A DISTRIBUTED VIRTUAL REALITY SYSTEM BASED ON REAL-TIME DYNAMIC CALCULATION AND MULTI-PERSON COLLABORATIVE OPERATION APPLIED TO THE DEVELOPMENT OF SUBSEA PRODUCTION SYSTEMS

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SUMMARY

To train inexperienced workers for the construction, production, and maintenance of subsea production systems, a virtual reality simulation platform was developed. The entire framework, software, and hardware platforms of the system were designed and introduced. A multi-person collaborative simulation was achieved based on the high-level architecture protocol. The real-time dynamic calculation software Vortex was used to add physical properties to each geometrical model and set collision detections and motion constraints so that the VR system can reflect the real motion response of the structures in real-time during virtual simulation. Visual simulation software Vega Prime and Vortex were integrated to realise the real-time rendering and drawing of virtual ocean engineering scenes. Thus, a virtual simulation system with large-scale complex scenes based on real-time dynamic calculation and multi-person collaborative operation was established. A typical ocean engineering case of subsea manifold installation was simulated using the virtual simulation system, and the detailed simulation flow was explained. A multibody dynamics system of the ship-cable-subsea manifold was established using Orcaflex to obtain the accurate motion response of the subsea manifold during lowering. In the virtual simulation process, the obtained hydrodynamic calculation results can provide an important guideline and reference to the operators. The developed simulation system is a suitable tool for training ocean engineering workers and realistically simulating ocean operation cases.

1. INTRODUCTION

With the progress made in the virtual reality (VR) technology and the development of computer software and hardware, the application of virtual simulation has become increasingly extensive. VR technology has evolved from military and simulation trainings to entertainment, education, medical treatment, architecture, and other fields. Based on a precise computational fluid dynamics simulation, a series of data conversion techniques and real-time processing framework were proposed by Cha *et al*. (2012) for developing a fire training simulator, which can calculate various invisible physical quantities, such as toxic gases and heat, and visible factors, such as smoke and flame. Cultural heritage is a precious resource, based on VR methodologies Jiménez Fernández-Palacios *et al*. (2017) presented a visualisation pipeline that was developed to exploit and access large and complex heritage three-dimensional (3D) contents in an easy and interactive way. Li *et al*. (2018) used virtual simulation as an auxiliary tool for radiation protection and dose assessment, and a simple voxel model for virtual humans was also proposed. They proposed dose assessment and visualisation methods for virtual humans in a radiation environment based on a voxel model. Using VR, Pérez *et al*. (2019) studied the synergies between VR and robotics and presented the use of commercial gaming technologies for creating a totally immersive environment. For helicopter emergency rescues, Sun *et al*. (2020) proposed a novel VR-based evaluation model to train the crew, which was suited for complex missions involving multiple tasks, scenarios, and persons. Using the adaptive game-based learning concept, Feng *et al*. (2020) presented a customisation framework for an immersive VR and serious games, which was suitable for earthquake emergency trainings.

Due to the complexity of ocean environmental conditions and considerable investments in ocean projects, it becomes necessary to use the VR technology to simulate the process of practical operations. Many researchers have carried out many studies on virtual simulations involving ocean engineering to provide training and demonstration platforms for inexperienced workers. For marine applications, Chen *et al*. (2012) designed a 3D VR and visualisation engine, named as VV-Ocean, to render the ocean. A sea-land integration platform was established using VV-Ocean that can reproduce the drifting and diffusion processes of oil spilling from the seabed to the sea surface. Zhang *et al*. (2016) designed the architecture of a VR system and crane simulator used for simulating deep-water installations of subsea production facilities. A mathematical model was proposed for the response analysis of a multibody system comprising vessel, crane, cable, and lifted equipment. Based on a precise dynamic calculation, Yu *et al*. (2017) proposed a real-time virtual simulation method to develop a lifting and installation simulator. This VR system can be used to train and evaluate both offshore installation and subsea emergency maintenance in ocean engineering. In the early stages, before actual operation, it is difficult to observe the potential risks of lifting or turn-over operations. Li *et al*. (2019) proposed an integrated method for a collaborative simulation that allowed multiple workers to operate together in a virtual environment to predict the risks and reduce the possibility of accidents. Wang *et al*. (2019) presented a comprehensive description of an innovation training program and its successful application. It mainly included the VR simulations of offshore fields, numerical and visual modelling for met-ocean environment, and DP2 floatover vessel, as well as key personnel performance when executing floatover operations. Furthermore, based on VR technologies, Ferrara *et al*. (2020) described a virtual drilling system, which can be used as an overall digital twin of the well throughout its lifecycle, including well planning, operations follow-up, and post-analysis.

Subsea production system is a high-investment and high-risk technology that has dominated the exploration of deep water oil and gas fields because of its economic superiority (Cao *et al*., 2016). The main equipment of the subsea production system includes subsea manifolds, subsea trees, and pipeline end terminations. Subsea equipment is affected by strong nonlinear environmental loads during deep water installations, such as wind, wave, and current loads. This easily causes structural damage, such as deformation and bending, thereby resulting in installation failure.

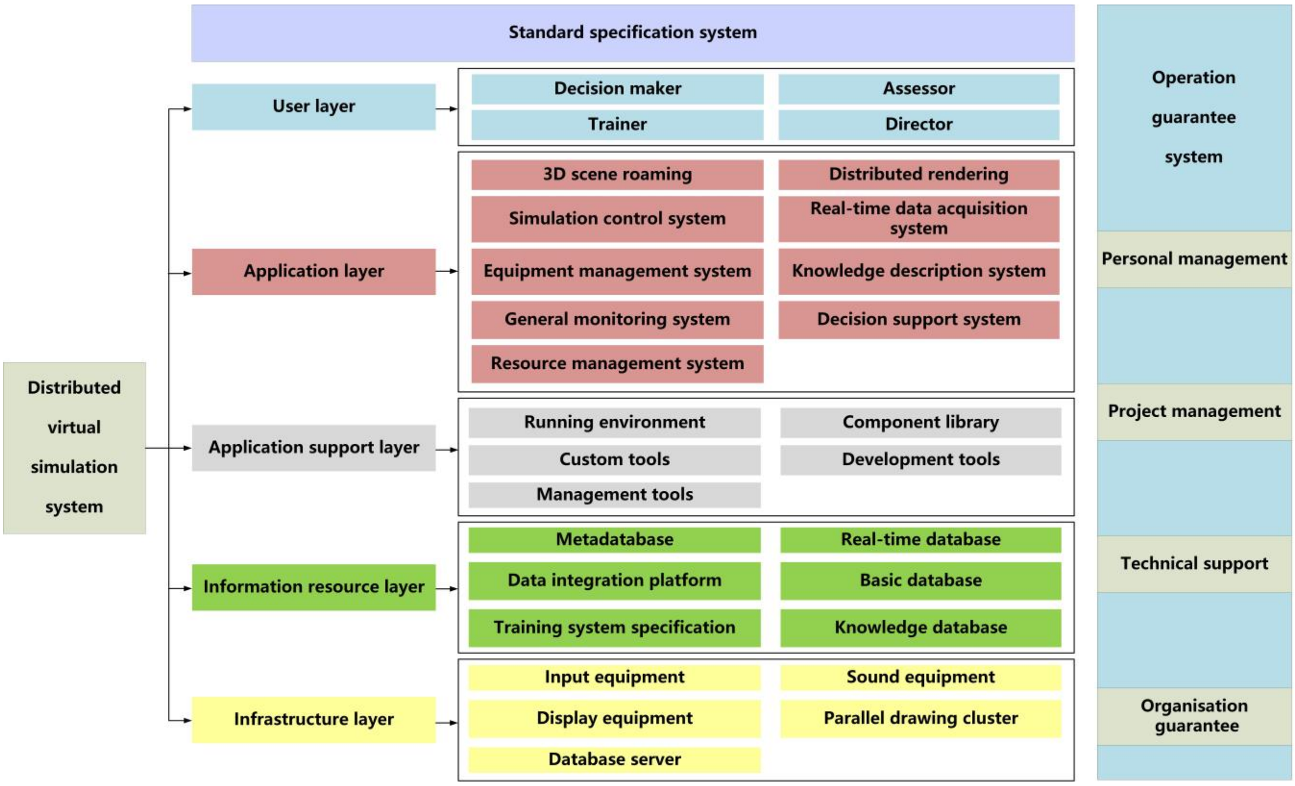

Figure 1: Fundamental architecture of the distributed virtual simulation system.

