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Parallel End-to-End Autonomous Mining: An IoT-Oriented Approach

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***Abstract*—This paper proposes a new solution for end-to-end autonomous mining operations: Internet of Things (IoT) based parallel mining, consisting of the concept definition, the solution given and the concrete realization. The proposed parallel mining is inspired by the ACP (artificial societies (A) for modeling, computational experiments (C) for analysis, and parallel execution (P) for control) approach. The basic framework of parallel mining is given and its advantages are expounded. Then the solution of parallel mining is proposed, which is mainly composed of four parts: the management and control center for autonomous mining, the autonomous transportation platform of truck, the semi-autonomous mining / shovel platform, and the remote take-over platform. Key technologies of IoT based parallel mining are discussed in detail, namely, network communication, virtual parallel mining construction, mining environment perception over-the-horizon for the moving area and obstacle detection, collaborative decision-making, planning and control for unmanned mining equipment, parallel taking-over and remote control. Finally, the performance of IoT based parallel mining, including fusion perception, collaborative decision-making, planning and control, are evaluated. The realization of parallel mining can fundamentally improve the safety of personnel and equipment, reduce the cost of mining operation and increase the production rate.**

***Index Terms*—Internet of things, ACP approach, parallel mines, management & control, decision-making, autonomous truck**

I. Introduction

Today, the world has entered a new era of intellectualized development. Cyber, physical and social systems can be integrated by the Internet of Things (IoT) which enables the perception, computation and execution in an intelligent design paradigm [1]. Under such a background, the mining industry is facing many challenges, such as relatively low price of mineral products, deeper exploitation of resources, poor working environment, etc. [2,3]. In addition, the serious aging of employees, the shortage of skilled workers, the rising cost of manpower and the stricter requirements of safety and environmental protection have brought great challenges to the development of mining industry[4, 5].

As the driving force of the automobile industry reform, auto-driving technology has not only become the focus of many traditional automobile enterprises all over the world, but also one of the focuses of major Internet giants. However, due to limitations of policies, security, technology, ethics and many other factors, the commercial success of unmanned vehicles in the open scenario on public roads is facing many bottlenecks. Noticeable obstacles includes complex traffic signs, unpredictable behavior of road participants and unstable hardwares [6]. While general purpose autonomous driving suffers from these difficulties, specialized applications for mining sites could be realized relatively easily and provide novel solutions to above mentioned challenges in the mining industry. On the one hand, by connecting the vehicles to the Internet of Things, they can transmit all kinds of information to the central processing unit to realize the intelligent traffic management and vehicle control [7]. On the other hand, the special vehicles under limited scenarios with low or medium speed conditions will be the first rigid requirement for auto-driving technology to commercialize. As a relatively closed scenario, mining system has become one of the most important areas concerned by many auto-driving related enterprises [8,9]. As the mining and transportation operation in the mines implied a degree of repeatability and have some commonly used conditions, the construction machineries, such as excavators, wheel loaders, mining dump trucks, etc., first started the process of unmanned refit [10,11].

Unmanned mining has huge market potential, which can bring the mining enterprises (users) with cost, safety, efficiency and environmental benefits. Correspondingly, it will bring huge profits to the mining equipment manufacturers. It has attracted competing investment from mining equipment manufacturers, self-driving technology companies and large mining enterprises. However, the proportion of mines using automated equipments is still very low at present. With the pursuing for zero casualties and entering the era of skilled workers shortage in developed countries, it is estimated that by 2020, 50% of the major mining

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companies in Australia, Europe and the Americas will use the unmanned products, and some mines have decided to adopt unmanned mining equipments wholly. [12]

To realize the end-to-end autonomous mining operations, *Komatsu* launched the Autonomous Haulage System (AHS) to operate and manage fleets of self-driving mining trucks with capacities between 200 and 400 tons [13]. *Caterpillar* released Cat MineStar system to optimize productivity, enhance security, and improve machine utilization [14]. *Sandvik* developed autonomous loaders and trucks which operate underground [15]. *Volvo* tested it's self-driving tipper inside the earth at a depth of 1,320 meters and even with artificial lighting [16].

Overall, it has been possible to realize the autonomous driving on a single mining equipment no matter in an above-ground mine or an underground mine. However, more researches are needed on the control robustness of unmanned equipment, on the cooperative operation among equipment and on the cluster operation to achieve the overall improvement of safety, cost and efficiency of unmanned mines. As a typical complex system, mine system includes production subsystem, dispatching subsystem, water and power supply subsystem, transportation subsystem, management and control subsystem, safety subsystem etc. Of which production, transportation, dispatching and safety are the key subsystems in realizing the unmanned operation of mining system [17]. Faced with the control and management of such a complex and huge system, parallel theory [18,19] and ACP approach [20-22] provide a good solution for mining intellectualization and unmanned operation. The parallel mines inspired by parallel theory and ACP approach is a highly networked intelligent system, which is in the scope of IoT. The IoT based parallel mining also refers to humans, excavators, off-road dump trucks, high-speed heavy trucks and other devices connected in the mining environment.

By using IoT technology, the real-time data of key systems in mining are collected and transmitted to the management center, where a dynamic artificial system corresponding to the real system are constructed. This artificial system is proposed to simulate the real complex system in real time, dynamically and on-line. By studying the evolution and prediction of artificial systems, the prediction and management of real mining systems are realized.

The main contributions of this work include: 1)The proposing of the framework and solution for IoT based parallel mining, which may improve the safety of personnel and equipment, reduce the cost of mining operation and increase production rate by improved efficiency. 2)The key technologies motivated by IoT thought [23-25] in the implementation of autonomous mining are introduced: from the network communication, model construction, integrated perception, to the collaborative decision-making, take-over and control.

The rest of the paper is organized as follows. Section II describes the framework of the IoT based parallel mining. Section III gives the solution for the realization of parallel mining. The key technologies of parallel mining are introduced in Section IV in detail, which mainly include: the network communication, virtual parallel mining construction, mining environment perception, collaborative decision-making, unmanned mining equipment control, as well as parallel taking-over and remote control. Section V evaluates the performance of the key technologies based on Internet of Things in parallel autonomous mining. Finally, our conclusion is provided in Section VI.

II. THE FRAMEWORK OF IOT BASED PARALLEL MINES

The concept of parallel system was first put forward by F. Wang in 2004 [26], that is, to study the control, management, optimization and guidance of complex systems by constructing the virtual-real interactive artificial system and real system model. In parallel system, the ACP approach is the hard-core technical section, in which A refers to artificial society, C refers to computational experiments and P refers to parallel execution [27,28].

As a relatively closed and structured environment without interference from foreign vehicles and pedestrians except for operating equipment and professionals, mining system becomes one of the main scenarios in which driverless technology can be realized quickly. The driver's high labor intensity and poor working conditions also promoted this progress. Compared with the unmanned operation of single equipment, the cluster cooperative unmanned operation among all the mining equipments is more needed, which is exactly the important solution provided by parallel driving [27]. Parallel driving could obtain the data and scenarios in perceptual limits and other situations via the describing system. Knowledges and experiences can be shared to all vehicles in the system through analysis of a large number of algorithms and large-scale computation and evaluation of driving decisions. Relying on a single vehicle's own ability of perception, decision-making and control, as well as the powerful GPU behind it for data processing, the vehicle itself possess the ability to adjust its own behavior according to the environmental changes. The human remote control is only activated when the early warning had occurred. The IoT based parallel mining is an intelligent solution that applies parallel driving technology to the mining scenarios.

