Research and Application of 3D Real-Time Simulation Technology for Thermal and Hydraulic Mechanism in Nuclear Power Plant

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Abstract. The nuclear power plant simulator displays the thermal-hydraulic conditions of nuclear power plant in 2D. To enhance the 3D effect of the thermal-hydraulic display of nuclear power plant, the real-time simulation of thermal-hydraulic mechanism of nuclear power plant is studied based on 3D visualization. Firstly, a 3D model is established that can express thermal-hydraulic characteristics; secondly the real-time data is connected to the simulator through a program interface; finally Unity3d is used to integrate the 3D model with the received data in real time, and display it in a data-driven 3D model. At the same time, taking the primary circuit equipment of a nuclear power plant as an example, a 3D visual test is carried out on the thermal-hydraulic mechanism of temperature, pressure, and flow rate. The results show that this method can well display the thermal-hydraulic mechanism in 3D, providing a new idea about the training of nuclear power plant personnel.

Keywords: Simulator · Thermal-Hydraulic · Real-time simulation

1 Introduction

The operation of nuclear power facilities requires high human reliability, and the simulation of accident conditions of nuclear power facilities is a necessary part of operator training [1]. At present, the most important and direct method of this training is to use the nuclear power plant simulator to complete it. The simulator can enable the nuclear power plant operators to master the analysis and processing skills of various operating conditions of the nuclear power plant. But, when the simulator simulates the operating conditions of nuclear power plant, it is displayed through 2D pictures. It cannot visualize the change process of thermal-hydraulic phenomena, and lacks intuitive and 3D visual effects. Moreover, it is used by nuclear power plant operators and has strong professionalism, which makes it difficult to prove and analyze the thermal-hydraulic mechanism to new employees and non-operators.

This paper adopts VR technology to view nuclear power equipment in a 3D environment, and displays the operation simulation of various phenomena such as temperature,

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pressure and flow rate of nuclear power equipment in a 3D dynamic virtual way. The thermal-hydraulic model can be connected with the data onto the simulator in real time, thus realizing the real-time dynamic simulation of nuclear power thermal-hydraulic in 3D visualization. The system can reproduce the operation of the system under various conditions of the power plant, and it provides a 3D visualization method for the simulator training, so as to enhance the 3D perception of trainers and improve the training effect.

2 Virtual Reality Technology and Application

Great changes have taken place in today's world industry, and the advanced science has shown great power, especially VR is carrying out an unprecedented revolution to industry [2]. VR is defined as a set of technologies and a technical system integrating users and computing has been developed. Its goal is to give users a feeling of living in a virtual world in real time through advanced interfaces. So VR can be regarded as an experience of users and Computerized System in 3D.

Due to the characteristics of immersion, interactivity and conception of virtual reality [3], this technology has been widely used in all aspects of industry by large enterprises in the world. It has played an important role in improving development efficiency, strengthening data collection, analysis-processing capabilities, reducing decision-making mistakes and reducing enterprise risks. Similarly, it has played an important role in information exchanges, generation, operation and management decisions in the nuclear power industry. This foreign research and application started early. O.Fridtjov studied the application of virtual reality of nuclear power plant accident management [4]. I. Yukihiro et al. [5] developed a radiation dose assessment system based on virtual reality technology in the decommissioning engineering support system of Fugen nuclear power plant in Japan. G. Romero et al. [6] developed a substation virtual reality simulation system. At present, a lot of domestic researches have been conducted in this field, and certain results have been achieved. Zhao Pengcheng had realized the application of virtual maintenance training for nuclear power plant by VR [7]. Ma Jianming used VR technology to research and apply nuclear power plant accident emergency response [8]. Chen Ming conducted a preliminary 3D visualization study of nuclear power plant simulator based on Unity3d [9]. The above cases show that using 3D digital virtual simulation technology to build digital factory applications for the nuclear energy industry, providing multi-person online interactive training function, and implementing visual demonstration, guided operation and open and free operation management modes can effectively solve the problems faced by nuclear energy enterprises.

3 System Implementation

3.1 Design Idea

The design idea of the whole system is mainly shown in Fig. 1. The whole design phase includes 3D modeling, real-time data processing, data driving and 3D visual interaction.

