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Original Paper

Research on Key Technologies of Autonomous Driving in Open-pit Mines

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Abstract

This article sorts out and analyzes the operation scenarios and typical applications of intelligent networked automatic driving in the open-pit mine scene, and analyzes the corresponding relationship between them. Based on this, the overall technical architecture of the open-pit mine intelligent networked autonomous driving is analyzed, and the technical attributes of the vehicle end, network and cloud platform are studied under this architecture. Finally, the trend of future technology and industry development is forecasted.

Keywords

smart mining, intelligent network connection, autonomous driving, 5G, car networking

1. Industry Development Overview

The mining industry is the foundation and pillar industry of the national economy, and the intelligentization of mines is an important trend in the development of the current mining industry. At present, the automation and information systems that have been built in some mines in China have played an important role in the safety production process (Ma, Hu, & Miao, 2014; Ye, Wang, Liang, & Su, 2015; Yan & Zhang, 2013). Specifically, the open-pit mine operating environment is harsh and dangerous. The use of autonomous driving technology can not only avoid or reduce the hazards or threats to the health and safety of drivers, but also greatly improve efficiency, reduce costs, and become more economical, energy-saving and environmentally friendly (Fisher & Schnittger, 2012). According to calculations by Australian iron ore exporter FMG Group, the production efficiency of its 137 self-driving mining trucks has increased by 30% compared with traditional manual transportation. In addition, the complexity of the open-pit mine scene is relatively simpler than that of the public transportation scene (strict personnel control, strict control of the speed limit of the mine truck, and relatively fixed driving route), and automatic driving is relatively easy to implement in the open-pit mine scene.

From an international perspective, Caterpillar, Komatsu and other construction machinery companies have deployed mining truck autonomous driving solutions in Australia, Chile, Brazil and other places in open-pit mines, including intelligent networked mining trucks, communication networks, and system platforms. In order to realize the commercial application of autonomous driving in mining areas, Caterpillar’s mining truck products have been autonomously driving for nearly 35 million kilometers, and the material transportation volume has reached 1 billion tons. From the perspective of China, since the “13th Five-Year Plan” period, the national level has successively introduced related policies for smart mines. Speeding up the construction of digital smart mines in my country has become an important way and effective means for the transformation and upgrading of the mining industry (Wang, 2014; Zhang, Li, Huang, & Wang, 2014). With the transformation and upgrading of China’s domestic industrial economy and demographic changes, the demand for machine substitution in China’s mining industry has become more and more obvious. Driven by industrial demand, a number of construction machinery companies, autonomous driving technology companies, and information communication companies have emerged one after another in China to invest in the research and industrial application of autonomous driving related technologies in open-pit mines.

2. Automatic Driving Operation Scenarios and Typical Applications in Open-pit Mines

The automatic driving of open-pit mines still follows the basic production process of “drilling, blasting, mining, transportation, and discharge” in open-pit mining. According to the transportation operation process of “mining, transportation, and discharging”, the automatic driving application operation scene of the mine is divided into three operation scenes of loading, transportation and unloading. In addition, there are scenes of operation guarantee (refueling and water supplementing, repair and maintenance, etc.) to support the above-mentioned operation process. From the perspective of the application of intelligent networked automatic driving, the realization of applications such as remote driving of mining trucks, operations between mining trucks and other construction machinery, and mining truck driving path planning are required to support the safe operation of automatic driving.

2.1 Operation Scenario

2.1.1 Loading

The loading operation scenario means that the unloaded mining trucks are driven to the loading operation point in sequence, the loading equipment (such as excavators, electric shovel, etc.) loads the materials into the mining truck bucket, and the mining trucks leave the operation point in turn. In this scenario, mining trucks, mining equipment, and cloud platforms need to communicate and clarify the entire loading collaboration process (including coordinated entry, loading, and exit steps). The mining truck automatically drives to the loading area according to the path and task planned by the cloud platform, combined with the perception of the surrounding environment, and sends real-time status information (including position, speed, direction, acceleration, etc.) and task information of its own vehicle to the loading equipment in real time. At the same time, the loading equipment also needs to send its own location, orientation and other information to the mining truck, so as to achieve efficient cooperation. If an abnormal condition of the mining truck is found (such as a roadblock that cannot be avoided by the own vehicle), the mining truck will brake urgently and enter the remote takeover process, that is, send warning information to the excavator, surrounding vehicles and cloud platform to avoid dangerous operations, and The cloud platform takes over remotely to get out of the predicament.

