Multi-agent-based Modelling and Virtual Reality Simulation System of Major Accidents in Petrochemical Enterprise

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Abstract: The major accidents usually cause massive property loss and casualties in petrochemical enterprise. The simulation system of major accidents plays an important role in safety management, risk assessment, accident prevention and emergency drill and others. In this paper, the Multi-Agent block model for simulating major accidents is based on Multi-Agent technology. A method for reconstructing major accidents is proposed based on virtual reality (VR) idea. Then, a VR simulation system (VRSS) of major accidents is developed by introducing the established methodologies. Finally, the VRSS is applied to simulate the occurrence and consequences of major accidents including fire, explosion, leakage and diffusion triggered by liquefied petroleum gas tank in the storage area of petrochemical enterprise. The application results show that the established methodologies are reasonable and stable. The advantages of VRSS include intelligence, real-time consequence assessment, high efficiency and immersive sense.

Key words: Multi-agent, virtual reality, major accidents, major hazard installation.

1. Introduction

There are many major hazard installations (MHIs) that store large amount of flammable, explosive or toxic substances in the storage area of petrochemical enterprise. The major accidents, such as fire, explosion or poisoning, probably occur due to the improper management of MHIs. In case of an accident, what is the extent of damage to the surrounding area? And how to describe it? As people pay more and more attention to major accidents, some commercial software packages on two-dimensional (2D) simulation of accident consequences have been developed, such as SAFETI [1], PHAST [2], SIGEM [3] and WHAZAN [4]. These software packages mainly reflect 2D level information so that the consequences can’t be described objectively for accidents of three-dimensional (3D) characteristics. Besides, there are other software packages, such as FLACS [5], EXSIM [6], AUTOREAGAS [7], [8] and three-dimensional (3D) simulation platform bases on CFX [9], which have a function of 3D dynamic simulation of accident consequences and have been tested in some experiments. However, they need professionals and a large amount of their work. The efficiency of calculation is usually low and it is difficult for MHIs of regional distributed characteristics to evaluate the real-time consequences that vary with various ambient factors including wind speed and temperature.

In aspect of accident prevention, the real-time supervision of hazard installations is required in the whole process of production. And the autonomy and intelligence are required to adapt to the complex circumstances of WAN and Internet during the process of supervision. With the development of artificial intelligence (AI), Multi-Agent-based system has become a major research topic and has been applied in many fields, such as traffic safety management [10], industrial safety and risk analysis [11] – [14], fault detection [15], environment monitoring [16] and prevention of disaster [17], etc. Some characteristics of Agent, such as autonomy, learning, response and so on, are very helpful for designing and implementation of complex distributed systems.

In this work, Multi-Agent-based theory and technology can be applied in virtual reality (VR) simulation system (VRSS) of major accidents in petrochemical enterprise. The structural model of Multi-Agent is designed in accordance to the requirements of simulation. Based on the established mechanisms of communication and collaboration among Agents, a 3D simulation system of major accidents is developed by introducing VR idea. And the system is applied to simulate the dynamic effects of major accidents and the hazard characteristics of consequences in the virtual accident scene corresponding to the actual petrochemical enterprise.

2. Methodologies

2.1. Multi-agent-based Modelling

2.1.1. Requirements of simulation

It is well known that accidents are of the predictable, regular and 3D characteristics. A simulation system for major accidents should be able to intelligently predict the occurrence, evolution trend and consequences of accidents, as well as reconstruct the virtual scenes in accordance with the actual circumstances. Thus, the system is required to have the abilities including communicating with the outside world, analyzing the current working conditions, predicting the consequences of accident evolutions, reconstructing the accident scenes and so on. Actually, these are also the main tasks and goal of accident simulation.

In human society, a team which is composed of a group of people with different skills is formed to complete some specific tasks. It is difficult or impossible for a single person to complete these tasks. In the field of AI, Agent is defined as an entity with the abilities of perception, solving problems and communicating with the outside world. However, the intelligence of a single Agent is limited. Generally, several Agents are organized together by the appropriate structure to make up the insufficiency of a single Agent, and to enhance the whole capability of system. Based on the theory of team management, several Agents are organized as a team to complete the specific tasks for the same goal. As an intelligent node of network, Agents are connected by a computer network to form a distributed Multi-Agent system. The advantages of Multi-Agent are just in line with the distributed characteristic of MHIs in petrochemical enterprise. It is of important significance for safety management to establish a VRSS of major accidents triggered by MHIs based on Multi-Agent. Thus, the organizational structure of Multi-Agent is the core of the simulation system to complete the above tasks and goal.

