

Application of Robotics in Decommissioning and Decontamination – 12536

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ABSTRACT

Decommissioning and dismantling of nuclear facilities is a significant challenge world-wide and one which is growing in size as more plants reach the end of their operational lives. The strategy chosen for individual projects varies from the hands-on approach with significant manual intervention using traditional demolition equipment at one extreme to bespoke highly engineered robotic solutions at the other. The degree of manual intervention is limited by the hazards and risks involved, and in some plants are unacceptable.

Robotic remote engineering is often viewed as more expensive and less reliable than manual approaches, with significant lead times and capital expenditure. However, advances in robotics and automation in other industries offer potential benefits for future decommissioning activities, with the high probability of reducing worker exposure and other safety risks as well as reducing the schedule and costs required to complete these activities.

INTRODUCTION

For some Decommissioning and Decontamination (D&D) tasks in the nuclear industry associated with the characterization and removal of bulk activity there is no other option than to deploy remotely operable technologies, if operator dosage levels are to be as low as reasonably practical (ALARP).

In the United States (US), the White House Office of Science and Technology Policy, which was involved in spearheading the new National Robotics Initiative affirms that, “Robotics technology is reaching a “tipping point” and is poised for explosive growth because of improvements in core technologies such as microprocessors, sensors, and algorithms.” Robotic systems for manufacturing operations are growing in popularity based largely on productivity gains and substantial returns on investment in a short time period. While D&D robotic operations are more complex and less repetitive than manufacturing operations, the potential gains are still quite substantial.

In the United Kingdom (UK), the National Nuclear Laboratory recognized the potential benefit of step changes in approach to remote operations and has made this one of the

Hallmark Areas of its Legacy Waste and Decommissioning Signature Research Programme. Working together with university partners, stakeholders and supply chain organizations, the laboratory is exploring the potential of the technologies such as tele-autonomy, visualization and human machine interface to deliver for the nuclear decommissioning sector.

Over the last 15 years significant investment in robotics research and development (R&D) has been made by a number of industrial sectors which are now reaping rewards of increased productivity, increased reliability and increased value. For example:

- Automated manufacturing sector - Advances in industrial robotics have produced significant increases in productivity;
- Off-shore sector – Investments have enabled the development of a wide range of highly specialized tele-operated Remote Operated Vehicles (ROV) used for a wide range of deep ocean tasks from oil field work to mineral and scientific exploration;
- Medical sector – The significant investment in this sector has produced advanced tele-operational systems, such as the da Vinci[®] surgical system. This highly sophisticated man-machine interface can reliably perform complex surgical procedures using the smallest of incisions.
- Space sector - The fundamental and unique link between the space and nuclear sectors is the finality of committing a device into a hazardous arena of operation. This commitment is with the awareness that it is technologically challenging and costly to retrieve a device for hands-on maintenance and modifications. Highly sophisticated tele-operated systems are regularly deployed into space and planets without the possibility of retrieval. Hence, reliability is paramount, such that systems must have redundancy and contingency to ensure mission success. The scale of the technological investment by this sector in terms of capital and technical resources in order to achieve this level of reliability and confidence has delivered this mission success.

By comparison the nuclear industry has made relatively little investment in the development of nuclear tele-operated systems since the late 1990's. Instead, the strategy has been to use technology developed by others and apply it to solve a specific short term project driven task. By adopting this strategy of selecting technologies from the market place the nuclear industry has managed to avoid any major investment in these technologies. In the short term, this is financially appealing, but it has the following limitations:

- The industry has had to accept the limitations of the market, instead of using technology that has been specifically optimized for the nuclear industry. For example, industrial tele-operated systems do not have the radiation hardened circuitry required to work in high radiation nuclear environments.

- Selectively picking robotic solutions from other industrial sectors often involves a return to a lower technology readiness level (TRL) in order to redevelop it for generic nuclear applications.
- Nuclear decommissioning projects that need the technology today must either develop and advance the technology, or increase the level of manual intervention and subsequent operator risk and dose. Whichever option is selected, there is a consequential increase in cost and time scales, compared to using readily available and specifically optimized technology.

