Scientific Visualization, 2025, volume 17, number 2, pages 23 - 35, DOI: 10.26583/sv.17.2.02

Visualization of the BREST-OD-300 RP FA assembly and inspection area using virtual reality technologies

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Abstract

Currently, virtual reality technologies are used to train specialists in the field of nuclear energy, which allow the student to directly immerse himself in the environment of his activity, to carry out training as close as possible to real conditions, without causing harm to his health. In order to manufacture a fuel assembly (FA), it is necessary to undergo a number of control settings at the production stage, confirming quality and safety. The authors proposed the development of a virtual simulator with fuel assembly control installations for the BREST-OD-300 reactor plant, such as: washing and drying fuel assemblies, monitoring the tightness of fuel assemblies, monitoring the surface contamination of fuel assemblies, monitoring the mass and inclusion of fuel assemblies in the slipway, monitoring the geometry of fuel assemblies.

This simulator was developed in the Unity environment using Oculus virtual reality glasses. The results of visualization of the inspection area make it possible to check the appearance of the fuel assembly for the presence of defects and damage, measure the mass and length of the fuel assembly, as well as check for leaks, absence of leaks and contamination.

Keywords: training simulators, three-dimensional modeling, graphic objects, fuel assembly, visual representation.

Introduction

Currently, with the development of information technology, virtual reality is rapidly gaining popularity - an amazing technology that promises to radically change the interaction of people with information.

Virtual reality is understood as the modeling of a 3-dimensional environment, when interacting with which a person perceives it as real, which causes a feeling of presence in it. This effect is achieved with the help of special equipment: glasses or a virtual reality helmet, due to their design, provide a stereoscopic 3D image of the simulated world, motion sensors calculate movements in the real world and transform them into the virtual world. In addition, the equipment set may include controllers that track the movement of a person's hands and transfer them to the virtual world, which allows you to pick up virtual objects, throw them, or perform other actions involving the use of hands [1].

In the early stages of its development, virtual reality was used mostly in the gaming industry, but at the moment its use is rapidly growing in other areas. Currently, virtual reality technologies are actively used in design, construction, various training machines and simulators, medicine and other areas of human activity [2,3].

There is also a process of introducing VR technologies into the nuclear industry, which will reduce errors in design, improve the quality of training specialists, and facilitate the verification of various scenarios of the technological process.

In the virtual world, emergency situations can be simulated that cannot be reproduced in real life, and thanks to this, a specialist previously familiar with theoretical material gains experience close to real life [4].

An important role in the process of training specialists in the field of nuclear energy is played by training, which involves immersion in a professional environment in order to obtain the necessary skills. For this, various training systems are used, which are aimed at creating working conditions similar to real ones in order to consolidate theoretical knowledge. The simulators visualize ongoing technological operations, allow you to consider various situations, thanks to which skills are developed in choosing the best actions in each case. The introduction of virtual reality technologies in such simulators will improve the quality of training specialists.

In this work, the integration of VR technologies into a training simulator for controlling the technological process of a FA line was carried out.

General information about the analytical 3D simulator and virtual reality (VR) simulator

Currently, various training systems in the form of full-scale or analytical simulators are used to train specialists in the nuclear industry.

A full-scale simulator is usually a digital twin of a nuclear power plant. It provides modeling of all operating modes on a real scale: normal operating modes, design emergency modes and beyond design basis accidents.

An analytical simulator is a simulator whose information and motor fields are presented on display screens, and the equipment is controlled using a "mouse" or screen sensors.

During training on the above simulators, the output of certain dynamic parameters is carried out in graphic form, usually on the screen or a file for printing.

A simulator using virtual reality technologies differs from the above-mentioned ones in that employees are immersed in a full-fledged copy of the workplace during training and practice all routine actions until they become automatic, which allows them to increase their level of awareness when working on real equipment and reduce the risks of incidents and emergency situations. Such simulators allow simulating situations that may arise in practice, without exposing students to any risks or restrictions [5].

Thus, the implementation of virtual simulators is relevant at the present time. This can become a useful tool in the educational process and will significantly improve its quality and efficiency, as well as save time and resources in a rapidly changing world. Currently, various training systems in the form of full-scale or analytical simulators are used in the training of specialists in the nuclear industry [6].

The simulator for assembly and control of the RU BREST-OD-300 FA using virtual reality technologies is designed as shown in Figure 1. When the trainee puts on virtual reality glasses, the application in Unity is launched on the graphics server to form a virtual space.

