Virtual and augmented reality in the nuclear plant lifecycle perspective

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Abstract: The paper presents a subset of the research and development performed over the last decade by the OECD Halden Reactor Project (HRP) using virtual reality (VR) and augmented reality (AR) in design, operation, maintenance and decommissioning to solve real world problems in the nuclear plant lifecycle. The use of VR in training at Leningrad Nuclear Power Plant (LNPP) in Russia started in 1999 with the introduction of VR technology developed by Institute for Energy Technology (IFE) for the training and presentation of procedures related to safe operation and maintenance of the refuelling machine. At Chernobyl Nuclear Power Plant (ChNPP) in Ukraine, the establishment of the Chernobyl Decommissioning Visualisation Centre (CDVC) was started in 2007. The CDVC will be used for planning, training and presentation of dismantling procedures. In the future, the CDVC will also offer calculation of the occupational dose. VR has proven to be an effective technology for better communicating the layout of project proposals in design of control rooms. AR can be used to supplement reality by blending the physical and the virtual in the actual physical environment. IFE has developed a practical solution for using the AR technology. The paper also discusses how and for what areas the VR and AR applications can contribute to the nuclear safety for symbiosis and sustainability. Finally, IFE's plans for future use of VR and AR technologies in a nuclear plant lifecycle perspective are discussed.

Keyword: virtual reality, augmented reality, nuclear plant, lifecycle, decommissioning

1 Introduction

The OECD Halden Reactor Project (HRP)[1] has carried out safety oriented R&D for more than 50 years and is one of the largest and longest lasting safety focused international research centres in the nuclear energy sector. The Project is currently supported by 18 countries and more than 130 organisations worldwide. These organisations are from vendors, utilities, licensing organisations and R&D labs worldwide. Participation in the HRP cooperation offers access to a unique international network. The Institute for Energy Technology (IFE) in Halden, Norway hosts the HRP.

Safe and reliable operation of nuclear power installations benefit from international R&D advances and related technical solutions. The OECD Halden Reactor Project is a leader in these advances with programmes devised to provide answers in a direct and effective manner. The Project's strong international profile and solid technical basis represent an asset for the nuclear community in times when there is a renewed interest in nuclear energy all over the world.

Received date: April 29, 2010

1.1 The Halden Boiling Heavy Water Reactor

The Halden Boiling Heavy Water Reactor (HBWR) is a unique test facility that was designed as a prototype reactor in the mid 1950ties. The HRP research programme in the fuel and materials area includes fuel assessments in postulated accident conditions and investigations in the high and very high burn-up range (under normal operating conditions and transients). The material research also encompasses the embrittlement and cracking behaviour of internal reactor materials. These investigations are carried out under representative reactor conditions in the HBWR using advanced experimental loop and instrumentation systems.

HBWR uniqueness is mainly found in its ability to measure all main parameters of fuel and material properties "on-line" during different plant conditions, e.g. normal, transient, and even accident conditions like LOCA (loss of coolant accidents). The reason why we can "simulate" accidents is that several separate external loops are connected to the inside of the reactor tank which can provide the conditions experienced in conventional light water reactors like PWR, BWRs, and VVERs. The loops are closed in the sense that no release of radioactive material is escaping these loops thus not contaminating the rest of the plant during experimental tests.

1.2 Safety MTO – Man Technology Organisation

The HRP has also an extended R&D program into the emerging important area of Safety MTO – Man Technology Organisation. Experimental labs (HAMMLAB – Halden Man Machine Laboratory, HVRC – Halden Virtual Reality Centre), as illustrated in Fig. 1, are available for conducting various human factors experiments collecting data on human performance and for human reliability assessment (HRA).

Fig. 1 The MTO Laboratories.

Further, various new technologies and knowledge for plant surveillance, information presentation and software reliability are developed and distributed to members of the HRP.