Although the response actions during the ongoing Fukushima Daiichi incident is recognized as very different from D&D, the implications resulting from the lack of investment in the development of nuclear tele-operated systems (and the obvious consequent lack of such systems), were clearly exhibited. This was especially clear during the early days of the incident when characterization and visualization of conditions inside the reactor buildings could not be initiated due to the lack of robotic systems.

CHALLENGES

National decommissioning challenges

There are numerous facilities in the US and the UK awaiting D&D that are hazardous or inaccessible for human entry. This can be due to structure instability, high radiation levels, hazardous materials, or confined spaces. Government agencies are committed to adhering to the ALARP principle for radiation exposure to workers while minimizing the cost of a D&D project. Tremendous opportunities exist to reduce cost and schedule and improve safety in D&D activities through the use of robotic and/or tele-operated systems. Advancements will focus on development of the next generation robotic systems that will be adaptable to a variety of environments and topographies, semi-autonomous to provide a more intuitive human-robot interface, prevent accidents, optimize execution of tasks, and achieve high reliability. Remote mapping systems can more safely, economically, and reliably characterize a facility or area of a facility while distancing the worker from the imminent hazards.

The main objectives of robotic or tele-operated systems are 1) improved safety, especially for the D&D worker; 2) improved efficiency and productivity of remote systems; and 3) cost-effective development and deployment. Some nuclear decommissioning tasks and facility environments are so hazardous that they can only be accomplished by exclusive use of robotic and remote intervention. Less hazardous tasks can be accomplished by manual intervention and the use of personal protective equipment (PPE). Most of the currently available remotely operated equipment has significant limitations in that they are slow compared to direct human manipulation and require a more highly trained and skilled work force. Therefore, the challenge for developers is to develop versatile robotic technology that can be economically deployed to a wide range of future D&D projects and industrial sectors and for facility owners and

project managers to partner with the developers to provide accurate systems requirements and an open and receptive environment for testing and deployment.

Since many nuclear facilities are process plants, the use of a wide range of chemicals is typical. Many of the processes involve dissolution and hence the presence of acids and alkali neutralizers (frequently comingled with radionuclides) are common. Initial and detailed characterization and decontamination aimed at reducing such hazards - and which are mostly manual operations today - could significantly benefit from remote operations.

Typical problems

Decommissioning a nuclear facility has a fairly unique set of problems in terms of the development of remote technologies, because of the highly non-structured environment and the man inaccessibility. Some of the following problems demonstrate this:

- Legacy plants, some of which are over 60 years old contain large quantities of corroding radioactive material, which is highly hazardous.
- Nuclear facilities are typically highly congested (Fig. 1) with items, such as pipes and vessels, such that maneuverability, navigation, trajectory planning, obstacle avoidance are non-trivial.
- Nuclear and chemical material accountancy – the contents of pipes and vessels may or may not be known, especially for old legacy plants that have not been in service for years or decades.
- Structural integrity – plant items and their supports may have corroded or have become embrittled because of radiation during the last few decades. Unlike conventional process plants, these may not have been repaired or replaced.
- Disposal of contaminated equipment and effluents that may have been introduced by nuclear decommissioning equipment for decontamination must be minimized. There are limited nuclear storage and disposal sites.
- Floors of cells may never have been cleaned during the life of the plant and therefore could potentially contain contaminated dust, debris, spillages and dropped equipment.
- Ponds storage facilities, especially those that are outside have radiological debris submerged on the pond floor. This is similar to a murky sludge.
- For some legacy plants, accurate plant design drawings are either incomplete or non-existent. Even if these drawings exist, it will not represent the ‘as-built’ state.
- The non routine deployment of equipment is usually only possible through wall penetrations, that can be relatively small, such as 100 mm or less

- Site welded pipe work installed during the construction phase of the plant may have become pre-stressed and may therefore move when cut during decommissioning.
- Withdrawing and retrieving any hardware and equipment from service is likely to be radiologically and / or chemically contaminated.

