An integration platform for smart, integrated mining

K. Kruger[1], D. Sparrow[2], and T. Defty[2]

[1]Stellenbosch University, South Africa
[2]Cybarete, Stellenbosch, South Africa

The mining sector frequently faces the two-fold challenge of integrating data from various sources, and integrating various decision makers and decision-making processes that utilise the data. This paper presents an integration platform to support real-time monitoring, coordination and decision making in mining contexts. The integration platform is based on a *Holonic Systems* approach and is implemented using the *Biography-Attributes-Schedule-Execution* architecture. The functionality of the platform is illustrated by means of a case study implementation, which integrates sensors, human and non-human resources, business processes, and decision maker interfaces.

INTRODUCTION

The mining sector frequently faces a two-fold challenge: integration of data from various sources, and integration of various decision-making processes that utilise the data. Even when mines adopt sophisticated systems and solutions to address this challenge, the functionality and data frequently remain isolated within *silos* – with little provision and capability for integration.

As per the vision of the fourth industrial revolution, new opportunities for value-generation lie within the integration of data, systems and technologies. To achieve this integration, development should be focused on two aspects: firstly, the functional and data silos have to be fused in a structured and reconfigurable manner; and, secondly, decisions and reactions to the data need to be effectively communicated and executed for the value to be realised. Furthermore, when human workers directly execute mining processes, it presents particular challenges – to obtain data from the humans, to use data-driven systems to direct their actions (in response to decisions made at higher organisational levels), and to aid their decision-making in their immediate context. These challenges are acute when the workers have low skill levels and where their actions significantly impact safety and productivity.

This paper presents an integration platform to support near real-time monitoring, coordination and decision making in mining contexts – specifically, where human workers play an integral role. The development of the platform, using the *Holonic Systems* approach and *Biography-Attributes-Schedule-Execution* (BASE) architecture, is described. The functionality of the platform is illustrated by means of a case study implementation, which integrates sensors, human and non-human resources, business processes, and decision maker interfaces.

The developed integration platform promises to unlock new opportunities for value-addition through the integration of various aspects of mine operation and management and, specifically, the integration and information management of mine workers – thereby improving situational awareness and supporting reactive and proactive decision-making.

The paper presents some related work, to place the presented research in context. Thereafter, the design of the integration platform is presented, the case study implementation is discussed, and, finally, a conclusion is offered.

RELATED WORK

This section presents a brief review of literature on software systems, connectivity solutions and system integration applications in mining. The related work includes underground and surface-level mining case studies. Furthermore, this section presents research related to Industry 4.0 technologies and concepts. Lastly, background is given on the BASE architecture, which is used to implement the integration platform presented in this paper.

Software System and Data Integration in Mining

Bassan, Srinivasan, Knights, *et al.,* (2008) proposed the *mine of the future* for 2025, which included smart mining systems designed to automate business processes and decision-making, using advanced analytics tools. This idea relied on the improvement of system integration technologies and virtual collaboration systems to provide a 'network effect' between 'isolated' systems so that the overall goals of the entire system are achieved. To achieve such a future, amongst other reasons, Industry 4.0 (I4.0) concepts and technologies from manufacturing have begun coming into effect in the mining industry (Lööw, Abrahamsson & Johansson, 2019).

Enabling technologies for I4.0 include the Internet of Things (IoT) devices and communication protocols, big data and analytics, autonomous robots, system integration, augmented reality and Cyber-Physical Systems (CPSs) (Bigliardi, Bottani & Casella, 2020). CPSs aim to connect the physical and virtual world using various networking, computing, sensing, data storage, and software technologies (Pivoto, de Almeida, da Rosa Righi, *et al.*, 2021). A prominent architecture for CPSs is the 5C's architecture, which defined smart connection, data-to-information conversion, cyber, cognition and configuration layers (Lee, Bagheri & Kao, 2015). Related work on CPSs in the mining industry has relied on IoT advancements in wireless sensor networks (WSN), wireless area networks (WAN) and communication protocols, such as ZigBee.

