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The Impact of a Haptic Digital Twin in the Nuclear Industry and Potential Applications*

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Abstract— **Robotic systems that enable operators to remotely manipulate delicate materials with high dexterity, and sufficient force feedback will pave the path for improvements of the safe maintenance and decommissioning processes within the nuclear industry. Training the operators, however, for challenging conditions (e.g., low visibility, restricted motion in confined spaces, and limited interaction force) in a time- and cost-effective manner is difficult. This paper introduces the economic and operational implications of using haptic digital twin technology to prepare operators for remote manipulation of hazardous materials. This technology simulates various tasks, robots, and environments in hazardous settings, allowing operators to perform their work more efficiently and cost-effectively. The proposed use cases within the nuclear industry for such simulation platform varies from the post-operational clean-out process to operations in the contaminated environment after a disaster.**

I. INTRODUCTION

Touch is one of the proficient senses that enables humankind to gain awareness of their surroundings by proving very specific information about the texture and stiffness of the objects they are interacting with. Haptic technology integrates such tactile feedback into robotic operations to provide realistic touch sensations so that users adequately feel and manipulate objects or computer simulations in an attempt to increase the perceived reality. Embedding additional force feedback, along with the vision, in to the robotic systems enhance precision of the tasks in-hand, such as in minimally invasive surgery [1] or remote handling [2].

Nuclear sites are prime examples of the extreme environments that hold specific application challenges for telerobotic systems. The hazardous conditions limit or prevent human access to the facilities, and require additional safety measures on the remote operations in order to prevent potential damage. Robots are mainly utilised in remote inspection or deployed for remote manipulation with additional force feedback for handling delicate materials (see, e.g., [3], [4]). Post Operational Clean Out (POCO), which describes operations undertaken for decommissioning nuclear facilities after reaching the end of work-life, is another significant application area for robots that provide force feedback [5], [6]. However, operators are required to carry out extensive training in order to safely drive the robots in confined spaces. These spaces may contain a number of obstacles such as piping, ducts, and cable racks, also the operators must be capable of manipulating delicate materials with limited touch information within these spaces.

Training operators for remote handling in difficult conditions (e.g., low visibility, restricted range of motion, limited force feedback, etc.) is a challenge within the nuclear industry. One can list some of the challenges as

- Creating a physical mock-up of the remote site is not always possible for training purposes (e.g., due complexity or overall size of the environment),
- It is not cost-effective to use valuable and bespoke systems, being deployed for safety-critical applications like nuclear, in the early stage of the operator training programs,
- Operationally deployed robotic systems have tight schedule for maintenance purposes; thus, they are not always available to be used for other purposes such as operator training,
- Nuclear sites around the world generally have legacy hardware systems where it is a challenge to maintain the components for the operations as finding replacement parts is not always straightforward.

To solve the aforementioned problems, one can create a digital twin of the remote manipulator along with its environment and utilise off the shelf available haptic devices (e.g., Haption Virtuose$^{\text{TM}}$ 6D, Phantom Touch) to train the operators. Fig. 1 illustrates a schematic diagram of such architecture where the remote side, including the robotic system, is replaced by a simulation platform, and commercial off-the-shelf (COTS) devices can also be used at the local side. In this way, the operators can be cost-effectively trained for a variety of tasks, possible breakdown scenarios can be generated to enhance readiness during actual operations, and proficiency levels can be quantitatively measured within the simulated environment. It is important to note that

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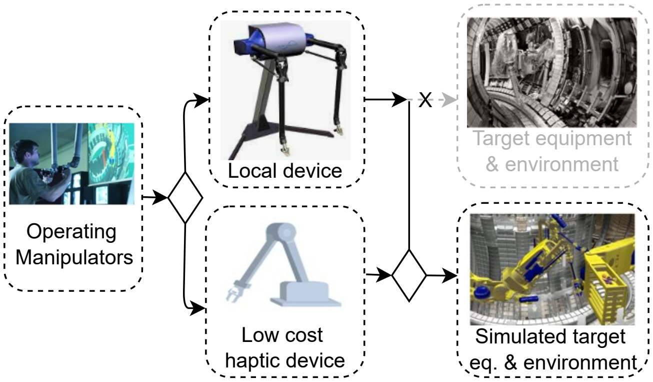