1.3 Halden Virtual Reality Centre (HVRC)

The three pillars of the HVRC are HRP joint research, bilateral projects, and academic cooperation with universities. In addition to highly qualified staff, HVRC has a well-equipped virtual reality laboratory in which experimental studies are performed in cooperation with human factors specialists.

The research addresses activities where spatially oriented decision-making is required during the lifecycle of a nuclear facility, and in particular where decision-making can be enhanced through improved visualisation. By developing concepts and methods, and performing experimental studies, novel 2D and 3D technologies are implemented in specific applications and assessed, to determine how best they can support real industry requirements and expectations, without introducing new unforeseen problems.

While the research is primarily focused on the requirements of the nuclear industry, the transfer of results to (and from) the petroleum industry and other industries is also an important goal of the HVRC.

1.4 Definition of Virtual Reality

VR is a way of visualising, interacting with and navigating through an environment described by a 3D computer model. A commonly accepted definition is "A computer system to create an artificial world in which the user has an impression of being in that world and with the ability to navigate through the world and to manipulate objects in the world"[2]. VR technology is useful for planning, training and presentation because it offers a realistic way of simulating the real world in 3D, with the potential for direct user interaction and system feedback. In addition, VR enables users to see objects or phenomenon that are normally invisible, such as ionising radiation.

1.5 Definition of Augmented Reality

AR is a variant of VR technology in which digital models and location-specific information are combined with the physical world. Rather than creating an entirely virtual environment, an AR system displays a composite view, with a mix of virtual and real objects that are displayed in real time to the viewer to enhance the view of a real environment. Fig. 2 shows an example of mixing virtual and real objects exemplified by a building inspired by Japanese architecture drawn by the famous Norwegian architect Sverre Fehn in 1963.

Fig. 2 AR system mixing reality and a building drawn by the Norwegian architect Sverre Fehn.

1.6 Areas of use of VR and AR at IFE

IFE performs research and development related to practical applications of VR and AR technology, and has gained world-class expertise in these fields within the energy industry. The work has been done in a broad field and at all stages of a plant's lifecycle, from design, via operation and maintenance, to decommissioning. The stages are closely connected since activities and decisions taken in one stage will influence the other stages. Common for all stages is the need for data. Therefore data storage, data sharing and data management throughout the lifecycle of the plant is considered essential for safety and for achieving reasonable economical costs. The format in which the information is stored is very important for optimal reuse of data throughout the different stages.

A large number of the projects that IFE has done in the nuclear field as well as in other related fields, e.g. the petroleum industry, could illustrate the usefulness of VR and AR technology applying available information efficiently. In this paper, the main experiences gained in a nuclear plant lifecycle perspective are presented.

2 VR and AR in design

During design, planners, engineers and technicians use drawings, maps and models to present projects and modification proposals to each other, to the authorities, and the public. These means of communication utilise abstract symbols and require expert knowledge and experience for full comprehension. The limitation of traditional representations of planned modifications is that viewers are typically positioned outside the representation; they remain spectators rather than participants. Due to this, there is a common problem of understanding scale, quality and implications of the proposed design. As a result, experts, politicians, decision-makers, and the public often have expectations based on their interpretation of the presented material that differ, and problems can arise from miscommunication and misunderstanding[3].

2.1 Reuse of 3D models in the design phase

IFE has found VR and AR to be effective for communication in the design phase, increasing the quality of the final solution and saving costs. Today, digital tools are generally used in design, and there is a move towards implementing 3D models as common practice using commercial software. 3D models can be imported and viewed directly in VR and AR for visualising the main physical design characteristics of such projects. Usually the file format of the 3D models will be a proprietary one, which has to be converted to another format before it can be used outside the application where it was created. Today solid converters are available for a reasonable price and IFE has done many VR projects with good results based on proprietary 3D data, which was converted to the non-proprietary ISO VRML97 and X3D[4] formats used by IFE's software. Having the 3D models converted to a non-proprietary file format will usually be the best way to ensure that the 3D data will be available and can be updated in a long-time perspective, such as the whole lifetime of a plant.