The framework of IoT based parallel mining is shown in Fig.1. It is a true embodiment of parallel system in the field of mining. The parallel mines has five important locations, namely the loading site *A*, the dumping site *B*, the transfer belt unloading site *C*, the freight station *D*, the parallel management & control center *E*. Among them, *A*, *B*, *C* and *D* can be regarded as real systems, while *E* and *F* can be regarded as virtual systems.

Within the parallel mining system, we mainly study and solve four problems: the first is the semi-autonomous excavation at point *A*, which improves the efficiency of excavation through the cooperation between excavator and mining truck. The second is the autonomous transportation of off-road dump truck from point *A* to point *B*. By installing sensors and developing algorithms of intelligent sensing, decision-making and control, the dump truck could realize it's autonomous driving. The third is the autonomous transportation of high-speed heavy truck from point *C* to point *D*. Unlike off-road dump truck, the high-speed heavy truck is operated on the open road and running in a relatively high speed. It requires higher level automated driving capacity which could avoid possible obstacles. The fourth is the management and control of parallel unmanned mining, which is responsible for the communication, supervision, coordinated control and dispatch for the automatic operation of all equipment. The end-to-end unmanned mining operation can be realized by the cooperation of these four sections, which aims at improving the safety and efficiency of the whole system and reducing the cost of mining operation.

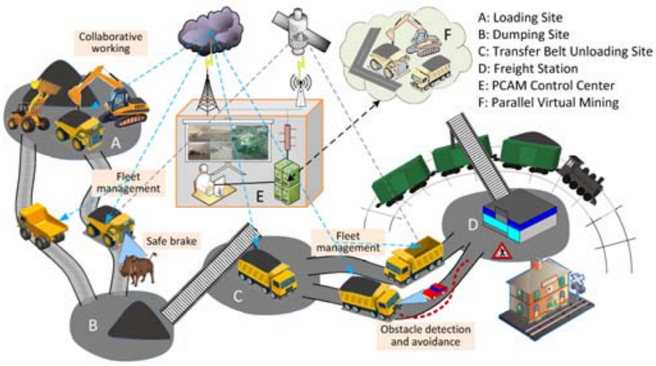

Fig.1 The framework of IoT based parallel mines

In the parallel mining, parallel subsystems corresponding to their real counterparts will be established to realize the physical system in real space mapping into virtual space. It could essentially solve the problems of low degree of network connection, difficult scheduling and confused management of each subsystem. Driven by data, a series of virtual mining organizations and institutions that interact with the actual mining system are constructed to form the parallel unmanned mining system. Various complex problems including mining scheduling, coordination, management, control and communication are constantly analyzed and evaluated by means of computational experiments. The aim is to change the production mode of the mining system and improve the synergy level and intelligence degree between the mining subsystems. The parallel mining divides a complex huge mining system which is difficult to manage, control and forecast into several parallel subsystems according to its functions, which can be flexibly optimized. At the same time, the forecasting and management strategy explored in the virtual world through computational experiments and parallel execution can be applied on the real mining system, enabling the real mining system's ability of coping with unknown work scenarios and tasks.

III. SOLUTION FOR IOT BASED PARALLEL MINES

The IoT based parallel mining system consists of four parts: the parallel management and control center (hereafter called M&C center), the autonomous transportation platform, the semi-autonomous mining/shovelling platform, and the remote take-over platform. As the nerve center of the mining system, the parallel M&C center is responsible for comprehensive real-time monitoring and comprehensive dispatching of unmanned mining equipment. The real-time interaction and two-way optimization through the established virtual mining system and their real counterparts ensure the safe and efficient operation of actual mining. The semi-autonomous mining/ shovelling platform and the autonomous transportation platform are equipped with a variety of sensing devices to realize semi-autonomous excavation, loading, unmanned transportation and unloading of minerals. The remote take-over platform is responsible for monitoring the operation of the mining equipment. Under the initiative request of the takeover from the semi-autonomous mining/shovelling platform or autonomous transportation platform, or in a special emergency, the remote take-over platform realizes the intervention and takeover for multiple devices according to the decision made by the parallel M&C center.

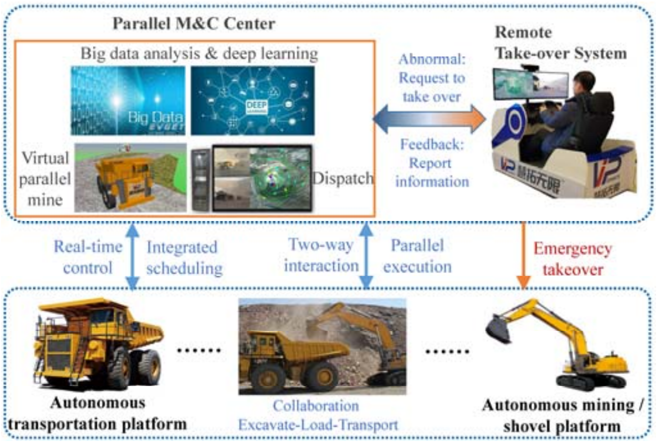

Fig.2 Solution for IoT based parallel mines

A. The parallel M&C center

The parallel M&C center consists of a description system defined by the virtual parallel mining system, a prediction system defined by big data analysis and the deep learning center, and a guidance system defined by the dispatch center. Various data generated during mining production and operation are transmitted to the information processing center, where each subsystems parallel to the actual mining operation are constructed through data fusion, data mining, and visualization processing. In this way, on the one hand, the virtual data are built using actual data to complete parallel, online and real-time simulation of all aspects of mining production operations; on the other hand, the prediction, evaluation and optimization of real systems are completed through the evolution of parallel systems and collaborative interaction with real systems, thereby achieving the management and control of the unmanned mining system. The hardware in parallel M&C center includes simulation equipment, industrial computers, servers, video monitoring devices, image splicers, remote network equipment, etc. Each device corresponds to the function of the control center. In particular, if a dangerous situation occurs at the mining site which may affects the normal operation of other systems or the safety of workers, the control center will make intelligent decisions and monitor the mining site in real time.

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B. The autonomous transportation platform

The autonomous transportation platform mainly includes off-road dump truck and high-speed heavy truck, which are used for short and long distance transportation, respectively. The autonomous truck is equipped with lidar, radar, inertial navigation system, camera, V2X equipment, industrial computer, wireless network tester, on-board monitor, etc. The transportation route of autonomous truck is assigned by the parallel M&C center. The truck runs automatically at a suitable speed in the cycle of loading, transportation and unloading according to the target route, its own position and the surrounding environment.

The autonomous transportation platform includes functions such as autonomous driving, mode switching, status detection and display, information communication and management. The mining environment information perceived through lidar, radar, camera, as well as the positioning information provided by the inertial navigation system, are provided to the decision-making subsystem and control subsystem for the decision, planning and control. The communication subsystem is responsible for the wireless communication between the unmanned equipment, the M&C center and the remote take-over platform, thus providing support for the remote monitoring and control, and the cooperation between excavators and mining trucks. The data management subsystem performs data backup for the operation of autonomous truck, which can be used for data playback and further research. Considering the special requirements of mining operation safety, the autonomous transportation platform also has a state detection subsystem and a mode switching subsystem. The state detection subsystem displays the health status of each section. Integrating the data and commands from the state detection subsystem, the M&C center, and the remote take-over platform, the mode switching subsystem make decisions on the switching between manual mode and the automatic mode.

C. The semi-autonomous mining/shovelling platform

The semi-autonomous mining/shovelling platform is equipped with sensors such as displacement sensor, pressure sensor, lidar, inertial navigation system, camera, radars, etc. The excavators or loaders cooperate with the autonomous truck by semi-autonomous mining or autonomous shoveling at mining sites.

