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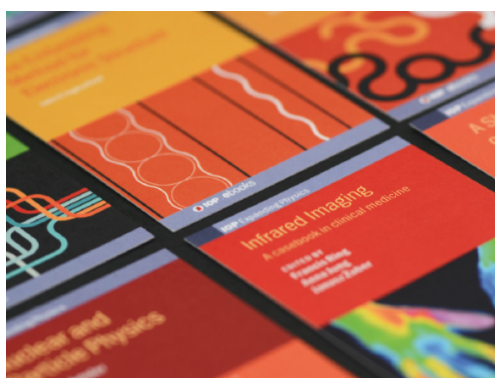
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Integrating motion capture in a virtual reality intervention planning platform to study radiation protection measures for the ATLAS inner detector decommissioning

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ABSTRACT: An intervention planning and evaluation platform has been developed to enable dose estimation and personnel training for the ATLAS inner detector decommissioning. The present paper describes the integration of motion capture into the system, including the dose estimation results for the recorded decommissioning steps.

KEYWORDS: Dosimetry concepts and apparatus; Models and simulations; Radiation calculations; Simulation methods and programs

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1 Introduction

Upgrades to the ATLAS detector required for the High Luminosity Large Hadron Collider (HL-LHC) are scheduled to take place during CERN's next Long Shutdown (LS3), 2025. This includes the replacement of the ATLAS Inner Detector (ID) by the Inner Tracker (ITk). It will require significant manpower over several months for a complete removal of both the ID and its associated services. The ATLAS ID has been exposed to intense high energy particle beams for several years, creating a challenging radiation environment for personnel [1]. Observing the "as low as reasonable achievable", ALARA principle [2] in radiation protection requires careful planning of all human interventions. Reliable feedback is needed to get an accurate dose estimate for optimising the work however, familiarisation of the situation in-situ is limited without entering the irradiated area.

In order to address these issues, an intervention planning and evaluation platform was designed to double as a tool for dose estimation and training for personnel. This paper presents the addition of motion capture (MoCap) in the development of the platform, including the dose estimation results for a subset of anticipated work.

There are some key advantages to assessing and training for high-risk interventions using this virtual reality (VR) platform, however there are drawbacks to a wholly VR system. These centre around the lack of effort expended to interact with the virtual environment while using the HTC Vive headset and hand controllers. Intervention planning and dose estimation relies firstly on an accurate map of the radiation in the environment, and secondly on accurate simulation of where

the worker will move, and how long they will spend at each point. Previous dose estimations were carried out using a spreadsheet, listing the position of people with approximate distance from the activated material. The result was often an over-estimation of the dose by a factor of 2 to 4 compared to the actual received dose recorded by the personal dosimeter, as this method did not take into account the actual movement of a person and precise timing. In order to anticipate and adapt to higher dose levels in future decommissioning scenarios, the accuracy of the dose estimation needed to be improved.

Furthermore, effortless motions could introduce errors in timing estimations for task completion and thus reduce the accuracy of the dose estimation. The use of MoCap to obtain external location data was introduced to address these concerns and improve dose estimations. Motion capture was used to track real-life movements of a technician performing the decommissioning steps on a purpose built mock-up. This provided accurate location and timing data for each of the tasks, ready to then be imported into the Virtual Reality Intervention Planning Platform.

2 Related work

Using Virtual Reality to train for high exposure procedures has been investigated as early as 2003, by the CIPRES (Calculós Interactivos de Protección Radiológica en Entorno Simulado) project [3].

Networked VR headsets navigating a shared environment was a key aspect of a platform developed to train workers in the case of nuclear industrial accidents in 2016 [4]. Research into virtual reality applications in the nuclear sector has put emphasis on the immersive experience that VR headsets give to the user [5].

The combination of motion capture and virtual reality has been explored in fusion reactor assembly [6].

Mapping radiation in 3D for VR decommissioning training has also been developed as a response to the Fukushima disaster [7].

CERN itself has used virtual environments for planning and design since the 1990s, with its VENUS project (Virtual Environment Navigation in the Underground Sites) [8], and it has ongoing research using Augmented Reality for the collimator exchange process [9], and AR with robotics inside the Collider tunnel [10].