In this study, a distributed virtual simulation system was designed and developed to simulate the construction, production, and maintenance of a subsea production system. None of the above-mentioned VR systems have a wide simulation range for subsea production systems. The proposed simulation system is a distributed VR system composed of multiple simulation subsystems, oriented to large-scale and complex ocean scenes, and also allowing multiple persons to work in the same virtual environment. Nodes of different hardware and operation subsystems can coexist in the same system. This system not only contains a real-time simulation performance, but also high-precision hydrodynamic calculation capability. To improve the operating efficiency of the operators, and better control the motion attitude of the subsea equipment, the same ocean operating environment and structures with the VR system were established in the professional hydrodynamic analysis software Orcaflex. The accurate and detailed motion response prediction of structures was conducted for workers to understand the movement of subsea equipment before actual operation. VR system provides a training and cognitive platform for inexperienced workers to perform virtual practices, and offshore operators can be effectively trained and examined at low risk and cost. The entire development process of a subsea production system can be understood in a 3D and intuitive manner.

2. KEY POINTS FOR THE DEVELOPMENT OF A DISTRIBUTED VIRTUAL SIMULATION SYSTEM

2.1 FUNDAMENTAL ARCHITECTURE

This distributed virtual simulation system is suitable for simulating large-scale and complex scenes, mainly reflected in following aspects. The system has a mass of virtual scenes, and the operation of the virtual scenes and geometrical models requires many hardware input devices. Furthermore, a large amount of data needs to be calculated in real-time during the running of the virtual simulation system. Large-scale 3D ocean environments, atmospheric environments, and various subsea equipment must be rendered, drawn, and displayed in this VR system. The virtual scene data of the distributed simulation system include basic geographical and massive program application data. Therefore, considering the availability, maintainability, and extendibility of the system, a multi-tier logical architecture was adopted, as shown in Figure 1.

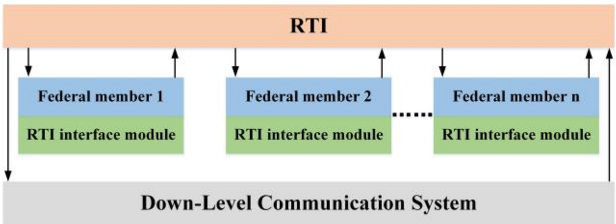

Figure 2: Logical structure of the simulation federation.

The multi-tier logical architecture was mainly divided into seven layers: infrastructure, information resource, application support, application, and user layers, and operation guarantee and standard specification systems. The infrastructure layer is located at the most basic position in the entire system, providing basic services, such as network transmission, computational power, and storage space. The information resource layer mainly included training tasks, multiple databases, and the data needed for system application. The application support layer was established based on the hardware network and software platform, which directly provided services for specific application software. The application support layer is a service platform that encapsulates public and bottom services needed to be solved to establish the application software. The application support layer can rapidly realise the construction of an application system. The application layer can be used to realise the application of a virtual simulation system, including 3D scene roaming, real-time data acquisition, simulation control, and distributed rendering. The user layer can provide access to a variety of information resources to the decision makers, assessors, trainers, and directors. The user layer can be used to share various information resources, unify their management, and centralise the access to information. The operation guarantee system contains personnel management, project management, technical support, and organisation guarantee needed for the construction and maintenance of the VR system. The standard specification system is the foundation for guiding the construction of the entire system.

2.2 SCHEME OF MULTI-PERSON COLLABORATIVE OPERATION

The distributed virtual simulation system for large-scale complex scenes is composed of multiple simulation subsystems. The scheme of multi-person collaborative simulation based on high-level architecture (HLA) was employed in this present study. HLA technology divides federal members and constructs a simulation federation based on an object-oriented method (Solberg, 1993), which can be used to realise the interoperability and reusability of the distributed simulation system. In an HLA application, any number of physically distributed simulation systems can be combined into a unified simulation environment to satisfy the needs of new applications (IEEE 1516.3, 2003). In a simulation system based on HLA, a federation is established to achieve specific simulation tasks using collaborative operations. A federation is composed of several interacting federal members, and all applications participating in the running of the VR system can be called federal members. HLA protocol defines the basic guidelines and methods for federation construction and the interaction between federal members.

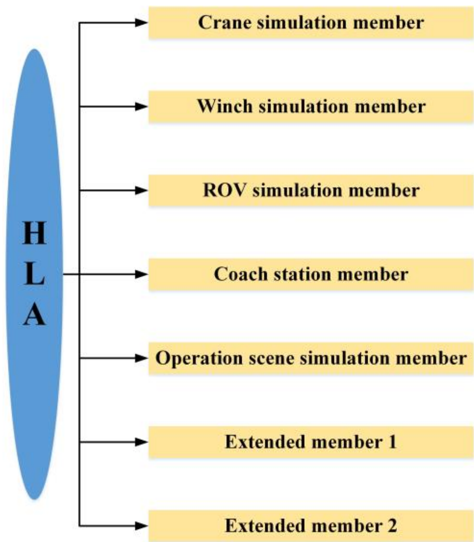

Figure 3: Federal members of the virtual simulation system.

Runtime Infrastructure (RTI) is a service program developed according to the HLA, and can support and synchronise the interactions between different federal members that comply with standard HLA specification, realising the interoperability of federal members (Chen *et al*., 2008). For the distributed simulation system, the running of the federation and interaction between the federal members were realised by RTI, the logical structure of simulation federation is shown in Figure 2.

According to the task object, architecture, and operating process of the system, the federal design scheme for the distributed virtual simulation system based on HLA was as follows:

- The simulation system was set to the federation.
- A specific simulation case was set for federal execution.
- The simulation device that undertakes the simulation task was set to a federal member.
- The operating flow of each simulation facility and relationship between the facilities were standardised and abstracted to establish the object model of the federation.

Based on the above design scheme, the distributed virtual simulation system was divided into seven federal members, as shown in Figure 3.

2.3 HARDWARE PLATFORM OF THE VIRTUAL SIMULATION SYSTEM

The simulation system is mainly composed of six simulation subsystems, namely operation, communication, control, display, audio, and solution subsystems. Based on the HLA protocol, a distributed network was established to integrate the federal members to perform collaborative operations on the same platform. The construction scheme of the hardware platform is shown in Figure 4.

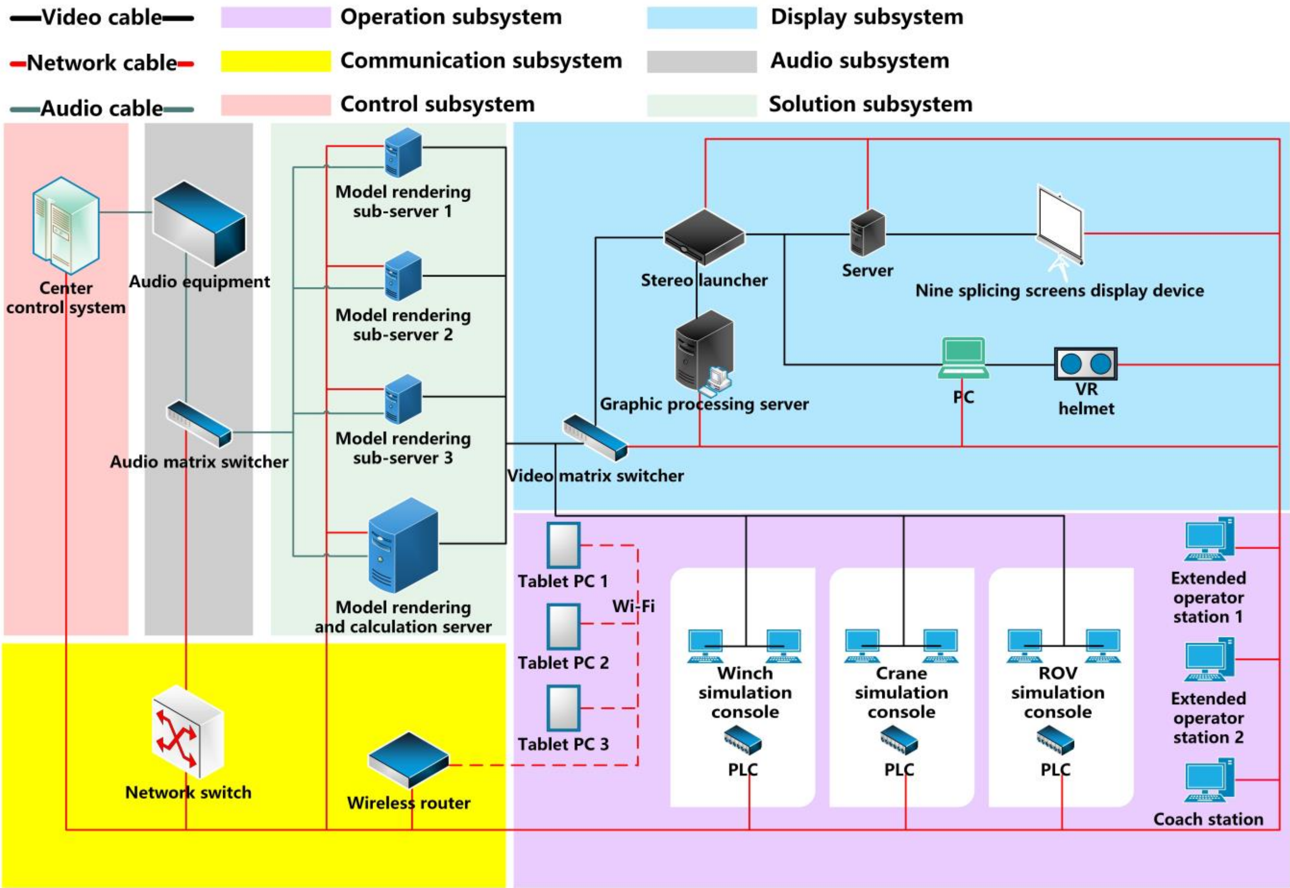

Figure 4: Schematic diagram of the hardware system integration.