Fig. 1. Replacing the 'remote' side of a telemanipulation system with a haptic-enabled digital twin platform can enhance the feasibility of task evaluation and reduce the cost of the operator training programs. Utilising low-cost haptic devices in the early stage of operator training also reduces the burden on hardware availability.

Fig. 2. Fuel element conditions in pile 1: destroyed, severely damaged, and with minor damage around the fire affected zone [10].

such haptic devices (COTS) are not proposed as the main training equipment as they are limited in providing the full competency required for most nuclear tasks, however, such devices can help to improve the operators perception on using robotic equipment and force feedback for tasks as part of the training programme to utilise the training process.

This paper introduces the operational and economic impacts of a haptic digital twin (HDT) technology, along with some challenging use cases, within the nuclear industry. Also, illustrations are provided to describe how such a platform could be a direct cost-saving technique, once utilised as a training platform, that also increases overall safety for remote manipulation in hazardous conditions via enhancing operator training programs.

II. USE CASES IN THE NUCLEAR INDUSTRY

The impacts of the HDT are proposed with four different use cases, varying from the post-disaster cleaning-up processes to decommissioning legacy components. One can state that the economical impact and the application areas within the nuclear industry are not limited to the ones mentioned here; for instance, by 2020 the average age of nuclear sites around the world is nearly 35 years indicating the potential increase in the number of plants close to the decommissioning process [7].

A. *Fuel Debris Retrieval in the Sellafield*

Sellafield, located on the coast of Cumbria in north-west England, is the UK's oldest (more than 70 years old) and biggest (covering an area of $2.65\,\mathrm{km}^2$) nuclear site where different nuclear operations have been carried out; production of plutonium, recovering and reusing uranium, or treating and storing all types of nuclear waste [8]. Decommissioning legacy nuclear facilities and cleaning the hazardous materials in the site requires an extensive amount of effort in technical development and great expense; yearly operation cost is more than $\pounds 2,000$ million (2020: $\pounds 2,070$ million) [9].

Retrieving damaged fuel elements, as a result of the Windscale fire of 1957 that impaired the natural uranium fuelled Unit 1 beyond repair [11], is one of the main challenges of the decommissioning process at Sellafield due to the conditions and locations of the fuel elements and isotope cartridges after the accident [12], [13]. Fig. 2 illustrates the condition of the damaged fuel elements within the graphite moderator, called a pile, after the fire occurred during an anneal of the core [10]. Each fuel channel would have contained a full fuel stringer which is made of 21 fuel elements [14]. The fuels, nearly $15\,\mathrm{t}$, remain in the reactor in various conditions and need to be removed from the blocked channels with remote technology [15] assistance.

One method to retrieve the damaged fuel debriswithin the graphite pile is via a tube shaped extensible long reach robotic arm mounted with a gripper (for intact elements) or a scoop (for damaged grit types fuels) [16], [17]. The system can be deployed from the top of the reactor or behind the bio-shield to the charge face, which had previously been used for charging the reactor during normal operation, see Fig. 3.

Retrieving fuel elements in different conditions from a narrow tube with a remote end-effector presents significant challenges to the operator:

- Radiation resistant cameras will be used resulting in limited quality and resolution with the currently available technology; thus, the operator will not have clear visual reference during the operations.
- Due to the narrow passageway, the end-effector need to carry a forward-facing camera for the operation, yet operators might not understand the success of the pull because the camera will move with the target.
- The location of the camera does not allow the operator to understand the situation/condition of the grasp.