2.2 Control room design and validation using VR

IFE has developed a suite of tools for control room design and validation called HVRC CREATE[5]. It supports a human-centered iterative design process and is designed to support preliminary and detailed design of a new control room or a control room upgrade. It is used for designing and testing room layouts, with version management for tracking design iterations. Based on IFE's VR technology, it enables designers to rapidly prototype and test designs against ergonomic guidelines and recommendations. Although it is designed for control room engineering, it can also be used for other applications where the layout of an environment is important as seen in Fig. 3.

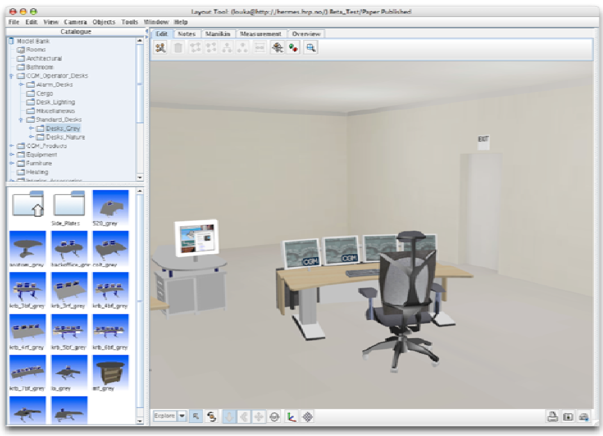

Fig. 3 HVRC CREATE is designed for control room engineering.

HVRC CREATE is a commercial product and has proved its value in a large number of projects when used for review and optimisation of the layout of control rooms, thereby saving the owners annoyance and costs.

2.3 User-friendly AR technology for real world use

AR technology enables users to see a design proposal within the actual setting and thus provides a more complete sensory experience compared to VR. Experiencing projects with AR requires no previous knowledge or training to interpret project representations; the user can immediately see the implications of proposed solutions. IFE has developed an accurate geo-position and orientation-tracking system, which is robust and transportable, and that enables outdoor augmented reality. In Fig. 4, the AR binocular viewing unit is shown in use.

Fig. 4 Demonstrating the AR binocular viewing unit from IF.

2.3.1 The AR solution developed at IFE

The product consists of a software and hardware package that enables users to view real environments augmented with location specific interactive information and geo-positioned 3D models. The hardware consists of a custom-built binocular viewing unit and base station with integrated position and orientation sensors, and a portable computer.

The system enables users to rapidly view real environments from any location, with interactive information. This is achieved in real-time, enabling virtual and real objects to coexist in the user's view as the view changes in response to changes in the user's position and direction of gaze. Therefore, AR has the potential of helping us to manage change in the man-made environment as can be seen in Fig. 5.

Fig. 5 Technical cooperation between Kyoto University, Oslo School of Architecture and Design and IFE.

The AR concept described here has emerged from IFE's research through the HRP, multi-disciplinary collaboration between IFE and the Oslo School of Architecture and Design (AHO), and IFE's collaboration with Kyoto University on image-processing-based tracking using visual markers[6].

2.3.2 The role of AR in the plant life cycle

AR technology is expected to support activities in all phases of the plant lifecycle. For example, in operation and maintenance the technology can be used to monitor and control the process itself by overlaying information[7].

Sharing information and deployment of distributed AR systems could be an important part of emerging work organizations. These systems allow multi-disciplinary teams consisting of management, external experts, control room operators and field operators to work together in the same AR environment regardless of physical distance.

The recent hardware and software development on hand-held devices and smart-phones shown in Fig. 6 is creating new possibilities for AR applications on these devices.

Fig. 6 Popular smart-phones from Apple, Motorola and HTC enabling AR experience.