The operation subsystem generates instructions to drive simulation scenarios, with the main hardware being a coach station, crane, winch, remotely operated vehicle (ROV) simulation consoles, tablet personal computer (tablet PC), and extended operator station. The communication subsystem ensures the communication between the subsystems, with the hardware being a network switch and wireless router. The control subsystem centrally controls the output of the sound and video signals, which can significantly improve the operating efficiency of the user. The main hardware of the control subsystem is a high-performance Hewlett-Packard (HP) workstation. The display subsystem displays virtual scenarios in real-time, with the main hardware being a nine splicing screens display system and VR helmet. The audio subsystem outputs sounds during a virtual simulation, with the main hardware being a sound console, power amplifier, sound box, and audio matrix switcher. The solution subsystem calculates the motion response of geometrical models and generates corresponding virtual scenarios based on the instructions of the operation subsystem, and simultaneously sends visual images to the display subsystem. The main hardware of the solution subsystem is a model rendering and calculation server, and three model rendering sub-servers.

The overall layout of the VR system is shown in Figure 5. A winch simulation console simulates the various operations of the winch in practical installation, and has the monitoring and alarm functions. A crane simulation console was applied to simulate actual offshore crane operations that can collect different parameters, such as depth, velocity, and angle of subsea structures. An ROV simulation console is mainly used to simulate the various operations of the ROV in actual subsea operations, including grasping, rotating, lighting, and monitoring. OLE for process control (OPC) protocol is used for transmitting data between different consoles and virtual geometrical models. Each console is equipped with two displays and can be applied to display 3D virtual scenes and control parameters, respectively.

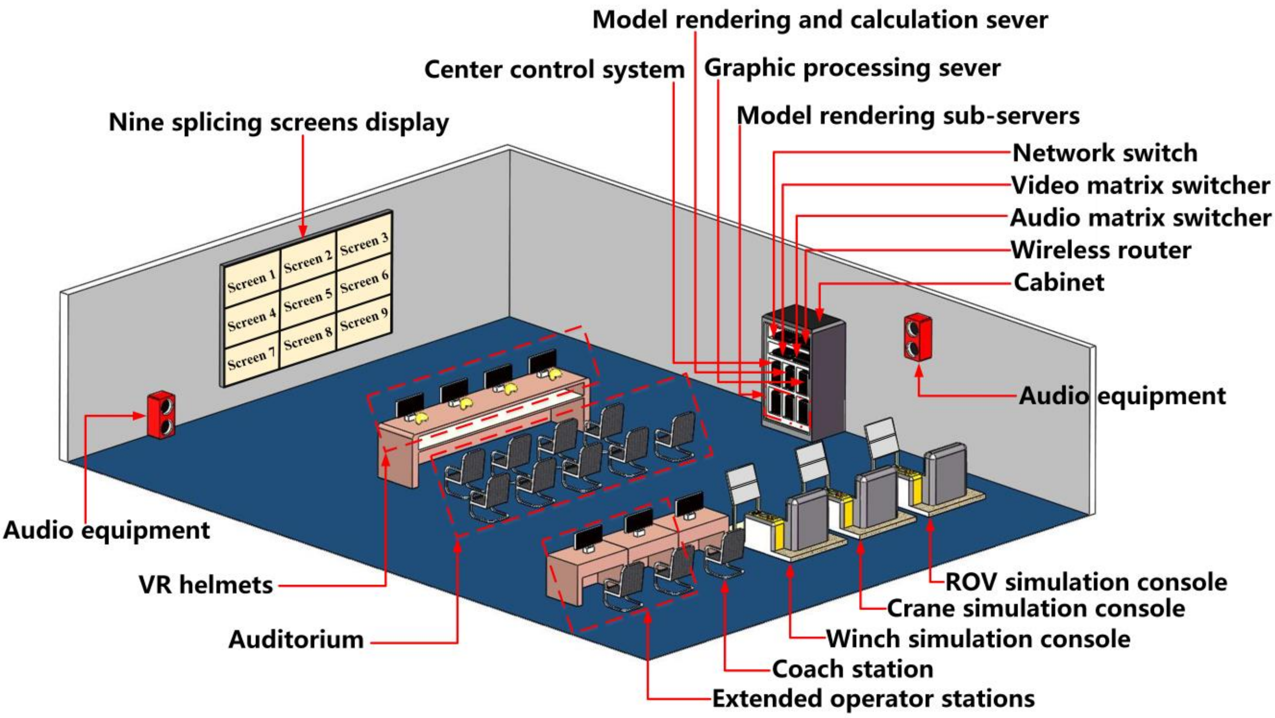

Figure 5: Overall layout diagram of the distributed virtual simulation system.

In the hardware platform, to enhance the advancement, operability, and extendibility of the VR system, a wireless system with mobile touch screen is developed, with the operating signal being issued by the tablet PC. This PC is a part of the operation subsystem to issue operating instructions through the wireless router, which can replace the functions of the winch, crane, and ROV simulation consoles in some aspects. The nine splicing screens display is used to synchronously display the virtual scenes, which has great practicability and flexibility, as shown in Figure 5. The gap between each screen is small enough to realise the integration of nine screens and display large-scale complex offshore operating scenarios. Additionally, each display can be used to separately display a specific viewpoint. This makes it convenient for the operators and viewers to see the entire process of ocean operations from both overall and local perspectives. The VR auxiliary helmet, as a type of display approach, is also used by the viewers, giving them an immersive 3D experience.

2.4 SIMULATION PROCEDURE OF THE SYSTEM

For the distributed virtual simulation system, the integration scheme of the software and hardware platforms is shown in Figure 6. The coach station is the dispatcher, manager, and leader of the simulation system. It is responsible for system initialisation, training process settings, and output information recording. Additionally, the coach station inputs student information, sets system simulation content, monitors, analyses, and scores the operation process, and outputs assessment score.

The start instruction is issued by the coach station. Subsequently, operators control simulation consoles to release the operating instructions. The PLC system installed in the cabinet of the console is used by the operators to acquire real-time data and interact with simulation consoles. Based on the OPC protocol, the communication between the consoles and model rendering and calculation server is realised to actualise the interaction between 3D geometrical models and simulation consoles. According to the operating signal, a model rendering and calculation server are employed to obtain and calculate the information of manipulated objects, such as position and attitude. Afterwards, the motion of these manipulated objects is driven by the model rendering and calculation server. To reproduce large-scale ocean scenes in real-time, video matrix and windows processor run synchronously with the model rendering and calculation server. The related simulation scenes are output by the display subsystem. Based on the HLA protocol, the calculation data obtained by the model rendering and calculation server are fed back to the simulation consoles in real-time. Operators can operate the next simulation step based on the response data of the virtual models. Thus, step-by-step operating cycle constitutes the entire simulation process.

3. VEGA PRIME-BASED VISUAL SIMULATION

In this study, the modelling tool Creator and visual simulation platform Vega Prim were used to develop simulation scenes. Creator modelling software was used to create the required geometrical models for virtual simulation. Vega Prime was applied for virtual scene generation, and the LynX Prime interface of Vega Prime was applied to set the environmental parameters of the virtual scenes.