The graphic server provides information on the formation of 3D space from the first person for virtual reality glasses, and also sends data for monitoring, displaying the location and behavior of the character in the virtual environment. Thanks to this, the engineer-instructor can monitor the actions performed by the operator and set the necessary scenarios.

Fig. 1. Concept of the simulator operation using virtual reality

Fuel Assembly (FA) Assembly and Control Process

FA (fuel assemblies) are structural elements of a nuclear reactor that contain nuclear fuel and serve to control nuclear reactions and heat release. The FA assembly and control process includes several stages:

Component manufacturing. FA manufacturing typically involves the production of fuel rods, which contain the nuclear fuel (e.g., uranium-235) and a cladding to prevent leakage of radioactive materials. This process also includes the production of structural components of the FA, such as rod holders, containment cladding, and other necessary components.

FA *assembly*. Fuel rods are placed in a certain order inside the frame. Structural elements are secured in such a way as to ensure the reliability and integrity of the FA.

Quality and safety control. This process includes visual inspections for defects, cracks or other damage to FA components. Measuring dimensions and geometric parameters to ensure that the FA meets design requirements. Conducting material tests and analysis to standardize and ensure safety standards. Checking radiation levels and ensuring that there are no leaks from the FA.

Pre-operation testing. Testing the strength and stability of FA under loads and vibrations. Simulating heat generation conditions in the reactor to test the efficiency of cooling and heat generation control.

Packaging and transportation. Protecting FA from damage during transportation and storage. Preparation of all necessary documents and quality certificates to accompany fuel assemblies.

The entire process of FA and control is carefully regulated and subject to numerous checks to ensure the safety and efficiency of the nuclear reactor.

Unity Virtual Reality Application Development Tool

Unity is one of the most popular game engines used to create various game applications on various platforms. A free version is provided for beginner developers. Unity can be used to develop both 2D and 3D projects [7].

Unity has relatively low system requirements, which is an obvious advantage, since many novice developers do not have excellent system parameters. In addition, the engine itself and projects on it do not take up much disk space, which makes you pay attention, especially when the computer memory is occupied by other important applications [8].

The C# language is used for writing scripts, which gives a winning position, since it is much easier for a beginner to write in this language [9].

In terms of the number of game resources, called assets, Unity takes the leading position, in the Unity store you can find a huge variety of ready-made animations, 3D models, textures, audio and much more. There are over 50,000 such resources available in the built-in store, many of which are free [11].

Virtual reality helmet

The equipment used in this work is represented by virtual reality glasses Oculus Rift S and two Oculus touch controllers (one for each hand) (see fig. 2). These glasses have excellent light insulation, a good viewing angle and are quite convenient to use due to the comfortable weight distribution. The controllers track the movement of hands and fingers, transmitting all gestures to the virtual world with good accuracy, which allows you to take objects inside this world, throw them, press buttons and much more [12].

An important advantage of the Oculus Rift S equipment, which distinguishes it from other models, is the presence of the Oculus Passthroug+ functionality, which is responsible for the user's safety [13]. It works like this: when the user leaves the previously configured play area, the picture displayed on the glasses' display switches to the real world in black and white so that the user can see the surrounding world and avoid hitting obstacles. The user will not be able to continue playing until he or she returns to the play area.

So, the Oculus Rift S hardware has an excellent price-quality ratio and is the optimal choice that meets the requirements and conditions of this work.

Fig. 2. Oculus Rift S equipment

Installation of head mounts on the FA frame.

The operation of the unit is as follows. The FA head, the lock drive head, nuts and flaring are fed on the sluice installation plate with a conveyor to the operating area of the unit robot. The tilter moves the FA frame, fixed in the witness cradle, into a vertical position (see fig. 3).