Nikolakis, Kantaris, Bourmpouchakis, *et al.,* (2020) developed a CPS to support smart on-demand ventilation control for underground mining. The CPS included sensors that measured air quality, temperature and humidity in the mine environment and actuators for the ventilation fan control. Additionally, the networking was achieved through implementing a long-range wireless communication network, which utilised IoT nodes installed throughout the mine tunnel. This case study evaluation indicated that the CPS reduced the energy consumption of the ventilation system.

A recent review by Molaei, Rahimi, Siavoshi, *et al.,* (2020) of IoT and its application in mining has argued how IoT devices and networking have:

- Improved the resource utilisation of mining fleets.
- Improved the visibility and control of mining operations.
- Aided business processes.
- Aided predictive analysis to reduce breakdowns and operating costs.
- Improved mine worker safety.

Research into software systems and data integration in mining has generally orientated itself around the application of smart sensor devices and WSN to improve the traceability of mining operations and improve safety in mining. The use of these IoT devices and systems for specific use cases, such as detecting hazardous gasses or positioning equipment, has shown benefits. However, there is no integrated infrastructure to support data from different IoT systems across applications (Molaei *et al.*, 2020).

Mineworker-related Systems and Technology

A key aspect of digital transformation in mining is ensuring that digital systems and equipment are effectively integrated with people (Ulewicz & Ingaldi, 2022). Human Cyber-Physical Systems (HCPSs), as defined by Yilma, Panetto & Naudet (2021), is "*a system of interconnected systems (i.e. computers, devices and people) that interact in real-time, working together to achieve the goals of the system*". HCPS concepts, such as the Operator 4.0 model developed by Romero *et al.,* (2016), have since been translated to the mining industry – described as the Miner 4.0 (Lööw *et al*., 2019).

Lööw *et al.,* (2019) described a Miner 4.0, supported by I4.0 technology, as being:

- *Smarter* - having intelligent personal assistants for interfacing with information systems and machines.
- *Collaborative* – capable of reducing the miner's workload by collaborating with other machinery or humans.
- *Healthy* – using wearable sensors and systems for monitoring health-related metrics.
- *Analytical* – having decision-support systems which analyse data captured from the environment.

Progression towards a smart and integrated miner, or Miner 4.0, can be seen in the recent application of I4.0 technology for mine workers. These technologies are generally related to position tracking and health and safety monitoring. Such technologies include the use of smart wearable devices, as well as utilising IoT networking technology for data communication.

Singh *et al.,* (2022) developed an IoT-enabled helmet to improve the health and safety monitoring of mineworkers underground. The smart helmet utilised various gas sensors, accelerometers, GPS and IoT connectivity to aid in the early detection of hazardous conditions for the mine worker. This real-time smart helmet device is able to alert the mineworker of hazardous gas exposure, high temperature, early fire detection and silicosis dust particles. Other wearable developments include a smart jacket that can monitor the miner's pulse rate, global position, temperature and humidity exposure and can transmit alerts along the network in the event of an emergency (Ananth, Thenmozhi, Vadakkan, *et al.*, 2022). Baek & Choi, (2019) developed a low-cost proximity warning system for mineworkers and equipment underground, using smartphones and Bluetooth beacons. These developments demonstrate the application of smart devices and IoT networking to implement a mineworker safety system.

The BASE Architecture

The Reference Architecture Model Industry 4.0 (RAMI 4.0), which aims to support I4.0 integrations, describes six interoperability layers: *business*, *functional*, *information*, *communication*, *integration* and *asset* (Zezulka, Marcon, Vesely, *et al.*, 2016). The *asset* layer represents the physical world which is connected to the virtual world through developments in the *integration* layer. A I4.0 component model, developed as an extension of RAMI 4.0, prescribes a digital administration shell for each physical *asset* that must contain specific information and enable standardised communication between administration shells.

