Collaborative Control Digital Twin Technology for Mines

Yue Cao [1], Yuhan Zhong [*2]

College of Business Administration, Liaoning Technical University, Huludao 125105, Liaoning, China[1,2]

Email: CAO_YUE1995@163.COM[1], 1363931976@qq.com[*2]

Abstract. Digital twin technology can provide strong technical support for data integration, collaborative management, and intelligent linkage of the global mining business system. By constructing a business dynamic collaborative control architecture based on digital twins, covering the physical object perception layer, virtual space simulation layer, and collaborative control decision-making layer, the virtual model construction and forward-looking static planning of the diversified business of "safety production operation" in mines can be achieved, significantly improving the effectiveness of decision-making. The current application status of digital twin technology in mining safety management, production, and operation management shows that it is expected to solve the interaction problem between the physical world, promote the intelligent construction of the entire life cycle of mines, and promote the high-quality development of the coal industry.

Keywords: digital twin; intelligent control; information exchange; system digitization; potential obstacles

1 Introduction

As the core of the new generation of information technology, digital twin technology integrates advanced technologies such as artificial intelligence, cloud computing, and big data, and has been widely applied in the industrial field. In smart mines, with the integration and intelligence of coal mining equipment, the difficulty of managing safety, production, and operation has significantly increased [1-2]. By high fidelity virtual mapping of entities and processes in mining, transportation, and other links [3], combined with real-time data feedback, functions such as mine space design, disaster prediction and prevention, production scheduling optimization, and equipment lifecycle management can be achieved, effectively improving the intelligence level of mines.

In February 2020, the National Development and Reform Commission and eight other ministries jointly issued the "Guiding Opinions on Accelerating the Intelligent Development of Coal Mines", emphasizing the construction that integrates multiple systems and intelligent application of coal mine business [4]. Although a single system in the digital mining era can independently monitor the environment, store and ana-

S. M. Ghadiri et al. (eds.), *Proceedings of the 2025 4th International Conference on Engineering Management and Information Science (EMIS 2025)*, Advances in Computer Science Research 121,
https://doi.org/10.2991/978-94-6463-736-6_13

lyze data, relying solely on a single system perspective appears to be somewhat one-sided [5]. Emerging technologies such as artificial intelligence, cloud computing, and big data can provide technical support for global analysis for coal mine decision-makers [6-7].

Digital twin has become a research hotspot in the field of information technology since it was first proposed by Professor Michael Grieves at the University of Michigan in 2002[8]. NASA's definition of digital twins in 2010 emphasized their mapping of the entire lifecycle of physical equipment in virtual space [9]. Georgia Tech University proposed the concept of digital twin cities in 2017[10]. In recent years, with the continuous expansion of the concept of digital twins, related standardization work is also gradually underway.

2 The Overall Idea of Building a Digital Twin Mine

Building a digital twin mine is a strategic and systematic project. Through the integration of cloud computing, big data, the Internet of Things, mobile Internet, artificial intelligence and other cutting-edge technologies, the convergence of industrial technology, information technology and management art is realized [11].

In this process, it is necessary to start with a solid top-level architecture design for digital intelligence to ensure a clear construction path [12]. The blueprint for building a digital twin mine needs to be built around three core dimensions, six key business activities, and seven data elements. It can improving operational efficiency and decision-making accuracy, promoting efficient resource allocation and sustainable utilization, as shown in Figure 1.

