The Use of Robotics and Automation in Nuclear Decommissioning

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Abstract—The paper reviews the scope for automation and robotics in the rapidly expanding field of nuclear decommissioning. The basic strategies for decommissioning are discussed together with the essential physical steps. The role that automation and robotics can play in enabling quicker demolition and at the same time reducing the exposure of workers to harmful radiation is discussed. The key issues surrounding radioactive materials and safe dose levels are explained. Examples of a wide range of recently developed automated technologies are provided.
The paper will conclude by describing those areas that are currently the subject research and development.

***Index Terms*—automation, decommissioning, nuclear, robotics.**

I. Introduction

Over the next two decades literally hundreds of nuclear facilities will come to the end of their working lives and require decommissioning. These range from nuclear power stations, submarines, fuel processing plants and mines. In the UK alone it is estimated that the total cost of dealing with the nuclear legacy is nearly $100Bn.

Much of the decommissioning process utilises well established demolition techniques, however the overwhelming complication in the case of the decommissioning of nuclear facilities is the hazard of radiation release. Workers, the general public and the environment must be adequately protected. There is, however, considerable political pressure to complete the task quickly, and, in many cases, the only means of facilitating this is through the use of automation and robotics in order to reduce the dose exposure of workers.

II. Scope of the Task

A. Definition of decommissioning

Wherever significant quantities of radioactive material are stored, used or processed on a site the national regulating authorities will require the site to be licensed, which implies the enforcement of strict regulations to ensure that radioactive material is not released into the environment. Nuclear decommissioning can be defined as "removing a facility safely from service and reducing residual radioactivity to a level that permits either:

- Licence termination and release of the site for unrestricted use

Or

- Release of the site under restricted conditions"

B. Range of facilities

The obvious type of facility that requires decommissioning is the redundant nuclear power station however it should be remembered that these are only one part of a complete fuel cycle as shown in Fig. 1. Each stage of the cycle requires significant plant and facilities. Power reactors are regarded as relatively straightforward to decommission. The real challenge comes from the wide range of non-standard process plant, silos and ponds, some of which have been used as a repository for highly radioactive materials over many years.

In addition to commercial power stations, many research reactors exist, together with extensive military facilities for weapons research and manufacture. Also a large number of nuclear powered submarines are at the end of their working lives.

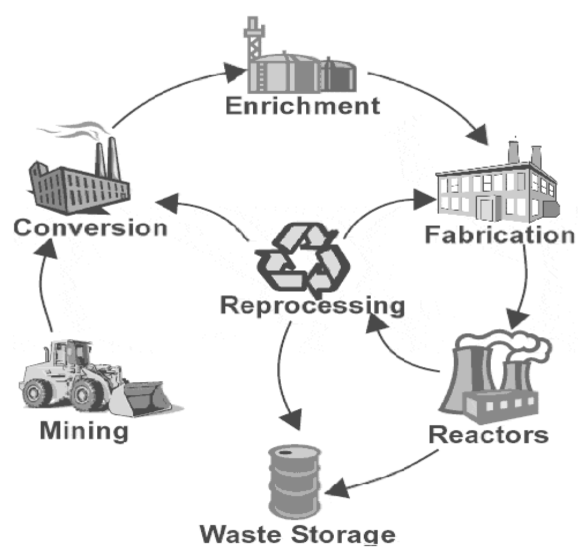

Fig. 1. Nuclear fuel cycle

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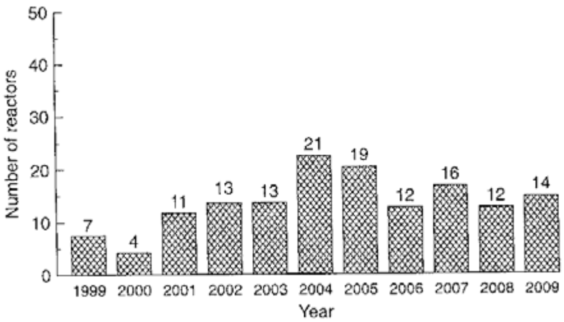

Fig. 2. World reactors reaching 30 years old [1]

Fig. 2, shows the number of reactors reaching a typical working life of 30 years.

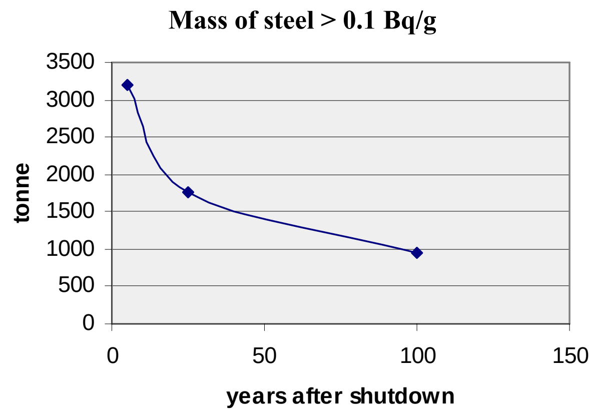

Fig. 3. Weight of radioactive steel in a PWR reactor with time [2]

III. Decommissioning strategies and process

Decommissioning is considered to start **after** fuel rods or other concentrated sources of radiation have been removed from the site. In the case of a nuclear power station this reduces the amount of residual radiation to less than 1% of that during operation.