2.1.2 Transportation

The transportation operation scenario means that the mining truck drives automatically on the roads of the mining area according to the path planned by the cloud platform, combined with environmental perception information. During the driving process, the mining truck communicates with other vehicles (including unmanned/manned vehicles), roadside equipment, and cloud platforms to realize forward collision warning and beyond-the-horizon sensing functions to improve driving safety. Similarly, if an abnormal situation is found, the mining truck brakes urgently and enters the remote takeover process.

2.1.3 Unloading

The unloading operation scenario means that the fully loaded mining truck drives to the unloading point in turn and unloads the materials, and then the unloading equipment (such as bulldozers, loaders, etc.) sorts the materials. “Operation cycle”. In this scenario, the mining truck, unloading equipment, and cloud platform need to communicate and clarify the entire unloading collaboration process (including coordinated entry, unloading, and exit steps). The mining truck can automatically drive to the unloading area according to path planning and operation tasks, combined with the perception of the surrounding environment, and send the real-time status and task information of its own vehicle to the loading equipment. The unloading device also sends its own location and other information to the mining truck, so as to achieve efficient cooperation. Similarly, if an abnormal situation is found, the mining truck brakes urgently and enters the remote takeover process.

2.1.4 Work Security

The operation support scenario refers to the mining truck driving to a specific area for refueling and water supply, maintenance, etc. During the operation, the cloud platform regularly arranges maintenance or overhaul tasks for the mining truck. At the same time, when the mining truck detects oil or water shortage or its own failure, it needs to coordinate with the cloud platform to timely plan the task of refueling and water supply. According to the route planned by the cloud platform, the mining truck automatically drives to the corresponding operation guarantee area in combination with environmental perception information, and at the same time periodically broadcasts the real-time status and task information of the vehicle to the outside. Similarly, if an abnormal situation is found, the mining truck brakes urgently and enters the remote takeover process.

2.2 Typical Application

2.2.1 Remote Control Driving

Remote control driving means that when the mining truck encounters a special road section or emergency, the vehicle can continue to drive or move to a safe location by means of remote takeover processing. Remote takeover methods include responsive takeover and emergency takeover. The former means that when the mining truck encounters a situation that cannot be processed, it sends a remote takeover request to the platform, and the platform starts remote takeover immediately after receiving the request; the latter means that the remote control driving platform receives the status information uploaded in real time from the car terminal and actively discovers the vehicle An alarm signal is issued to remind manual takeover. The remote driving center can obtain real-time high-definition video of vehicle-mounted and roadside imaging equipment through 5G large-bandwidth communication, and send control signals to the vehicle end to realize emergency takeover of the vehicle.

2.2.2 Operation Coordination

Operation coordination refers to the coordination of loading/unloading operations between mining trucks and other construction machinery and equipment such as excavators and bulldozers. Under current technical conditions, excavators and bulldozers still adopt a manned driving mode, but they can cooperate with mining trucks to improve operation efficiency. On the one hand, excavators and bulldozers can upload equipment operating data to the cloud platform, and use the intelligent scheduling function of the cloud platform to achieve coordination with the operation process of the mining truck; on the other hand, the on-board collaborative operation management system of the excavator or bulldozer can be Deploy sensors on the excavator or bulldozer to monitor the posture and position of the equipment, and communicate with the mining truck vehicle system through LTE-V2X direct connection to realize loading/unloading mode setting, loading point setting and other functions, and guiding the mining truck Guide the mining truck out of the field after the completion of installation and loading/unloading to improve the efficiency of loading/unloading operations.

2.2.3 Path Planning

Path planning refers to calculating the driving path of the mining truck based on map information, real-time vehicle status, comprehensive perception information, etc., and providing driving path planning and driving guidance for the mining truck. Path planning can be divided into global path planning and local path planning. The former is generated by the cloud platform based on the high-precision map and then issued to the unmanned mining truck. The mining truck follows the global path file provided by the platform in the entire operation scene; The card generates real-time paths based on high-precision maps for obstacle avoidance, bypassing, and coordinated operations in loading/unloading areas.

