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Advantages of Virtual Reality in the Teaching and Training of Radiation Protection during Interventions in Harsh Environments

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Abstract—**Human interventions in radioactive environments have high stakes. They are often time-sensitive and radiation exposure must be minimised for the safety of personnel. Existing sites were not developed with remote decommissioning in mind, therefore human intervention remains the preferred approach for dexterous manual labour over robotic systems.**

For ageing sites, knowledge transfer after retirement is an increasingly relevant problem for maintenance and decommissioning tasks, where new workers lack the in-depth "on the ground" experience of the installation.

Virtual Reality provides workers the agency to explore an accurate representation of the area, enabling them to gain experience without undue radiation exposure.

This paper explores and discusses the teaching and training applications of a Virtual Reality environment with integrated radiation dose maps, and looks at where the system may be developed further.

I. INTRODUCTION

An important concept in radiation protection (RP) is the ALARA (as low as reasonable achievable) principle. It was introduced as the 'optimisation of Radiation protection' in 1977 by International Commission for Radiological Protection (ICRP)[1]. The World Health Organisation follow ICRP recommendations, though they conduct their own research into the risks of Ionising Radiation as well [2].

While the likelihood of negative biological effects increases with radiation dose, human presence inside a radioactive area is sometimes required for maintenance and decommissioning. The ALARA principle requires radiation exposure to be as low as possible, while still allowing workers the ability to carry out important tasks. With this in mind, human intervention in radioactive areas required careful planning.

Familiarisation with the situation "on the ground" is often limited without entering the irradiated area; reliable knowledge of the physical environment (location of radiation hot-spots, etc.), required time-frame, and personnel movements, are required to get an accurate dose estimate for the planned work. This is especially difficult for unique interventions when there are no similar previous situations to draw experience or knowledge from.

Besides the ALARA principle, there are also legislative limits on radiation exposure. Expending a skilled radiation worker's allowed radiation exposure, when the knowledge could be gained through other methods, needlessly limits the workforce and man-hours available to carry out the planned intervention. Lengthy interventions have greater cost implications and increase the economic impact of the work.

Remote laboratories are becoming increasingly popular as a way of enabling the teaching practical lab work online, and this is especially attractive for handling hazardous material[3]. However, our focus is on training for maintenance and decommissioning tasks that cannot be accomplished using remote laboratories.

The system was designed for radiation personnel intervention planning, which includes teaching and training radiation workers about the scenario and expected work. The application aims to balance a realistic experience for training workers in their individual required tasks, with an accurate dose estimation for the work for the supervisors and radiation protection officers.

II. RELATED WORK

Using simulations to train for high-exposure procedures has been investigated as early at 2003 by a collaboration between the University of Valencia and IBERDROLA Ingeniería y Construcción [4]. Their CIPRES (Calculós Interactivos de Protección Radiológica en Entorno Simulado) project aimed to create a simulation of refuelling operations for nuclear power plants, where both instantaneous and accumulated doses of the phantom-personnel were available. However, the software suffered from lack of accuracy due to poor data. Increasing the data for interpolation came with the risk of compromising the plant operations.

In 2011, it was proposed to use neural networks to interpolate a radiation dose rate map for nuclear plants [5]. Like the CIPRES VR software, it is a desktop application that shows both dose rate and accumulated dosage for an individual moving around virtual space.

More recently, in 2014, a virtual simulation prototype has been created for the refuelling process of the China Lead-based Research Reactor (CLEAR-I) [6]. It was designed to train users on the refuelling process and was not optimised to produce data on the expected radiation dosage of the procedure.

In 2018, a simulation dose-assessment program was created to assess dose exposure across the human body. It created a real time dose assessment of a simulated human worker enacting different walking paths through a radioactive environment[7].

These applications were all desktop orientated, and did not use Virtual Reality headsets to increase the user reality of the training program. It was highlighted that the development of VR headsets would present a more experience in a review of Brazilian research into Virtual Reality applications in the nuclear sector [8].

Networked VR headsets were used to navigate a shared environment [9]. It was developed to train workers for a nuclear industrial accident, for specific predefined scenarios, using MCNP to estimate dose. The system is similar to the one described by this paper, however their focus was to familiarise workers with a new environment to prevent accidents, rather than a more generalised training purpose.

