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Theory and Method of Time-varying Computational Experiments for the Fully Mechanized Mining Process in an Artificial System Environment

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ABSTRACT As mining depth gradually increases, the complex and changeable behavior state of mine production systems leads to the increasingly prominent problem of ''planning is difficult to control''. The safety production situation and the difficulty of emergency management are gradually upgraded. However, the theoretical study on the behavioral trend of complex mine production systems is still an immature field. This paper proposes the scientific problem of ''theory and method of time-varying computational experiments for fully mechanized mining processes in artificial system environments''. Taking the typical fully mechanized mining process in the Yushen mining area in northern Shaanxi, China, as the research object, through computer modeling, simulation and use of multiagent system theory, APSM (Agent Publish-Subscribe Model) coordination technology, multiagent cross-emergence and multilayer learning networks, the artificial fully mechanized mining system modeling, sequential mining process deduction and state transfer theory are systematically studied. First, an artificial system model equivalent to the function of the actual fully mechanized mining system is constructed. Then, under the artificial system environment, the time-varying computational experiments of the fully mechanized mining process are realized through the autonomous deduction of the fully mechanized mining agent based on a multilayer neural network and the emergence of multiagent interactions based on subscription perception; this approach aims to solve the problem of determining the overall behavior trend of the mine under the condition of ''long time and large space'' and to provide intellectual support and scientific basis for the ''first experiment and then produce'' technological model of intelligent mining.

INDEX TERMS Mine, fully mechanized mining process, artificial system, time-varying computational experiments.

I. INTRODUCTION

A. RESEARCH SIGNIFICANCE

The Yushen mining area is located in the middle of the Jurassic coalfield in northern Shaanxi. This area is an important energy and chemical base in China. It is approximately 23-42 km wide from north to south and 43-68 km long from east to west and has an area of 2625 km^2. Its proven reserves are 30.17 billion tons. It is one of the seven largest mining areas in the world. Coal is shallowly buried, and fully mechanized mining technology is adopted. With the increase of mining depth, the mining conditions become more and more complex, and the prediction and early warning of mine events become more difficult under the high-intensity, large-scale and fast-speed fully mechanized mining mode. The complex and changeable state of the production system

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leads to the increasingly prominent problem of ‘‘planning is difficult to control.’’ Repeated personnel safety incidents, equipment failures and task failures occur frequently. The safety production situation and the difficulty of emergency management are gradually upgraded. According to the data from January 2015 to September 2017 of a mine in northern Shaanxi province [1], in December 2015, there was a small-scale water inrush in the 31110 working face, which resulted in two people being trapped and shut down for two days; from July to October 2016, a maintenance electrician made the same mistake during two explosion-proof inspections and suffered a high-voltage electric shock, resulting in permanent loss of labor force for the last time; just from January to March 2016, the same staff-same unsafe behavior occurred 22 times; sudden failure of a belt conveyor, shearer or scraper conveyor resulted in 31 shutdowns and overhauls, with a cumulative failure time of 86 hours. ‘‘Planning is difficult to control’’ has become a key bottleneck that hinders our ‘‘intelligent mining strategy’’ [2], [3]. In fact, the main reason is that the behavior trend of personnel, equipment and the environment in the production process is difficult to grasp and predict, and it is unreasonable to formulate the production plan without considering unexpected situations. It will become an inevitable requirement of intelligent mine production technology to make a plan considering the trend of the mine's overall behavior. However, the research on mine behavior trend calculation is still a weak field, so there is a strategic need for intelligent mining to study mine behavior trend computation in depth.

‘‘Experiments of production schemes’’ will surely become the key means to cope with ‘‘making plans considering the trend of overall mine behavior.’’ However, actual production experiments on ‘‘long-term and large-space’’ physical environments have a huge cost, and they cannot be carried out [4]. ‘‘Is it possible to carry out production experiments by means of computer?’’ is the author's long-term thinking. Driven by the data of the Internet of Things, this low-cost, high-efficiency, zero-risk and fast prerehearsal method is bound to become possible, which is of great significance for assistant planning. Given the current situation and production plan of the production system, at any input time point, the computer can quickly output the behavior state of the production system at that time point (the element attribute state of personnel, equipment and environment and the entire state of economy, space and security), that is, the core scientific problem of this paper: the theory and method of time-varying computational experiments regarding the production process in an artificial system environment. Some scholars use mathematical methods, such as goal programming, to calculate the trend of production process behavior [5]. However, due to the selection of parameters, a defect of the model itself or unexpected situations, the calculation results are not necessarily economical and reasonable, often from solution to implementation of the waterfall model, which has obvious shortcomings in dynamic optimization, feedback verification and strategy preview; BIM management and 4D (4 Dimension) spatiotemporal expression of the mining process well reflect the overall behavior trend of a mine system, but they overemphasize the spatiotemporal change relationship and lack other attribute expression except spatial state. In addition, they are both ‘‘hard sequence states’’ based on planning and data, which cannot take into account the randomness, initiative and emergence of complex systems; in recent years, people have begun to solve the problem of industrial production planning and control by means of CPS (Cyber-Physical System) methods, but there is a lack of consideration of human factors [6], which fails to reflect the sociality of the mine production system; parallel system theory can better solve the problem of determining the overall behavior trend of mining process, but it is still in the exploratory stage, and there is little basic research in artificial mine system modeling and calculation experiments. The theoretical basis of time-varying computational experiments regarding the mine behavior trend in this project has not yet been addressed and needs to be further studied.

From the perspective of national demand for mining production, with the increase of mining depth, the mine production environment becomes more complex and changeable, and it is more difficult to separate and restore in physics, which leads to the substantial cost of production scheme tests. Without previrtual experiments, the bottleneck problem of the abovementioned ‘‘plan is difficult to control’’ will not be solved for a long time. The experimental method of time-varying computational experiments will lay the foundation for the production process mode of ‘‘first experiment and then produce’’ and will become the basic guarantee of intelligent mining in the new era. From the perspective of discipline development, the experimental research of time-varying computational experiments of the mine production process is relatively lagging behind, and the research work and data are scarce. The theoretical basis for determining the overall behavior trend of the mine production process under a complex system environment is imminent. However, thus far, the basic principles and methods of artificial mine production system modeling, cross-emergence, sequential deduction and time-varying calculation are not clear. It has become one of the bottlenecks in the development of mining system science in the new era. Research on time-varying computational experiment theory and methods of the mine production process can deepen the understanding of a complex mine system and lay a foundation for determining the overall behavior of the production system.

