UK Atomic Energy Authority

UKAEA-RACE-CP(23)02

Harun Tugal, Salvador Pacheco-Gutierrez, Myles Verdon, Ipek Caliskanelli, Alfie Sargent, Alice Cryer, Ronan Kelly, Alexandros Plianos, Andika Yudha, Qasim Kapasi, Robert Skilton

Haptic Training Simulation: Potential Applications in the Nuclear Industry

Haptic Training Simulation: Potential Applications in the Nuclear Industry

Harun Tugal, Salvador Pacheco-Gutierrez, Myles Verdon, Ipek Caliskanelli, Alfie Sargent, Alice Cryer, Ronan Kelly, Alexandros Plianos, Andika Yudha, Qasim Kapasi, Robert Skilton

This paper has been submitted to
IEEE Haptics Symposium 2022, Santa Barbara, California, USA, 21-24 March 2022

Haptic Training Simulator: Potential Applications in the Nuclear Industry*

Harun Tugal[1], Fumiaki Abe[2], Ipek Caliskanelli[1], Alice Cryer[1], Chris Hope[3], Ronan Kelly[1], Salvador Pacheco-Gutierrez[1], Alexandros Plianos[1], Masaki Sakamoto[2], Tomoki Sakaue[2], Alfie Sargent[1], Wataru Sato[2], Shu Shirai[2], Yolande Smith[3], Yoshimasa Sugawara[2], Myles Verdon[1], Andika Yudha[1], and Robert Skilton[1]

Abstract— **Robotic systems that enable the 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 motions in the confined spaces, limited interaction force) in a time- and cost-effective manner is difficult. This paper proposes possible application areas of a haptic training simulation platform that can prepare the operators to remotely manipulate hazardous materials more economically by simulating different tasks, robots, and their surroundings in the hazardous environment. 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, and 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. Firstly, it is not always possible to create a physical mock-up of the 'remote' site for training purposes; this could be due to the limited knowledge of the environment and harsh operating conditions. Moreover, high cost and bespoke systems are being deployed for safety-critical applications like nuclear and using these systems is not cost-effective for training purposes. Furthermore, robotic systems currently in operation have a tight schedule for maintenance and operational purposes, and therefore not always available to be used for training. In addition, 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. Therefore, limiting the operating times of the hardware apart from the non-essential tasks is desirable to reduce the maintenance cycle.

To solve the aforementioned problems, one can simulate the 'remote' manipulator along with its environment by utilizing off the shelf available haptic devices (e.g., Haption Virtuose™ 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 an additional device is used for 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 such haptic devices 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

*This research was fully funded within the LongOps programme by UKRI under the Project Reference 107463, NDA, and TEPCO. The views and opinions expressed herein do not necessarily reflect those of the organizations.

[1]Authors are with UK Atomic Energy Authority, Remote Applications in Challenging Environments (RACE), Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, United Kingdom. E-mail: name.surname@ukaea.uk.

[2]Authors are with Tokyo Electric Power Company (TEPCO) and currently secondees at UK Atomic Energy Authority, Remote Applications in Challenging Environments (RACE), Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, United Kingdom. E-mail: name.surname@ukaea.uk.

[3]Authors are with Sellafield Ltd, Hinton House, Risley, Warrington, Cheshire, WA3 6GR, United Kingdom. E-mail: name.surname@sellafieldsites.com.

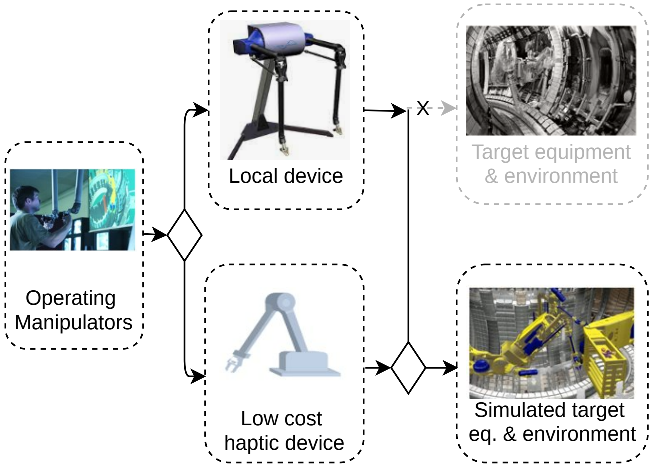

Fig. 1. Replacing 'remote' side of the tele-manipulation with a virtual platform to enhance feasibility on task evaluation and reduce the cost of the operator training programs.

robotic equipment and force feedback for tasks as part of the training programme to utilise the training process.

This paper introduces some challenging use cases within the nuclear industry for a haptic training simulation platform with illustrations provided to describe how such a platform could be a direct cost-saving technique that also increases overall safety for remote manipulation in hazardous conditions via enhancing operator training programs.