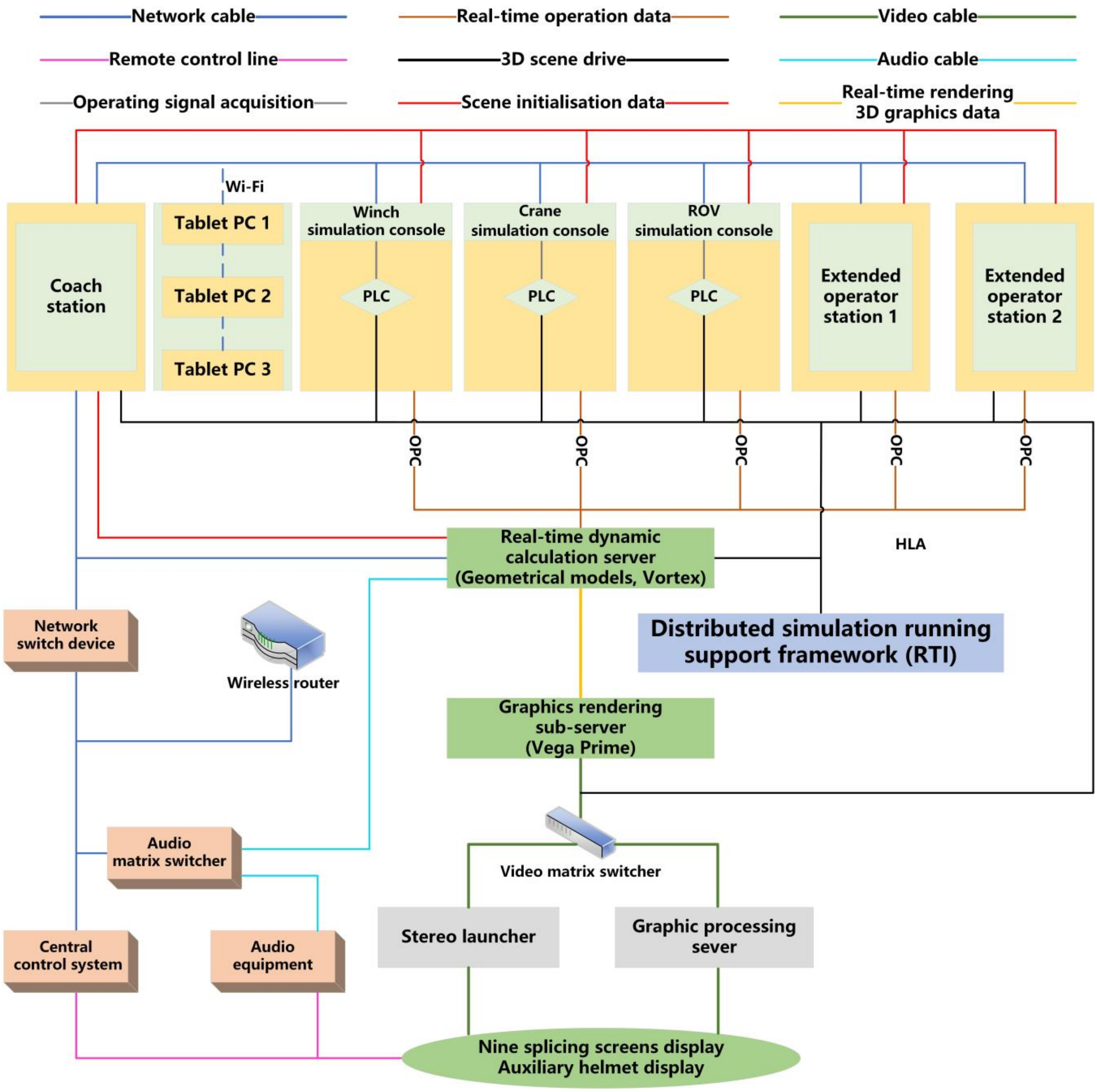

Figure 6: Schematic diagram of the integration of software and hardware platforms.

3.1 MODELLING TOOL FOR 3D GEOMETRICAL MODELS

Creator is a simulation modelling software mainly used in VR systems. The powerful polygon modelling function and texture application tool can be used to establish a highly realistic and optimised 3D models. Creator is mainly advantageous for modelling because it contains some critical technologies. The level of detail (LOD) technology of Creator can be used to improve the real-time performance of running a simulation system. LOD technology reduces the complexity of the scene and realises its real-time rendering by extracting a series of simplified models that can reflect important features from the most primitive and accurate models. Additionally, LOD technology uses interactive nodes for modelling. During the modelling process, the model can be conveniently modified, thus, significantly reducing the time required for model creation and improving the operating efficiency of the simulation system.

Degree of freedom (DOF) is used to describe the response characteristics of the physical field of a simulation system. It defines the position of a geometrical part in relation to its parent node, thus, enabling the simultaneous movement of the parts of the geometrical model to ensure the ability of relative movement. Texture technology can be used to make geometrical models to obtain realistic visual effects without increasing polygon numbers. Texture refers to a two-dimensional image mapped onto the surface of a 3D model. The original texture material can be obtained by shooting or scanning various pictures, and subsequently using the picture processing software to edit accordingly.

3.2 VISUAL SIMULATION FOR VIRTUAL OCEAN ENVIRONMENT

Vega Prime is a 3D visual simulation platform, mainly used in real-time visual simulations, sound simulations, and other fields. Vega Prime is used for creating virtual sea and atmospheric environments, establishing the scene library, storing different scenarios needed for establishing a virtual environment, and rendering ocean optical effects. Scenes generated by Vega Prime can be presented to the operators and observers in real-time during the running of the simulation system.

LynX Prime graphic interface tool is a critical part of Vega Prime, and can be used to set environmental and operating parameters easily and quickly. LynX Prime generates an application configuration file (ACF), that can significantly reduce the operational difficulties of the users. ACF contains the data required during the initiation and execution of the program, which mainly includes geometrical models, virtual scenes, and physical properties. LynX Prime interface enables us to see a clear and intuitive hierarchy of scene graphs, and also create relationships between these graphs. Additionally, users only need to set simulation parameters using the LynX Prime interface to complete the configuration of the ACF, thus, simplifying the development process of a virtual ocean environment.

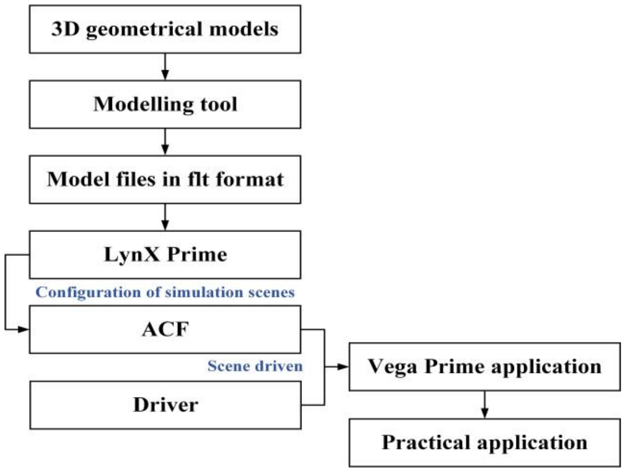

Figure 7: Schematic diagram of Vega Prime development in this VR system.

As a professional visual simulation software, Vega Prime has its own independent development flow. In this distributed VR system, geometrical modelling tool can be combined with Vega Prime to perform visual simulations, the development flow as shown in Figure 7. The development process mainly includes 3D modelling, file configuration, scene driven, and practical application. 3D modelling is mainly used to create the required geometrical models using professional modelling tool. LynX Prime is used to load geometrical models and configure simulation scenes based on the needs of the virtual simulation, and subsequently generate the ACF. The scene driven is a critical part of a visual simulation program, and based on the scene driven, the predetermined simulation effects can be obtained and optimised. Finally, a visual system is developed and issued for practical application.

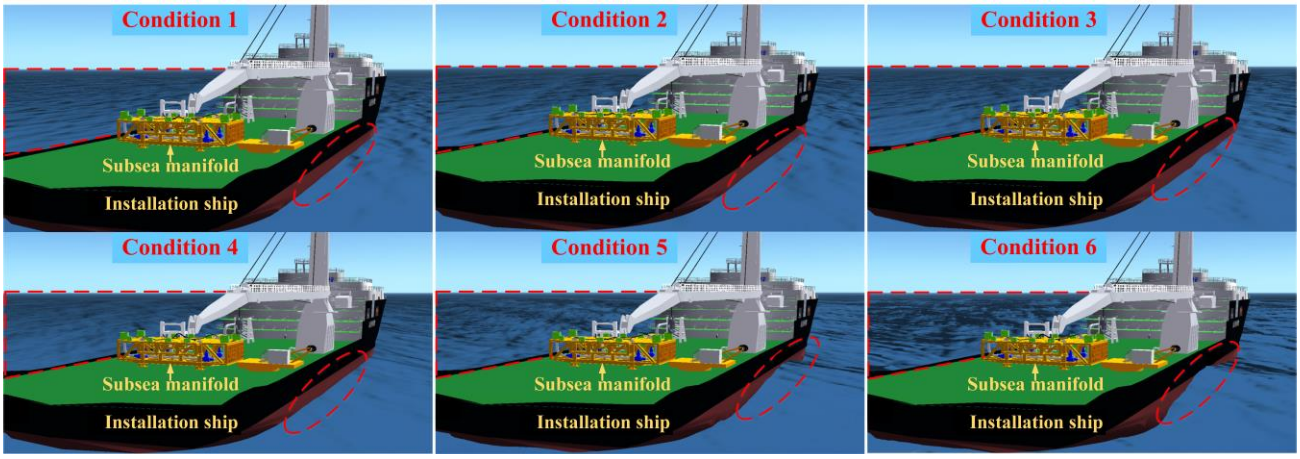

Figure 8: Virtual simulation scenes in different ocean environmental conditions.

