Virtual Reality: a way to prepare and optimize operations in decommissioning projects

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ASTRACT

The CEA has operated numerous nuclear facilities to carry out R&D and define nuclear fuel life cycle processes since the 1950s. It must now manage the clean-up and dismantling of those which have reached the end of their lifetime. These high priority actions have led to the creation of a dismantling R&D division which provides innovative tools, including in-situ radiological characterization, remote handling and cutting, and intervention scenario simulation. The latter involves running defined scenarios and verifying their suitability for the environment. Simulation is an ideal means of visualizing and therefore better knowing highly radioactive environments where humans cannot enter, of testing different technical alternatives, and of training workers prior to interventions. This paper describes Virtual Reality (VR) uses on dismantling projects. A VR simulation can be defined as an interactive and immersive simulation that enables the user to interact with a computer-simulated environment. VR environments, mostly based on visual immersion displayed through stereoscopic devices, can also include additional sensory information, such as sound or touch. Our application, based on audio, tactile and visual immersion, provides a useful support to verify pre-defined scenarios and to design alternative solutions if necessary. Thanks to a stereoscopic visualization, users are immersed in a virtual world, where they can hear virtual sounds when there is a collision, and can manipulate virtual objects and touch them via a haptic interface. This article first describes the PRESAGE immersive room in Marcoule. Then, the data preparation is explained, especially the 3D model reconstruction and the simulation configuration (remote handling and radiological). Next, different VR uses on decommissioning projects are shown and illustrated by examples. The advantages of such technologies include their speed in testing, user-friendliness, reactivity and usefulness in the preparation for complex dismantling operations. Finally, the perspectives for future applications are mentioned, especially radioactive dose rate and virtual human simulation.

I. Introduction

The CEA (French Atomic and Alternative Energies Commission), leader in research, development and innovation especially in the energy field, must manage the end of its nuclear fuel cycle facilities' lifetimes. Clean-up and dismantling actions are a CEA priority [1]. The Marcoule site (Gard, France) is one of the biggest clean-up and dismantling worksites in the world. The CEA must carry out these

operations while respecting three vital issues: worker protection by dose rate limitation, environment protection by research into lowering nuclear waste volume and activity, and financial management, which combines cost efficiency and respect of the regulations and ever-stricter safety requirements.

In order to address these three issues, the CEA has created a dismantling division, which runs an R&D program to provide innovative tools. This program focuses on the development and industrialization of measurement tools and techniques to better characterize in-situ radiological conditions, of remote handling and cutting tools, designed for highly radioactive environments, and of intervention scenario simulations. The latter involves running pre-defined scenarios and verifying their suitability for the environment. This highly-realistic simulation is possible thanks to Virtual Reality (VR) technologies, which enable a user to interact with a computer-simulated environment. VR environments, mostly based on visual immersion, also include additional sensory information such as sound or touch.

This paper describes how VR technologies, adapted to the nuclear decommissioning context, can provide useful support to engineers in charge of scenario design. Before beginning the actual operations, such a set of tools is also well adapted to communicating and sharing information during project reviews, or to training workers and ensuring they are aware of the risks they or their equipment could be exposed to. First, the VR technologies used will be described. Secondly, the paper will present the different simulation preparation steps, like 3D reconstruction, radiological characterization, remote handling simulation… Then, application examples will be presented and show how VR simulation can be applied in decommissioning. In the last section, we will describe the limits of such simulations, and the perspectives.