The BASE architecture, developed by Sparrow, Kruger & Basson (2021), guides the development of such *digital administration shells*. Despite being initially intended to provide the digital administration shells for humans specifically, the BASE architecture has been successfully applied to other physical entities – non-human assets/resources and even activities (or processes) (Wasserman, Kruger & Basson, 2023; Defty, 2022). The BASE architecture is visualised in Figure 1.

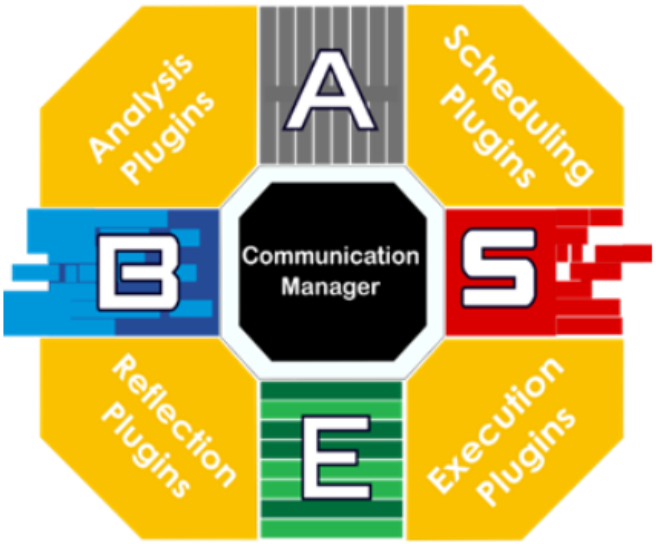

Figure 1. The BASE architecture for digital administration shells (Sparrow, 2021).

The BASE architecture specifies that digital administration shells must consist of both *core* and *plugin* components. The core components are generic and serve as the necessary infrastructure for the administration shell functionality, while the plugin components are interchangeable components, developed to provide the functionality required for a specific application.

The core components of the BASE architecture are: *Biography*, *Attributes*, *Schedule* and *Execution*. The Biography stores data of activities that the physical entity was involved with and relevant data from the worker's surrounding environment. Attributes stores data related to the unique properties of the individual physical entity. The Schedule component manages all data related to the activities the physical entity will be involved with in the future. The Execution component manages all data related to the dynamic state of the physical entity as it performs activities.

The BASE architecture also specifies a *Communication Manager* component. The Communication Manager serves as the gateway for communication between the digital administration shell and other digital administration shells or external digital systems.

The plugin components are the interchangeable and application-specific components of the BASE digital administration shell, which are developed for a specific use case. The BASE architecture defines four types of plugins: *Scheduling Plugins*, *Execution Plugins*, *Reflection Plugins* and *Analysis Plugins*. For a specific application:

- Scheduling Plugins (SPs) will be developed to manage the schedule of the physical entity.
- Execution Plugins (EPs) will be developed to support the physical entity in its performance of tasks (e.g. provide instructions) and gather data to represent the physical entity's dynamic state.
- Reflection Plugins (RPs) will be developed to acquire data on the tasks performed by the physical entity retrospectively and store relevant data to the Biography.
- Analysis Plugins (APs) will be developed to analyse data in the Biography to update the physical entity's Attributes (ensuring an accurate and updated model of the physical entity) and provide insight for decision making.

AN INTEGRATION PLATFORM USING THE BASE ARCHITECTURE

This section describes the development of the integration platform. The design of the platform, as based on the Holonic Systems approach, is discussed first. Therafter, the implementation of the platform using the BASE architecture is described.

Platform design
The integration platform is developed using a *Holonic Systems* approach and the *Biography-Attributes-Schedule-Execution* (BASE) architecture, which allows physical entities in the mine context (human and non-human) to be represented by active, individualised *digital administration shells*.

The Holonic Systems approach employs the philosophy that complex systems can be constructed from an organisation of simpler components – called *holons* – which exhibit the key characteristics of *autonomy* and *cooperability* (Koestler, 1967). Autonomy refers to the ability of holons to encapsulate their own decision-making logic and to perform their own functions. Cooperability refers to the ability of holons to interact with other holons to achieve their own goals/functions, or to collaborate to achieve goals of greater scope or complexity.