To simulate a virtual 3D ocean environment, rendering realistic ocean water effects during the simulation is necessary. Vega Prime Marine module can be used to create four different fluid surfaces. vpMarineOceanFixedLocation can be used to simulate a fixed area and static water surface. vpMarineOceanObserverCentered can be used to set the viewpoint location of the observers to the drawing centre, and set the observation range to the drawing range, thus, simulating the wave effect of the dynamic ocean surface. vpMarineOceanSurfZone can be used to simulate wave impacts on coasts and structures. vpMarineOceanTechnique can be used to simulate large-area and irregular ocean zones.

Table 1: Ocean operational conditions.

Items (unit)	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5	Condition 6
Water depth (m)	1500–2000	1500–2000	1500–2000	1500–2000	1500–2000	1500–2000
Wave height (m)	0.12	0.16	0.18	0.27	1.22	2.13
Wave frequency (rad/s)	0.90	0.90	0.84	0.84	0.71	0.65
Wind velocity (m/s)	0.5	2.0	5.0	8.5	15.0	20.0
Current velocity (m/s)	0.8	1.0	1.2	1.5	1.8	2.0

Table 2: Geometrical models for the virtual simulation case.

Equipment	Function	Number
Installation ship	Ship equipped with crane and winch. Used for lifting and lowering the subsea manifold.	1
ROV	Includes cable, robot arm, lighting equipment, and propeller. Used for adjusting the attitude of subsea manifold, aligning the subsea manifold and guide base.	1
Guide base	Installed on the seabed to lock the subsea manifold.	1
Sling	Used to connect the cable and subsea manifold.	Several
Subsea manifold	Main equipment of the subsea production system.	1

In the visual simulation of ocean engineering, six operational conditions were designed based on the actual ocean operating environment, as shown in Table 1. Corresponding virtual scenes were rendered by Vega Prime according to the listed parameters, as shown in Figure 8. This indicated that the distributed simulation system could obtain a good visual effect of the virtual ocean environment, with the rendering results being close to the real environmental status. Comparing the dashed line parts in these sub-pictures, it can be seen that under different environmental conditions, wave height and frequency significantly changed, and the visual effect of the wave surface was evidently different.

4. MULTIBODY DYNAMICS SIMULATION IN THE VR SYSTEM

4.1 ESTABLISHMENT OF A PHYSICAL MODEL

Simple geometrical models do not contain real-world physical properties, thus, to obtain realistic simulation results, virtual simulation process needs to consider the effect of physical dynamic factors. Vortex is a dynamic simulation software used for dynamic modelling and real-time dynamic calculation during a VR simulation, which emphasises both accurate dynamic calculation and real-time virtual simulation. Vortex can address highly realistic dynamic problems, such as fluid-structure interaction and collision interference. Using the hierarchical structure method, as shown in Figure 9, Vortex abstracts the established rigid body models into physical models with dynamic and kinematic properties, which can make the simulation results similar to the actual motion law. Multibody dynamic characteristics, such as collisions and rigid body constraints, can be realised.

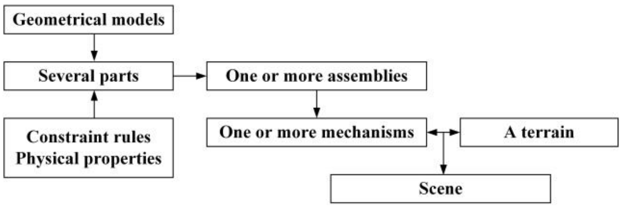

Figure 9: Diagram of the hierarchical structure of Vortex.

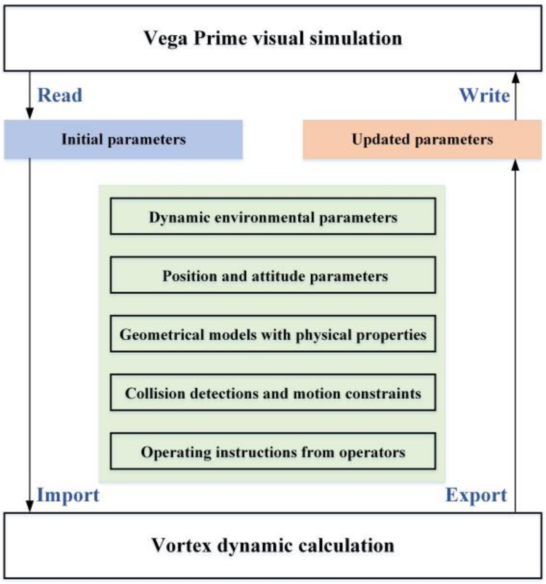

Figure 10: Integration of Vortex and Vega Prime.

During the establishment of 3D virtual models, some models should be divided into several parts for modelling, and subsequently form a body. Therefore, for each part, its physical properties, such as material and mass, can be added to geometrical models using Vortex, with multiple parts forming an assembly. Assemblies contain many constraints and parts. Constraints combine related parts to restrict the motion of the components to simulate real-world movements and behaviours. A mechanism contains one or more assemblies, one or more mechanisms and a terrain form a complete scene. Additionally, during virtual simulation, Vortex can be applied to calculate hydrodynamic forces acting on subsea equipment, and obtain the motion responses of the multibody dynamics system. Therefore, a physical model needs to be established for the distributed simulation system to make simulation results agree with the actual motion law.

It should be mentioned that the reliability of the simulation system mainly depends on the consistency of motion response of the virtual geometrical model with the actual offshore operation, implying that the system must be able to simulate the real physical law. In the simulation system, the core of dynamic calculation is Vortex software, and the reliability of using Vortex to simulate actual subsea installation has been validated. Yu *et al*. (2017) applied Vortex to simulate the subsea installation of a connector installation tool. Regarding the displacement in the x-direction of the lifting object, Vortex simulation results showed good agreement with the results obtained through the finite element software SESAM. Error analysis between Vortex and SESAM showed that all errors were below 10%, which proved the reliability of Vortex.

Dynamic simulations in this distributed simulation system can be divided into rigid and flexible bodies. Most geometrical models in the VR system are rigid bodies, such as ROV, subsea manifold, and guide base. The first step in a dynamic simulation is to establish physical models. The critical steps of physical model establishment are to define collision detection rules, create constraints between the parts, and set the physical properties of the models. Collision detection is the core part of a dynamic simulation. Vortex uses collision detection rules to identify the occurrence of collisions and calculate the corresponding motion responses of the structures. After the physical models are successfully created, they should be imported into the dynamic simulation space to obtain geometrical models with realistic dynamic effects.

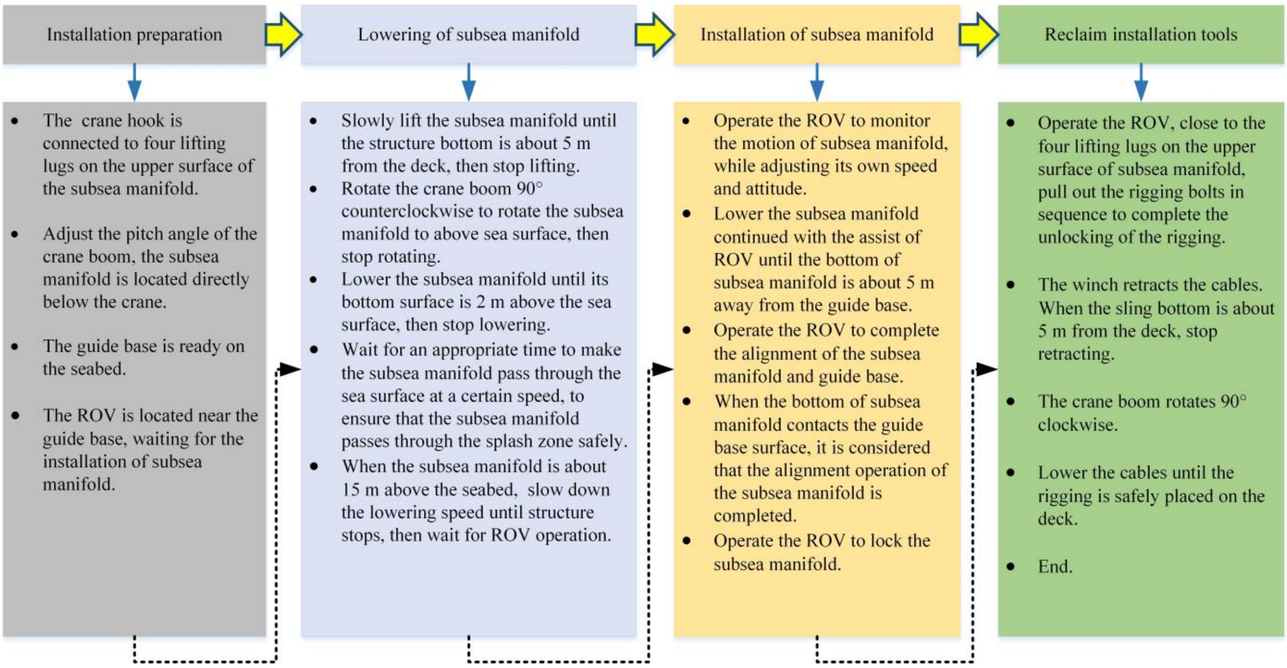

Figure 11: Process flow for lowering and installing the subsea manifold.

