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Early design validation on the Vacuum Vessel ports sealing interface installation and removal with Virtual Reality in ITER TBM port cells

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A R T I C L E I N F O

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A B S T R A C T

Port Cell (PC) rooms in the ITER tokamak building host the devices required for the Port Plugs operation and provide connection to services. During Plasma Operation State, the Vacuum Vessel ports sealing interface provides vacuum tightness and first confinement barrier as essential functions. When a Port Plug needs to be replaced or maintained, this significant sealing component must be removed and reinstalled. The general strategy for this operation has been reviewed resulting in modification proposals to address the requirements for static and dynamic confinement and management of radiation considering the ALARA (As Low As Reasonably Achievable) approach. As Dose Reduction Measures (DRM), additional provisions have been proposed to ensure a robust confinement control during the machine shutdown operation. They mostly consist in an airlock that allows the extension of the first confinement barrier equipped with specific handling equipment to perform human-assisted operations on the sealing flanges. In particular, this paper presents the study carried out in TBM dedicated PC during the conceptual design phase of the maintenance cabin airlock and the handling tools by means of Virtual Reality (VR). VR techniques allow working with virtual prototypes at full scale from the early design stage to ease the design process and the concepts validation with important results concerning the assessments of accessibility issues. The study describes also the outcomes of the VR studies and explains how VR can be an effective instrument to conduct integration studies with complex kinematics and human access operations in the execution of the engineering validation process.

1. Port sealing interface replacement in ITER TBM port cells

The Test Blanket Modules research plan for tritium breeding development requires a replacement of the testing breeding units (TBM sets) at every Tokamak major shutdown LTM (Long Term Maintenance), occurring every 2 years after 16 months of plasma campaign. This requires moving 200 tons of components in each of the two TBM port cells each time [1].

The TBMs are hosted in the Port Plugs (PP) that are cooled stainless steel structures inserted in a Vacuum Vessel (VV) Port extension [2]. A sealing flange interfaces the PP and the VV providing the primary static confinement barrier between the VV and the PC area (Fig. 1).

The PP and the sealing interface are represented in Fig. 2.

In order to perform the PP replacement during each LTM shutdown, a reconfiguration of the PC area is required.

Based on the estimated atmospheric contamination, the VV, the PC and the galleries of the tokamak building have different radiological threshold requirements.

Since the removal operation involves personal and equipment access from galleries to the PC area, the radiological contamination could be potentially released in non-contaminated areas.

The management of contamination must follow the ALARA principle [3].

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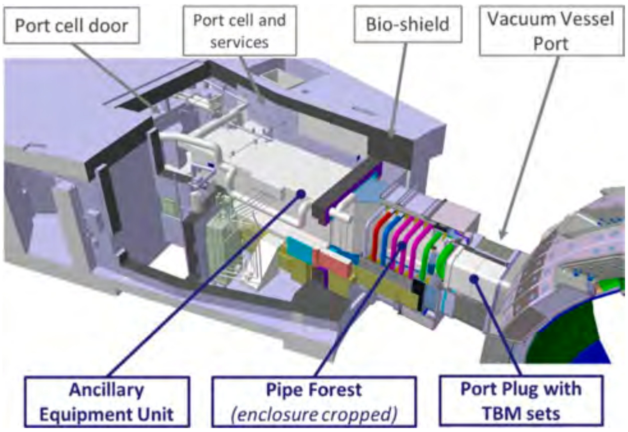

Fig. 1. View of the 3D model of the PC area. The main components of a TBM Port Cell are labelled in blue.

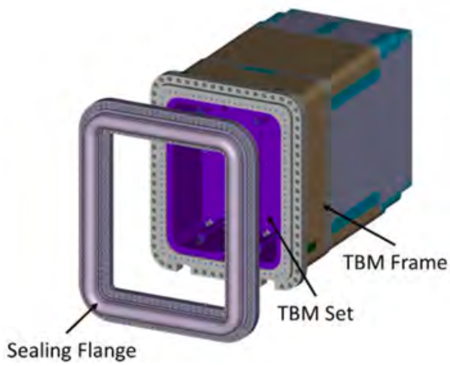

Fig. 2. TBM PP Frame and Sealing flange 3D model.

As Dose Reduction Measures (DRM), airlocks to perform human-assisted operations on the sealing flanges, equipped with specific handling equipment (Fig. 3), and for personnel access purposes (Fig. 4) have been proposed.

The airlocks will extend the first confinement barrier after the removal of the sealing flange and protect the PC and the gallery from contamination spreading during the operation.