2.1.2. Organizational structure of multi-agent

According to the requirements of the VRSS, these tasks are divided into three modules, such as real-time monitoring, consequence assessment and 3D simulation. The specific tasks are assigned into each Agent. Then the goal of the system can be achieved by the communication and collaboration among Agents including monitoring Agent (MA), communication Agent (CA), 3D scene management Agent (SMA), data analysis and processing Agent (DAPA), 3D effects display Agent (EDA) and human-computer interaction Agent (HCIA). They are organized together as a Multi-Agent block (MAB) in the VRSS. And the structural model of MAB is shown in Fig. 1.

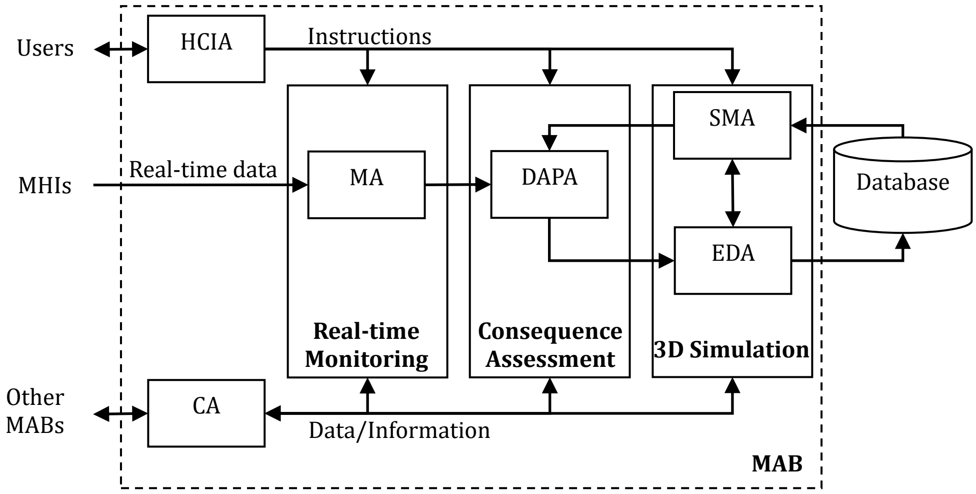


Fig. 1. Structural model of MAB.

In the structural model, HCIA sends a variety of instructions to every module to implement users' intention. CA is the only interface for communication among MABs. It can realize the data or information sharing among MABs. CA takes transmission control protocol/Internet protocol (TCP/IP) as communication protocol among MABs. The communication language between MABs is FIPA (Foundation for Intelligent Physical Agents) normative Agent communication language (FIPA-ACL) to interact information. It is expanded to implement the communication of data and information among MABs by XML extensible markup language. However, the network congestion is probably caused by large amounts of data from each module. In this case, CA can adaptively control the network flow of data. The minimum cycle of data transmission among MABs is determined by the parameters including the sampling frequency, number of MABs connected and communication board band. When the parameters change, CA can automatically adjust the minimum cycle of data transmission.

The function of the real-time monitoring module is achieved by MA. MA acquires the real-time data from MHIs at the accident scene either by the local monitoring system or by the remote monitoring system on line. MA has the abilities of learning to analyze the characteristics of state parameters. The function of consequence assessment module is achieved by DAPA. DAPA obtains the real-time data from MA and the geographic information from SMA. Then it can quickly analyze and process the data based on the models of accident consequences. Next, the results of analysis are transmitted to EDA. For a vividly visual effect, EDA has the ability of adjusting the number of frames in buffer automatically to control the animation rate. The function of 3D simulation module is achieved by SMA and EDA. Between them, SMA accesses the geographic information from the database on the server. Then the geographic information is recalled from SMA by DAPA or EDA at any time. SMA can manage and display the geographic information from the database and 3D simulation results from EDA. EDA obtains the analysis results of accident consequences from DAPA, displays the results in the virtual scene in the form of 3D effects by combining SMA, and stores the results in the database.

As mentioned, Fig. 2 shows the relationship of collaboration among Agents in the MAB. The collaboration among Agents is the key to ensure that each module works together. It is also one of the key concepts which distinguish Multi-Agent from other related research fields, such as the distributed computing, object-oriented system and expert system, etc. HCIA plays a dominant role in the MAB. And other Agents respond to its instruction control and provide services. These behaviors stand for a collaboration of master-slave service. MA is responsible for the interaction with the monitoring objects. It acquires real-time data from MHIs. Then it provides other Agents with data service by controlling its own state. However, it is an equal partnership of the collaboration among CA, DAPA, SMA and EDA. They run in parallel and independently with their own abilities of responding, learning and analysis. By decomposing the tasks of accident simulation, each Agent only takes part in some of tasks to achieve some specific goal. In this case, it is relatively easy to make each Agent more flexible.

A VRSS of major accidents is developed based on the established mechanisms of communication and collaboration among Agents. The details of developing the simulation system are as follows.