B. CURRENT RESEARCH SITUATION OF MINE TIME-VARYING COMPUTATIONAL EXPERIMENTS

Thus far, no scholars have explicitly proposed the theory and method of time-varying calculation experiments for a fully mechanized mining system. However, in recent years, some studies have similarities or promote the development of this theory, which gradually makes its concept clear. Other research results are the basic conditions or important

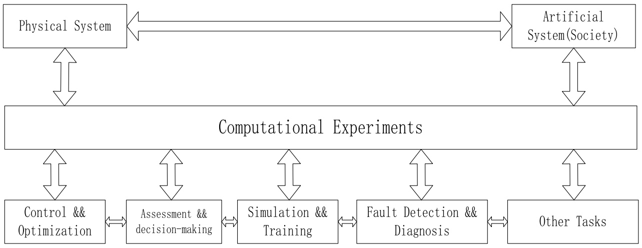

FIGURE 1. ACP framework (Wang Feiyue, 2004).

guarantee for the realization of this method. The following aspects are discussed:

First, BIM (Building Information Model) management of a mining process and its 4D space-time expression were proposed, which became the ideological basis of time-varying computational experiments for mine production. Some scholars put forward the BIM mine [7]. In view of the mine production process, a three-dimensional visualization model management concept based on a lifecycle process is emphasized. Other scholars have studied the 4D spatiotemporal concept of the mining production process [8], [9]. Using four-dimensional space coding and spatial database storage technology, a four-dimensional data model for mining development is proposed, which realizes the 4D spatiotemporal dynamic simulation of the mining production process and assists in the formulation and implementation of optimization schemes. These concepts and ideas actually take into account the time change problem. If we abstract it further, aiming to master the overall behavior and trend of the mine production system, it will be sublimated into the time-varying computational experiment proposed by this paper.

Second, parallel system theory has developed to a certain extent, which provides basic support and a feasible method for time-varying computational experiment theory. Some scholars have proposed parallel system methods to solve complex system management and control, namely, artificial society - computational experiments - the parallel execution method [10]–[12], as shown in Figure 1.

This method, also known as ACP (Artificial systems, computational experiments, parallel execution) theory, combines data analysis, mechanism research and virtual reality methods and technologies to construct an artificial system equivalent to the actual system. By using the autonomy and randomness of simple entities, through the collaborative promotion, interactive crossover and emergence observation of simple objects, zero-harm, low-cost and high-speed management strategies, production processes and control steps can be achieved. The artificial system and the actual system are implemented in parallel through perception and communication control, synchronizing or interfering with the actual system. After the parallel method was put forward, basic research has been widely applied [12]–[18] in the fields of transportation, water conservancy, agriculture, chemical process control and emergency management. However, this method is still in its initial stage of development, and its effectiveness and practicability must be further tested.

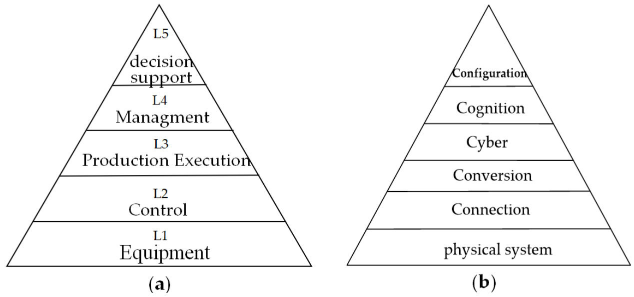

FIGURE 2. (a) Digital mine integrated technology architecture (b) CPS technology architecture.

Time-varying computational experiments can be carried out on the basis of the ACP system, using collaborative propulsion and multiagent emergence interaction, to implement the computational experiments based on an artificial mine production system.

Finally, the CPS architecture under the background of intelligent mine and industry 4.0 has become a hot topic in recent years. It provides a large amount of heterogeneous multisource data for the time-varying computational experiments of the fully mechanized mining process and can be used as the data-driven basis and platform framework of time-varying computational experiments. Since the concepts of ‘‘mining system engineering’’ and ‘‘digital mine’’ were put forward, the theory and technology based on software engineering, visualization technology, automation technology and system science have promoted the rapid development of mining efficiency, safety, greenness and sustainability [28], [37].

In 2012, scholars proposed use of the Internet of Things to ensure mine safety and intelligent mining. Intelligent mining has become a hot issue in the field of Digital Mine Research [28], [30]. In recent years, the five-tier technology architecture model shown in Figure 2 (a) has gradually been accepted by most experts and scholars [38], [40]. From bottom to top, there is the equipment layer, control layer, production execution layer, management layer and decision support layer. The lower layer is the foundation of the upper layer, providing the information and data needed by the upper layer. On this basis, the intelligent mine has been put forward and has good development in applied basic research [40].

At the same time, the theory and framework system of intelligent control at home and abroad have developed rapidly [41]–[46], which has brought new ideas and approaches to the research of mining system engineering and the intelligent mine field and has become a hot issue in the field of intelligent mining production. In 2006, the US NSF (National Science Foundation) proposed the Cyber-Physical System (CPS). The physical device is connected to the Internet, and the physical device has the functions of calculation, communication, precise control, remote coordination and self-management. The virtual network world and real physics will achieve deep integration, as shown in Figure 2(b). Similarly, in November 2012, GE (General Electric Company) proposed the "Industrial Internet"; in 2013, the German government and industry proposed "Industry 4.0"; in March 2015, the Chinese government proposed the "Internet +" action plan, and in May the same year, it proposed the "Made-in-China 2025 Programme of Action." Such systems and frameworks are still in the theoretical and exploratory phase, and there is no integrated solution for standardization systems and applications.

