

# Parallel Mining Operating Systems: From Digital Twins to Mining Intelligence

Long Chen  
Sun Yat-sen University, Guangzhou 510006,  
China. Waytous Inc. Qingdao 266109, China.  
chenl46@mail.sysu.edu.cn

Xiaoming Hu  
College of Intelligence and Computing,  
Tianjin University,  
Tianjin 300350, China.

Ge Wang  
Institute of Systems Engineering, Macau  
University of Science and Technology,  
Macau 999078, China.

Dongpu Cao  
Waytous Inc. Qingdao 266109, China.  
Oscar\_cao2016@163.com

Lingxi Li  
ECE Department,  
Indiana University-Purdue University  
Indianapolis, IN 46202, USA. ll7@iupui.edu

Fei-Yue Wang  
Institute of Automation  
Chinese Academy of Sciences, Beijing  
100190, China. feiyue.wang@ia.ac.cn

**Abstract**— With the rapid development and modernization requirement of global coal industry, there is an emerging need for intelligent and unmanned mining systems. In this paper, the Intelligent Mining Operating System (IMOS) is proposed and developed, based on the parallel management and control of mining operating infrastructure that integrates the intelligent mining theory, the ACP-based (Artificial societies, Computational experiments, Parallel execution) parallel intelligence approaches, and the new generation of artificial intelligence (AI) technologies. To satisfy the intelligent and unmanned demand of open-pit mines, the IMOS architecture is developed by integrating the theory of digital quadruplets. The main subsystems and functions of IMOS are elaborated in detail, including a single-vehicle operating subsystem, multi-vehicle collaboration subsystem, vehicle-road collaboration subsystem, unmanned intelligent subsystem, dispatch management subsystem, parallel management and control subsystem, supervisory subsystem, remote takeover subsystem, and communication subsystem. The IMOS presented in this paper is the first integrated solution for intelligent and unmanned mines in China, and has been implemented over ten main open pits in the past few years. Its deployment and utilization will effectively improve the production efficiency and safety level of open-pit mines, promote the construction of ecological mines, and bring great significance to the realization of sustainable mining development.

**Keywords**—Intelligent mining operating system, parallel mining, digital twins, digital quadruplets.

## I. INTRODUCTION

Ore is one of the essential natural resources in China, which plays a vital role in the country's industrialization and modernization. The rich mineral deposits can make a significant contribution to the national economy [1]. Because of the challenging and complex working environment in the mining areas and the low efficiency of manual mining, the deployment of intelligent mining is particularly important. A range of foreign open-pit intelligent mining technologies have been developed in the past years. For instance, the EDC system developed by the Swedish Sandvik Mining Engineering Machinery Group can alert the operator when the drilling rig driver's operation exceeds the set range. Caterpillar Inc. has upgraded the original automation system into a modern computer technology system and launched the MineStar™ system and drilling

programmable control system (HolePro system). The rig terrain kit of the MineStar™ system can timely and accurately manage the drilling operations in the mining operating system via management and guidance of the entire mining production.

Compared with the developed countries, the construction of intelligent mines in China started relatively late. China's open-pit coal mining industry has experienced four stages: manual blast mining, mechanized mining, integrated mechanized mining, and intelligent mining [2]. Around 2010, the rise of the Internet of Things (IoT) technology, along with big data, artificial intelligence, and other technologies, has gradually coupled with the coal industry and realized advanced functions such as automatic blasting, mining coordination, and unmanned transportation. Thus, the mining industry has gradually entered the stage of intelligence. In recent years, with the guidance of national policies and big data, artificial intelligence, and 5G technologies, the domestic mines have made great progress in their automation and intelligence. In January 2018, Waytous Inc. released the "YuGong" Parallel Mining System, which provides the first self-developed integrated solution for unmanned mines in China. This system can be applied to both underground mines and open-pit mines. As of January 2021, the "YuGong" system has been implemented and deployed in more than 20 mining areas in China [3,4].

Although mining has entered the intelligence stage, there is still much room for improvement in the construction of intelligent mines. Firstly, the degree of intelligence is not high enough, and generally only a single ADAS (Advanced Driver Assistance Systems) function has been implemented, such as anti-collision, positioning calibration, yaw reminder, etc. Secondly, it is almost impossible to conduct comprehensive learning approaches based on limited data so as to optimize the intelligent decision-making system iteratively. Finally, the dispatch center cannot solve the problem of optimizing the resource scheduling of each subsystem. This paper proposes an Intelligent Mining Operating System (IMOS) that integrates parallel theory and intelligent mining technologies [5] for improving the operation intelligence of open-pit and underground coal mines. It offers a feasible technical path for the realization of intelligent, ecological, and effective mining operation [6].