Popular phones like the Apples iPhone and Google's Android based phones are all equipped with necessary sensors and camera for giving the user an AR experience. It is anticipated that the marked for AR on these devices will grow very fast.

3 VR in operation and maintenance

As part of its programme for increased safety towards nuclear power plants in Russia, Central, and Eastern Europe, the Norwegian Ministry of Foreign Affairs has, since 1999, funded five projects at LNPP in Russia. The reactor type at the operating LNPP is similar to the one at the now closed ChNPP. It is designed for online refuelling during full power using a refuelling machine. VR technology in maintenance operation has also been used by Electricité de France[8].

3.1 Requirements to training safer refuelling

Human errors may have significant impact on power plant safety, productivity, and operation. The complexity of both the refuelling operation and the refuelling machine itself means that the personnel need good knowledge and skills about the correct procedures. The training should familiarise the trainees with procedures, equipment, steps, coordination, inspections, and safety concerns. To be effective, the training must transfer to the actual work environment, meaning that the skills and behaviours learned during training must be demonstrated in the working conditions. The training should therefore satisfy some general requirements stating that the training must involve the active participation of the user. In addition, the trainee should receive feedback on his performance.

3.2 VR applications at LNPP for training

The results from the projects at LNPP are two closely-related VR applications

1. A simulator (RMS-VR OPT) for the unguided (by the computer) simulation-based training of the refuelling operation that normally would be done together with an instructor and,
2. A procedural training system (RMPT) for training procedures related to the maintenance of the safety-critical interior components of the refuelling machine.

The procedural training system is designed for pre-authored computer-based training, enabling the trainee to use the computer as a guide without the presence of an instructor. Fig. 7 is a picture from the VR model used in RMS-VR OPT showing the LNPP reactor hall with the reactor top and the refuelling machine.

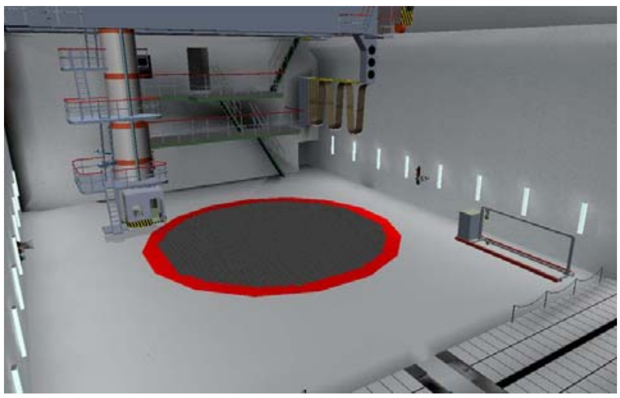

Fig. 7 VR model of the LNPP reactor hall with the refuelling machine.

Figure 8 shows the user interface in the procedure trainer RMPT with a 3D view in the main window and information about the procedure to be trained in the right window.

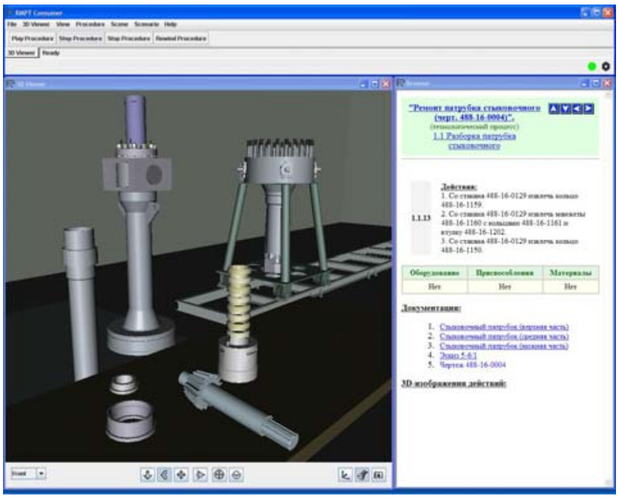

Fig. 8 Procedure trainer RMPT with 3D view showing parts of refuelling machine and procedural information.