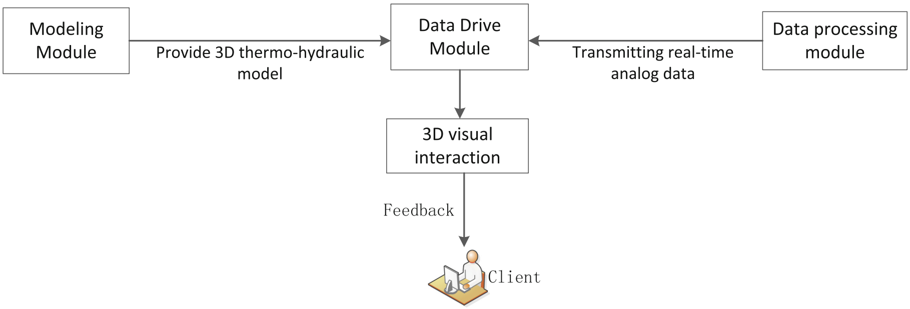

Fig. 1. System design module

3.2 Technical Framework

The system development process involves 3D model building and processing, simulator data docking, database connection, Unity data real-time drive, Unity 3D visualization development, cross-platform publishing and other technical contents. According to the development process, the technical framework adopted by the system is shown in Fig. 2.

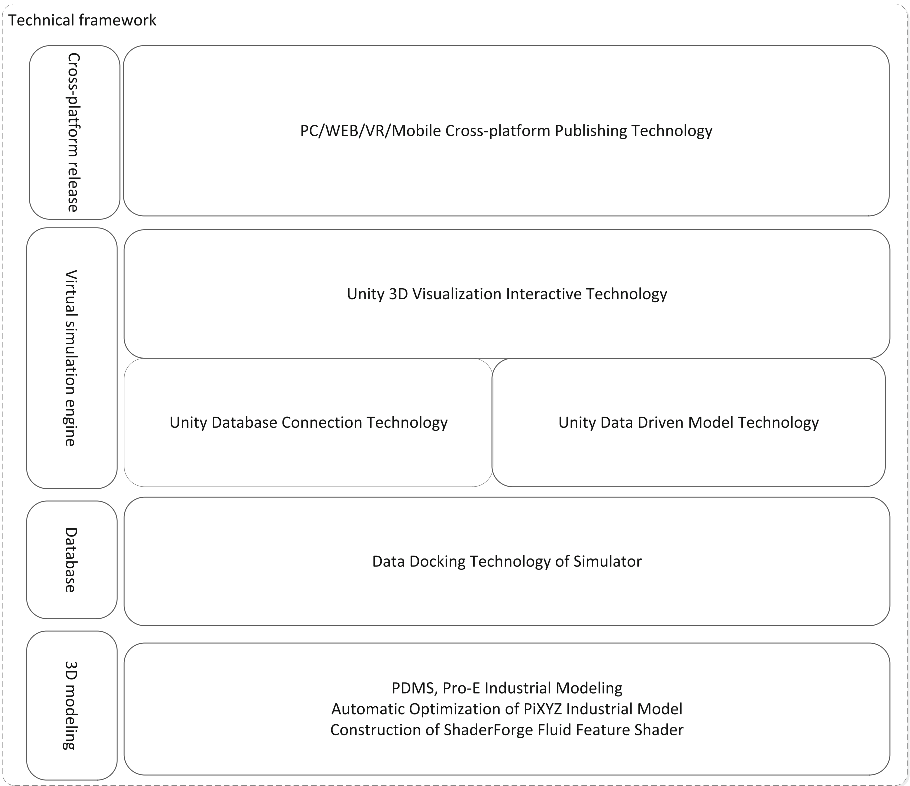

Fig. 2. System technical framework

3.3 Thermal Hydraulic Modeling

Construction and Processing of Foundation Model. In this system, PDMS and Pro-E are used to build the layout model of nuclear Power-Loop system and the mechanical models of RPV, SG and other equipments. As we all know, Unity native supports importing standard polygon formats such as Obj, FBX, 3ds, etc. [10], but it cannot directly import industrial models created by PDMS and Pro-E. In the past workflow, it is necessary to use 3DMAX and other tools to carry out manual optimization to adjust model wiring and vertex topology. This paper studies the use of PiXYZ Plugin for Unity to import the industrial digital model built by PDMS and Pro-E. It can automatically optimize the model, and ensure that the model runs smoothly in the engine and restores highly the real scene to improve application performance.

Construction of Thermal-Hydraulic Characteristic Shader. The shader with thermal-hydraulic characteristics is constructed by using shader editor ShaderForge. Liquid disturbance is mainly formed into shader texture superposition and UV offset, and color to value change is controlled through node parameter adjustment, thus realizing temperature and pressure color change, bubble generation, flow and bursting, etc. Finally, the quality of the coloring equipment is endowed with the model grid renderer to complete the establishment and rendering of the thermal-hydraulic 3D model.

