Virtual Reality Technologies: A Way to Verify and Design Dismantling Operations

First application case in a highly radioactive cell

Caroline Chabal, Jean-François Mante, Jean-Marc Idasiak
CEA, DEN, SDTC, LSTD
30207 Bagnols-sur-Cèze, France.
caroline.chabal@cea.fr, jean-francois.mante@cea.fr, jean-marc.idasiak@cea.fr

***Abstract* - The CEA must manage the end of its nuclear fuel cycle facilities' lifetime. Cleansing and dismantling actions are among its priorities. In order to address these issues, the CEA has created a dismantling division, which runs an R&D program to provide innovative tools. Intervention scenario simulation is one of these R&D projects, enabling defined scenarios to be run, their suitability for the environment or scenario key points to be verified, taking into account unexpected situations and providing technical answers. Simulation is a good means of visualizing and therefore understanding constraints, of testing different alternatives, and is a way to train workers prior to interventions. This paper describes an application of such a technology: dismantling a chemical cell in the APM (Marcoule Pilot Workshop) facility at Marcoule (France). This highly radioactive cell will be dismantled by a remote handling system using the Maestro slave arm. An immersive room has helped to design the dismantling scenarios. The article presents all the pieces of equipment in detail. Then, we focus on the processes of building the 3D model, especially the photogrammetric study step. Next, the software development we have done to couple the Maestro with a haptic interface and its carrier with game joysticks is described. All the remote handling is controlled in real time and with interactivity and detection collision. Thanks to force feedback and visual immersion, accessibility, operational trajectories and maintainability on the carrier have been verified. The overall scenario has been tested and problems have been found, which have meant modifications and updates of the final scenario to guarantee the system will work properly. The results are very encouraging. Finally, the perspectives for the project are mentioned, especially worker training and radioactive dose rate simulation.**

Keywords-virtual reality; dismantling operation; haptic interface; accessibility study; remote handling; collision detection; interactivity; real-time

I. INTRODUCTION

The CEA is the French Atomic and Alternative Energies Commission. A leader in research, development and innovation, the CEA is active in four main fields: low carbon energies (including nuclear energy), IT and health technologies, very large Research Infrastructures (TGIR), defense and global security. It is part of the European research community, and its international presence is growing.

Among other activities, it must manage the end of its nuclear fuel cycle facilities' lifetime. Cleansing and dismantling actions are a CEA priority [2]. It has the objective of managing its legacy through exemplary Decommissioning & Decontamination programs for its old nuclear plants, in order to better prepare the future. The stakes are high. It must be shown that the nuclear industry is able to control the complete lifecycle of first generation facilities (built 1950-1960), from their construction, commissioning, operation, and shut down through to dismantling and site release. In parallel, the 2nd generation facility lifecycle must be managed, the 3rd generation started up and the 4th prepared for.

The Marcoule site (Gard, France) is one of the biggest cleansing and dismantling worksite in the world. It was created in the 1960s, as part of France's atomic energy program. Today, the D&D operations are dealing with G1, G2 and G3 shutdown reactors, workshops used to develop reprocessing and vitrification processes (APM), the first French spent fuel reprocessing plant (UP1) and the fast breeder demonstration reactor (Phenix).

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 costs efficiency and respect of the regulations and ever-stricter safety requirements [3].

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 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 scenarios simulation. The latter involves running defined scenarios and verifying their suitability for the environment.

This simulation is possible thanks to Virtual Reality (VR) technologies, which enable a user to interact with a computer-simulated environment, whether that environment is a simulation of the real world or of an imaginary world. VR environments mostly based on visual immersion and displayed either on a computer screen or through stereoscopic displays, can 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 [1]. 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 could be exposed to.

First, the chosen VR technologies will be presented. Secondly, the first application case will be presented and explained as well as the nuclear environment and the remote handling system used for dismantling. Then, we will describe the simulator developed to validate scenarios.

In the last section, we will describe our first results and the perspectives.

II. Virtual Reality and Dismantling: the State of the Art

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 [4]. Other research fields in which the use of virtual reality is being explored are physical medicine, pediatrics or surgery training [5]. 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 development of applications for maintenance training [6], or to new methodologies for disassembly evaluation of CAD models designs for maintenance [7]. Some works have also focused on using VR as a training program for simulating refueling operations while reducing the doses received by workers [8]. Lastly, some studies target decommissioning assistance thanks to VR, in the Chernobyl NPP dismantling, for example [9]. Our work is slightly different because it is the first time that a whole dismantling scenario has been simulated via VR technologies and especially with force feedback, which gives more confidence, reliability and reality to the simulated scenario.

III. The Marcoule Immersive Room

The CEA created the Marcoule immersive room (Fig. 1) at the end of 2008 in order to validate maintenance or dismantling operations. It is a resource shared by all the CEA decommissioning projects described in the introduction (APM, Phenix, UP1), and can be used for project reviews, for accessibility, ergonomics or scenario feasibility studies, and for training workers.

The team works on new plant design as well as dismantling projects.

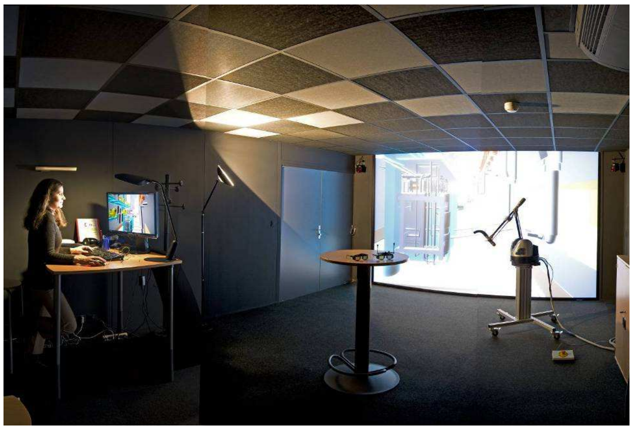


Figure 1. Marcoule immersive room.

The CEA Marcoule immersive room groups all the technologies enabling user immersion in a virtual environment and interaction. The figure below shows the immersive room configuration (Fig. 2). The main pieces of equipment will be described hereafter.

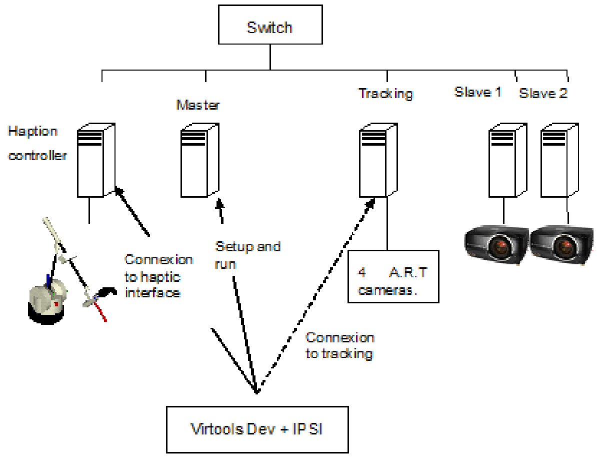


Figure 2. Marcoule immersive room configuration.