The robot determines the coordinates of the location of the pipes on the frame with the probe of the tightening and gripping mechanism. The head of the FA is fixed on the installation plate of the lock with the conveyor by the gripper of the twisting and gripping mechanism, it is lifted vertically, and the force-torque sensor installed on the twisting and gripping mechanism weighs the head of the FA, thereby determining the presence of the head of the FA in the twisting and gripping mechanism. The FA head is installed on the FA frame pipes, pressed and fixed with a grip. After that, the grip of the tightening and gripping mechanism is released and moved behind the nut to the installation plate of the sluice with a conveyor. The clamp of the tightening and gripping mechanism grips the nut on the sluice plate with a conveyor and moves the robot, to determine the presence of the nut, to the bracket with the sensor. The presence of the nut is determined. The nut is moved to the FA frame and screwed onto the pipe. The nut is considered to be screwed if the number of nut turns is between 10 and 12 turns and the tightening torque exceeds 1 N/m. If the number of turns is less than 10 and the torque on the nut tightening mechanism exceeds 1 N/m, the nut is considered to be loose. In this case, the nut is unscrewed by the nut tightening mechanism. Then the operator decides whether to tighten it again or send the FA for disassembly. The remaining nuts are tightened. After tightening the nuts, the installation robot, with its tightening and gripping mechanism, grabs the flare from the installation plate of the gateway with the conveyor and checks for the flare on the bracket with the sensor. After determining the presence of flaring, the robot of the installation flares the FA frame pipes, rolling the edges of the pipes. The operator controls the flaring of the pipes using three video surveillance devices located around the head of the FA. The robot of the installation fixes the head of the lock drive with a twisting and gripping mechanism and determines the presence of the head of the lock drive with a force-torque sensor. The lock drive head is fed oriented inside the FA head, rotates inside the FA head by 30° and is held. The tilter, using a pneumatic cylinder, moves the lock drive rods. The rods enter the holes of the lock drive head and fix it. The operator, using video cameras, controls the fixation of the lock drive head. After fixing the lock drive head, the robot returns to its original position. The coordinate non-copying manipulator grasps the FA by the head, the grippers of the cradle are released, the FA is moved by the CM to the next technological position. The tilter moves the cradle to a horizontal position for transporting it to the next technological position [1].

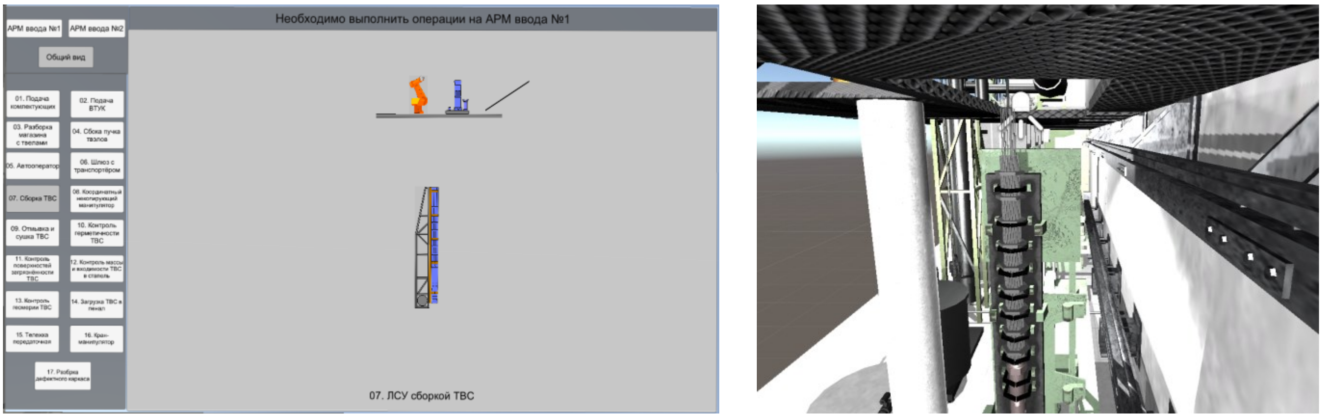

Fig. 3. Mnemonic diagram and 3D visualization of the FA section

Installation for washing and drying FA

The retort is designed to accommodate the FA during washing and drying. The installation includes: a retort, a water supply device, an air preparation device, a bubbler, a drain device, a drying device, and biological protection (see fig. 4). The water supply device is designed to fill with distilled water. The air preparation device is designed to prepare and supply air to the bubbler. The drain device is designed to drain water from the retort into a special container. The drying device is designed to heat the air and blow off the FA. Biological protection is designed to protect repair personnel from exposure to FA during repair work in the event of a FA hanging inside the installation.

From the FA tilter, the CM is transported to the retort of the FA washing and drying unit. The FA is washed with distilled water (at a temperature of 20 to 30 °C) in two cycles, including filling the retort with water, washing the FA with bubbling, and draining the water. The washing time in one cycle is at least 30 minutes.

The wash water is collected in receiving tanks. From the receiving tanks, the wash water is pumped for processing in another building.

Drying of the fuel assemblies is carried out in a retort by blowing hot air over the fuel assemblies (at a temperature of 100 to 120 °C). The drying time is at least 40 minutes [16].