3 Overview of the system

The Virtual Reality Intervention Planning Platform has two complementary parts. Firstly, it is an intervention planning platform that tracks the radiation dose of animated avatars, and secondly, it is a personnel training platform that uses VR headsets to immerse trainees in the environment with minimal risk.

The Virtualis Visionary Render [11] was used as the development platform. It is a 3D-model viewing software with a basic physics engine. The software 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 copy and interact within the same virtual environment simultaneously.

The Visionary Render software creates a 3D space which can then be populated with CAD models. However, there is a limited capability to modify the CAD objects inside the software, as

well as create basic geometric volumes. Certain properties of these CAD 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). Collision-enabled objects are useful to determine logistics of an intervention. If moving an object is more complicated than first anticipated e.g. it is too long and will get stuck around a corner, it is better to discover this inside an accurate simulated environment, rather than in the field while workers' doses accumulate. Conversely, scripts can be triggered by entering a delimited area — which is only possible if the object marking the volume boundary is intangible.

The radiation data is contained in an external csv file. In this work, the radiation maps were made by CERN RP using FLUKA simulations. FLUKA is a particle transport code to simulate nuclear and sub-nuclear particle interactions through complex geometries [12]. When the VR scene is opened, the first recorded map is loaded. During run-time, other maps can be loaded and swapped to the scenario. A change of radiation map can be triggered by any single or combination of events, such as a timers or objects being moved.

The training side of the system was conceived and designed to give users the maximum amount of agency while in the environment. Workers get a realistic experience and can practise jobs without physical consequences; supervisors can oversee the expected radiation doses for each intervention. This is especially useful when planning one-time interventions where there is a significant dose risk, and no previous similar circumstance to exploit.

HTC Vive headsets are used with the Steam VR interface to immerse the users inside the environment. The headset can track the user around an unobstructed physical area using two base-station towers that scan in infrared. For movements that would be too large for natural movement inside the delimited area, the HTC Vive hand controllers can translate or teleport the user inside the virtual world, as well as interact with virtual objects.

3.1 Advantages of using virtual reality for training

Virtual Reality removes many of the constraints around the exploration of harsh environments by providing an accurate facsimile of the situation without the associated risks [13]. It also opens a whole new perspective on the 'learn-by-doing' approach to teaching. There is no exposure to radiation while using immersive technologies, as opposed to traditional 'on the ground' methods of demonstration. The system also allows multiple workers to interact with and within a shared environment.

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. This system can be translated into any situation requiring human presence in a 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, hazardous waste handling in construction and decommissioning of power stations, oil rigs, factories and buildings; as well as scenarios such as disaster prevention training or post-disaster exploration. It could also be adapted for space applications.

3.2 Proof of concept

A proof of concept for the platform was performed using the Birmingham cyclotron vault [14]. The vault was rendered in a virtual world, and its background radiation mapped for the system. The virtual dosimeter calculations used the rectangle rule of integration computation. Six easily identifiable points inside the radiation area were chosen, and a path around the space incorporating these points was plotted. A person stood at each point for 30 seconds and measured the immediate dose. After the 6th point, their total radiation dose was noted. The radiation dose of the path was recorded as $2.9 \pm 0.3 \mu\text{Sv}$ using the average of multiple measurements. The same route was followed in the virtual environment using the HTC Vive headset. With guidance checkpoints and dosimeter visible, the mean radiation dose was $2.6 \pm 0.2 \mu\text{Sv}$.

This proof of concept showed the VR platform returned a comparable result to the real radiation exposure for a predefined route through the vault, well within the accuracy of standard dosimeters ($\pm 20\%$). The errors of the system were found to be dependent on the accuracy of the dose map used, and the user following the same established route. With an accurate dose map and reliable location data, the system will produce reliable results. The conclusion drawn from the study determined that the accuracy of the virtual dosimeter depended on the accuracy of the dose maps.