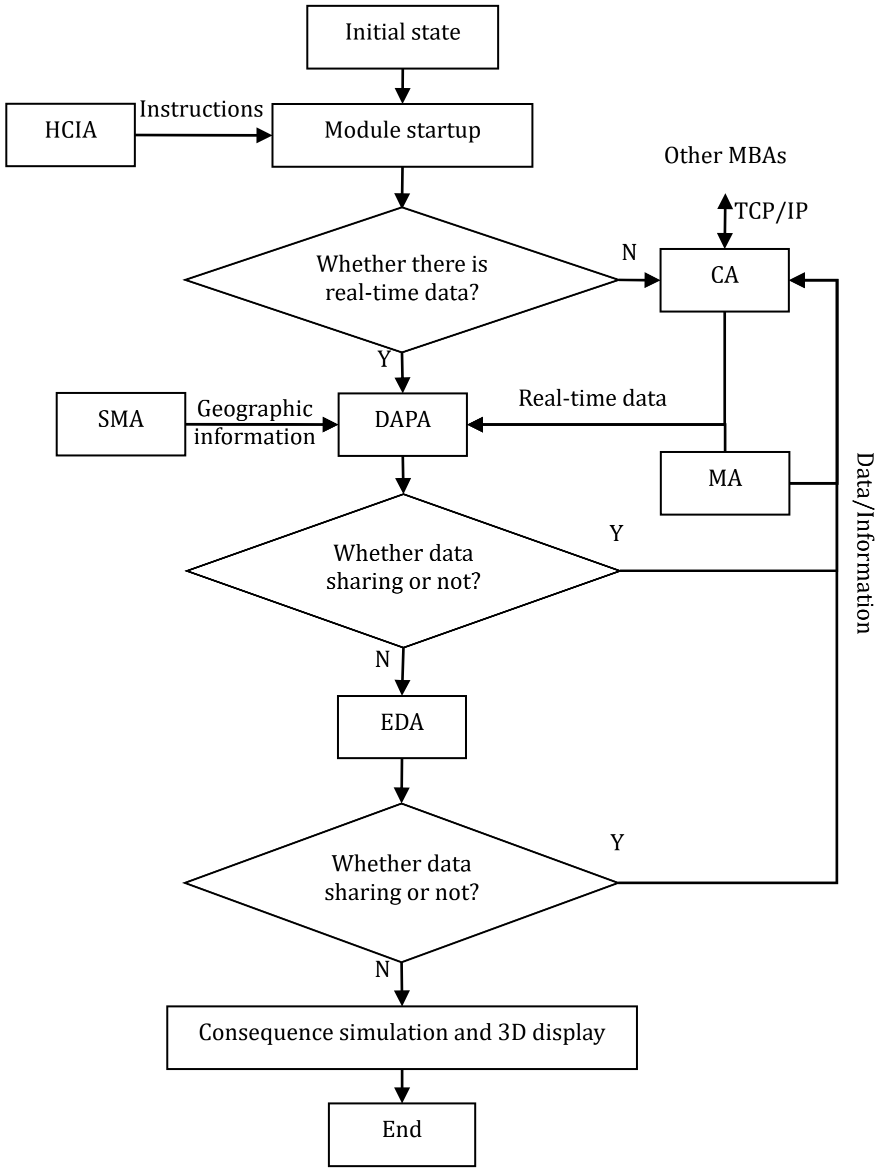


Fig. 2. The relationship of collaboration among agents.

2.2. Development of the VRSS

2.2.1. Hardware Environment

The parameters, such as concentration, pressure and temperature, which reflect the current safety state, are concerned as the monitored objects in a simulation system of major accidents because there are flammable, explosive, toxic and harmful mediums inside and outside of MHIs in general. MA which acquires the real-time data from the accident scene works with some sensors together, as follows.

The temperature sensor, whose temperature range is from -55 degrees Celsius to 125 degrees Celsius and temperature resolution can reach 0.0625 degrees Celsius, is DS18B20 digital temperature sensor from the semiconductor company named DALLAS in USA.

The concentration sensor, which can output the signal from 4 mA to 20 mA, is S1097GP explosion-proof gas detector from the company named SENSITRON in Italy.

The wind speed sensor, whose starting wing speed is less than 0.4 m/s, measuring range is from 0 to 70 m/s and resolution ratio can reach 0.1 m/s, is of LVFSC series products. It is suitable for the ambient temperature from -40 C to 80 C and humidity of 100% RH.

Besides, the pressure sensor and flowmeter are also used in this system as an experiment. A controlling device LTM8662 is used to control different sensors in the lower computer which communicates with the upper computer in the mode of RS485.

