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Longwall automation: trends, challenges and opportunities

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ABSTRACT

This paper explores the ongoing development and implementation of longwall automation technology to achieve greater levels of underground coal mining performance. The primary driver behind the research and development effort is to increase the safety, productivity and efficiency of longwall mining operations to enhance the underlying mining business. A brief review of major longwall automation challenges is given followed by a review of the insights and benefits associated with the LASC longwall shearer automation solution. Areas of technical challenge in sensing, decision support, autonomy and human interaction are then highlighted, with specific attention given to remote operating centres, proximity detection and systems-level architectures in order to motivate further automation system development. The vision for a fully integrated coal mining ecosystem is discussed with the goal of delivering a high-performance, zero-exposure and environmentally coherent mining operations.

1. Introduction

1.1. Motivation and purpose

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) is Australia's national science organisation which delivers innovative solutions domestically and globally across a wide range of industries. In the mining domain, CSIRO engages in mission-directed research to promote transformational change that will directly benefit the industry. A major target is to create advanced remote operation and automated technologies that directly contribute to safer, cleaner, and more productive mining processes.

1.2. Industry-led drivers

The global coal mining industry is constantly driven by the need to improve mining productivity, increase personnel safety, and achieve credible environmental stewardship [1]. The need to deliver improved safety and productivity presents an open challenge and a powerful incentive to develop new solutions. Whilst key technical contributions have directly influenced the direction and capability of present-day automation solutions, further innovation is clearly needed to develop enabling technologies to support advanced remote and automated systems for underground coal mining operations [2]. The reasons are compelling: the coal industry accounts for 24% of employment and 27% of total revenue for the Australian mining sector [1,2]. Longwall coal mining, in particular, accounts for around 90% of Australia's total underground coal production [2]. Methods to improve the performance of longwall operations is thus a major priority for research and development.

1.3. Longwall mining: background

Longwall 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 5 km 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 [3]. 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 [3,4].

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 shearer is no longer supported and thus is allowed to collapse into the void (goaf) behind the shields. A section of a longwall operation is shown in Fig. 1, where the direction of mining is into the coal seam on the left hand side of the image, and the coal seam is indicated by the hatched layer between the underlying and overlying strata.

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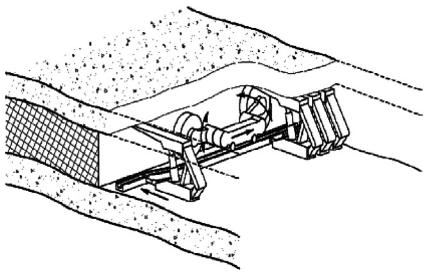


Fig. 1. Stylised cut-away view of the underground longwall mining process (not to scale).

Further detailed technical reviews of the longwall mining process can be found in study by Singh [5].

As shown in Fig. 1, the shearer is in centre view, mechanised roof supports are to the left and right, and both are embedded in coal (hatched) and host strata (dots). The direction of mining is to the left.

1.4. Need for improvement

Despite the productivity associated with longwall mining, the operational environment presents many hazards to personnel, including the proximity to machinery, hydraulic and electrical power, roof falls and exposure to explosive mine gases and dust. Miners are often required to work in this hazardous environment in order to manually control equipment at close range and thereby achieve efficient extraction [6].

Ensuring the optimal orientation of the longwall face and equipment is critical: under manual control there is a need to stop production periodically to carry out adjustments which reduce operating machine time and thus productivity. Further, extraction needs to be maintained in the coal seam as failure to correctly align 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 operating time and thus efficiency of the mining process. The complexity of manually operating equipment of this scale also has practical impacts in terms of potential health and safety for personnel [3,6].

1.5. Longwall operator perspective

Operators consistently express the view that the longwall is the prime profit centre and that a high level of production consistency (rather than reducing personnel) should be the focus of automation [2]. A second focus expressed is the removal of persons from exposure to respirable dust. Even with advanced dust control techniques, most high production faces can find statutory standards difficult to achieve. The industry recognised that this situation was unacceptable and unsustainable in the long term and sought answers to these problems [7,8].