4 Experimental setup

4.1 ATLAS ID decommissioning steps to be recorded

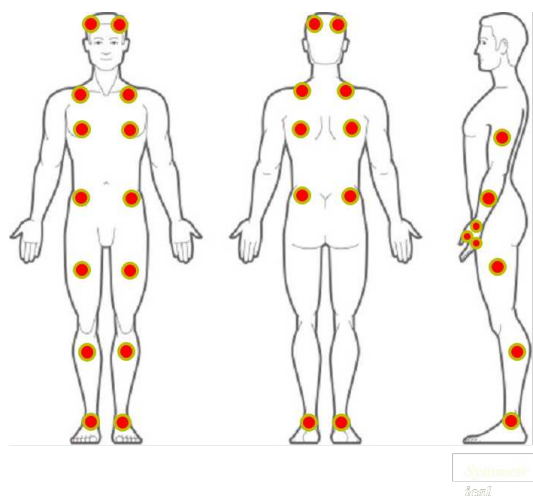
The planned total duration of the ATLAS ID decommissioning is six months. It was therefore not feasible to attempt motion capture of the whole process. Instead, the removal of the beampipe, and preparation for the Pixel Detector extraction were recorded. These sections of work were prioritised for their location close to the relatively radiation 'hot' beampipe, and can be performed on an accurate existent model of the CERN ATLAS Inner Detector, also referred to as the ATLAS ID Mockup.

The ATLAS ID Mockup exists physically at CERN in Geneva in a surface building. It was created to train for the installation and assess wiring for the Pixel Detector Inner Layer (IBL), and was updated and reused for the Motion Capture work for the ATLAS ID decommissioning presented in this paper.

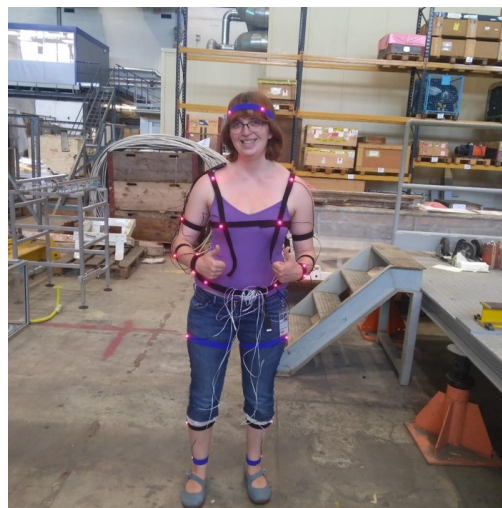
4.2 Motion capture setup

The motion capture system used was a commercial solution called PhaseSpace [15]. The setup comprised of eight stereo cameras set up at varying heights in an approximate circle, and forty LEDs. The LEDs pulse at individual frequencies allowing the system to track each of them independently. The system requires line-of-sight, however the target area included the scaffolding around the Mockup ID end-plate. This was not ideal; the extrapolation of location was possible, albeit with some occlusions. An occlusion is an obstruction preventing line-of-sight between the LED and the cameras. This in turn prevents the system from successfully calculating the LED's 3D location.

Figure 1 shows the placement of LEDs on the body. Velcro strips were used to attach the LEDs to the body. Using LEDs sewn to Velcro had several advantages: it made the setup flexible,



(a) The placement of LEDs on the body



(b) One of the authors wearing the LEDs to calibrate the system and test for occlusions. Velcro strips were used to attach the LEDs to the body.

Figure 1. LED placement was determined through trial-and-error to determine the best setup with the least obtrusive occlusions.

simplifying the trial of different LED positions; it kept the LEDs close to the body, whereas LEDs attached to baggy clothing deformed the capture result; and made it easier to wear. Adhesive tapes on clothing had been used in the beginning, however Velcro proved more durable, less wasteful, and gave a more consistently reliable result. The optimal setup of the cameras and LEDs for best coverage was determined through trial and error, however occlusions could not be totally avoided.

Figure 2 shows the position of the stereo cameras. The software calculates their whereabouts in space from an initial calibration using LEDs set in a baton. The yellow pyramids show the cameras field of vision.

4.3 Motion capture data processing

After the motions were recorded by the cameras, the data was then processed, initially to move from disassociated individual moving points, to a human skeleton with its associated form. This was achieved using PhaseSpace's associated software Recap2. The skeleton data was then imported and further processed in Autodesk MotionBuilder [16].

