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Longwall automation: Delivering enabling technology to achieve safer and more productive underground mining

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ABSTRACT

The ongoing need to deliver improved safety, productivity and environmental benefit in coal mining presents an open challenge as well as a powerful incentive to develop new and improved solutions. This paper assesses the critical role that enabling technologies have played in the delivery of remote and automated capability for longwall mining. A brief historical account is given to highlight key technical contributions which have influenced the direction and development of present-day longwall technology. The current state of longwall automation is discussed with particular attention drawn to the technologies that enable automated capability. Outcomes are presented from an independently conducted case study that assessed the impact that CSIRO's LASC longwall automation research has made to the longwall mining industry in Australia. Importantly, this study reveals how uptake of this innovative technology has significantly benefitted coal mine productivity, improved working conditions for personnel and enhanced environmental outcomes. These benefits have been widely adopted with CSIRO automation technology being used in 60 per cent of all Australian underground operations. International deployment of the technology is also emerging. The paper concludes with future challenges and opportunities to highlight the ongoing scope for longwall automation research and development.

1. Introduction

1.1. CSIRO mining strategy and rationale

Industrial Research Organisation (CSIRO) undertakes mission-directed research to promote transformational change in the Australian mining and resource ecosystems. The vision is to secure a clean energy future in order to sustain long term benefits across environmental, economic and societal sectors. The fundamental approach has been to collaborate with industry, research organisations and government to create cost-competitive, low-emission energy technologies. A vital component of this strategy has been the development of remote and automated mining technologies to achieve safer, more productive and more environmentally sustainable coal mining systems. Coal accounts for around 24% of employment and 27% of total revenue for the Australian mining sector. Longwall coal mining, in particular, accounts for around 90% of Australia's total underground coal production and thus represents a major interest area for innovative research and development.

1.2. Longwall coal mining process

Longwall coal mining is a full extraction underground mining method that involves the removal of coal in large blocks or panels using a mechanised shearer. The coal panel is typically 200–450 m wide and can be up to five kilometres in length. The mechanical shearer is mounted on a shearer pan and rails which guide the shearer as it moves back and forth along the coal face. Coal cut from the longwall face by the shearer is removed by an Armoured Face Conveyor (AFC) that transports coal to the adjoining gateroad for conveyance to the surface.

The roof over the working area is supported by hydraulic shields that are advanced towards the freshly cut face according to a well-defined motion configuration. As the roof support system advances into the coal panel, the roof behind the shields is no longer supported and is thus allowed to collapse into the void (goaf) behind the shields. For reference, a representation of a small portion of a longwall operation and shearer is shown in Fig. 1. The coal seam is indicated by the hatched layer between the underlying and overlying strata.

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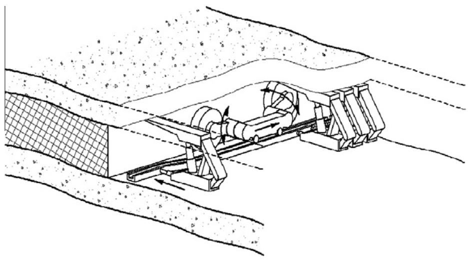

Fig. 1. Cut-away view of the underground longwall mining process (the shearer is in centre view, mechanised roof supports to the left and right, and embedded in coal (hatched) and host strata (dots)).

1.3. Need for improvement

Despite the high potential productivity associated with longwall mining, the operational environment presents many hazards to personnel, including proximity to machinery, hydraulic and electrical power, roof falls and exposure to explosive mine gases and dust. Miners have for decades been required to work in this hazardous environment to manually control the equipment at close range in an attempt to achieve an efficient mining operation. However, ensuring the optimal orientation of the longwall face and equipment is critical: a need to stop production periodically to carry out manual adjustments reduces operating machine time and thus is a lost opportunity. Further, extraction needs to be maintained in the coal seam: failure to correctly position the shearer drums can lead to loss of coal recovery and/or unwanted spoil (rock) diluting the coal product. Either of these events reduces the efficiency of the mining process. Thus the complexity of manually operating equipment of this scale has led to suboptimal product recovery and potential health and safety concerns for personnel.

Underground mining operations have consistently expressed the view that the longwall is the prime profit centre. Any automation effort therefore needs to achieve a high level of production consistency and reduce the exposure of personnel to respirable dust and other hazards. This safety aspect of automation is important as most high production faces often find statutory standards difficult to achieve, even with advanced dust control techniques. The industry recognised that this was increasingly unacceptable and unsustainable in the long term and sought answers to these problems.

Mining automation technology demonstrates significant potential to provide meaningful solutions to this problem by facilitating more accurate mining methods, incorporating sensing to optimally control equipment, and increasing personnel safety through remote process operation. However many previous attempts at achieving longwall automation were not sustainable, lacking the necessary degree of technology readiness [1].

CSIRO has successfully developed ways to help automate longwall mining through the introduction of innovative enabling technologies. Elements of these technologies, known in the industry as Longwall Automation Steering Committee (LASC), have been taken up by all major longwall Original Equipment Manufacturers (OEMs) under technology licensing agreements with CSIRO. Each OEM has incorporated the LASC open intercommunication standards into their proprietary control system architecture and shearer manufacturers have integrated the core automation hardware systems into their equipment. This paper details these innovative technology developments and describes their practical impact on the underground coal mining industry.

1.4. Paper overview

The paper begins with a brief historical review of the automation-centric initiatives which played an important role in the development of longwall automation capability. The drivers and outcomes of these efforts are then described. An overview of the state of current automation research and development is given with a specific focus on innovation and impacts associated with LASC automation technology for Australian longwall operations. A case study is given to highlight the technical and industrial impacts associated with the introduction of LASC automation technology. Finally, new and emerging trends are presented to highlight both the ongoing challenges as well as opportunities that exist to support safer and more productive underground mining.

2. Longwall automation history

This section overviews the major historical drivers of, and developments towards, present-day longwall automation technology. Whilst many initiatives did not manage to fully realise their overall aim or scope, collectively these efforts proved to positively influence both mining culture and industry confidence in the use of technology for longwall automation. This historical background provides an ideal context to describe the automation research and development undertaken by CSIRO to improve the safety and productivity of longwall mining.

Since the 1960s there have been a number of attempts worldwide to develop longwall automation systems [2,3]. These had been largely unsuccessful because it had not been possible to accurately and reliably measure the positions in space of the principal elements of the longwall. This information is fundamental to automation because unless the current location of equipment is known it is impossible to command the equipment to travel on a desired path. The CSIRO research team realised that if the position of the longwall shearer could be measured continuously in three-dimensions, the path the shearer takes in the mining process would then enable the positions of all the individual powered supports and, moreover, the track of the mined roof and floor, to be calculated. This was a breakthrough in the evolution of mining automation.

2.1. Remotely operated longwall face (ROLF)

The drive to develop remote and automated capabilities for longwall operations can be traced back to as early as the 1950s in the British underground coal industry. Here, interestingly, the primary driver for automation was not safety or efficiency per se but rather as a strategy to support the rationalisation of wage structures for workers in the coal industry. At the time, mining was largely a pick-and-shovel process, but mechanisation was being rapidly (but not uniformly) introduced. This change was leading to wide disparities in task equity and remuneration for mining personnel [2,4].