1.6. Paper scope and overview

An outline of the paper is as follows. In Section 2, a brief history of longwall automation is given as context for current automation capability. Section 3 describes global trends and industry challenges, explored through two high-value use cases. Section 4 outlines emerging opportunities and related technology developments underway to inspire ongoing automation development towards a future mining ecosystem described in Section 5.

2. Longwall automation: a brief history

2.1. Automation goal

The goal of automating the longwall mining process was deemed to be the principle means to drive significant improvements in efficiency and safety.

A number of important developments have been undertaken over the past fifty years by international researchers in an attempt to increase the level of automation capability available for longwall operations. In fact, the concept of a remotely operated longwall face (ROLF) was proposed as early as the 1950s by the British National Coal Board [9]. Later developments in the 1970–80s explored a mine operating system concept to provide distributed system control. None of these research efforts, however, were able to provide a consistent solution to the automation problem.

2.2. CSIRO guidance system development

In the 1990s, CSIRO reviewed global research in the area of longwall automation technologies to identify what aspects of the longwall mining process could be realistically automated, as well to investigate what could be learned from previous automation attempts [6]. The following 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) Many attempts were not sustainable due to the lack of technology readiness and industry acceptance.
(3) The required level of system performance and reliability could only be achieved by combining complimentary sensor technologies with inertial navigation as the central enabling technology.
(4) The resulting automation system needed to integrate closely with the proprietary control systems provided by each of the longwall equipment manufacturers.

These insights led directly to the selection of an inertial navigation system as the primary sensing technology. CSIRO had convincingly demonstrated the use of inertial navigation techniques for the guidance of underground equipment in highwall mining. The primary technological breakthrough occurred when CSIRO recognised and subsequently demonstrated that the position of all the relevant components in the longwall system could be inferred accurately from a real-time 3D measurement of the position of the shearer [8].

The application of inertial navigation technology in underground environments to accurately position and guide a longwall machine was innovative [10]. A successful short-term trial implementation of the technology on a longwall face was carried out at Glencore's (then Xstrata) South Bulga Mine in NSW, Australia. This outcome was a pivotal moment as it provided the mining industry with the first real indication of the viability of the approach with relatively low technical risk.

In 2000, support from the Australian Coal Association Research Program (ACARP) was gained to accelerate the deployment of this automation technology in order to address specific needs identified by the underground coal mining industry. The activity was overseen by an industry-initiated and industry-led Longwall Automation Steering Committee (LASC) and comprised a series of highly aligned research and development projects to systematically to address critical gaps in technology capability, communications, OEM systems integration, and technology transfer.

As the key research organisation involved in this process, CSIRO has successfully developed new ways to help automate longwall mining through the introduction of innovative enabling technologies (Fig. 2). Now known in the industry as LASC, the technology has been taken up by all major longwall OEMs under technology licensing agreements with CSIRO [11–13]. Each global longwall OEM has integrated the LASC open intercommunication standards into their proprietary control system architecture and shearer manufacturers have installed the automation systems into their equipment.

2.3. Impact of longwall automation technology

The primary outcome from CSIRO's industry-focussed research has been the development and commercialisation of technology that enables a higher level of automated operation of underground longwall mining equipment. These LASC automation technologies are accessible to the national and international mining industry through the major longwall OEMs who have integrated the LASC open intercommunication standards into their proprietary shearer automation equipment. LASC technology has been widely adopted, with CSIRO automation technology now deployed in more than 70% of the automated underground coal mining equipment operating in Australia today, and with international deployments growing [12–14].

2.4. Key benefits to industry

The main beneficiaries of the LASC technologies include equipment manufacturers who benefit through the provision of the technology, mining companies who save on operating costs and achieve greater productivity, and employees of mining companies that use the technology to achieve safer working conditions. LASC also provides an open platform for technology extensions, allowing third-party vendors to develop and integrate their own capabilities in a standard and robust method.