3.3 Creating up-to-date data and 3D models

LNPP was constructed in the period 1970-80 so all the original documentation about the layout is paper-based, and in some cases not up-to-date. Therefore, detailed 3D models of the refuelling machine and the reactor hall were developed in the ISO VRML97 format. Both RMS-VR OPT and RMPT enable the trainee to interact with the 3D models in real-time. After being introduced to VR, LNPP has created additional 3D models of other parts of the plant and today LNPP has a database of 3D models that is re-used widely for visualising any aspect regarding planning, training and operation.

3.4 Use of the VR solutions in daily training

The VR applications have a potentially powerful interface, providing both static and dynamic information. The information presented may consist of data that will be available to the trainee in the real world and additional data given for assisting the trainee in order to make the training more effective. The two systems can be used by both groups of people or individuals, either alone or in a classroom context.

Today, both VR systems are in use at LNPP for training the refuelling operation and maintenance. The applications are expected to play an important role in the transfer of knowledge to the younger generation. In 2006-2007 Rosenergoatom, the owner of the Russian NPPs, financed the deployment of the refuelling operation simulator (RMS-VR OPT) to Kursk NPP and Smolensk NPP for use in training there.

3.5 Future enhancements for use on new scenarios

At LNPP, the development of VR software is continuing in 2008-2010 funded by the Norwegian authorities. RMPT is being extended into a tool called LNPP PCT that supports easy set-up of training scenarios by the instructor and more advanced training, for example collaborative training. LNPP PCT will support training of both maintenance and decommissioning tasks in a radioactive environment having functions for radiation visualisation. The first scenario to be trained will be the procedure for moving the spent fuel from the cooling pool in the reactor hall to the storage area outside.

4 VR in decommissioning

An explosion hit reactor unit 4 at the Chernobyl Nuclear Power Plant (ChNPP) site in Ukraine in April 1986. The explosion destroyed the reactor and spread radioactive material to the surroundings. After the disaster, unit 4 could no longer be used and the entire plant was closed in December 2000. The decommissioning of units 1, 2 and 3 at the site is now in the planning phase. Safely decommissioning of the three intact reactors will be a long-lasting technological and organisational challenge because of the complexity of the plant units, the need for transferring knowledge to the next generations, and the contamination. The overall time schedule for the decommissioning indicates that the final shutdown and preservation will take about 10 years from now. Then the complete safe enclosure is estimated to take 100 years, followed by the final dismantling taking 8-10 years. The state of the final plant site will be a “grey spot”. That is, when all systems are removed from the buildings, the radioactivity of the constructions is lowered to free-release level.

4.1 Challenges in decommissioning planning

When planning, training, and performing the dismantling, the need for information about the actual design and the current state of the plant is of highest importance for the staff, the authorities, and the public, in order to perform the work safely, efficiently and with acceptable economic costs. Therefore dismantling a NPP requires highly detailed documentation. Unfortunately, a large quantity of the documentation at ChNPP has been lost and must be reconstructed, and if documentation exists it may be contaminated. Another problem is the loss of skills among the personnel, because major parts of the equipment ha not been used for a long time meaning that the personnel is unfamiliar with it or the experienced staff have left the plant. Careful analysis and planning for the dismantling tasks are important in addition to training of the personnel, both theoretical subjects and practice.

4.2 Establishing a visualisation centre at ChNPP

In 2006, the Norwegian authorities decided to fund a project at ChNPP establishing the Chernobyl Decommissioning Visualisation Centre (CDVC) using VR technology in the decommissioning of the three intact units[9]. A first version of CDVC was established in 2007, and the project continues in 2008-2010. When finished, CDVC will offer stereoscopic visualisation of a 3D virtual environment, features for dismantling procedure development and documentation, in addition to features for radiation visualisation and dose calculation.