There are three recognised decommissioning strategies:

- Immediate decontamination and dismantling (D & D) or DECON
- Safe storage or SAFESTOR
- Entombment or ENTOMB

Under DECON everything is decontaminated to a level that permits removal of regulatory control shortly after shutdown of operations. Residual waste is treated, packaged and removed for disposal. No benefit is derived from waiting for additional decay of radioactivity. Advantages are that the site is freed quicker and at least some of the previous workforce can be retrained for decommissioning. Disadvantages are that more waste is produced and workers are exposed to a greater radiation hazard. Automation and robotics have a significant role to play.

SAFESTOR involves placing the facility in a safe condition and waiting until the radioactive materials have decayed to reduced levels. Fig. 3, shows how the quantity of radioactive steel in a pressurised water reactor reduces with time. This leads to easier dismantling and reduced quantities of waste. Particularly if discounted cash flow principles are employed, this approach can often be cheaper than DECON, however additional costs for surveillance and maintenance but be allowed for. Another factor that must be considered is that worker dose and material release levels may become more restrictive with time. Fig. 4 shows how typical worker exposure standards have changed over the years.

ENTOMB involves the encasement of radioactive materials in a robust structure such as concrete until the radiation decays to the level that permits free release. It is essentially turning the facility into a permanent waste-disposal site and is hence generally thought to be politically unacceptable in most countries.

Current U.K. policy is that decommissioning should proceed as quickly as possible taking into account both safety and economic considerations. This tends to point towards a combination of DECON and SAFESTOR. All peripheral buildings and plant are demolished and reactor halls reduced in size and made safe for long-term storage. Because of the lack of an agreed intermediate waste store in the UK, it is common practice to build a new storage facility close to the reactor. The site footprint is then reduced by moving the site security fence to encompass the remaining SAFESTOR facilities.

IV. Radiation and dose

A. *Radiation issues*

One of the first steps in decommissioning a facility is a detailed characterisation survey to determine the nature of the radionuclide content (as well as other hazardous materials such as asbestos and PCB's).

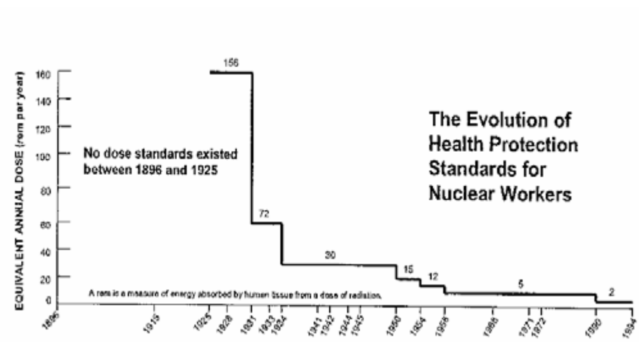

Fig. 4. Reduction in worker dose limits with time [3]
Note: 1 rem = 10 mSv

Radiation is a general term used to describe electromagnetic waves which can include radio waves and visible light, however **ionising radiation** describes waves and particles emitted from unstable radioactive materials. Such radiation contains enough energy to cause physical damage to surrounding matter. The main types of ionising radiation are:

Alpha (α) Radiation: can be stopped by a sheet of paper, a layer of skin or about 5 cm of air. For this reason, most (α) radiation does not reach the body and any that does would not penetrate the skin. However it does the most damage to the body if ingested, say through breathing contaminated dust or via a wound.

Beta (β) Radiation: travels a few metres in air, but can be stopped by a few centimetres of aluminium and clothing can provide some protection. (β) particles will thus only penetrate the top layer of skin.

Gamma (γ) Radiation: high penetration into most materials. Dense materials, such as lead, can be used as a shield against (γ) radiation. For example, the level of radiation may be halved by 25 mm of lead. (γ) radiation can travel several meters through air and many centimetres through human tissue, it is very damaging to body cells throughout the body. (X Rays are very similar)

Neutron Radiation: is similar to Gamma Radiation but stopped by hydrogenous material.

Radiation decays with time according to the inverse square law.