III. APPLICATION CONCEPT

The system is a Virtual Reality environment with integrated dosimeters. It can be used for radiation critical interventions, where detailed CAD drawings and dose maps are readily available. It gives users a realistic experience within the target environment without exposing them to harmful radiation. Each person using the system has a virtual dosimeter, which tracks movements and integrated radiation dose. As a result, workers undergoing training are able to practise the required tasks, and anticipate their exposure to radiation.

This allows a proper assessment of how best to complete the work without exposure, and helps optimise a trainee's approach to tasks, especially if they are infrequent and/or repetitive such as general maintenance tasks. It is also an effective way for Radiation Protection to assess the exposure risk of proposed interventions before they are carried out.

A complementary application of the system is the review of existing location data. An animated phantom-worker follows the 3D-motion path given by these coordinates, and the system tracks and records their radiation exposure. This allows for a 3rd person review of movements, and an alternate viewpoint to the 1st person headset operation. It grants an intuitive identification of high risk areas, and a offers a confirmation for other RP analyses.

The greatest asset for virtual reality applications is agency. Users are immersed in the virtual environment via headset and have the ability to explore freely. Simulation modelling where users cannot act on their surrounding is better defined as an animation inside a virtual environment, rather than true virtual reality. The system proposed in this paper offers both, however the novelty comes from the freedom of the setup - allowing users to experiment with different approaches and learn from their mistakes.

IV. VR TEACHING PLATFORM

The Virtalis Visionary Render 2.1.0 platform [10] was used as the simulator software. This platform can restrict users and objects to the laws of classical mechanics. It also has a networking function to allow multiple users to connect to a master server and interact within the same virtual environment, or scene simultaneously.

HTC Vive headsets [11] are used with the OpenVR API under SteamVR [12] to immerse the users inside the environment, as shown in figure 1. The headset can track the user around an unobstructed physical area using two base-station towers. The tracking system works in the near infrared spectrum. For movements that would be considered too large for natural movement inside the delimited area, the HTC Vive handheld controllers can translate or teleport the user inside the virtual world, as well as interact with virtual objects. The hardware used is shown in figure 2. The Virtalis Visionary Render software creates a 3D space with a basic physics engine which can then be populated with CAD models. It has the capability to modify the CAD objects inside the environment as well as create basic geometric volumes. Certain properties of these assemblies can be altered to the user's specifications, such as the colour, visibility, mobility, and solidity of an object (where the object can be always solid and always causes collisions, or collides only with other specified objects, or is completely intangible).

Fig. 1: Using the HTC Vive headset

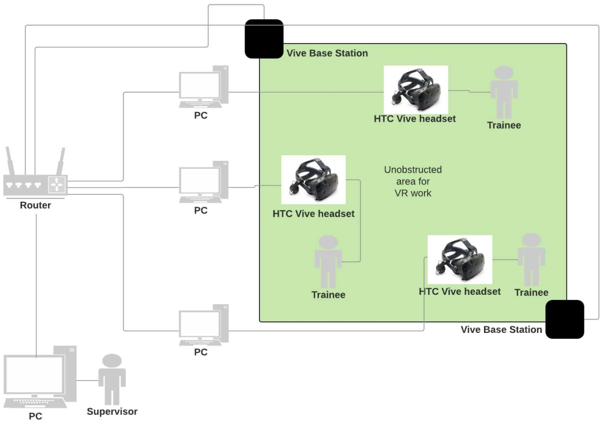

Fig. 2: Diagram of the hardware setup

The radiation data for the simulated area is formatted in a grid, as a background radiation map, and contained in an external file. The software can be programmed to dynamically change the dose map, based on triggers such as elapsed time and removal of certain objects. This feature adds an amount of dynamism to the radiation dose tracking.

The system has two distinct types of user. The student or trainee and the teacher or supervisor. In every environment there can be multiple students using VR headsets, but only one supervisor that is either immersed using a headset, or a common user with a flat screen.

The supervisor controls and monitors the whole environment. Unlike the trainees, the supervisor is not 'physically' present in the VR environment. Each trainee has a head's up display (HUD), which are physical objects that are programmed to always appear in their line of sight. They are customised to the type of user, where the trainee can see their own stats and control their own dosimeter, but cannot access the supervisor's scene or alter any scripts.

Dynamic workstations are created in predefined locations of the environment. They appear as disc markers, with relevant information (including radiation exposure predictions) regarding the associated task floating above them. The parameters of each workstation can be modified, and the radiation dose prediction will update automatically. The changes can be saved for future reference. The number of workstations is at the discretion of the supervisor and can be changed to give as much or as little guidance for students as needed.