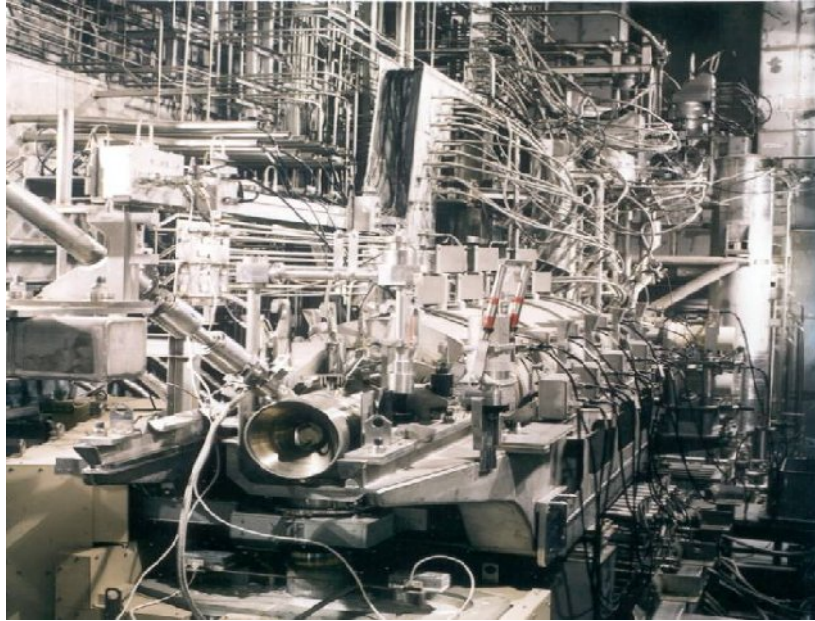


Fig.1. Example of congestion

CURRENT STATE OF TECHNOLOGY

Tele-operation

Tele-operation is the remote control of a robot system by a human operator by use of input devices, such as joysticks. Presently, tele-operation is the most common method of controlling a robot in a typical unstructured nuclear environment.

Fig.2 shows the basic components of a tele-operated system. The tele-operated robot / manipulator mechanism is shown on the right and the human operator and the robotic controller are shown on the left. In a nuclear application the robot / manipulator physically interacts with plant. The operator receives information as feedback generally via closed circuit television (CCTV), processes it and selects an action represented as a control input to the system.

Experience in a variety of applications across a number of industrial sectors has highlighted a number of problems of this traditional type of human-centric tele-operated system.

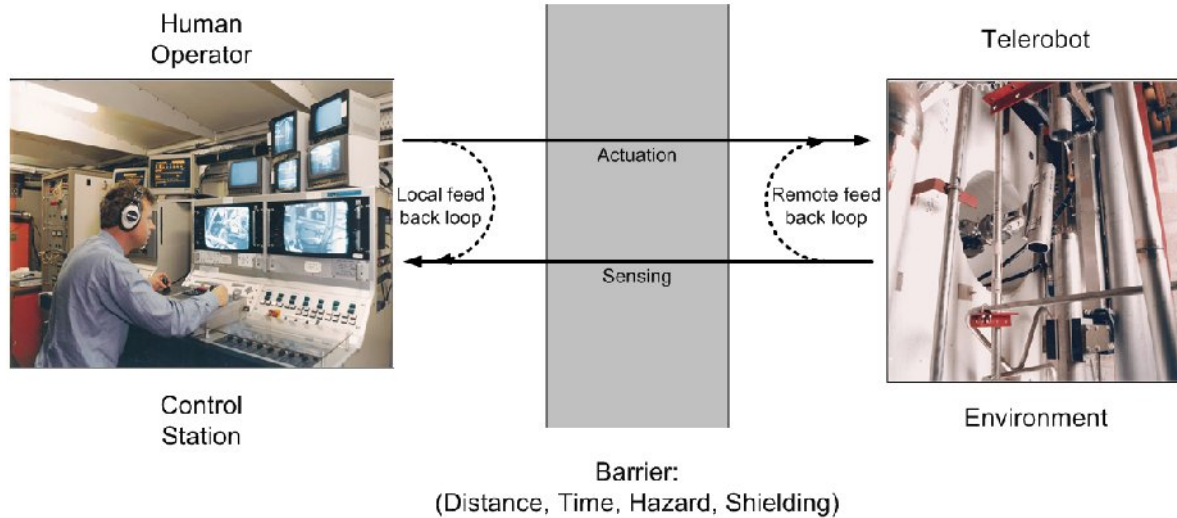


Fig.2. Components of a Tele-operational System

Tele-operation - operator limitations

Any tele-operational system must heavily rely upon the dexterity and skill of an operator and is particularly acute with direct tele-operation because of:

- Imprecise control of the robot / manipulator system, such as tracking errors, over-steering, time lags and latency.
- Operator perception errors, such as distance judgments and display interpretation.
- Operator cognitive errors, such as the human mental model differing from reality.
- Loss of situational awareness, perhaps because of insufficient sensor data, limited force feed back data and limited visual data from CCTVs.
- Operator fatigue, mood, reaction time, motor skills, knowledge and attention span.