The primary operational benefits associated with the introduction of mining automation technology have been:

(1) Improved consistency and continuity of mining systems, supporting overall mine productivity
(2) Increased resource throughput and increased resource quality
(3) Enhanced equipment performance through an ability to operate closer to OEM nameplate specification and therefore best practice
(4) Improved safety and health for personnel through reduced exposure and removal from hazardous areas.

Fig. 2. Longwall shearer localisation measurement solution consisting of an embedded system processor and communications unit (left), and instrumentation grade inertial navigation system (right).

The automation technology solution also served as an important business case driver for the introduction of standardised infrastructure such as networks, open communications protocols, and systems interoperability.

LASC Longwall Automation has had a number of related benefits to industry. 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 is 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 figures on the productivity gain related to the deployment of automated longwall mining technology are 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 productivity by approximately 10% [2].

3. Challenges and trends

3.1. Global technology trends

Globally, across virtually all industries, a powerful technology trend has been clearly emerging: a progressive transition from manual, non-cognitive work to automated, cognitive work. A similar force is also at work within the mining community, challenging both needs and expectations.

The rapid adoption of longwall automation technology is an indication that mine operators expect that productivity gains that will ensure a highly attractive return on investment. Furthermore, new and improved technologies are constantly in demand to meet the need for better remote and automated underground mining processes to achieve safer and more productive mining.

3.2. Key automation challenge areas

From an automation development perspective, four major areas are emerging as clear areas of challenge:

(1) **Sensing:** providing an awareness of resource mineralogy, geology, location and configuration for the mining process, personal location and state, and for equipment and infrastructure control.
(2) **Architecture:** interpreting and determining optimal mining sequences that incorporate safety, performance, economics, and sustainability measures. This will substantially improve communications capabilities as well as real-time information fusion for intelligent decision support.
(3) **Autonomy:** identifying and coordinating tasks across multiple independent extraction machines, and providing ways to ensure equipment safety integrity levels when operating in mixed (human-automation) or exceptional circumstances.
(4) **Human factors:** enhancing user experience and awareness to integrate immersive visualisation, advanced human-machine interfaces, remote feedback mechanisms, and perception-based knowledge.

These challenges are now highlighted through two high-value use cases for longwall automation: proximity detection and remote operating centres.

3.3. Interoperability and proximity detection

The progressive introduction of assistive automation technologies into longwall operations has increased the need to ensure safe and effective coordination between machine and human control components.

The LASC Interoperability Specification for Collision Avoidance (LISCA) was developed with the aim of providing new solutions to this problem [15]. LISCA provided an open communication specification to integrate collision avoidance systems to enhance the interoperability between plant and proximity detection systems. Collision avoidance systems provide an additional level of protection to reduce the risk of unwanted interactions between equipment and either personnel or other equipment. The current level of industry uptake for collision avoidance systems is low, due mainly to the difficulty of implementing customised integration solutions for every different vendor offering.

One of the major problems in getting proximity detection and collision avoidance systems integrated and tested has been the requirement to custom-build every implementation. As a solution to the integration problem, an open communication specification was designed to allow interoperability between OEMs of plant and OEMs of collision avoidance systems or proximity detection systems. The key was to clarify and distinguish between the different roles of behaviour and function as described in Fig. 3.

Importantly LISCA did not propose any technical method for detection, nor specify rules for behaviour to be undertaken if an unwanted interaction was imminent, however it did provide the enabling capability for these systems to be implemented by components that could operate in an integrated fashion. This approach provided an ideal way to ensure functional interoperability and vendor independence.

The LISCA specification received wide support from all industry sectors, including plant manufacturers, proximity detection system manufacturers, and mine sites. LISCA was an initial model for an open communications specification that was developed to resolve many of the interoperability issues plaguing the proximity detection industry. As such, it was a catalyst for deeper industry collaboration and engagement that has since led to the development of additional, industry-agreed, protocols such as the Earth Moving Equipment Safety Round Table (EMESRT) standards [24]. The continuing agenda for these standards is to improve industry safety by promoting the further uptake of proximity detection and collision avoidance systems, to identify technology gaps in proximity detection systems and encourage ongoing investment in collision avoidance technologies.