II. Virtual Reality and Dismantling: current practices

Virtual reality (VR) is a technology widely used in various fields. For instance, in medicine, the primary use of VR in a therapeutic role is its application to various forms of exposure therapy, from phobia treatments to newer approaches to treating Posttraumatic Stress Disorder [2]. Other research fields in which the use of virtual reality is being explored are physical medicine, pediatrics or surgery training [3]. In industry, VR can be applied to new product design (electronics, CAD, Computer Aided Manufacturing, naval, automotive or aerospace design, etc.), for urban regeneration and planning or in archeology to rebuild destroyed monuments. Applied to the nuclear industry, VR provides an intuitive and immersive human-computer interface, to verify intervention scenarios and train future operators. Some research has led to the development of applications for maintenance training, or to new methodologies for disassembly evaluation of CAD model designs for maintenance [4]. Some works have also focused on using VR in a training program for simulating refueling operations while reducing the doses received by workers [5]. Lastly, some studies target VR decommissioning assistance, in the Chernobyl NPP dismantling, for example [6]. Our work is slightly different because it is the first time that VR technologies have been used to prepare and optimize future operations, which gives more confidence and reliability to scenarios.

III. PRESAGE, the Marcoule Immersive Room

The CEA created the Marcoule immersive room (Fig. 1), called PRESAGE, at the end of 2008 in order to validate maintenance or dismantling operations. It is a resource shared by all the CEA decommissioning projects.

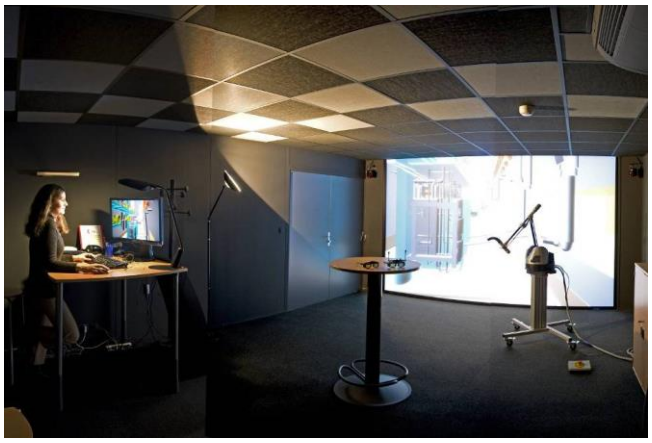

Figure 1: PRESAGE room.

The PRESAGE room groups all the technologies enabling user immersion and interaction in a virtual environment.

Three kinds of immersion are possible: visual, sound, and tactile.

First, a stereoscopic visualization system is based on a 3.7m x 2.3m image wall, giving the user a 3D vision of the virtual environment. The size of the screen means it is very comfortable to work on life-size simulations. The perception of 3D depth comes from the INFITEC technology [7]. It has been chosen because of its high rendering quality and its good user comfort.

Sound simulation has been added, to reproduce the sound received by the in-situ microphone: the operator will be able to hear the sound of collisions in the monitoring room. Generally, the sense of sound is very useful to operators working with remote handling systems. It helps them to better pilot the system, because they have feedback of what they are really doing. Therefore a specific type of sound has been associated with each collision, to enhance the information sent to the user.

To produce tactile immersion, haptic systems are used, enabling the sensations of touch and of effort. We chose to equip the room with two haptic interfaces, 6D Virtuose by Haption (Fig. 2), which give force feedback on all six degrees of freedom, together with a large workspace and high torques [8]. They are especially recommended for scale 1 manipulation of virtual objects such as assembly/disassembly simulations, ergonomic studies, or maintenance training. The Presage room is equipped with two haptic systems in order to simulate work with either two hands or two operators in collaboration.

Figure 2: 6D Virtuose.

A physics engine generates the forces to be applied to avoid objects' inter-penetration and sends the right information to haptic interfaces to create force feedback.

To interact with the simulation, motion capture is used to track a flystick enabling navigation in the virtual environment. Based on eight IR cameras, the device position is tracked in real-time and its virtual position is therefore updated [9]. It is also possible to track head position: as a result, when the user moves his head, the point of view of the simulation changes as if a genuine movement had taken place within the VR surroundings (Fig. 3). Last, the room is equipped for the use of a whole motion capture suit, which enables a virtual human to be inserted into the simulation, thanks to targets located on each part of the operator's body.

Figure 3: flystick (left), tracked glasses (middle) and suit (right).