The Holonic Systems approach has been applied to the domain of manufacturing systems – resulting in the Holonic Manufacturing Systems paradigm – to support the integration and coordination of complex and dynamic manufacturing processes and resources (Leitão & Restivo, 2006). The approach has also shown promise for application in different domains, such as logistics (Ounnar & Pujo, 2016) and healthcare (Defty, 2022).

To support the Holonic Systems approach to developing the integration platform for mining assets and operations, the Activity-Resource-Type-Instance (ARTI) holonic reference architecture (Valckenaers and Van Brussel, 2015) was used. The ARTI architecture guides the representation of the physical context (in this case, the mine environment) in terms of two types of holons: Resource holons, which represent the resources or assets in the context that can perform services (i.e. tasks or actions that may be useful to the system's operation); and Activity holons, which represent the processes that aim to coordinate the Resource holons to achieve the system's goals.

The vehicles, sensors, utilities (e.g. ventilation system), equipment, mine workers, etc. in the mining context are represented as Resource holons. The processes that coordinate and utilise these resources – e.g. an underground blasting activity – are represented as Activity holons. A depiction of how the various holons can interact, and their resulting organisation, is shown in Figure 2. The implementation of the various Resource and Activity holons and their interactions, by means of the BASE architecture, forms the basis of the integration platform.

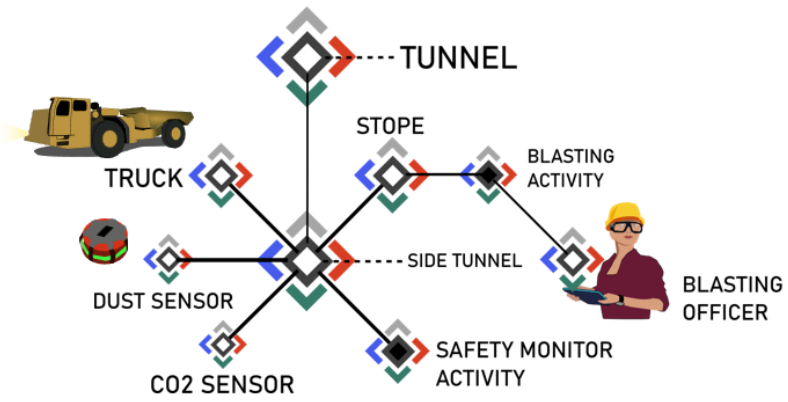

Figure 2. Interaction of Resource and Activity digital administration shells within the integration platform.

Platform implementation
The output of the Holonic Systems approach is the set of holons and their interactions that must be implemented. For the integration platform, each of the holons are implemented by means of their corresponding digital administration shells using the BASE architecture.

The functionality to enable the autonomy and cooperability of each of the holons is implemented through application-specific plugins to the BASE digital administration shells. As such, the digital administration shell of each Resource and Activity holon represented in the platform is equipped with SPs and EPs that allow them to communicate, schedule and execute their own operations. Each holon is also equipped with RPs and APs, which allow the holons to integrate their data and perform analyses on their data, respectively. Furthermore, where digital administration shells must exchange data with physical sources (e.g. capture measurements from sensors or display information to interface devices), EPs were deployed to handle such interfaces specifically.

The digital administration shells of the BASE architecture, and thus the presented integration platform, were developed using the Erlang programming language. Erlang was developed in the telecommunications sector; therefore, this functional programming language is ideal for developing robust, scalable and massively concurrent software systems. Each digital administration shell is implemented as a group of interacting, concurrent software processes.

CASE STUDY

To illustrate the functionality and capabilities of the integration platform, a case study was performed in a simulated mine environment. The case study focussed on the integrated monitoring and coordination of all mining resources involved in an underground blasting activity. The case study was performed in the Smart Integrated Mining Laboratory (SIMLAB) at the Department of Mechanical and Mechatronic Engineering at Stellenbosch University.