2.2.4 V2V Collision Warning

Vehicle-to-vehicle collision warning, to support the mining truck to avoid rear-end collision with the vehicle directly in front of the vehicle during driving. The mining truck and the vehicle directly in front exchange position, direction angle, speed, acceleration and other information in real time through LTE-V2X direct communication. When there is a danger of collision, the mining truck can make timely decisions based on the information of the preceding vehicle to avoid collision accidents and improve the safety of automatic driving.

2.2.5 Early Warning of Road

Early warning of road conditions means that roadside equipment uses sensors to identify road obstacles (such as falling rocks, leftovers, etc.), road conditions (such as standing water, icing, etc.), and upload them to the cloud platform through the 5G network. The platform performs intelligent analysis, and then the platform sends road event information to the mining trucks that may be affected; or analyzes the perception information locally through the edge computing platform deployed on the roadside, and then the roadside communication terminal directly transmits the road event information through LTE-V2X. The communication is sent to the mining truck that may be affected.

3 The Overall Technical Architecture of Automatic Driving Applications in Open-pit Mines

The overall technical architecture of the open-pit mine autonomous driving application includes three levels: "Intelligent Networked mining trucks, Internet of Vehicles, and Cloud Platform". Among them, the vehicle end has the capabilities of self-vehicle perception and communication, decision-making, and execution. Cars and other elements are based on 5G, LTE-V2X multi-mode car networking to achieve communication transmission, cloud platform collaborative control, path planning and other capabilities. Specifically, the vehicle end includes the vehicle body and vehicle intelligent equipment. The intelligent equipment includes 5G/LTE-V2X communication terminals, cameras, lidar, millimeter wave radar, vehicle positioning, vehicle computing platforms and other equipment to realize information transmission and environment Perception and intelligent decision-making, etc. The Internet of Vehicles is based on 5G and LTE-V2X technologies to realize information transmission between cars and cars, cars and roads, and cars and cloud platforms. The 5G system includes base stations, core networks, etc., to realize the control data and status data between the car and the cloud platform. Transmission, LTE-V2X direct communication mainly realizes the transmission of vehicle status, road status and other data between vehicles and between vehicles. The cloud platform realizes the fusion analysis of mine scene information, builds a virtual mine transportation operation model, provides job scheduling, path planning, joint decision-making and collaborative control for different application scenarios, can realize remote driving and automatic driving business management, and serves as the general application portal, Undertake all kinds of information return and instruction issuance, and plan the network path for the business.

3.1 Open-pit Mine Intelligent Networked Vehicle

3.1.1 Communication, Perception and Positioning

The communication, perception and positioning module of the mining truck is responsible for providing surrounding environment information, positioning information and cloud platform instructions. The following characteristics of the mining scene put forward higher requirements for communication, perception and positioning: 1) The road bumps in the mining area are serious, and the vehicle-mounted sensing equipment shakes seriously, which may easily lead to a decrease in the accuracy of the sensing data; 2) The working temperature of the mining area can be as low as minus 45 ℃, which needs to be considered Low temperature resistance of vehicle-mounted communication and sensing equipment or installation of thermal insulation devices; 3) The strong wind in the mining area, sand and dust cause some sensing equipment to fail; 4) For working conditions in which the work area is relatively low or the mountain is seriously blocked, the positioning signal strength is easy to be interfered.

In view of the particularity of the above mining scenes, a single perception solution is usually unable to effectively cope with complex environmental changes in the mining area. From the perspective of reliability and safety, the perception subsystem of the mining truck usually adopts multi-sensor fusion technology, including millimeter wave radar, lidar and camera, etc., to realize the location, speed, trajectory, category and other attributes of obstacles around the vehicle Probe. At the same time, it is equipped with 5G and LTE-V2X communication terminals to obtain traffic environment information (including the running status of surrounding vehicles, surrounding road environment, etc.) sent by other vehicles, roadside equipment and cloud platforms, so as to realize the beyond-the-horizon perception of the vehicle. Expand the perception range of mining trucks and overcome difficult scenes with limited perception or severe obstruction (such as intersections, loading/unloading work areas).

The positioning system of the intelligent networked mining truck usually uses GPS/Beidou positioning technology, but GPS/Beidou positioning technology has problems such as susceptibility to multipath interference and low update frequency. Usually can be combined with inertial sensors (IMU) for data fusion to achieve better positioning results. In addition, for long-term positioning signal loss, the laser radar point cloud SLAM (real-time positioning and map construction) or visual odometer positioning method can also be used to achieve more precise positioning accuracy through the integration of multiple positioning methods.

