

Virtual Reality-based Chemical Process Simulation of Pipeline System

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Abstract—In order to reduce danger and cost in physical chemical process training and testing, this paper designed a distributed virtual reality-based pipeline simulation system which has abilities of chemical process training, monitoring, testing and replaying. After proposing a data-driven simulation framework, this paper presented a virtual reality modeling method for pipeline simulation and a process path calculation method. Then a virtual prototypes pick-up method for device operation and related-information display was further analyzed. With Bernoulli's equation, a mathematical model for constant flowing and instant flowing of fluid in pipeline system are constructed to estimate flowing speed, flux and pressure in real time. Using aforementioned methods, a pipeline simulation system was developed and it was proven to be helpful for chemical process training, design and optimization by practical use.

Index Terms—Virtual reality, pipeline simulation, fluid model

I. INTRODUCTION

Pipeline systems have been widely used in industry fields such as petroleum, medicine and astronautics. The delivered liquid of pipeline systems is usually combustible, poisonous or explosible [1]. For these kinds of pipeline systems, training with physical equipments not only increases cost, but also causes danger and pollution threats to operators and surroundings.

With developments of computer simulation technology and virtual reality technology, the computer-generated simulation environment becomes a fairly good option to train new operators and test new chemical process with no physical chemical equipments involved. Virtual Reality (VR) simulation can incorporate visualization into simulation system. Comparing with traditional simulation system, VR simulation system can display simulation results in a more nature and intuitive manner, and make users to drive simulation by interacting with 3D virtual environment. So VR simulation will play an important role in system simulation of complicated equipments.

This paper will apply VR technology into pipeline simulation to design a distributed pipeline simulation system, which has abilities of chemical process training,

monitoring, testing and replaying. In VR-based pipeline simulation system, operators can not only operate the 3D virtual equipments, but also see the special effects of fluid, so the reality of pipeline simulation system can be greatly enhanced [2]. Several pipeline simulation systems have been developed. Hou [3] presented a simulation system for chemical process using object-oriented method and virtual reality technology. Wu [4] proposed an approach and the corresponding technology for integrating the defined modules of user with common simulation software. John [5] developed a virtual reality based simulator named Vicher which is used for chemical engineering educational applications. Tracy [6] used chemical process simulation to design industrial ecosystems. Chen [7] presented an object-oriented framework for modular chemical process.

According to characters of an existing chemical engineering system and functions for simulation system to be designed, this paper developed a VR simulation system for chemical process to reduce danger and cost in physical training and testing. Some related key technologies such as modeling and chemical process path calculation were discussed. In order to operate virtual prototypes and display related information, the virtual prototypes pick-up method was further analyzed. And the mathematical model for constant flowing and instant flowing of fluid in pipeline system are constructed using Bernoulli's equation.

The reminder of this paper is organized as follows. Section II proposes the framework for chemical process simulation using distributed virtual reality technology. Section III gives a VR environment modeling method for pipeline simulation. Section IV presents a path calculation method for chemical process simulation. Section V introduces virtual prototypes pick-up and operation method. Section VI constructs a mathematical model for constant flowing and instant flowing of fluid in specified pipeline. Section VII introduces the simulation system developed in this paper, and the last section gives the conclusions of this paper.

II. FRAMEWORK OF SIMULATION SYSTEM

A. Physical chemical engineering system

A brief diagram for physical chemical engineering system to be simulated is shown in **Figure 1**. There are four layers in this chemical engineering system. The bottom layer are some chemical equipments such as pipes, storage tanks, pumps, valves (include hand valve, electrically operated valve, pneumatic valve and electric control valve) and sensors (include temperature, pressure, flow, liquid level sensor). The second layer are PLCs which have two functions, the first function is to control or adjust chemical equipments, such as pumps and valves, according to instructions from computer and control panel; another function is to collect states of switch devices and data from sensors, then transmit them to computer. The third layer is human-machine interaction layer. Operators can operate controlling program on computer to send batch processing instruction to PLCs, and the states of switch devices and data from sensors can also be shown on controlling program. Operators can also press buttons on control panel and pneumatic panel to adjust electric control valve or switch corresponding electrically operated valve and pneumatic valve on or off. In addition, some hand valves should be control manually by operators. The top layer is intranet, all related data and states are sent to this intranet, so that other computers within this intranet can analyze and process these data and states.