C. PROBLEMS TO BE SOLVED URGENTLY AND RESEARCH IDEAS

In summary, scholars have conducted some work in the determination of the overall behavior trend or time-varying computation of mines and have made some progress and achievements. However, there are still many weaknesses in the theoretical system research on the determination of the overall behavior trend of the long-term and large-space physical system, mainly in the following aspects:

(1) The traditional mathematical methods, such as goal programming and dynamic programming, are not necessarily acceptable because of the selection of parameters, the defect of the planning model itself or the unexpected situations. In addition, these methods are often from one solution to one execution of the waterfall model and need to be improved in dynamic optimization, iteration verification and strategy preview.

(2) BIM management and 4D space-time expression of the mining process overemphasize the spatial change relation of time series and lack other attribute expressions except spatial state. In addition, both of them are "hard sequence states" based on historical and mathematical programming. They are difficult to deduce and cross-emerge independently and cannot take into account the randomness and initiative of complex systems.

(3) Industry 4.0 and CPS technology can determine the overall behavior trend of physical systems and solve the planning and control problems of the coal industry to a certain extent by means of industrial modeling. However, the current CPS systems and methods lack the consideration of human factors to a certain extent and fail to reflect the sociality of the fully mechanized mining system in mines, which needs to be further supplemented and improved.

(4) Parallel theory can better solve the problem of determining the overall behavior of the mining process and then solve the problem of precise "plan-control." However, this theoretical system is still in the exploratory stage, especially in the field of parallel production in mines; there is little basic research, and it is urgent for academic circles to carry out systematic and in-depth research on artificial system modeling, computational experiment methods and parallel execution technology.

The research group considers the key to overcome the above shortcomings to be the "virtual experiment of the production process with time as a dependent variable". Traditionally, when evaluating the pros and cons of a scheme, postmortem analysis or prior experimental evaluation are often required, while postevent analysis is only a summary of experience and cannot change the established facts. Therefore, pre-experimental evaluation is the key. Experiments on real physical systems are unbearable because 1) real physical systems operate over a long time and a large space, and the experimental efficiency is low, which 2) may cause loss of life, equipment and property, and the experimental cost is enormous. Therefore, the computational experiment method based on an artificial system has obvious advantages. Because the scheme experiment is carried out on the artificial system in computers, its low cost, zero risk and rapid pre-estimation means are of great significance to assistant production. In view of this, the purpose of this paper is to clarify the scientific problem: "time-varying computational experiment theory and method for the fully mechanized mining process in an artificial system environment," which will bring new ideas and references for complex system simulation and symmetry management in the field of mining intelligent production. The following is an introduction to the theory and method.

The innovation of this paper is as follows:

(1) The model of an artificial fully mechanized mining system and its construction method are proposed, which are virtual reconstruction and a logical copy of an actual mine production system.

(2) A simple, consistent and in-depth learning network-based artificial agent autonomous deduction method for state transition is proposed.

(3) The theoretical basis of time-varying computational experiments of the fully mechanized mining process under an artificial system environment is clarified.

II. RELEVANT DEFINITIONS AND BASIC IDEAS

Definition 1 (Artificial System Model): The theory of complex systems, intelligent science, modeling and simulation are used to model the actual fully mechanized mining system and realize an ideal computer simulation system similar to and parallel with the actual system. The object represented by this system includes the personnel, equipment and mine environment in the scenario space of fully mechanized mining. It is a virtual reconstruction and logical copy of a physical fully mechanized mining system.

Definition 2 (Time-Varying Computational Experiment): Compute the main elements' attributes and the key production indicators' states (including spatial state, health state and overall economic state) of the fully mechanized mining system at a certain time.

Definition 3 (Time-Varying Computational Experiments for the Fully Mechanized Mining Process in an Artificial System Environment): Taking the artificial fully mechanized mining system as the experimental environment, input the given initial state and the mining plan and then carry out the time-varying computational experiment, deducing the fully mechanized mining process and outputting the experimental results.

Basic Ideas: First, the main elements of the corresponding fully mechanized mining process are analyzed and mapped to simple agents, the relevant coordination content are determined, and the model of the artificial fully mechanized mining system based on a multiagent system is established; based on this artificial model, the time-varying computational experiment of the fully mechanized mining process is carried out, and the time-varying computation is divided into three situations: past, present and future. For the past and present, the results can be obtained directly through inquiry and comprehensive analysis. For the future, sequential deduction and the cross-emergence method are used. Based on the basic idea of simple consistency and cross-emergence, the artificial system is used as the carrier, and the sequential method is used. Starting from a single simple agent (element), considering the autonomy and randomness of each agent, and combining with the attributes of other related agents, the multilayer neural network is used to realize the state transition of a single agent. After the deduction, the attributes of each agent are the attributes of the key elements of the corresponding mine's comprehensive mining system. The overall spatial state and attribute state of the mine production system can be obtained by comprehensive statistical analysis of each agent state.

III. ARTIFICIAL SYSTEM MODEL

Basic Ideas: First, the key elements affecting the overall behavior of the fully mechanized mining process are extracted and abstracted as simple elements, including personnel (coal locomotive driver, support worker and belt conveyor driver), equipment (shearer, scraper conveyor, transporter, crusher, belt conveyor and hydraulic support) and environment (working face, roof, floor, shaft and roadway). Then, with the aid of multiagent theory and the APSM (Agent Publish-Subscribe Model) coordination model, the model of the artificial fully mechanized mining system is constructed as a logical copy of the real mine production system to a certain extent, which is the basic preparation for the time-varying computational experiment of the follow-up fully mechanized mining process.

To be clear, an agent in the computer field is an authorized "Personal Software Assistant." It is an active autonomous program object, often referred to as an agent. The key of an agent is to have autonomy. Once activated, the agent is a life subject, as a member of the entire system to complete its mission. Different from the traditional mathematical programming method, this paper adopts the multiagent method, which fully considers the autonomy, randomness and interaction of each element in the process of fully mechanized mining to construct the artificial system.

A. EXTRACTION OF KEY ELEMENTS AND SIMPLE AGENT MAPPING

Specifically, the simple elements are {coal machine driver}, {support worker}, {coal machine, left drum, right drum}, {support}, scraper conveyor, transporter, crusher, belt conveyor, roof, floor, working face and goaf, and the main attributes and characteristics of each element are analyzed. Mapping to simple agents one by one, the perceptual parameters and state transition equation of each agent are determined separately; the coordination model among agents is determined; at the same time, to ensure the complete operation of multiagent system, two agents are needed, namely, a visual interactive agent and data agent, which are responsible for user interaction and data acquisition/storage, respectively. Each simple agent is shown in Table 1.