3.1.2 Planning and Decision-making

In order to carry the business applications of autonomous driving, the planning and decision-making module first clarifies the current tasks according to the tasks and paths planned by the cloud platform. After receiving environmental information from the sensors and communication terminals, it analyzes the current environment and then issues instructions to the control unit. The decision-making planning system can basically be divided into the following four parts.

(1) Information decision

Vehicles need to perceive external information at all times during the driving process. The decision-making planning system first needs to receive vehicle sensing unit (lidar, millimeter wave radar, vision, etc.) information, V2X (V2I, V2V, etc.) information, vehicle current positioning information and other multi-sensor fusion After the information, predictions are made based on the external environment output by the perception and communication equipment and the road plan of oneself to ensure the safety of the driving process. After receiving data such as obstacles or other vehicles on the driving path, the information is provided to the path planning module for local path planning.

(2) Path planning module

The mine's road will change irregularly as the "mining" and "discharging" operations are carried out, especially the mining surface and dumping yard change frequently. After the cloud platform performs global path planning, the mining truck will follow the path tasks. When there are obstacles in front of the excavation surface and dump site, or when there are obstacles that need to be detoured, the mining truck will plan the local path of the drivable area according to the information input by the information decision module.

(3) Task decision module

According to the business process of "mining, transportation, and discharging", the mining truck will divide different task states, and need to refine the car control operations that need to be performed in different task states. In the "collecting" and "arranging" scenarios, local route planning is carried out based on high-precision maps and environmental information, driving according to the generated route, and collaborative and interactive operations with other construction machinery. In the process of driving on the main road, under the guidance of the global path, the mine card makes specific behavior decisions (tracking, avoiding obstacles, parking and waiting, Request remote takeover, etc.).

(4) Fault decision module

The fault decision module obtains the body status information through the in-vehicle communication network (such as CAN bus) during the driving of the mining truck, and at the same time monitors the real-time status of the automatic driving related modules, and stops according to the degree of influence on the automatic driving when an abnormal event occurs Wait for manual investigation, request the platform to dispatch to the maintenance area for maintenance, or perform other operations that can ensure the stable and reliable operation of autonomous driving.

3.1.3 Vehicle control

Vehicle control includes two modes: Drive-by-wire and Drive-by-wire control based on driving robot.

(1) Drive-by-wire control

Vehicle function drive-by-wire control is one of the important technical paths for mining trucks to realize automatic driving. It is mainly realized by the vehicle control system through electrical signals including drive-by-wire control steering, drive-by-wire controlled drive, drive-by-wire controlled movement, drive-by-wire controlled cargo box lifting and other functions. The vehicle control system is connected to the vehicle-mounted automatic driving planning and decision-making system through the in-vehicle communication network (such as CAN bus) to realize the control of the entire vehicle. At the same time, vehicle operating data, such as vehicle speed, load, tire pressure, water temperature, motor power, system voltage, fault alarm, etc. They are collected by the vehicle control system and connected to the planning and decision-making system through the in-vehicle communication network, and then pass through the communication equipment Interact with the outside world.

(2) Drive-by-wire control based on driving robot

For stock vehicles that cannot directly control the wiring control system through the in-vehicle communication network, it can be controlled by drive-by-wire based on the driving robot to meet the conditions for automatic driving applications. The drive-by-wire control based on the driving robot is mainly designed and developed through external actuators and vehicle controllers (VCU). In the automatic driving mode, it replaces the signals generated by the original human operation to realize the vehicle's wire-controlled control, thereby realizing the vehicle's Autopilot.

3.2 Internet of Vehicles Supporting Autonomous Driving Applications in Mines

The network architecture design for mine autonomous driving applications, on the one hand, needs to consider the characteristics and communication requirements of different working areas in the mining area, on the other hand, it combines 5G, LTE-V2X, and multi-access edge computing (MEC) The development status of other technologies, considering the combination of multiple communication technologies to support the needs of different businesses in the mining area. The overall network architecture consists of the vehicle terminal, the roadside terminal, the base station, and the multi-access edge computing platform MEC as the local data processing center and local application services, core network and cloud application services.