Ongoing negotiations involving the British Government, the National Coal Board and Unions eventually led to a National Agreement in 1955 based primarily on the concept of a *Remotely Operated Longwall Face*, colloquially referred to as 'ROLF' [2]. It was thought that if such a system could be developed, then task and wage equity would be immediately achieved as it would be machines, not men, fundamentally dictating performance. By 1960, the notion of a "manless face" was even being discussed, together with the tantalising prospect of coal production becoming a simple "push-button operation". The National Coal Board was charged to undertake the research into the development of a ROLF system. Pioneering experiments were conducted in the early 1960s in an attempt to develop the ROLF capability.

After a number of attempts at technology development, it was clear that ROLF simply did not have the level of maturity and performance necessary for production conditions. The lack of suitable sensing, computation, and remote-control technologies also contributed to this outcome. As a result, ROLF was soon withdrawn from practical use due to limitations in achievable performance [3]. It should however be noted that ROLF, as a vision, was in fact well ahead of its time.

2.2. A mine operating system (MINOS)

After ROLF, the National Coal Board continued to conduct ongoing research and developments to mechanise and automate coal mining processes. In the early 1970s, a new interest emerged to develop a framework that could support standardisation, promote reusable software, and increase systems reliability [5]. Known as the Mine Operating System (MINOS), the intended scope of the initiative was to extend to the incorporation of all mining operations including production, transport, environment and ancillary equipment operation [4]. MINOS aimed to reduce repair and maintenance costs, improve output quality, improve monitoring and information, eliminate human error, and increase safety levels for personnel [5]. MINOS represented a distributed systems architecture consisting of a number of mining subsystems that could be managed as independent modules. New developments in microprocessor capabilities aided MINOS implementation.

A number of experimental installations and pilots were conducted during the 1970s and early 1980s [6]. MINOS however lacked the critical sensing and processing capabilities required to achieve effective closed-loop mining control and was disbanded by the mid-1980s. MINOS, like ROLF, was perhaps well ahead of its time. Its introduction, however, promoted a step change in the performance and cost base of research in the industry.

2.3. USBM mining research

Mining research undertaken by the United States Bureau of Mines in 1980s made a number of pioneering advances in the development of remote and automated mining capability. Amongst other research, important technology trials were conducted to assess the performance of inertial navigation for mining guidance [7]. However, the researchers were unable to achieve the required accuracy and no commercial solutions were developed. The closure of the Bureau of Mines in 1995 and transfer of some of its activities to the National Institute of Occupational Safety and Health (NIOSH) resulted in drastic changes in the mining research focus, effectively terminating further development in mining guidance technology.

2.4. CSIRO guidance system development

In 1994, CSIRO reviewed global research into technologies to help automate and control longwall mining equipment. This systematic review showed that research had mainly been undertaken by government research institutions in the United States, United Kingdom, Germany, France and South Africa [8]. However, at that time there had been few useful outcomes from any of that research. Whilst it is possible that other individuals or organisations may have been attempting to develop technologies to support longwall automation, such outcomes, if any, were not apparent or accessible to industry. It is difficult to determine if or when such technologies might have emerged in the absence of CSIRO's activities.

During the 1990s, CSIRO convincingly demonstrated the use of inertial navigation techniques for the guidance of underground equipment in highwall mining [9]. Highwall mining is a remotely controlled mining method which extracts coal from the base of an exposed highwall, typically via a series of parallel entries driven to depths in excess of 400 m within the seam horizon. The method allows recovery of coal from surface pits that have reached their final highwall position due to uneconomic stripping ratios, or in areas where coal has become sterilized in, for example, service corridors [10]. The highwall mining scenario represented a very specific mining application where the motion of the mining equipment was largely constrained, meaning that navigation performance could be achieved using a conventional inertial navigation system (INS) and standard processing algorithms. The guidance technology was successfully applied to several different highwall mining scenarios using single auger, dual auger, and continuous miner highwall mining configurations [9,10]. This localisation technology continues to be applied extensively for highwall mining guidance with major deployments in the United States [11].

The confidence gained through the highwall guidance scenario led CSIRO to explore the technology for automating the longwall mining process. CSIRO's ground-breaking innovation in this area was to recognise and subsequently demonstrate that the position of all the relevant components in the longwall system could be inferred accurately from a 3D measurement of the position of the shearer component. In the late 1990s, CSIRO successfully patented an innovative application of INS for underground environments to accurately position and guide a longwall mining machine. A successful short-term trial implementation of the technology on a longwall face at South Bulga mine (NSW) followed. This outcome proved a pivotal moment as it provided industry with the first real indication of the viability of the approach with relatively low technical risk.

2.5. CSIRO longwall automation development

CSIRO's research and IP development coincided with a decision by the Australian Coal Association Research Program (ACARP) to address a specific need identified by the industry and give priority to research into improving the efficiency of the longwall mining process. ACARP decided that automating the longwall mining process was a key way to drive significant improvements in efficiency and safety and it consequently set this as a high priority for future R&D. ACARP subsequently provided Landmark project funding to CSIRO to support longwall automation R&D. The project was overseen by an industry Longwall Automation Steering Committee (LASC) which gave its name to the commercial automation technology subsequently produced.

CSIRO began this project by conducting a detailed analysis of what aspects of the longwall mining process could be realistically automated, as well as investigating what could be learned from previous attempts at technology development and deployment in this application. From this analysis the following three key insights were identified:

1. Previous efforts had achieved limited success due to the reliance on single sensor technology and stand-alone systems that failed to sufficiently integrate with the existing longwall control systems.
2. The required system-level performance and reliability could only be achieved by combining the complimentary advantages of multiple and diverse sensor technologies with inertial navigation as the central enabling technology.
3. The resulting automation system needed to closely integrate with the proprietary control systems provided by each of the longwall equipment manufacturers.

This understanding led directly to the selection of an inertial navigation system as the core technology for the implementation of this project. A series of highly aligned research projects were systematically undertaken from 2001–2007 to address critical gaps in technology capability, communications, OEM systems integration, and technology transfer.

The primary outcome has been the development and commercialisation of technology that enables a higher level of automated operation of underground longwall mining equipment. To date, CSIRO's longwall automation technology has been adopted in at least 60 per cent of operating longwall coal mines in Australia. The generally accepted view of the industry is that a maximum of 80 per cent of the longwall coal mines in the Australia are candidates to use mining machines which incorporate CSIRO's longwall mining technology. Increasingly, the LASC automation technology is being deployed internationally.

The main beneficiaries of the project include: equipment manufacturers who benefit through the sale of the technology, mining companies who save on operating costs and achieve greater productivity, and employees of mining companies which use the technology through safer working conditions. This provides strong support for the view that CSIRO's technology remains the best available longwall automation system some eight years after it was first commercialised. The technology outcomes of the project are now being supplied to the industry as LASC Technology in Australia and internationally through the major longwall OEMs with global scope for deployment.