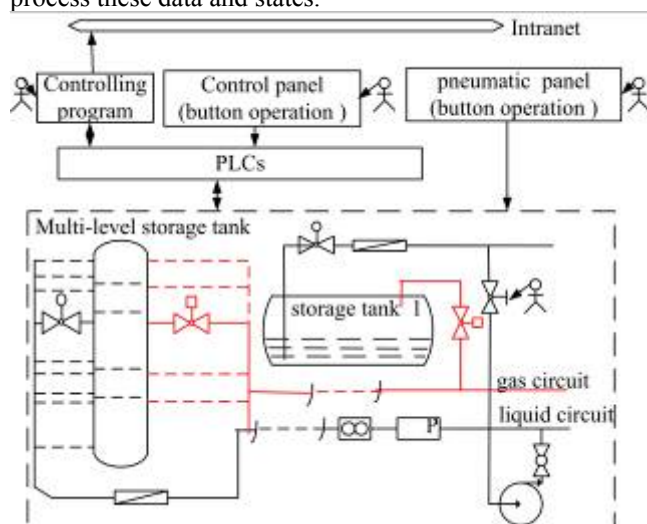


Figure 1. diagram for physical chemical engineering system

B. System framework

The presented simulation system in this paper has four functions, namely chemical process training, monitoring, testing and replaying. (1) In chemical process training function, team operators can simulate more than 110 chemical processes interactively, and operators can see

the process path update in real-time in 3D virtual environment. (2) With chemical process monitoring function, the presented system can receive states of physical switch devices and data of physical sensors from intranet, then these states and data are shown in simulation system, and are used to drive simulation system to monitor physical chemical processes. (3) Chemical processes testing means the simulation system to be designed can not only simulate existing processes, but also test new chemical process, in other words, the process path calculation module needs certain robustness. The mechanism of chemical process testing function is similar as that of chemical process training function. (4) With chemical process replaying function, the simulation system can replay any chemical processes saved in database, so that all operators can check their operations and find fault to improve their operations.

Based on the analyses of functions for the simulation system to be designed, a data-driven simulation framework is proposed in this paper. As shown in **Figure 2**, the proposed framework uses HLA (High Level Architecture) protocol as the communication protocol. HLA is general purpose architecture for distributed computer simulation systems. With HLA, simulation members can communicate with other simulation members regardless of the computing platforms. Four simulation members are included in the presented chemical process simulation system. They are main simulation member, 3D virtual environment member, virtual control panel member and virtual pneumatic panel member, which respectively simulate controlling program, all chemical equipments, control panel and pneumatic panel in physical chemical engineering system

The human-computer interface of main simulation member is similar to that of controlling program, so during simulation and testing functions, operator feels no difference from physical operations. When simulation or testing function works, team operators can operate the four simulation members to control states of virtual equipments, then 3D virtual environment member can calculate process paths in real-time. If states of equipments or data of sensors are changed, their new states or data with simulation time label will be saved in processes database. During replaying function, the states of equipments or data of sensors are taken from processes database by simulation time sequence, then they are sent to other simulation members, so that 3D virtual environment member is driven to calculate process paths. In monitoring function, communication interface receives UDP datagram from intranet sent by physical system, then the UDP datagram is interpreted by predefined protocol and the states of equipments and data of sensors are obtained, which are also saved in process database and sent to drive other simulation members.