A. *The hardware*

The Marcoule immersive room is equiped with VR pieces of equipment based on the following technologies.

1)Screen

The immersive room is equipped with a stereoscopic visualization system with a 3.7m x 2.3m image wall, giving the user a 3D vision of the virtual environment. The two Projection Design video-projectors (resolution 1920x1200) create the images and are each controlled by a separate PC (slaves 1 and 2 above). The result is a definition of 2 mm pixels. The size of the screen means it is very comfortable to work on life-size simulations.

2)Stereoscopy

Stereoscopy refers to a technique for creating or enhancing the illusion of depth in an image by presenting two offset images separately to the left and right eye of the viewer. Both of these 2D offset images are then combined in the brain to give the perception of 3D depth. Three strategies have been used to accomplish this: the viewer wears eyeglasses to combine separate images from two offset sources (passive stereoscopy), the viewer wears eyeglasses to filter offset images from a single source separated for each eye (active stereoscopy), or the light source splits the images directionally into the viewer's eyes (auto stereoscopy).

After examining the options available, we have chosen the Infitec (INterference FIlter TEChnology*)* passive stereoscopic technology. Infitec GmbH is a German company that owns a technique for channel separation in stereo projection based on interference filters [10].

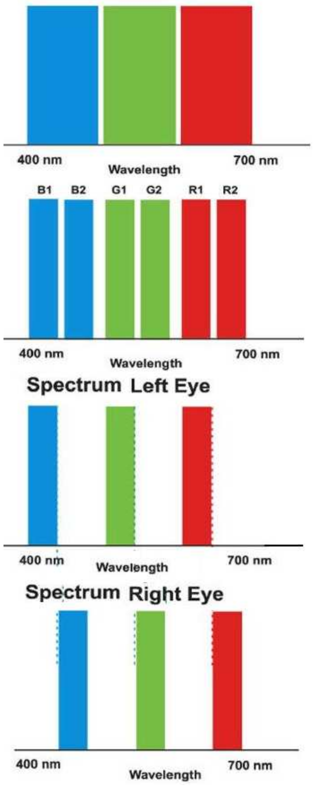


Figure 3. Infitec technology principle.

Special interference filters (dichromatic filters) in the glasses and in the projector form the main item of technology and have given it this name. The filters divide the visible color spectrum into six narrow bands - two in the red region, two in the green region, and two in the blue region (called R1, R2, G1, G2, B1 and B2). The R1, G1 and B1 bands are used for one eye image, and R2, G2, B2 for the other eye (Fig. 3). The human eye is largely insensitive to such fine spectral differences, so this technique is able to generate full-color 3D images with only slight color differences between the two eyes.

This technology presents many advantages: first, the quality of the generated picture is very high and stereoscopy is good when the user turns his head compared to other passive stereoscopic technologies; second, good user comfort because the glasses are very light and there is no visual tiredness. The only drawback of this technology is the slight color alteration generated, which is not an issue in our application.

3)Motion capture

Motion capture is the position measurement of bodies that move in a defined space. Tracking systems, based on various measurement principles, are available, e.g., mechanical, magnetic, optical (VIS or IR) and acoustic trackers, and systems based on inertial or gyro sensors. In the group of *contactless* trackers, i.e., trackers that do not work with mechanical digitizers, the highest accuracy is provided by optical trackers. Optical tracking does not suffer from image distortions due to ferromagnetic metals, like electromagnetic techniques, or from drift problems, like inertial sensors. ART GmBH is a German manufacturer of high-end tracking solutions, specialized in infrared optical tracking for professional applications. This technology was chosen for its accuracy and technical reliability.

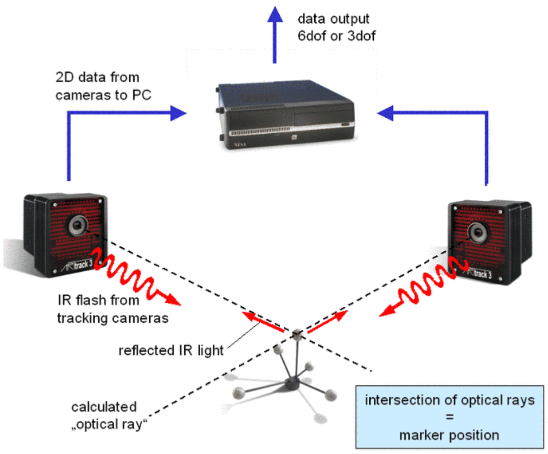


Figure 4. ART tracking architecture.

The user who shall be tracked is equipped with markers, which are light reflectors. Intelligent tracking cameras, scanning a certain volume, detect the light that comes from the markers and calculate 2D marker positions (image coordinates) with high accuracy (Fig. 4).

These data are handed over to a central ARTtrack Controller, which calculates the positions of rigid arrangements of several markers. The result of each measurement gives coordinates that describe the position of the markers, and hence the position of the body carrying the markers [11].

Figure 5. Flystick (left) and tracked glasses (right).

A flystick (Fig. 5) is a wireless interaction device for virtual reality (VR) applications. DTrack software takes up the flystick button and joystick events and correlates them with the 6DOF output data. This makes the matching of all data very user-friendly.

For head tracking in passive stereo systems, tracking targets must be attached to the stereo glasses (Fig. 6). 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.

4)Haptic device

A haptic system reproduces the sensations of touch and of effort applied to an object in a VR application. The device enables greater possibilities of immersion in handling virtual objects in 3D. Force-feedback interfaces are substituted for the traditional keyboard and mouse during tasks such as ergonomic studies or the simulation of maintenance or mechanical assembly operations. Actions involving the insertion of mechanical parts within a cluttered space can therefore be carried out very quickly and naturally, whereas they would require a lot more time and user skill with a keyboard and mouse.

We chose to equip the room with a haptic interface, the Virtuose 6D35-45 (Fig. 6). This device has been developed by Haption, a CEA spin-off, and is the only product on the market today, which offers force feedback on all six degrees of freedom (DOF) (three translations and three rotations), together with a large workspace and high torques [12] (the volume is equivalent to a 40 cm side cube). It is especially recommended for scale 1 manipulation of virtual objects such as assembly/disassembly simulations, ergonomic studies, or maintenance training.

Figure 6. Virtuose 6D35-45.

B. The software

In order to run the simulation, the Marcoule immersive room is equipped with specific software, described below.