The system was conceived and designed to give users the maximum amount of agency while in the environment. Students get a realistic experience and can practise tasks without physical consequences; supervisors can oversee the expected radiation doses for each intervention; and planning one-time interventions where there is a significant dose risk, and no previous similar circumstance to exploit. Figure 3 shows the supervisor scene of the ATLAS Mockup. The supervisor is not restricted to obey Newtonian physics, and the buttons along the right-hand side of the image control the different scripts.

Figure 4 shows a workpoint being modified by a trainee inside the ATLAS Mockup platform. The hand controller is visible, and the worker/trainee HUD is collapsed out of the way at the bottom of the image.

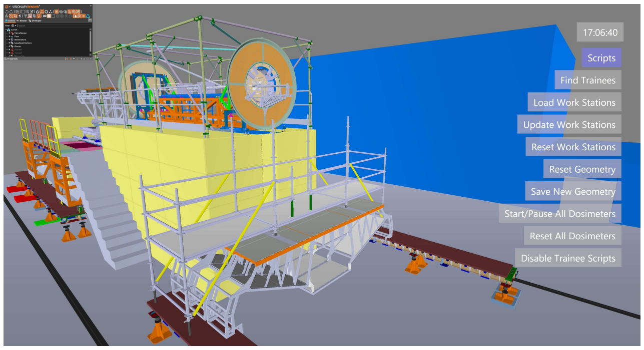

Fig. 3: The ATLAS Mockup in Virtual Reality 1:1 scale, used to train the decommissioning of the Inner Detector

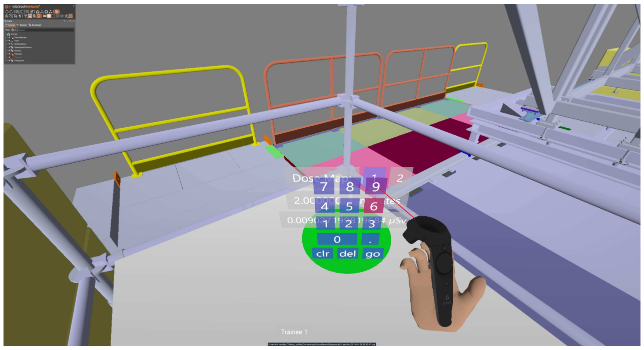

Fig. 4: Training exercise in the VR environment

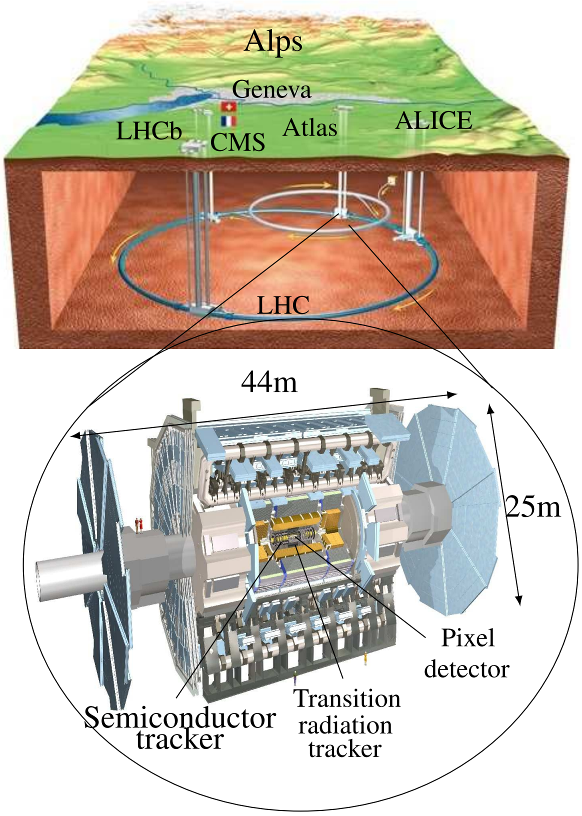

Fig. 5: The ATLAS Detector, located at the LHC

V. EXISTING AND FUTURE APPLICATIONS OF THE SYSTEM

A. *The ATLAS Inner Detector Decommissioning*

The first application of the VR system is in preparation for the decommissioning of the ATLAS Inner Detector (ID) at the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland.