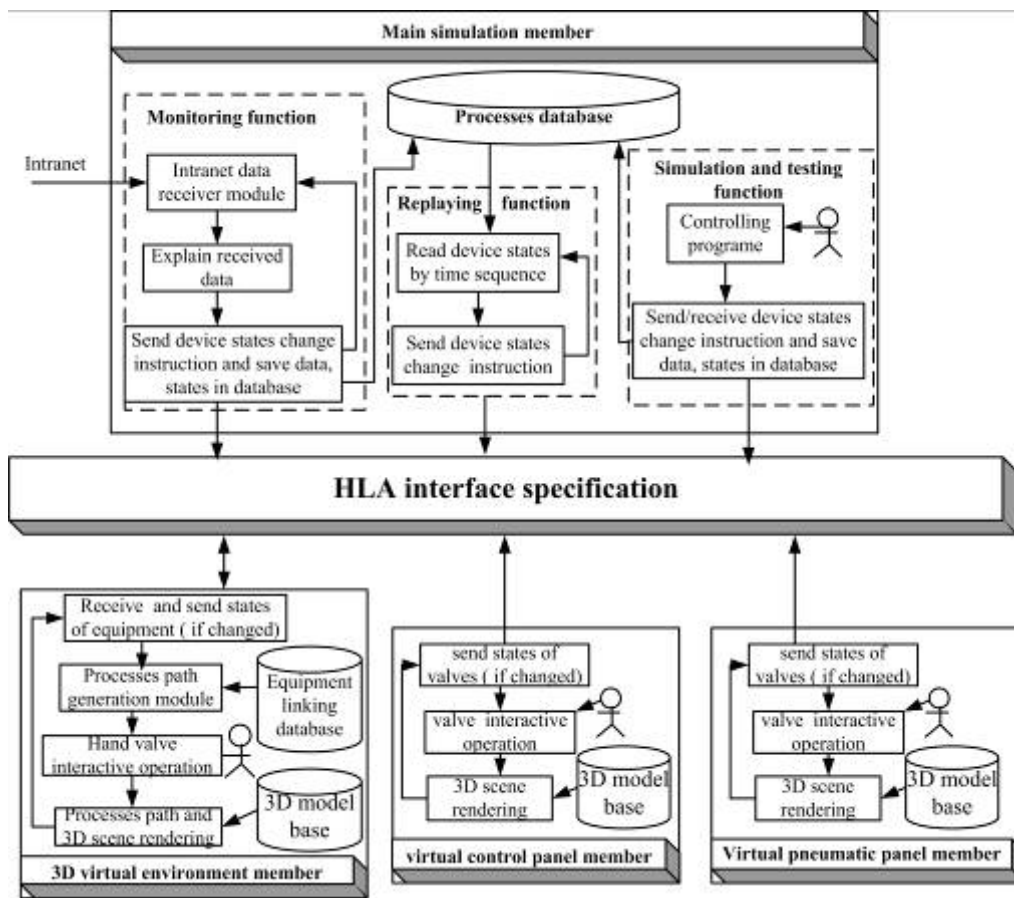


Figure 2. the framework for data-driven simulation

III. VIRTUAL ENVIRONMENT MODELING

For most virtual reality applications, 3D environment modeling is a time-consuming and cost-consuming work, because CAD models are usually represented in parameters and features. However VR models are often represented in triangles in order to accelerate graphic rendering speed. Moreover, most existing VR modeling software has weak ability to define complex mechanical models. Due to the above mentioned reasons, the CAD models, which are expected to be displayed in a virtual environment, should be transformed into triangle models. Although some toolkits can transform CAD models into triangle models automatically, they abandon topology information and assembly (or linking) information which are necessary for the presented simulation system.

This paper presents a method to transform SolidWorks models into topological triangle models with equipment linking relations, which totally meets the needs of the presented simulation system. The model transformation flow is depicted in **Figure 3**. The chemical equipments are modeled using SolidWorks software. Whenever there is a link relation between two equipments (for example valve and pipelines), an assembly constraint will be defined manually between these two equipments in SolidWorks. With secondary development of SolidWorks, the triangle information, topology information and assembly constraints (linking)

information are extracted automatically. Triangle information and topology information are saved in OpenFlight format, which is a hierarchical database format for VR simulation and has become the default standard format in the visual simulation industry. The OpenFlight format files can be compressed using “objconvert” command to accelerate model loading and 3D display. The linking relation among equipments can be modeled by coding number. Method for transforming assembly constraints into linking model will be explained in detail at next section.