The main simulation object of the flexible body is cable, and rigid body dynamic simulation module cannot be used for flexible body simulation. Cable system is usually part of the installation ship and subsea equipment, with its main functions being lifting and lowering the subsea facilities. During cable system establishment, its mechanism must be correctly configured. VxCable is an important module of Vortex which allows developers to easily simulate a flexible body. A lumped element model was applied to simulate the flexible body, that is, the flexible body is discretised into a series of rigid elements. These elements are connected by cylindrical joints with torsion, elongation, and bending properties, and angular spring constraints.

4.2 SOLUTION SCHEME OF VORTEX-ORIENTED DYNAMIC SIMULATION

In this VR system, visual simulation based on dynamic calculation in real-time was realised by integrating the Creator, Vortex, and Vega Prime software. Based on the subsea equipment required for ocean engineering, Creator software created geometrical models corresponding to the actual structures. Every created model was imported to Vortex to load physical properties for establishing physical models. Additionally, collision detections and motion constraints were set in Vortex software. Subsequently, the 3D models with real physical properties, collision, and constraint data were imported to Vega Prime for configuration, such as setting environmental and operating parameters, namely integrating Vortex and Prime.

The dynamic calculation process of the distributed simulation system includes the integration of Vortex and Vega Prime, which can be divided into three stages, as shown in Figure 10. In the first stage, Vortex reads the key dynamic data from Vega Prime, including the position and attitude parameters of geometrical models, environmental parameters, collision detections, and motion constraints. Additionally, operating instructions from the operators are transmitted to the Vortex solver using the OPC protocol. In the second stage, based on the data obtained from the first stage, real-time dynamic calculation is performed using the Vortex solver to calculate the motion responses of the geometrical models in a dynamic environment. In the third stage, based on a series of calculated data, the virtual simulation system updates the initial parameters of the current frame to obtain the corresponding updated parameters, and transmits them to Vega Prime. Subsequently, based on the obtained motion responses of the multibody dynamics system, such as the data of displacements and rotations of subsea equipment, Vega Prime renders and draws the virtual scenes. The above three stages update the dynamic parameters of geometrical models with physical properties in the current frame, ensuring that the motion responses of all geometrical models exhibit real physical effects.

While developing the virtual simulation system, a series of tests against some actual installation processes were conducted, such as simulation performance test based on hydrodynamic calculation, software module test, and hardware integration test. These tests were conducted to validate the stability, real-time, and temporal and spatial consistencies of the system. For these tests, a series of technical and economic indicators were set, such as the operation delay of each operation unit (e.g. handles and buttons) should be less than 500 ms, and after 6 h of continuous operation, the system should run smoothly without jams and delays. After many systematic tests, each test satisfied the predetermined requirements. This proved that the simulation system was suitable for simulating an actual subsea installation.

5. RESULTS AND DISCUSSION

In this section, the development and running of a subsea manifold installation case is described to present the detailed application process and show the simulation effect. Additionally, the multibody dynamics system of the ship-cable-subsea manifold was established in Orcaflex, and the motion response of the subsea manifold during the lowering process was obtained by numerical calculations. Numerical calculation results can be used as important guidelines and references by the operators to complete virtual operations. Based on the calculated motion response of the subsea manifold, operators can efficiently and accurately control its position and attitude using the simulation consoles.

5.1 ENTIRE PROCESS OF THE VIRTUAL SIMULATION OF SUBSEA MANIFOLD INSTALLATION

The first step for a virtual system application is investigating the basic data involving the simulation case and determining the relevant parameters of the environment and installation machines. To make virtual simulations more realistic, accurate, and reliable, providing specific and detailed operation process flow for each simulation case is necessary. The detailed process script developed for the subsea manifold installation is shown in Figure 11. The operators can complete the correct display of the main scene based on the accurate and detailed operating flow script. The subsea manifold installation case mainly involved five geometrical models, including a ship equipped with a winch and crane, ROV, guide base, sling, and subsea manifold. The functions and required numbers of each structure are shown in Table 2.

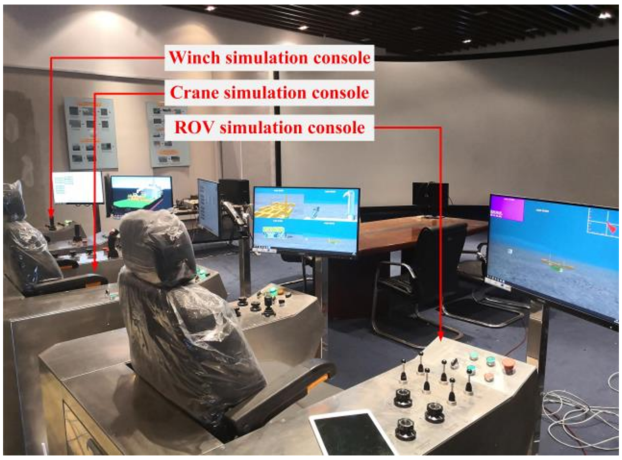

Figure 12: Simulation consoles used in the virtual operations.

3D geometrical models required for this case were established using Creator. These geometrical models were imported into Vortex to load physical parameters and set corresponding collision detections and motion constraints. The operating instructions of the subsea manifold installation are issued by the operators, and the main operating devices include winch, crane, and ROV simulation consoles, as shown in Figure 12. According to the process flow script, operators can control simulation consoles to perform distributed simulation operations based on HLA. The generated operating instructions are transmitted to the solution subsystem using the OPC interface protocol. The real-time dynamic calculation is performed in the model rendering and calculation server, based on the operating instructions, environmental parameters, and 3D models with physical properties.

Based on the real-time rendering and drawing of virtual ocean scenes by Vega Prime, the video matrix switcher, graphic processing server, and nine splicing screens display were integrated to reproduce the virtual ocean scenes in real-time. The main scenes of the completed virtual simulation of the subsea manifold installation are shown in Figure 13. These scenes drawn by Vega Prime can be divided into sea surface and seabed scenes. It should be mentioned that while installing equipment by the ROV operator, improving the operating efficiency and accuracy is necessary. Therefore, in the subsea sub-scene, coordinate and radar display systems were developed, which are located in the left and right corners of the ROV operating screen, respectively. The coordinate display system shows the position and attitude of structures such as ROV and subsea manifold. ROV_d13 is a part of ROV's robotic arm. GP_1 and GP_2 represent tow fixed points on the subsea manifold. ROV_a and ROV_p respectively correspond to the attitude and position of the ROV. The radar display system shows the relative position of the subsea manifold and guide base, and the origin of the coordinates of radar display system is the guide base.

5.2 NUMERICAL PREDICTION OF THE MOTION RESPONSE OF THE STRUCTURE

To improve the operating efficiency and ensure good progress of the virtual simulation process, the multibody dynamics system of the ship-cable-subsea manifold was established in Orcaflex. Orcaflex is a professional platform for the global static and dynamic analysis of offshore marine systems, with a wide application range that includes riser systems, moorings, and subsea equipment installations. It also exhibits high accuracy, efficiency, and good user friendliness (Guimarães Pestana *et al*., 2016; Yang *et al*., 2016; Tommasini *et al*., 2018). The motion response of the subsea manifold during the entire lowering process can be accurately predicted by numerical calculations. The entire process of lowering the subsea manifold can be approximately divided into four phases: lifting the structure from the deck of the installation ship, lowering through the splash zone, lowering in deep waters, and closing to the seabed (Veritas, 2011).