3.4. Remote mining operating centres

A wide range of operational centre designs have been considered over the past decade across different industrial sectors. Operations centres vary in size, physical layout, technical complexity and development cost. A major driver motivating the development of many remote mining operation centres has been centralisation: collocating all personnel, skills, control infrastructure into a common facility. One major reason for this approach is to reduce operational costs by retaining personnel in the cities instead of operating in remote locations. Centralisation can also promote improvements in operational efficiency as localised presence may assist in collaborative decision making processes.

However many remote mining operations centres simply replicate the same approach used in other domains for decades. As an example Fig. 4 shows a typical display and room configuration used for remotely monitoring processes.

This generic approach presents a high level of "information intensity" to the operator, which can easily lead to cognitive overload, inattention and poorer decision making. Simply moving an operator into a central location, but presenting the same information as before does not necessarily translate to any improvements in overall mining performance. In addition, dynamic controlling underground equipment from a remote location is a very different task to supervising a suite of interconnected mining activities.

3.5. Remote workstation module

One alternative approach to the large console control room approach is to utilise re-configurable, re-deployable management workstation modules [17]. These would be specifically designed to support the functions required for particular personnel. In one scenario, for example, the strategic overview supervision role (pilot) would be collaborative work with the tactical execution role (co-pilot) as shown in Fig. 5. Both single and dual operator module configurations are possible, which could be deployed in a very low-cost, agile manner given suitable communications infrastructure. The key to this approach is that it can more intelligently display information for the specific operational task in a thematic context to facilitate better decision making with less cognitive load.

4. Research innovation and opportunities

4.1. Innovation, technology and culture

Great scope exists for further innovation before the potential of a fully integrated longwall mining system will be realised. This will involve an understanding of mining culture, process and organisation in order to make the best use of technology. World's best long-

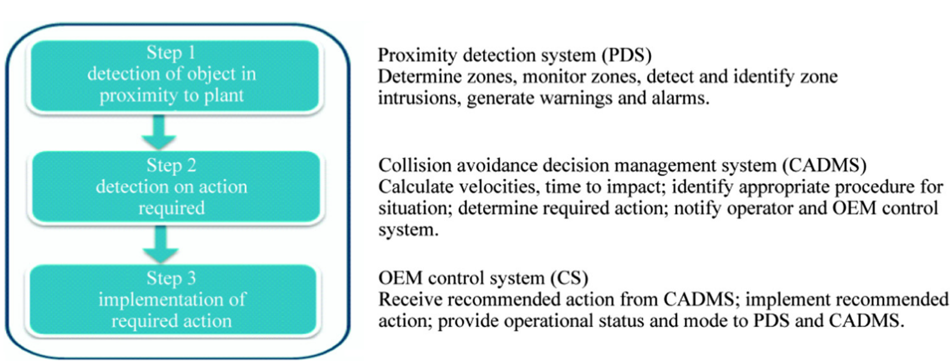


Fig. 3. Proximity detection interoperability schema used to achieving behaviour-function classification.

Fig. 4. A typical operator display configuration for remote management of operations (Image credit [16]).

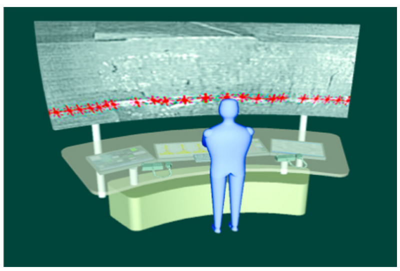


Fig. 5. Conceptual design of a low-cognitive effort operator workstation with thematic immersive awareness to enhance remote mining management performance.

wall practices are achieved by people, processes, and technology, in particular [18].

(1) Mining processes are driven by capacity, availability, utilization and efficiency.
(2) People operate best in planning, supervisory and decision making roles.