II. Use Cases in the Nuclear Industry

Four different use cases are proposed, varying from the post-disaster cleaning up processes to decommissioning legacy components, introduced for a haptic training simulation platform. One can state that the application area within the nuclear industry is 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 $£2,000$ million (2020: $£2,070$ 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 [10], 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 [11], [12]. 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 [13]. 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.

Fig. 2. Fuel element conditions in pile 1: destroyed, severely damaged, and with minor damage around the fire affected zone [13].

One method to retrieve the damaged fuel debris[1] within 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. The overall operation could potentially be simplified as using the following methodology. A rotating magazine, carrying extension rods, could deploy scoops and an end-effector, similar to the one illustrated in Fig. 3, to the narrow tubes with forward-facing cameras so that the fuel rods can be safely manipulated. Lastly, the elements will be pulled to the charge void where the retrieved material will be appropriately concealed for further clean-up processes.

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.

[1]Fuels melted and re-solidified with fuel assemblies, control, rod and internal structures, according to the International Atomic Energy Agency.

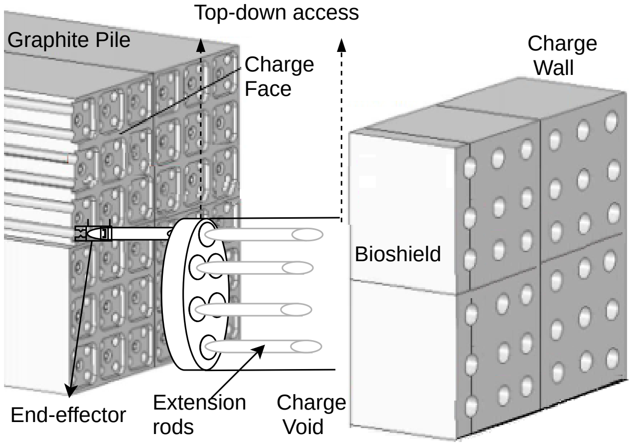

Fig. 3. A schematic representation of the Windscale reactor showing the graphite moderator and charging face. The damaged fuel retrieved system/method is illustrated where a rotating magazine allows to extend the length of the tube shape robotic arm and deploys the grippers/scoops.

- 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 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 a haptic virtual training 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 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 Fukushima-Daiichi 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.

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).

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 prepare 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

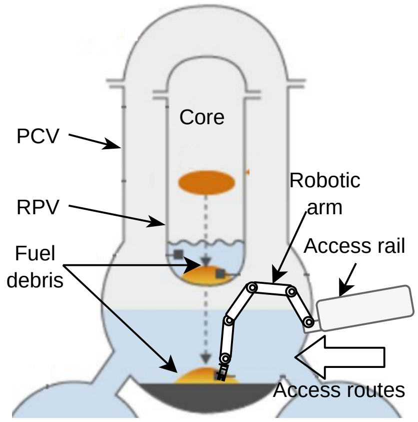

Fig. 5. Damaged reactor's condition after the fuel meltdown incident and possible fuel retrieval method with a long reach robotic manipulator.

environment. This feedback is particular prevalent and useful when the camera views are obscured.
- During the decommissioning process to reach some fuel debris, the operator might need to carry out complex tasks, such as cutting, unbolting and welding, where interacting between the 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], [24].

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 [25]. 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 [26].

There is a demand in the nuclear industry to increase robotic applications to reduce manned operations due to the radiation (see, e.g., [27]). 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 [28], [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 'master-slave' 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 collusion 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, 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.).
- With additional force feedback, the operator can think as if he is moving the material with his hand (with sufficient transparency) similar to the haptic feedback that he has while using gloves, yet with extra 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 [30]. In Sellafield, the majority of the gloveboxes have entered POCO by 2020 [25]. Legacy gloveboxes used for handling mainly contaminated with plutonium residue [29]. Alpha radiation emitted by the plutonium is the primary contamination that is non-penetrating and the

Fig. 7. Operators working in air-fed suits for protection during manual handling [29].

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 serious health risk. Thus, robotized gloveboxes can also be used for such decommissioning process with operators who are already been trained with haptic virtual platforms and gained experience via operating the robots within similar gloveboxes.

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 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.

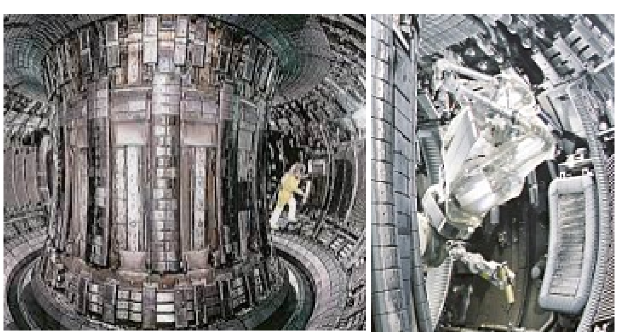

Fig. 8. Inside the JET tokamak: manual work to remote manipulation.