In the process of the cooperation between excavators and mining trucks, the driving path for the mining truck in the working area is firstly planned according to the position of the excavator, and the excavator guides the mining truck to the correct position for loading. Then the excavator fulfill the automatic excavation of target minerals [29,30] and automatic unloading into the container of the mining truck according to the sensor information. During the entire excavation process, the human operator in the control center could monitor the excavation process and manually intervene when necessary, which not only ensures the smooth progress of the automatic excavation, but also greatly improves the working environment of the driver.

For the cooperation between the loader and the mining truck, after the mining truck is guided to the target position, since the loader moves more conveniently, the self-loader is responsible for the mineral loading, driving route planning and tracking, and finally depositing the minerals into the truck container.

D. The remote take-over platform

To fulfill the high safety requirements for unmanned mining operation, the remote take-over platform is responsible for the safe manual control for the autonomous mining truck and the semi-autonomous excavators/loaders at emergency situations [31]. The remote take-over platform implements different processing strategies according to the fault levels, and designs a multi-level policy of security confirmation for mode switching and takeover. The remote take-over platform can realize the control for multiple autonomous mining trucks or excavators/loaders. It could also realize the cooperation between the excavator and the mining truck in the remote take-over state through the monitoring and dispatching of the M&C center. The remote take-over platform improves the operation quality and productivity while increasing the safety of human drivers and the equipment.

IV. Key Technologies of IoT Based Parallel Mines

This section introduces the key technologies we studied in the implementation of IoT based parallel mining, which mainly includes: the network communication, virtual parallel mining construction, environment perception, the collaborative decision-making, unmanned equipment control, as well as parallel taking-over and remote control. The details are as follows.

A. Mining network communication

Due to the influence of signal attenuation and Doppler effect caused by occlusion, air moisture content, equipment deployment, etc., the quality of wireless communication will be disturbed to a certain extent. It is necessary to design and choose a reasonable communication mode and equipment to ensure the security and reliability of information transmission. For traditional WiFi, the one-way transmission time of UDP packets may reach hundreds of milliseconds to seconds when the network is congested; For Mesh wireless network, the probability of packet loss and delay increases with the increase of hops, and the network topology will change and needs a certain time to converge, which further increases the probability of packet loss and delay.

To ensure the reliability and stability of network communication, we use a combined network scheme of WiFi-Mesh in parallel mining network communication. The principle of the network communication in parallel mining is shown in Fig.3, which is divided into the remote communication between equipment and center and the terminal management communication between different equipment. In the cooperative communication between mining truck and excavator, the Wifi-Mesh communication equipment is installed on roadside, enabling excavator and mining truck to realize the V2V communication. The CPE communication equipment is installed on excavators and mining trucks, and

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connected with the 4G base station to realize the V2Server communication.

In order to enhance the reliability and the anti-jamming ability of communication system, certain strategies, such as deploying multi-communication system, increasing link budget redundancy, increasing the budget margin of frequency band and bandwidth, are adopted in the WiFi link. The network transmission protocol can be selected according to the characteristics of various communication protocols, scenarios and applications.

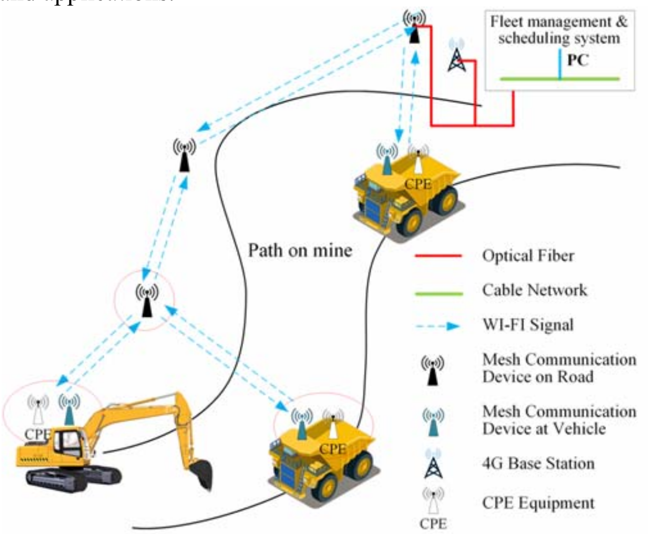

Fig.3 The principle of mine network communication

In the network communication, there will inevitably generate communication abnormalities, such as SUDP packet loss, the communication disconnection between vehicle and control center, etc. A well-designed exception handling mechanism can effectively reduce the impact of network anomalies. Abnormal handling methods include: displaying the loss of packets to the administrator, recording events and logs; alarming the control center in time to inform the administrator when communication disconnection occurs, or parking directly to ensure safety.

B. Virtual parallel mining construction

As the foundation of parallel M&C center of unmanned mining, the construction of virtual parallel mining is essential. In practice, the mining system is complex and changeable, and it is difficult to build a reliable mathematical model. Therefore, the mine production process is difficult to be controlled accurately, and of great safety hazard. To overcome these difficulties, information technology is used to collect data of key dynamic attributes for each subsystem in mining system. Besides, digital modelling, virtual technology and visualization technology are used to establish artificial system corresponding to the system in reality, and the collected data are imported into the artificial system in real time, making the artificial system parallel to the real system, which can be called as parallel system.[32] Furthermore, in the parallel systems, various intelligent algorithms and optimization algorithms are used to predict and optimize the operation of the real system, and send the results to the real system, so as to realize the optimal control of the real system.

Taking the autonomous truck as an example, the structure of virtual parallel mining is shown in Fig. 4, and its visual display scene is shown in Fig. 5. The autonomous truck simulation platform in virtual parallel mining covers the module of vehicle dynamic model, virtual reality model, virtual sensor and environment perception, deviation calculation, planning and decision-making, control, etc. The output data include camera videos from each view point, radar data, 3D coordinates of vehicles, heading angle, speed, steering wheel angle, throttle/brake pedal's position, tire forces and so on.

The input of the platform is the relevant data generated by the actual truck, including the current position, vehicle speed, the steering command from the controller, and the pedal instruction. After the collected data have been imported into the artificial system in real time, the autonomous truck in virtual parallel mining is synchronized with the real truck. With this platform, we can accurately simulate the truck performance and predict possible problems. It can also quickly verify the effectiveness of the autonomous driving algorithms in planning, decision-making and control, especially in various extreme conditions. Finally, the prediction, control and management strategies will be applied to the real mining system.

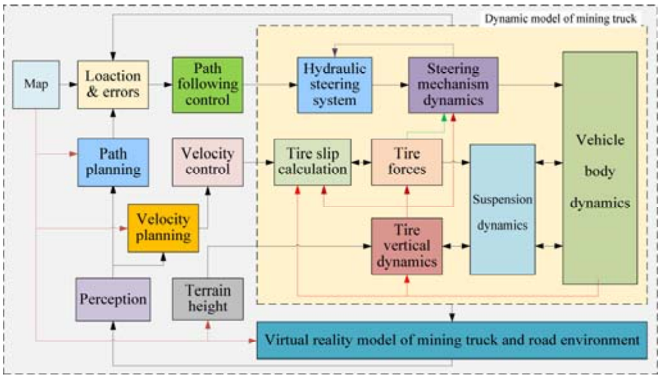

Fig.4 The structure of virtual parallel mine

Fig.5 Visual display of parallel mine

C. Perception over-the-horizon in mining Environment

The environment perception system of each mining truck uses a collection of sensors, such as lidar, millimeter-wave radar, camera, ultrasonic wave sensor, infrared sensor, etc., to perceive the environmental information. During the operation of mining machines, multi-sensor fusion technology is used to monitor the driving area in order to detect and track the

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obstacles. At the same time, it can identify specific targets to avoid collision and provide warning information while reversing.