Therefore, action is required now to ensure that future decommissioning tasks do not rely upon traditional commercial off-the-shelf software (COTS), tele-operable technology. Furthermore, there is an opportunity cost associated with a human operator, since a human is a valuable resource.

Tele-operation - hardware limitations

The quality of the interface between the human and the robot / manipulator system can significantly impact performance. An effective operator interface or control station is critical and must provide quality information and feedback to the operator in a user-friendly manner. For example:

- Representing 3 dimensional (3D) data on a 2 dimensional (2D) display decreases the situational awareness of the operator, leading to a higher risk of operator error. This can be circumvented by using three mutually orthogonal views. However, this increases project costs and complexity and requires the operator to assess data from three 2D views, instead of one.
- The presentation of key sensor data for alerts and operator awareness is essential. Data overloading must be prevented.
- Ergonomics of control inputs, such as keyboards and joysticks.
- Physical management of the umbilical system between the human and the robot / manipulator system. This may limit the specification of the communication links and available power.
- Communications links must be reliable and must have sufficient bandwidth, adequate response times and be capable of operating in noisy environments.

Tele-operation - navigation difficulties

As mentioned previously, typical nuclear environments are highly congested with plant process equipment. Navigating within such a congested, unstructured and changing environment is mentally exhausting for tele-operators as it requires:

- Avoiding multiple obstacles that may collide with any part of the manipulator.
- Avoiding hazards, such as high levels of radiation, temperature and corrosive materials.
- Optimizing geometric configuration for payload and reach.
- Performing the equivalent of an inverse kinematic analysis.
- An operator with high levels of skill, dexterity and patience.

Example – Raffinate Diversion

The National Nuclear Laboratory (NNL) (formerly a division of British Nuclear Fuels Limited), successfully completed the Raffinate Diversion [**Error! Bookmark not**

defined.] in 1997 at the Sellafield nuclear site in the UK. Although this was not a D&D project, it still remains a good example of the current state of nuclear tele-robotic technology in the UK.

The project objective was to cut and remove a 413 mm vertical section of pipe and replace it by welding in a new section that diverted the flow to another set of pipes. The operation was completed in a radiological environment that was man inaccessible. Originally, the project started in 1990 and the operation was to be completed approximately 2 years later in 1992. However, because of a number of successive plant life time extensions, the actual operation was postponed until later years.

The main component of the operation was a COTS 7-axis manipulator and the tool heads and cameras were modified COTS. The manipulator is illustrated in Figure 3(a) and was required to deliver all the tool heads, cameras, lights and ancillary equipment through a 700 mm diameter penetration and perform the actual operation, which consisted of the following steps:

- 1) Deployment and operation of cameras and lights
- 2) Deployment and operation of a pipe drill to drain the raffinate liquid in the pipe
- 3) Deployment and operation of equipment to restrain the pipes during and after the cutting
- 4) Deployment and operation of cutting heads
- 5) Deployment and operation of the pipe removal and decontamination device in a shielded container, the pipe was decontaminated, remotely prepped, cleaned, welded and x-rayed to validate the weld and prove the weld procedure.
- 6) Deployment and fixing of an end cap to the redundant lower pipe end
- 7) Deployment and operation of a weld prepping head for the upper pipe
- 8) Deployment and operation of a cleaning head for the upper pipe and the new section of pipe
- 9) Deployment and operation of an alignment device for the new section of pipe
- 10) Deployment and operation of an inert gas purge system for the weld
- 11) Deployment and operation of the weld head
- 12) Deployment and operation of the weld visual inspection camera
- 13) Deployment and operation of an x-ray welding head to validate the welds
- 14) Removal of all equipment

As the manipulator was tele-operated, a team of 8 operators were trained and because of the successive postponements, their training had to be maintained for 7 years. Originally, this was maintained by periodic operation of the manipulator and tool heads. However, this resulted in unplanned maintenance, repair and replacement as the equipment was subject to wear and tear, failure and accidental damage. This justified the construction of a bespoke simulator, as illustrated in Fig. 3(b). This consisted of a 3D computer assisted design (CAD) model of the manipulator and tool heads in the plant environment that could move in response to joystick commands from the operator.