2.6. Parallel longwall automation developments

The LASC outcomes have also supported other research efforts undertaken principally by equipment manufacturers before and during CSIRO's core automation technology development phase. For example, longwall OEMs had previously developed software and control systems to automate the motion of longwall shields as a means to implement face alignment. However, these systems suffered from the lack of effective sensing methods to measure the position of the longwall shield units [11], a problem only later overcome by reliable measurement of the shearer position using CSIRO's LASC technology. Other widely used developments over the last decade driven by industry and implemented by shearer OEMs, such as "state-based" automation of shearer motion where shearer actions are dependent on its location along the face, also greatly benefitted from LASC sensing and guidance technology.

The following section provides specific details on CSIRO's technology development.

3. LASC longwall automation: technology development

3.1. Industry-directed research goals

This section describes the research strategy and methodology adopted by CSIRO for the development of longwall automation capability. Based on the principle of automation with on-face system monitoring, a number of distinct but related research projects were systematically undertaken to address critical gaps in sensing capability, systems integration, and technology transfer to industry [12].

Achieving the automation goals specifically required the development of new enabling sensing capabilities and thus formed the basis for specific technical developments:

(1) Face alignment

In simplest terms, the longwall face should be straight and close to perpendicular to the gate roads. If the face is straight, both mechanical stresses on the AFC and roof support geotechnical issues are minimised. This is the primary and central technology to provide a step change in operational efficiency and productivity, by reducing manual tasks and production halts.

(2) Creep control

As the longwall mining system progresses, the assembly of supports should not move ('creep') towards either of the two gate roads. To achieve this result in practice the face line is often adjusted away from the perpendicular to compensate for sloping seams. Managing the lateral position of the longwall equipment in the panel is called creep control.

(3) Horizon control

In the vertical plane, the automation situation is more complex. The goal of longwall mining, similar to any mining operation, is to maximise extraction of product and minimise the extraction of waste. This means the longwall shearer should operate so that the coal seam is followed both along the face, and into the seam, whilst also abiding by system constraints such as limited articulation angles of longwall components.

Fundamental to achieving the above outcomes is an accurately georeferenced sensing system. At the basic level, the requirement for any automation of these mining systems is to be able to accurately determine the location and pose of each of the components. To this end it can be clearly seen that as the shearer travels along the face, measurement of the instantaneous orientation and location, as well as component states (such as cutting drum height), will provide the essential information describing the current and future position of the longwall system. The three key enabling technologies used to achieve primary sensing function are based on inertial navigation, laser range scanning and optical sensing methods.

3.2. Face alignment: inertial navigation

Central to achieving a practical inertial navigation solution for longwall automation is the performance of the underlying inertial sensor technology, in particular gyroscopes and accelerometers. The quality and technical sophistication of commercially available inertial technologies covers a wide range from Micro-Electro-Mechanical Systems (MEMS)-based devices used in mass consumer products such as mobile phones, automotive applications such as air-bag control and satellite navigation aiding, through to fibre-optic and laser-based devices which are essential for high performance air, land and sea navigation systems.

Common to all inertial navigation systems, irrespective of the gyroscope and accelerometer technologies used, is the fundamental requirement to compute a positional translation by means of the numerical double integration of acceleration and an angular rotation by the single integration of angular rate.

In recent decades a large body of strap down navigation theory has been developed that builds a theoretical framework for optimally combining the inertial sensor data to compute 3D position and thereby a navigation solution. Even with the highest performing sensor devices, the nature of numerical integration means that position errors will exponentially accumulate with time. In a free-inertial mode where only pure inertial information is used, this position error will grow quickly even for a high performance system.

Given this inherent limitation in inertial sensor performance, practical inertial navigation solutions operate in an aided-inertial mode to limit the growth of these errors by taking advantage of external (non-inertial) information. The most convenient and commonly used strategy is to periodically correct the integration error build-up by taking advantage of times when the inertial system is stationary (i.e., in a non-moving position relative to the earth) to correct and recalibrate the internal velocity calculations. Further improvements can be made by incorporating other external aiding.

For example, the addition of velocity sensing to allow the inertial navigation system to continually correct for sensor noise and integration error build-up by comparing internally computed velocity to the external source (see Fig. 2).

A localisation method was subsequently developed to accurately measure the shearer position in 3D. Using this principle, which enabled position to be measured using a robust sensor mounted inside the shearer body for protection without the need for other sensors, a reliable method for 3D shearer position measurement was developed. Fig. 3 shows the resulting inertial navigation unit development for real-time shearer localisation. This unit is installed into the body of the shearer to provide accurate real-time shearer position and orientation measurement.

To validate the performance of the localisation solution, the 3D position of the AFC rail along which the shearer travels was manually surveyed and compared with the LASC-derived position at the completion of a production cycle. Fig. 4 shows representative information generated by the INS-based sensing solution, where the three-dimensional path of the shearer is displayed over several shear cycles. This information is utilised as a reference for related control processes associated with automation.

Fundamental to this outcome was the development of a "Cut Model", which provided a dynamic, georeferenced volume that accurately describes the vertical profile of material cut by the shearer. In addition to representing a source of information regarding extracted volume and resource reconciliation, the Cut Model is utilised as a critical input to achieve superior management of horizon control for subsequent shearer cycles. The validity of this model can be demonstrated by comparison of predicted versus actual coal seam floor. Fig. 5 (left) shows the coal floor boundary as predicted through seismic exploration-scale sensing processed using the Vulcan mine planning tool. Fig. 5 (right) shows the as-mined floor recorded using the LASC cut model. As can be seen, the two data sets are in good agreement which provides confidence in the long term stability of the LASC 3D position sensing system.

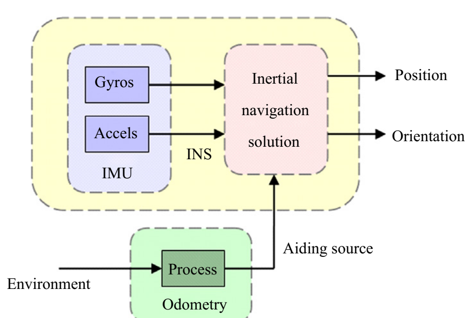

Fig. 2. Block diagram showing the relationship between the inertial sensors and the aiding source used to compute the overall navigation output.

Fig. 3. Longwall shearer localisation measurement solution consisting of an embedded system processor and communications unit (left), and instrumentation grade inertial navigation system (right).

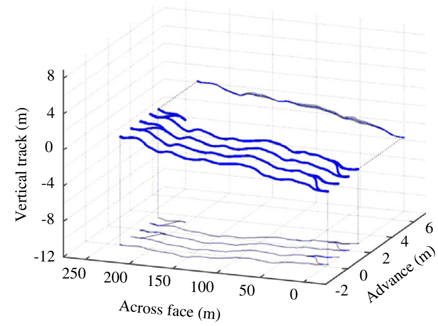

Fig. 4. 3D path (bold trace) of the shearer as measured by the inertial navigation system during two full cycles of the shearer (the 3D data is projected onto the horizontal plane to more clearly show the longwall face profile).

3.3. Creep control

Creep is the cross-track displacement of longwall equipment in the roadway which occurs during the AFC advance process. Ideally, the longwall equipment undergoes no creep age, which implies that the equipment remains at a constant lateral position in the roadway over the life of the panel. In practice, however, a small amount of creep regularly occurs as the longwall system advances. The cumulative effect of creep is highly undesirable as it degrades face and horizon controllability and creates operational hazards for personnel.