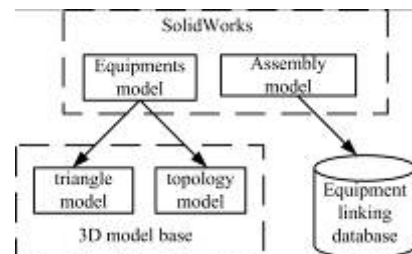


Figure 3. model transformation

The presented model transformation method can transform CAD models to virtual reality models that can be loaded directly in the chemical process simulation system. Practice has proved it can speed modeling greatly in developing virtual reality applications.

IV. PROCESS PATH CALCULATION

Process path is a collection of pipelines that are delivering or will deliver liquid. When some switch equipment is switched on or off, the 3D virtual environment member should calculate new process path, and mark the process path with certain color. This paper presents a method to calculate process path using equipment linking database and current states of all switch equipments such as valves, pumps, tee pipes and storage tanks. Tee pipes and storage tanks are regards as normally open switch equipments.

The principle of presented method is shown in **Figure 4**. During SolidWorks modeling stage, all valves, pumps, tee pipes and storage tanks are coded manually with numbers less than 1000, and each linking relation between two equipments are defined with an assembly constraint. By program traversing assembly constraint list, two switch equipments at the ends of each pipeline can be found, then the pipeline is coded by program with combination of coding for these two switch equipments. For example, if a valve number is 45, and a tee pipes is 308, then the pipeline between these two switch equipments is coded automatically with 45308, with small number before large number. Coding number, type and link relations of equipments are stored in database named equipment linking database automatically with secondary development of SolidWorks.

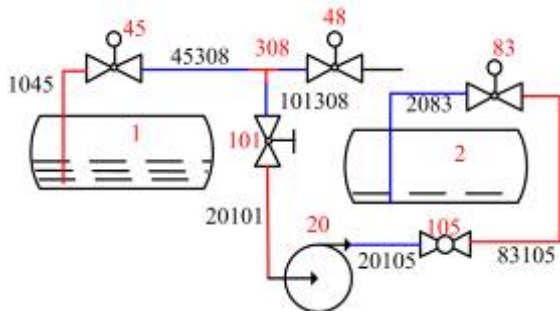


Figure 4. equipment coding and process path generation

The valves are classified into two classes, namely normal valve and tank valve. Tank valve type is the valves connected directly to storage tank. For example, in Figure 4, both valve 45 and valve 83 belong to tank valve type. During running stage, the process path generation module will search process path from each opened tank valve. Only if another tank valve is reached, is the path a valid process path. For example, if valves 45, 101, 105, 83 and pump 20 are switched on, the process path generation module will get a valid path 1045-45-45308-308-101308-101-20101-20-20105-105-83105-83-2083. When there is switch equipment which is opened or closed during last frame, the process path generation module will start a new calculation, and a new process path is updated.

V. OBJECT PICK-UP AND OPERATION

This paper used Vega software as 3D scene rendering software, The Vega software can not only load and display OpenFlight format model, but also provide some

other interfaces such as special effect, object management, navigation management and so on. Two most important functions of the developed pipeline simulation are state query and operation of device. The first step to operate a valve or display related state information of virtual device is to pick up a virtual prototype. This paper used the following workflow to pick up a virtual prototype.

- (1) At the initialization of the system, a vgPicker type variable (picker) is defined. Then Vega API "vgAddFunc (pick, VGPICK_PICKED, symshow ,mydata)" is used to define a callback relation, which indicates that the function named "symshow()" will be executed whenever a virtual prototype is picked up using vgPicker type variable named "picker".
- (2) During system running, whenever the left button of mouse is press, the Vega API vgPerformPickProcessing(pick, postown) will be executed to do 3D scene intersection test using mouse position and viewer position (postown). The first virtual prototype lying under mouse on the display screen will be picked up.
- (3) In callback function "symshow()", the Vega API "vgGetPickerPickedPart (pick)" is used to get part being picked up, which name can be obtained using function "vgGetName()". With the name of part being picked up, all related information can be queried from database.