Multi-sensor data fusion is also used to eliminate the data redundancy between different sensors, and enhance the robustness of the system through data complementarity, so as to improve the reliability of the environmental sensing system. The sensors and their coverage areas of the mining truck are shown in Fig.6. The overlapped coverage areas of multiple sensors are the working areas of data sensing and fusion.

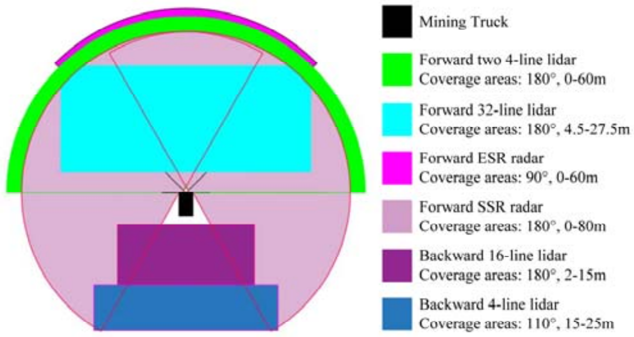

Fig.6 Sensors & it's coverage of the mining truck

The resolution of sensors used in our truck is usually not very high, which reduces the capital cost, at the expense of moderate perception ability lose. In addition, the road width in the mining area could easily reach 30-40 meters, and the effective perception range of sensors in dust/sand environment is greatly reduced. Therefore, it is difficult to make safe and efficient decisions based on the perceptual results of a single vehicle in complex traffic scenarios. Thanks to the cluster management and control system and V2X communication technology, all perceptual results, such as vehicle localization, status information and surrounding environment perception information, can be uploaded to the cluster center. The center can further send the perception results of other vehicles, within a certain range around it, to a vehicle, so as to realize the sharing of perception results among multiple vehicles and achieve the ability to perceive over-the-horizon. The principle of fusion perception over-the-horizon is shown in the Fig.7.

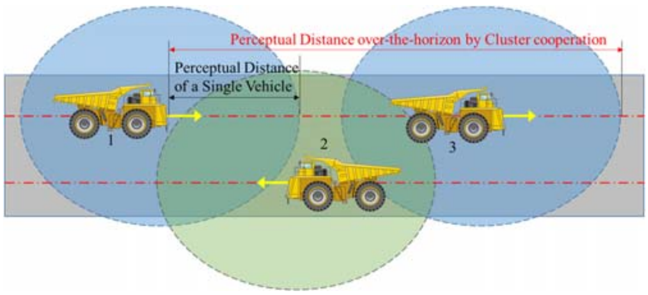

Fig.7 Perception over-the-horizon by sharing

D.Collaborative decision-making

Based on the perception results of over-the-horizon for mining environment acquired via V2X communication, the scheduling and management of the fleet in complex mining scenes can be realized by designing the decision-making algorithm for autonomous mining trucks. In the parallel autonomous mining transportation, the collaborative decision-making between the management & control center and autonomous truck is designed, which could greatly improves the efficiency of transportation for each autonomous truck. In order to ensure the reliability of the unmanned system, each autonomous truck still maintains its own decision-making within the range of its perception ability. In addition to emergency scenarios, the decision-making instructions issued by the center have the highest priority. If the center does not issue any instructions, the decision-making by the autonomous truck is used.

In areas beyond the perception range of a single vehicle, the decisions can be made by the M&C center, or by each autonomous truck according to the information from other vehicles that is issued by the center. The comparison of two decision-making modes is shown in Fig. 8. When a decision is made by the center, all vehicle parameters are calculated only once at the central terminal, and the processing speed of decision-making is faster because of the higher central computer specs. When a decision is made by each autonomous truck, the center needs to send the perception/location information of surrounding vehicles to each vehicle, which not only increases the amount of data transmission, but also increases the network communication burden. And the decision-making process is slower because of the limited computing power of the calculation unit mounted at each vehicle, and the multiple calculations carried out on each vehicle. For example, assuming that there are n autonomous truck in the whole mining area, all the positioning and sensing information of the truck is uploaded to the central terminal. The network occupancy rate is very low when the decision is made by the center, which does not need to send a large number of vehicle perception information to individual vehicles. Only one calculation was made at the central terminal, and then the decision-making instructions is sent to individual vehicles. However, if the decision is made by individual autonomous trucks, each vehicle needs to do a decision-making calculation (totally n times of calculation) in addition to sending a large number of perception data to surrounding vehicles. Moreover, if the decision is only made by autonomous trucks, the traffic problem among the autonomous trucks can not be effectively coordinated.

Therefore, the integrated dispatch of all vehicles through the fleet management system at the central terminal has the advantages of fast decision-making speed and low network burden, which can effectively improve the transportation efficiency of autonomous trucks and ensure the traffic safety.

After all the vehicle perception information is uploaded to the central terminal for decision-making, the fleet management of autonomous truck is transformed into the decision-making and planning for traffic flow. Here, the decision-making at the intersection is taken as an example to illustrate. The road in the mining area is specially designed. Traffic lights are usually not used at intersections, so the "first come first go" traffic rules are

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adopted. Under this traffic rule, vehicles need to slow down or stop at the intersection before passing, which affects the transportation efficiency of mining area and increases the fuel consumption of transportation. In parallel autonomous mining transportation, the M&C center predicts, plans, and manages all vehicles passing through the intersection in advance, automatically manages the order and speed of vehicles, avoids collision or parking at the intersection, and enables all vehicles to pass through the intersection in efficient and smooth motion.

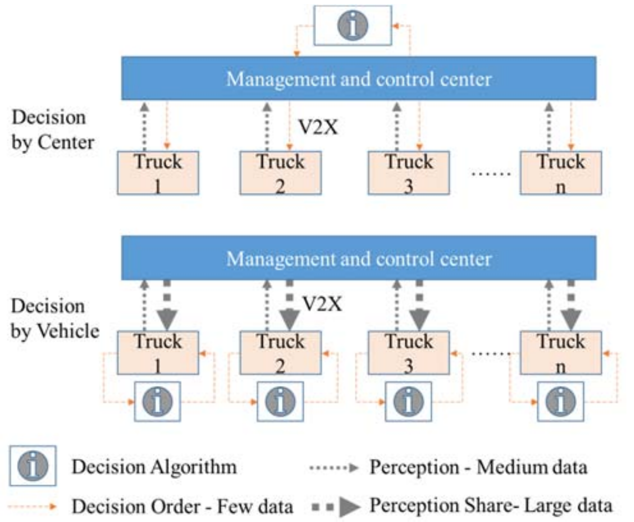

Fig.8 Comparison of decision-making made by center and by vehicle

The principle of collaborative decision-making at intersection is shown in Fig. 9. Two circular areas are designed in the intersection area: the rescheduling area between outer cycle and inner cycle for passing order and speed planning, and the crossing area within inner cycle with determined rules. When a new vehicle enters the outer circle in a certain speed, the velocity and passing order of all vehicles within the annulus will be rescheduled. Once a vehicle enters the inner circle, its planned passing order and speed will not be changed for safety reasons. It should be noted that the decision-making algorithms should arrange the velocities of each autonomous truck to ensure that they will not collide in intersection area. [33,34]

E. Unmanned mining equipment control

Mining equipment, such as off-road dump trucks, high-speed heavy trucks, excavators, loaders etc., are much different from conventional passenger vehicles. Their size and weight are very large, and the used transmission and steering systems also have certain particularities. Therefore, the mining equipment have many unique characteristics, such as large inertia, large system delay and large variation of load. In addition, the working environment of the mining site is harsh and the pavement conditions are complex. There are a lot of continuous climbing, turning and uneven pavement. Therefore, both the facility performance and working environment are more complex than conventional passenger vehicle's scenario. It makes the control of these equipment more difficult, which requires the control algorithm to have better adaptability and robustness.