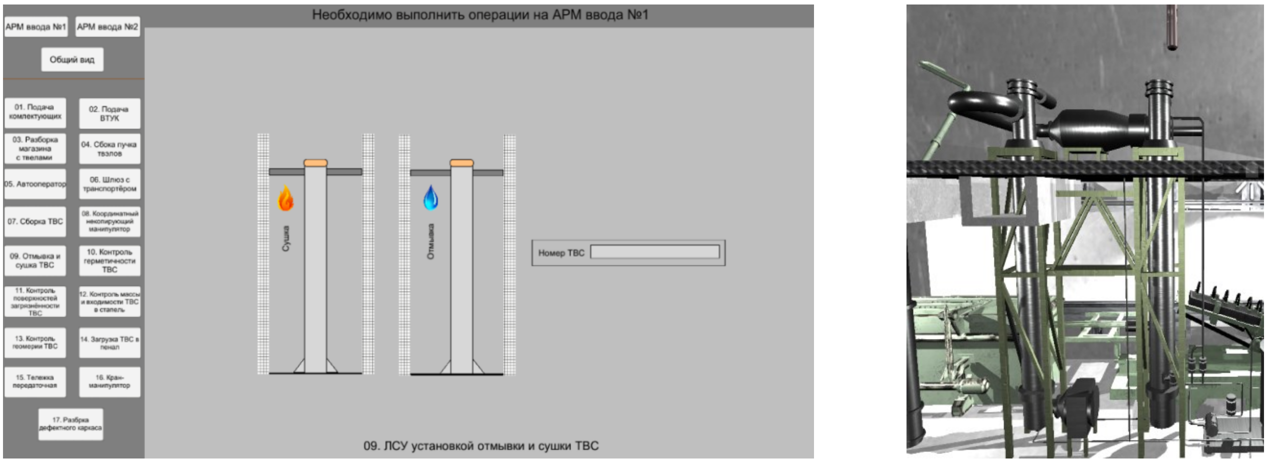

Fig. 4. Mnemonic diagram and 3D visualization of the FA washing and drying unit

Installation of leakage control of the FA

After switching on the LCS, the leak detector will automatically start and perform a check and adjustment of the sensitivity threshold for the internal calibrated leak (determination of the sensitivity threshold of the leak detector, LDST), and the leak detector will be calibrated (see fig. 5). The value of the LDST is determined automatically and displayed on the leak detector control panel (to continue operations, the LDST should not exceed $7 \cdot 10^{-11}$ m^3Pa/s). If the LDST exceeds the permissible value, it is necessary to re-check and adjust the leak detector sensitivity threshold, as well as re-calibrate the leak detector). If the permissible value of the LDST is exceeded after 2 cycles of testing and adjustment of the sensitivity threshold for the internal control leak, suspend work until the causes of the negative test result are eliminated.

Open the retort pneumatic actuator and purge the retort with nitrogen for at least 5 minutes. After the purge time has expired, close the actuator.

Check the system sensitivity threshold (SST) of the system using an external calibrated leak. SST should be no more than $2.5\ 10^{-10}$ m^3Pa/s. If the obtained value of the SST exceeds the permissible value (the plant control system will issue a message about an unsatisfactory result of the SST), repeat the SST determination using an external calibrated leak. Repeat the vacuuming of the system. The permissible number of repetitions of the SST test for the external control leak is two. If the SST exceeds the permissible value after repeated tests, suspend the work until the causes of the negative result of the SST test are eliminated.

The FA is delivered to the CM unit, which moves it and stops above the retort. Upon reaching the specified CM positioning coordinates, the retort pneumatic actuator is opened, and the nitrogen supply is switched on. The CM carriage drive is switched to lowering. When the marking of the FA is aligned with the reading device, the FA is stopped to read its number. Then the lowering of the FA continues until it is completely inserted into the retort.

The CM carriage drive stops, the CM gripper is disengaged from the FA head and moved away from the retort. A necessary condition for disengaging the CM gripper from the FA head is the operation of the product presence sensor, confirming the full entry of the FA into the retort. The actuator closes. The nitrogen supply is stopped using a fore vacuum pump and the retort is pumped down to a pressure of less than 6 Pa. The pressure in the retort is controlled by a vacuum sensor. After reaching the specified vacuum value, the leak detector switches to leak control mode and is connected to the retort. The operation of checking the tightness of the FA is performed. If the obtained leak value is less than the permissible helium leak flow (the FA is tight), then a calibrated helium leak (helit) is connected to the retort to check the operability of the installation. The leak detector should show the corresponding leak value. After disconnecting the helit from the retort, the leak value should return to the background flow from the tight (good) FA. If the leak value obtained during FA inspection is greater than or equal to the permissible helium leak threshold, the FA is considered leaky and is rejected. Before extracting the FA, nitrogen is released into the retort. The release is performed through a pipeline connected to the lower part of the retort. The CM gripper is oriented along the retort axis. Upon reaching the specified CM positioning coordinates, the vacuum valve is opened. The CM gripper is lowered and mated with the FA head. With the help of the CM, the FA is unloaded from the retort and fed to the subsequent position of the FA assembly and inspection section. The vacuum valve is closed. The nitrogen supply is stopped [17].