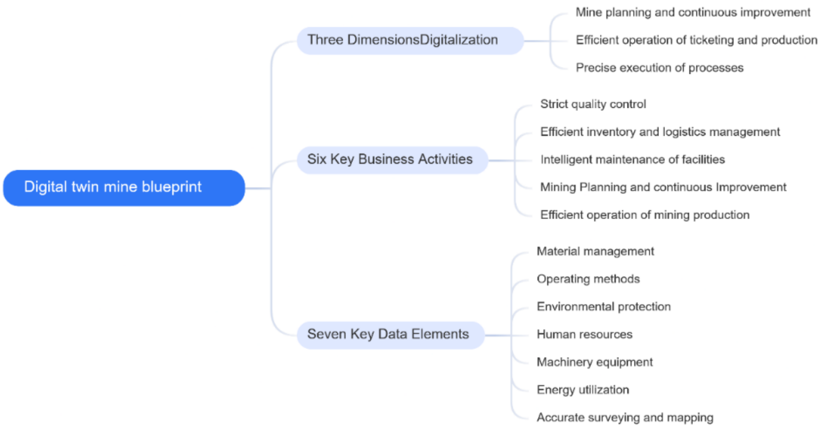

Fig. 1. Blueprint for the Digital Twin Mine

To comply with this trend and based on unified standards, specifications, and strict security operation and maintenance guarantee system, the overall business architecture of digital twin mines can be divided into five key levels from bottom to top: equipment layer (L1), technology layer (L2), production data layer (L3), management layer (L4), and decision analysis layer (L5) [13-14], as shown in Table 1.

Table 1. Overall Business Architecture of Digital Twin Mines

Equipment Layer (L1)	Control Layer (L2)	Production Execution Layer (L3)	Management Layer (L4)	Decision Making Layer (L5)
Network Sensors Smart Devices Intelligent Instrument Digital Camera	Centralized Monitoring Collaborative Control Stable Communication Data Transmission Integration of Multiple Software Hardware Interfaces Real Time Monitoring	Business Integration Business Collaboration Safety Production Production Scheduling Data Acquisition Decision Support	Human Resource Enterprise Financial Material Supply Equipment Asset Mineral Transportation Sales Management Digital Archive	Strategic Planning Decision Making Resource Allocation Risk Management and Response Information Integration Decision Support Continuous Improvement

3 Specific Architecture for Building a Digital Twin Mine

3.1 Detail Architecture "Points" - Digitalization of a Single System

The route to building a digital twin mine should follow the principle of four levels of progressive expansion in spatial dimension, focusing first on the digitization of "points". The goal of this level is to achieve digitalization of individual systems, equipment, and technologies in mining production [15]. By introducing advanced sensors, control technologies, and intelligent algorithms, specific systems (such as monitoring systems, ventilation systems), individual production equipment (such as excavators, loaders), and specific technological applications (such as intelligent mining software, geological exploration technology) can operate independently, with the ability to self monitor, self optimize, and self adjust.

3.2 Detail Architecture "Line" - Multi System Digital Interconnection

The construction of a digital twin mine should follow the principle of four levels of progressive expansion in spatial dimension, with the second level focusing on the digitization of "lines". This level aims to achieve digital interconnection between multiple systems, collaborative operation of multiple machine equipment, and integrated management of multiple systems [16]. By building a unified data platform and communication protocol, it promotes information sharing and interaction among production management, safety monitoring, environmental monitoring and other systems, achieving seamless integration and efficient collaboration between systems. At the same time, we will promote the digital scheduling and coordination of multi machine equipment such as unmanned mining cars and intelligent mining equipment, improve operational efficiency and safety, and strengthen the integration of multiple systems to form a unified, efficient, and intelligent comprehensive management system.

3.3 Detail Architecture "Surface" - Full System Digital Integration

The construction of a digital twin mine should follow the principle of four levels of progressive expansion in spatial dimension, with the third level focusing on the digitization of the "face". The goal is to build a functional production control system and promote deep digital integration of the entire mine system [17]. By integrating all production, safety, management, monitoring and other systems within the mine, comprehensive sharing and deep mining of data resources can be achieved, forming a unified digital management platform. This platform can monitor the real-time operation status of mines, intelligently analyze production data, predict potential risks, and automatically adjust production plans and resource allocation, achieving efficient, safe, and green production in mines [18]. At the same time, the digital production control system significantly improves the automation level of mines, reduces manual intervention, lowers operating costs, and improves economic benefits.

3.4 Detail Architecture "Body" - Full Area Digital Control System

The construction of a digital twin mine should follow the principle of four levels of progressive expansion in spatial dimension, with the fourth level focusing on the digitization of the "body". Aiming to build a regional digital control system covering the entire mining area. This system covers key links such as production, logistics, safety, and environmental protection [19]. Through integrated information systems and digital management methods, it achieves optimized resource allocation, fine production management, and comprehensive safety prevention and control, promotes close linkage between the mining area and the external environment, promotes sustainable development, and helps mines to make digital leaps from a single mine to the entire mining area.