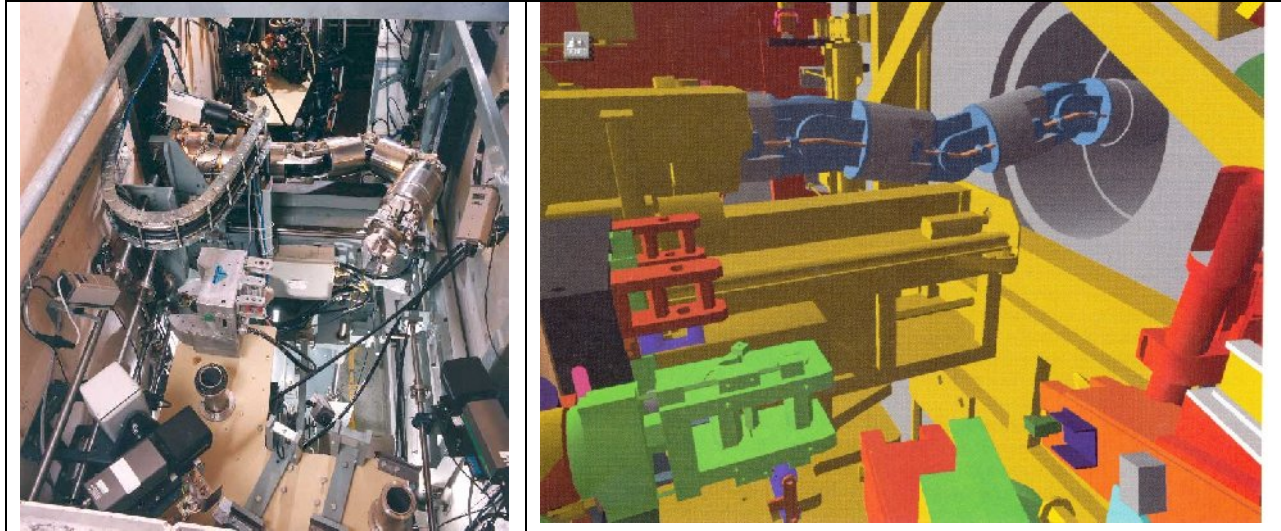


Fig. 3. (a) COTS-7 Axis Manipulator

(b) Raffinate Diversion Simulator

IDENTIFYING EMERGING TECHNOLOGIES

Application of emerging technologies

The main objectives of robotic or tele-operated systems are 1) improved safety, especially for the D&D worker; 2) improved efficiency and productivity of remote systems; and 3) cost-effective development and deployment. To realize this, some emerging technologies must be advanced for nuclear specific applications.

The Raffinate Diversion is an example of a highly successful deployment. However, the project costs in today's prices were of the order of several million dollars and the project life from an initial concept to deployment was several years. Additionally, there were significant project and technical risks. These costs, time scales and risks are typical for such large-scale projects and therefore represent significant and sometimes prohibitive levels of investment and resource commitments for a nuclear plant owner.

By applying new and emerging technologies, these costs, time scales and risks can be reduced to acceptable levels for a nuclear plant owner. Analyzing these projects, the major contributors to costs, time scales and risks can be reduced by implementing emerging technologies.

Optimising the remote intervention level

In the Raffinate Diversion project, there were high levels of remote intervention. Optimizing the level of remote intervention at the start of a project could significantly reduce these costs, time scales and risks. A Remote Intervention Scale could be used to determine the level of intervention. On this scale, at one extreme there is no remote

intervention and all tasks require complete human intervention. At the other extremity, there is complete remote intervention and no human intervention.

For the example project, the Remote Intervention Scale was at the high extremity. Although this was probably correct a formal means of optimizing and quantifying the position on the scale could reduce these costs, time scales and risks.