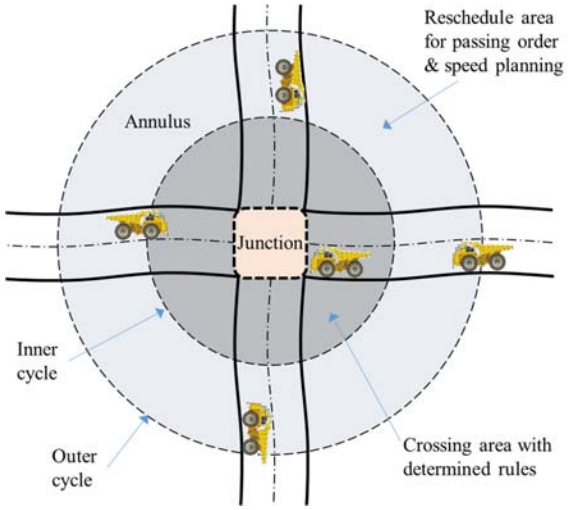

Fig.9 Collaborative decision-making at intersection

For the lateral control in the course of driving, the steering system needs to be controlled by the path following control algorithm according to the information provided by the integrated navigation and positioning system and the planned ideal trajectory. The path-following control based on the virtual terrain field (VTF) method is used for the heavy mining truck control [35,36]. For the VTF control, a virtual U-shaped terrain field is assumed to exist along the reference path. The altitude of terrain field will goes higher as the lateral error becomes larger. If the vehicle deviates from the reference line, additional lateral restoring forces caused by the virtual banked road will be applied on the vehicle. The vehicle will be pulled back to the lowest position (reference centerline) under the influence of the additional lateral forces.

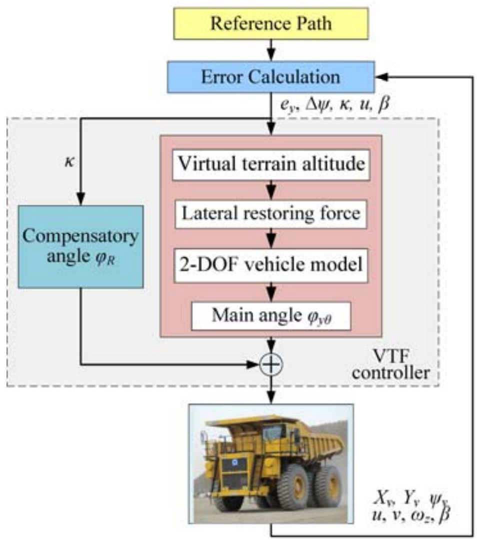

Fig.10 The processing flow of VTF control

Fig.10 is the processing flow of VTF control. First, the tracking errors is calculated according to the digital map and parameters acquired by sensors. Then the function of VTF

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altitude and the lateral tire forces are established and derived, respectively. According to the 2-DoF vehicle dynamics model, the target steering angle are derived, which is applied to the vehicle for path-following control.

F. Parallel taking-over and remote control

The large-scale unmanned mining is a centralized operation business scenario, in which thousands of engineering machines (including mining truck, semi-autonomous excavator, patrol cars, etc.), surveillance cameras and various sensors, etc, are used. It should be pointed out that the unmanned mining scenario is not completely unmanned operation. Its main meaning is the unattended operation and intelligent decision-making for mining. Therefore, in the current planning, a certain number of professionals are still needed to manage and assist decision-making through appropriate takeover or remote control, so as to maintain the normal operation of various equipment.

In the remote supervision, the experienced drivers can send takeover request for the supervised mining trucks in the control center. Through the identification and processing of the central processor, the command can be sent to the specific trucks that need to be controlled, so as to realize the remote control by driving simulator. The main purpose of the remote control is to ensure the safety of the truck through human operation in the case of abnormal condition, so as to enhance the robustness of the whole intelligent mining system.

For parallel unmanned mining system, a large number of unmanned equipment and a certain amount of takeover drivers are need. The specific number of equipment needed to be supervised by each driver needs to be allocated reasonably. Insufficient supervisors can not guarantee the safe and reliable operation of equipment, and excessive supervisors will cause waste of personnel, costs and resources.

The decision-making process of remote takeover for parallel unmanned mining is shown in Fig.11. The detailed process is as follows:

Firstly, it is needed to judge whether the takeover is necessary according to the emergency situations such as the break down of the equipment or large path tracking error. If the remote takeover is needed, the take-over index of the equipment is calculated according to the parameters such as position deviation, signal fault, speed and acceleration. By comparing the demand index of all the equipment that need to be takeover, the priority grade of takeover of each equipment is determined. After the takeover index and the priority grade of all monitored equipment are determined, those equipment that need to be takeover can be controlled. For the equipment with the highest priority grade of takeover (p_i=1), the monitor screen and control are directly allocated to the takeover driver for remote control; If other equipment request to takeover at the same time, it is necessary to determine whether the driver is sufficient. If the takeover grade of the equipment is less than or equal to the total number of takeover drivers, the monitor screen and control are allocated to one of the drivers. Otherwise, there is no remaining driver to takeover. At this time, braking/parking control must be carried out on the equipment with low level of takeover to ensure safety. When a driver completes the takeover for an equipment and is idle, the stopped equipment that cannot be takeover due to insufficient driver can continue to takeover until all the equipment are completed.

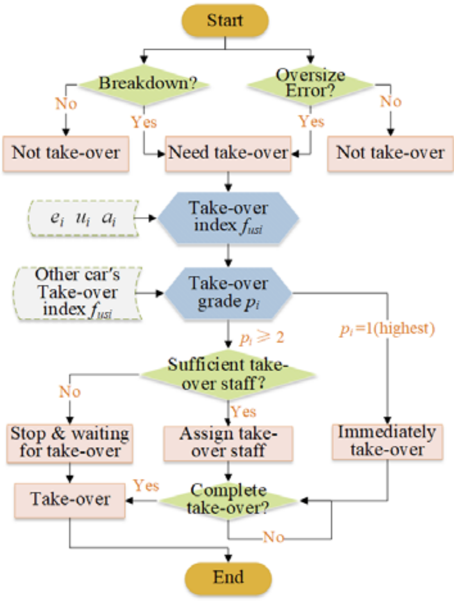


Fig.11 The decision-making process of remote takeover

In the way of remote takeover, due to the difference of the specific operation, the control mode of different equipment is also different. For driving-oriented equipment (such as mining truck), the control mode is relatively simple, and remote control can be carried out by driving simulator [31]. For excavator, loader or other equipment, excavation, shovelling and loading operations are also needed besides driving. This paper takes the remote gesture control of excavator as an example to illustrate:

The remote operator of excavator wears the wearable equipment on his upper body as shown in Fig.12, which can measure the three-axis angle of the arm, and then calculate the spatial position of the hand and some arm postures. The relevant control program is designed to realize the movement control of the excavator arm bucket in tracking the spatial position of the human hand and the action control of each mechanism of the excavator arm. The movement of the excavator includes the swing and lifting of the main boom, the lifting of the stick boom and the swing of the bucket. The left hand is responsible for switching gears, and the right hand is responsible for specific displacement control. The specific implementation scheme is shown in Fig.12.