Case Study Description

As context, the case study considers a representative section of the underground mine environment – a section of a mine tunnel with branching stope tunnels leading to stope faces, as depicted in Figure 3. The mine environment is equipped with typical sensors and connectivity infrastructure, as illustrated in Figure 4. The mine tunnel provides connectivity to devices via RS485, Ethernet and WiFi, which connect to the mine's main underground fibre network. The stope tunnels provide connectivity through a Bluetooth low-energy network. Furthermore, the case study context includes computation devices in the mine tunnel, as well as at the entrances to each of the stope tunnels.

For the case study, the integration platform will ingest, process and contextualise the data from the stope and mine tunnel sensors to:

- monitor and coordinate the human and non-human resources involved in an underground blasting operation; and
- provide real-time, human-centred and contextualised information on underground operations to the aboveground control room and a Cloud-based Geographical Information System dashboard.

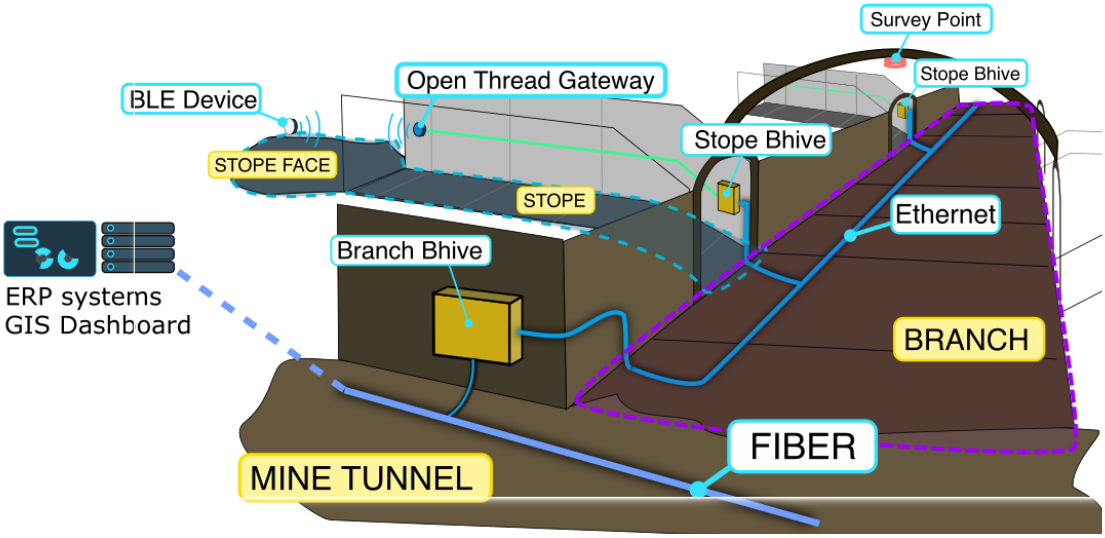

Figure 3. Case study underground mine environment.