IV. From real to virtual: the steps to build the simulation

In order to do VR studies on decommissioning projects, certain steps are necessary to build the VR simulation. To run such simulations, a new software, called iDROP, has been developed by the CEA. This software is made up with several real-time modules: collision detection, robotics, virtual human, and dose rate calculation. It allows a scenario global approach, taking into account all the aspects of a decommissioning project. IDROP takes 3D models, remote handling model and radiological data in input. This part describes all the steps necessary to build a iDROP simulation.

A. *Step one: build the 3D models*

3D models of the environment have to be built. First, 2D facility plans are collected and used to build the corresponding 3D model. To verify if the 2D plans are up-to-date, an in-situ photo campaign can be necessary. In some cases, this step is enough and the 3D model is made up from 2D plans.

If the 2D facility plans available are not sufficiently up-to-date to design a precise digital mock-up, 3D reconstruction is necessary to be sure the 3D model will be faithful to reality. Two main rebuilding techniques exist and can now be used in a nuclear environment.

The photogrammetic reconstruction enables a 3D model to be built up, using the parallax obtained between the images acquired depending on the different points of view. It implements the correlation calculation between the digital images to give a 3D reconstruction of the model. After an in-situ photo campaign, processing consists in identifying and digitalizing the points with common physical details on the photos, as well as the apparent contours of lines and cylinders. This reconstruction is semi-

automatic, and is carried out from basic trade elements (tube valve, nut, screw, elbow…). This technique was used on the APM Cell 414 decommissioning project, and the study was carried out by the subcontractor ESIC SN [10]. It consisted in taking 700 photos along the existing rails (Fig. 4), for one week. The 3D reconstruction took four weeks. The model obtained is accurate to about 5 cm. Nevertheless, the photos taken do not allow all the pipes to be seen, especially those located behind other elements.

Figure 4:4 of 700 photos taken during the measurement campaign.

The images below enable the comparison between a real photo and a VR view of the same scene (Fig.5).

Figure 5: a real photo (left) and 3D view (right).

The other technique available is 3D-laser scanning. It is based on a scanner, and the measurement is done via a laser beam. The scanned environment is transferred into points. The result is a 'cloud' of tens of millions of points, each defined by a 3D (X, Y and Z) value. This 3D 'point cloud' serves as a basis for 3D reconstruction, e.g. in a CAD tool. Laser scanning meets the need for highly accurate, complete and quickly-obtained images.

In both techniques, CAD models can be directly imported in the immersive room. However to enhance performances, simplifications can be made to reduce the size of the 3D model, by for example removing fastenings (screws, nuts, washers…), filling holes (deleting drilling or simplifying extrusion profiles), and suppressing non visible or hidden objects.

B. Step two: build the remote handling models

When decommissioning operations will use remote handling systems, a model preparation is necessary to simulate the correct motions. A robot is shown by 3D objects linked by father-child kinematic links. Objects called "axes" make up the robot skeleton. There are two types of 1 degree of freedom motion that can be applied on these axes: rotation around x, y or z and translation (in the direction of x, y or z). These movements can be used on a single axis and are limited by minimal and

maximal end-stops, applied on the object pivot. Virtual robots can then be manipulated with their constraints, like in reality. Robots and carriers can therefore be described easily (Fig.6).