1)Techviz

We use TechViz XL, developed by the French company TechViz, in order to capture the OpenGL flow from an application, generate stereoscopic images and send them to both projectors. It works especially well with 3DSMax, SolidWorks or Virtools. It is used to display 3D models on any display solution (CAVE, HMD, visualization wall …). TechViz XL offers the ability to work directly within 3D applications and to see 3D model displays in real-time on an immersive room [13].

2)3DVIA Virtools

3DVIA Virtools produced by Dassault Systèmes is used to manage a simulation. It is a complete development and deployment platform with an innovative approach to interactive 3D content creation. The 3DVIA Virtools production process facilitates prototyping and robust development up to large-scale, immersive or online, lifelike experience delivery. Thanks to its development environment and its Software Development Kit (SDK), we can create 3D real-time applications and add our own functionalities [14].

3)The IPSI physics engine

A physics engine is an independent software library applied to classical mechanics problem resolution (collisions, falls, forces, kinematics...). The purpose is to give a « physical » existence to graphical objects. One of the most robust and reliable principles is based on 3D model voxelisation. The word v*oxel* means volume element (by analogy with "pixel") and *voxelize an* object means finding all the v*oxels* ("small cubes"), which are inside the object. We can move from a surface representation to a volume [15]. The figure below shows that depending on the voxel size, model voxelisation is more or less faithful to the graphical object (Fig. 7).

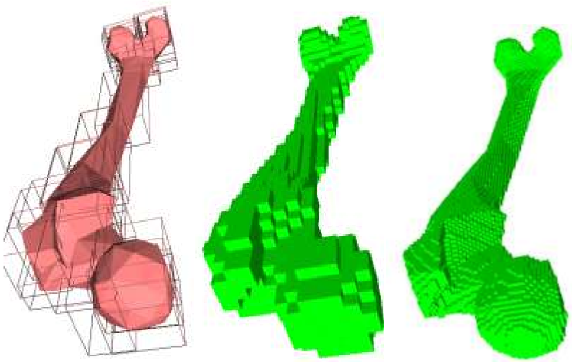


Figure 7. Examples of voxellistion with 2 different voxel sizes.

In this voxelized environment, the physics engine generates the forces to be applied to avoid objects inter-penetration. IPSI is a physics engine provided by Haption, based on voxelisation, and enables the testing of intersections between volumetric solids, in order to calculate trajectories and impact points. The real-time collision detection disables penetration between objects. It also offers kinematic chains creation and haptic interface plug-in with force feedback [16].

IV. First Application: Cell 414

We chose to implement the first application case on the Cell 414 decommissioning project.

A. Presentation of the project

The vitrification process currently used in La Hague was developed by the CEA in the Marcoule Pilot Workshop (APM facility). It was a prototype plant for reprocessing spent fuel, first commissioned in 1962, with production activities shut down in 1997. The plant is currently undergoing clean-up and dismantling.

Cell 414 is one of the 760 places in APM and one of the 30 very high radioactive cells. It was a chemical unit used to process liquids from irradiated fuel dissolution operations. It is a particularly large cell: 20m long, 4m wide and 6m high. There are approximately 5km of pipes to remove (Fig. 8). The total weight is estimated to be 18 tons of waste. The present high level of radioactivity rules out direct manual dismantling, so the choice of a remote handling system called Maestro has been made.

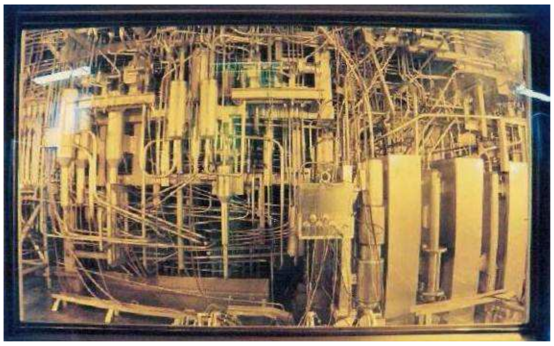


Figure 8. Very complex cell interior seen from a porthole.

The first step of decommissioning is to remove high level radioactivity. Data was gathered from an initial inventory: hot spots were identified with a gamma camera. These hot spots like the dosing wheels, the centrifuges, the pulsed filter and some parts of the pipes have to be removed first in order to reduce cell radioactivity (Fig. 9):

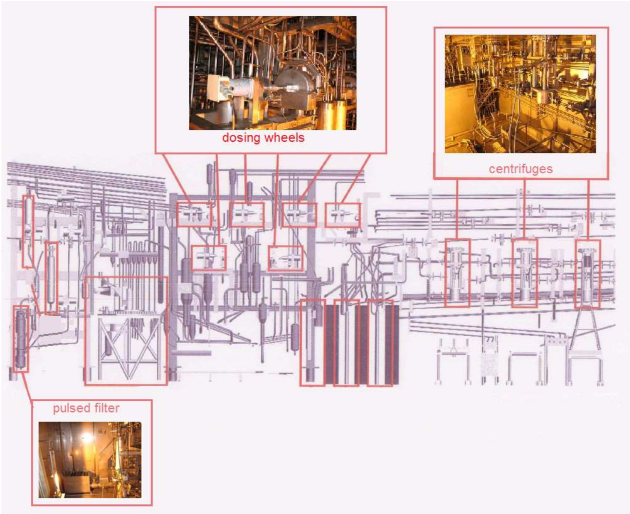


Figure 9. Pieces of equipment to be dismantled.

B. The remote handling system

The remote handling system is made up with the Maestro system and a carrier specifically designed for the dismantling.

1) The Maestro system

The Maestro system is the result of 10 years of collaboration between the CEA and Cybernetix, in charge of its manufacturing [17]. This advanced remote manipulator is used when human intervention is not possible, as in nuclear or offshore hostile environments. Maestro is dedicated to many tasks like inspection, maintenance, dismantling, cleaning, etc. Dexterity, accuracy and strength are its main advantages. It can be used in either robotic mode (automatic sequence) or in manual remote control mode with or without force feedback management.

Figure 10. The Maestro slave arm (left) and the Maestro master arm (right).

This system is made up of two parts: the master arm and the slave arm. The master arm is a device allowing the control of the slave arm end-effecter in Cartesian mode with a complete force feedback. This device is a Virtuose 6D40-40 from Haption **Erreur ! Source du renvoi introuvable.**.

The slave arm is a hydraulic robot with six degrees of freedom (Fig. 10).

The Cell 414 dismantling project will be the first worksite where Maestro will be used to dismantle a whole cell.

2) The carrier

The carrier was especially designed for Cell 414 dismantling, and will enable the Maestro system to reach all parts of the cell.

It works on three axes, using existing rails to move along the cell (20m), with vertical (3m) and rotating movements. A crane-type handling bracket is also set up on the carrier to hold parts during dismantling and for other handling operations. This carrier is currently undergoing tests (Fig. 11).

Figure 11. The carrier.