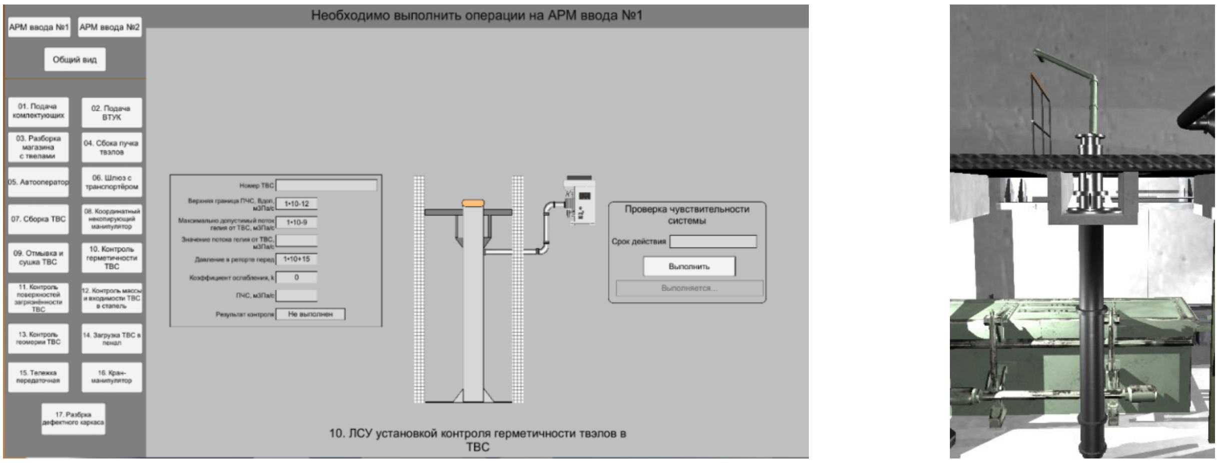

Fig. 5. Mnemonic diagram and 3D visualization of the FA leakage control unit

Installation for monitoring surface contamination of FA

The installation for monitoring the surface contamination of fuel assemblies is designed to monitor the contamination of the FA surface using the smear method (see fig. 6). The installation includes: a retort, a sampling unit, a device for reading FA markings, and biological protection of the retort.

The FA is lowered into the retort using the CM through the sampling unit, where the smear is collected. The samples are collected from the surface of the peripheral fuel elements when the FA is lowered at a reduced speed. The replacement cartridge is removed from the sampling unit after the FA is removed from the retort. The cartridge removed from the clip is packed in a plastic bag, after which it is sent to the laboratory for preparation of counting samples and subsequent measurements.

The numerical values of the dosimetric characteristics of the FA contamination surface are entered into the FA passport.

