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A simulator based on virtual reality to dismantle a research reactor assembly using master-slave manipulators

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ABSTRACT

The use of simulation within the nuclear industry has been limited by the perceived cost and benefits that such tools offer. In this paper, we present the development of a simulator based on the use of master-slave-manipulators to dismantle a small research reactor core assembly. We discuss the design of the simulator hardware and the different software elements that make up the system. We show how this type of tool can be used to explore various options during the development of a nuclear decommissioning process. Finally, we discuss the benefits that have been observed from using the system to support the decommissioning of the CONSORT research reactor.

1. Introduction

The cost of decommissioning nuclear facilities and hardware can be very high. Decommissioning tasks are complex and present numerous challenges to operators. Using remote handling tools such as master-slave manipulators (MSMs) can further increase the challenge of dismantling operations. Reach, and accessibility is often affected by the use of manipulators. Special tooling may need to be designed to overcome these difficulties.

Process development and optimisation are a critical stage of planning for a decommissioning activity. Poorly developed processes increase complexity, making operations more challenging and can, therefore, take longer to perform. By using simulation tools, we can better understand the physical constraints and challenges. By using process walkthroughs, different options can be assessed, and the process can be optimised. Tooling requirements can be captured and supporting hardware can be designed.

When planning for a decommissioning activity, training is often limited to *'on the job'* training. This may be due to time constraints or limited resources. Often it is down to lack of training hardware. This is especially true for smaller decommissioning projects where budgets can be limited. Using simulation, low-cost training can be provided that will not only help to develop the motor-skills required to perform a task but will ensure that operators are familiar with the process and understand the different operations that make up the task including its layout and potential sizing issues.

Using simulation to develop the skills of operators and to optimise processes, it is possible to reduce the cost of a decommissioning task. By including stakeholders in the design and development of a process, there is a greater opportunity to improve the process. By involving operators in the design process, there is the additional benefit that this time can be used to provide training. By using simulation tools to develop processes, it is possible to optimise those processes to reduce the time taken to perform a given task and therefore reduce the overall cost of a decommissioning activity, to include time saved in safety case drafting and regulatory approvals.

2. Decommissioning the CONSORT research reactor

The decommissioning of the CONSORT research reactor has provided a case study to assess the use of simulation for process development and training. CONSORT is a small research reactor that since 1965 has been owned and operated by Imperial College London. In this paper, we discuss the dismantling of the reactor core assembly using MSMs and the development of a simulation tool to provide training for that process.

Fig. 1 shows the configuration of a shielded cell for dismantling the reactor core assembly. The cell consists of a concrete wall that surrounds a central raised table. The core assembly is mounted on a support structure that is located on a turntable in the middle of

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Fig. 1. Cell Configuration.

the cell. MSMs are mounted on a frame that bridges the front wall; these provide the only form of manipulation within the cell. Images from within the cell are relayed by cameras mounted on the cell walls to a screen located in front of the user.

There are a number of challenges to using this configuration. Due to the limited space within the cell, careful consideration was needed as to what tooling would be placed in the cell. The reach and accessibility of the manipulators were considered to be sufficient to dismantle the core assembly. However, consideration was needed as to the accessibility to the rear of the core assembly, for this reason, a turntable was placed in the cell. This would allow an operator to turn the core assembly using the manipulators.

To remove fasteners, a set of tooling was manufactured and placed in the cell. The tools consisted of a socket tool, Allen keys and levers that were mounted to tooling blocks that could easily be picked up and manipulated. Many of the tools also included 'Tommy' bars allowing the operators to apply extra force to the second manipulator when necessary.

3. Related works

Use of virtual reality and simulation has been explored for different use cases within the nuclear industry. Much of the published work has focused on estimating an operators dose (Mól et al., 2009) and visualising dose during a maintenance operation or dismantling process (Park et al., 2008). Using simulation, opportunities to reduce occupational dose can be identified such as mapping the minimum dose path through a facility (Liu et al., 2015). As well as using simulation for dose assessment, it can also be used to provide evacuation training (Da Silva et al., 2016) and can be used to provide a tool for waste management calculations.