3) The surrounding rooms

Corridor 417, which is adjacent to Cell 414, will be used to assemble, maintain and disassemble remote handling pieces of equipment and will be the parking and transfer zone. A radiation-proof safety door between Cell 414 and Corridor 417 provides radioactivity containment (Fig. 12).

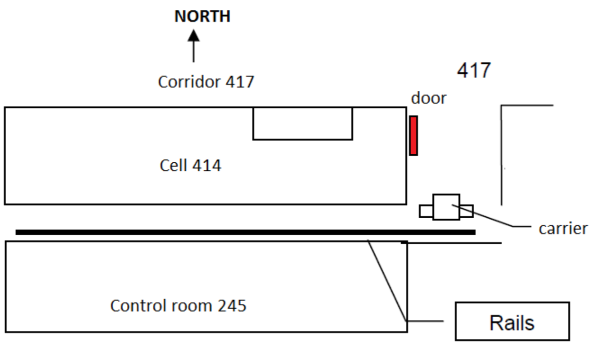


Figure 12. Control room and maintenance corridor.

During the dismantling, operations will be realized with indirect vision from the control room located in Room 245 (Fig. 12), via audio and video equipment installed inside Cell 414 and on the remote handling system. The control room includes four control screens, which display the images from the six in situ video cameras, two set up in the cell and four on the carrier.

V. From Real to Virtual: The Steps to Build the Simulation

In order to verify accessibility and maintainability on the carrier and to validate technical choices, it was decided to design the dismantling scenarios using a simulator and the VR technologies available in Marcoule.

A. Step one: build the 3D models

1) Cell 414 and surroundings

First, 3D models of the environment had to be built. As the 2D facility plans available were not sufficiently up-to-date to design a precise digital mock-up, a photogrammetric technique was used.

The photogrammetic reconstruction enabled 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 consisted of 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 basing trade elements (tube valve, nut, screw, elbow…).

The Cell 414 photogrammetric study was carried out by the subcontractor ESIC SN [18], as the model obtained is compatible with standard CAD software (Microstation, SolidWorks). It consisted in taking 700 photos along the existing rails (Fig. 13), for one week. The 3D reconstruction lasted 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 13. 6 of 700 photos taken during the measurement campaign.

To import 3D models into 3DVIA Virtools, they must be in a specific format, .NMO. Therefore 3DSMax was used, as it provides an exporter from .MAX format to .NMO format used by Virtools.

Next, the modeling of the building containing Cell 414 was made based on the plans of construction in SolidWorks. We also designed Cell 417 and Control Room 245.

Finally, we merged these parts to obtain a whole model in 3DSMax software. The images below enable the comparison between a real photo and a VR view of the same scene. We can see that the 3D simulation is very close to reality (Fig. 14).

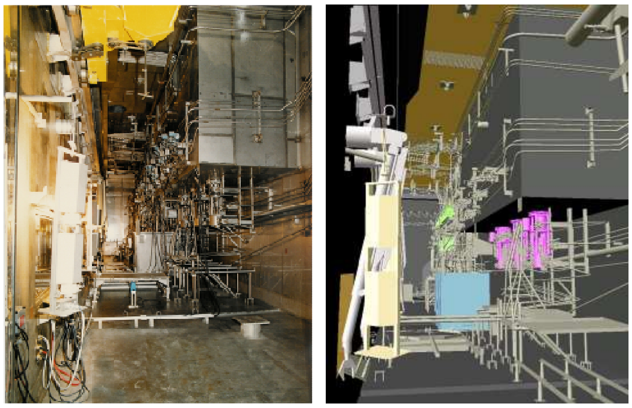


Figure 14. A real photo (left) and 3D view (right).

2) The robots

Concerning the robots previously described, we obtained the CAD model made by Cybernetix, the manufacturer. The modeling is in SolidWorks format and we did the necessary conversions to use it in 3DSMax (Fig. 15).

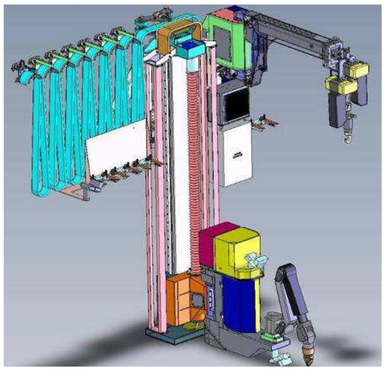


Figure 15. Carrier 3D model.

3) Simplification of the complete model

When all the models were merged, the result proved to be too big to manage easily and generated performance slowness in the 3D rendering. This first model contained more than 10 million faces. It had to be simplified to reach correct display performances. Whereas the civil engineering and Cell 414 internals could not be simplified, the reduction of the remote handling model was not complicated. It was the manufacturer's model and included modeling of all the elements down to screws and nuts. For accessibility studies, it is not necessary to have such accuracy. It is therefore possible to remove fastenings (screws, nuts, washers…), fill holes by deleting drilling or simplifying extrusion profiles, and suppressing non visible, hidden objects or those contained in others.

4) Results

The example below (Fig. 16) illustrates the simplification of a part: screws, grooves, rounded edges and holes have been removed. The overall shape is respected and the number of faces decreases from 2693 to 98.

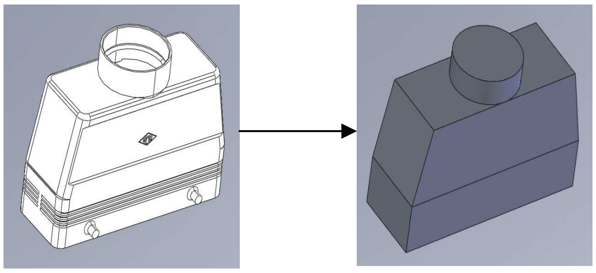


Figure 16. Example of part simplication

This step was very useful because without distorting the model, the simplification of every part of the carrier model leads to 180 000 faces, instead of 2.5 million.

As a result, the final 3D model has 1.2 million faces, compared to 10 million before simplification.

B. Step two: develop the simulator

In order to verify accessibility, we need to be able to pilot kinematics chains and detect collisions with the environment in real time. We have developed a physics module, integrating IPSI in 3DVIA Virtools, by using a specific script language and functions called Building Block (BB).

1) Kinematics creation

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 1DOF 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 as in reality.