To provide a creep management solution, a sensor based on a 2D laser scanner was developed and installed on the gate road conveyor structure—which is rigidly linked to the AFC—to actively measure this per-cycle closing distance. This work included the development of a new flameproof enclosure and window, selection of a suitable laser scanner, initial mounting location and configuration, device communications, data processing and underground trials.

Fig. 6 shows a picture of a flameproof enclosure that houses the laser scanner and associated communications equipment. This enclosure is located on the main gate equipment on the longwall operation. In this figure the window has been recently cleaned by longwall personnel and so can provide quality data for processing to provide creep distance estimates.

Two SICK LMS200 scanning lasers were mounted back to back and perpendicular to the direction of longwall retreat so that both sides of the roadway were simultaneously scanned in the horizontal plane. An example of the raw output from the scanning lasers in plan view is shown in Fig. 7 where the red line indicates the general position and orientation of the main gate equipment in the roadway.

Scan-matching algorithms then use probabilistic methods to estimate the rotation and translation of the (rigidly mounted) lasers that provide the best match of the current scan to the global map. As the longwall moves, the global map is updated with the newly detected features. The output of this processing algorithm provided a measure of the creep distance. An example of the output of this creep measurement system is shown graphically in Fig. 8. The creep measurement information was integrated into the main information system database for use with the LASC system to automatically improve the performance of the INS-based measurement solution and to provide a guidance display for remote management of the mining process.

The horizontal axis corresponds to retreat distances and the vertical axis to creep. Note the differences in scale as the creep distance is far smaller in magnitude than the retreat distance. Small incremental creep distances are be very difficult to measure by eye, but the cumulative creepage can be considerable. The need for an accurate and automatic monitoring tool is therefore highly apparent.

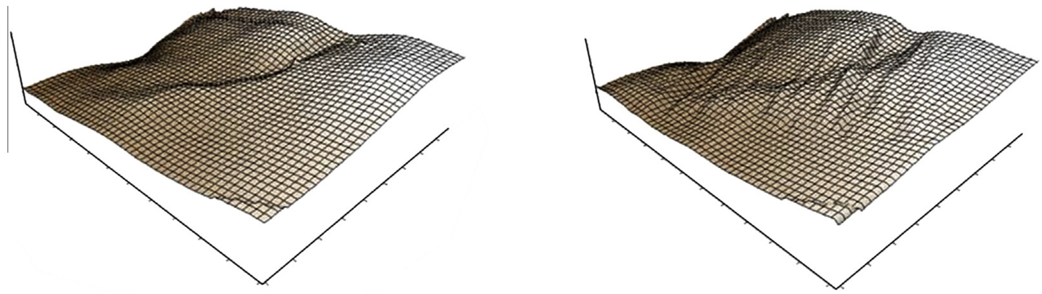

Fig. 5. Comparison of *seam floor profiles generated by exploration prediction (left) and LASC cut model (right) generated as-mined floor profile.*

Fig. 6. Flameproof enclosure used to house the laser scanning equipment.

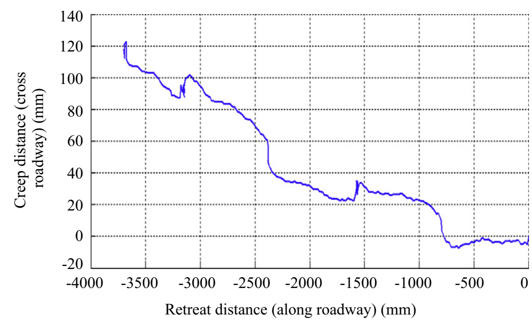

Fig. 8. Processed output from the scanning laser-based creep measurement system for a several longwall push events (the differences in scale for vertical and horizontal axis).

3.4. Horizon control

Coal mining horizon control refers to the process of maintaining desired roof and floor extraction profiles during mining in order to meet given strata management and resource recovery strategies. Fundamental to the success of any mining horizon control strategy is the availability of a reliable vertical reference datum to provide the vertical extraction depth profile along the mining surface. The requirement for real-time horizon control arises from the need to dynamically adjust the mining machine's vertical extraction depth in response to the inherent geological variations of the confining coal and/or strata. In the case of automatic horizon control, a means is required that can automatically and reliably generate a vertical datum in such a way that the input is suitable for direct control of a mining control system.

Achieving an automated longwall operation not only relies on accurate shearer position information but also on spatial information regarding the location of the coal seam. This resource location information is critical in order to maintain the shearer in an optimal position for extraction within the coal seam. Operating the shearer in the coal seam is also important in terms of minimising damage to equipment, reducing dust production, and to relieve personnel from potential hazards such as hard-rock debris dislodged from out-of-seam mining.

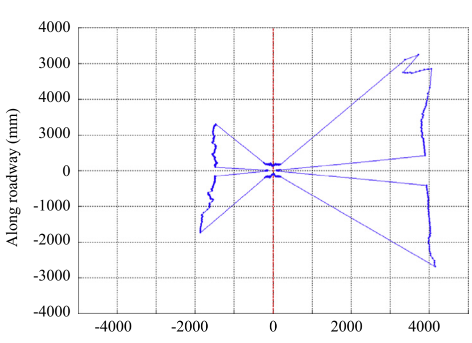

Fig. 7. An example of the raw output from the back to back scanning lasers in plan view (the red line indicates the general position and orientation of main gate equipment along the roadway).

The standard approach used for identifying coal seam boundaries during longwall operations requires operators to monitor various indicators in the mining face. These indicators include visual cues present in the geology, a change in dust conditions or noise and/or vibration of machinery when transitioning coal-rock boundaries, or inspection of the extracted resource. The most effective methods are based on observing variations in geological characteristics associated with the overall coal seam trends.

Depending on the site, the material mined during the longwall operation can be composed of several layers of coal, clay or ash of varying thicknesses. This horizontal layering characteristic is well known in underground coal operations [13,14], where the overall body of coal to be extracted also contains thin horizontal layers or bands which consist of high ash-content material. These thin horizontal layers are often referred to as marker or 'penny' bands, which visibly contrast with the coal strata because of their light-grey or white colour. The nature and presence of marker bands is geology-dependent, so that they may or may not be observable to the naked eye in a given longwall operation.

Both visible light and thermal infrared cameras were evaluated in a variety of locations and configurations, including on the body of the shearer and distributed across the roof supports. Fig. 9 (top) shows a short section of a longwall face displaying the characteristic horizontal seam geology associated with coal and marker bands measured using a set of visible light cameras installed on the roof supports. Fig. 9 (bottom) shows a short section of a longwall face reconstructed using a thermal infrared camera mounted on the shearer. In this case features identified in the face are not necessarily visible to the eye.