As far as cellular communication is concerned, according to the coverage of the cellular network in the mining area, the initial 4G coverage can be gradually increased with 5G coverage to support functions such as high-definition video upload and remote control takeover. The interaction of perception data and control information is realized between the car and the cloud through the 4G/5G network. Part of the business data can be uploaded to the cloud application service through the core network to realize the comprehensive management of multiple mining areas. As far as LTE-V2X direct communication is concerned, OBU is installed on the car side, and roadside communication equipment RSU is installed on the roadside, so as to support vehicle-vehicle and vehicle-road communication through LTE-V2X direct communication technology. Interactive. The MEC platform can support mine local business data processing and local application services, such as video analysis, high-precision positioning, V2X equipment and connection management, perception data fusion processing, etc. The mine's local business services can be directly connected to the MEC platform to achieve business Localization.

Specifically, through the large bandwidth advantage of the 5G network, high-definition video surveillance data can be uploaded to the local control center to support remote control takeover. The high-definition video collected by the camera in the mine cart is uploaded to the MEC platform through the 5G CPE and 5G base station; the roadside camera collects the work area video and is also uploaded to the MEC platform through the mine router and 5G CPE and 5G base station. The MEC platform is directly connected to the remote control center of the mine, and the video data is directly distributed to the remote control center locally without being transmitted to the core network, which reduces the transmission delay. According to the video perception information, with the help of the low-latency and high-reliability communication capabilities of the 5G system, the remote control center issues control commands to remotely control the automatic driving mining truck in real time. Supported by LTE-V2X direct communication technology: 1) Car-to-vehicle direct communication: support forward collision warning, inter-vehicle operation coordination, etc.; 2) vehicle and intelligent roadside equipment communication: support road condition reminders, perception fusion, etc., to improve the safety of autonomous driving and the efficiency of collaborative operations.

Table 1. Network Deployment Plans and Corresponding Business Applications

Network deployment	Business Applications
5G Uu support	Remote control driving, road condition warning, etc.
4G/5G Uu All support	Path planning, etc.
LTE-V2X PC-5 support	Work coordination, collision warning, road condition warning, etc.

3.3 Cloud Platform Supporting Mine Autonomous Driving Applications

3.3.1 Platform Function Requirements

The cloud platform carries the operation management and service provision capabilities of open-pit mine autonomous driving. For mine business scenarios, the main functions that the cloud platform needs to meet include:

1) Real-time collection of all-round data including RSU messages, camera and radar perception information, weather environment information, positioning information, etc.;

2) Perform fusion analysis based on big data, intelligent learning and other technical means, actively perceive, predict, analyze, and quickly make correct processing business models, and provide joint decision-making and coordinated control for application scenarios such as loading/unloading, transportation, and security. Autonomous driving and collaborative operations of operating vehicles in mining areas, as well as supervision and scheduling of operations. At the same time, it integrates a high-precision map module to realize the basis for functions such as vehicle trajectory planning and vehicle anti-collision;

3) Vehicle, infrastructure and user authentication management, to realize the platform to authenticate all vehicles and infrastructure in the mining area, which is convenient for fleet management and network management, and users can check the working status of vehicles at any time through their

identification;

4) To undertake the return of various information and the issuance of instructions.