The Maestro arm has 6 rotation DOF, as shown in the figure below (Fig. 17):

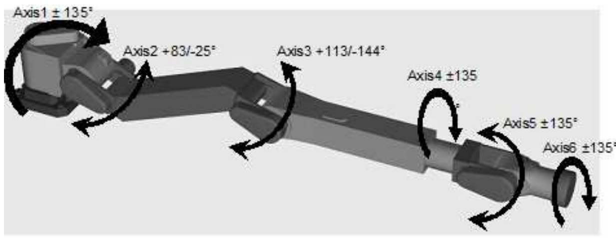


Figure 17. Maestro kinematics

The carrier can move all along the cell (20 m). The lifting mechanism enables the support platform to be raised. This platform has one rotation axis (±90°). The carrier therefore has three DOF, two translations and one rotation, as illustrated below (Fig. 18):

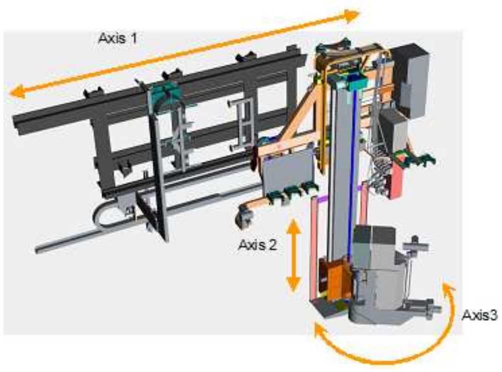


Figure 18. Carrier kinematics

Lastly, the handling bracket, which holds parts being dismantled, has three DOF; one rotation (±90°), one translation (extension of the bracket arm) and one other translation enabling the pulley to be lowered (see Fig. 19):

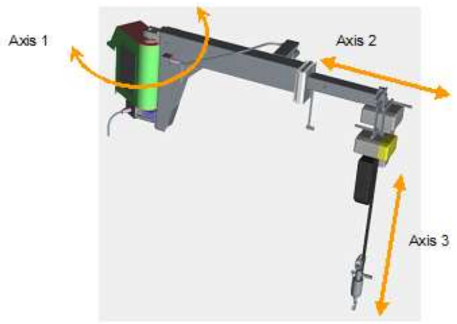


Figure 19. Handling bracket crane kinematics

Each robot has its own object hierarchy and they are attached to each other: The Maestro base is fastened to the carrier's object #5 (the support platform) and the bracket crane base is on the carrier's object #3 (Figure 20. 20). A Maestro tool is attached to Maestro object #6.

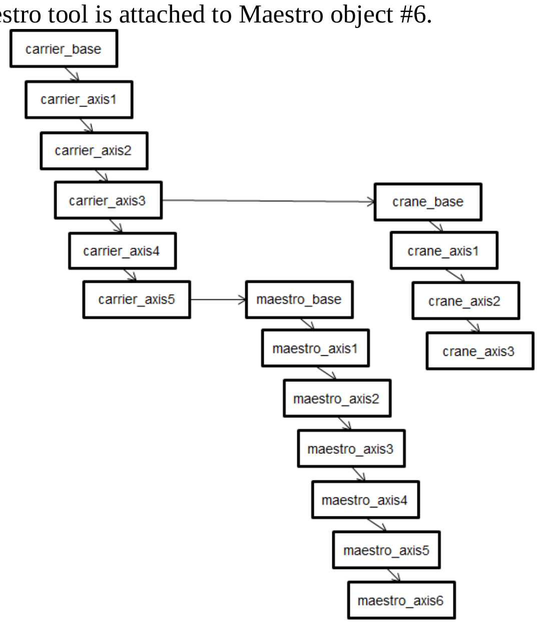


Figure 20. Robots' hierarchies

2) Maestro tools

All the tools below can be connected to the Maestro end-effecter. They are all used in the dismantling scenarios either to cut, like the saw or the grinder, or to grasp pieces of equipment, like the clamp. Collisions and contacts with the environment can be felt on each of them (Figure 21.).

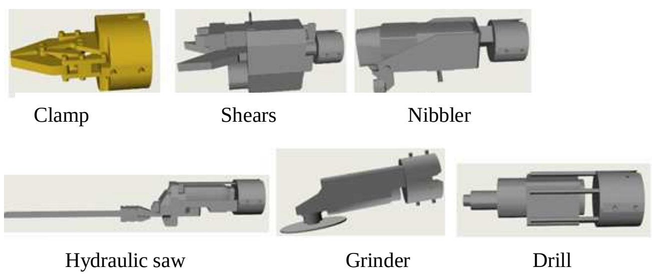


Figure 21. Tools to be used to dismantle

3) The simulator

The simulator was created with Virtools for the graphical part and IPSI for the physical part., with a Dynamic Link Library (DLL) to interface IPSI functions.

In the simulation initialization, all the 3D objects we want to add to the physical simulation are sent to IPSI as well as the information about robots (hierarchies, degrees of freedom, end stops etc.). The kinematics of the Maestro arm and the carrier were then created.

The graphical representation of the objects is updated in Virtools by IPSI, which calculates the new position in real-time. During the simulation life, we use a callback function to match graphical and physical objects (Figure 22.).

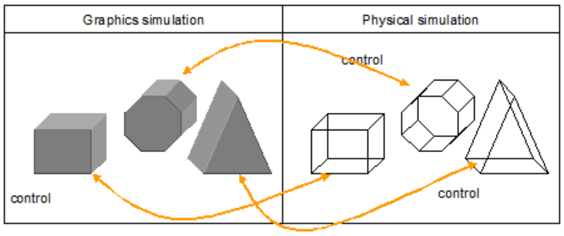


Figure 22. graphics and physical simulation coupling

C. *Step three: control the simulation*

To control the robots, two gaming joysticks are used to pilot the carrier and the crane (Figure 23.). The first one controls the carrier's three DOF and the second those of the crane. These controls are very similar to the interface, which will be used for the final dismantling system. Each robot is controlled axis by axis (the articular mode).

Figure 23. Gaming joysticks used to pilot the carrier and the crane.

The Maestro arm has been coupled to the Virtuose 6D 35-45 haptic interface. The Virtuose enables manipulation of the Maestro end-effecter, and thus control of the Maestro extremity, while respecting the kinematics chain and all the end-stops. The Maestro arm is not piloted axis by axis like the carrier and the handling bracket crane, but it is used in the Cartesian mode via the Virtuose, as it will be during the actual dismantling operation. The Virtuose sends force-feedback when the Maestro is in collision with a « voxelized » element of the environment. The operator can also feel when one or several axes reaches end stop: the user manipulation is blocked on the axis concerned.

D. *Step four: add interactive functionalities*

An interactive real-time simulator was developed into which the whole cell, the Maestro slave arm and the carrier are loaded. The Maestro arm and its carrier can be maneuvered using the joysticks and the Virtuose. Any of the six available tools can be connected to the Maestro arm or changed, as necessary.

The points of view of the six cameras can also be displayed in the simulator. It has been checked that every part of the cell is visible and controllable. 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. This sense will be very useful to operators when piloting the system; therefore a specific sound has been associated with each tool and collision, to enhance the information sent to the user.