The maintenance airlock design is under investigation and it might

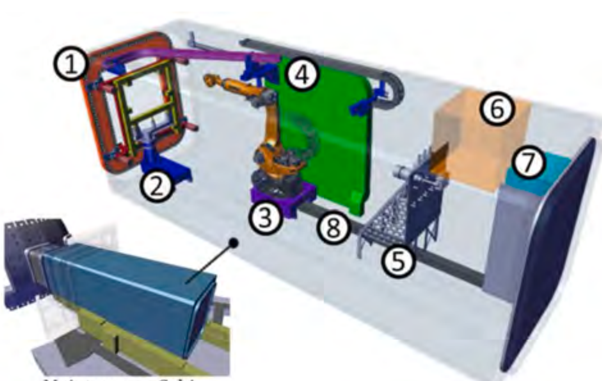

Fig. 3. Maintenance Airlock 3D model: 1. Sealing flange, 2. Handling Frame, 3. Kuka Robot, 4. Double Door and opening mechanism, 5. Bolts storage rack, 6. Reserved space for local ventilation, 7. Main electrical switchboard, 8. Energy chains.

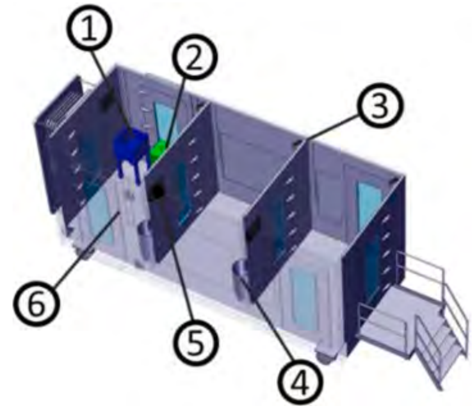

Fig. 4. Personnel access Airlock 3D model: 1. Tool rack, 2. Online tritium monitoring, 3. Cameras, 4. Waste drums and Glove waste bins, 5. Monitor Screen, 6. Breathable air connection Electrical outlet.

be later introduced in the ITER baseline.

The components replacement is a crucial part of the scientific program and its complexity pushed the use of advanced technologies in the design process.

VR simulations have been introduced in the design process to perform integration studies, accessibility assessment, and validation of human access especially including rescue scenarios.

The advantages of using VR mock-ups in saving time, reducing costs, and for the early recognizing of design problems and assembly issues of complex systems have been highlighted by several studies concerning the design of fusion components [4–6] and remote handling operations [7]. Its application for scenarios requiring human access and tight integration shall allow the operation tasks optimization, shortening consequently the exposure time of the operators and reducing the Operational Radiation Exposure, following the ALARA principle [8,9].

2. VR tools and simulation set-up

Virtual Reality technologies permit the development of real-time simulations to reproduce maintenance operations with operators fully immersed in virtual mock-ups on a one to one scale or to support remote handling operations. For this study, virtual reality simulations have been developed in the Unity 3D platform.

The physics engine used in the simulation is the Extended Dynamical Engine (XDE) [10] integrated into the unity plug-in called INTERACT [11].

The CAD models come mostly from native CATIA files and are processed in PIXYZ [12] to be imported into Unity.

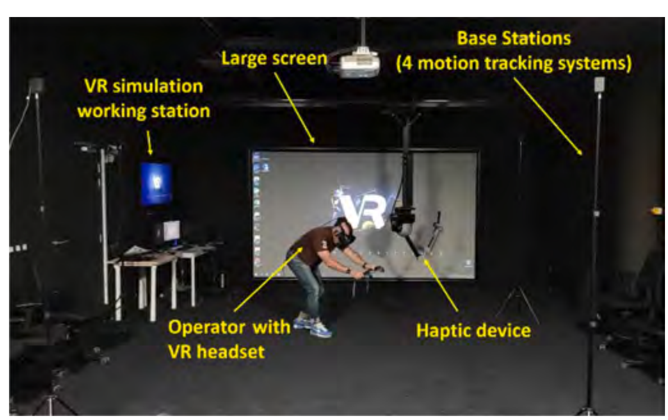

Fig. 5. ITER VR room configuration.

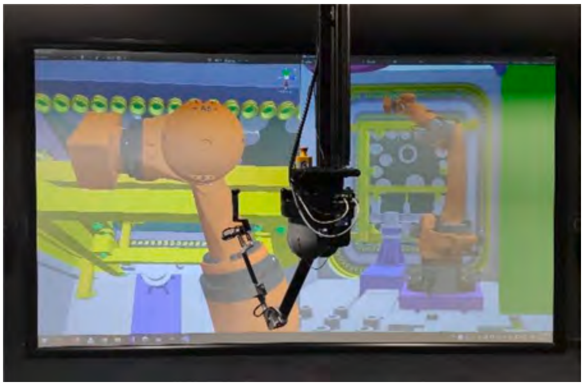

Fig. 6. Virtuose 6D: haptic device in ITER VR room.