4.3 Overall features of the CDVC

CDVC enables a group of engineers to test plans and procedures for various work tasks involved in dismantling a nuclear facility. The VR technology will also be a valuable tool to support the making of the needed documentation and for training the dismantling phase. Intensive training before the real dismantling process may be effective for reducing radiation exposure dose, workload and for enhancing safety. In addition, CDVC provides the decommissioning project team with an effective medium in presentations to the public as well as for communicating with the management and the licensing authorities.

4.4 Reducing radiation exposure dose using VR

The VR system in the final version of CDVC will consist of two applications called ChNPP ProCre and ChNPP Planner. ChNPP ProCre is for planning the dismantling sequence of objects while ChNPP Planner is for planning the use of staff and for demonstration of work tasks. ChNPP Planner is based on results and experience gained from the VRdose™ application[10][11] and the DEXUS[12] system developed for decommissioning of the Fugen NPP in Japan and the LNPP project. VRdose™ enables users to plan work by simulating tasks in a VR model of the work environment, using manikins to represent workers. VRdose™ can then calculate the radiation exposure for a given scenario. VRdose™ also allows users to visualise the radiation in a work area, so they can familiarise themselves with the radiation distribution and plan their work to minimise exposure[13]. In Fig. 9 is given an example of the user interface in ProCre.

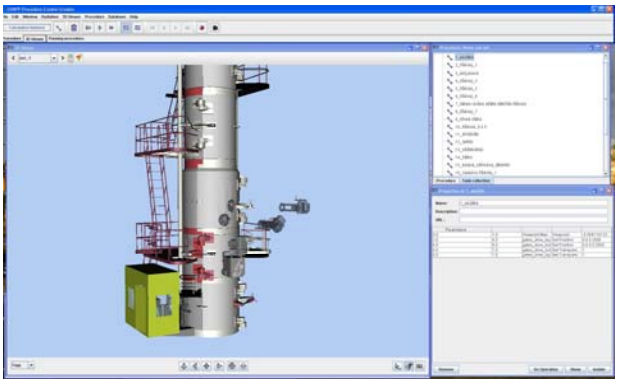

Fig. 9 User interface from the ChNPP ProCre with a VR model of the refuelling machine in the main window and dismantling procedures to the right.

Figure 10 shows the user interface in VRdose™ with 3D model, list of tasks to the left and a graph showing the dose rate at the bottom.

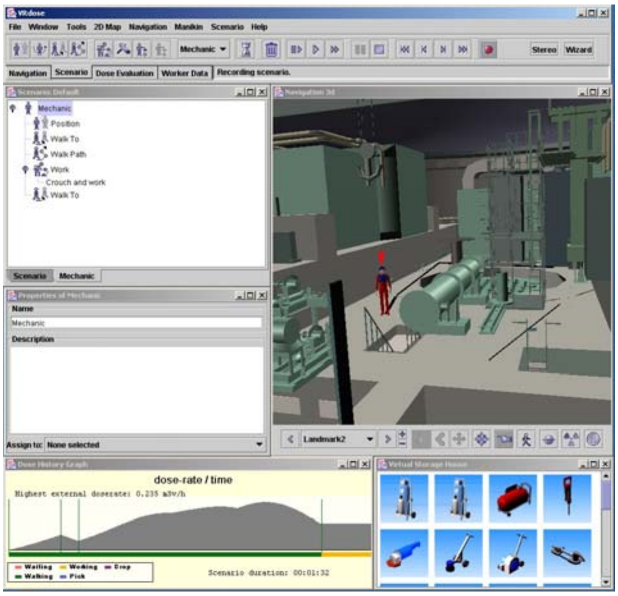

Fig. 10 User interface from VRdose™ with a 3D model in the main window, task list to the left and a graph showing the dose rate at the bottom.