The three kinds shift switching control of left-handed attitude are tracking control (A), stopping control (B) and separate mechanism control (C). When tracking control, the left hand sags naturally, which is used to track the spatial position of the human hand in real time by the excavator bucket; the left arm is placed in front of the chest to indicate that the excavator arm stops moving; and the mechanism is controlled separately to indicate that the four main movements of the excavator are controlled separately.

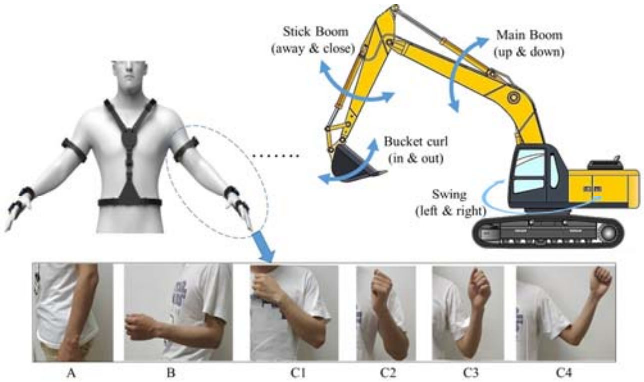


Fig.12 The remote gesture control of excavator

Thanks to the virtual parallel mining and equipment models which correspond to the real system, the video around the equipment is no longer need to be retransmitted during remote operation, but only the main parameters such as the position and attitude of the equipment are sent to the remote takeover terminal. Based on the limited data, the virtual equipment model is directly driven and displayed to the operator, which is used for the remote operation. As there is no need for video data transmission, the general 4G network can meet the network bandwidth requirements and achieve better control effect. Otherwise, it will cause a greater pressure on network communication, and 5G must be used to meet the demand.

V. Performance Evaluation of IoT Based Parallel Mines

This section evaluates the performance of the key technologies based on Internet of Things in parallel autonomous mining, including the fusion perception, collaborative decision-making, planning and control.

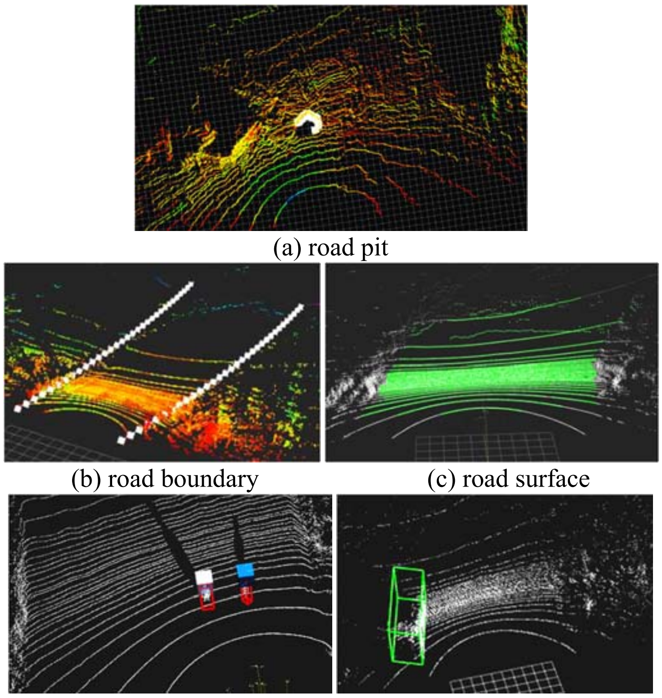
A. Perception

The detection module can collect information of road surface, driving area and obstacles, and provide reliable guarantee for safe and fast autonomous navigation. For road surface and driving area detection, lidar, camera and other sensors are used to extract roads and driving areas, so that mining machinery can reach the target point safely within the driving area when GPS positioning fails. As for target detection and tracking, by processing the sensor data from lidars and cameras, the obstacle information is detected and the dynamic obstacles are tracked. This information is transmitted to the planning module to realize the autonomous obstacle avoidance.

As the road for mining truck running is the unstructured type, it makes the road detection much difficult. First, the point cloud data of lidar is processed to eliminate the noise interference and to determine the grid map [37,38]. Then DBSCAN clustering is conducted to extract the ground point [39]. As the features of scanning points in vertical direction are distinct after dilation operation [40], if the difference between the maximum and minimum value of each grid is less than a set threshold, the grid is considered to be the ground, otherwise it is considered an obstacle. An example result of road pit detection is shown in Fig. 13 (a).

Ground points are fitted with Hough transform so as to extract the straight lines from laser scans on the ground and the end points of lines are taken as the contour points. Quadratic curve fitting with least square algorithm is used to find the road boundaries. The real detection results for road boundary and surface of the unstructured road are shown in Fig. 13 (b), (c).

The clustered obstacles, including pedestrians and vehicles, are fitted with boundaries. As the two-dimensional shape of the vehicle is rectangular, the L-shape fitting algorithm [41] is used. The minimum area rectangle (MAR) method [42] is used for pedestrian detection. The detection results are shown in Fig. 13 (d), (e).



(a) road pit

(b) road boundary (c) road surface

(d) pedestrians (e) vehicles

Fig.13 Detection for road and obstacle

B. Decision-making & planning

(1) Decision-making at intersection

To verify the effectiveness of collaborative decision-making for the fleet management of autonomous mining trucks, the whole time to pass through an intersection with different arriving rate λ (traffic load) are simulated. The results comparing with "ad hoc negotiation based" strategy are given in Fig.14. The testing arriving rate of autonomous truck is varying from 0.05veh/(lane•s) to 0.9veh/(lane•s). When the traffic arriving rate is very low (e.g. λ=0.05veh/(lane•s)), the performance of the collaborative decision-making strategy is similar to that of "ad hoc negotiation based" strategy. This in mainly because the vehicles pass through the intersection do not need to stop when the traffic rate is low, so the passing time are basically the same. But when the traffic arriving rate goes higher, the time to pass through the intersection by the "ad hoc negotiation based" approach increases much faster than that of the collaborative decision-making strategy, which means the

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collaborative decision-making strategy has a notably advantage in leading to a quick and efficient passing performance. [43]

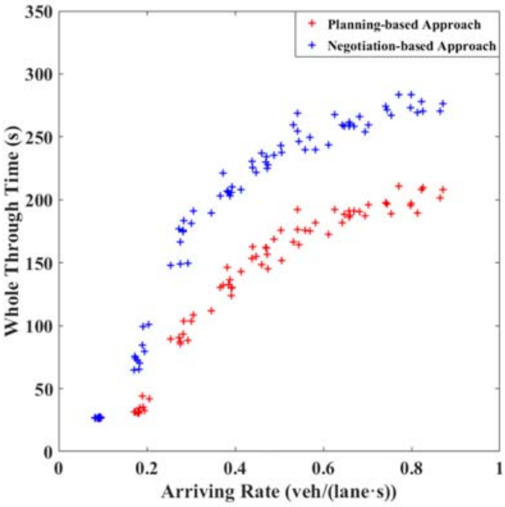

Fig. 14. The time to pass through an intersection with different traffic load [43]

(2) Local speed planning

Once the start and end points for the operation are determined, the fleet M&C center distributes the global path and speed planning results to each autonomous mining truck. However, it is inevitable to suffer discontinuous region of the planned global speed. When switching between different speed regions, the large speed deviation could result in sudden acceleration or braking of vehicles. For urgent acceleration, the target value can be gradually achieved through continuous acceleration without dangerous. However, the urgent braking must be accurately executed immediately for extra braking distance could bring about collision and other dangers. Therefore, the local speed planning for the braking buffer area must be determined before the discontinuous region of speed, and the braking begins when the vehicle enters the area.