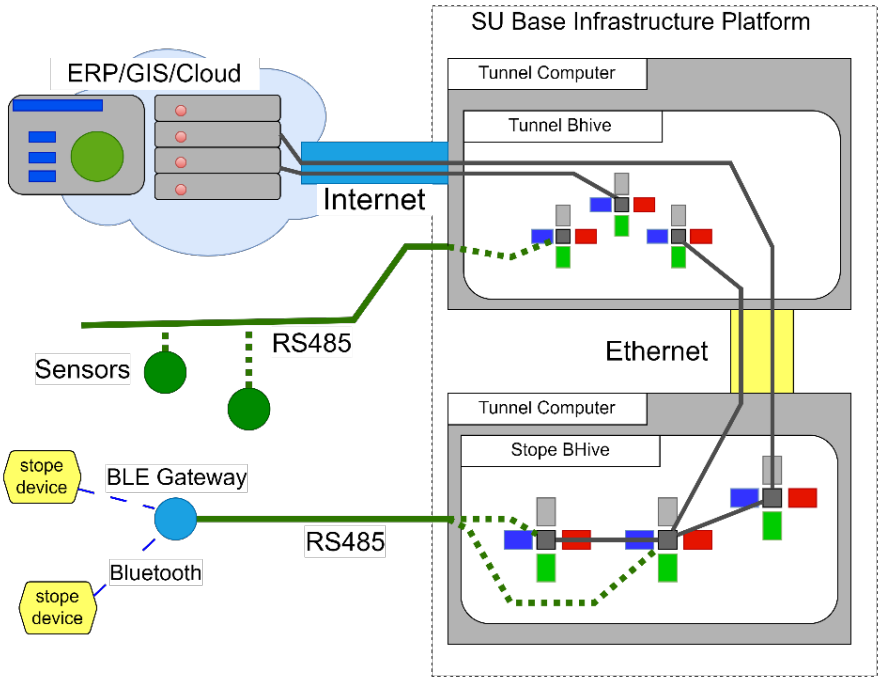

Figure 4. Data flows from stope devices to the integration platform and through to the Cloud dashboard.

Test Scenario

The SIMLAB is an aboveground testbed for researching and evaluating digital underground mining technologies – specifically focussed on the integration of such technologies and the coordination and monitoring of underground resources and operations. Figure 5 shows the SIMLAB configuration to represent a test scenario that matches the case study. The SIMLAB is equipped with the connectivity infrastructure (as per Figure 4) and sensors (for measuring atmospheric conditions and for proximity detection) within the replicated mine and stope tunnels.

Figure 5. SIMLAB mine and stope tunnels.

Integrated Monitoring and Coordination

For the case study, a blasting activity was selected as a typical mining business process that involves the coordination of multiple human and non-human resources. Blasting activities also emphasise the importance of traceability of underground operations. The integration platform must thus perform functions related to near real-time monitoring and coordination, while acquiring, intergating and contextualising relevant data for various sources to enable traceability.

For the case study, the integration platform deployed BASE digital administration shells for all the human and non-human resources involved in the blasting activity, as well as a digital administration shell that represents the blasting activity itself – corresponding to the architecture shown in Figure 2.

The digital administration shells developed and deployed for non-human resources included those for the various sensors (such as the dust monitor and gas level sensors), proximity detection system, ventilation system, and simulated vehicles and equipment. The mine tunnel, as an integration point for all the operations and data in the underground environment, was also represented by a digital administration shell. Digital administration shells were also deployed for each of the interface devices (specifically, the blasting officer's hand-held device and the control room dashboard).

A digital administration shell was also developed and deployed for each mineworker. For each mineworker, their digital administration shell continuously (and in near real-time) integrated data related to their exposure (from the digital administration shells representing the tunnel sensors) and location (from the digital administration shell representing the proximity detection system). The digital administration shell for the blasting officer also integrated exposure information and was further equipped with plugins that gather data from other resources regarding the execution and progress of the blasting activity.

The digital administration shell that represents the blasting activity implemented plugins that coordinate the sequence of operations required for a successful blasting activity. This shell gathers data from the resources represented within the integration platform in order to monitor the progress of the activity, and communicates instructions to the relevant resources.

The digital administration shells of the mine tunnel, mineworkers and blasting activity provided contextualised information to the data interfaces of the integration platform. Each of these interfaces were maintained and managed by a dedicated digital administration shell as well – equipped with the

functionality to process and display integrated information and to capture and communicate decision-maker input. An example of the control room interface is shown in Figure 6.