To sum up, the whole thermal-hydraulic modeling process of the system is shown in Fig. 3.

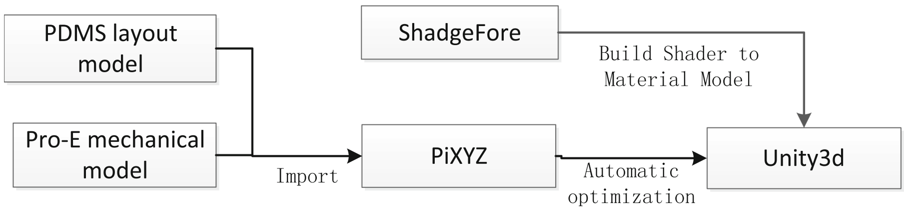

Fig. 3. Schematic diagram of thermal hydraulic modeling process

3.4 Real-Time Analog Data Processing

The data of simulator is the data support of thermal-hydraulic 3D real-time dynamic simulation system. The data interface system is a transit system that connects the visualization system and the simulator. This part serves as the background data interface of the entire system. It aims at sending real-time data generated by the simulator to the data driving model module through the designated protocol. so as to ensure that the data of simulator can drive the thermal-hydraulic 3D model on time.

The simulator can export the data such as pressure, temperature, flow rate in real time through internal functions and stores them in Excel tables. Due to the large amount of information such as multi-tables and multi-fields of exported data, the system needs to use programs to filter, simplify and fuse various data, and store the fused data in the database for the 3D engine program to call. The final data structure is shown in Table 1.

Table 1. Real-time Visualization Data Structure of Thermal Hydraulic System

Name	Temperature	Pressure	Velocity of flow
130101010	423.842	1.74065E + 07	5778.5
130101020	423.851	1.74165 E + 07	5778.79
130101030	423.860	1.74266E + 07	5778.77
130101040	423.869	1.74366E + 07	5778.77
130101050	423.877	1.74467 E + 07	5778.66
130101060	423.886	1.74566 E + 07	5781.26

The flow of real-time data processing of the simulator is shown in Fig. 4.

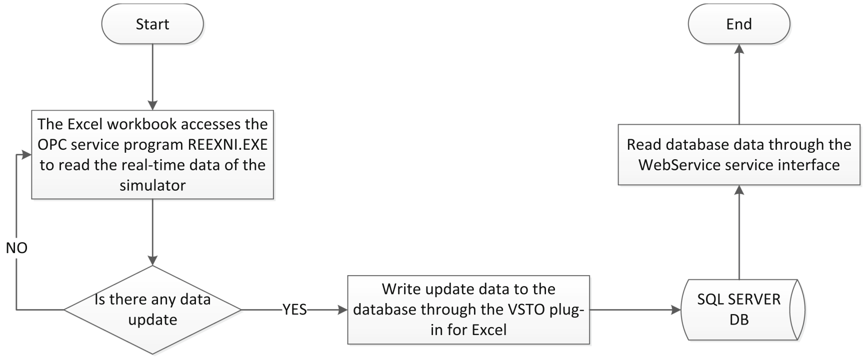

Fig. 4. Real-time data processing flow of simulator

Due to the variety of data types exported by the received simulator, the amount of data is huge. This system screens for the data related to thermal-hydraulic through the VSTO plugin program of Excel and stores them in the database, thereby greatly reducing the data capacity, avoiding data blocking, and improving the data validity and retrieval efficiency. The data stored in the database is regularly read into the data queue of WebService for the 3D engine program to call, thus improving the data independence.

3.5 Data Driven Model

The main function of this part is to receive the transmitted real-time data and drive the real-time changes of the thermal-hydraulic 3D model. Its data access and driving process is shown in Fig. 5. Its greatest feature is to convert the acquired real-time data of the simulator into JSON format data for the 3D engine program to call. JSON data has the characteristics of more efficient transmission and analysis [11, 12]. The correlation between simulator data and 3D model is realized through JSON lightweight data driven, which can effectively to improve the refresh frequency of Unity read data, thus ensuring smooth real-time picture of data drives model.

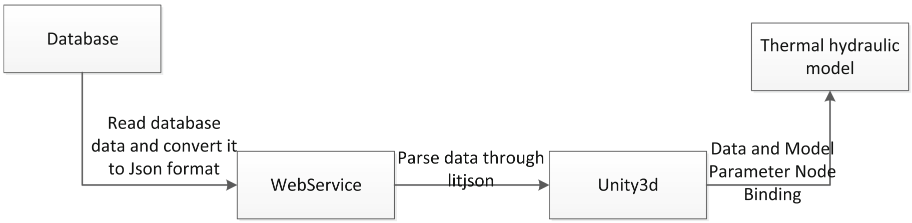

Fig. 5. Data Drive Module Design Flow Chart

The specific implementation steps of the module are as follows:

(1) Reading data onto the database through the Web Service interface and converting the data object to JSON format through the serialization interface.