B. APSM COORDINATION MODEL

Based on the simple elements and their behavior characteristics of the abovementioned artificial fully mechanized mining system, the coordination scheme between agents is a further problem to be solved. The coordination and decoupling problem of multiagent systems has been a hot topic for experts and scholars. Organizational structure negotiation, commitment-agreement coordination, result sharing models and contract network models have been proposed successively. These coordination models play an important role in multiagent systems in the fields of artificial intelligence and distributed processing.

However, in the face of the modeling of some industrial control systems, real-time monitoring systems and emergency command systems, the complex coordination media, semantics and primitive models of traditional coordination models are clumsy and lagging in system implementation, scalability and performance. In 2015, the author proposed a new coordination model, the Agent-based Publish-Subscribe Model (APSM) [4], which focuses on the modeling of parallel emergency management artificial systems. The coordination model itself is an agent system, which is based on the principle of system decoupling, centered on the scalable cooperation between agents, and aimed at programming. This model defines the subscription dependency relationship between agents. Many subscription agents monitor a topic agent. When the status changes, the subject agent publishes the information to all subscription agents so that the subscription agent can grasp the knowledge and update its status in time. Therefore, it can be ideally applied to the Multi-Agent Coordination Scheme of the artificial fully mechanized mining system studied in this project.

Define 4 (The Agent Publish-Subscribe Model (APSM)): The Agent Publish-Subscribe Model consists of the coordination semantics, publishing agent, service agent and subscription agent, which are expressed as follows:

$$APSM = C(P.A, Serv.A, S.A) \tag{1}$$

Among them, C: the coordination semantics, which specify the communication semantics between P.A, Serv.A and S.A; P.A - Publishing Agent, the producer of data; S.A: the subscribing agent, i.e., data business processing consumer; Serv.A: the service agent, i.e., middleware between P.A and S.A, which can receive publishing information from P.A and send to S.A what it is interested in. P.A, Serv.A and S.A have a quantitative relationship of n-1-n, that is, there may

TABLE 1. Characteristics of simple agent behavior in an artificial mining system.

ID	agent name	classification	role description	Perception (or Input) Characteristics	Behavior (or Output) Characteristics	count
01	Coal machine driver	personnel	coal machine operator	health status, proficiency, safety awareness, environmental status	Control Characteristic of Coal Machine	2
02	support worker	personnel	scraper pushing, pulling frame and bracket rectification	Health status, proficiency, safety awareness, environmental status	Control Characteristics of Scraper and Bracket	4-6
03	coal machine	equipment	driving drum to cut coal	dynamic performance, control characteristics, environmental conditions	driving performance and control characteristics of drum	1
04	left drum of coal machine	equipment	coal cutting	driving performance and control characteristics of drum	coal cutting speed	1
05	right drum of coal machine	equipment	coal cutting	driving performance and control characteristics of drum	coal cutting speed	1
06	hydraulic support	equipment	roof support	support performance and control characteristics	moving frame and supporting performance	l / l_0
07	Scraper conveyor	equipment	coal conveying in mining face	Scraper performance, control characteristics and environment	pushing and conveying speed	1
08	reloading machines	equipment	transfer to crusher	reloader performance, reproduction velocity, environmental conditions	reload volume	1
09	crusher	equipment	breaks large coals	crusher performance, crushing speed, environmental conditions	crushing capacity	1
10	belt conveyor	equipment	transport coal to the ground	transport belt performance and transport speed	traffic volume	1
11	roof	equipment	roof of mining face			1
12	floor	environment	Floor of mining face	geographical location, time and geological survey data	geological condition, water output, coal dust and gas emission	1
13	mining face	environment	mining face			1
14	mined out area	environment	mined out area			1
15	3DUI agent	auxiliary	User interaction and visual simulation	status of agents and user input	virtual reconstruction and matching to agents	1
16	data agent	auxiliary	storage and query of data	agent status (storage) and agent requirements (query)	persistent storage or data query	1

be multiple publishers and subscribers in the system but only one service agent, as shown in Figure 3.

In fact, the publishing agent may also appear as a subscription agent at the same time. Similarly, the subscription agent needs to publish messages at the same time. Therefore, the above subscription model can be abstracted as follows:

$$APSM = C(P.A, Serv.A) \tag{2}$$

Among them, P.S.A. is an agent with both publishing and subscribing functions.

The specific working principle and relevant rules were detailed in Zhidong Feng's doctoral dissertation "Research on Parallel Emergency Management of Mine Water Inrush" in 2015.

C. COORDINATION RELATION AND CONTENT OF AN ARTIFICIAL FULLY MECHANIZED MINING SYSTEM

Determine the coordination relationship and content between these agents, that is, determine who coordinates with whom and what. As shown in Figure 4, the framework can be divided into three types of agent layers as a whole: the three-dimensional interactive agent layer (3D UI), business agent layer and data agent layer (Data Agent), in which the business logic layer is composed of the personnel layer, device layer and environment layer. Specifically, it consists of 16 core agents, including the coal engine, support worker, coal machine driver, left drum, right drum, scraper conveyor, loader, crusher, belt conveyor, support, mining face, goaf, roof and floor, as well as the three-dimensional interactive agent and data agent.

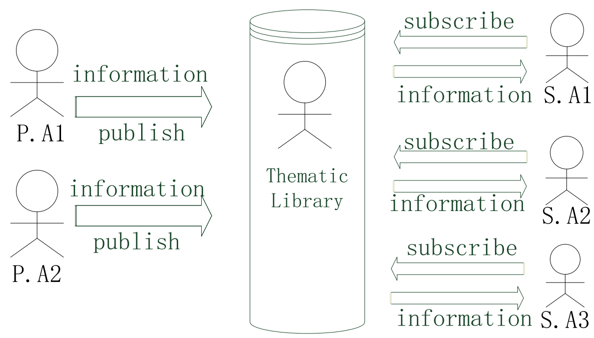

FIGURE 3. Agent publish-subscribe model structural diagram.