3.3.2 Overall Framework of the Platform

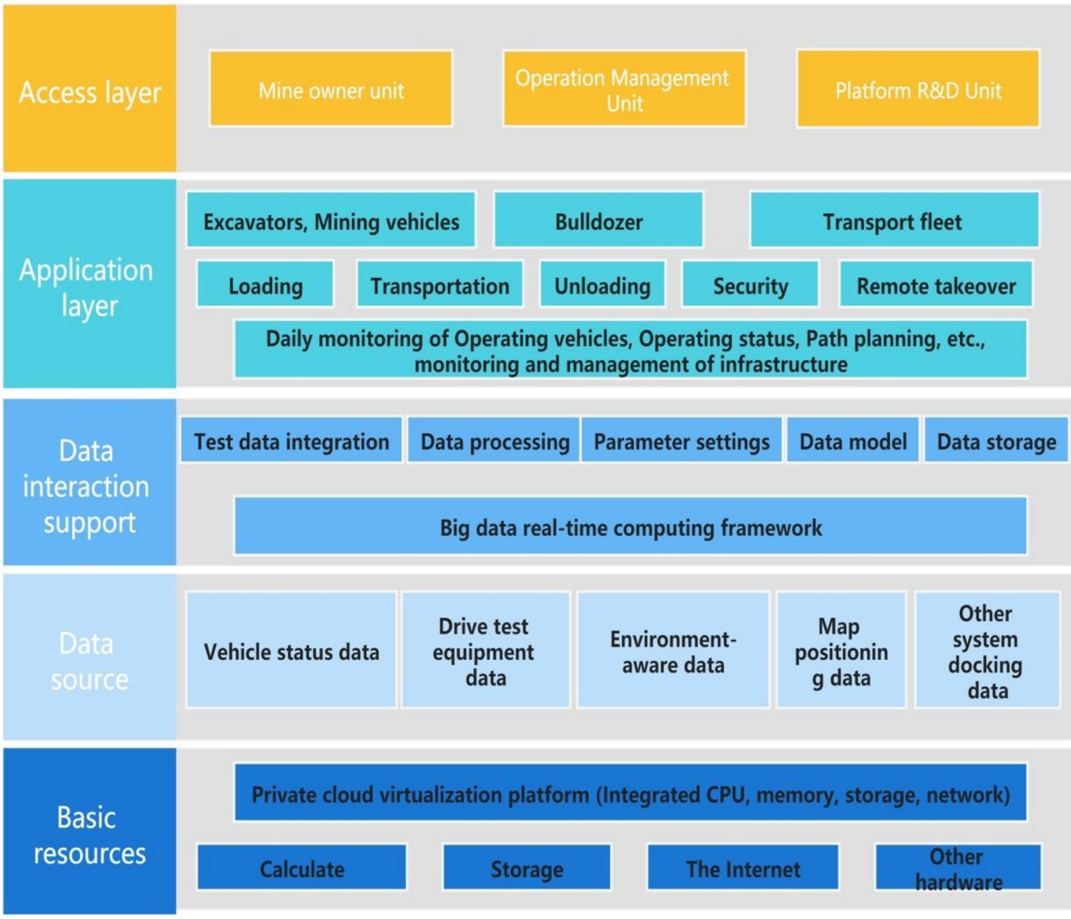

Figure 1. Cloud Platform Architecture Supporting Autonomous Driving in Open-pit Mines

The open-pit mine cloud platform architecture is shown in Figure 1. Through the comprehensive information aggregation and application of vehicles and driving environment, cloud computing, intelligent sensing, communication network, positioning, maps and other technologies are integrated. The autonomous driving cloud platform supports the realization of the digitalization of mining operations. Intelligent management. The cloud platform architecture includes the following levels:

1) The basic resource layer of the platform provides a basic hardware environment for data storage management and calculation analysis;

2) Platform data sources, including status information of the vehicle itself and driving, road environment information (including RSU, camera, radar, etc.), high-precision maps of the mining operation area, and the cloud platform is scalable and can be obtained by docking with third-party

platforms External data;

3) Data support layer, which mainly integrates and analyzes the collected multi-dimensional data of the traffic environment, establishes algorithms and models suitable for the road network environment of the mining operation park, and dynamically adjusts the model based on real-time data;

4) The application layer is mainly based on data modeling, processing and analysis. It conducts daily monitoring and dispatch control of the operating status of the operating vehicle, and provides timely and reasonable decision-making suggestions for the safe and reliable operation of the vehicle. When an emergency occurs, the platform takes over the vehicle's operation. Operation right for remote control;

5) User layer provides an intuitive presentation of mining operations for mine owners, operators, platform developers, etc. Users can intuitively understand the overall operation of the mining area, and can also query the working status of specific vehicles, roadside equipment, base stations, etc.

3. Conclusions

The development of automatic driving applications in mines is of practical significance for improving the level of intelligent production of mining enterprises, promoting safe production, and improving overall production efficiency. In addition, mining trucks have single driving routes, low vehicle speeds, and closed scenarios. This is one of the important scenarios for the rapid implementation of autonomous driving applications. The development of mining autonomous driving applications is important for the development of autonomous driving technology in scenarios such as ports, airports, and logistics parks. It has important reference value and will promote the improvement of the overall technical level of intelligent networked vehicles. In the future, intelligent networked automatic driving will be applied in more types of open-pit mines and construction machinery, presenting more diverse intelligent driving scenarios and more complex driving conditions. Therefore, all parties in the industry need to further collaborate to jointly promote the innovative development of intelligent networked autonomous driving in open-pit mines.

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