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## II. INTELLIGENT MINING BASED ON PARALLEL THEORY

### A. Parallel theory

In the late 1980s, Dr. Fei-Yue Wang from the Institute of Automation, Chinese Academy of Sciences, has cooperated with NASA Center for Intelligent Robotic Systems for Space Exploration (CIRSSE) and Space Engineering Research Center (SERC) to establish the mission process of the CIRSSE space robot platform and the ISRU (In Situation Resources Utilization) Mars oxygen plant simulation verification system [7,8]. Facing the difficulty of slow communication speed, limited local resources, and extensive calculation needed, Fei-Yue Wang proposed to build a “shadow system” remotely following the “locally simple, remotely complex” principle, which offers a feasible solution to tackle the challenges.

In the 1990s, when developing core technologies for autonomous mining with Caterpillar Inc., Fei-Yue Wang combined the agent method, fuzzy logic, and neural network by integrating local vehicle and remote control center computing resources [9,10]. The finite state machine and Petri nets were applied to simulate human mining strategies on 98t automatic loading vehicles with hierarchical intelligent control theory and intelligent mining algorithms, which improved the mining efficiency significantly [10-12].

In 2004, Fei-Yue Wang published a paper entitled “Parallel system method and complex system management and control,” which first proposed the concept of parallel system, where the real system is able to interact with the artificial system in parallel and provides solutions for highly complex problems that are difficult to model, learn, and predict in reality [13]. The method has been generalized to many application domains [14-17].

In 2017, based on the frameworks of parallel systems and parallel intelligence, Fei-Yue Wang further proposed the concept of Parallel Mining Operating Systems (PMOS), where the foundation of intelligent mining has been developed by combining human mining workers, digital mining employees, mining robots, and unmanned vehicles [18].

### B. Parallel intelligent mining

Intelligent mining is a highly complex task [19-21], which involves integrating multiple disciplines and a variety of advanced technologies [22-25]. The parallel mining operating system can significantly enhance the safety of personnel and reduce the cost of operators, fuel, and maintenance. In addition, it can optimize the management of the mining system, improve scheduling and coordination efficiency, achieve an increase in output, and minimize the losses caused by human error and deliberate damages.

## III. DESIGN OF PARALLEL INTELLIGENT MINING OPERATING SYSTEM

### A. Parallel intelligent mining operating system

The concept of parallel mining is shown in Figure 1. The key idea is to collaborate the parallel virtual mines with the real mines and update both systems via interaction. In reality, intelligent mining vehicles can complete each operation through the single-vehicle operating system, the multi-vehicle collaboration system, and the vehicle-road collaboration system.

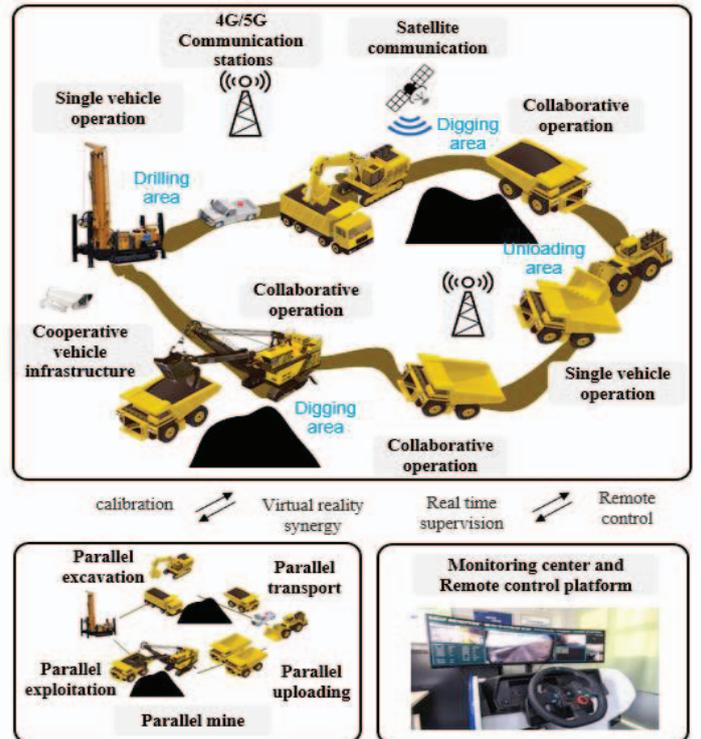


Figure 1. The concept of parallel mining.

A parallel virtual mining system completes virtual operations of mining vehicles and guides the real vehicles via machine learning algorithms and parallel theory. The remote monitoring center oversees the status of mining areas and provides a control interface. The entire system completes resource scheduling under a collaborative work of various subsystems to ensure the rational and efficient operation of intelligent mining processes.