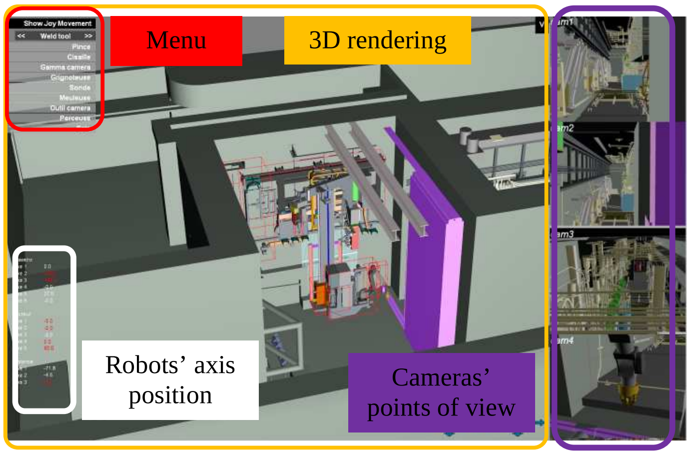


Figure 24. MMI

The current value of each robot's axis is displayed and written in red if it corresponds to the end stop value. The axis is also highlighted and a sound is heard.

A menu enables specific functions to be launched, such as tool grasping, MMI configuration or automatic scenarios; the carrier entry in the cell for example (Fig. 24).

VI. FIRST RESULTS

This part describes the first results, coming from the simulation of the dismantling scenarios.

A. *Gamma-3D superimposition*

This consists in superimposing radiological imaging data and 3D environment (Fig. 25 and 26). An in situ measurement campaign was carried out in 2006 and enabled identification of about twenty radioactive hot spots in the cell, with ambient dose between 15 and 25mGy/h. The dominant radioelement is ^{137}Cs (80%). The image of each gamma hot spot has been superimposed on the corresponding 3D object.

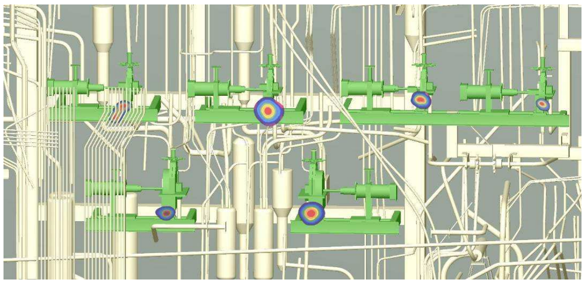
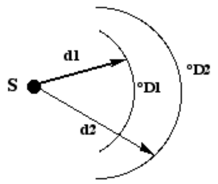


Figure 25. Hot spots on dosing wheels

Figure 26. Hot spots on centrifuges.

This superimposition has allowed better understanding of every hot spot's location in the environment.

We developed a function that generates a more or less intense Geiger sound, depending on 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. To reduce this number, one way 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 squared distance inverse (Fig. 27).



$$\frac{°D1}{°D2} = \frac{(d_2)^2}{(d_1)^2} \Longrightarrow °D1 \,.\, (d_1)^2 = °D2 \,.\, (d_2)^2$$

Figure 27. Equation of the squared distance inverse.

This formula has been implemented and applied to the navigation camera. When it moves, the dose rate changes, depending on the distance from hot spots. The possibility to activate or deactivate a source has been added, to see the influence of each of them.

B. Global accessibility study

Tests carried out on the system had two objectives: first, to check that the carrier design was suitable for the Cell 414 environment, and second, to verify the whole dismantling operation design.

Two interface 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. 28).

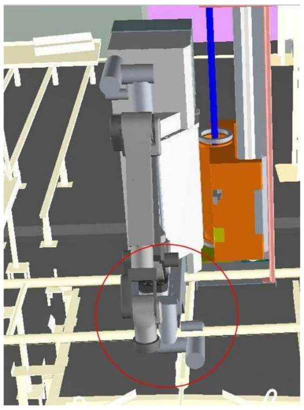


Figure 28. Interference between carrier and environment.

C. Verification of the overall scenario

The dismantling scenarios take into account that the Maestro ideal position is the configuration called "elbow at the top"; as illustrated below (Fig. 29). It guarantees tool maximal maneuverability by reducing the risk of working from an end stop. They also consider each cutting tool footprint (which are very variable from one to the other) to adapt the scenario depending on the means.

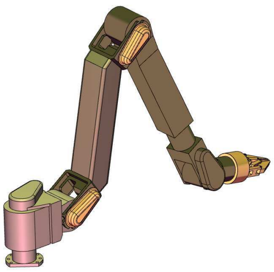


Figure 29. Maestro "elbow at the top".

The overall scenario is divided into five sub-scenarios, each managing the dismantling of specific pieces of equipment as illustrated in the graph below (Fig. 30):

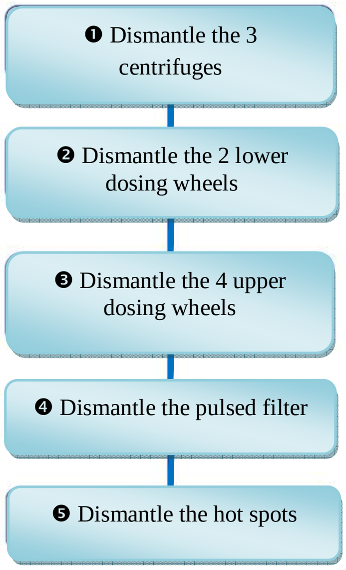


Figure 30. Dismantling flowsheet.

1) Centrifuge dismantling

This first scenario is quite complex, because the pieces of equipment 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 has been verified. We found several technical key points, which need to be clarified in order to prove the feasibility of the task. The following section presents some of these key points.

First example: the simulation ran the waste basket loading before the Cell 414 entry: the pulley cable enters in collision with the embedded tool holder. The bracket arm needs to be extended to avoid this situation, as shown below (Fig. 31).

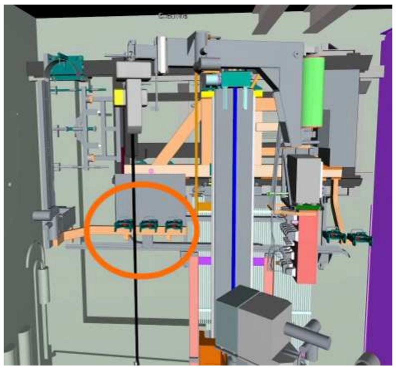


Figure 31. Interference between cable and tool holder.

Second example: to enter Cell 414, the handling bracket has to be in a rearward position, but then has to turn to be in forward position to be close to the Maestro arm. The crane must carry out a half-turn in the beginning of the cell. The simulation showed that this half-turn cannot be done in one step, but has to advance enough not to hit the fixed camera (Fig. 32), then turn and pull back the telescopic arm and finally go back to continue the half-turn (Fig. 33).