Therefore, additional feedback information, such as grasping or pulling force, needs to be provided to the operators to enhance situational awareness. Measuring the interaction force between the end-effector and the fuel element informing the operator about that is crucial for the safety and success of the operation:

- An excessive grasping force applied by the fingers could break the fuel elements or entangle the end effector in the fuel.
- The fuel elements are connected via the graphite boat hooks (to form the fuel rod) that need to be snapped via pull to free an element. The operator should feel (or know) the snap to make sure that the retrieved element is free to be removed and swiftly reduce the pulling force limiting energy input to prevent operational limits being exceeded by the additional input from the release

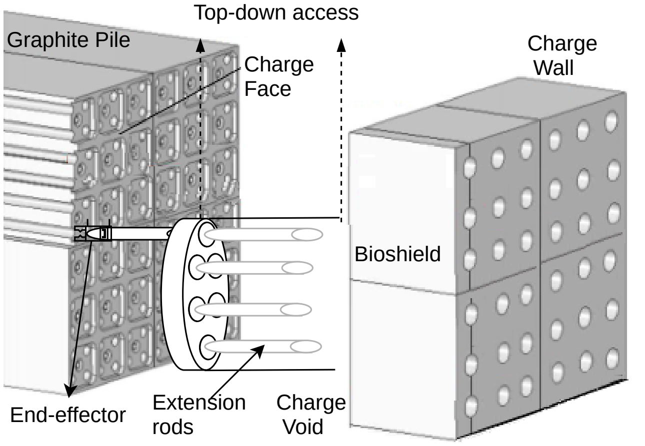

Fig. 3. A schematic representation of the Windscale reactor showing the graphite moderator and charging face. The damaged fuel retrieved system/method is illustrated where a rotating magazine allows to extend the length of the tube shape robotic arm and deploys the grippers/scoops.

Fig. 4. Inside the pressure containment vessel of the Unit 2 at the Fukushima Daiichi: melted fuels (brown elements are believed to be fuel debris) have fallen from the pressure vessel. Source: International Research Institute for Nuclear Decommissioning (IRID).

of any residual Wigner energy.

Operator training is significantly important for such applications where there is no room for failure and eliminating human error is crucial for the safety of the operation. The environment creates unique challenges to the operator and using bespoke hardware components for the training is not a cost or time-efficient solution. Therefore, one can use an HDT platform to train the operators for such a dedicated operation. Operators can gain experience with the haptic feedback delivered to them immersed in a virtual environment while manipulating virtual characters [18]. The constructed virtual environment can be deployed in the real operations as well by utilizing actual sensor readings and representing the current status of the robots virtually to enhance the operator's situational awareness.

B. Clean-Up Process of the Fukushima-Daiichi Nuclear Power Plant

The Fukushima Daiichi nuclear power plant (1F) is located on the Pacific coast of Fukushima Prefecture in Japan. Out of the 6 boiling water reactors in the plant, 3 reactors (Units 1-3) were severely damaged in 2011 (fuels melted down) due to the station block out (i.e., unable to cool down the cores) caused by a tsunami followed after an earthquake [19]. The clean-up process at 1F aims to develop a remotely operated fuel debris collection system for Units 1-3 that have been damaged with the nuclear meltdown accident [20]. Retrieving impaired fuels, which has absolute priority within the overall operation, from a hazardous (radiation level even within the reactor building around $10\,\mathrm{Sv\,h^{-1}}$ [21]) and highly unstructured environments is a challenging process, see Fig. 4 which illustrates the interior condition of the damaged reactor. Decommissioning the plant is estimated to cost ¥8 trillion ($\approx$ £48 billion).