Occlusions obstruct the camera's view of the LEDs, so the system could not locate their point in space. The longer the LEDs were occluded, the more their location data deteriorates. This led to many unpredictable un-physical effects to the character's movement and had to be 'cleaned' from the raw data.

The data was cleaned firstly by creating 'rigid bodies'. Rigid bodies work by grouping LEDs together and imposing that they should not move relative to one another. Rigid bodies are useful in the case of an occlusion, as the system is able to extrapolate where the missing LED can be found, despite not being able to see it. Rigid bodies were most effective defining a cross section of the body, for example: grouping the four hip LEDs, or the four head LEDs together. As these

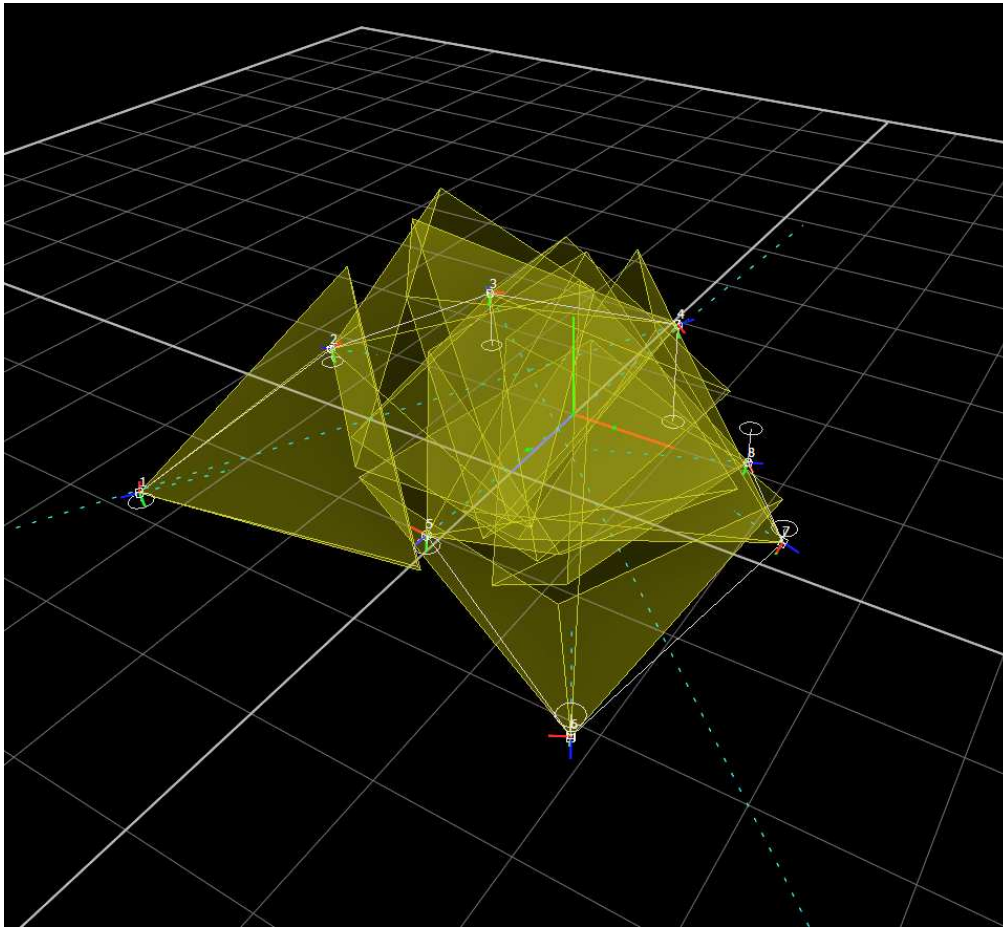
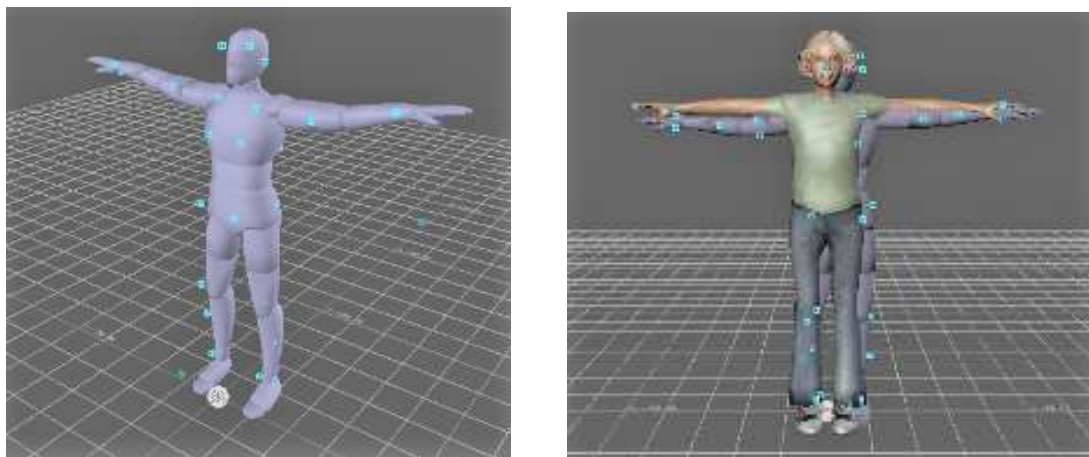