4 Potential obstacles and solutions for digital twin mining technology

4.1 Potential obstacles

Mines are usually located in remote areas with complex geographical environments and insufficient network signal coverage, which makes it difficult to ensure real-time and stable data transmission. At the same time, the mining process involves monitoring various physical quantities, such as geological parameters, equipment status, etc. However, existing sensors have shortcomings in accuracy, range, and anti-interference ability, which cannot meet the requirements of digital twin technology for high-precision and all-round data acquisition.

The implementation of digital twin technology requires the purchase of a large amount of hardware equipment, such as high-performance servers, advanced sensor networks, industrial grade network devices, etc., while also requiring a significant investment in software platform development and integration. For mining enterprises, this is a huge initial investment. In addition to initial investment, the operation and maintenance costs of digital twin systems cannot be ignored. Hardware devices require regular maintenance, upgrades, and software platforms also need to be continuously optimized and updated according to actual needs. In addition, professional technicians are required for system monitoring, troubleshooting, and data management.

Some mining enterprises have insufficient understanding of digital twin technology and have doubts about its actual benefits. Some business decision-makers believe that digital twin technology is only a conceptual hype and cannot truly solve practical problems in mining production, thus lacking the motivation for implementation. At the same time, there is currently a relative shortage of such talents in the mining industry, and enterprises face difficulties in talent recruitment and high training costs during the implementation process.

4.2 Solution

The government and enterprises should increase investment in network infrastructure in mining areas to improve the coverage and quality of network signals. In special environments such as underground mines, a network architecture combining wired and wireless can be adopted, utilizing technologies such as industrial Ethernet and 5G private networks to ensure the stability and real-time performance of data transmission. At the same time, strengthen cooperation with research institutions and equipment manufacturers to jointly develop high-performance sensors suitable for mining environments. By adopting advanced sensing technologies such as fiber optic sensing and microelectromechanical systems (MEMS) sensing, the accuracy, range, and anti-interference ability of sensors are improved to meet the requirements of digital twin technology for data acquisition. Establish a sensor calibration and maintenance mechanism to ensure the accuracy and reliability of data.

Mining enterprises can divide the implementation of digital twin technology into multiple stages and gradually promote it based on their actual situation. In the initial stage, key production processes or equipment can be selected for pilot applications, accumulating experience and optimizing solutions before gradually expanding the application scope to avoid excessive one-time investment. With the powerful computing and storage resources of cloud service providers, enterprises do not need to purchase a large number of hardware equipment on their own, and can rent cloud servers, storage space, and other resources as needed, reducing hardware investment costs. At the same time, fully utilize the power of open source software and technology communities, adopt mature open source digital twin platforms or frameworks for secondary development and integration, and reduce software development costs.

By organizing technical seminars, industry exhibitions, internal training, and other methods, we aim to promote the principles, advantages, and successful application cases of digital twin technology to decision-makers, technical personnel, and frontline workers, and increase their awareness and acceptance of digital twin technology. At the same time, mining enterprises should establish close cooperative relationships with universities and research institutions to jointly carry out talent training projects related to digital twin technology. Develop preferential policies to attract outstanding external talents and strengthen the technical team of the enterprise.

5 Application Cases and Impact Analysis of Digital Twin Mines

5.1 Actual Cases

Shaanxi Coal Zhangjiamao Coal Mine is one of the typical representatives of intelligent construction in China's coal mines. The mine has achieved digital management of all elements, processes, and lifecycle by introducing digital twin technology. Firstly, a high-precision 3D geological model is constructed, utilizing advanced geological exploration techniques and data acquisition equipment to establish an accurate 3D geological model of the mine, providing scientific basis for mine design, construction, and production. Secondly, digital twin modeling and monitoring of equipment can be achieved. By modeling key equipment such as coal mining machines and tunneling machines with digital twins, real-time data on equipment operation can be collected. Through real-time interaction between virtual models and physical equipment, remote monitoring and fault warning of equipment can be achieved, effectively reducing equipment failure rates and improving production efficiency. Finally, optimizing the production process, virtual simulation and optimization of the mining production process were carried out to identify bottleneck links in the production process, formulate reasonable production plans and scheduling schemes, and improve resource utilization and production efficiency. Through these measures, Shaanxi Coal Zhangjiamao Coal Mine has achieved significant results in intelligent construction, not only improving production efficiency and safety, but also significantly reducing production costs.