Ongoing innovation is required to monitor, control, predict and integrate these operational factors in order to achieve new levels of personnel safety, enhance operational efficiency, and deliver new options for cleaner coal recovery. Technology therefore is not the driver but an important enabler to achieve these purposes.

4.2. A mining systems-level approach

Mining is a dynamic situation that consists of several complex systems which interact with each other under changing operational conditions. A system is more than the sum of its individual parts, and so it is important to understand the both the function and level of interdependence between subsystems will directly influence the overall system behaviour. Because mining system components tend to evolve over time as new equipment or technology is introduced, it is often a challenge to characterise the dynamic nature of the overall integrated mining system.

In a manually operated longwall process, maintaining an overall sense of mining situational awareness is achieved entirely through human skill. This includes retaining a sense of the overall mining objective, identifying and interpreting environmental factors, managing the state of longwall equipment including exceptions, anticipating future operational requirements, and coordinating other personnel to manage the mining objectives. All these functions are undertaken in order to make decisions to best operate longwall shearer functions to deliver the coal product. These key aspects are shown hierarchically in Fig. 6.

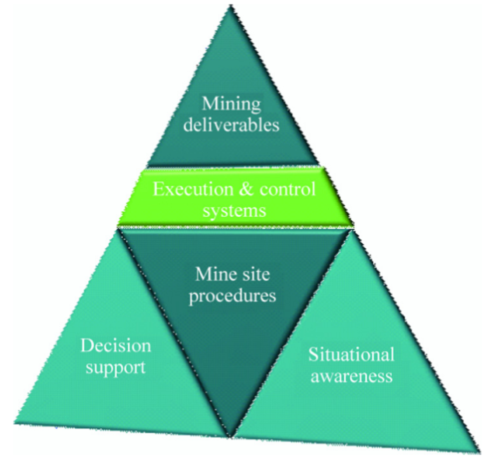


Fig. 6. Hierarchy of process and functional components involved in achieving the mining automation goal.

4.3. Enhancing remote situational awareness

The complexity of the mining environment can make recognising consistent features from a remote location difficult. To aid this process a visual analytics approach can be employed based on the fusion of data sources in a 3D interactive display to facilitate examination of significant features. The resulting display overlays the physical surface structures with complementary scanner data as shown in Fig. 7.

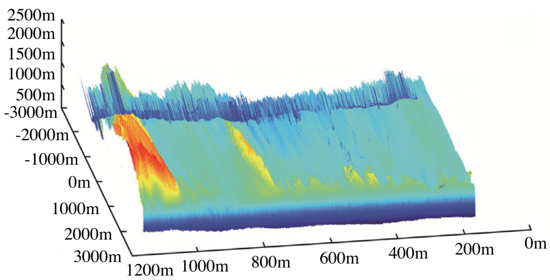
This visualisation approach can provide a highly effective way to reveal characteristics and features of the underground operational environment that may not be immediately apparent, even to an in-situ operator. Visual analytics can therefore provide a highly informative framework to provide the level of situational awareness required for effective remote mining.

A novel data fusion and visual analytics approach was employed based on combining the laser scanner and radar data in a 3D interactive display to facilitate examination of significant features. The goal of this work was to provide a comparative tool whereby radar data could be examined directly with the profile surfaces generated from the laser scanner data. The data was obtained using a combination of a 26 GHz radar sensor and a 2D laser scanner mounted on a vehicle that traversed a section of gateroad, allowing a 3D map to be generated.

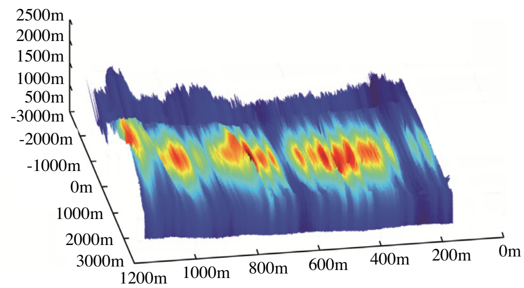
Fig.7a is section of roadway roof that has been mapped using 3D scanning laser sensor, and shows roof profile distances from the floor. Fig.7b presents the same 3D surface as generated from the laser data, but overlaid with radar-based data using a false colour-map. A visual inspection of the data shows how clearly different features present in the radar data can be identified and correlated with profile structures generated by the laser based data. The combination of radar and laser data provides a powerful mechanism for characterising particular radar dataset features that correspond to important geotechnical support elements such as bolts, bolt-plates and mesh. Here the combination of sensing modalities provides greater levels of situational awareness to allow a remote operator to perform monitoring and auditing tasks with higher levels of confidence and insight.