Figure 2. The position of the stereo cameras shown in PhaseSpace Master software, single white squares are 1m^2 .

are defined by the size of the cranium and the pelvis, it can be assumed these LEDs will not move relative to each other. Defining a rigid body over the front chest area was less effective, as when the technician crouched or stretched, these LEDs would move relative to one another. Since this went against the principles of the rigid body, the extrapolation of the missing LED's position was less successful.

Secondly, an actor and a character skin were added to the skeleton. An actor adds volume to the skeleton using body segments. These are mapped to the relevant LEDs, and will rotate with these LEDs and the skeleton as they move in time. A character skin was then applied on top. Figure 3 shows the actor and character skin being added to the skeleton. The character skin is not only cosmetic, it also makes sure the actor segments do not detach from the whole. This occurrence was particularly common if there was an occlusion of a significant joint LED such as the shoulder.

Not all LEDs are given equal importance by the system. Some, such as the feet, have a greater bearing on the avatar's pose and position than others. An occluded foot LED could be the deciding factor determining the avatar's location in virtual reality, despite contradicting information from all the other LEDs. Although the previous steps succeeded in addressing most of the issues, problems such as these had to be corrected individually, case-by-case.



(a) The “actor” is aligned with the motion capture points in Autodesk MotionBuilder (b) The “character skin” is added to the actor in Autodesk MotionBuilder

Figure 3. Autodesk MotionBuilder was used to process the data, moving from an animated skeleton to a character.

Finally this clean processed data — character model, skeleton and animation, was imported into the Intervention Dose Estimation platform in Virtualis Visionary Render as an filmbox (.FBX) file.

4.4 Virtual reality implementation

The data imported in the FBX file is then added to an animation sequence in Virtualis. This sequence links all the imported animations, with added effects on the virtual environment.

This allows the worker’s movements to be put in context, with the environment responding to the simulated actions (e.g. parts of the detector are added/removed, or the dose map is changed). The two dose maps used for the work carried out for the ATLAS Experiment were provided by CERN’s Radiation Protection team, have a resolution of 10 cm^2 and are a result of extensive simulations of LHC operations [1]. The validity of these dose maps were tested by direct measurements of the radiation levels during the ongoing shutdown LS2. Where needed the FLUKA model was improved. Measured and calculated values agreed within $\leq 20\%$ in all relevant areas. A subsection of one of the dose maps used in this work can be seen in figure 4. The first dose map (Case 1) is with the beam-pipe and the IBL subsections installed. The second dose map (Case 2) is with the beam pipe and the IBL removed, but the rest of the Pixel Detector still in place.

It was decided to focus on simulating the dosimeter readings of the technician’s interventions with the dosimeter resting the technician’s chest. Certain decommissioning steps will be repeated. Rather than record the same process multiple times, instead the simulation multiplies the dose added to the dosimeter at the end of the required section of work, as needed.