A method being investigated to retrieve the fuel debris is to use the side access where a long reach robotic manipulator can enter the reactor core from the side of the structure to enhance the accessibility and requires minimum additional construction within the contaminated area [22]. For this, the pressure containment vessel (PCV) and pedestal of the reactor pressure vessel (RPV) need to be penetrated so that the long reach robotic system can access the damaged fuels, see Fig. 5 where overall reactor condition and a possible access method are illustrated. From the secured access opening the fuels can be retrieved by a remotely operated robotic system where a highly dexterous manipulator mounted on a long boom could be used. Remote operation in such conditions imposes several challenges that the operators need to be prepared for:

- Significantly reduced visibility due to the environmental conditions present within the reactor. The opening point or the access point might allow inserting multiple cameras for the operation from different angles, yet visibility would be severely restricted due to water dripping from above (in order to cool the fuel debris) and submerged fuel. Moreover, dust might obscure the viewing after manipulating partially burned materials.
- Moving complex machinery in compact spaces poses a difficult challenge within this environment. The joint configuration of the inserted manipulator is critically important to eliminate any possible fail-reach scenario, also eliminating unexpected contact with the surrounding objects is difficult due to the unstructured environment.

Therefore, to enhance situational awareness of the operator and increase operational safety, additional feedback systems need to be provided. Benefits of force feedback, for instance, can be summarized as:

- The use of haptic feedback can provide the operator a sense of feel between the remote robot and the environment. This feedback is particularly prevalent and useful when the camera views are obscured.
- During the decommissioning process, the contaminated electromechanical systems also need to be remotely replaced, maintained, or upgraded, where the operator might need to carry out complex tasks, such as cutting, unbolting and welding, where interacting between the

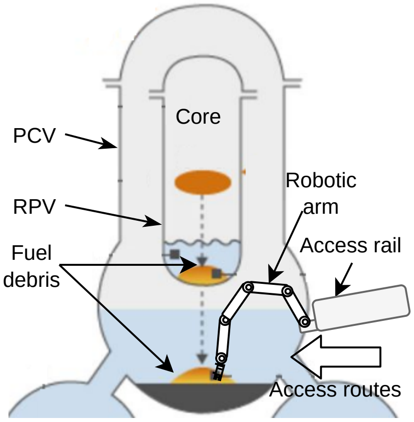

Fig. 5. Damaged reactor's condition after the fuel meltdown incident and possible fuel retrieval method with a long reach robotic manipulator.

task and end-effector is crucial for the quality of the task. Furthermore, when conducting these tasks, it is difficult to observe some failure scenarios, e.g., jammed tool, without appropriate force feedback.

Creating physical mock-ups similar to the damaged Units is possible yet very costly specifically due to the produced hardware components for the training purposes; it is not cost or time-effective. At this stage, one can use a haptic training simulation to train the operators for different types of challenges that they might face during the operation thereby, training time on the actual hardware components can be reduced. Also, such a platform enables objective operator assessment via analysing recorded data of the trainees. Similarly, simulations have been practically implemented in medicine for training and assessment purposes due to ethical and cost reasons, see for instance [23].

C. Hazardous Material Handling with Robotic Arms within the Gloveboxes

In nuclear laboratories/facilities, the glovebox is a sealed enclosed space allowing hazardous material handling in a safe environment by preventing the spread of contamination. Personal protective equipment and puncture-proof gloves are used by the users while examining/studying the hazardous materials. Due to the limited view (insufficient lighting, window, etc.) and restricted motions, a simple manual task can be tedious to do within a glovebox. To overcome the limitation of the human hand/arm within a protective glove and to handle high-risk elements mechanically connected arms are also used. Such remote handling also enhances operational safety; e.g., the majority of the reported incidents within the gloveboxes caused by the gloves failure (26% of the total accidents) in the Sellafield nuclear site [24]. In fact, early bilateral teleoperation systems were implemented for these applications to provide additional force feedback for the operator to increase precision in material handling while enhancing operational safety [25].

There is a demand in the nuclear industry to increase robotic applications to reduce crewed operations due to the radiation (see, e.g., [26]). The latest technological developments on the hardware and software has enabled cost-effective solutions for tasks, such as inspection, maintenance, or material handling, in hazardous environmental conditions. Embedding telerobotic systems into the gloveboxes with additional assistive technologies is one of these approaches [27], [5], see Fig. 6 where traditional hand in the box and more advance robotized gloveboxes are illustrated.