(2) Parsing and restoring the converted JSON data through litJson library at the end of Unity3d 3D engine.

(3) The analyzed data are bound to the node parameters on the thermal-hydraulic 3D model according to their respective attribute types, and the binding drives the node parameters on the 3D model to change in real time, thus achieving the 3D real-time dynamic change simulation of the thermal-hydraulic model.

Because it involves thermal-hydraulic real-time simulation of multiple physical characteristics inside different equipment, it is necessary to classify the acquired real-time data and match and associate the parameters of corresponding model shader nodes. In thwill control the color change of different states through the values of node parameters. The correlation matching between the data and the model only needs to convert the acquired real-time data value into the value f (x) (0–1) through mathematical operation, and the conversion formulas such as (1), min and max which are the minimum and maximum values set by temperature, pressure and flow rate respectively. Finally, according to the conversion values in different intervals, corresponding parameter nodes can be given, thus realizing a universal shader template to simultaneously represent different thermal-hydraulic characteristics changes.

$$f(x) = \begin{cases} (\text{value} - \min)/(\max - \min), \ \text{value} \geq \min \ \&\&\text{value} \leq \max \\ 0, \ \text{value} < \min \\ 1, \ \text{value} > \max \end{cases} \tag{1}$$

3.6 Dynamic Visualization Interaction

The system not only completes the main function of thermal hydraulic real-time simulation, but also provides a convenient dynamic 2–3-D visual interactive operation mode.

It can present the thermal hydraulic real-time 3D dynamic simulation functions as all directions.

3D Models Interaction

This paper expands and develops a set of standard Unity 3D interaction toolkit based on the conventional 3D interaction operation mode. Common operations such as flight roaming, panning, dragging, positioning, centering, looking around and highlighting the selected border can be easily realized by Keyboard mouse, as shown in Fig. 6.

Fig. 6. Interactive schematic of 3D model

2D Interface Interaction

Navigation and Positioning with Tree Structure. The interface provides a hierarchical navigation tree that completely matches the model. Its function mainly establishes a 2D hierarchical tree that completely matches the internal structure of the 3D model. The structure tree and the 3D model can synchronously link navigation and positioning in both positive and negative directions. At the same time, it can realize the functions of displaying and hiding parts, positioning, centering, searching, etc., the interface shown in Fig. 7.

Fig. 7. Navigation tree interface

Dynamic Color Scheme. Since the system involves a variety of thermal-hydraulic characteristics, and the numerical value of these characteristic varies widely. The system uses UGUI to classify and differentiate the different characteristics. In order to make the display more intuitive and effective, the system adds transparent channel calculation, and it provides a dynamically configurable color scheme. Color matching values can be modified according to actual needs and reflected on the 3D model in real time. Its functional interface is shown in Fig. 8.

Fig. 8. Color scheme interface

Real-time Display of Data Status. When selecting the corresponding node or model, the system updates the corresponding model code name, temperature, pressure, flow rate in real time through the attribute interface. It makes intuitive matching comparison with the color depth of the 3D model through the parameter data. The interface diagram is shown in Fig. 9.

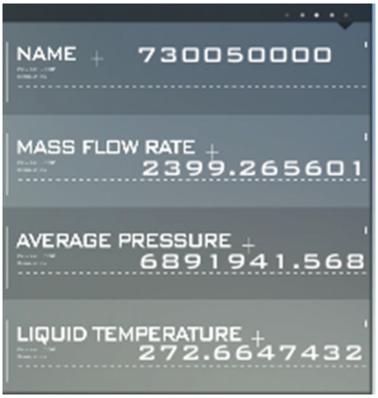

Fig. 9. Real-time display interface of parameter data

4 Application Status

In order to verify the stability, reliability and smoothness of the system, it mainly simulates Reactor, Steam Generator and Pump, etc. It has many functions such as rotation, perspective and hiding. Through color, bubble, flow, burst values temperature, liquid level, flow velocity of the equipments. it can also values selected parameter. The specific application effect is shown in Fig. 10.