Figure 5 shows the scaffolding around the ATLAS Endplate, and its the Digital Twin inside the Intervention Planning Platform, while figure 6 shows the different stages of data gathering and processing from the Motion Capture setup to the Intervention Planning Platform.

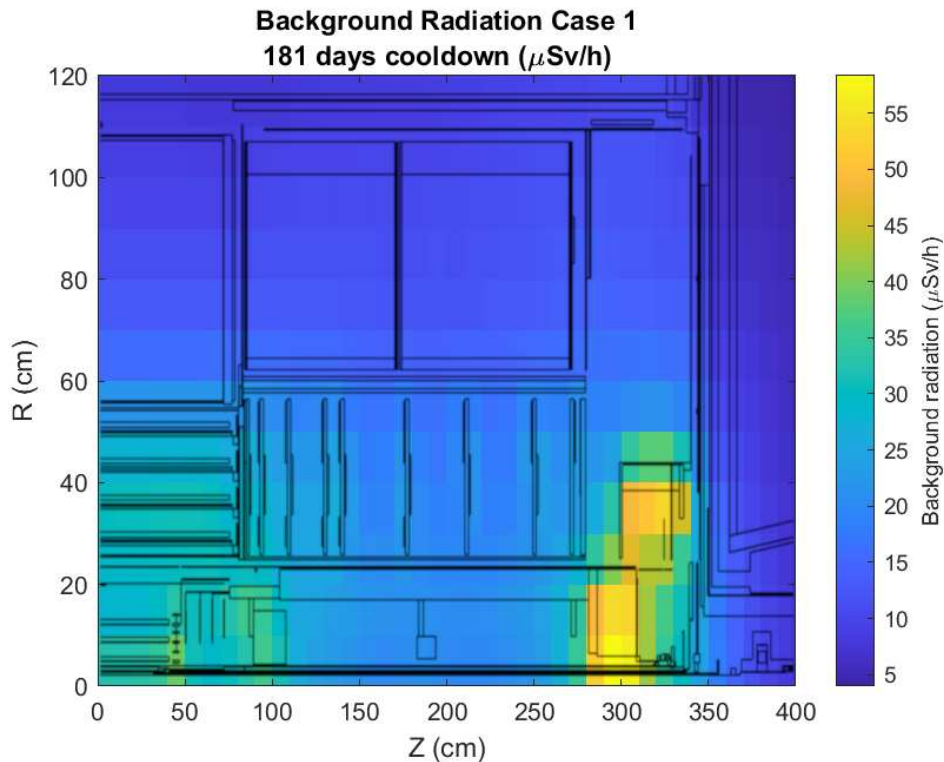


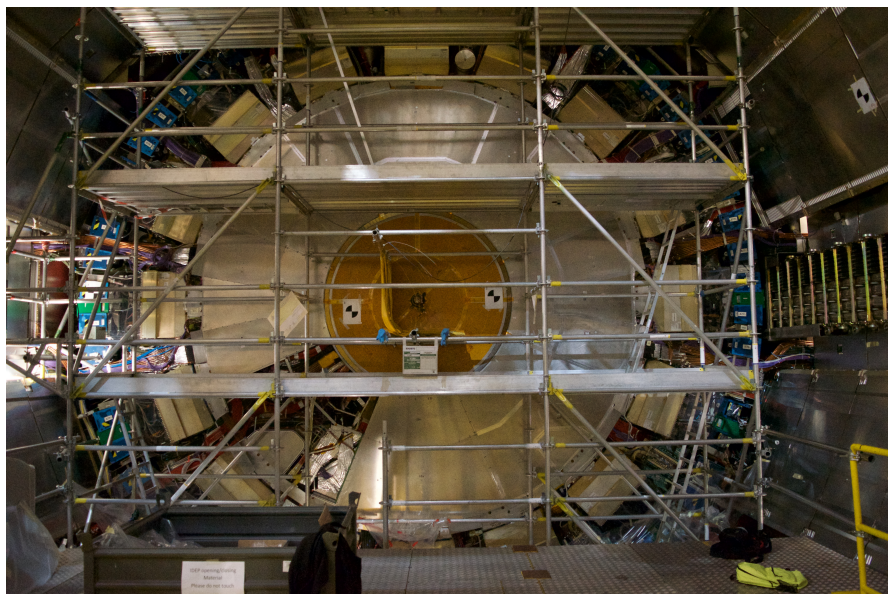
Figure 4. Map of the background radiation in the ATLAS cavern after 181 days cooling time, zooming in on the ATLAS ID with the detector geometry overlaid, based on [1]. The origin is the collision point. The dose map shows a quadrant of the detector, as it is symmetric along the Z and R axes. The radiation dose is the average over all the points of ϕ .

