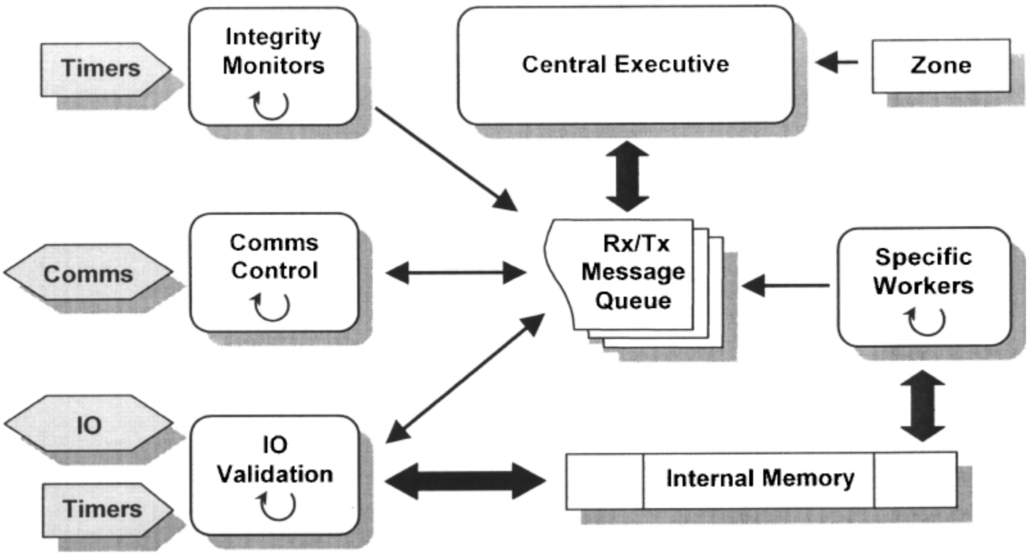


Fig. 21. Block diagram showing internal structure of software flow and management. A similar software control paradigm is utilised for the vehicle and surface programs.

inter-thread, process and system communication. Synchronous and asynchronous requests from internal and external sources are enqueued in the receive message queue (and thus never lost). These requests are subsequently delivered, in priority order, to the central executive in a simple and uniform manner. The message queue approach also facilitates the introduction of new components into the system function with minimal effort. Outgoing messages to other computers are managed in a similar fashion.

4.7. Numbat summary

The Numbat draws together a diverse range of sensing, communications, control, mobility, powering, and real-time software technologies. These components are integrated and managed in software through an efficient rule-based scheduling executive. Considerable emphasis has been given to the resolution of software modularity to provide system determinism and robustness. A key feature of the Numbat is its unique communication link which provides both real-time control of the Numbat vehicle as well as relaying information to the control station concerning the condition of the immediate environment.

5. CONCLUSION

The coal mining environment presents a unique set of theoretical and practical challenges for mining equipment automation. To date, most emphasis on mining automation has focused on a sensor-based, computer-assisted, machine control, communication and guidance systems. Here the operational tasks are shared between a remotely-located human operator and a multi-sensor processing and display system, providing a so-called "man-in-the-loop" control. This technology naturally involves the integration of communication systems, position and navigation, process engineering, mapping, monitoring and troubleshooting utilities, and control and guidance systems. This has been successfully applied to a highwall mining operations.

The automation task naturally requires the use of a diverse range of sensors and systems in order to deliver useful guidance and communication systems. Highly robust software is also required to integrate, process, display, and communicate such data. Integrated multisensor sensor systems are seen to be the key in providing reliable solutions to the underlying lateral and horizon control problems. Two sensors were discussed in detail, namely ground penetrating radar and inertial navigation systems, which can be used to maintain the mining operation in the coal seam through lateral and horizon guidance. Both of these sensing technologies have been successfully used in real coal mining scenarios. A novel teleoperated robot was also presented which serves in a novel role for mine safety and remote surveying tasks.

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