The mascot is a two-armed local-remote tele-manipulator robot where each arm has seven degrees of freedom (see, e.g., [34], [35] for the upgrades within the control architecture of the long-lasting system). The robotic system is routinely used for remote maintenance and reconfiguration of the JET tokamak without the need for manned entry into the hazardous environment, see Fig. 9 where connected 'local' and 'remote' manipulators are illustrated. The bilateral tele-operation system provides haptic feedback to the operators during the remote operation. Hence, the operator can carry out remote complex tasks, such as bolting, mechanical device assembly, or cable handling, in a safe manner. In addition to the force feedback, the operators rely on the video streams coming from the cameras on the remote side along with a virtual representation of the current state of the robotic system within the confined environment.

Fig. 9. Mascot is two-armed bilateral teleoperation system allowing remote maintenance and reconfiguration of the JET tokamak. Source: UKAEA.

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. The operator training is mainly carried out 'off-line' yet using real nuclear telerobotic devices and physical mock-ups for that is highly expensive and typically unavailable due to high demand and tight maintenance schedules of the vessel. 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 a haptic simulation 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,
- 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.

III. Discussion and 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.

Remotely operating complex devices via 2D screens has a challenging learning curve (accustom to the loss of depth perception, the discrepancy between the 'local' and 'remote' devices, etc.). Rendering the task interaction force in a virtual platform and feeding back such information to a trainee operator will expedite the proficiency level of the operations that require delicate remote manipulation.

References

[1] G. Tholey, J. P. Desai, and A. E. Castellanos, "Force feedback plays a significant role in minimally invasive surgery: Results and analysis," *Annals of Surgery*, vol. 241, no. 1, pp. 102–109, 2005.

[2] H. Boessenkool, D. A. Abbink, C. J. Heemskerk, F. C. Van Der Helm, and J. G. Wildenbeest, "A task-specific analysis of the benefit of haptic shared control during telemanipulation," *IEEE Transactions on Haptics*, vol. 6, no. 1, pp. 2–12, 2013.

[3] H. Sugiura, T. Fukushima, M. Kuroda, R. Ishizaki, and T. Matsumoto, "Development of high-access survey robot for TEPCO's fukushima daiichi nuclear power station," Honda, Tech. Rep., 2014.

[4] I. Tsitsimpelis, C. J. Taylor, B. Lennox, and M. J. Joyce, "A review of ground-based robotic systems for the characterization of nuclear environments," *Progress in Nuclear Energy*, vol. 111, pp. 109–124, 2019.

[5] O. Tokatli, P. Das, R. Nath, L. Pangione, E. T. Jonasson, M. F. Turner, R. Skilton, A. Altobelli, and G. Burroughes, "Robot-assisted glovebox teleoperation for nuclear industry," *Robotics*, vol. 10, no. 3, p. 85, 2021.

[6] R. Bloss, "How do you decommission a nuclear installation? Call in the robots," *Industrial Robot: An International Journal*, vol. 37, no. 2, pp. 133–136, 2010.

[7] E. Neri, A. French, M. E. Urso, M. Deffrennes, G. Rothwell, I. Rehak, W. Inge, S. Carroll, and V. Daniska, "Costs of decommissioning nuclear power plants," Tech. Rep., 2016.

[8] Nuclear Decommissioning Authority, "Draft Strategy: Cleaning up the UK's earliest nuclear sites, caring for people and the environment," Tech. Rep. August, 2020.

[9] Sellafield Ltd, "Annual report and financial statements 2020/2021," Tech. Rep. March, 2021.

[10] W. Penney, B. F. Schonland, J. M. Kay, J. Diamond, and D. E. Peirson, "Report on the accident at Windscale No. 1 Pile on 10 October 1957," *Journal of Radiological Protection*, vol. 37, no. 3, pp. 780–796, 2017.

[11] D. G. Pomfret, "Safety and dose management during decommissioning of a fire damaged nuclear reactor," *Safety*, vol. 2, no. 2, 2000.

[12] M. T. Cross, W. C. Mullinaeux, J. C. Jennings, W. A. Ingamells, and M. L. Ferris, "Resolving the technical challenges in the decommissioning of an accident damaged reactor – Windscale pile 1," in *WM'05 Conference*, Tucson, AZ, 2005.

[13] M. T. Cross, "Decommissioning preparations for the accident-damaged pile 1 reactor at Windscale, UK," in *Decommissioning after a Nuclear Accident, IAEA*, Vienna, 2013.