5 Results and discussion

The result of the simulation showed that the decommissioning steps performed would take 3 hours 7 min and the technician would accrue $13.47 \mu\text{Sv}$ radiation dose, see table 1. To put in context, the radiation restrictions for occupational exposure for both France and Switzerland is 20 mSv/year [17]. CERN itself aims for worker exposure below 3 mSv/year [18], which is approximately an individual's annual background exposure.

The technician who carried out the decommissioning steps for the motion capture, shown in the top left of figure 6, was involved with the original ID installation and was familiar with the expected decommissioning tasks. He is also anticipated to carry out the real ID decommissioning during the LS3 shutdown. While during the real decommissioning, he will be wearing the appropriate PPE as expected for ATLAS work. These will be a helmet, safety shoes and operational dosimeter. A self-rescue mask will be placed nearby, but not worn. However in this work concessions were made for the motion capture data processing algorithms, which returned the best results when the LEDs had body contact. The effect of the extra PPE on the technician's movements is considered negligible.

Due to time constraints, the data recording was undertaken just once so far, but can be repeated when needed. While the training aspect of the platform was not utilised in this work, the estimation



(a) The real scaffolding around the ID Endplate in the ATLAS underground cavern



(b) A virtual avatar on the scaffolding around the ID Endplate in the VR Intervention Planning Platform

Figure 5. The ATLAS detector and its Digital Twin inside the Intervention Planning Platform.

provides a baseline result for an experienced technician familiar with the tasks, and can be used as a reference for training.

The technician worked without any restriction on where he stood and no direct knowledge of the dose accumulation as he worked. It was noted that the technician spent a significant amount of time in front of the beam pipe — the most radioactive section of the detector. By carefully analysing the data collected in this work, it is now possible to minimise the received dose by adjusting the location and posture of each technician. In a next step, various shielding concepts can be analysed by updating the corresponding radiation maps and directly compare the effectiveness of the shielding on the estimated dose. This will become more important in future HL-LHC shutdowns due to the significantly higher radiation doses.