The principle of subscription between agents is "subscribe to the upper level and active service", that is, the lower-level agent provides services for the upper-level agent, the lower-level agent subscribes to the state and instructions of the upper-level agent, and the lower-level agent reacts actively and executes independently according to the information of the pushed state and instructions.

Each agent coordinates and communicates with each other through the above APSM. In the process of evolution, the agent needs to subscribe to relevant information as its own

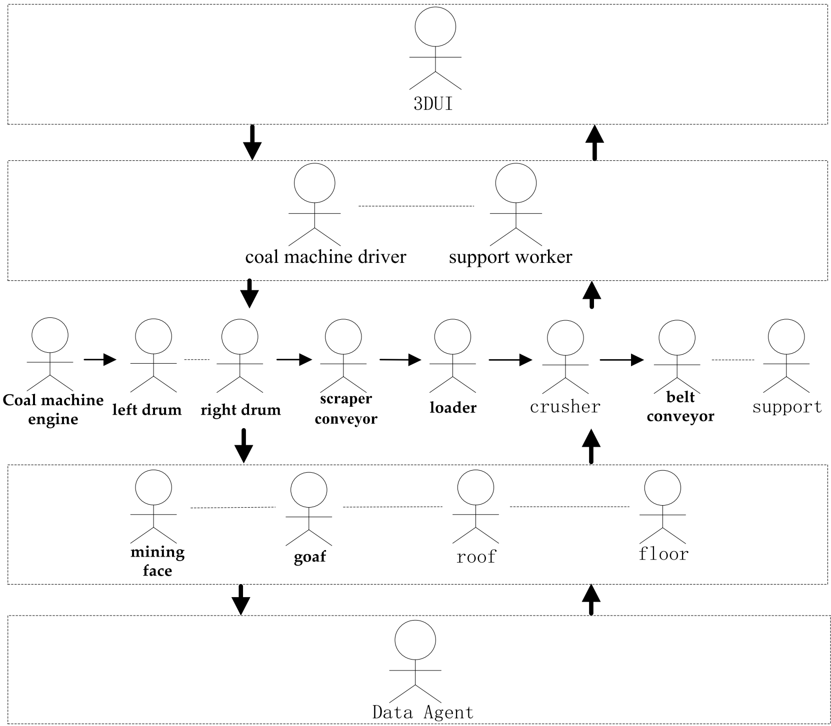

FIGURE 4. Multiagent model of fully mechanized mining system.

evolution reference and publish its own status information for other agents to subscribe to. In the comprehensive mining system of artificial mines, the service information issued by each agent is as follows:

1 Coal machine driver: 1.a position; 1.b business technical characteristics; 1.c operation characteristics; 1.d health characteristics

2 Support worker: 2.a position; 2.b business technical characteristics; 2.c operation characteristics; 2.d health characteristics

3 Coal machine engine: 3.a driving force; 3.b control direction; 3.c health characteristics

4 Left shearer drum: 4.a moving speed; 4.b moving direction; 4.c health characteristics

5 Right shearer drum: 5.a moving speed; 5.b moving direction; 4.c health characteristics

6 Support: 6.a support performance characteristics; 6.b shift status; 6.c health characteristics

7 Scraper conveyor: 7.a convenience state; 7.b running speed; 7.c health characteristics

8 Loader: 8.a reproducing speed; 8.b reproducing capacity; 8.c health characteristics

9 Crusher: 9.a crushing speed; 9.b crushing volume; 9.c health characteristics

10 Belt conveyor: 10.a belt speed; 10.b transport speed (volume); 10.c health characteristics

11 Roofs: 11.a geological characteristics; 11.b outflow velocity (quantity); 11.c outflow velocity of coal dust and gas (quantity)

12 Floor:12.a geologic characteristics; 12.b effluent velocity (quantity); 12.c coal dust and gas emission velocity (quantity)

13 Mining face: 13.a geological characteristics; 13.b outflow velocity (quantity); 13.c outflow velocity of coal dust and gas (quantity)

14 Goaf:14.a geologic characteristics; 14.b water flow rate (quantity); 14.c coal dust and gas emission rate (quantity)

15 3D UI Agent:15.a virtual reconstruction; 15.b user instructions

16 Data Agent: 16.a persistent storage; 16.b integrated sensing (environment) data

According to the concept of "subscribe to the upper level and active service," the subscription among agents is shown in Table 2.

At this point, the construction of the artificial fully mechanized mining system is completed. It needs to be pointed out that the services listed above are only visible to the outside of each agent, while its internal functions, such as optimal path calculation, need not be published, and only the real-time information in the evolution process, such as the location of personnel, health status and so on, is released.

IV. TIME-VARYING COMPUTATIONAL EXPERIMENT BASED ON THE ARTIFICIAL MINING SYSTEM

A. KEY INDICATORS OF THE TIME-VARYING COMPUTATIONAL EXPERIMENT

Time-varying computation of the mine production system not only computes component elements in the system but

TABLE 2. Service subscription table of the artificial fully mechanized mining system.

Agent ID	Status ID of subscription	Agent ID	Status ID of subscription
1	15.b, 16.b, 16.b	9	8.a, 8.b, 16.b, 10.a
2	15.b, 16.b, 16.b	10	9.a, 9.b, 16.b
3	1.b, 1.c, 1.d, 16.b, 7.b	11	4.a, 4.b, 5.a, 5.b
4	3.a, 3.b, 3.c, 16.b	12	4.a, 4.b, 5.a, 5.b
5	3.a, 3.b, 3.c, 16.b	13	4.a, 4.b, 5.a, 5.b
6	2.b, 2.c, 2.d, 16.b	14	4.a, 4.b, 5.a, 5.b
7	2.b, 2.c, 2.d, 4.a, 4.b, 5.a,5.b,16.b	15	-
8	7.b, 16.b	16	15.a

also calculates overall behavior state. As mentioned above, the key to time-varying computation of the mine production system is to deduce and predict the following six indicators changing with time. The main elements are: 1) personnel status (recorded as o); 2) equipment status (recorded as p) 3) environmental status (recorded as q); and overall behavior: 1) economic rationality(recorded as u; 2) the controllability of the actual execution process and results (recorded as v); 3) the degree of loss of life, equipment and property (recorded as w). Then, the deductive computation can be formalized as follows:

$$Info(\{\{(o_i)|i=1,2,\ldots,m\},\quad \{(p_j)|j=1,2,\ldots,n\}, \{(q_k)|k=1,2,\ldots,l\},u,v,w\})=f(init,s,t) \quad (3)$$

The input parameters are "init" of the initial state of the mine production system, "s" of the plan scheme and "t" of the actual time point, and the return results are a set of values: the information set of the main elements (i = 1,2,..., m, where m is the total number of personnel; j = 1,2,..., n, where n is the total number of pieces of equipment; and k = 1,2,..., l, where l is the total number of environments) and the key production indicators u, v, w.