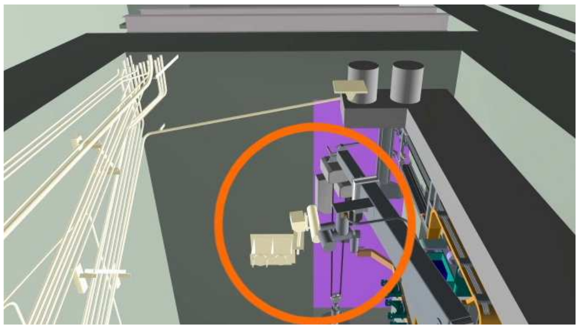


Figure 32. Interference between the bracket crane and the environment.

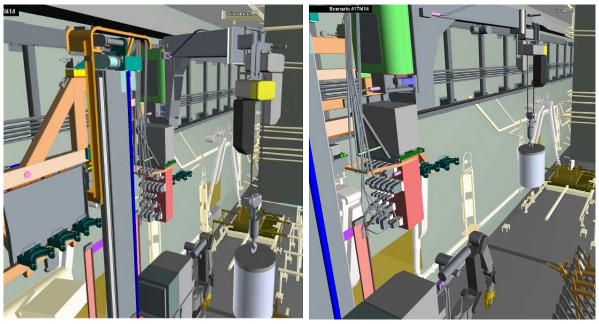


Figure 33. Handling bracket crane half-turn.

The simulation study also showed that the space near the centrifuges is very limited and the waste basket can only be put down in one specific zone, as illustrated in the next figure (Fig. 34):

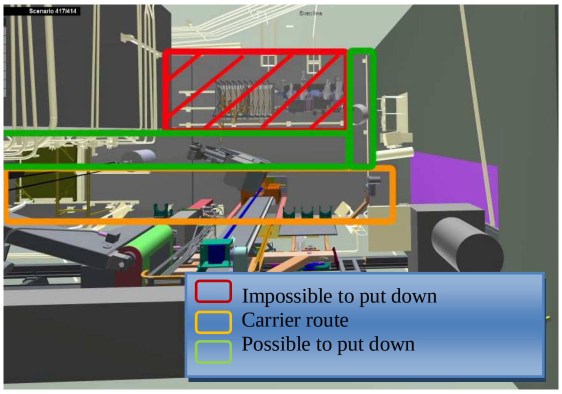


Figure 34. Limited zone to unload waste basket near centrifuges.

We have also proved that dismantling the centrifuges in situ with the hydraulic shears would not be feasible as originally planned. In fact, the shears footprint is too big and it cannot access the centrifuges. 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 the hydraulic shears. This scenario has been validated and approved by the dismantling project engineers.

Another example: the simulation enables Maestro configuration during tool grasping on the embedded tool holder to be shown. To grasp tools, the arm must have "the elbow at the bottom", two axes must be close to end stops and the support platform must have a 45 degree orientation (Fig. 35). This configuration is not optimal and needs a large footprint in the cell. While it is not an issue in the half-turn zone, it causes interferences with an embedded camera near the cutting table: the camera orientation needs to be modified in order not to touch the table (Fig. 36).

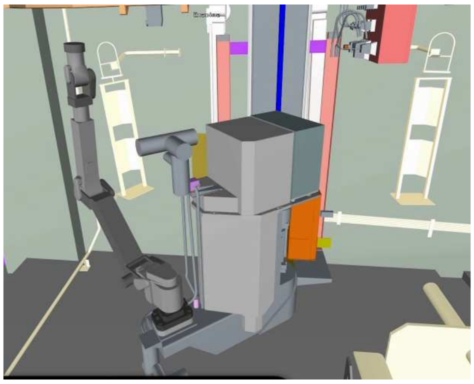


Figure 35. The tool grasping

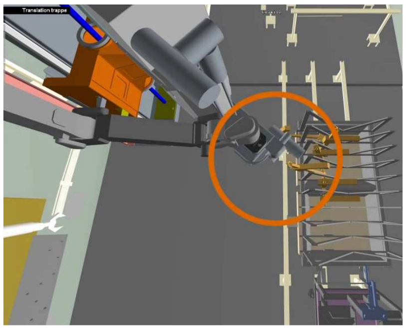


Figure 36. Interference between camera and cutting table.

Other such situations have been found and embedded tool grasping is not possible in some parts of the cell. This kind of problem had not been identified before, and the manufacturer has had to take these issues into account.

Thus, from the first simulation runs, the project has already provided vital information to implement in its dismantling scenarios. The chosen VR technologies have proved their worth, and the various capabilities of the Maestro system and carrier will continue to be tested as the dismantling project enters its next phase.

VII. Limits and Perspectives

The results are quite satisfying, but some limits exist and some developments can be made to use the simulation to train the future operators.

A. Current limits

First, the mismatch of information relevant to reality 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 with 5cm precision. The most difficult task is to obtain a true model of the cell. The present model created by photogrammetry is accurate enough for the first steps of scenario study, but because of the layout of the cell, the complete model of the pipes could not be rebuilt with this technique. Only the first row of pipes was modeled, so the cell modeling will have to be updated after the first steps of dismantling if we want to match the reality.

Next, we are limited by the physics engine, which is directly dependent on the computing power. With the current hardware, we cannot physicalize the robots and the whole cell with a high precision for collision detection and get a real-time simulation. Therefore, only the robots and some key parts of the cell have been physicalized. These parts depend on the scenario being tested. Collision detection precision has to be inferior or equal to 10mm, so that the accessibility studies can be realistic.

B. Add the radioactivity dose rate information

The CEA, in collaboration with Euriware, a French company, has developed an application called NARVEOS [20] capable of calculating the radioactivity dose rate. It is specifically used to simulate scenarios in nuclear environments. In NARVEOS, we can import a 3D model of a nuclear facility, specify the kinds of materials (steel, lead, concrete …) of each 3D object and add radioactive pieces of information to the 3D model: sources coming from the in situ measurement campaign mentioned earlier in this article, protection screens defined by the material of each object, and measurement points where we want to have the calculation done. From this data, NARVEOS is able to calculate the radioactive dose rate received by the measurement points in real-time and interactively. In the following figure (Fig. 37), sources and protection screens have been added and the measurement point has been located on the operator's chest. It is controlled interactively via mouse and keyboard. The curve below displays the changes to the dose rate received by the operator depending on the motion he makes.