To verify the effectiveness of the local speed planning algorithm, the local speed planning and control for mining truck on circular road was simulated on virtual simulation platform. The preliminary global speed planning result with discontinuity is shown by the grey curve in Fig.15. It can be seen that there is a sudden change in the planned speed value at the junction of straight line and turning, especially during the braking at 10s and 41.3s. If not replanned to decelerate in advance, the mining truck will rush into the turning area at a higher speed, which will affect the comfort and even safety of the truck. Under the established local speed planning algorithm, the mining truck can be accurately braked in advance before 10s and 41.3s, respectively. When the truck arrives at the turning area, it can exactly reach the preliminary planned velocity (about 20km/h).

The local speed planning takes into account the braking ability of the mining truck by controlling the deceleration according to the initial planned speed within the preview distance and the current speed. The braking related operations can be carried out timely and accurately. As the actual power of the truck is considered, the driving speed changes smoothly and the maximum deceleration can also be limited, which improves the stability, comfort and safety of the mining truck.

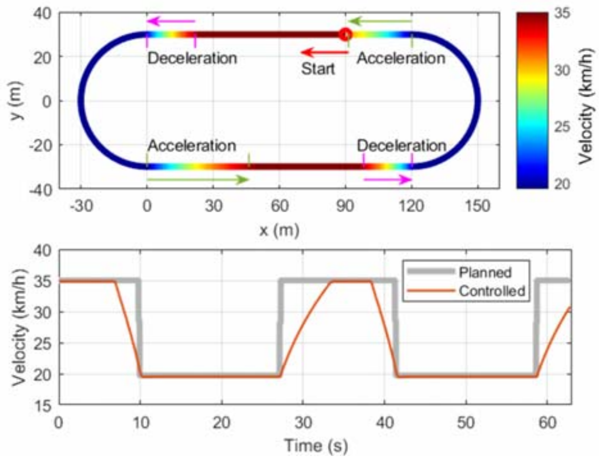

Fig.15. The local speed planning to solve discontinuities

C. Control

In view of the particularity of the mining equipment and their working environment, if the control algorithm is directly verified on the real facilities, it may cause unnecessary risks, increase the waste of humans and costs. With the virtual simulation platform, the control algorithm for unmanned equipment can be quickly, safely and fully validated. Simulations of steering control by VTF approach at annular road, double-lane change road and snaking road were conducted to compare with PID control and preview feedback control (PFB) [44].

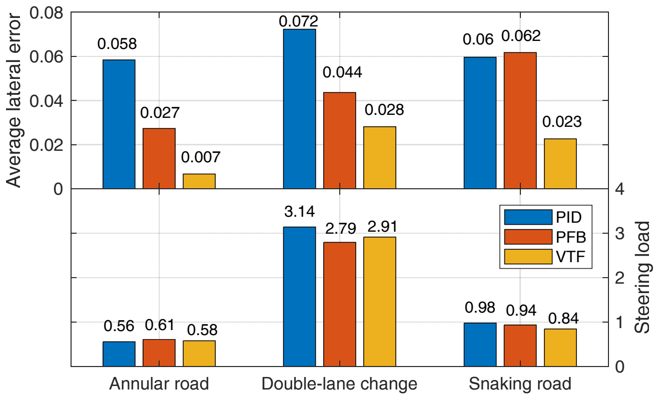

Fig. 16. Results comparison by different type controllers

To evaluate the driving performance of different controllers, the average lateral error and the average driver steering load under different scenarios are compared in Fig. 16. The results show that the average lateral errors controlled by VTF approach has significant advantages with the minimum value under the three scenarios compared with the other two scenarios. Compared with PID control and PFB control, the VTF approach could reduce the lateral error by 61%~88% and by 36%~74%, respectively. At the same time, the steering load of all the control algorithms are basically the same under all scenarios.

In addition, we compared the computer resource consumption during the process of the steering control to evaluate the real-time performance of different algorithms. Besides PID and VTF control, the linear quadratic regulator control (LQR) and model predictive control (MPC) are compared in Table 1. The memory utilization of different controllers are the same value. However, the CPU utilization are much different.

TABLE I
COMPUTER RESOURCE CONSUMPTION OF DIFFERENT CONTROLLERS

Method	CPU utilization	Memory utilization
PID	2%	0.1%
VTF	1.9%	0.1%
LQR	30.9% (with 150 iterations)	0.1%
MPC	7.2% (Prediction domain: 10 steps)	0.1%

The LQR approach has the maximum CPU utilization (as high as 30.9%) when its maximum iteration is set to 150. The CPU utilization of MPC approach is 7.2% even though the prediction domain is only 10 steps. The CPU utilization of VTF approach is only 1.9%, which is even smaller than that of PID control.

From the above analysis, it can be concluded that the steering control based on VTF approach has a robustness in fitting different working conditions without increasing the steering load. At the same time, the real-time performance is also excellent.

VI. CONCLUSION

Inspired by the ACP approach, this paper presented the IoT based parallel mining as a new solution for end-to-end autonomous mining operations, to improve the safety of personnel and equipment, reduce the cost of mining operation and increase production rate fundamentally. As the four main parts of parallel mining, the M&C center, the autonomous transportation platform of truck, the semi-autonomous mining/shovelling platform, as well as the remote take-over platform, were discussed in detail. The key technological advances achieved in the construction of parallel mining, including the network communication, virtual parallel mine construction, mining environment perception, collaborative decision-making, unmanned mining equipment control, as well as parallel taking-over and remote control, were presented and discussed as examples.

The case study for performance evaluation of IoT based parallel mining were evaluated. From the study results, it can be concluded that the IoT-oriented approach has obvious advantage in perception, decision-making, planning and control. IoT based parallel mining has excellent real-time performance for decision-making and control, and could improves the stability, efficiency and safety of the autonomous trucks.

Our on-going work is devoted to the improvement and implementation of intelligent scheduling algorithm. Future work involves the statistical analysis of operation data of several unmanned mines, to evaluate the advantages of IoT based parallel mining solutions in reducing operation costs, improving efficiency and enhancing safety.

REFERENCES

[1] M. A. Razzaque, M. Milojevic-Jevric, A. Palade, and S. Clarke, “Middleware for internet of things: A survey,” *IEEE Internet of Things Journal*, vol. 3, no. 1, pp. 70–95, 2016.

[2] Paul J. A. Lever and Fei-Yue Wang, “Intelligent Excavator Control System for Lunar Mining System”, *Journal of Aerospace Engineering*, 1995, Vol. 8, No. 1, pp. 16-24.

[3] Paul Lever, Fei-Yue Wang, “Intelligent Excavation Control for a Lunar Mining System”, *Proc. of 4th International Conference on Robotics for Challenging Environments*, Albuquerque, NM, 1994, pp. 97-105.

[4] Levelling the Playing Field: The Mining Association of Canada. Report. April,2015.

[5] Mining Feature: Fatigue Management for Haul Truck Drivers: A Low-Tech Solution for a Small Mine". Office of Mine Safety and Health Research, National Institute for Occupational Safety and Health. 28 October 2014.

[6] Nunes, Ashley, Bryan Reimer, and JosephÂ F. Coughlin. "People must retain control of autonomous vehicles." *Nature* 556 (2018): 169-171.