B. BASIC THOUGHT OF THE TIME-VARYING COMPUTATIONAL EXPERIMENT

The time-varying computation in this paper includes the computation of past, present and future states. The past and present can be directly obtained through queries and comprehensive analysis. This is not elaborated here. The future time-varying computation mainly relies on the sequential deduction and cross-inrush method based on intelligent agents. The fully mechanized mining system is a complex system. It is precisely because of its complexity that people often have different opinions on its calculated overall behavior. The "simple consistency principle" provides a feasible method for the calculation experiment of the complex system. According to the basic viewpoint of "people agree on the behavior of simple things," the time-varying computation for the future state can be realized by making full use of the initiative, randomness and cross-emergence characteristics of simple agents themselves.

Specifically, the behavior state of the fully mechanized mining system is continuous in time, and computer science is a discrete science, so the computational experiment process of the artificial mining system running on the computer is discrete. Based on this, the entire deduction process can be divided into stages according to a certain time granularity, and the basic units are simple agents. At the beginning of the state transition, the subscription information of each agent is regarded as its own perceptual input to realize the cross-emergence so that the transition can be deduced step by step until the end of all stages. After the deduction is completed, each agent state is the element state of the fully mechanized mining system, and the comprehensive analysis of each agent is the overall behavior state of the system. At the same time, according to the basic content of the above time-varying computation, the above six indicators are analyzed one by one.

C. SPECIFIC STEPS OF THE TIME-VARYING COMPUTATIONAL EXPERIMENTS

Step 1 (Time series discretization Unified Time Granularity Stage Division): As shown in Figure 5, the future given time period can be divided according to a certain time granularity. Three-dimensional interactive layer input time granularity, termination time, planning scheme (feed mode, coal cutting route, speed, total propulsion, scraper speed and belt speed, etc.) and initial state information. The model automatically divides all agent behavior into uniform time stages according to a sequential method or dynamic programming. These stages follow the Markov property. The entire computation process will be a local agent deduction process in the dynamic sequential environment.

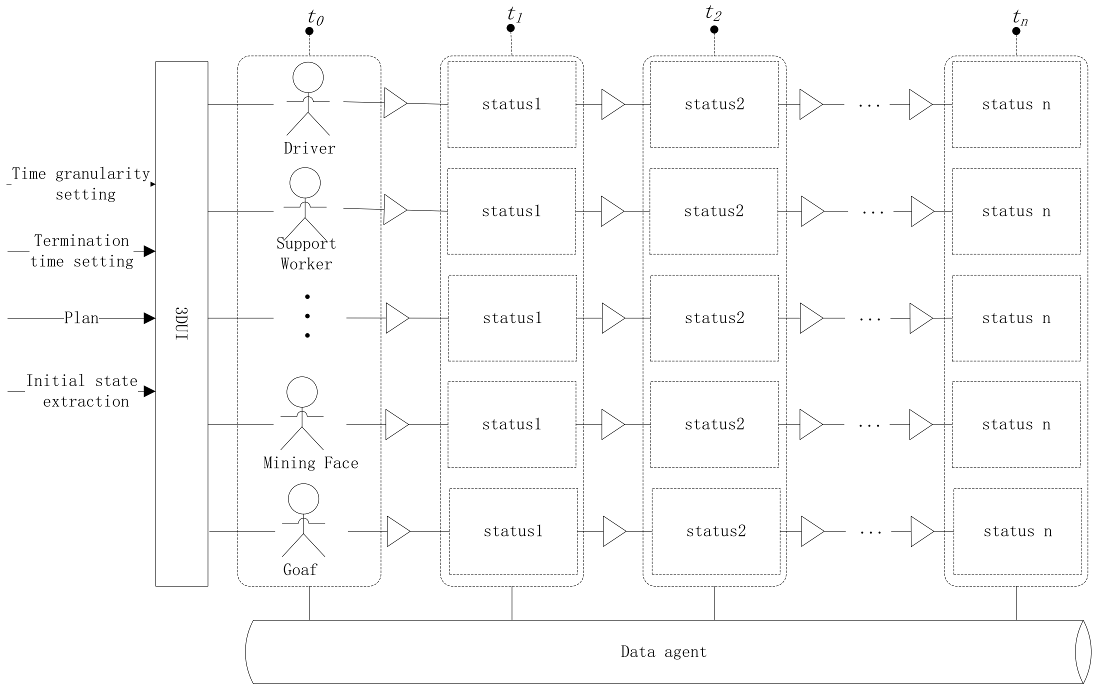

FIGURE 5. Time-varying computational time series discretization deduction model.

Step 2 (Subscription Sensing and Local Agent Initialization): Each simple agent initializes its own state information, which is, on the one hand, the environmental information obtained from the data agent (self-health information, gas, temperature and humidity, geology, etc.) and, on the other hand, from other relevant agent status information subscribed to by the agent, for example, the scraper conveyor agent can obtain the transfer speed information of the transfer agent, thereby reporting the abnormal status. This type of subscription awareness is the basic guarantee for cross-emergence.