Standardising equipment

In the Raffinate Diversion project, deployment relied heavily upon bespoke tooling equipment, such as orbital welders and cutting equipment. The main deployment devices were multi-axis bespoke manipulators.

Similar to the Remote Intervention Scale, a Bespoke Equipment Scale could be used to determine the level of bespoke equipment. On this scale, at one extreme there is no bespoke equipment and all equipment requires COTS equipment. At the other extremity, all equipment is bespoke and there is no COTS equipment. In between is a combination of both, including modifying and adapting COTS for the task.

For the Raffinate Diversion project, the Bespoke Equipment Scale was at the high extremity. Although this was probably correct a formal means of optimizing and quantifying the position on the scale could reduce these costs, time scales, and risks. However, such a formal analysis would only provide a reduction if there were a sufficient number of COTS nuclear equipment at approximately TRL 6 or higher.

Both the NNL and the Department of Energy collectively have much experience in developing COTS nuclear equipment and are currently both in partnership in developing CryoGrab. This product uses freezing technology to perform remote retrieval operations, such as pick and place tasks and retrieval of nuclear sludges and embedded debris.

Standardising communications

Inter-communications between the COTS must also be standardized. In the Raffinate Diversion project, much development was required in developing inter-communication between the equipment. As a consequence, assuming that the engineering market had provided a substantial range of COTS nuclear equipment, then a further reduction in costs and time scales could be achieved if standard communication protocols were employed. Subsequently, the simplicity of 'plug and play' operations could be realized. Additionally, this technology must also:

- Permit all connected equipment to access all the data from other connected equipment
- Permit long ranges or cable lengths
- Be wireless compatible with long ranges
- Provide large bandwidth for high volumes of data

- Be secure in order to prevent accidental or malicious access, which could result in unforeseen and undesirable events

Tele-Autonomy

In the Raffinate Diversion project, control of the bespoke manipulators was tele-operational. Whilst tele-operations are acceptable for some applications, for these typical examples, it increased costs, time scales and was risky due to the operator and hardware limitations and navigation difficulties.

As a consequence, nuclear tele-operational tasks can be slow, subject to human error, risky and may be less than optimal from a task perspective. Additionally, operator training is costly, because an operator requires an extensive amount of training, often with an elaborate and expensive off-line simulator. This is exacerbated during the operation, as operators require regular breaks from the mental exhaustion. If continuous operation is required, perhaps to minimize equipment dosage and damage, then a team of operators require training, adding to the costs.

Advances in robotic related fields, such as machine vision, situation awareness, haptics and cognition permits some of the low-level operator commands to be transferred to a more sophisticated control system. The operator would then have a supervisory and high-level command role, which is better suited to humans. Such a sophisticated control system is known as a tele-autonomous system and has been achieved in other non-nuclear sectors.

Progressing from tele-operation to tele-autonomy in the nuclear sector would require much investment and long term commitment. To realize this, requires developing some of the emerging technologies, such as environmental and data acquisition, assessment of the data, situational awareness, object recognition and complex decision making. Additionally, the level of autonomy must be determined by either the operator or the autonomous system or both. Again a tele-autonomy scale could be introduced, which will determine the level of tele-autonomy required for a task.

The availability of tele-autonomy would provide a substantial reduction in the costs, time scales and risks of a nuclear decommissioning project. A full tele-autonomous operation only requires the operator to specify a task to a tele-autonomous system. Subsequently, the system optimally completes the task by avoiding the obstacles and hazards, performing inverse kinematics, conditioning monitoring and responding to any changes in the environment and task.

Tele-autonomy is a disruptive technology in term of transition from tele-robotics and this progression requires a fundamental shift in technological advance for robot control systems and the associated interfacing. Tele-autonomy would enable an operator to perform high level commands and eliminate low level commands, which cause operator fatigue and error.

Dextrous manipulators

Large manipulators and Remotely Operated Vehicles (ROVs) can only be used if the plant access is sufficiently large and there is adequate working space. Nuclear plant consists of highly congested environments and often remote intervention tasks must be completely executed through small wall penetrations. As a consequence, there is a requirement for dextrous manipulators that can be passed through small penetrations, such as kinematically redundant manipulators.

Human machine interfaces

Advances in human machine interfaces (HMI), such as joysticks with feedback, haptics and virtual reality would contribute to improving reliability and task optimization, resulting in project risk reduction. HMIs must also be user-friendly in order to minimize the mental exhaustion and stress.