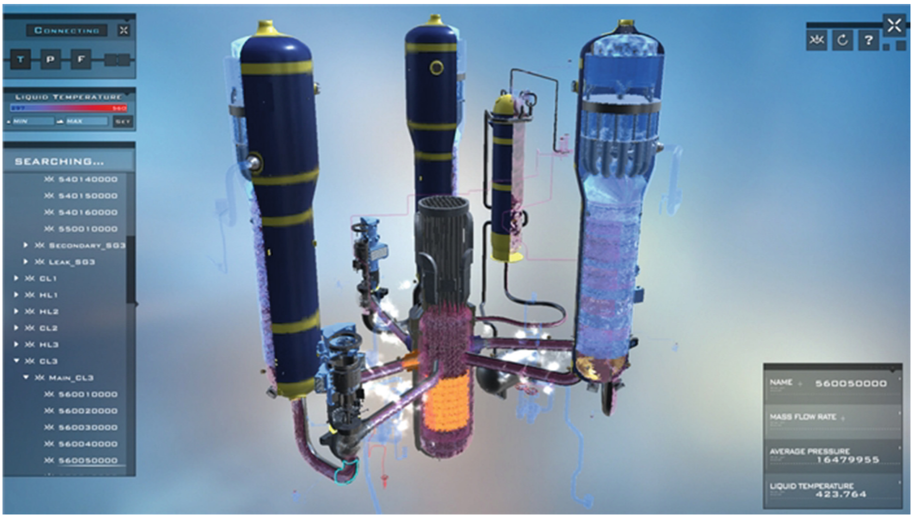

Fig. 10. Schematic diagram of system operation effect

The system has gradually started to run online. After completing 3D modeling, function development, data docking, installation, debugging and optimization, the system runs stably. The system was driven by model data and measured with precise size of power plant equipment. It used advanced 3D technology to display the physical parameters and states of the core and a Loop system, thereby presenting real-time, dynamic, high-definition and all-round 3D visualization effects of Nuclear Island system operation under different working conditions. Finally, it realized the dynamic display and analysis functions of the thermal-hydraulic mechanism.

5 Conclusion

The system combines the simulator and the 3D dynamic thermal-hydraulic working condition display, and can demonstrate, analyze and train thermal-hydraulic phenomena. The simulation effect is realistic and the picture is novel. Dynamic visual effects are supported by background data onto various working conditions, covering complete working conditions. From the comprehensive comparison of simulation accuracy, working condition types and visual effects, the system has reached the domestic leading level, with advanced technology and good training value. The system can be used for personnel training to deepen the understanding of thermal-hydraulic phenomena and principles, and improve training effects.

References

1. Chen, X.: Simulation of Nuclear Power Plant accident conditions based on virtual reality technology. Enterprise Technol. Dev. **31**(16), 85–86 (2012)
2. Gao-Qi, H., Kai-Lin, Y., et al.: Research on interactive display technology of energy station based on Unity3D. J. Syst. Simul. **28**(10), 2626–2631 (2016)
3. Wei-Jian, R., Fei, T., Qing, Z., et al.: Research on simulation of oil field drilling system based on virtual reality technology. Sci. Technol. Eng. **11**(13), 2981–2985 (2011)
4. Fridtjov, O.: Role of the man-machine interface in accident management strategies. Nucl. Eng. Des. **209**, 201–210 (2001)
5. Yukihiro, I., Yoshiki, K., Mitsuo, T., et al.: Development of decommissioning engineering support system(DEXUS) of the Fugen nuclear power station. J. Nucl. Sci. Technol. **41**(3), 367–375 (2004)
6. Romero, G., Maroto, J., Felez, J., et al.: Virtual reality applied to a full simulator of electrical sub-stations. Electr. Power Syst. Res. **78**, 409–417 (2008)
7. Peng-Cheng, Z., Bo, P., Hao, Z.: Research on virtual maintenance training technology for nuclear power plants. Sci. Technol. Innov. Appl. **20**, 60–61 (2015)
8. Jian-Ming, M.: Application of virtual reality technology in emergency response of nuclear power plant accidents. Sci. Technol. Innov. Guide **07**, 168 (2019)
9. Ming, C., Kun, Q.: Research on 3D visualization design of nuclear power plant simulator. Electron. Instrum. Custom. **26**, 72–75 (2019)
10. Chun-Yan, L., Shaohua, L.: Analysis on the ways of importing Unity3d into several 3D model formats. New Technol. New Prod. China **03**, 23–24 (2016)
11. Jian-Hua, G.: Application of JSON formatted data in web development. Office Inform. **264**, 46–48 (2013)
12. Jing, G., Duan, H.: Research on data transmission efficiency of JSON. Comput. Eng. Des. **32**, 2276–2270 (2011)