Fig. 8. Example of scenario in PC Maintenance Cabin with sealing flange handling frame failure and operator access to release the brake of the trolley. The Operator is simulated with the CEA Nuclear Avatar in Air Fed Suit.

The tests were performed in the ITER VR room (Fig. 5) with a size of 58 m^2 (9.7m x 6m). The room dimension allows reproducing the workspace of the Airlocks (8.4m x 2.6m and 6.1m x 2.4m).

The operator can perform the immersive experiences moving freely in the simulated mock-up on a 1:1 scale without using the teleport function in the virtual environment, which means that the operator can naturally perform the activity, as it would be in a real environment.

For immersive experience in VR simulation, the hardware setup consists of a Virtual Reality head-mounted display (HMD) HTC Vive Pro, wireless HDM adapter and power banks, two wireless handheld controllers to interact with the virtual mock-up, and four wide-area tracking base stations. Steam VR is used for the HTC Vive control and room calibration.

The Haption Virtuose 6D with its Scale1 motorized platform is installed in the VR room (Fig. 6) and it is used for master arm and virtual slave robot simulations.

The Virtuose is a six active degrees-of-freedom haptic device with force feedback yield from interacting with digital mock-ups [13].

3. Methodology for concept design validation

The concept design process of the airlocks is based on the identification and validation of functions and interfaces to be covered by the design.

The methodology (Fig. 9) followed for the concept design study and requirements validation is based on the following stages:

- **Stage 1: Functional analysis and Hazards and Operability (HAZOP) study**. The studies were performed in parallel with the purpose to list the functions, the interfaces, the risk associated with the operation and their mitigation to be covered by the design of the components. The outcomes of these analyses are the **input for the conceptual design phase.**
- **Stage 2: Navigation into CAD models.** The 3D models of the airlocks and other components associated with the flange removal operation are developed in CATIA. The design review is performed by sharing the numerical mock-up between the design experts and several stakeholders of the interfacing components. **The large screen and the Techviz software** are used for navigation into the CAD environments in flight mode with the possibility of having different viewing angles and taking measurements and cuts (Fig. 7). The navigation in 3D models on a large screen at true size is essential for integration studies and to support engineering discussion around the design requirements validation. However, some limits have been detected for design validation in crowded and narrow areas. The immersion in a 3D environment provided on a 2D screen cannot offer the perspective and the understanding of a complete immersion as with VR headsets and interactions in the models.

  The outcome at this stage is a **partial feasibility validation of the operation and design** based on the available space for integration.
- **Stage 3: Virtual Prototype.** The simulations are developed in Unity 3D **with the use of the XDE physics** providing collision detections and complex joint simulations. It is possible to realize complete removal scenarios and rescue scenarios. In Unity, movable and fixed objects are defined, collision layers are assigned, the virtual manipulator is coupled with the haptic arm and the assembly scenarios are created. Three types of simulation have been studied: the **Immersive Virtual reality simulation** for rescue scenarios with human intervention in Ventilated Suit, the **haptic arm master/virtual robot-arm slave simulation** for the robot accessibility assessment, including inverse kinematics, and **Remote Handling off-line simulations** with a virtual manipulator for task development and operation feasibility assessment.
- **Stage 4: Test of real-time simulations and requirements validation.** The immersive and the haptic arm master-robot slave simulations have been tested by engineers, designers and technicians involved in the project. The users wearing the Head-mounted display (HMD) were immersed in the virtual mock-up, performing the tasks foreseen by the scenario (Fig. 8). The tests were projected on a large monitor to share simultaneously the simulations between several experts. The real live movements and the virtual scene have been recorded for post-processing evaluation to assess the feasibility and the accessibility. Remote Handling engineers tested the simulation with the haptic arm. The off-line automatic scenarios were shared for analysis and discussion. The outcomes of the sessions are the **accessibility validation for human access**, the **feasibility validation of the operational tasks** and, potentially, the proposal of local optimizations. The results are documented in digital documents with the record of the decisions and the videos recorded.

Fig. 7. Design review on large screen (powerwall display) with the Techviz software.