The Ruihai Gold Mine Digital Twin System is an intelligent mining project jointly established by China Enfi and Zhaojin Mining Industry. This project implements platform based management of the entire lifecycle of mining construction, achieving digitalization of the entire process from design to operation and maintenance. Firstly, the use of digital twin technology for three-dimensional visualization of geological data in mining areas helps geologists to more intuitively understand the distribution of ore bodies and geological structures, thereby improving exploration efficiency and accuracy. Secondly, by deploying a large number of sensors and monitoring equipment on the construction site, real-time construction data is collected, and digital twin models are used to comprehensively monitor construction progress, quality, safety, etc., achieving refined management of the construction process. Finally, digital twin modeling was conducted on mining and beneficiation equipment to monitor their operational status in real-time, optimize production process parameters, improve mining and beneficiation efficiency, and reduce energy consumption and resource waste.

5.2 Impact Analysis

Firstly, digital twin technology helps achieve sustainable development in the mining industry by optimizing mining production processes and improving resource utilization. For example, through precise analysis and simulation of mining geological data, mining areas and mining sequences can be planned more reasonably, reducing damage to non target ore bodies and improving the recovery rate of mineral resources.

Meanwhile, digital twin technology can also achieve real-time monitoring and evaluation of the ecological environment of mines, providing scientific basis for the formulation of ecological protection measures and minimizing the negative impact of mining activities on the environment.

Secondly, in the mining process, digital twin technology can monitor the discharge of pollutants such as wastewater, exhaust gas, and waste residue in real-time, and promptly detect and address environmental pollution issues. For example, by installing water quality monitoring sensors in the mine drainage system and using digital twin models for real-time analysis and warning of water quality data, once water quality exceeds the standard, corresponding treatment measures will be taken immediately to ensure that the mine wastewater meets the discharge standards. In addition, digital twin technology can optimize the energy management system of mines, reduce energy consumption, decrease greenhouse gas emissions, and have a positive impact on mitigating global climate change.

Finally, the application of digital twin technology will have a profound impact on the social development of the mining industry. On the one hand, it will improve the safety and efficiency of mining production, reduce the incidence of accidents, improve their working environment and quality of life. On the other hand, the technology will promote the digital transformation of the mining industry, create more job opportunities, attract more high-quality talents to join the mining industry, promote the coordinated development of the mining industry and related industries, and make greater contributions to the socio-economic development.

6 Conclusion

From the perspective of production practice, the core of measuring mining digitization lies in its essential transformation and inherent characteristics. Building an ideal digital twin mine relies on three pillars: comprehensive connectivity, cross platform integration, and intelligent incentives. Through two platforms of big data analysis and storage, the upgrade of intelligent production management in mines can be achieved. These two platforms run through the entire chain from geological exploration to data management, promoting the transformation of mining operations towards networking. The digitization of mining operations is enhanced, the automation of selection and smelting processes is deepened, and transportation scheduling is seamlessly connected. The digital twin mine blueprint covers four pillars: production process automation, unmanned fixed facilities, and information-based production management. It aims to achieve safe, green, and efficient mining, leading the comprehensive innovation of concepts, systems, management, and technology.

From the perspective of technological innovation, mining enterprises, driven by new generation information technology, the Internet of Things, and big data, are able to develop efficient, low-cost, and accurate decision-making strategies, achieving the "five correct" decision-making optimization paths, that is, ensuring that correct information is delivered to the right personnel at the right time and in the right way to assist in making correct decisions. This not only promotes the free flow of data within the mine, but also promotes automation and unmanned operations such as mining and transportation, reducing reliance on physical labor and moving towards an advanced stage of invisible digitization. Only when digitalization fully permeates every production and operation link and unit system of mining enterprises can the true digitalization level of mines be demonstrated.