Figure 11 shows the user interface in ChNPP Planner with a 3D model in the main window with the radiation map, task list to the right and a graph showing the dose rate in a separate window for the manikin as he passes two sources of which the one in the background is partly shielded by a lead wall.

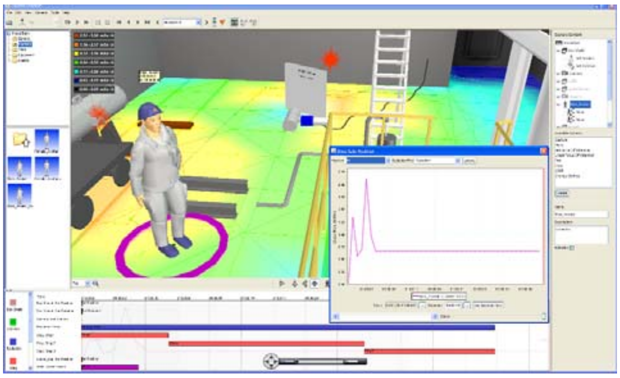

Fig. 11 A 3D model with radiation map, a task list and a graph showing the dose rate for a manikin passing two sources of which the one in the background is partly shielded by a lead wall.

4.5 Efficient reuse of 3D data

The scenario implemented in the first version of ChNPP ProCre in 2007 was the procedure for dismantling the refuelling machine. Approximately 70% of the 3D models of the refuelling machine have been reused from IFE's VR projects at LNPP due to close similarities between the reactor layout at ChNPP and LNPP. The last 30% of the 3D models were made in cooperation between ChNPP's specialists and IFE's Russian subcontractor InterDCM. Thus the project saved both funds and time, making it possible to establish the first version of CDVC within one year.

5 Future plans at LNPP and ChNPP

At LNPP and ChNPP, the development of VR software will continue in 2008-2010. A primary focus area will be to develop better tools for use in decommissioning activities. It is expected that use of VR technology in the planning phase will prove to be beneficial both with regards to minimizing the workers' radiation exposure as well as in helping to achieve an efficient use of manpower. Intensive VR training before the real dismantling process is expected to be effective for reducing radiation exposure, workload and for enhancing safety. The features should include collaborate training and risk visualisation. The VR tools for decommissioning should support the nuclear plant in preserving the decommissioning expertise and knowledge at the plant in a long-term perspective.

6 Nuclear energy's role in future sustainable energy supplies

The world is facing new challenges in growth of energy demands and increased focus on CO2 emissions in climate changes. The nuclear energy's role is to minimise the negative consequences of these challenges[14].

Safety is paramount for peaceful utilisation of nuclear fission energy. From the very beginning various safety features have been built into the technical design of nuclear power plants and described in international standards, e.g. as issued by IAEA. The main principles are: safety barriers/protection with many layers based on defence-in-depth including redundancy and diversity.

The aim is to avoid accidents and protect the public from radiation exposure. This comprises not only robust physical/technical solutions, but also robustness against possible human failure events, organisational weaknesses and terror/sabotage. This holistic approach to safety research is the basis for the international research and cooperation taking place in the Man-Technology-Organisation (MTO) sector at IFE Halden.

6.1 VR and AR contribution to the nuclear safety for symbiosis and sustainability

Examples of VR and AR research and development at HRP described in this paper has pointed out that the technology can support activities in all phases of the life cycle of nuclear installations. That is, starting from the early design phases, through the production phase of maintenance and upgrades, and finally in the decommissioning phase. Further on, experience from decommissioning of old installations can be fed back into the design of new ones.

In general, these technologies can be used to 'visualise the invisible' as seen in Fig. 12. This means that any physical phenomenon that can be measured or simulated otherwise, is a potential candidate for VR and AR technologies.