Step 3 (Intelligent Agent State Transition Based on Multilayer Neural Network Learning): The action plan of each agent is determined by its own agent information, subscription agent information, environment status, subscription information and time information:

$$result = action(a_1, a_2, e, t) \tag{4}$$

Among them, result - state transfer result; action - behavior; a_1- agent itself state information; a_2- subscription agent status information; e - environmental information; t - time period;

Based on this, according to the actual elements of the fully mechanized mining system, 500 milliseconds can be specified as a fixed time granularity, and a time-varying data set is formed according to actual historical data:

{agent's own state, environment state, other agent's status of the subscription => new agent's own status}

For example, 14 types of fully mechanized mining agents form 14 data sets of the above form according to their respective characteristics and historical running trajectories. The sample data set formed by the coal machine driver agent is shown in Table 3:

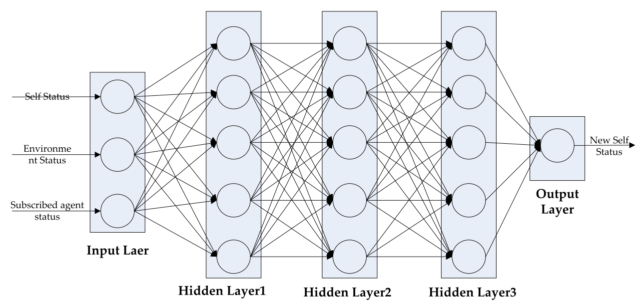

FIGURE 6. Schematic diagram of a simple intelligent agent state transition multilayer neural network.

According to the multilayer neural network training state transition model as shown in Figure 6, the model is used to predict the new agent's own state.

Select sigmoid as the activation function:

$$\sigma(x) = \frac{1}{1+e^{-x}} \tag{5}$$

Select cross entropy as the loss function for network training:

$$\begin{aligned} Loss &= H_{y'}(y) \\ &= -\frac{1}{\mathrm{n}} \sum_i \left[y_i' \ln(y_i) + (1-y_i') \ln(1-y_i) \right] \end{aligned} \tag{6}$$

TABLE 3. Sample of coal machine driver training data set.

ID	PosX	PosY	...	Health	CO	O2	NextX	NextY	...	NHealth
101	112	223	...	0.80	20	18.2	111	224	...	0.80
101	118	226	...	0.82	19	18.5	117	228	...	0.83
...										
109	120	238	...	0.81	19	18.6	118	240	...	0.82

where y' is the actual tag value and y is the predicted output value of the simple fully mechanized agent depth network:

$$y = \sigma(\sum_j w_j x_j + b) \tag{7}$$

Here, x_j are the input parameters (self information, subscription perception, environmental status, etc.) of the comprehensive mining agent, w_j are the corresponding weights, and b is the offset.

It should be noted that, when the lost rate of the model is large, the next time state can be calculated directly according to the simple rule. For example, the next position information of the drum agent can be directly calculated according to the moving direction and speed using a simple formula.

Step 4 (Result Output and Overall Behavior Analysis): After the computation is completed, according to the simple agent itself and the abnormal status report, the key indicators of the fully mechanized mining system can be comprehensively calculated by simple methods, such as arithmetic summation.

D. RULE EXPLANATION OF THE TIME-VARYING COMPUTATIONAL EXPERIMENT

Rule 1: In this calculation model, the number of agents is not unique, e.g., the coal machine driver agent, support worker agent, etc. may have multiple instances.

Rule 2: Before calculation, the user first sets parameters, including time granularity, termination time, plan scheme and initial state of the system, extracts key data by means of data agent (which can be configured to the Internet of Things acquisition interface in a CPS platform or to a historical database), and combines them with manual confirmation; this work is undertaken by a visual agent and the UI of the cognitive layer.

Rule 3: After receiving the instructions for setting and calculating parameters, the cognitive agent first gives the parameters to the agents, including the coal locomotive driver agent, bracketer agent, coal machine agent, support worker agent and mining surface agent. After receiving the ready state (subscription information) of the agents, the agents are ordered to deduce.

Rule 4: Agents cooperate with each other in the deduction process. This collaboration relies on the agent subscription publishing model, APSM, proposed by this project. Simple elements subscribe forward in the direction of the fully mechanized mining work flow to reflect the abnormal state in the deduction process. For example, a ''loader agent'' subscribes to the speed information of the front element ''scraper conveyor'' in its work flow direction. When the loader agent finds that the speed of the scraper conveyor is lower than its own speed, it will enter an abnormal state and push its own status information to all agents in its subscription list. Command each agent to deduce.

Rule 5: Each simple agent makes full use of its interaction and randomness to evolve independently according to its own nature, subscription information and time cycle described in formula (4). In Figure 5, $t_0, t_1, t_2, \ldots, t_n$ can be simplified to take unit time T as a computation period. When a period is computed, the agents are in state T, and then they continue to evolve to 2T, 3T and other states with state T as the initial condition until the termination time. In the process of deduction, some agents have fast computing speed, and some other agents have slow computing speed. To ensure time synchronization, each agent needs to wait for all other agents to complete the computation before entering the next computation cycle.

Rule 6: Each agent subscribes to the data storage service of the data agent, and after each computing cycle, the data agent stores the state. The three-dimensional interactive agent subscribes to the status information of each agent. Whenever there is a new state, it immediately performs three-dimensional rendering to achieve visual expression.

Rule 7: The output of this experiment is the status of each agent after the end of each computing cycle. The status covers the identity information, time information, spatial information and attribute information of each agent. The status information is stored persistently by the data agent.

Rule 8: Time granularity determines the fineness of the evolution process. The smaller the granularity is, the finer the computation process is, but the slower the speed is.

Rule 9: The computational experiment results are mainly composed of two parts: the state information of each component of the system and the comprehensive state information of the entire system.

After the computational deduction experiment, the state of each agent is the component information of its corresponding role (including personnel, equipment and environment). By comprehensively analyzing the agents after these

TABLE 4. Simple case of a time-varying computational experiment.