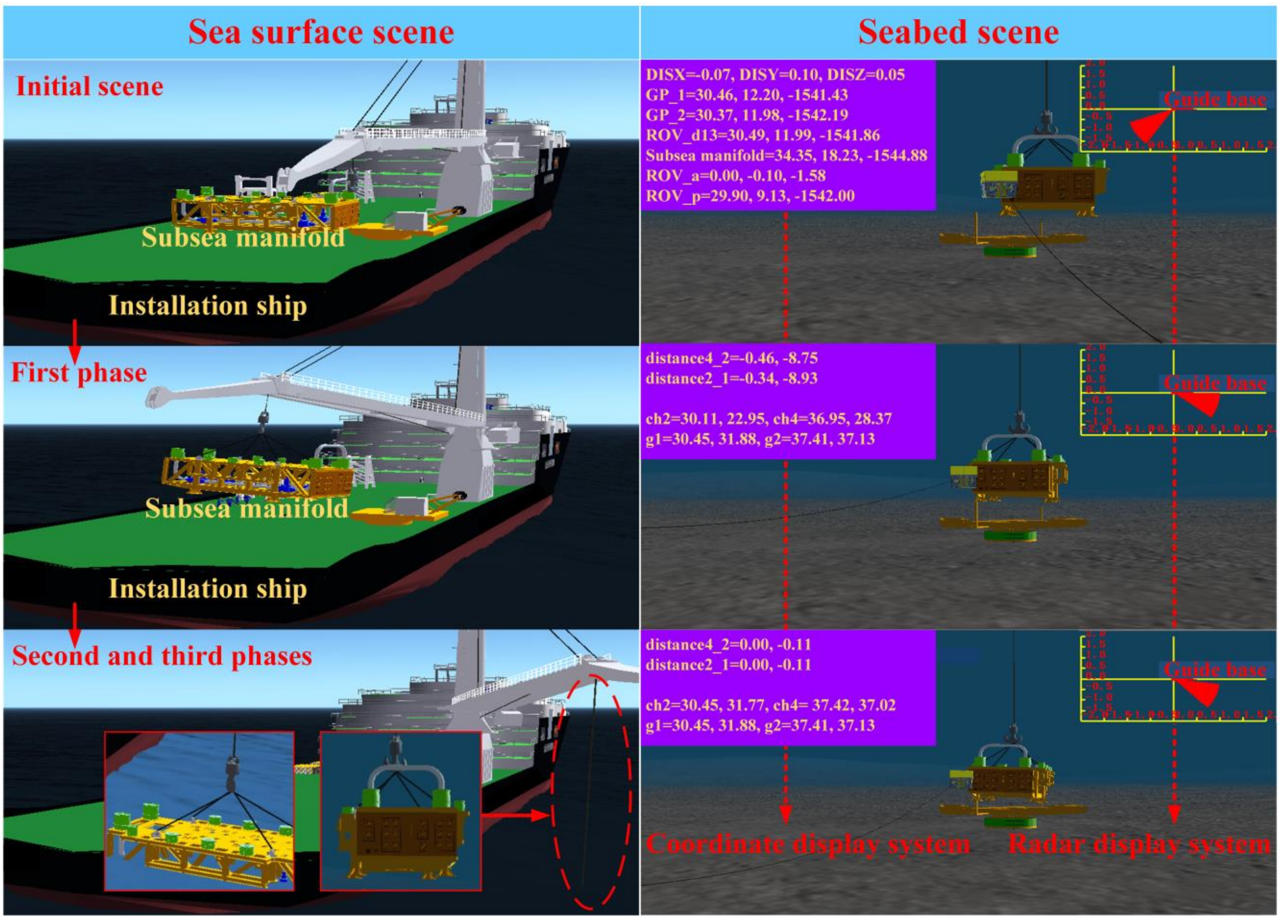

Figure 13: Main virtual scenes of the subsea manifold installation.

In the second phase, particularly, the subsea manifold may be affected by strong nonlinear environmental loads, including winds, waves, and currents. Strong nonlinear coupling phenomena, such as wave breaking and slamming, occur between the subsea manifold and fluid. The third phase consists of a long operating time. Without the assistance of the ROV, the position and attitude of the subsea manifold may unknowingly vary due to current loads, such as rolls, pitches, and yaws. In the fourth phase, the motion responses of the ROV and subsea manifold and the relative position of the subsea manifold and guide base can be displayed on the ROV simulation console screen in real-time. This can help the ROV operator to efficiently complete the fourth phase. Therefore, it is necessary to accurately simulate environmental conditions and obtain accurate motion responses of the subsea manifold in the second and third phases based on professional hydrodynamic analysis software before virtual operations. If numerical results show that the position and attitude of the subsea manifold will evidently change during deep water lowering, the operator can adjust it in advance. Thus, the operating accuracy of the operators and training efficiency of the system can be greatly improved.

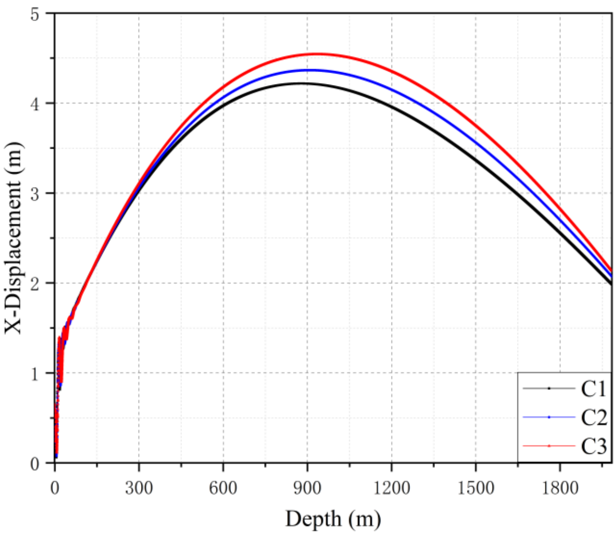

Figure 14: Subsea manifold displacement along the x-axis.

In Orcaflex, x-, y-, and z-axes of the global coordinate system correspond to the length, width, and height directions of the subsea manifold at the initial moment, respectively. In the numerical simulation, environmental parameters were set according to Condition 3 mentioned in Table 1. Current velocities at the wave surface and seabed were set as 1.2 and 0.25 m/s, with the current velocity between the wave surface and seabed being linearly distributed. Water depth was set as 2000 m. The phases of lowering through the splash zone and lowering in deep waters were simulated, which represented the complex and critical phases of the entire lowering process. Additionally, the safe and stable lowering of the subsea manifold in the second and third phases was the foundation of the ROV auxiliary installation. The motion responses of the subsea manifold during the lowering process are shown in Figures 14–17. C1, C2, and C3 represent subsea manifold lowering at 0.6, 0.7, and 0.8 m/s, respectively.

Figures 14 and 15 show the displacements of the subsea manifold along the x- and y-axes, respectively, where the abscissa represents the water depth at which the subsea manifold was located. It can be seen that from the subsea manifold touching the wave surface to its submergence at the water depth of approximately 70 m, its displacement along the x- and y-axes changed rapidly. Figure 14 shows that the maximum displacements of the subsea manifold along the x-axis in C1, C2, and C3 cases were 4.217, 4.365, and 4.541 m, with corresponding water depths being approximately 879, 909, and 935 m, respectively. The displacement of the subsea manifold along the x-axis increased with increasing lowering speed. Current velocity was linearly distributed; the closer to the seabed, the smaller the velocity. Therefore, with increasing water depth, the displacement of the subsea manifold along the x-axis first increased, and gradually decreased after reaching the maximum displacement.

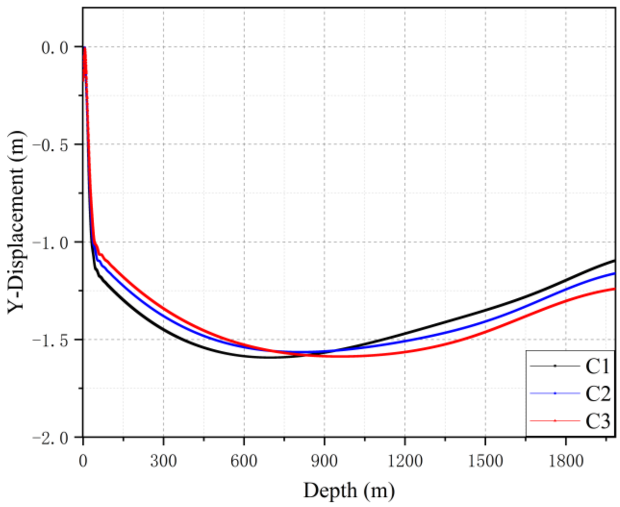

Figure 15: Subsea manifold displacement along the y-axis.