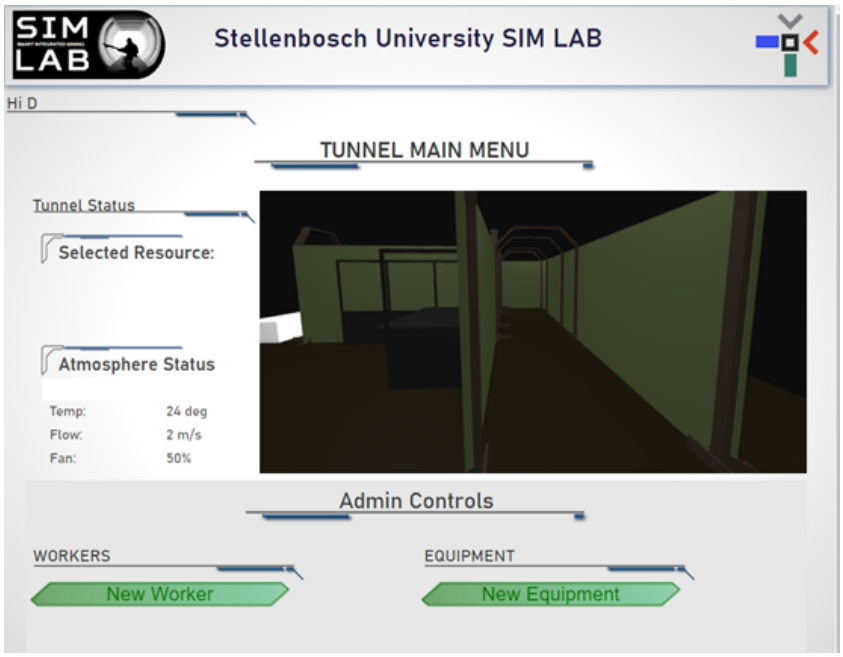

Figure 6. Example output of the control room interface.

CONCLUSION

The paper presents an integration platform for smart, integrated mining. The platform aims to address the challenges of functional and data integration of systems, human and non-human resources and operations involved in the underground mining operations.

The development of the integration platform is described, with the platform design guided by the Holonic Systems approach and the implementation thereof enabled by the BASE architecture for digital administration shells. As a result, the integration platform is composed of various autonomous and cooperative entities that actively represent the physical resources and processes present in the underground mining operations.

The functionality of the integration platform was discussed by means of a case study. The case study considered a typical underground mine environment (replicated in the SIMLAB testing facility) and a representative mining business process (an underground blasting activity). By means of the case study, the functionality and role of the various digital administration shells executing within the integration platform was discussed.

Future work on the integration of underground mining resources and processes will focus on deploying and evaluating the integration platform in real underground environments. Challenges to be addressed include: achieving interoperability between a diverse range of systems, technology and suppliers in the mining sector; achieving software system reliability that is similar or better than existing systems; and achieving technology acceptance by mines and mineworkers. The last challenge will be addressed in planned future work to expand the functionality of the mineworker BASE digital administration shell and related technologies.

ACKNOWLEDGEMENT

The research presented in this paper was supported by funding from the Mandela Mining Precinct Real-Time Information Management Systems programme and the National Research Foundation (grant number: 129360).

REFERENCES

Ananth, C., Thenmozhi, P., Vadakkan, D.J., Kavitha, S. & Kumar, T.A. (2022). Wearable Smart Jacket for Coal Miners Using Iot. in *Proceedings of International Conference on Technological Advancements in Computational Sciences, ICTACS 2022* IEEE. 573–577.

Baek, J. & Choi, Y. (2019). Development of a low-cost Proximity Warning System for mine equipment using smartphone and Bluetooth beacons. in *Mining Goes Digital* London: CRC Press. 715–719.

Bassan, J., Srinivasan, V., Knights, P. & Farrelly, C.T. (2008). A Day in the Life of a Mine Worker in 2025. *1st International Future Mining Conference and Exhibition*. 71–78.

Bigliardi, B., Bottani, E. & Casella, G. (2020). Enabling technologies, application areas and impact of industry 4.0: A bibliographic analysis. in *Procedia Manufacturing*. Elsevier B.V. 42:322–326.

Defty, T. (2022). *A Holonic Human Cyber-Physical System in Healthcare*. Masters Thesis, Stellenbosch University.

Koestler, A. (1967). *The Ghost in the Machine*. Penguin Group.

Lee, J., Bagheri, B. & Kao, H.A. (2015). A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters*. 3:18–23.