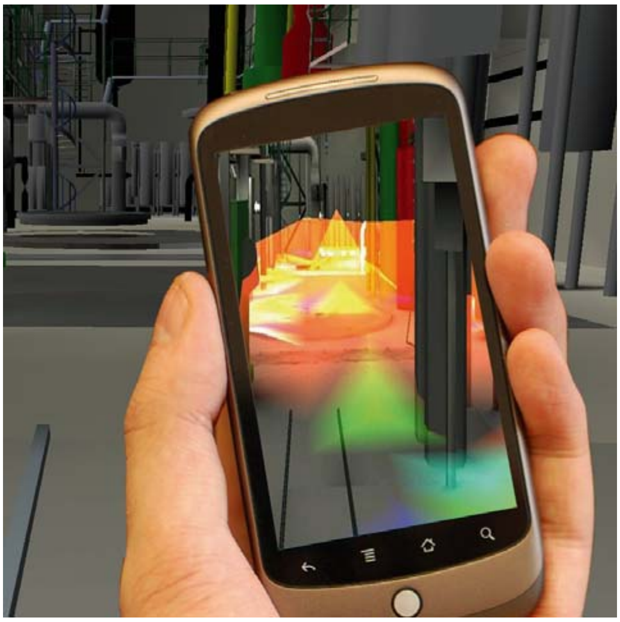

Fig. 12 AR on hand-held device enhancing radiation awareness by 'visualising the invisible'.

This can also be utilised in communication and public relations in general. The need for easily comprehensive information is particularly important for decommissioning of nuclear installations. HRP experiences and expectations from development and deployment of VR technologies in decommissioning of nuclear facilities, has been summarized in a report to IAEA[15]. Allowing for training in a safe environment is one of the great possibilities of these technologies that is described in this report.

Further on, HRP research and development of VR and AR technologies for the nuclear industry have also contributed to development in other industries and disciplines. Examples here are the use of AR in architecture and design and also in the entertainment industry.

7 Summary

In the last decade IFE has gained world-class expertise in VR and AR technology through research as part of the international OECD Halden Reactor Project hosted by IFE, and in additional bilateral projects. A large number of the projects in the nuclear field as well as in other related fields illustrate the usefulness of VR and AR technology through efficient application of available data and information.

In a nuclear plant's lifecycle, from design, via operation and maintenance, to decommissioning, the activities and decisions taken in one stage influence the other stages. Common for all stages throughout is the need for data making: data storage, data sharing and data management. This is essential for safety and for achieving reasonable economic costs. The use of non-proprietary file formats, e.g. the ISO VRML97 format for storing 3D models, will usually be the best way to ensure that the data will be available in the whole lifetime of the plant.

For design, IFE has developed VR tools, which enable designers to rapidly prototype and test designs. HVRC CREATE is made for preliminary and detailed control room design and validation. Being a commercial software tool that supports a human-centered iterative design process it has proved the value of visualising a design using VR in several projects. AR can be used in design to supplement reality by blending the physical and the virtual in the actual physical environment so that the user immediately can see the implications of proposed solutions. IFE has developed a robust and transportable prototype of an AR system for outdoor augmented reality.

In operation and maintenance, VR tools developed by IFE have been successfully used since 1999 for training in the refuelling operation and the maintenance of the refuelling machine at LNPP in Russia.

For use in the decommissioning of ChNPP in Ukraine, the establishing of the Chernobyl Decommissioning Visualisation Centre (CDVC) was started in 2007. CDVC will be used for planning, training and presentation of the dismantling procedures. The project continues in 2008-2010, and when finished CDVC will also offer calculation of the occupational dose using experience and knowledge from the VRdose™ system. A VR project using the technology in training will take place in the same period at LNPP.

The results presented in this paper illustrate the usefulness of VR and AR in a nuclear plant lifecycle perspective. IFE will continue its research in, and development of, VR and AR technology. The systems developed should be reusable, so that solutions can be used widely. Decommissioning is one major field where the use of VR and AR is believed by IFE to increase in the years to come.

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