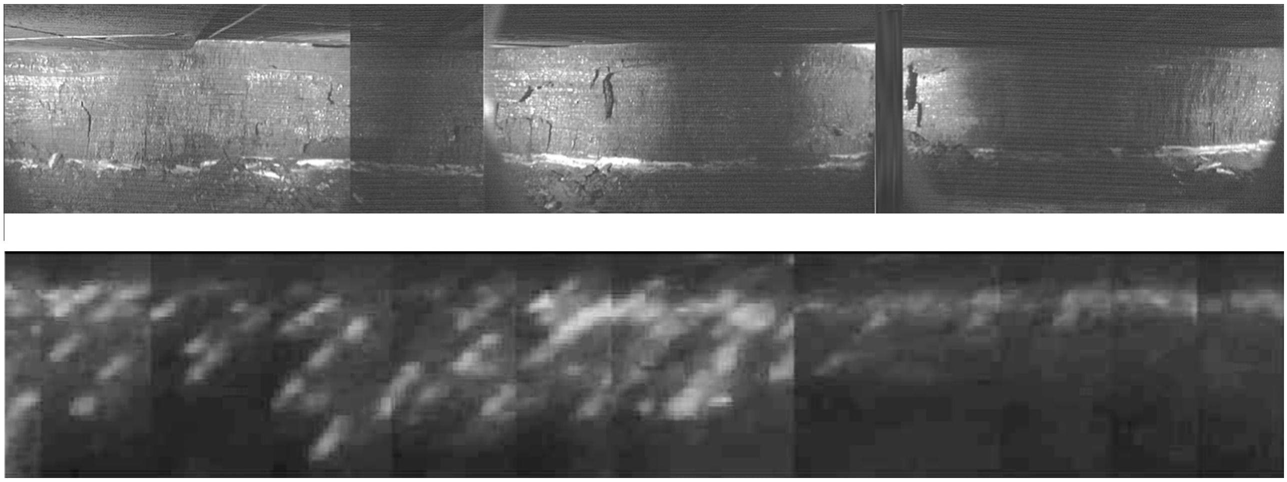

Fig. 9. Top: visible light panorama of underground longwall coal face showing: a dominant marker band is seen at bottom of the image which is the target for tracking. Thinner marker bands are also apparent. Bottom: thermal infrared panorama showing thermal marker band features where whiter colours correspond to higher temperatures.

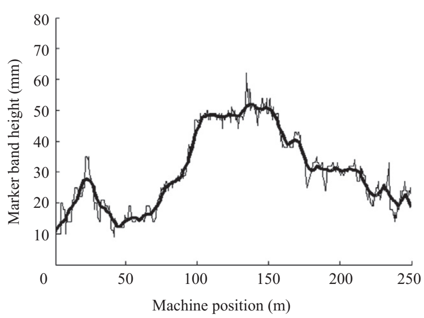

Fig. 10. Computed output from the seam horizon tracking system showing raw (thin line) and filtered (thick line) estimates of the marker band heights.

In terms of sensing for horizon control, the major interest is identifying a feature that can be used as a vertical datum. This is of benefit because the bands typically exhibit similar horizontal trends to the surrounding coal seam geology and floor and roof extraction horizons can thus be set as constant vertical offsets from the identified band.

A robust, real-time marker band tracking implementation was developed by noting that the task of estimating the marker band height at each time instant was equivalent to tracking the motion of a particle moving at constant velocity in a 1D plane subject to random perturbations in trajectory. This is a scenario for which the Kalman filter represents a robust and established estimation framework. A simple position-velocity (PV) Kalman filter was subsequently applied to this tracking scenario [13,14]. A similar approach can be adopted for both optical data inputs.

A representative output from the optical tracking approach for horizon control appears in Fig. 10, showing marker band height estimates in real-world coordinates across a typical longwall face. The tracked thermal feature is mapped into the shearer's coordinate system through a simple calibration process. By using the highly accurate position and orientation of the shearer, the cutting drum position can be established to achieve the desired mining extraction horizon. The marker band tracker system is designed to be compliant with the LASC open systems interoperability protocol. This means that the information generated by the system can be readily integrated with any existing LASC Longwall automation horizon control system.

Note that in the absence of seam tracking and coal interface information, the LASC Cut Model describes only the as-mined floor. Horizon control adjustments are then computed from floor predictions. This is referred to as INS-based enhanced horizon control and provides additional information to assist in the horizon control task.

3.5. Open standards for systems interoperability

A key aspect of any modern industrial automation process is the use of open communication protocols to ensure seamless interoperability of equipment. Longwall equipment is produced by several major and numerous smaller manufacturers worldwide and it is common for mine sites to mix and match longwall equipment from different manufacturers in order to best suit their particular mining conditions.

Prior to the ACARP longwall automation project, there was little or no provision for data communication between equipment from different manufacturers. Mine sites and third party vendors devised closed ad hoc solutions for communications between longwall equipment and were restricted by low data rates. Given the fundamental role of the proprietary control systems in the automation system it was imperative that reliable high speed interconnectivity be established across all commonly used longwall equipment.

The availability of Ethernet underground, the requirement for open-architecture and the increasing use and acceptance of industrial Ethernet in process control, greatly influenced the selection of Ethernet as the primary communications medium. After extensive evaluation, Ethernet/IP was chosen as the primary LASC communications protocol. In simple terms Ethernet/IP describes the verbatim encapsulation of a well-known, open communications standard known as Control and Information Protocol (CIP). CIP is also common to DeviceNet and ControlNet and had been used extensively for industrial control worldwide prior to the development of the Ethernet/IP standard. Ethernet/IP builds on the benefits of Ethernet-open specification, low cost and readily available hardware, maintainability, versatility and most importantly exponential improvements in technology driven by the office and enterprise markets.

Key benefits of the LASC open standard implementation include step-change improvements in equipment interoperability and intercommunications, vendor neutrality, new opportunities for technology leveraging for supplier and client, and enhanced options in remote and autonomous mining capability. Further, the LASC interoperability specification is both open and free for use. It is also being constantly expanded to support the growing number of new and improved sensors and systems being developed. This interoperability standard has been fully embraced and rapidly adopted by major OEMs, vendors and mine sites, and now has been successfully deployed for over a decade for mining production.

3.6. Information and representation systems

A key enabling component to support the longwall automation process was the development of a real-time information management system. This system was necessary to capture, process, integrated and coordinate information from the automation system components. This system also provided the platform to host cut profiles with the modelled mine site geology and planning data. Relevant data from multiple sensors and sources are processed and applied to a geological model that takes into account the sensor measurement properties and weighting of the information. The reference surface in the Cut Model is the as-mined floor as supplied by the INS which is computed in a three-dimensional mine-referenced coordinate system. This integrated information system is shown in the block diagram of Fig. 11.

LASC horizon control predictions are computed on a shear by shear basis. The horizon control output of the Cut Model describes the recommended horizon adjustment for the next shear based not only on the last completed shear but also the preceding shears. The adjustment information is provided to the LASC-compliant shearer control system by the means and in the format described in the LASC specification [12].

For non-control related information, a suitable display system efficiently reports different aspects of system operation and conditions existing on the longwall to personnel located remotely. This visualisation software produces high quality representations of the state of the longwall system, an example of which is depicted in Fig. 12. The information system is also able to generate operational-level information to inform the decision making process for personnel working directly underground on the longwall.

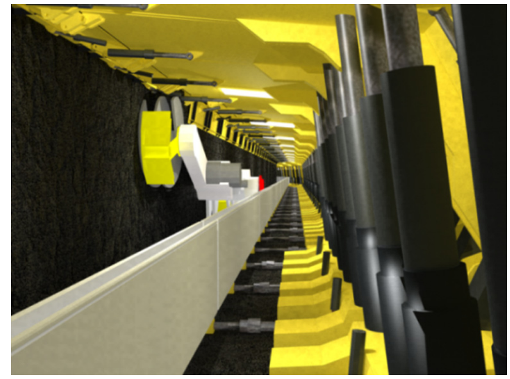

Fig. 12. Visualisation showing the longwall shearer, powered roof supports and AFC pan line for real-time remote system representation.