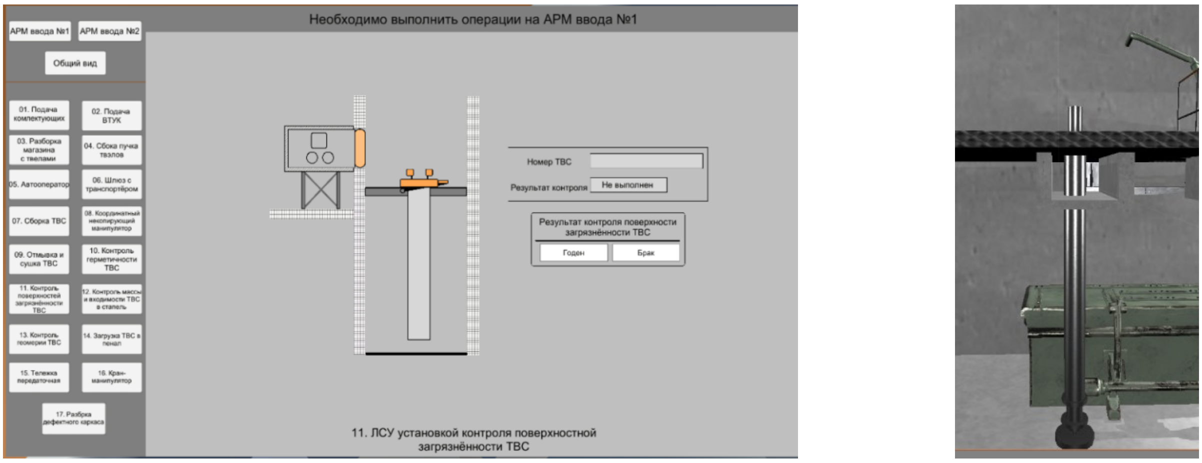

Fig. 6. Mnemonic diagram and 3D visualization of the installation for monitoring the surface contamination of FA

Installation of FA mass control, FA entry control into the slipway, tailstock control mechanism operability, and movement of RCPS rods (for FA with RCPS rods)

The FA is delivered to the CM unit, which moves it from the surface contamination control unit and stops above the slipway (see fig. 7). Upon reaching the specified CM positioning coordinates, the weighing device measures the mass of the FA. If the mass of the FA is within the permissible mass values for this type of FA, then the CM carriage drive is switched on for lowering, which is performed by aligning the FA marking with the reading device. The CM carriage drive stops, the reading and transmission of the received FA number to the upper level of the APCS is performed, after which the FA continues to lower until it is completely inserted into the slipway. Before lowering, the CM grip opens the tailpiece lock, moving the lock drive to the lower position. The cycle of checking the FA entry into the stack includes sequentially performed operations: lifting the CM carriage until the FA is completely extracted from the stack, turning the CM grip by 60°, lowering and then lifting the FA, turning the CM grip by 60° and repeating the lowering/lifting of the FA; return (rotation) of the CM grip to the initial position, lowering the CM carriage until the FA is fully inserted into the pile. The CM carriage drive is stopped and switched from lowering to lifting after the weighing device readings are reset, while the full insertion of the FA into the pile is confirmed by the operation of the FA presence sensor in the pile. During the movement of the FA in the slipway, the value of the change in the actual weight of the FA is constantly monitored (according to the current readings of the weighing device) with the transfer of the monitoring results to the upper level of the APCS. At the line control AWS, the monitoring results can be displayed both as current readings of the weighing device and as maximum values of the change in the weight of the FA during each lowering/lifting. If all the obtained values of the FA weight deviation do not exceed the permissible values, the operability of the tailstock lock is checked. The CM gripper closes the tailstock lock, moving the lock drive to the upper position. The result of the check is determined by the joint operation of the drive movement control sensor and at least one of the lock collet control sensors. For FA with the RCPS, it is envisaged to perform operations to control the patency of the FA channel. To perform this control, the CM gripping device is disconnected from the FA head and moved from the stock, while a necessary condition for disconnecting the CM gripping device from the FA head is the activation of the FA presence sensor.

The cycle of monitoring the patency of the FA channel includes the following sequentially performed operations: switching on the drive and moving the crossbar of the control unit of the RCPS to the slipway, switching on the drive of the gripping device of the RCPS to lower it to the stop in the head the head of the RCPS, which is confirmed by the sensor of the gripper approach to the RCPS, switching on the gripper drive and turning it 90° clockwise (gripping the gripper with the head of the RCPS), switching on the drive of the gripping device of the RCPS to raise the upper position with subsequent switching it to lower the RCPS of the control system to the lower position. During the movement of the RCPS of the control system in the FA channel, the value of the change in the weight of the control system. Next, the following is performed on the installation: turning on the gripper drive and turning it 90° counterclockwise (disconnecting the RCPS gripper from the RCPS head), turning on the RCPS gripper drive to lift to the initial position, turning on the drive and returning the crossbar to the initial position (from the slipway), positioning the CM above the slipway and coupling the CM gripper with the FA. If the obtained values of the FA mass and the deviations in the FA weight and the RCPS are within the permissible values and the operability of the tailstock lock is confirmed, then the FA is considered suitable, and the control results are entered into the APCS database in the form of a report. Upon completion of all inspection cycles provided for a given type of FA, the CM opens the shank lock, removes the FA from the stock and moves it to the geometry and appearance inspection unit.