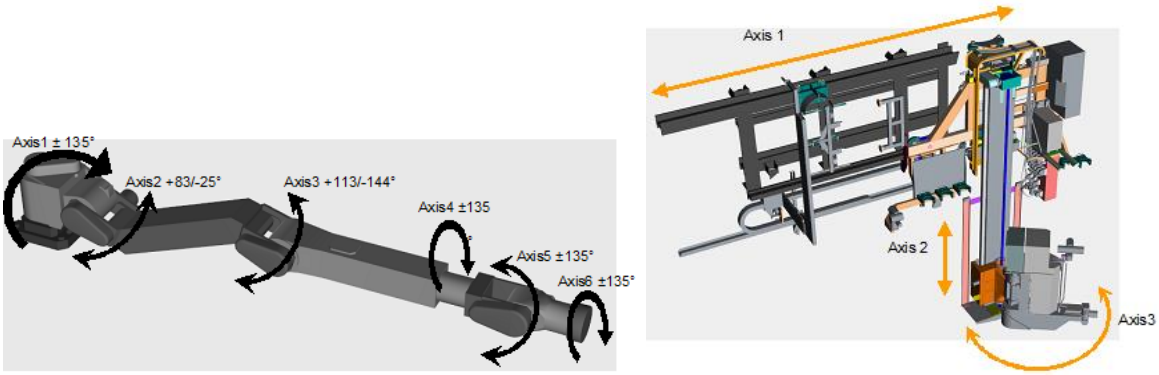

Figure 6: examples of a robot (left) and a carrier (right) kinematics

To do this configuration, the robot specifications have to be known. We can also connect tools (Fig.7) to robots, to dismantle (saw or grinder), or to grasp pieces of equipment (clamp). Collisions and contacts with the environment can be felt on each of them.

Figure 7: clamp (left), shears (middle) and nibbler (right).

C. *Step three: build the radiological models*

This consists in superimposing radiological data and the 3D environment. In-situ measurement campaigns enable identification of radioactive hot spots, with ambient dose. After having characterized dominant radioelements and source activity, it is possible to add these pieces of information on the corresponding 3D objects. Material characteristics can be added on the other 3D objects (concrete, iron, aluminum…).

Once the model is prepared, a dose rate calculation is done in the iDROP software, developed by the CEA. It calculates the dose rate received in every point of the cell, with each hot spot taken into account. This calculation is based on the minimization of the dose rate absorbed with the distance from the radioactive source: the dose rate absorbed is proportional to the number of particles which penetrate a mass element, given by time unit. One way to reduce this number is to increase the distance between the operator and the radioactive source. If the source is considered as a point, the dose rate absorbed follows the law of the inverse of the square of the distance [11]. The innovative character of the dose rate simulation consists in calculating dose on several measurement points at the same time, taking into account several radiological sources in real-time. It means that dose rate evolution is immediately observable, when a parameter is evolving (movement of a measurement point, a source or a screen for instance).

V. Uses of VR on decommissioning projects

Among all the facilities to dismantle, VR technologies have been used on the APM (Marcoule Pilot Workshop) cell 414 [12] and the MAR 200 (Marcoule fuel retreatment workshop) dissolver blind cells

[13]. Due to the high radiation, all operations must be carried out with remote handling systems. These operations are very complex, which clearly justifies using VR. VR simulation helps in preparing the future actions: verifying scenarios, designing remote handling systems, studying accessibility, optimizing the operating workstation and training operators. In both application cases, engineers, operators and project teams came into the Presage room, "interacted" with VR simulation thanks to the immersive devices, and tested and verified all the dismantling operations.

A. Accessibility studies

Using the Presage room, tests were carried out on remote handling systems to verify the suitability of equipment for the environment. For example, on the Cell 414 project, accessibility problems preventing the forward movement of the carrier were quickly identified. While the first obstacle could be avoided by raising the Maestro base, the second will have to be dismantled by existing in-cell equipment before the carrier enters the cell (Fig. 8).

For the MAR200 project, tests were realized on the tools' grasping in the glovebox and their introductions into the blind cell. For each tool, the robot was controlled in order to place it in front of the tool and then verify if grasping was possible. Technical issues were revealed: for example, originally, the probe was placed in a position that prevented the laser torch grasping. Modifications were therfore made to the probe rack (Fig. 8).