After the above hardware preparation, the following section shows the details of designing the software functions of the simulation system.

2.2.2. Overall framework

In line with the VR idea, the VRSS of major accidents is designed based on the established structural model of Multi-Agent. According to the requirements of simulation and the tasks of each Agent, the main functions are shown in Fig. 3, including the virtual scene management, consequence assessment and 3D simulation.

The virtual scene management subsystem is modularized to reconstruct the arbitrary scenes of major accidents. It can not only establish the virtual geographic information corresponding to the actual accident scene, such as the virtual sky, terrain, building, green area, road, water area, MHIs (such as cylindrical tank and spherical tank) and other elements, but also access the geographic information stored in the database. Besides, it provides some convenient operations to manage the virtual scenes.

In the reconstructed virtual scene, the consequence assessment subsystem takes responsibility for analyzing the damage extents based on the theoretical methods of calculating the hazardous characteristic parameters of different accidents, such as jet fire, pool fire, vapor cloud explosion (VCE), boiling liquid expanding vapor explosion (BLEVE), toxic gas leakage and diffusion. It can acquire the real-time data of the characteristic parameters from the accident scene according to the requirements of the theoretical methods.

In the reconstructed virtual scene, the 3D simulation subsystem takes responsibility for simulating the dynamic processes of accidents and displaying the analysis results transmitted from the consequence assessment subsystem, as well as storing the simulation results in the database.

2.2.3. The method of reconstructing major accidents

In accordance with the overall framework shown in Fig. 3, the details of implementing the VRSS are described as follows.

(1) Development tools

Considering the friendliness of human-computer interfaces and the timeliness of data accessing, the VRSS of major accidents is developed by Delphi as the main programming tool, SQL Server as the database management tool and GLScene as the VR tool. GLScene is an open graphics library (OpenGL) based on 3D library for Delphi and provides visual components and objects.

(2) The process of reconstructing major accidents

In line with the VR idea, the functions shown in Fig. 3 are implemented by GLScene. The process of reconstructing major accidents is described as shown in Fig. 4.

Reconstructing the virtual accident scene is actually the process of 3D entity modeling and rendering by utilizing GLScene in this work. Before this, the geographic information corresponding to the actual accident scene should be prepared to provide a reference for reconstruct an accident scene. There are the modularized designs of various geographic elements including the building, green area, water area, road, MHIs and so on. Users can design the arbitrary entity models by setting some properties, such as coordinates, size, name, color and texture, so that a virtual scene corresponding to the actual accident scene can be eventually reconstructed. Moreover, some human-computer interaction operations provide the convenience for users to manage the virtual scene, such as reconstruct, edit, pick, pan, rotation, zoom, search and so on.

Major accidents in petrochemical enterprise are mainly fire, explosion, leakage and diffusion, etc. There are different characteristic parameters for each accident. The assessment methods that are used to calculate the characteristic parameters are modularized to enhance the applicability of the simulation system. What's more, the consequence assessment subsystem is implemented by integrating with the developed monitoring system [18]. For the dynamic parameters, the real-time data can be acquired from the accident scene to achieve the real-time consequence assessment.

On the basis of the analysis results from the consequence assessment subsystem, the dynamic effects of accident occurrence can be simulated by the particle system and animations that are encapsulated in GLScene, and the consequences can be efficiently calculated and displayed by combining the real-time data.