Intelligent mining consists of real mines, virtual mines, parallel control centers, and remote control platforms. As demonstrated in Figure 2, the parallel intelligent mining operating system mainly includes a single-vehicle operation system, multi-vehicle collaboration system, vehicle-road collaboration system, unmanned intelligent system, dispatch management system, parallel system, and remote takeover system.

### B. Single vehicle operating system

The open-pit mining operations mainly include perforation, blasting, mining, transportation, and dumping. Perforation blasting aims to dig a directional blast hole with a specific diameter and depth in the ore rock of an open-pit mine and blast to break large pieces of ore to facilitate subsequent loading and transportation. Perforation equipment mainly includes impact drills, down-the-hole drills, and roller drills, etc. Mining and loading utilize the machinery to load the blasted ore fragments into the transportation equipment. Commonly used equipment are excavators (multi-bucket and single-bucket), bucket shovel and front-end loaders, and single-bucket excavators. Transportation is to transport the blasted ore and rock fragments of the open pit to the unloading point or dumpsite as well as the transportation of production personnel, equipment, and materials within the mining site. The transportation equipment

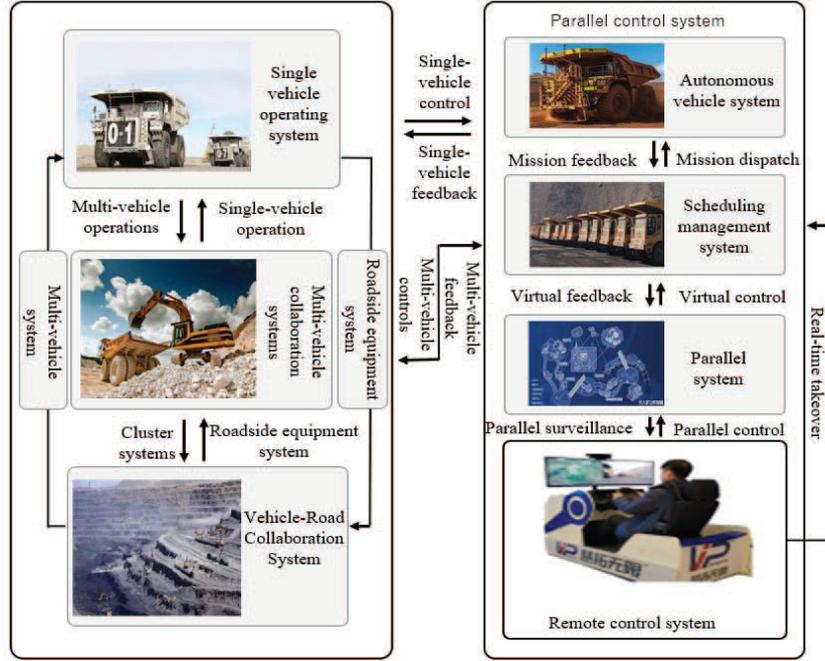


Figure 2. Schematic diagram of the parallel intelligent mining operating system.

is a heavy-duty mining truck. Dumping refers to the operation of transporting a large amount of topsoil and rocks at the blasting site to a specially site for disposal. Dumping methods are divided into bulldozing plows, bulldozers, front-loading machines, drag scrapers or draglines, etc., according to the different dumping equipment.

### C. Multi-vehicle collaboration system

Many collaborative operations are required in the mining area, such as electric shovel digging, loading, mining vehicles coordination, mining trucks transportation, and virtual vehicle collaborative operations. These operations must ensure the accuracy of the single-vehicle operation and the efficiency of collaborative operations. The outputs of the virtual collaborative operation control in the parallel system are sent to the real vehicles via the dispatch system, while the real vehicles are controlled by the multi-vehicle collaboration system. In the multi-vehicle case, the loss calculations of the collaborative task become more challenging due to coordinated positioning and speed control. In addition, the status change of a single vehicle will affect the performance of the entire collaborative system. Thus, it is necessary to continuously correct and complete the tasks. The multi-vehicle collaboration system feeds back the actual operating conditions to the parallel system using the data captured in real-time from external sensors, which can deal with errors in both real and virtual operations.

### D. Unmanned intelligent system

The unmanned intelligent system is capable of handling complex tasks in vehicle operations, such as autonomous positioning, intelligent perception, obstacle avoidance, path planning, and decision-making.

Autonomous positioning is achieved by installing a global navigation satellite system (GNSS) receiver on the vehicle. The challenge is that mining area typically has a weak satellite signal

due to the geomagnetism effect and the tunnel environment. Thus, it is necessary to integrate the base station positioning strategy of the network operator, the navigation positioning strategy assisted by the inertial odometer, the Ultra-Wide Band (UWB) positioning strategy of the outdoor wireless carrier communication technology, and the laser point cloud registration positioning strategy. The precise positioning of vehicles in the mining area can be achieved via a combination of these advanced approaches. Intelligent perception requires data captured by sensors such as LIDAR, millimeter-wave radar, and cameras installed in the vehicle, as well as enhanced data obtained in parallel systems, to achieve target detection and prediction via deep learning algorithms. Autonomous obstacle avoidance requires the system to capture the dynamics and kinematics of the front target in time and provide a stable, safe, and effective obstacle avoidance path through path planning algorithms. Path planning and decision-making require that intelligent vehicles can achieve optimal path selection by using Reinforcement learning and transfer learning algorithms based on the positioning points and target points. They can also make reliable decisions based on the real-time environmental changes in the real and virtual environment.