The Vega application provides a meter module which can display characters overlay 3D scene, but with the meter module, only alphabet and numeric characters can be displayed and Chinese characters can not be displayed directly on the screen. This paper designed a Chinese characters display interface using OpenGL API. This interface display Chinese characters in bitmap manner, so all related information can be displayed smoothly.

In order to enhance the reality of system simulation, manual valves should be switched on or off in 3D scene by rotating handgrips. This paper designed a manual valves class which can make operators to rotate handgrips interactively. In virtual reality software named creator, the handgrips of manual valves are define as a DOF (degrees of freedom) nodes, so that the position and orientation of handgrips can be changed during simulation. After a handgrip is picked up, the right and left buttons are used to switch handgrip on or off. If the right button is pressed, the handgrip will be switched on and vice versa.

VI. MATHEMATIC MODEL OF FLUID

Mathematic model of fluid is one of key issues in pipeline simulation. In this simulation, parameters including flowing speed, flux and pressure in any position of the pipeline at any time are required to be calculated in real time. By modeling fluid for typical pipeline system, the mathematical model for constant flowing and instant

flowing of fluid in specified pipeline are constructed using Bernoulli's equation.

A simple diagram of pipeline system is shown in **Figure 5**. Suppose the system is long pipeline system and the fluid is constant fluid, so Bernoulli's equation can be applied. The fluid in pipeline is regarded as ideal fluid which has small viscosity and high Reynolds number, and the ideal fluid mechanics theory can be used to model the pipeline system.

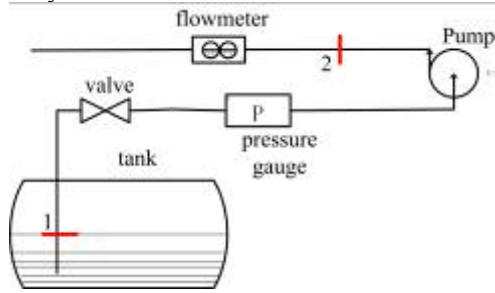


Figure 5. simple diagram of pipeline system

A. Instant flowing

In instant flowing, the mathematic model of fluid in pipeline is listed in Equation (1).

$$gz_1 + \frac{p_1}{\rho} + \frac{u_1^2}{2} + W_s = gz_2 + \frac{p_2}{\rho} + \frac{u_2^2}{2} + \sum h_w + \frac{1}{g} \int_1^2 \frac{du}{dt} dl \quad (1)$$

In which, W_s is the shaft power of pump;

z_1 and z_2 are the heights of pipeline cross section;

p_1 and p_2 are the pressures of fluid at height z_1 and z_2 respectively ;

ρ is the density of fluid, which is a constant, because of incompressibility of fluid;

u_1 and u_2 are the flowing speeds at cross section z_1 and z_2 respectively ;

$\sum h_w$ is the total resisting force between z_1 and z_2 , including tube resistance and local resistance;

For stream with constant cross-sectional area, the acceleration of fluid is the same at any given time, that is $\frac{\partial u}{\partial t} = a$. As shown in **Figure 5**, suppose cross section 1

lies at fluid level of tank, $z_1 = 0$ and cross section 2 lies at fluid head of pipeline. Since the cross-sectional area of tank is much larger than that of pipeline, u_1 , which is the flowing speeds at cross section 1, can be regarded as 0, that is $u_1 = 0$. p_2 , which is the pressure of fluid head, can also be regarded as 0. p_1 and W_s are known.