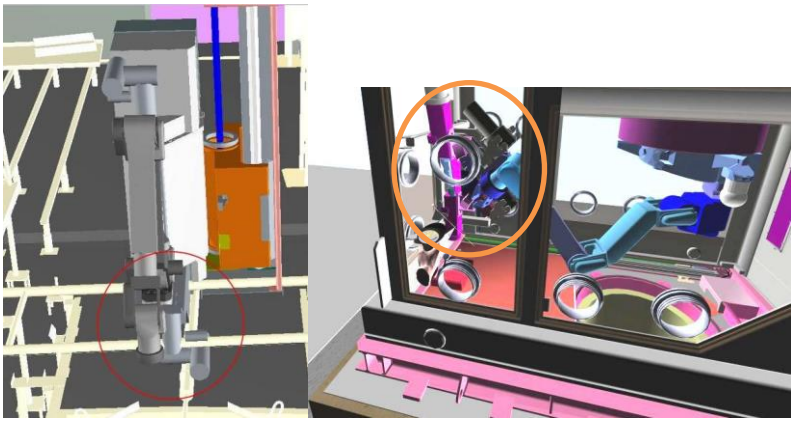

Figure 8: accessibility problems in the environment: APM (left) and MAR200 (right).

B. Validation of overall scenarios

For the MAR200 project, the dismantling scenarios were simulated: first, the simulation of the shaft cutting showed that vertical cutting has to be done by the carrier in motion. Then, the pipes located above the tank can be cut by the laser torch. For the more distant ones, the laser torch is in an extreme configuration. The simulation also proved that it will be easier to cut the tank top from inside than outside. That involves changing the order of dismantling sequences, by cutting the inner pipes first, then cutting the tank top (Fig.9).

Another simulation took waste elements and put them in the waste basket. It enabled the validation of the proposed cutting size (300 mm long maximum) (Fig.9). The cutting entry hatch has to be better located in order to improve the waste extraction from the cell, and the visibility of the tasks for the in situ cameras.

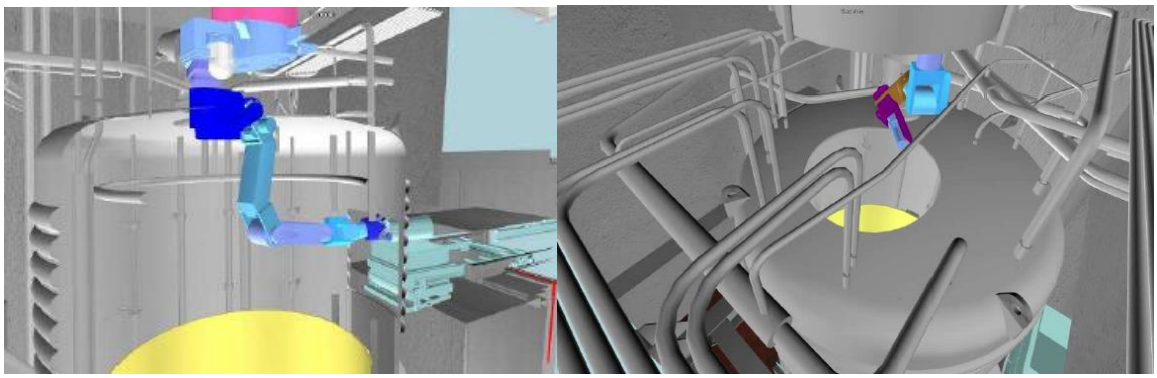

Figure 9: laser torch cutting the pipes above the tank (left) and waste removal (right).

Concerning APM Cell 414 dismantling, the pieces of equipment (centrifuges) to be dismantled are located under a jutting block, in a zone, which is very difficult to reach. The pieces of equipment are quite big and heavy, which has raised questions about how to dismantle the structure. This scenario needs specific handling tools to help remove parts, as the pulley cannot be used under the jutting block. The detailed dismantling scenario from the carrier entry to the centrifuges' cutting was verified. We proved that dismantling the centrifuges in situ with hydraulic shears would not be feasible as originally planned. In fact, the shears footprint is too big and it cannot access the centrifuges (Fig.10). A new scenario was proposed, consisting in removing the centrifuges from under the jutting block, bringing them close to the cutting table where there is more space, and cutting them up with hydraulic shears. This scenario was validated and approved by the dismantling project engineers.