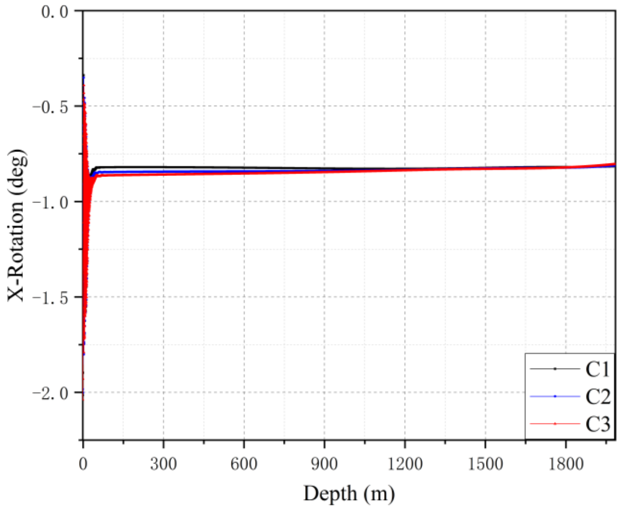

Figure 16: Subsea manifold rotation around the x-axis.

Figure 15 shows that the maximum absolute value of the displacements of subsea manifold along the y-axis for C1, C2, and C3 cases were 1.5923, 1.565, and 1.589 m, with corresponding water depths being approximately 696, 809, and 959 m, respectively. Negative sign indicates the direction of displacement, i.e. the negative direction of y-axis. With the increasing water depth, the absolute value of the subsea manifold displacement along the y-axis first increased, and gradually decreased after reaching the maximum absolute value. During the deep water lowering, the subsea manifold displacement along the x- and y-axes changed steadily without large fluctuations. The change in displacement along the x-axis was larger than that along the y-axis because the direction of current was along the x-axis.

Figures 16 and 17 show the rotation of the subsea manifold around the x- and y-axes, respectively. Negative sign indicates the rotation direction, with the negative rotation being anticlockwise in Orcaflex. From the subsea manifold touching the wave surface to its submerged water depth of approximately 70 m, the rotation motions of subsea manifold around the x- and y-axes were similar to the decaying oscillatory motions. After the water depth exceeded 70 m, the rotation of the subsea manifold around the x- and y-axes changed steadily without large fluctuations. The maximum absolute values of the rotation angles of the subsea manifold around the x- and y-axes occurred while crossing through the splash zone. This was because the subsea manifold was affected by wind, wave, and current loads when lowering through the splash zone, with the environmental conditions being complex, thus, the attitude of the subsea manifold is prone to change.

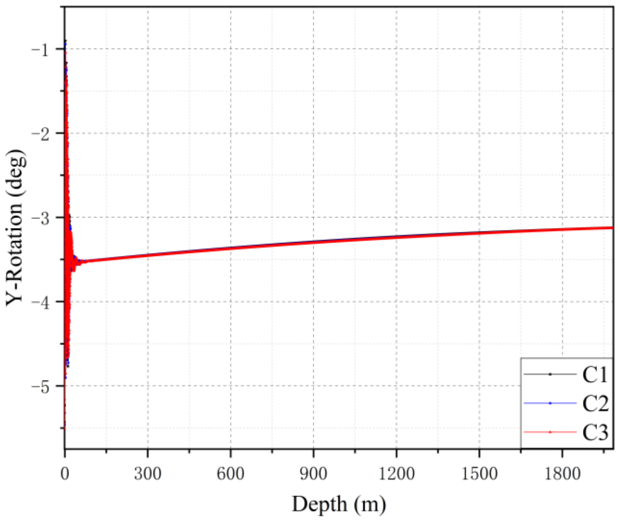

Figure 17: Subsea manifold rotation around the y-axis.

Figure 16 shows that before the water depth of approximately 1200 m, the absolute value of the subsea manifold rotation angle around the x-axis increased with increasing lowering speed. As water depth continued to increase, the rotation angle at different lowering speeds gradually converged to a fixed value of approximately -0.83 degrees. Figure 17 shows that after the water depth exceeded 70 m, the absolute value of the subsea manifold rotation angle around the y-axis decreased slightly with increasing water depth, with an approximately linear relationship observed between them. Additionally, lowering speed only slightly affected the subsea manifold rotation angle around the y-axis.

6. CONCLUSIONS

This paper described the design and development of a distributed virtual simulation system based on real-time dynamic calculation and multi-person collaborative operation, mainly for the construction, production, and maintenance of subsea production systems. Compared to other VR systems, this system has a wider application range for subsea production systems. The conclusions of the research are summarised as follows:

- The overall framework of the system was designed and built, and a hardware platform was constructed based on the HLA protocol.
- Based on the dynamic calculation platform Vortex, the physical models of the simulation system were established, so that the simulation results were in accordance with the actual motion law of the structures. Vortex and Vega Prime were integrated to draw and render virtual ocean scenes to obtain a realistic visual effect with accurate motion response.
- To demonstrate the application flow of the virtual simulation system and show simulation effects in detail, a typical case of ocean construction was run, which was subsea manifold installation. A detailed script of the process for this case was developed, with multiple persons working together in the same virtual environment to complete the virtual simulation.
- The same ship-cable-subsea manifold multibody dynamics system and environmental conditions as the virtual simulation system were established in Orcaflex to calculate the motion response of the subsea manifold during the process of lowering. The obtained results provide a significant guideline and reference for the operators that can greatly improve operating efficiency.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

1. CAO, Y., *et al.* (2016) *Design of a novel installation device for a subsea production system.* Applied Ocean Research, 59, 24-37.

2. CHA, M., *et al.* (2012) *A virtual reality based fire training simulator integrated with fire dynamics data.* Fire Safety Journal, 50, 12-24.
3. CHEN, D., *et al.* (2008) *A decoupled federate architecture for high level architecture-based distributed simulation.* Journal of Parallel and Distributed Computing, 68 (11), 1487-1503.
4. CHEN, G., *et al.* (2012) *Design and implementation of a 3D ocean virtual reality and visualization engine.* Journal of Ocean University of China, 11 (4), 481-487.
5. FENG, Z., *et al.* (2020) *Towards a customizable immersive virtual reality serious game for earthquake emergency training.* Advanced Engineering Informatics, 46.
6. FERRARA, P., *et al.* (2020) *Virtual Reality: New Concepts for Virtual Drilling Environment and Well Digital Twin.* International Petroleum Technology Conference.
7. GUIMARãES PESTANA, R., *et al.* (2016) *Marine riser emergency disconnection analysis using scalar elements for tensioner modelling.* Applied Ocean Research, 59, 83-92.
8. IEEE 1516.3. (2003) *IEEE Recommended Practice for High Level Architecture (HLA) Federation Development and Execution Process (FEDEP).* IEEE Std 1516.3-2003, 1-40.
9. JIMéNEZ FERNáNDEZ-PALACIOS, B., *et al.* (2017) *Access to complex reality-based 3D models using virtual reality solutions.* Journal of Cultural Heritage, 23, 40-48.
10. LI, M.-K., *et al.* (2018) *A simple voxel-based assessment and visualization of dose to human for radiation protection using virtual simulation.* Progress in Nuclear Energy, 105, 8-20.
11. LI, X., *et al.* (2019) *A collaborative simulation in shipbuilding and the offshore installation based on the integration of the dynamic analysis, virtual reality, and control devices.* International Journal of Naval Architecture and Ocean Engineering, 11 (2), 699-722.
12. PéREZ, L., *et al*. (2019) *Industrial robot control and operator training using virtual reality interfaces.* Computers in Industry, 109, 114-120.
13. SOLBERG, H. E. (1993) *Object-oriented methods.* Clinica Chimica Acta, 222 (1), 3-11.
14. SUN, X., *et al.* (2020) *Team effectiveness evaluation and virtual reality scenario mapping model for helicopter emergency rescue.* Chinese Journal of Aeronautics, 33 (12), 3306-3317.
15. TOMMASINI, R. B., *et al.* (2018) *A dynamic model to evaluate the influence of the laying or retrieval speed on the installation and recovery of subsea equipment.* Applied Ocean Research, 77, 34-44.
16. VERITAS, D. N. (2011) *Modelling and Analysis of Marine Operations.* DNV-RP-H103, Det Norske Veritas, Høvik, Norway.
17. WANG, A. M., *et al.* (2019) *Virtual Reality Simulations for Dynamic Positioning Floatover Installation.* The 29th International Ocean and Polar Engineering Conference.
18. YANG, Y., *et al.* (2016) *Mooring line damping due to low-frequency superimposed with wave-frequency random line top end motion.* Ocean Engineering, 112, 243-252.
19. YU, Y., *et al.* (2017) *A virtual reality simulation for coordination and interaction based on dynamics calculation.* Ships and Offshore Structures, 12 (6), 873-884.
20. ZHANG, X. H., *et al.* (2016) *A mathematical model of virtual simulation for deepwater installation of subsea production facilities.* Ships and Offshore Structures, 12 (2), 182-195.