The total resisting force includes tube resistance and local resistance. In this paper, the Reynolds number is supposed to be less than 2000, so motion of fluid belongs to laminar flow. The tube resistance h_t of pipeline is estimated as following.

$$h_t = \frac{32ulv}{d^2} \quad (2)$$

In which, l is the length of fluid head; d is the inner diameter of pipeline.

The local resistance h_l is involved by connecting pieces in pipeline system, such as valves, tee pipes, elbows and other meters. In this paper, the properties of connecting pieces are saved in database. During running, these properties can be queried and equivalent resistances can be looked up, then the equivalent length h is calculated using method described in [8], and $h_l = hg$. So Equation (1) can be rewritten as following.

$$0 + \frac{p_1}{\rho} + 0 + W_s = gz_2 + 0 + \frac{u_2^2}{2} + \frac{32u_2lv}{d^2} + hg + a_2l \quad (3)$$

Supposing $l = l(t)$, which is length of fluid head, then $u_2 = \frac{dl(t)}{dt}$, $a_2 = \frac{d^2l(t)}{dt^2}$. So the Equation (3) can be rewritten as following.

$$0 + \frac{p_1}{\rho} + 0 + W_s = gz_2 + \frac{1}{2} \left[\frac{dl(t)}{dt} \right]^2 + \frac{32l(t)v}{d^2} \frac{dl(t)}{dt} + hg + \frac{d^2l(t)}{dt^2} l(t) \quad (4)$$

In which, t is the simulation time, u_2 is speed of fluid head, and v is the viscosity of liquid.

B. Constant flowing

In constant flowing, the mathematic model of fluid in pipeline is listed in Equation (5).

$$gz_1 + \frac{p_1}{\rho} + \frac{u_1^2}{2} + W_s = gz_2 + \frac{p_2}{\rho} + \frac{u_2^2}{2} + \sum h_w \quad (5)$$

Similar as instant flowing, $z_1 = 0$, $u_1 = 0$, both p_1 and W_s are known. In constant flowing, since the fluid is incompressible and density of liquid is constant, the flux W is an invariant, which can be expressed with flowing speed u as following.

$$W = \frac{\pi d^2}{4} u \quad (6)$$

In this paper, the critical flux of instant flowing is regarded as flux of constant flowing. Using Equation (4), the critical flux of instant flowing W can be calculated. With Equation (6), u_2 in Equation (5) can be estimated.

So the pressure p_2 in constant flowing can be calculated as following.

$$p_2 = p_1 + \rho W_s - \rho g z_2 - \frac{u_2^2 \rho}{2} - \rho \sum h_w \quad (7)$$

With Equation (4), Equation (5) and Equation (7), the position of flowing head in instant flowing, flux and pressure in constant flowing can be estimated. But all aforementioned equations are continuous, which can not be used directly for programming. So fourth order Runge-Kutta method is employed to discrete the continuous equations.

VII. SYSTEM DEVELOPMENT

In order to explore the effectiveness and usability of the presented framework and methods, the pipeline simulation system was developed on windows OS using VC++ integration environment. The screenshot of the developed system was shown in figure 6. 3D scene modeled using SolidWorks was transformed to OpenFlight files which were compressed into “.fst” suffix format using tools provided by Vega software, so the model was reduced and the rendering efficiency was enhanced. Vega was used as virtual reality rendering software. At present the system is put into practical use, and now is playing an important role in chemical process training, monitoring and replaying of the existing system introduced at section 2 of this paper.



Figure 6. Screenshot of developed system.

VIII. CONCLUSIONS

In order to reduce danger and cost in physical chemical process training and testing, this paper proposed a pipeline simulation system based on distributed virtual reality technologies. Firstly a data-driven simulation

framework was proposed. Then an AR modeling method for pipeline simulation and a process path calculation method were presented. In order to operate virtual prototypes and display related information, a virtual prototypes pick-up method was further analyzed. At last, the mathematical model for constant flowing and instant flowing of fluid in pipeline system are constructed using Bernoulli's equation. The presented pipeline simulation system has abilities of chemical process training, monitoring, testing and replaying.

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