### E. Dispatch management system

The functions of the parallel mining dispatch management system include maintenance of high-precision maps, fleet traffic management, intelligent dispatch tasks, macro-management of mining area production, and statistical data analysis. The overall system transmits all the data captured by vehicle-end and road-end sensors in the mining area to the data server. Combined with the operation plan of the mining area, the optimal strategy is developed in the computing center of the control system. The command is then issued to the vehicle-end controller through the console, which coordinates the operation of all intelligent devices. Meanwhile, it has a visual data server to visualize

scheduling scenarios and monitor the production status of the mining area. The management system can also be connected to the entire mining area ecology to calculate the production and operation costs of the entire mining area.

#### F. Parallel system

The parallel system includes the construction of virtual mines, virtual data enhancement, virtual and real mines collaboration, and model training. The 3D virtual simulation environment is the basis of the entire parallel system. The simulated mine was completed through the 3D reconstruction work by scanning the actual scenes with drones. The internal construction of the mines can be achieved via mine surveying and geological exploration. It will not only make the virtual mine space have a physical meaning, but also combine geological factors to obtain the optimal mining strategy through iterative learning. Data enhancement refers to data collection in the virtual space corresponding to the real mining area. To expand the limited data and make the knowledge learned by the agent in the virtual space richer, extremely adverse weather conditions and unknown/unexpected risk scenarios can be introduced in the virtual space. Virtual and real collaboration requires constructing a virtual environment to simulate the open-pit mining area as much as possible, which is based on the strategy in the virtual space for guiding reality while receiving feedback from reality to adjust the virtual mines in real-time. Since it is a virtual space, reinforcement learning-based training and testing can be applied without cost and the model can be obtained through continuous interaction with the environment. In consideration of time, mining deduction will reproduce all behaviors in advance, such as early mining and late filling in the virtual space, which involves the dynamic development and changes of open-pit mines in three-dimensional time and space. After many deductions, the best mining strategy is selected, which not only considers development costs but also comprehensively considers factors such as exploration, excavation, and post-backfilling. The system supports the retrospect of the historical production status of the open-pit mine, the simulation of unmanned intelligent mining, and the inspection of the pros and cons of the production plan. From a long-term perspective, it can significantly help companies formulate sustainable production plans, increase revenue, and assist management and operation. The parallel system provides a visual interface for the three-dimensional space-time evolution, which is convenient for engineers to observe and study the digital dynamic model and its evolution.

#### G. Remote takeover system

The main purpose of the remote takeover system is to provide a backup option to guarantee the safe operating of intelligent mining. It can be triggered under the following three conditions: 1) the fault monitoring system issues an equipment fault alarm, 2) the equipment cannot deal with the fault according to the original strategy, and 3) the system does not issue an early warning action but takes the wrong decision. Thus, the remote takeover system allows the supervisor of the control center to quickly and conveniently operate single or cluster equipment to ensure the safety and stability of the entire system.



(a)



(b)

Figure 3. Implementation of parallel mining: (a) parallel control center; and (b) collaborated autonomous mining trucks.

#### IV. REAL WORLD IMPLEMENTATION AND MINING OPERATION

Parallel mine system has been implemented in over ten main open pits in China in the past few years, as seen in Figure 3 as an example. The character of virtual-real-interaction of parallel mine not only significantly helped to facilitate the development of algorithms and technologies (considerable time reduction in the development cycle), but also enhanced the operating safety and efficiency. Within the parallel mining systems, dozens of autonomous mining trucks have been operating. Figure 4 shows examples of these trucks on site.

#### V. SUMMARY

This paper proposes an intelligent mining operating system that is based on parallel theory and advanced information technology. It provides a systematic solution to the mining industry and enables intelligent and unmanned mining capabilities. This system can significantly improve the intelligence level of a single mining vehicle and make the overall management of the mining processes safe, reliable, efficient, and intelligent. Thus, it has a great potential for reducing labor costs, minimizing risks and the number of accidents in mining areas, achieving energy saving and emission reduction, and increasing corporate benefits and efficiency. The system has been implemented in over ten main open pits in China in the past few years, with proven effectiveness and efficiency. Large scale implementation is being deployed.



Figure 4. Examples of autonomous mining trucks implemented within the parallel mine systems in the open pits.

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