5. Next decade of automation research

The call to deliver improved safety, productivity and environmental outcomes remains urgent, and the next decade will also see a drive towards a more agile, dynamic, and integrated coal mining industry [19]. This will require a review of present mining



(a) 3D laser based data



(b) Combination of laser and radar based data (false colour represents signal intensity)

Fig. 7. Mine information fusion concept (units are in metres).

assumptions and practice to identify what is both essential and efficacious, giving rise to operational models for vertical integration and service provision, convergence of mining operations and business operations, and opportunities for ongoing development and deployment of innovative mining technologies (e.g., see [20–22]).

5.1. Automated exception management

Sensing, processing and control technologies will continue to evolve and mature to provide enhanced options for both assistive and full mining automation capability. However beyond these automation solutions is the need for the next tier of system supervisory control that can intelligently manage exceptions in the operating environment. Here, new research and development is required to explore ways to achieve automated means to not only detect and preempt operational exceptions, but then autonomously undertake the specific steps required to restore operations into the correct operational mode. Because of the complexity and variation of exception modes, this recovery process is currently being undertaken in an entirely manual manner. This factor is a bottleneck to achieving broader acceptance of advanced autonomous control as a failure requires a personnel in-situ to manage the exception, circumventing the value of remote capability.

5.2. Industry factors for increased automation

The continued adoption and utilisation of automation technologies into mining processes will be driven by industry's need for business competitiveness, availability of new functionality through innovations, and governmental regulations. This will deliver a more efficient mining process with enhanced operational continuity and reduced production variability. We expect innovation to be evolutionary rather than revolutionary with the pace of technology adoption and utilisation progressively increasing with industry confidence. The progression in mining technology capability will continue to progress along an automation spectrum, from manual control to full automation with no operator interaction [23]. Immediate short-term development will focus on achieving greater levels of assistive automation to allow the mining process to be more effectively controlled from a remote location.

5.3. Our vision: digital mining ecosystem

The longwall automation developments provide a convincing used case as to what can be achieved in terms of coal mining performance, safety and sustainability [2]. However our vision for mining is much greater: to realise a fully integrated coal mining ecosystem to deliver high-performance, zero-exposure mining. This will require complete visibility of all relevant system and mining processes, where the mining ecosystem is driven by digital information and operated as a mission. It will be implemented using automation technologies which are enabled by decision-support services. The process of operational integration will be achieved through these high-integrity autonomous mining systems which operate with a high-level of trusted autonomy to provide continuous and consistent resource recovery. These systems incorporate self-monitoring capabilities that will automatically self-diagnose and repair, pre-empt failures and provide graceful degradation on exceptions. This system is also environmentally coherent, achieving significantly reduced environmental impacts and emissions through optimal asset and resource utilisation. A comprehensive awareness of resource location and material characteristics will directly enhance optimal resource recovery strategies through advanced selective mining capabilities.

6. Summary

Automation technology has significant potential to provide meaningful solutions by facilitating more accurate mining methods, incorporating sensing to optimally control equipment, and increasing personnel safety through remote process operation. These benefits include reduced operating cost, higher productivity, new operation culture, a reduced environmental footprint, and increased operator safety. Technology innovation needs to be ultimately guided by the vision, culture and process of the organisation. Technology developments in sensing, processing and control, however, are essential enablers to realise higher levels of automation performance. The outcomes gained through past and present developments provide critical insights and lessons to help understand the value of emerging automation technologies towards achieving the future integrated mining ecosystem.

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