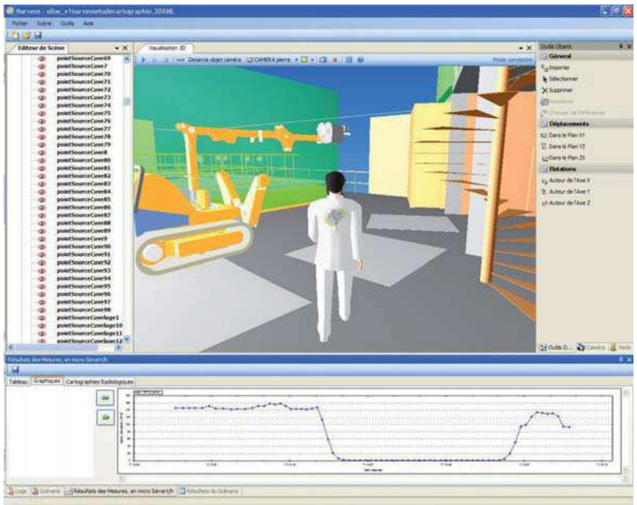


Figure 37. NARVEOS GUI

In the near future, it is hoped to assemble the functionalities of NARVEOS within our simulator. Thus, it will be possible to follow in real-time the decrease of the radioactivity levels during decommissioning and calculate the new levels after the removal of hot spots. It will also be used to simulate decreasing operator dose rates, and to know when safe manual dismantling will be possible.

C. *Train the operators*

From the beginning of this project, the idea of training operators was predominant. The models are very close to the reality and we can work with a life-size simulation. Currently, the control of the robots with the joysticks plus the Virtuose device allows the real robot motion in the cell to be tested. For instance, the most suitable carrier positions can be found to work at optimal efficiency with the Maestro slave arm. The simulation can also be used to increase the operators' awareness of the risks they could be exposed to, like collisions between the carrier and its environment, or robot damage.

Moreover, the main purpose of the training is to avoid nuclear incidents, like possible worker irradiation. Therefore, the radioactivity dose rate simulation will help to train operators and inform them about where the radioactive areas are located.

Another advantage of the training is to show operators that there is no direct vision, so they will get used to working with only video and sound monitoring from the cell.

VIII. CONCLUSION

This project has shown that VR technologies can contribute to improving knowledge regarding project preparation and validating technical choices. It can even be used to design scenarios. With this first application case, several technical key points to be solved have been identified, in order to improve the dismantling scenarios and be sure that the real operation will be without foreseeable problems.

The simulator involved is generic and can load any 3D model of a building. A comprehensive robotics library has also been compiled and enables VR versions of scenarios to be run with any of these systems, in order to test alternative solutions. We are already working on another dismantling project and using our development to help choose the best remote handling slave arm adapted to the dismantling operations involved. Our work there takes place earlier in the dismantling project because the scenarios are not yet defined as the likely technical solutions have not been decided on. The VR study will simulate different technical alternatives and indicate the best solution.

Our simulator will also be useful for the operators' training. As the operation will not be easy because of the complexity of the cell and of the remote handling system, training the future operators via a VR simulation will allow them to better know the environment to be dismantled and how to use the different pieces of remote handling equipment. They will therefore better understand the difficulties and key points of the scenario.

Given the first results, the CEA has proved that VR tools open up new perspectives for studies and for decommissioning cost and deadline management, as well as for communication between project teams, contractors and Nuclear Safety Authorities.

REFERENCES

[1] C. Chabal, A. Proietti, JF. Mante, and JM. Idasiak, "Virtual Reality Technologies: a Way to Verify Dismantling Operations, First application case in a highly radioactive cell", ACHI, Digital World, Le Gosier, France, pp. 153-157, 2011.

[2] P. Guiberteau, "Démantèlement au CEA. Dismantling at the CEA.", 4th European Forum on Radiation Protection, La Grande Motte, France, pp. 8, 2010.

[3] IAEA Safety Standards Series, "Decommissioning of Nuclear Fuel Cycle Facilities", Safety Guide, No WS-G-2.4.

[4] B.K. Wiederhold and M.D. Wiederhold. "Three-Year Follow-Up for Virtual Reality Exposure for Fear of Flying" CyberPsychology & Behavior, volume 6 issue 4, pp. 441-445, 2003.

[5] F. Yaacoub, "Development of virtual reality tools for arthroscopic surgery training", Université Paris-Est, Phd thesis in computer science, Paris, France, 2008.

[6] J.R.Li, L.P. Khoo, and S.B.Tor, "Desktop virtual reality for maintenance training: an object oriented prototype system (V-REALISM)", Computers in Industry, vol 52, issue 2, pp. 109-125, 2003.

[7] R. Gadh,H. Srinivasan, S. Nuggehalli, and R. Figueroa, "Virtual disassembly-a software tool for developing product dismantling and maintenance systems", Reliability and Maintainability Symposium, 1998. Proceedings., pp. 120-125, 1988.

[8] J. Ródenas, I. Zarza, M. C. Burgos, A. Felipe, and M. L. Sánchez-Mayoral, "Developing a virtual reality application for training nuclear power plant operators: setting up a database containing dose rates in the refuelling plant", Radiation Protection Dosimetry, volume 111 issue 2, pp. 173-180, 2004.

[9] Institute for Energy Technology, datasheet on Chernobyl NPP decommissioning assistance project, http://www.ife.no/departments/visual_interface_technologies/projects/chnpp/view .

[10] H. Jorke and M. Fritz, "INFITEC- a new stereoscopic visualisation tool by wavelength multiplex imaging", Journal of Three Dimensional Images, vol.19, pp. 50-56, Japan, 2005.

[11] ARTracking, http://www.ar-tracking.de

[12] F. Gosselin, C. Andriot, J. Savall, and J. Martin, "Large workspace Haptic Devices for Human-Scale Interaction: A Survey", EuroHaptics, LNCS 5024, pp.523-528, 2008.

[13] C. Limousin, J. Sebot, A. Vartanian, and N. Drach, "Architecture optimization for multimedia application exploiting data and thread-level parallelism", Journal of Systems Architecture, vol. 51, issue 1, pp. 15-27, 2005.

[14] 3DVIA, http://www.3ds.com/products/3dvia/3dvia-virtools/welcome/

[15] M.W. Jones and R. Satherley, "Voxelisation: Modelling for Volume Graphics", proceedings VMV'2000, pp. 319-326, 2000.

[16] Haption, IPSI datasheet. Available from http://www.haption.com/site/eng/images/pdf_download/Datasheet_IPSI.pdf.

[17] O. David, Y. Measson, C. Rotinat, F-X. Russotto, and C. Bidard, "Maestro, a Hydraulic Manipulator for Maintenance and Decommissioning Application", ENC, Bruxelles, Belgium, pp. 54-61, 2007.

[18] Haption, Virtuose 6D35-45 datasheet, Available from http://www.haption.com/site/pdf/Datasheet_Virtuose_6D35-45.pdf.

[19] ESIC SN, MEEX datasheet, Available from http://www.esic-sn.fr/spip.php?article14.

[20] J-B. Thevenon, L. Lopez, C. Chabal, and J-M. Idasiak, "Using simulation for intervention design in radiating environment: first evaluation of NARVEOS", GLOBAL, Paris, France, pp.153-157, 2009.