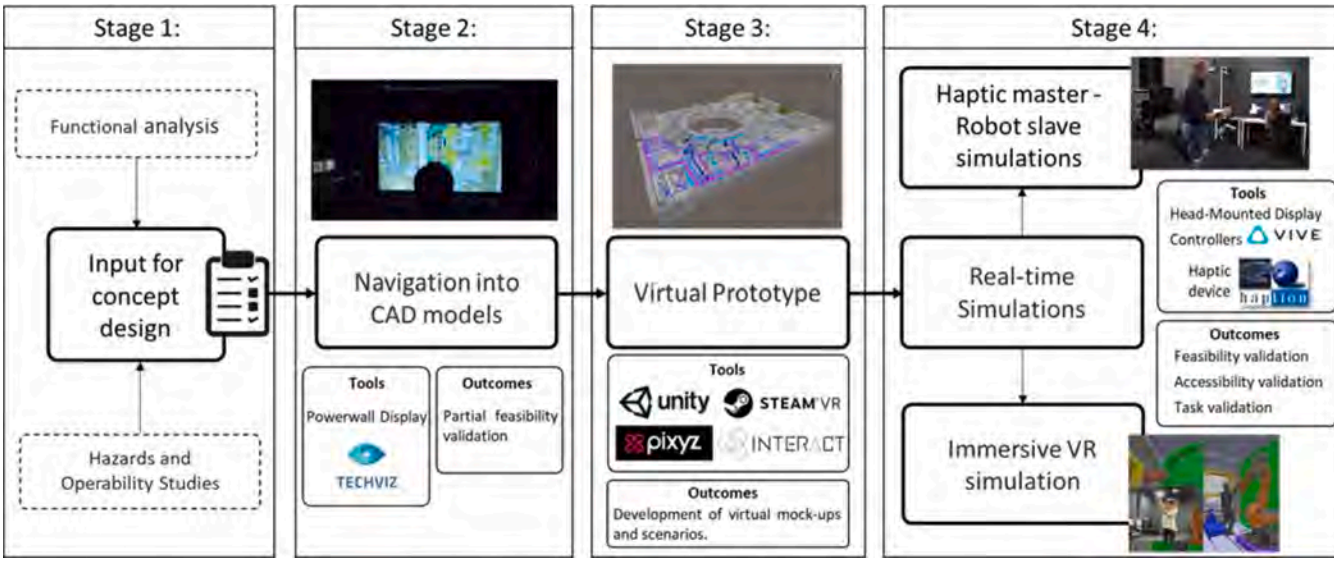

Fig. 9. Methodology for concept design validation.

4. Virtual reality simulations

4.1. VR interactive immersive simulations

The **interactive immersive simulations** with **CEA nuclear avatar** [14,15] have been developed to represent the rescue scenarios identified with the risk analysis.

The worst-case scenarios correspond to robotic arm or sealing flange handling frame failures, and they will require human access in ventilated suit (Fig. 10).

In the VR environment, simulating the condition of the worker wearing a bubble suit increased the realism of the simulation (Fig. 11) and gave more reliable results to assess the accessibility during the operation.

The tests were performed by several design experts involved in the projects.

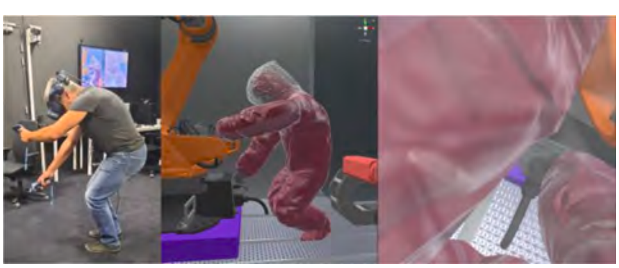

Fig. 10. Study of rescue scenario: robot arm failure. Human access required to release the brake of the trolley and pull the robot back.

Fig. 11. Simulated visual field with avatar in a standard suit and simulated visual field with avatar in ventilated suits.

With these simulations, it is possible to verify the adequacy between workplace configuration, components and tools volumes, and workers in bubble suits.

The study for the maintenance cabin airlock validated the accessibility in case of rescue scenarios, but some indications and design modification proposals were identified.

For example, the hands-on access to all the bolts was checked in the configuration with the handling frame connected to the sealing flange and relative trolley failure. Performing the operation in VR, some clashes have been detected between the handling frame and the operator's arms and legs, in particular, the access was challenging due to the size of the motors on the frame (Fig. 12). Therefore, a reduction of the size of the motors and the use of long-reach tools was recommended.