This section has outlined major sensing and information technologies that have enabled the development of longwall automation capabilities. The primary technical outputs of the CSIRO longwall automation system provide the core sensing and processing functions to achieve for face alignment, creep control and horizon control. LASC also includes a system to manage transfer of information between OEM shearer and roof support control systems. These outcomes have been implemented through open system specifications to greatly facilitate interoperability between LASC and OEM system components.

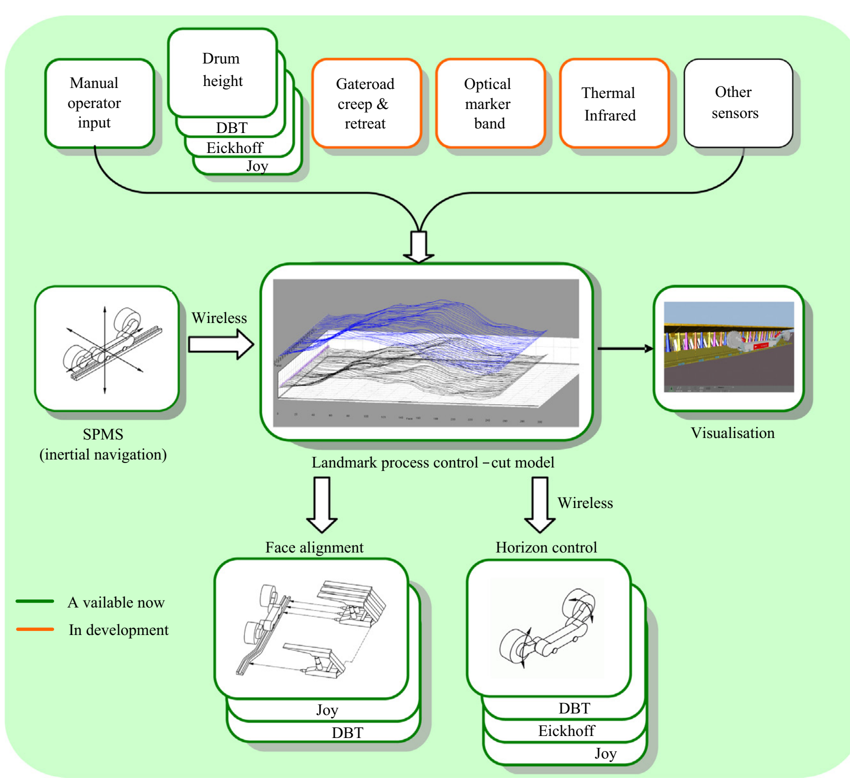

Fig. 11. Block diagram showing integrated LASC system architecture and inputs into the cut model.

4. Longwall automation: case studies

4.1. LASC implementation: broad meadow

This section reports on one of the first LASC installations at Broadmeadow mine, Queensland Australia [15]. The initial face alignment trials were conducted in February 6, 2007 and utilised inertial navigation technology to provide 3D shearer position information. The face alignment system was put into full production on 25 January, 2007. Using the longwall OEM's visualisation system, it is seen that prior to installation of the LASC automation technology the face profile was not linear as desired nor did the information provided by the OEM system accurately represent the true shape of the face. This is shown in Fig. 13.

In contrast, following the commissioning of the LASC system, the operators were able to obtain a true representation of pan alignment, which then was used to display and control the pan line. This information was automatically supplied to the OEM roof support control system to deliver the desired linear face profile (see Fig. 14).

As a result of the introduction the LASC automation system, the mine site reported a number of immediate benefits. These included [15]:

- Major operational advantages gained through removal of manual "string-line" face alignment.
- Operators removed from immediate hazardous and dusty locations.
- Mechanical stresses (due to over articulation) dramatically reduced.
- New information providing historical trending of the pan line over the lifetime of the longwall panel.

As an indication of the consistency of achievable face straightening, Fig. 15 shows a series of face profiles as the longwall retreated into the panel. The arrow indicates the level of face straightening achieved, with the most recent shear at the top of the display.

Based on the positive outcomes associated with the deployment of the LASC automation technology, the mine is firmly committed to continuing the process towards full face automation [15].

4.2. LASC industry impact: case study

An independent case study has been undertaken to assess the economic, social and environmental impact of the LASC Longwall Automation project. This section presents a summary of the findings of the case study which details the inputs, activities, outputs, outcomes and impacts of the research.

The primary outcome of this project has been the commercialisation of technology to enable a higher level of automated operation of underground longwall mining equipment. The technology was delivered to the industry as a critical part of longwall mining equipment rather than an optional add-on. ACARP required that the technology could not be exclusive to a single manufacturer and CSIRO stipulated that, being an R&D entity, it would not be able to support the technology directly in the field.

The main beneficiaries of the project include: equipment manufacturers who benefit through the sale of the technology; mining companies who save on operating costs and achieve greater productivity; and employees of mining companies who install the technology through safer working conditions [15].

4.3. Assessment of outcomes

The LASC Longwall Automation project has provided licensed OEMs with an opportunity to sell a successful new product, delivering increased business and revenue for those OEMs. The adoption of the technology has so far been outstanding. To date, CSIRO's longwall automation technology has been adopted in 20 longwall mines in Australia, representing around 60 per cent of operating longwall coal mines in Australia. The generally accepted view of the industry is that a maximum of 80 per cent of the longwall coal mines in the Australia are candidates to use mining machines which incorporate CSIRO's longwall mining technology.

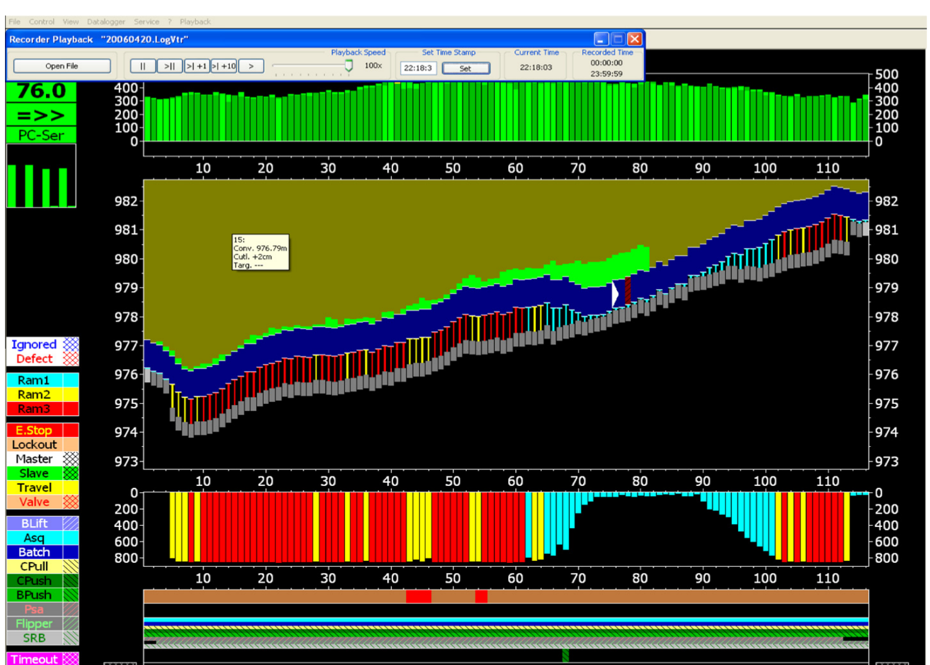

Fig. 13. Face alignment prior to the installation of LASC automation (note the irregularity of the face position information and the departure of the alignment from the desired linear profile (image courtesy BMA)).