If the obtained values of the FA mass, FA weight deviation or the RCPS go beyond the permissible values, the monitoring will be continued until the completion of the current operations of the corresponding cycle (until the FA is removed from the slipway), after which the monitoring cycle is interrupted and the monitoring results are entered into the APCS database with the corresponding defect indicator. If, during the inspection of the tailpiece lock, the drive movement control sensor or none of the lock collet control sensors are triggered, then the CM gripping device opens the tailpiece lock and the CM carriage is switched on to lift until the FA is completely removed from the stack, and the inspection results are entered into the APCS database with the corresponding defect indicator. All the above operations with the FA, recognized as defective by any parameter, are performed without exiting the "Automated" mode. In case of interruption of control, the CM opens the tailstock lock, extracts the FA from the stack and moves it to the foaming section [19].

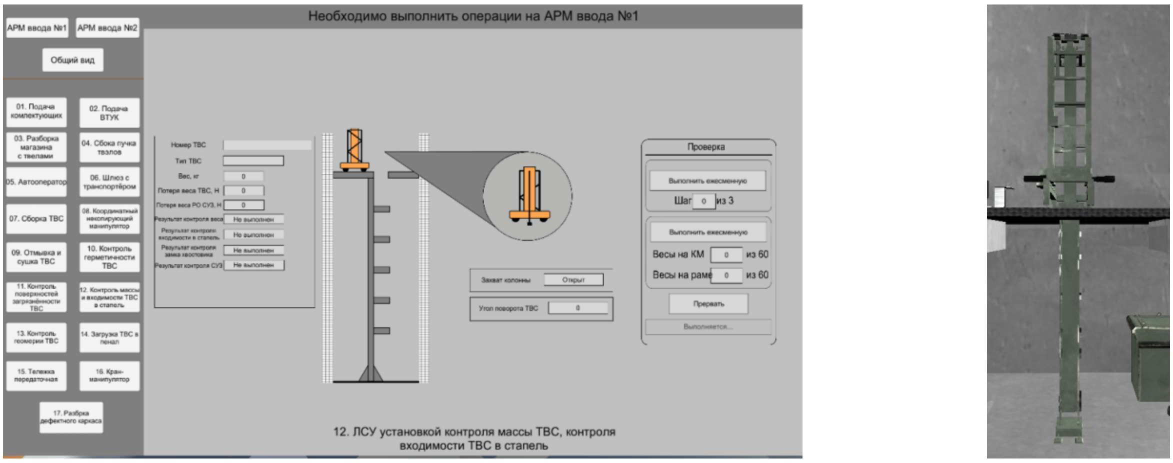

Fig. 7. Mnemonic diagram and 3D visualization of the installation for monitoring the mass of FA, monitoring the entry of FA into the slipway

Installation of control of evaluation and appearance of FA

When the CM performs the specified coordinates, the gripping device of the CM platform opens the tailstock lock, moving the lock drive to the lower position, after which the CM carriage drive is switched on for lowering, which is the result of combining the FA card with the reading device (see fig. 8). The CM carriage drive stops, the marking is read and the FA number is transmitted to the upper level of the APCS of the FA line. Then the FA continues to be lowered until it is fully inserted into the retort (until it lands on the support surface of the centralizer), at which point the FA final position sensor is triggered. After the end position sensor of the FA is triggered, the CM closes the tailpiece lock, disconnects the gripping device and removes it from the FA head and from the area of action of the upper sensor of the length measurement device (upper optical micrometer). After this, the FA length is measured by two optical micrometers located at a known distance from each other (determined in advance by the FA simulator). The upper optical micrometer records the position of the upper edge of the FA head, the lower micrometer is used to determine the position of the lower edge of the FA tip. The measurement result is transmitted to the upper level of the APCS of the FA assembly line.

Next, the CM gripper is lowered, it is coupled with the FA head, and the FA is lifted from the retort. The CM moves the FA upward until the middle of the lower spacing grid coincides with the plane in which the spanner size is measured and stops lowering. Two opposite faces of the spacing grid rim are scanned with laser sensors along lines perpendicular to the FA axis. Based on the results of scanning the profile of the edges of the spacer grid rim and the distance between the sensors, previously determined by the FA simulator, the "wrench" size is calculated, and the result is saved. The CM lowers the FA to measure the middle spacer grid and the "wrench" size is measured, then the operations are repeated to control the upper spacer grid. Upon completion of the inspection of the upper spacer grid, the FA is lowered until the upper edge of the FA head is in the inspection zone of the external appearance inspection device, then the “Automated” mode switches to the “External appearance inspection” section.