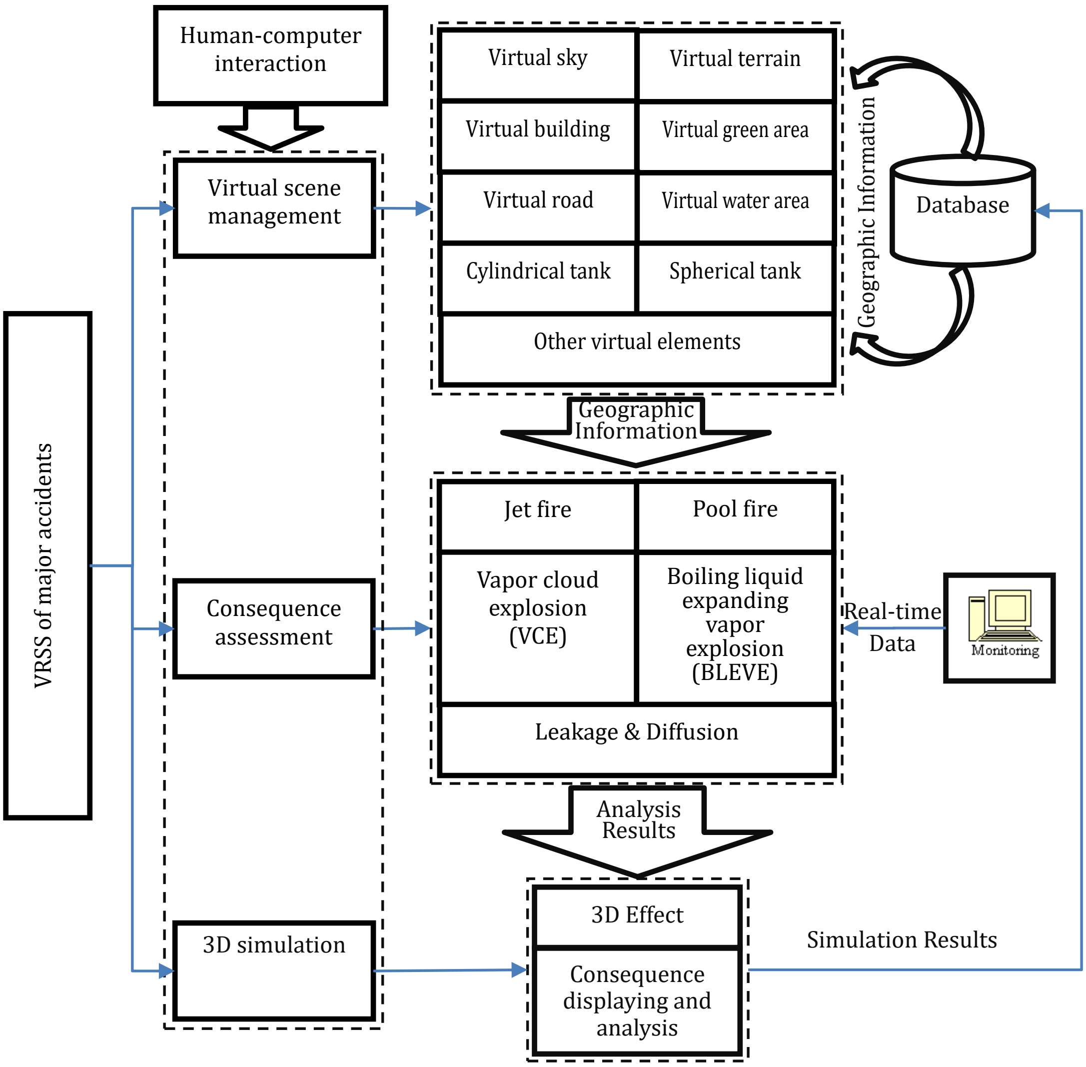


Fig. 3. Overall framework of VRSS.

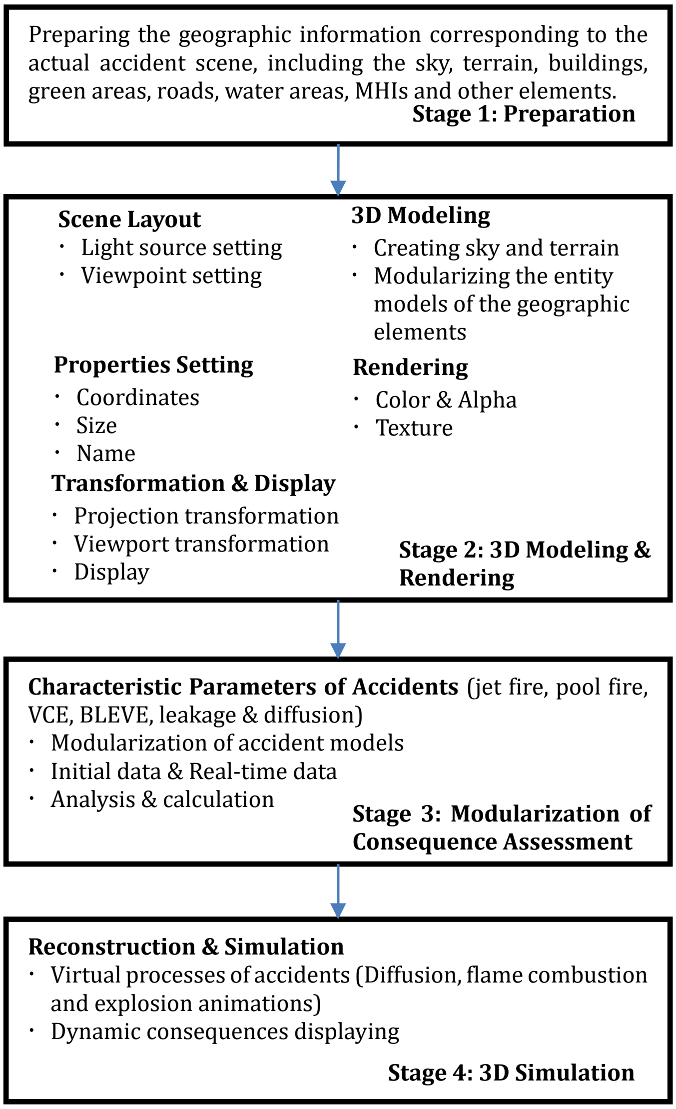


Fig. 4. The process of reconstructing major accidents.