Fig. 6. Gloveboxes where the operator is wearing special gloves for protection while analysing/examining hazardous material or using local-remote robotic manipulator system for the enhanced safety measures. Sources: U.S. Department of Energy and UKAEA.

Operating two robotic arms in a confined space, where collision with the interior of the glovebox needs to be avoided, is a difficult task for the operators. Additionally, the visibility can be restricted to the task in progress. Therefore, operators are required to carry out training for the gloveboxes mounted with the robotic system before any operation. Before using any remote hardware components, the operators can be trained in a simulation platform, where there exists a virtual robotic glovebox, that provides force feedback as in a bilateral robotic system. Thus, their proficiency level can be increased in a low-cost manner creating a unique advantage in such training programs. The gloveboxes can also be used in an advanced stage of the operators' training for remote material handling or task evaluation.

Efforts in bilateral teleoperation system development within the gloveboxes has proved the benefits of haptic feedback for the handling of the hazardous materials (see, e.g., [28], [5]), for instance,

- Interaction force information allows the operator to manipulate delicate materials without any damage and boost the quality of the tasks (e.g., cutting, resizing, polishing, grinding, etc.).
- By providing additional force feedback, the operator can feel as if they are moving the material with their own hand, similar to the haptic feedback experienced while wearing gloves, but with the added safety provided by the manipulators.

On the other hand, the decommissioning of the legacy gloveboxes that have been used in the UK or any other country for hazardous material handling is another challenge in the nuclear industry [29]. In Sellafield, the majority of the gloveboxes have entered POCO by 2020 [24]. Legacy gloveboxes were mainly used for handling materials contaminated with plutonium residue. [30]. Alpha radiation emitted by the plutonium is the primary contamination that is non-penetrating and the main hazard to human health is inhalation. Thus, currently, the majority of the decommissioning of such contaminated gloveboxes takes place by operators in air-fed suits using handheld power tools as seen in Fig. 7. However, wearing such suits limits the operator motion and using power tools, such as disk cutter, impose a risk of puncture on the safety suits, therefore, manual operations include

Fig. 7. Operators working in air-fed suits for protection during manual handling [30].

serious health risk. Thus, the knowledge acquired from using robotized gloveboxes, including experience operating robots within similar gloveboxes using haptic virtual platforms, can be applied to the robotization of decommissioning. As a result, operators can leverage their skills and knowledge to operate decommissioning systems effectively as well.

D. Joint European Torus (JET) Tokamak Decommissioning

The JET tokamak, located at Oxfordshire in England, is an operational plasma reactor used for experiments analysing the sustainability of nuclear fusion energy. It has been in operation since 1983 and the local authority, UKAEA, is planning to start decommissioning process of the reactor and remove/demolish the associated equipment and buildings by the end of 2022 [31]. Due to the hazardous conditions within the vessel (e.g., 81 days after a shutdown radiation level was $270\,\mu\mathrm{Sv\,h^{-1}}$ in the centre of the vessel [32]), maintenance and any upgrades required for the scientific experiments have been carried out via a remote bilateral robotic system as seen in Fig. 8. The manipulator is called Mascot, consisting of connected local and remote robotic manipulators. It is aimed to use the same robotic system operated by the experienced operator for the decommissioning process, see [33] for the possible challenges and hazardous conditions during the decommissioning process of the JET.