After this, the operator of the AWS of the line control (controller) gives permission to lift the FA and carries out visual inspection of the appearance using video cameras of the appearance control device by comparing it with the appearance of the control sample. When checking the appearance, it is possible to stop lifting, lower the FA and change the image scale. Upon completion of the appearance control, the controller enters the control result, the “Appearance Control” section is closed, and the installation is switched to the “Automated” mode. The CM rotates the FA by 120° relative to the longitudinal axis. After this, the operations of measuring the "wrench" size and checking the appearance are repeated on other pairs of faces.

Then the CM rotates the FA to the position of minus 120° relative to the initial one, after which the operations of checking the remaining pairs of faces of the lower, middle and upper lattices and checking the appearance of the remaining faces of the FA are carried out. If the inspection results are positive, the FA is placed in a case for shipment to the finished product warehouse. If the spanner size of at least one pair of edges is outside the tolerance limits or if a discrepancy in appearance is detected, the FA is sent to the defective product warehouse after being cased [20].

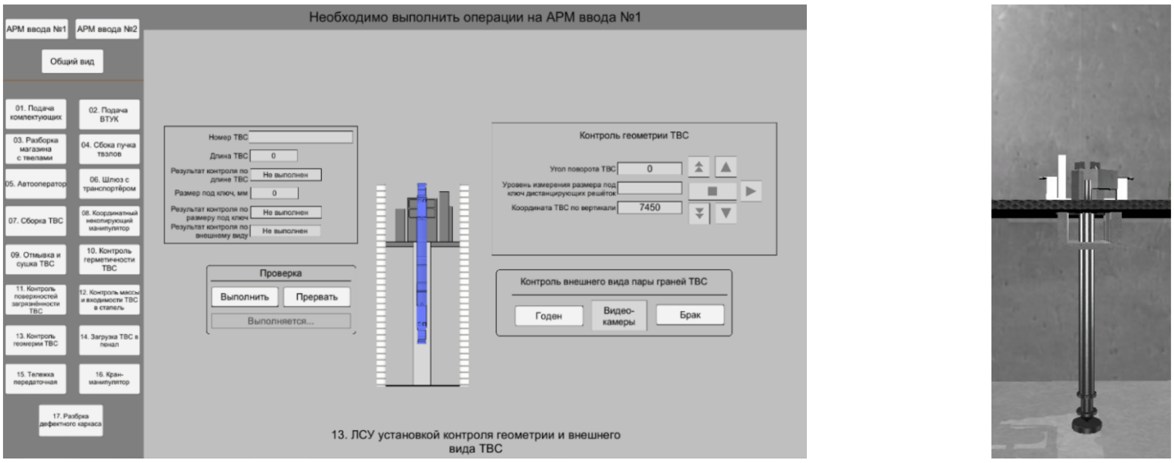

Fig. 8. Mnemonic diagram and 3D visualization of the installation for monitoring the geometry and appearance of FA

Conclusion

Experience in using three-dimensional models shows the relevance of using virtual reality technologies in nuclear power engineering. Virtual reality software allows creating models of technological equipment of nuclear power devices considering anthropometric characteristics.

The use of reality assessment tools such as Unity 3D allows us to create an environment for training and modeling of technological lines, create computational models, and build models with maximum proximity to reality.

The software and hardware tools in this study allowed modeling the FA and control section. In this work, certain FA control units were visualized, such as the FA section, the FA washing and drying unit, the FA leakage control unit, installation for monitoring the surface contamination of FA, installation for monitoring the mass of FA, monitoring the entry of FA into the slipway, the operability of the tail control mechanism, the movement of RCPS rods (for FA with RCPS rods), installation for monitoring the geometry and appearance of FA.

The results of visualization of fuel element control installations allow:

– to clearly see the location of the main components of FA and control.

– to observe the process and sequence of operations performed during the control installations.

– manage assembly and control technological operations using video frames.

The developed system allows training specialists working in the nuclear industry to produce nuclear power devices. The advantage of this development is that it is as close as possible to the technologies of real equipment, is mobile and does not require large economic costs. It also ensures a high level of radiation safety and in the future can be implemented in personnel training centers in the nuclear industry.

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List of abbreviations

APCS – automated process control system
AWS – automated workstation.
BREST – russian project of fast neutron reactors with lead coolant, dual-circuit heat removal to the turbine and supercritical steam parameters
CM – coordinate manipulator
RU – reactor unit
FA – fuel assembly
FE – fuel element
LDST – leak detector sensitivity threshold
SST – system sensitivity threshold
LCS – local control system
RCPS – reactivity control and protection system rod
C# – C Sharp programming language
VR – virtual reality
2D – two-dimensional space
3D – three-dimensional space