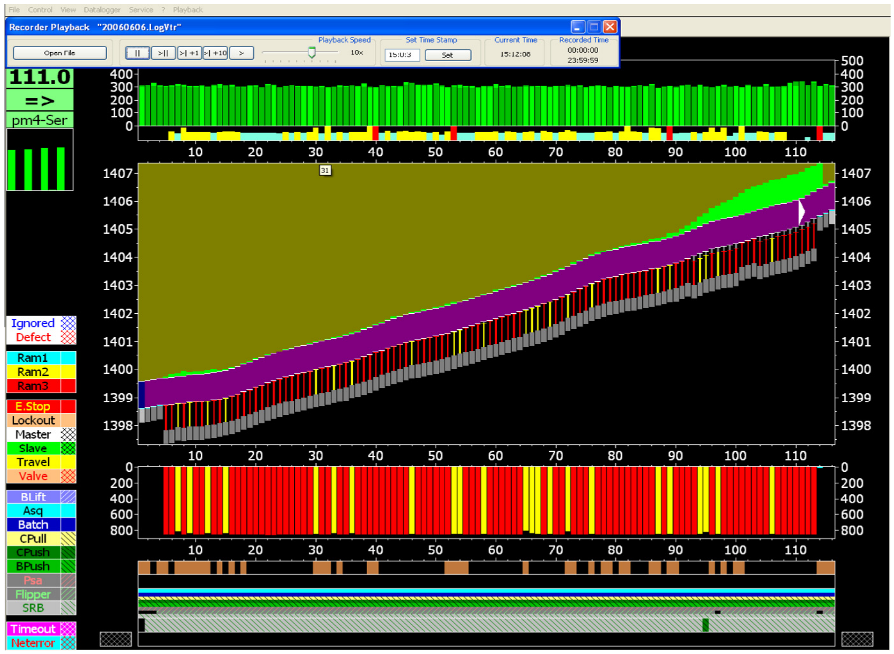

Fig. 14. Face alignment following installation of LASC automation (note the consistency and linearity of the face position and roof support systems (image courtesy BMA)).

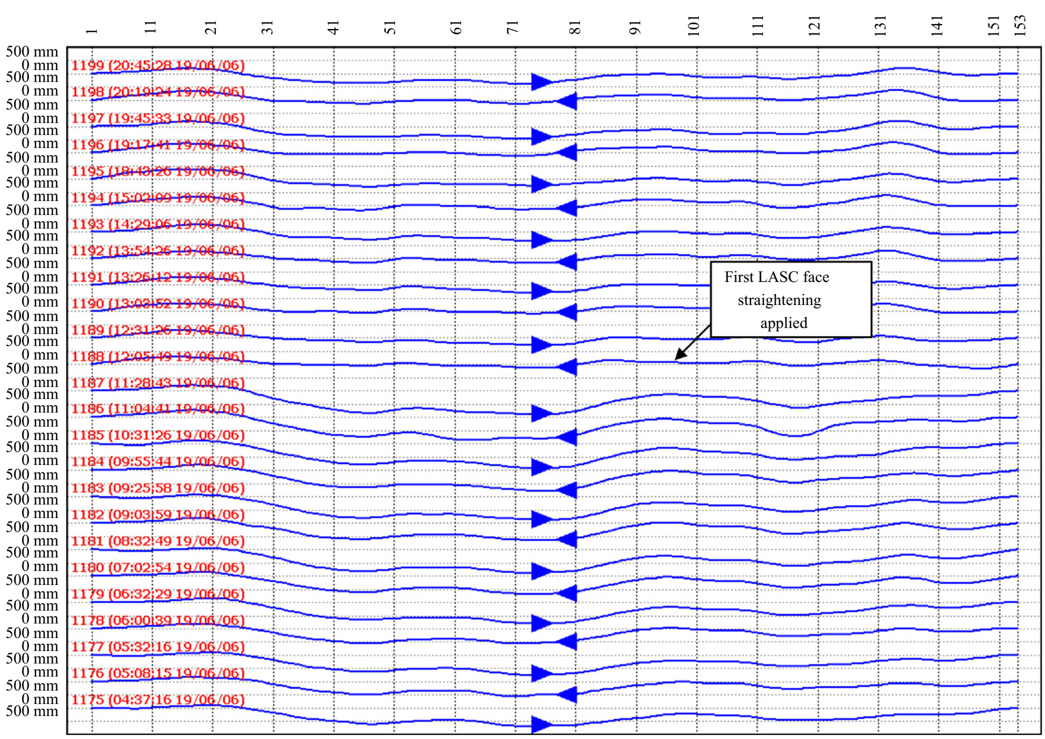

Fig. 15. Historical display of the face alignment system over a number of shear cycles (most recent shear at the top of image) (this display represents a simplified, linear representation to aid the interpretability of the LASC system output for underground operators. A significant improvement in face alignment performance is observed when the LASC system is first enabled (as noted)).

Specifically, the LASC longwall automation technology development has delivered impacts into industry in three key areas:

- Increased longwall coal productivity by at least 5 per cent, leading to a stream of net benefits attributable to CSIRO exceeding $800 million over the anticipated technology deployment lifetime.
- Directly contributed to improving the working conditions and safety of coal mine employees, reduced numbers of accidents and deaths, likely to save mining companies millions of dollars a year.
- Reduced environmental disruption and rehabilitation cost through the use of more accurate selective resource recovery on longwall mining operations.

The extremely rapid adoption of the technology by Australian underground coal mines is an excellent indication that mine operators expect that the productivity gains will ensure that the return on investment for installing the technology will be very attractive.

4.4. Broader technology impacts

The LASC Longwall Automation project has also had a number of wider benefits. The most significant of these is the decreased time required for maintenance of mining equipment in mines that use CSIRO's longwall automation technology. This has occurred due to the need to ensure that all parts of the mining operation, including equipment-specific automation technology developed by individual equipment manufacturers are fully optimised to maximise the benefit of this technology. As a result, all machines are consistently operating in a manner that optimises their performance. This results in fewer stoppages, better alignment in the workloads of the various components of the mining operation and optimal maintenance of machinery. While precise information on the productivity gain due to the automated longwall mining technology is difficult to obtain due to the commercially sensitive nature of such information, it is broadly accepted within the industry that adoption of LASC Longwall Automation technology has increased peak productivity by around 10 per cent. However, the major benefit to the industry of LASC has been greater consistency in operations because of the factors described above, which, with other enhancements has generated a long term productivity improvement conservatively in the order of 5%.