3. Results

As mentioned, a VRSS of major accidents was eventually developed based on the above methodologies shown in section 2. And the system is applied in a petrochemical enterprise.

3.1. Case Profiles

This case will show how to simulate major accidents triggered by a tank storing liquefied petroleum gas (LPG). There are five propane tanks with a volume of 3500 m^3, five propane tanks with a volume of 3000 m^3, three butane tanks with a volume of 10000 m^3, one butane tank with a volume of 6500 m^3, two horizontal tanks with a volume of 100 m^3 and other cylindrical tanks in the storage area of the enterprise. The natural conditions of the city in which the enterprise operates are as follows: annual mean wind speed equals 2.4 m/s, annual mean temperature equals 21.9 °C and annual mean relative humidity equals 81%.

3.2. Simulation Results

In order to test the performances of each Agent executing tasks, the main function modules of the VRSS are applied to simulate jet fire, pool fire, explosion and toxic gas diffusion. The simulation steps include establishing virtual accident scene, acquisition of real-time data, dynamic effects of accident occurrence and 3D visualization of accident consequences. The simulation results of each step are as follows.

3.2.1. Virtual accident scene

In accordance with the method of 3D entity modeling and rendering shown in Fig. 4, the virtual scene is established and the simulation result is as shown in Fig. 5. Besides, VRSS can also import and edit the predesigned maps of petrochemical enterprises.

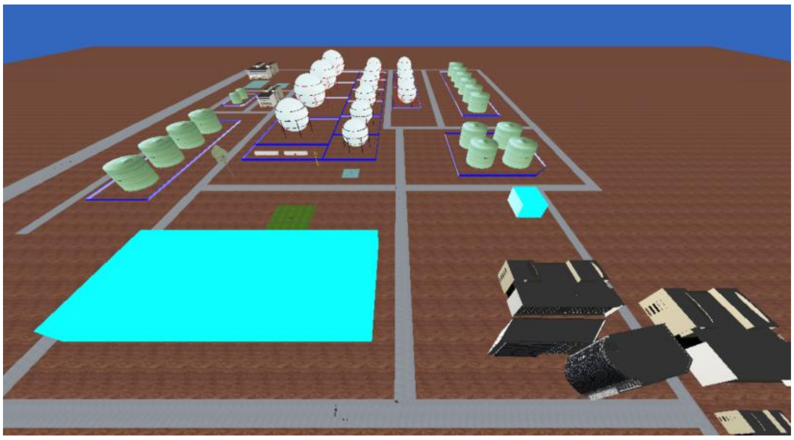


Fig. 5. The established virtual accident scene.

3.2.2. Acquisition of real-time data

Based on MA, a monitoring system of MHI was developed to acquire the real-time data. It provide the data sources for the consequence assessment subsystem. Fig. 6 shows the real-time data acquired from LPG tank.

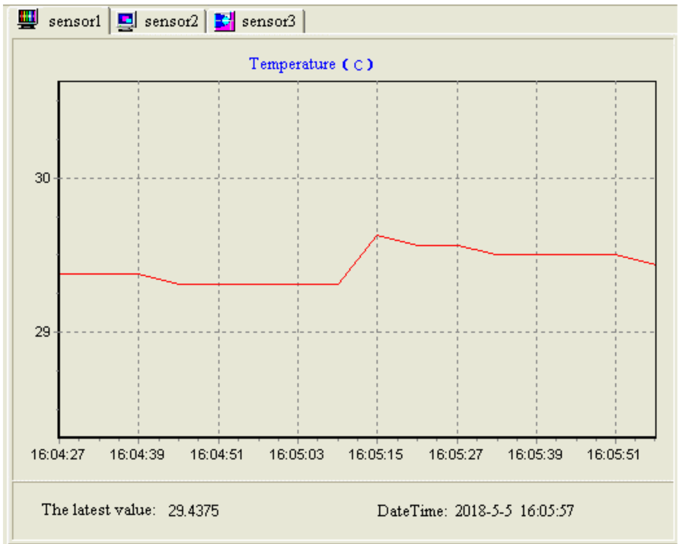
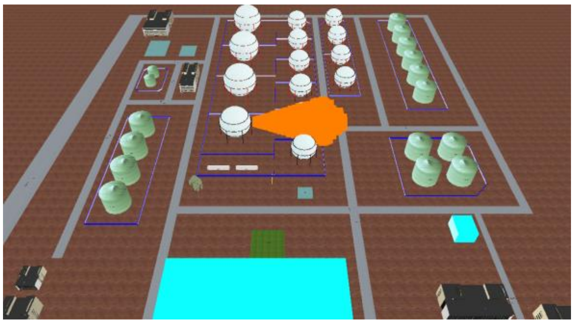