AgentID	0 min	10 min	20 min	30 min
1 coal machine driver	[(0,0),10]	[(0.1,0),9.9]	[(0.2,0),9.8]	[(0.3,0),9.7]
2 support worker	[(0,-1),10]	[(0.1,-1),9.9]	[(0.1,-1),9.8]	[(0.1,-1),9.7]
3 coal machine engine	[(0,0),10]	[(0.1,0),9.99]	[(0.2,0),9.98]	[(0.3,0),9.97]
4 left shearer drum	[(-1,0),10,0]	[(-0.9,0),9.99,50]	[(-0.8,0),9.98,100]	[(-0.7,0),9.97,150]
5 right shearer drum	[(0,1),10,0]	[(0.1,0),9.99,50]	[(0.2,0),9.98,100]	[(0.3,0),9.97,150]
6 support	[(0,-1),10]	[(0.1,-1),10]	[(0.2,-1),10]	[(0.3,-1),10]
7 scraper conveyor	[(0,0),10]	[(0,0),9.99]	[(0,0),9.98]	[(0,0),9.97]
8 loader	[(-2,0),10]	[(-2,0),9.99]	[(-2,0),9.98]	[(-2,0),9.97]
9 crusher	[(-3,0),10,0]	[(-3,0),9.99,80]	[(-3,0),9.98,160]	[(-3,0),9.97,240]
10 belt conveyor	[(-4,0),5.2,0]	[(-4,0),5.1,100]	[(-4,0),5.0,200]	[(-4,0),4.9,300]
11 roofs	[(0,0),10]	[(0,0),10]	[(0,0),10]	[(0,0),10]
12 work face	[(0,0),10]	[(0,0),10]	[(0,0),10]	[(0,0),10]

experiments, the overall economic indicators, the loss of personnel life and property, are obtained. The visual agent directly reflects the spatial state of the entire production system. The spatial relationship can be obtained through spatial analysis (Boolean operation, collision detection and block modeling) to achieve the purpose of time, space and attribute evolution.

V. EXPERIMENTAL EXAMPLE OF TIME-VARYING COMPUTATION FOR THE FULLY MECHANIZED MINING PROCESS

An example is given to illustrate the concrete process of a time-varying computational experiment. To simplify the problem, this example uses a simple state transition. Each agent can reduce the information subscription to other agents as much as possible. It does not consider the randomness of personnel agency and the burst of environmental information. The basic information of each agent includes:

$$\text{ag\_inf} = \{(\text{location}), \text{health}, [\text{production}], [\text{other}]\} \quad (8)$$

The information in "[ ]" is optional. The purpose of time-varying computation is to compute the above proxy information at the next time point. There are three key elements of time-varying computational experiments: current information, work plan and state transition equation:

$$ag\_\inf_{i+1} = f(ag\_\inf o_i, wp_i) \quad (9)$$

Table 4 briefly describes the 30-minute time-varying calculation experiment of the fully mechanized mining process, with the time granularity of 10 minutes. For a coal machine driver agent, its initial state is [(0,0),10], location is (0,0), and health is 10. Assuming that the plan is to cut coal in the right direction, the state transition of the position can be simply defined as $(x_{i+1}, y_{i+1}) = (x_i + 0.1, y_i)$, so the next position is (0.1,0). The state transition of health information can be simply defined as $h_{i+1} = h_i - 0.1$, so the next health value can be calculated as 0.99. That is, the information of the driver's agent of the coal machine in 10 minutes is [(0.1,0),9.9]. The calculation process of other agents is similar.

The last column in the table indicates all of the proxy information after calculation, that is, the state information of the components of the system. Now, through this agent information, we can synthetically analyze the entire state information of the system and the related hidden danger information:

(1) The health information of personnel and equipment is good, mostly above 9, but the belt conveyor has dropped to 4.9. If health information is required to be above 5, the belt conveyor is not enough to produce for 30 minutes and needs to be repaired first.

(2) According to the given coal cutting plan, the coal cutting output of the left and right drums reaches 300, while the crusher's crushing capacity is 240, which indicates that the coal cutting plan is too fast and needs to reduce the speed or increase the crushing capacity of the crusher.

(3) It can be seen that the overall system output is 240 in 30 minutes. Similar information, such as equipment loss and safety risk, can also be analyzed. Because there are many factors involved, this is not elaborated here.

VI. CONCLUSION AND PROSPECTS

Facing the production mode of "model-experiment-execution", this paper proposes, for the first time, the scientific problem of the time-varying computational experiment theory and method of the mine production process under an artificial system environment. This paper takes simulation drilling, interactive emergence and production cultivation as the basic methods, fully considers human factors and emergencies, and provides zero risk, low cost, high efficiency and rapidity for the mine production process. Repeated tests can solve the problem of rapid determination of the overall behavior and trend of the fully mechanized mining process under the condition of ''long time and large space'', which provides a new theoretical reference for the analysis of the complex production system, symmetry management, prediction, early warning and simulation drilling of the mine. This theoretical reference yields great scientific value with distinct characteristics.

The purpose of this paper is to discuss the theory and method of time-varying computational experiments. The main contents of this paper are:

(1) Model of the artificial fully mechanized mining system. Constructing the model of the artificial fully mechanized mining system as a logical copy of the real mine production system to a certain extent.

(2) Time-varying analysis and calculation of the fully mechanized mining process under an artificial system environment. Calculating the main elements and key production indicators of the fully mechanized mining system at a certain time.

Driven by the data of the Internet of Things, this low-cost, high-efficiency, zero-risk and fast prerehearsal method is likely to become possible, which is of great significance for assistant planning.

Because the authors' energy and ability are limited, we welcome our colleagues to study and develop the simulation software system of time-varying computational experiments for the fully mechanized mining process based on the above theory and method, combined with the actual mine production system, facing the comprehensive automation mine production process. The basic ideas of the software system are as follows:

(1) Design the model of the artificial mine system, including the use case model, domain agent model and agent association model, time series model, component model and deployment model;

(2) Construct a distributed multiagent system of the fully mechanized mining system by means of multiagent modeling tools (such as JADE4.0, Java Agent Development Framework);

(3) Select an integrated development language and tools (Java or C#, Hoops rendering engine, etc.) to develop the multiagent system and realize a software prototype of the fully mechanized mining system in artificial mine;

(4) Collect the relevant production data of a real mining area, form the data set of simple agent behavior of the fully mechanized mining system, integrate the Python language and TensorFlow platform to train the agent state transition model, and obtain the calculation results.

(5) Compare with the state of various elements and production indicators in historical real production processes, analyze the effectiveness of the algorithm, and make feedback improvements. It is the author's greatest hope to develop a time-varying computing experimental platform based on this theory and method by peer scholars or engineers.

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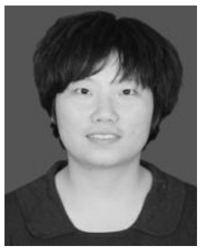

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