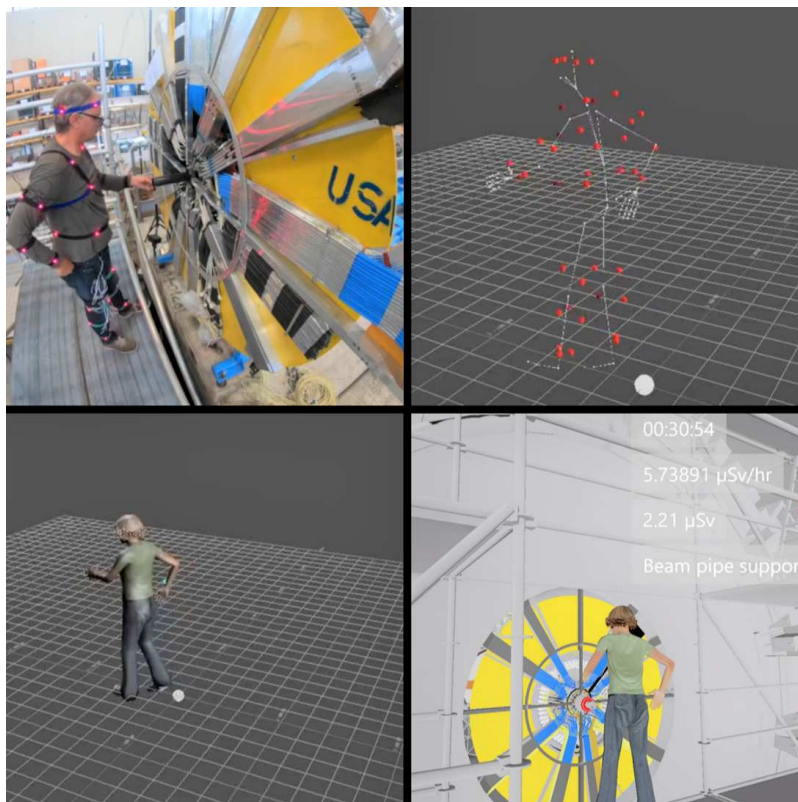


Figure 6. Top left: Technician performing decommissioning step with LEDs for Motion Capture; Top right: the MoCap data with Skeleton in PhaseSpace; Bottom left: The MoCap data with actor in MotionBuilder; Bottom right: The MoCap data in the Intervention Planning Platform.

Table 1. Results of the Motion Capture dose estimation. Summing the individual parts of the work leads to an estimated 13.50 μSv , this caused by rounding the results of each section.

Objective	Steps	Duration hh:mm:ss.ff	Dose Estimate μSv
Remove IDEP	Remove inner IDEP Nose	25:44.52	1.95
	Remove outer IDEP Nose		
Clear BeamPipe/IBL support structures	Remove rad monitor quarter circles, BP support beams, and BP sliding ring	6:49.33	0.57
	Remove outer quarter ring	3:02.00	0.22
Clear IBL and pixel services	Cut IBL services and Remove IBL service guide	9:18.33	0.61
	Remove heater trays and tubing	42:36.60	2.89
	Cut ER bundle	2:48.96	0.21
	Cutting internal Pixel services	1:08:40.72	5.23
Prepare Pixel for extraction	Remove PST seal plate	8:56.64	0.67
	Install PST rail interface	3:23.64	0.27
	Install pixel support ring	9:51.19	0.60
	Install internal transition rails	1:07.73	0.06
	Install intermediate rail and frogs	4:20.65	0.22
	Total	3:06:47.61	13.47

6 Conclusion

An intervention planning and evaluation platform was created to evaluate expected dose exposure rates during the ATLAS ID decommissioning. Motion capture was used to record the movements of a technician performing decommissioning tasks on the ATLAS ID Mockup. The addition

of motion capture was motivated by the main drawback to VR-based training and simulation platforms, where work carried out in VR has no effort, skewing the dose estimate as tasks are easier and faster to accomplish. The motion capture records the technician's movements while performing decommissioning tasks in real-time on the mockup, meaning that the location and timing in completing the tasks is accurate.

The platform provided important information for the dose estimation for the ATLAS ID decommissioning. The expected time-frame for removal was revised down, due to the speed at which the technician carried out the work. The platform calculated the dose estimation as parts of the detector are programmed to (dis)appear as the decommissioning simulation runs. The total work duration was 3 hours 7 minutes, and the radiation dose exposure estimate was 13.47 μSv for this first part of the decommissioning. The later steps will be performed in a significantly reduced radiation field, as the most activated parts (the beam pipe and the Pixel Detector) will have been removed. The analysis of these later steps is still ongoing and will add to the total received dose of the personnel.

The motion capture complements the hands-on training aspect of the platform, which uses VR headsets. The two uses of the system balance each other — the motion capture gives the more accurate result, however immersion and interactivity are more important when the platform is used for training. Peaks in the dose rate can be assessed, and improvements to the predicted exposure can be demonstrated, such as targeted shielding, or by physically avoiding certain high-risk areas.

Improvements to the system such as the development of dynamic dose maps have been proposed which would allow for a gradual movement of parts of the detector instead of an instantaneous removal by switching between static dose maps as implemented currently. This would make the platform more flexible in its possible applications.

The development of a Digital Twin to the platform has been proposed. The addition would allow training for cooperative human-robot interventions. Provided the Digital Twin could interact and alter the VR environment, the setup would also provide an extra point of view to oversee the robot's execution of tasks — beyond camera and sensor feedback. Adding to this, once the radiation tolerance of the robotic components is known, malfunctions or mechanical failures can be anticipated and repairs planned — including ordering spare components in advance, which reduces down time.

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