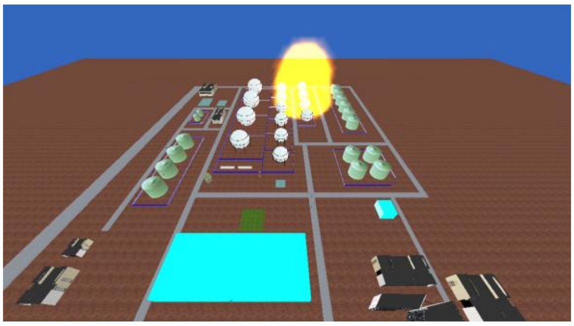
Fig. 6. Acquisition of real-time data.

3.2.3. Dynamic effects of major accidents

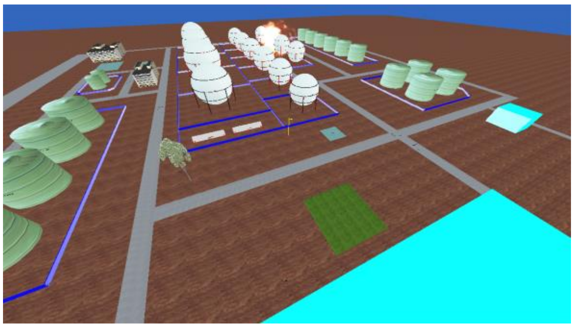
After initializing some state parameters, the characteristic parameters of accidents will be efficiently analyzed and the dynamic effects of accident occurrence will be simulated by combining the real-time data. Fig. 7(a) and Fig. 7(b) show the dynamic combustion of jet flame and pool flame. Fig. 7(d) show the dynamic process of toxic gas leakage and diffusion. These dynamic effects are achieved based on particle system in GLScene. Fig. 7(c) show the deflagration effect of explosion that is achieved by the component of animation player in GLScene.



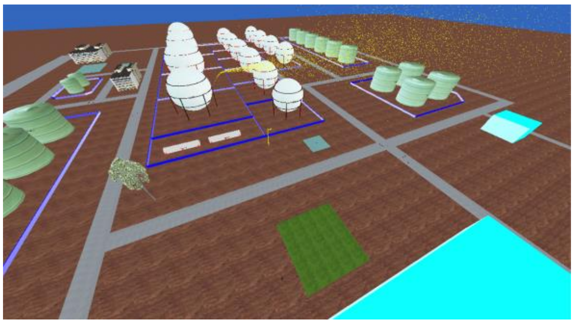
(a) Jet fire



(b) Pool fire



(c) Explosion

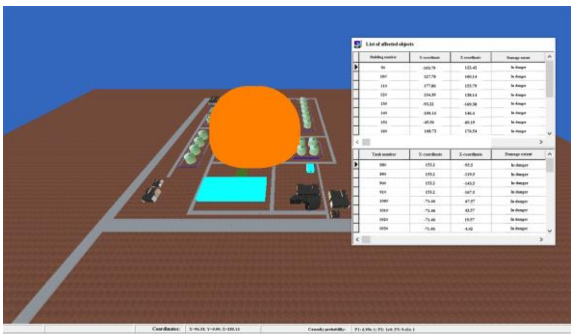


(d) Leakage & diffusion

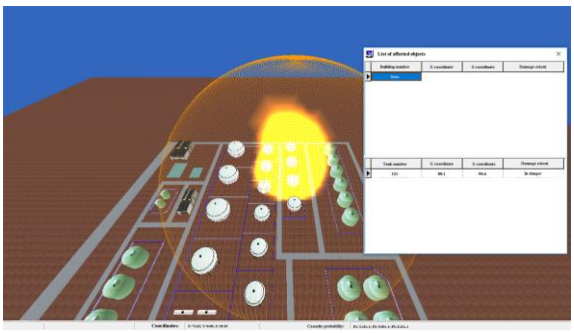
Fig. 7. Dynamic process of major accidents.