[7] Contreras J, Zeadally S, Guerrero-Ibanez J A. "Internet of vehicles: Architecture, protocols, and security." *IEEE Internet of Things Journal* (2017).

[8] "Map of unmanned enterprises in China, 2018 Edition". Zhigu news. Available: http://zhigu.news.cn/2018-09/29/c_129963390.htm.

[9] "2017 RBR50 List Names the Leading Robotics Companies of the Year ". Robotics Business Review. Retrieved 2017. Available: https://www.roboticsbusinessreview.com/companies/?companyType=rbr_50.

[10] Paul J.A.Lever, Fei-Yue Wang, D.Q. Chen, “A Fuzzy Control System for an Automated Mining Excavator”, *Proceedings of 1994 IEEE International Conference on Robotics and Automatio*n, San Diego, CA, May. 8-13, 1994, Vol. 4, pp. 3284-3289.

[11] Lever, Paul JA, et al. "Autonomous robotic mining excavation using fuzzy logic and neural networks." *Journal of Intelligent & Fuzzy Systems* 3.1 (1995): 31-42.

[12] X. Chen, M. He. "Framework system and key technology of intelligent mine construction." *Coal Science and Technology*, 2018, 46(2).

[13] Parreira, Juliana, and John Meech. "Autonomous haulage systems–justification and opportunity." *International Conference on Autonomous and Intelligent Systems*. Springer, Berlin, Heidelberg, 2011.

[14] Mining technology - CAT® minestar. Available: https://www.cat.com/en_US/by-industry/mining/mining-solutions/technology-new.html

[15] Glass labyrinth: 38-tonne automated loader. Available: https://www.rocktechnology.sandvik/en/

[16] Volvo tests a self-driving truck in a swedish mine, Blows Our Minds. Available: https://www.guidingtech.com/61345/volvo-tests-self-driving-truck-swedish-mine/

[17] Min Zuo. The "Application of Parallel System Theory in Modern Mine Managemnet. " *METAL MINE*, 2011, 40(9):131-133.

[18] Wang F Y. "Parallel system methods for management and control of complex systems. " *Control and Decision*, 2004, 19(5): 485-489.

[19] Bai T., Wang S., Shen Z., et al., "Parallel Robotics and Parallel Unmanned Systems: Framework, Structure, Process, Platform and Applications. " *Acta Automatica Sinica*, 2017, 43(2): 161-175.

[20] Wang F Y. "Software-defined Systems and Knowledge Automation: a Parallel Paradigm Shift from Newton to Merton." *Acta Automatica Sinica*, 2015, 41(1): 1-8.

[21] Wang F Y. "Parallel Control: A Method for Data-Driven and Computational Control." *Acta Automatica Sinica*, 2013, 39(4): 293-302.

[22] Wang F Y. "Artificial Societies, Computational Expermients, and Parallel Systems:A Discussion on Computational Theory of Complex Social-Economic Systems." *Complex Systems and Complexity Science*, 2004, 1(4): 25-35.

[23] Fortino, Giancarlo, et al. "Towards a development methodology for smart object-oriented IoT systems: A metamodel approach." *2015 IEEE international conference on systems, man, and cybernetics*. IEEE, 2015.

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[24] Fortino, Giancarlo, et al. "Agent-oriented cooperative smart objects: From IoT system design to implementation." *IEEE Transactions on Systems, Man, and Cybernetics: Systems*48.11 (2017): 1939-1956.

[25] Chen, Min, et al. "A Dynamic Service Migration Mechanism in Edge Cognitive Computing." *ACM Transactions on Internet Technology (TOIT)* 19.2 (2019): 30.

[26] Wang F Y. "Computational Theory and Method on Complex System." *China Basic Science*, 2004, 6(5): 3-10.

[27] Wang F Y, ZHENG N N, CAO D P, et al. "Parallel driving in CPSS: a unified approach for transport automation and vehicle intelligence." *IEEE/CAA Journal of Automatica Sinica*, 2017, 4(4): 577-587.

[28] Wang F Y. "The emergence of intelligent enterprises: from CPS to CPSS". *IEEE Intelligent Systems*, 2010, 25(4): 85-88.

[29] Paul Lever, Fei-Yue Wang and X. Shi, "An Intelligent Task Control System for Dynamic Mining Environments", *AIME Transactions on Mining, Metallurgy and Exploratio*n, 1994, Vol. 174, No. 1, pp. 165-174.

[30] P. J. A. Lever, Fei-Yue Wang, X. Shi, D. Chen, "A fuzzy-behavior-based approach for controlling mining excavator bucket/rock interactions", *Proceedings of 1994 IEEE Industry Applications Society Annual Meeting*, Denver, CO, USA, Oct. 2-6, 1994, Vol. 3, pp. 2126-2133.

[31] LIU T., YU H., TIAN B., et al. "Intelligent command and control systems for intelligent vehicle: primary methods and systemic construction." *Journal of Command and Control*, 2018, 4(1): 22-31.

[32] Li, Li, et al. "Parallel testing of vehicle intelligence via virtual-real interaction." *Sci. Robot* 4 (2019).

[33] Huile Xu, Yi Zhang, Li Li, Weixia Li, "Cooperative driving at unsignalized intersections using tree search," https://arxiv.org/abs/1902.01024

[34] Li Li, Fei-Yue Wang, "Cooperative driving at blind crossings using intervehicle communication," *IEEE Transactions on Vehicular Technology*, vol. 55, no. 6, pp. 1712-1724, 2006.

[35] Gao, Y., Shen, Y., Zhang, W., Wang, H. et al., "Robust Path Tracking Control for Autonomous Heavy Vehicles," *SAE Technical Paper* 2018-01-1082, 2018, doi:10.4271/2018-01-1082.

[36] Gao, Y., Shen, Y., Cao, D., "Path-Following Control by Dynamic Virtual Terrain Field for Articulated Steer Vehicles" *Vehicle System Dynamics*, https://doi.org/10.1080/00423114.2019.1648837.

[37] M. Darms, C. R. Baker, P. E. Rybski, and C. Urmson, "Vehicle detection and tracking for the Urban Challenge Vehicle Detection and Trackin g for the Urban Challenge," vol. 10,no. 3, pp. 57 - 67, 2008.

[38] Yang F., Zhu Z. , Dong X., et al. "Real-time dynamic obstacle detection and tracking using 3D Lidar." *Journal of Zhejiang University (Engineering Science)*, 2012, 46(9):1565 - 1571.

[39] Ester, Martin, et al. "A density-based algorithm for discovering clusters in large spatial databases with noise." *Kdd*. Vol. 96. No. 34. 1996.

[40] S . Thrun , M . Montemerlo, and A. Aron, "Probabilistic Terrain Analysis For High-Speed Desert Driving." *Robotics: Science and Systems*. 2006.

[41] Y. Ye, L. Fu, and B. Li, "Object Detection and Tracking Using Multi - layer Laser for Autonomous Urban Driving," *ITSC, 2016 IEEE 19th International Conference on*. IEEE, 2016.

[42] Matti Lehtomäki, et al. "Object Classification and Recognition From Mobile Laser Scanning Point Clouds in a Road Environment." *IEEE Transactions on Geoscience & Remote Sensing* 54.2(2016):1226-1239.

[43] Yue Meng, Li Li, Fei-Yue Wang, Keqiang Li, Zhiheng Li, "Analysis of cooperative driving strategies for nonsignalized intersections," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 4, pp. 2900-2911, 2018.

[44] Kritayakirana, Krisada, and J. Christian Gerdes. Autonomous vehicle control at the limits of handling. *International Journal of Vehicle Autonomous Systems* 10.4 (2012): 271-296.

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