The Human Access Airlock study validated the accessibility, demonstrating that the size of the rooms is suitable for dressing/undressing operators in ventilated suits. However, the size of the platform to enter into the airlock needs to be increased, as there is not enough space on the platform to open the door (Fig. 13).

4.2. VR haptic arm simulation with force feedback and sequence animation

The **haptic master arm and virtual slave robot simulations**

Fig. 12. Accessibility study to the bolts with clashes detection.

Fig. 13. Opening of the door of the Human Access Airlock.

Fig. 14. Accessibility study of the Kuka Robot with force feedback.

(Fig. 14) have been developed to represent the unfastening of the 16 captive bolts to be removed by the robotic arm when the handling frame is inserted and attached to the sealing flange.

This corresponds to one of the critical steps of the operation.

Due to the complex kinematics and design of the industrial robot, and considering the tight available space around the sealing flange and the handling frame to execute the intervention, the VR proposes a more efficient and reliable way of assessing the robot accessibility instead of using classical articular control of the joints.

The possibility to simulate the complex kinematics of the robot with the force feedback as soon as the robot interacts with other elements of the simulation permits the Remote Handling (RH) engineers to precisely identify the environmental and maintenance constraints from the earliest design concept and will help to optimize design and procedures on the virtual mock-up.

With these simulations, it is possible to verify the adequacy of the workplace configuration, the volumes reserved and the tools inside the maintenance cabin.

Off-line automatic simulations of operational sequences (Fig. 15) were developed for the different scenarios in order to help the procedures validation and the overall logistics. Observation of movements and trajectory variants of handling equipment can be used by RH engineers

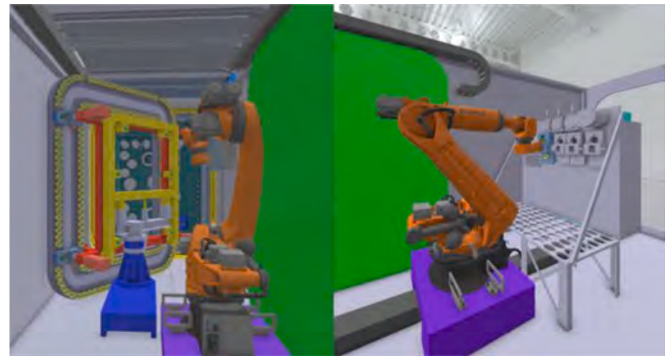

Fig. 15. Captures of operational scenarios animations.

to plan and examine handling concepts and the Operation Sequences Description.

The simulation of scenarios in the maintenance cabin confirmed the feasibility of the operation, the removal trajectory validation, and accessibility validation thanks to some design changes. For example, the opening position of the double door limits the accessibility of the Kuka robot to the bolts, therefore, the door has been moved 50 mm at the back. It was observed that the accessibility to the bolts on the sealing flanges is limited, so a new design of the robot tool was recommended.

5. Conclusions

The study showed the significance of using the Virtual Reality capabilities for components and operations concept design validation.

With these tools, it is possible to build a virtual mock-up 1:1 scale with the possibility to develop real-time immersive and interactive simulations. The benefit of using these tools comes clear when the integration and accessibly studies have to be performed in very congested areas (such as the tokamak building environment), when complex robot kinematics for remote handling, cobotics or co-manipulation modes are involved or when human access in harsh environments is required. In these cases, the pure navigation within 3D cad models on a flat screen is not sufficient to carry accessibility reliable studies compared to the recent VR immersive simulation.

The relevance of introducing VR tools in the early design stages with a non-fixed design is related to the possibility of anticipating issues, optimizing the design of components and procedures on virtual mock-ups, before building physical mock-ups, and consequently saving time and costs.

In particular, the paper investigated the application of VR technology for concept validation of the removal operational procedure for the Port Plug flange at ITER and the feasibility of rescue scenarios. The virtual sessions were shared with several experts like Remote Handling engineers, Mechanical engineers, designers, and Occupational Health & Safety representatives involved in the project.

The design reviews at ITER are carried out by means of 3D models navigation. This study demonstrates that VR tools can be of benefit in design review processes applied at ITER. Thanks to the performed simulations, some of the requirements to be covered by the design of the airlocks and the maintenance strategy proposal have been validated, and the robustness of the concept design was supported by the verification of rescue scenarios in ventilated suits. For TBM PC the PP removal is a key part of the scientific program and this approach is useful to anticipate the potential issues and to optimize the procedures at an early design stage. For future developments, Virtual Reality studies will continue to gather feedback for camera views and equipment rescue. For human access assessment, the use of real-time dose rate analysis is planned.

Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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