Leitão, P. & Restivo, F. (2006). ADACOR: A holonic architecture for agile and adaptive manufacturing control. *Computers in Industry*. 57(2):121–130.

Lööw, J., Abrahamsson, L. & Johansson, J. (2019). Mining 4.0—the Impact of New Technology from a Work Place Perspective. *Mining, Metallurgy and Exploration*. 36(4):701–707.

Molaei, F., Rahimi, E., Siavoshi, H., Afrouz, S.G. & Tenorio, V. (2020). A Comprehensive Review on Internet of Things (IoT) and its Implications in the Mining Industry. *American Journal of Engineering and Applied Sciences*. 13(3):499–515.

Nikolakis, N., Kantaris, G., Bourmpouchakis, K. & Alexopoulos, K. (2020). A cyber-physical system approach for enabling ventilation on-demand in an underground mining site. in *Procedia CIRP*. Elsevier B.V. 97:487–490.

Ounnar, F., & Pujo, P. (2016). Holonic Logistics System: a novel point of view for Physical Internet. In *Proceedings of International Conference on Information Systems, Logistics and Supply Chain* (ILS 2016), June (pp. 1-4).

Pivoto, D.G.S., de Almeida, L.F.F., da Rosa Righi, R., Rodrigues, J.J.P.C., Lugli, A.B. & Alberti, A.M. (2021). Cyber-physical systems architectures for industrial internet of things applications in Industry 4.0: A literature review. *Journal of Manufacturing Systems*. 58:176–192.

Romero, D., Bernus, P., Noran, O., Stahre, J., Fast-berglund, Å. (2016). The Operator 4 . 0 : Human Cyber-Physical Systems Adaptive Automation Towards Human-Automation Symbiosis Work Systems. *IFIP International Conference on Advances in Production Management Systems (APMS)*. 677–686.

Singh, N., Gunjan, V.K., Chaudhary, G., Kaluri, R., Victor, N. & Lakshmanna, K. (2022). IoT enabled HELMET to safeguard the health of mine workers. *Computer Communications*. 193:1–9.

Sparrow, D. (2021). *An architecture to facilitate the integration of human workers into an Industry 4.0 manufcaturing environment*. Doctoral thesis, Stellenbosch University.

Sparrow, D., Kruger, K. and Basson, A. (2021). An architecture to facilitate the integration of human workers in Industry 4.0 environments. *International Journal of Production Research*. 60(15):4778-4796. DOI: 10.1080/00207543.2021.1937747

Ulewicz, R., Ć, B.K. & Ingaldi, M. (2022). Mining Industry 4.0 – Opportunities and Barriers. *Acta Montanistica Slovaca*. 22(27):291–305.

Valckenaers, P. & Van Brussel, H. (2015). Design for the unexpected: From holonic manufacturing systems towards a humane mechatronics society. Butterworth-Heinemann.

Wasserman, A., Kruger, K. and Basson, A.H. (2023). ARTI-Based Holonic Manufacturing Execution System Using the BASE Architecture: A Case Study Implementation. In *Smart, Sustainable Manufacturing in an Ever-Changing World: Proceedings of International Conference on Competitive Manufacturing (COMA'22)*. Cham: Springer International Publishing. 45-58.

Yilma, B.A., Panetto, H. & Naudet, Y. (2021). Systemic formalisation of Cyber-Physical-Social System (CPSS): A systematic literature review. *Computers in Industry*. 129:103458.

Zezulka, F., Marcon, P., Vesely, I. & Sajdl, O. (2016). Industry 4.0 – An Introduction in the phenomenon. *IFAC-PapersOnLine*. 49(25):8–12.

Dale Eric Sparrow

CEO
Cybarete

Dr Dale Sparrow completed his PhD in mechatronic engineering at Stellenbosch University in 2021. His PhD developed a digital platform for human and system integration in Industry 4.0 environments. He has since guided the commercialization of the platform as CEO of the technology start-up company, Cybarete.