Szőke et al. provide an in-depth look at how simulation and VR technology can be used to support nuclear engineering activities throughout a project (Szőke et al., 2014). Wang et al. discuss a digital knowledge management system that can be used as a repository for all information and documentation throughout the lifecycle of a nuclear facility (Wang et al., 2017).

Thompson & McCann explore the use of discrete event simulation and how it is being used at Sellafield to improve decommissioning operations (Thompson and McCann, 2010). By modelling a system in detail, a better understanding of that system can be gained, and opportunities to improve the flow of operations within that system identified.

When learning new information, using VR can have a substantial cognitive impact (Neguţ et al., 2016), enhancing how much information is retained compared to traditional classroom-based learning. Of particular interest to this research is how simulation can be used to develop skills in physically demanding operations and how those skills transfer from the virtual world to the physical world (Garrett and McMahon, 2013).

Using simulation, familiarisation of a facility or process can be gained before starting work. Training in virtual environments has been shown to improve a worker's contextual awareness of where they are in an environment and what processes are going on around them; this enhanced awareness can lead to improved safety and a reduction in the frequency of accidents or near misses (Jeong et al., 2014). In a nuclear facility such as a radioactive waste store, virtual reality can be used to plan material movements and study occupational dose, providing further opportunities to improve safety (Freitas et al., 2014).

Simulation has been used to explore different dismantling operations of nuclear power plants (Jeong et al., 2014) and to study the ergonomics of various decommissioning tasks (Jeong et al., 2016). As a method of operator training, VR has been used to train for refuelling operations in a facility (Zhao et al., 2015). Virtual reality has also been used to replace traditional methods of training such as building physical mock-ups (Oosterhout et al., 2014). Virtual mock-ups provide a low-cost alternative to manufacturing physical hardware. If the physical hardware is going to get destroyed during training, then virtual hardware offers the benefit that it can repeatedly be used to practice cutting and other destructive operations without incurring the cost of manufacturing additional hardware. A further advantage of using VR is that it can easily be modified and reused for future projects and related activities.

As well as using simulation for decommissioning, simulation has been used to plan and practice maintenance operations (Yang et al., 2015). Augmented reality has been used to provide on-site instructions for real-world tasks (Yim and Seong, 2010).

When developing a simulator for performing decommissioning operations, it is important first to define the scope of what the simulator will be capable of doing. For example, will cutting of components be required (Kim et al., 2016).

Digital mock-ups can be used to verify the suitability of remote handling for different operations (Seong et al., 2011). This can be beneficial during the design stages of a cell to identify potential problems. Using simulation, the range of movement for the MSMs can be overlaid on a virtual model to aid designers in understanding reach and limitations of a particular design.

4. Design of the simulator hardware

To explore the use of simulation for training, a low-cost simulator was built (Fig. 2) that aims to replicate the functionality of the real-world hardware. The simulator is built around a low-cost framework, which provides support for the manipulators and the screen. The manipulator-arms were made using low-cost off the shelf components, and custom 3D printed parts. The input to the simulator is provided by a pair of HTC Vive™ controllers. The controllers were chosen based on their sub-millimetre accuracy and relative ease of configuration. The controller's movements are mapped to the movements of their virtual counterparts.

A kinematic model was developed that describes the movement of the real-world master-slave manipulators. The manipulator's jaw location is calculated using an offset from the controller location. The jaw location is then used to drive the input to a physics simulation. The physics simulation stops the jaw from penetrating other 3D virtual objects.

The controller's triggers are used to control the manipulator jaws, providing the primary method of interaction. This allows the user to pick up and interact with objects and tools within the simulation software.

To ensure that the simulator would provide a close approximation of the real-world hardware, the spacing of the arms, the