The LHC is the largest particle accelerator in the world. It sits over 100m underground, and is 27km long. Protons are accelerated to over 99.99% the speed of light before entering the LHC, where superconducting magnets keep the particles together and on track. Collisions occur at 4 points along the beam-line, over which each sits a unique particle detector, designed to sift through the sub-atomic debris and either find new particles, or make precision measurements for known physics.

The ATLAS experiment, shown in figure 5, is a large multipurpose detector which became famous for finding the Higgs Boson in 2012 [13], inciting worldwide media coverage. It is composed of multiple sub-detectors, each dedicated to measuring specific properties of the transient particles. Considering all these measurements together allows the particles to each be identified and tracked through the detector [14]. An artist's rendering of the particle collisions is shown in figure 6.

In 2024 [15], the LHC will be upgraded to the High-Luminosity LHC (HL-LHC), increasing the collider's luminosity by 10. For the HL-LHC to be successful, several detectors & components of the experiments need to be replaced with upgraded versions, designed to take full advantage of the increased luminosity. The ATLAS Inner Detector (ID), shown in figure 7, is one of those to be upgraded, and will be replaced by the Inner Tracker (ITk).

The ID is the ATLAS sub-detector closest to the particle collisions. Subjected to large numbers of particles at high energies, it has suffered the most radiation damage, and is now radioactive. The radioactivity is monitored very closely through measurement during the annual shutdowns, and by using simulations [16]–[22]. The high level of radioactivity creates a challenging environment for personnel and will require significant manpower over several months for a complete removal of the

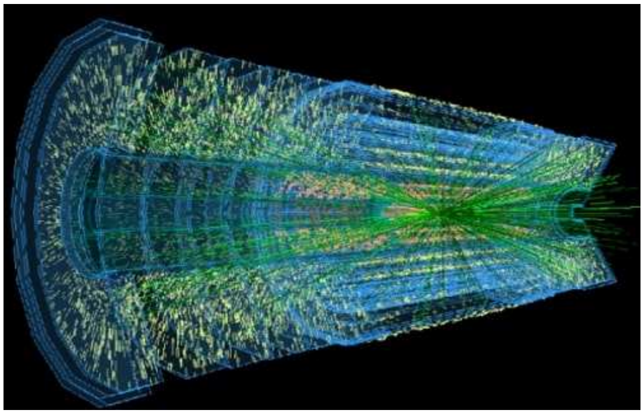

Fig. 6: Collision inside the ATLAS detector

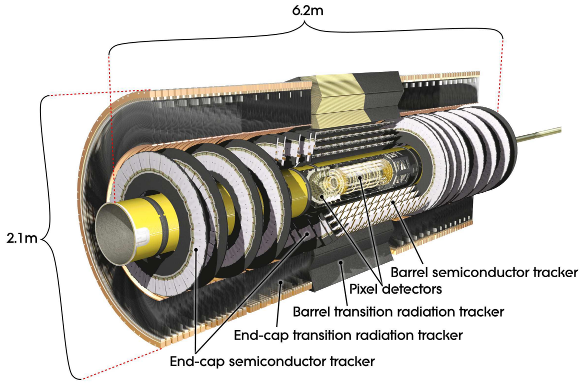

Fig. 7: The ATLAS Inner Detector

Task Name	**Duration**
Beampipe Removal:	11.5d
Side A	1d
–Disconnect VI Support	1d
Side C (removal side)	10.5d
–Lower Pit Table	1d
–Install Pit Table	2d
–Lower IBL Table	1d
–Lower BP Transfer/Storage Vessel	1d
–Install IBL Table/BP Vessel	1d
–Survey and Position IBL Table/BP Vessel	1d
–Cut BP Cables	0.25d
–Attach Traction Cable	0.25d
–Disconnect VI Support	0.25d
–Remove Beampipe	1d
–Close BP Vessel	0.25d
–Retract IBL Table/BP Vessel	0.5d
–Raise BP Vessel	1d

TABLE I: Excerpt of decommissioning steps for the ATLAS Inner Detector, taken from [26], Human workers are limited to 20mSv per year[27]

detector and its associated services. An excerpt of the task breakdown is shown in table I. Research into methods to reduced human exposure to radiation are being explored, including robotics [23]–[25].