Operators are required to carry out an intensive training program (taking a significant amount of time, approximately 6 months) to reach the appropriate proficiency level for Mascot operations. Typically, operator training is conducted offline. However, using real nuclear telerobotic devices and physical mock-ups for this purpose is highly expensive and often unavailable due to the vessels' high demand and tight maintenance schedules. Furthermore, it is difficult to maintain a long-lasting robotic system due to the limited availability of the spare hardware components; thus, it is desirable to use the system in actual operations only. Hence, a simulation/mock-up, compatible with the haptic feedback via haptic devices, can be used for operator training and task development in a more cost-effective way. Some benefits of utilizing an HDT as a training platform can be summarized as:

- Reduces the demand for the hardware which is essential for the system operation; in this way, the life span of the hardware required for the decommissioning can be increased,

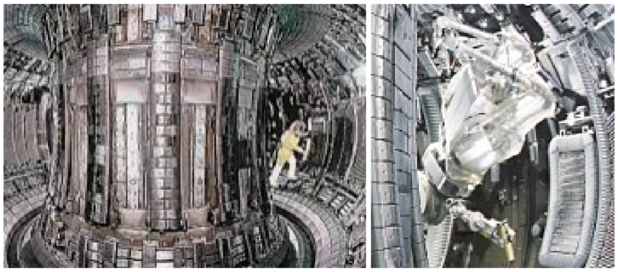

Fig. 8. Inside the JET tokamak: manual work to remote manipulation.

- Training cost and time can be reduced as operators can use off the shelf, low-cost haptic manipulators with the software platform for initial training,
- Different tasks and fail scenarios (hardware malfunction or task-related; jamming, stacking, etc.) can be developed within the simulation platform which enhances operators' proficiency level,
- Decommissioning strategies can be evaluated by the operators in the simulation platform during the initial planning process.

A haptic digital mock-up can have a direct impact on the operational management and training costs of decommissioning activities. Implementing such a system is expected to significantly reduce long-term robotic operational costs, which would be a valuable cost-saving measure given the overall expenses associated with decommissioning activities.

III. CHALLENGES

Despite the benefits, developing a HDT is a difficult task and there exist many challenges to overcome. The main challenge is related to accurately modelling robotic manipulators and environments in a simulator that provides sufficient physical accuracy. In the nuclear industry, the remote side of the telerobotic system is designed to be robust against radiation; thus, they contain tendon or gear-driven joins (to put distance between radiation and sensitive electronics) where accurately modelling elasticity of the tendons under the loads or backlash within the gearboxes is challenging. And modelling mismatch has a direct impact on the effectiveness of the simulator. Also, modelling soft-deformable materials or rigid objects in fluids (e.g., fuel debris in 1F are submerged and it is expected that water will be present during the retrieval process) for stable haptic rendering with sufficient computational efficiency is still a burden.

Additionally, utilizing COTS haptic devices with a simulator is an effective way to reduce overall cost within the operator training programme. These haptic devices, however, have significantly smaller workspaces compared to the local devices which generally have kinematic similarities with the remote devices. Thus, operators need to accustom operating dissimilar local-remote manipulators when incorporating with the haptic training simulators. The effect of a such discrepancy between the training program and actual operation needs to be well studied.

IV. CONCLUSION

The application area for a haptic training simulator is not limited to the ones provided here within the nuclear industry. There are many industries around the world (e.g., oil and gas) that require reducing manned activities, such as repair and maintenance, with robots to enhance operational safety. These operations require highly qualified operators to use the robotic systems in critical environmental conditions. To increase the proficiency level of the operators, an extensive amount of training is required and the vital training can be accomplished within the virtual platform in a cost and time effective manner.

Operating complex electro-mechanical systems in challenging environmental conditions for bilateral remote manipulation is a challenging task. Operators must adjust to the loss of depth perception and force feedback that is provided via the local device. Fortunately, creating a digital mock-up of the remote manipulator and surrounding environment can enable faster, safer, and more cost-effective decommissioning activities. Additionally, rendering the interaction force in a virtual environment and creating a haptic training simulator can enhance training programs for remote robotic operations. Utilizing digital technology is crucial for establishing reliable maintenance practices for nuclear systems, which ensures their continuous operation not only for energy and isotope production but also for future nuclear technologies, thus contributing to the betterment of society.

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