References

1. Wang Guofa, Ren Huaixi, Zhao Guorui, Du Yibo, Pang Yihui, Xu Yajun, Zhang Desheng. Analysis and countermeasures of ten "pain points" in coal mine intelligence [J]. Mining Automation,2021(06):4-14.
2. Wang Guofa, Ren Huaixi, Zhao Guorui, Gong Shixin, Du Yibo, Xue Zhongxin, Pang Yihui, Zhang Xiao. Intelligent coal mine data model and complex giant system coupling technology system[J]. Journal of China Coal Society,2022(01):67-80.
3. Wang Guofa, Du Yibo, Chen Xiaojing, Wang Hui, Bao Jianjun, Xing Zhen, He Yaoyi, Han An, Gu Yidong. Development and innovation practice from coal mine mechanization to automation and intelligence-in commemoration of the 50th anniversary of the founding of "Mining Automation"[J]. Mining Automation,2023(06):4-21.
4. National Development and Reform Commission, National Energy Administration, Ministry of Emergency Management, National Coal Mine Safety Administration, Ministry of Industry and Information Technology, Ministry of Finance, Ministry of Science and Technology, Ministry of Education. Guidelines on accelerating the development of coal mine intelligence[J]. China Safety Production,2020,15(03):5.
5. Ding Enjie, Liao Yubo, Zhang Lei, Liu Zhongyu. Review and prospect of coal mine informatization construction[J]. Mining Automation,2020(07):8-14.
6. Hu Qingsong, Qian Jiansheng, Li Shiyin, Sun Yanjing. Revisiting the Construction Route of Intelligent Coal Mines from the Perspective of Artificial Intelligence 3.0[J]. Coal Science and Technology,2022(01):262-270.
7. Xing Zhen. Digital Twin Driven Global Dynamic Collaborative Control of Coal Mine Diverse Business[J]. Industrial and Mining Automation,2023,49(07):60-66+82.
8. Zhang Fan, Ge Shirong. Construction Method and Evolution Mechanism of Mine Digital Twin[J]. Journal of China Coal Society,2023,48(01):510-522.
9. Wang Wei, Liu Yongsheng, Liao Jun, Cai Yixin. Key Technologies and System Architecture of Digital Twin[J]. Telecommunication Engineering Technology,2021(08):15-19.
10. Business - Engineering Management; New Engineering Management Study Findings Have Been Reported by Investigators at Georgia Institute of Technology (Smart City Digital Twin-enabled Energy Management: Toward Real-time Urban Building Energy Benchmarking) [J]. Information Technology Newsweekly,2020.
11. Li Zhongcheng. Research on the Necessity of Intelligent Mine Construction[J]. Inner Mongolia Coal Economy,2021, (02):154-156.
12. National Energy Administration, National Mine Safety Administration. Guidelines for Intelligent Mine Construction (2021 Edition) [S]. National Energy Administration,2021.6.5.
13. Jonghyun C.Research on the Position System Reform of THREESTARS Company[D]. Shanghai Jiao Tong University,2018.
14. Mao Shanjun, Xia Liang, Chen Huazhou. Intelligent Mine Control System Based on Safe Production[J]. Mine Safety,2018,49(12):102-107.
15. Xu Jin. Research on the Architecture System of Intelligent Mines[J]. Energy and Environmental Protection,2017,39(11):14-19.

16. Mao Shanjun. Discussion on Coal Science Research and Talent Training under the Concept of "High-tech Mining"-Lessons from the Development of Aerospace Technology[J]. Coal Higher Education,2010,28(03):7-10.
17. Wang Guofa, Du Yibo. Framework and Construction Ideas of Intelligent Coal Mine Standard System[J]. Coal Science and Technology,2020,48(01):1-9.
18. Zhou Zhu. The True Face of Intelligent Mines[N]. China Mining News,2018-10-24(003).
19. Lv Tao. Research on the Development Strategy of Coal Enterprises in China[J]. Modern Marketing (Academic Edition), 2011, (06):176.