Industry sources suggest that the cost of lost production can be as high as $1000 a minute. While this figure is likely to vary significantly from mine to mine, it provides an indication of the scale of benefits that can result from the productivity gains that result from the use of the automated longwall mining technology itself and the system-wide efficiencies that use of this technology encourages.

4.5. Sustained delivery of R&D into industry

CSIRO's aim was always to achieve full technology transfer to OEMs as they are the agency with maximum reach to the global mining industry. To help ensure this outcome, CSIRO provided technical support and advice to OEM licensees during the initial stages of the technology transfer. CSIRO also provided some initial support to mining companies. Ongoing CSIRO support however was largely provided in partnership with the OEMs rather than through any direct contract with the users. By doing so the OEMs would gain the skills needed to provide the full suite of support services for the product they were providing to their mining company customers, without the need for any CSIRO assistance.

However not all OEMs possessed the capacity to provide the level of technical support some mining companies sought. To address this issue, CSIRO actively encouraged the creation of third-party providers to serve as "LASC service agents" to provide turn-key LASC hardware solutions, deployment and commissioning support, and ongoing maintenance. These third-party companies offer specialised support to OEMs and industry and are ensuring long term commercial supply of the automation technology.

5. Underground mining automation: the future

5.1. Need for mining technology research

The rapid adoption of longwall automation technology by Australian underground coal mines is an excellent indication that mine operators expect that the productivity gains will ensure that the return on investment for installing the technology will be very attractive. New and improved technologies are constantly in demand to meet the need for greater automated mining capability to achieve safer and more productive mining. A key aspect in delivering these improved automation outcomes is the development of high performance in-situ sensing in order to adequately monitor the environment, equipment, personnel and geology.

5.2. Current and emergent research

At present, technology gaps remain in terms of deployable sensing technologies and so ongoing research and development is required. CSIRO continues to develop and adapt technology to meet such needs. For example, the core inertial guidance technologies developed during the longwall automation projects have been adapted for use in continuous miner operations for underground roadway development both in longwall and bord and pillar operations. The technology has been validated through pre-commercial installations and trials in underground mines in Australia where positive outcomes have already been realised [16,17]. This technology will significantly improve the speed of roadway development, which currently is a limiting factor in mine production and will also enhance safety by removing miner operators from the vicinity of the machine and working face. Here the primary enabling technology is a means to accurately localise the position and orientation of the continuous miner in real-time as shown in Fig. 16.

5.3. Enabling technologies

Overcoming the lack of comprehensive information regarding the precise location and nature of resources will require the development of sufficiently well-integrated technology and equipment to exploit resources efficiently with reduced environmental impact. This information is critical towards delivering safer, more productive and more sustainable mining. For automation, four major areas of open research are:

- Sensing to provide a comprehensive awareness of resource mineralogy, geology, location and configuration for the mining process, personal location and state; and equipment and infrastructure control.
- Information frameworks that process, interpret and determine optimal mining sequences that incorporate safety, performance, economics, and sustainability measures. This aspect will substantially improve communications capabilities as well as real-time information fusion for intelligent decision support.
- Autonomy that can intelligently identify and coordinate tasks across multiple independent extraction machines (e.g., continuous miner-shuttle car-continuous haulage-mobile boot end). A

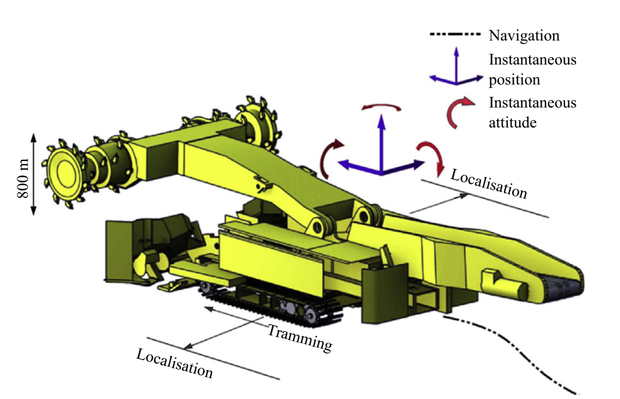

Fig. 16. Diagram showing the main position and orientation parameters of interest towards delivery of self-guided continuous miner functionality.

key related research challenge is to provide ways to ensure equipment safety integrity levels (SIL) when operating in mixed (human–automation) or exceptional circumstances.
- Human factors development to provide significantly enhanced user experience and awareness. These technical innovations will integrate immersive visualisation, advanced human–machine interfaces, dynamic remote feedback mechanisms, and perception-based knowledge.

5.4. Next decade

The call to deliver improved safety, productivity and environmental outcomes for the coal industry remains as cogent as ever. The next decade will see an unprecedented drive towards a more agile, more dynamic, and more integrated coal mining business. Achieving this outcome will require a searching review of present mining assumptions and practice to identify what is both essential and efficacious. An effective review will likely result in strategies that will challenge traditional mining culture. It will also give rise to new operational models for vertical integration and service provision, convergence of mining operations and business operations, and opportunities for deployment innovative mining technologies.

In terms of technology development it is likely that innovations will be continue to be introduced to industry through well targeted steps that are evolutionary rather than revolutionary. The pace, however, of technology adoption and utilisation will increase. The familiar progression in mining technology capability will continue to progress along an automation spectrum, from manual control to full automation with no operator interaction [18]. Immediate short-term development therefore will focus on achieving greater levels of assistive automation to allow the mining process to be more effectively controlled from a remote location. The aim of this activity however is towards remotely supervised mining, with the ultimate goal of remotely managed mining.

Support for much of the change will rely on the development of new information systems. These systems are the architectures that intelligently integrate and manage the increased level of information associated with the mining process. New systems are necessary to manage the inherent uncertainties and variability associated with underground mining activity. It will be exciting to see the impacts that increased communications capabilities, high performance computing, and information systems will have on the industry. It is hoped these capabilities will drive new sensing methods, new ways to dynamically assess risk, new decision support functions, and machine with high levels of trusted autonomy.

6. Conclusions

This paper has highlighted the significant role that research and development plays in the delivery of safer, productive and environmentally sustainable mining. Using the successful LASC longwall automation technology development as a motivating study, the technical innovations have delivered impacts into industry in three key areas:

- Increased longwall coal productivity by at least 5 per cent, leading to a stream of net benefits attributable to CSIRO exceeding $800 million over the anticipated technology deployment lifetime.
- Directly contributed to improving the working conditions and safety of coal mine employees reduced numbers of accidents and deaths, the costs likely to save mining companies millions of dollars a year.
- Reduced environmental disruption and rehabilitation cost through the use of more accurate selective resource recovery on longwall mining operations.

Key to achieving these outcomes has been the development of technologies which enable new remote and assistive automation capabilities to be realised for longwall mining operations. To date, CSIRO's longwall automation technology has been adopted in 20 longwall mines in Australia, representing around 60 per cent of operating longwall coal mines in Australia. International LASC automation deployments are also emerging. The benefits of this outcome have been broadly recognised and embraced by the longwall community and have subsequently been taken through to commercial maturity. Ongoing research and development continues to expand the scope and performance of the mining technologies to further advance automation capability for the underground coal mining industry.

Acknowledgments

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