3.2.4. 3D visualization of accident consequences

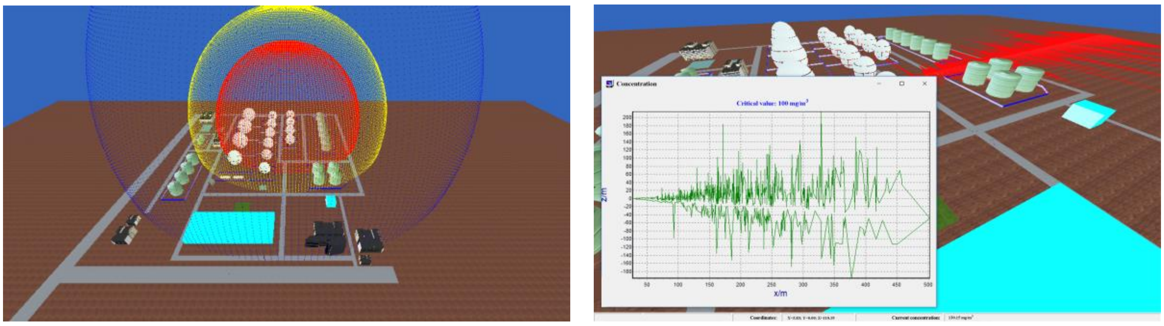
By the 3D modeling functions of GLScene, the analysis results are displayed in a form of 3D visualization. From Fig. 8(a) and Fig. 8(b), VRSS can analyze the influence ranges corresponding to the critical values of different damage extents. The influence ranges of heat radiation are drawn with the object named TGLSphere. And the affected objects involved in the influence range can be also marked with different colors. The list of affected objects is displayed in a single interface according to users' needs. Moreover, VRSS can also calculate the real-time casualty probabilities of people at any position, and they are displayed on the status bar. From Fig. 8(c), VRSS can achieve 3D visualization of explosion consequences in the form of drawing the influence ranges marked with different colors corresponding to different damage extents, such as the death radius marked with red sphere, severe injury radius marked with yellow sphere and light injury radius marked with blue sphere. From Fig. 8(d), VRSS can achieve the visualization of leakage and diffusion consequences by the forms of 2D and 3D levels. VRSS describes the influence ranges of diffusion not only by the 2D numerical report but also by drawing them in the virtual scene with the red polygon entity block. Furthermore, the real-time concentration of toxic gas at any position can be quickly calculated and displayed on the status bar.



(a) Jet fire



(b) Pool fire



(c) Explosion (d) Leakage & diffusion

Fig. 8. Consequence visualization of major accidents.

4. Discussion

From the simulation results, the superiorities of the VRSS of major accidents are involved intelligence, real time, efficiency and immersive sense by comparing with the widely used commercial software packages, such as the 3D simulators based on computational fluid dynamics (CFD), and 2D simulators based on the classic calculation methods.

4.1.1. Intelligence

Agent-based VRSS can intelligently adjust the minimum cycle of data transmission to adapt to the complex network environment. VRSS has the abilities of learning to analyze the characteristics of state parameters. For these, the real-time data can be successfully acquired and smoothly transmitted, as shown in Fig. 6. Furthermore, VRSS can adaptively control the animation rate to ensure the stability of 3D dynamic visualization, as shown in Fig. 7.

4.1.2. Real time

The VRSS has the functions of real-time monitoring and data transmission to ensure the real-time consequence assessment of major accidents that vary with dynamic parameters, so that the analysis results shown in Fig. 8 are more timeliness and objectivity.

4.1.3. Efficiency

From the calculation efficiency, CFD will take much time to obtain the results through iterative operation based on a grid for the analysis of accidents. By comparison, the VRSS has higher efficiency of analyzing the accident consequences. Because VRSS obtains the analysis results through the basic mathematical operation based on the classic calculation methods. Besides, compared with the 2D simulators, the VRSS can obtain the real-time analysis results without repeatedly setting state parameters, because the module of real-time monitoring can provide data sources acquired from accident scene.

4.1.4. Immersive sense

From Fig. 5, Fig. 7 and Fig. 8, the VRSS that is developed based on VR idea can simulate the virtual scene corresponding to the actual circumstance, animation effects of accident occurrence and dynamic consequences to systematically and vividly describe the hazard characteristics of major accidents, so that users have much more immersive sense.

5. Conclusions

From the application results, the VRSS can meet the requirements of simulation proposed in this paper, as well as the tasks and goal are successfully completed. It is proved that the methodologies, including the established Multi-Agent model and VR idea-based development method of system, are reasonable. Furthermore, the VRSS of major accidents has these advantages including intelligence, real-time analysis results, high calculation efficiency and immersive visualization effects. The application results not only embody the great engineering value of Multi-Agent and VR technologies in the field of safety engineering, but also can provide the technology supports for safety management, risk assessment and safety planning of petrochemical enterprises.

Conflict of interest

The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Author Contributions

Wenjiang Chen, Jinxing Hu, Diping Yuan contributed to the conception of the study.

Jiaoyang Liu performed the simulation experiment.

Wenjiang Chen, Jiaoyang Liu performed the data analyses and wrote the manuscript.

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