[14] L. C.-A. Bourva, P. Cowan, S. Croft, and M. Ferris, "The benchmark results between MCNP and MONK criticality codes for a full scale model of a sub-critical graphite assembly," in *JAERI-CONF–2003-019-PT1*, 2003, pp. 314–319.

[15] Nuclear Decommissioning Authority, "Packaging of windscale piles fuel and isotope cartridges (conceptual stage) summary of assessment report," Tech. Rep. June, 2007.

[16] M. T. Cross, "Research and development activities in support of the decommissioning of Windscale pile 1: characterization studies," *IAEA Innovative and adaptive technologies in decommissioning of nuclear facilities*, no. IAEA-TECDOC–1602, pp. 267–282, 2008.

[17] Kurion Inc., "Overview of the windscale piles decontamination and decommissioning project," 2015. [Online]. Available: https://bit.ly/2Y07w5L

[18] A. Lelevé, T. McDaniel, and C. Rossa, "Haptic Training Simulation," *Frontiers in Virtual Reality*, vol. 1, p. 3, 2020.

[19] IAEA, "The Fukushima Daiichi Accident: Description and Context of the Accident," Tech. Rep., 2015.

[20] Tokyo Electric Power Company, "Technical strategic plan 2016 for decommissioning of the fukushima daiichi nuclear power station of tokyo electric power company holdings, Inc." Nuclear Damage Compensation and Decommissioning Facilitation Corporation, Tech. Rep., 2016.

[21] ——, "Development of a technology to investigate inside the Reactor Primary Containment Vessel (PCV)- Results of site test "Investigation B1" on grating around the pedestal inside Unit 1 PCV," Tech. Rep., 2015.

[22] E. Watanabe, "Advanced technologies for fuel debris retrieval towards fukushima daiichi decommissioning," pp. 1–18, 2017. [Online]. Available: https://bit.ly/3ANmBpk

[23] B. Chebbi, D. Lazaroff, and P. X. Liu, "A collaborative virtual haptic environment for surgical training and tele-mentoring," *International Journal of Robotics and Automation*, vol. 22, no. 1, pp. 69–77, 2007.

[24] B. M. Kyaw, N. Saxena, P. Posadzki, J. Vseteckova, C. K. Nikolaou, P. P. George, U. Divakar, I. Masiello, A. A. Kononowicz, N. Zary, and L. T. Car, "Virtual reality for health professions education: Systematic review and meta-analysis by the digital health education collaboration," *Journal of Medical Internet Research*, vol. 21, no. 1, p. e12959, 2019.

[25] R. Smith, "Enhanced glovebox operations overview," National Nuclear Laboratory Limited, Tech. Rep. 2, 2019.

[26] R. C. Goertz, "Remote-Control Manipulator, U.S Patent Number: 2,632,574, March 24," 1953.

[27] Nuclear Decommissioning Authority, "Robotics and artificial intelligence research and development: preferred option," Nuclear Decommissioning Authority, Tech. Rep. 1, 2018.

[28] R. M. Crowder, "A manipulator for glove-box operations," *Mechatronics*, vol. 1, no. 1, pp. 37–58, 1991.

[29] R. Alford, "Plant dismantling and decommissioning challenges," Sellafield Ltd, Tech. Rep., 2016. [Online]. Available: https://bit.ly/2VPXYtr

[30] D. Pancake, C. M. Rock, R. Creed, T. Donohoue, E. R. Martin, A. John, C. J. Norton, D. Crosby, and T. J. Nachtman, "A novel and cost effective approach to the decommissioning and decontamination of legacy glove boxes - minimizing TRU waste and maximizing LLW Waste - 13634," in *Waste Management Symposium (WM2013)*, Phoenix, AZ, 2013, pp. 1–7.

[31] K. A. Wilson, "JET decommissioning project," *Nuclear Energy*, vol. 41, no. 6, 2002.

[32] R. Villari, P. Batistoni, S. Conroy, A. Manning, F. Moro, L. Petrizzi, S. Popovichev, and D. B. Syme, "Shutdown dose rate benchmark experiment at JET to validate the three-dimensional Advanced-D1S method," *Fusion Engineering and Design*, vol. 87, no. 7, pp. 1095–1100, 2012.

[33] K. A. Wilson and K. Stevens, "Decommissioning planning for the joint european torus fusion reactor," *WM07 Tuscon Conference*, vol. 1, no. 1, p. 20, 2007.

[34] D. Hamilton and G. Preece, "Development of the MASCOT telemanipulator control system," *International Topical Meeting on Robotics and Remote Systems- American Nuclear Society*, no. 01, p. 12, 2014.

[35] R. Skilton, N. Hamilton, R. Howell, C. Lamb, and J. Rodriguez, "MASCOT 6: Achieving high dexterity tele-manipulation with a modern architectural design for fusion remote maintenance," *Fusion Engineering and Design*, vol. 136, pp. 575–578, 2018.