Instead of using the detector itself, the virtual environment created was the CERN ATLAS Mockup Model. The mockup exists physically in Geneva at CERN, shown in figure 8. The model was created to train for the installation and assess wiring the inner pixel detector in 1999. This is to combine two training approaches which complement each other. The physical mockup can be used to practise using tools to physically cut and remove wires, remove bolts etc. The animation feature of the VR system can then show the predicted dose of the students once they have finished. The Virtual Reality aspect of the system can then be used to allow these students to reattempt their tasks with different approaches. The virtual mockup training can be reset instantaneously for multiple run-throughs, whereas the physical mockup will take a certain amount of time and resources to be put back together again.

Fig. 8: The ATLAS Mockup of the Inner Dectector, 1:1 real-world scale, used to train cabling the Inner Detector

By combining existing CAD models with dose maps from radiation simulations, a 3D virtual environment was created, which monitors the instantaneous dose rate with respect to position within the environment.

The dose map was created by data provided by CERN's radiation protection team. Per ATLAS detector nomenclature [14], location and orientation information is given in cylindrical coordinates (R, phi, Z), with the origin at the collision point. The detector is symmetrical along the Z axis, so the given dose map has 5cm resolution in R and Z, with the dose smeared around phi. The dose maps are created from FLUKA simulations [28], which are then backed up by in-situ measurements. The software dynamically changes the dose map based on triggers such as elapsed time and removal of pre-established parts of the detector.

B. Further applications of the system

Virtual Reality removes many of the constraints around the exploration of harsh environments by providing an accurate facsimile of the situation without the associated risk. It also opens a whole new perspective on the 'learn-by-doing' approach to teaching. There is no radiation cost to using VR, as opposed to traditional 'on the ground' methods of demonstration. With this in mind, the system can permit multiple students in the same environment, with one teacher supervising the whole group.

The environment can be explored at will, leaving users to assess the feasibility and dose-cost of a planned intervention, as well as allow a supervisor or radiation protection officer to demonstrate to their trainees or students what work needs carrying out, and how to accomplish it. The students' dosimeters are not just used to assess radiological protection requirements. They are programmed to always be in view, as a psychological reminder that the area is unsafe and that excess time in the radioactive environment should be avoided. It also acts as a comparison metric between repeat play-throughs. A student would be able to measure their improvement by the change in dose, and the elapsed time spent in the radioactive area.

Much like teaching pilots to fly aeroplanes, familiarisation of all manner of routine tasks can be achieved without the student setting a foot inside the hazardous environment.

This system can be translated into any situation requiring human presence in a highly radioactive environment. It can be used as a tool to teach protocols for different working scenarios; including routine tasks such as nuclear reactor refuelling, general maintenance for particle accelerators (medical and research), fusion reactors, plus decommissioning of all of these; as well as scenarios such as disaster prevention training or post-disaster exploration. It could also be adapted for space applications.

VI. CONCLUSION

Virtual Reality provides the opportunity to explore an accurate model of the harsh environment without exposure to radiation. This enables workers to gain experience without undue radiation exposure. While simulation modelling inside a virtual environment is not new, true virtual reality requires giving the users agency to move around and interact with their environment at will.

The VR environment developed gives the user a 1st person experience, as well as providing a 3rd person review of the movements within a radioactive area. It allows multiple users into the same environment, so that one teacher/supervisor might have multiple students/trainees.

The applications of the system include the familiarisation and training of routine tasks, and RP assessment of radiation interventions. In the case of maintenance and decommissioning work, this system is flexible and can be used to train engineers for one-off interventions, or recurring interventions.

Collaboration with CERN is ongoing to use the system in the training of workers for the decommissioning of the ATLAS inner detector.

VII. FUTURE WORK

Further investigation and development of this technology will be very important to meet the demands of future time-sensitive and location-sensitive projects.

Development is ongoing to improve dose prediction. This includes looking at preserving the time-cost of tasks where VR simplifies user effort, and creating dynamic dose maps which will adapt the dose rate for any user-made changes to the environmental geometry.

There is also interest in tracking the position of trainees' hands within a radiation area. While hands are less sensitive to radiation, they will likely be in much closer proximity to any radiation sources. Comparing the data between extremity and trunk exposure in training scenarios could be very informative when planning future interventions.

CERN has begun exploring the use of robots to aid in decommissioning to reduce human radiation exposure [23]. The use of digital twins would expand the application of our system from training, to training and intervention work. As the virtual world would mirror reality, it would remove the robot's human operator completely from the radioactive environment, while not limiting their perspective of the decommissioning process.

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