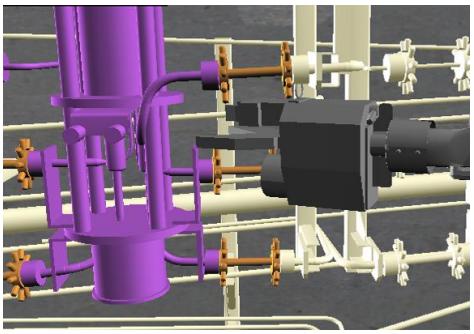

Figure 10: impossibility to cut with hydraulic shears

Other such situations were found. This kind of problem had not been identified before, and the dismantling project took these issues into account. Thus, from the simulations run, vital information was provided to implement in dismantling scenarios. The VR technologies have proved their worth.

C. *Training*

Training operators via such technologies can be very useful. 3D models are very close to reality and we can work with a life-size simulation. Currently, the control of robots with joysticks or 6D Virtuose devices allows the real robot motion in the cell to be tested. For APM Cell 414 dismantling, a real operating master arm was connected to the simulation and enabled the slave arm to be piloted (Fig.11). It could also be used to become familiar with the work environment, to train future operators to manipulate remote handling systems, and increase their awareness of the risks they could be exposed to, such as collisions between the carrier and its environment, or robot damage.

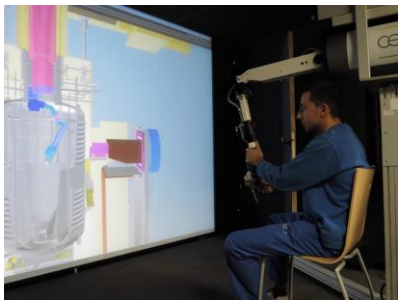

Figure 11: Industrial force feedback master arm used in Presage room

Another advantage of the VR training is to help operators get used to working with only video and sound monitoring from the blind cell.

D. *Dose rate simulation*

Thanks to iDROP software, it is possible to follow the evolution of the radioactivity levels during decommissioning in real-time, and calculate the new levels after the removal of hot spots. For APM Cell 414 project, hot spots were superimposed on the 3D models. This superimposition enabled better understanding of every hot spot's location in the environment. The first dismantling step consists in removing all the hot spots. With the superimposition, hot spot accessibility studies were carried out, which confirmed that every hot spot was accessible by the remote handling system (Fig.12). This verification was very useful because the feasibility was not so obvious to show without 3D superimposition.

Figure 12: hot spots in APM Cell 414.

VI. Limits and perspectives

First, any mismatch of information can affect safety and performance. For instance, if the modeling accuracy for the robot or the cell is not high enough, we cannot be sure that the scenarios that have to be tested with the simulator are reproducible in practice. The robot model comes directly from the manufacturer's CAD model, so it can be considered as identical to the actual robot. The modeling uncertainty comes from 3D reconstruction. It is known that photogrammetry is accurate to 5 cm precision. Laser scanning can be even more accurate (<1 cm).

Next, the physics engine can be limiting and is directly dependent on the computing power. With the current hardware, we cannot physicalize the robots and the whole cell with high precision for collision detection and obtain a real-time simulation. Collision detection precision has to be inferior or equal to 10 mm, so that the accessibility studies can be realistic.

The physics engine is not able to simulate cutting processes, which would however be very useful.

When dismantling operations include manual actions, human operations simulations could be much appreciated, in order to take into account human postures in dismantling scenarios and optimize them in terms of ergonomics.

VII. Conclusion

This paper has shown that VR tools open up new perspectives for decommissioning. Applied to complex projects, they can contribute to improving knowledge regarding project preparation and validating technical choices. The software involved is generic and can load any 3D model of a building. It is already functional and has proved useful, not only for studies but also for operator training. VR enables dismantling scenarios to be optimized, so that the real operations will avoid foreseeable problems. What is extremely promising is the very short time needed to test and validate the whole scenario. VR technologies are a very reactive solution, because changes can be taken into account rapidly and updates tested immediately. Given these results, VR advantages include user-friendliness, reactivity and applicability to complex dismantling operations.

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