Environmental data acquisition

Suitable sensors are required that are capable of operating within the hazardous environments. Examples of the type of physical data that are required are as follows:

- Radiation levels, including types
- Identification of radioisotopes, perhaps by analysis of electromagnetic wavelength spectra
- Temperature
- Visual
- Geometric data of the environment, using laser scanning, photogrammetry or other method

From the latter, 3D CAD models of the environment could be produced, which is essential, because plant design drawings do not represent the 'as-built' plant state. An efficient method of converting from raw Point Cloud Data from a laser scan to a CAD has yet to enter the market. By use of the CAD model, the data should be displayed to the operator in a user-friendly format, perhaps by overlaying contoured plots.

Visualization

A computer visualization system is arguably an essential part of a robotic nuclear decommissioning project. It is a 3D virtual model, perhaps derived from CAD geometry and primitives of the radiological environment and the decommissioning equipment, such as the robot manipulator. It is a live model, from the perspective that the model updates in response to the real live events. It is used as a multi-functional tool because:

- It provides the operator with live visual data to facilitate navigation and therefore overcomes some of the navigation problems. This is especially true because the

operator is able to pan, tilt and zoom a virtual camera and it therefore complements the real cameras.

- It can be used off-line as a robot training simulator with the trainee operating a set of input devices, such as joysticks. This reduces operational costs by minimizing damage to hardware, including wear and tear during training.
- It can be used off-line for mission planning and feasibility studies.

The challenge is for the next generation of visualization systems to be more realistic, compared to their predecessors. More realism is highly beneficial because of reduced human errors and mistakes. For example, technologies, such as haptics, feedback of a number of physical phenomena, virtual reality and immersive reality would contribute to realism. Additionally, accuracy and calibration of the model to the real environment is essential for successful navigation and mission planning.

A complementary technology that would need to be advanced would be quicker and cheaper methods of converting Point Cloud Data from a laser scan to 3D CAD geometry and primitives.

CONCLUSIONS

Some nuclear decommissioning tasks and facility environments are so hazardous that they can only be accomplished by exclusive use of robotic and remote intervention. Less hazardous tasks can be accomplished by manual intervention and the use of PPE. However, PPE greatly decreases worker productivity and still exposes the worker to both risk and dose making remote operation preferable to achieve ALARP. Before remote operations can be widely accepted and deployed, there are some economic and technological challenges that must be addressed. These challenges will require long term investment commitments in order for technology to be:

- Specifically developed for nuclear applications
- At a sufficient TRL for practical deployment
- Readily available as a COTS

Tremendous opportunities exist to reduce cost and schedule and improve safety in D&D activities through the use of robotic and/or tele-operated systems.

- Increasing the level of remote intervention reduces the risk and dose to an operator. Better environmental information identifies hazards, which can be assessed, managed and mitigated.
- Tele-autonomous control in a congested unstructured environment is more reliable compared to a human operator. Advances in Human Machine Interfaces contribute to reliability and task optimization. Use of standardized dexterous manipulators and COTS, including standardized communication protocols reduces project time scales.
- The technologies identified, if developed to a sufficient TRL would all contribute to cost reductions. Additionally, optimizing a project's position on a Remote Intervention Scale, a Bespoke Equipment Scale and a Tele-autonomy Scale

would provide cost reductions from the start of a project. Of the technologies identified, tele-autonomy is arguably the most significant, because this would provide a fundamental positive change for robotic control in the nuclear industry.

The challenge for technology developers is to develop versatile robotic technology that can be economically deployed to a wide range of future D&D projects and industrial sectors. The challenge for facility owners and project managers is to partner with the developers to provide accurate systems requirements and an open and receptive environment for testing and deployment. To facilitate this development and deployment effort, the NNL and DOE have initiated discussions to explore a collaborative R&D program that would accelerate development and support the optimum utilization of resources.

REFERENCES

[1] Robson C.J., “Remote Diversion of a Highly Radioactive Process Line”, *Telerobotic Applications*, edited by Tyler Schilling, 1st edition, 2000, John Wiley & Sons Inc., ISBN 978-1-860582-35-6, pp. 186-194.