B. *The effect of radiation on the human body*

The effect of radiation on the human body is measured in Sieverts (Sv). The International Commission on Radiological Protection (ICRP) has set public dose limits for exposure to radiation; this is linked to the requirement to keep exposure as low as can be achieved. These limits are usually set at 1 mSv/year above background [4]. In most countries the current maximum permissible dose to radiation workers is 20 mSv a year averaged over 5 years, with a maximum of 50 mSv in any one year [5]. The following table indicates the physical effects on humans of excessive exposure:

TABLE 1
Health Effects of Nuclear Radiation Doses

0.5 Sv	Possible minor blood changes, no obvious effect.
0.5–1 Sv	Radiation sickness vomiting and nausea. No deaths anticipated.
4 –5 Sv	Radiation sickness more severe. 50% deaths in 3 - 8 weeks from infection or anaemia. Survivors convalesce for about 6 months.
≈10 Sv	Vomiting and nausea within 1 - 2 hours. Probably no survivors. Death within 3 - 5 days following damage to lining of small intestine.
≈50 Sv	Tremors, convulsions almost immediately. All deaths in less than 2 days due to brain damage.

V. Treatment and Disposal of Nuclear Waste

Decontamination and Decommissioning (D&D) of all nuclear facilities produces radioactively contaminated materials. Some of these materials continue to have economic value because they are in forms that can be recycled or reused. Others will have little or no economic value and thus constitute waste that has to be disposed of or stored if no acceptable method of disposal exists.

The disposal route for nuclear waste depends upon the degree to which it is irradiated. It is generally divided into the following categories:

TABLE 2
Classification of Radioactive Waste and Disposal Route

Very low-level Waste (VLLW)	Can be disposed of in normal landfill sites
Low-Level Waste (LLW)	Contains 1% of the radioactivity but accounts for over 80% of the volume. Stored in containers at a dedicated site.
Intermediate-Level waste (ILW)	Contains higher amount of radioactivity than LLW and requires shielding. No dedicated facility in the UK at present.
Higher-Level Waste (HLW)	Contains at least 95% of the radioactivity in radiation waste but no more that 3% of the volume. Requires special storage with cooling.

For example: 1 tonne of spent fuel from fuel processing gives rise to $0.1m^3$ HLW, $1m^3$ ILW and 4 m^3 LLW.

The cost of long-term storage increases significantly as the level increases, so it pays to segregate material where possible. Also disposal cost is generally related to volume, so techniques for volume reduction, such as crushing pipe-work may be economic. Many techniques exist for removing contamination from material surfaces so that the remaining bulk can be freely released as landfill. For example bulky concrete containment vessels may have their inner surface scarified to remove say 50 mm of contaminated material, the remainder being demolished and disposed of conventionally.

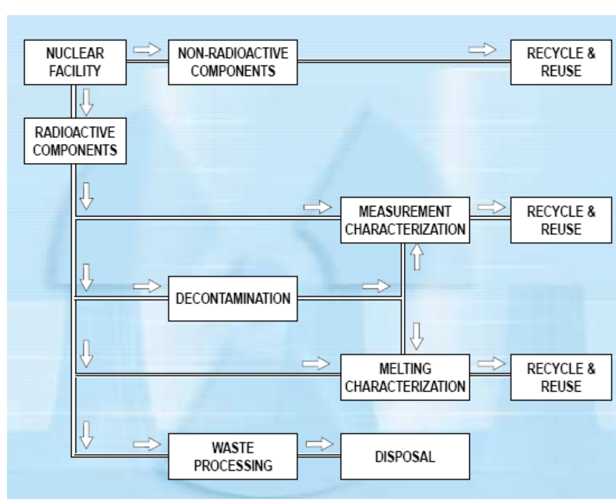

Fig. 5. Methods for Minimizing of Radioactive Waste from D&D of Nuclear Facilities [6]

During the process of decommissioning considerable effort must go into containing the spread of contamination to other parts of the facility by reducing air-born dust and fluids. For this reason many operations take place inside specially constructed cocoons. Fig. 5 shows methods for minimising radioactive waste from D&D of nuclear facilities.

VI. EXISTING USE OF ROBOTICS

A. *The role of automation and robotics*

The primary use of robotics in decommissioning applications is to reduce the radioactive dose levels to which workers are exposed. The more emphasis that is placed on immediate DECON, as opposed to SAFESTOR, the more likely it is that robotics will be required. There are many situations where, owing to the degree of radiation and the very long half-lives of the radioactive materials involved, robotics is the **only** feasible option.

The Nuclear Regulatory Commission's regulation 10 CFR 20 states that an occupational worker cannot receive more than 50 mSv per year for the full body dose [7], once this dose has been reached the worker has to stop working immediately. This necessitates an increased number of workers to be employed in order to accomplish the necessary task. By using robots the number of workers is minimised, this in turn creates many additional savings including a reduction in the quantity of protective clothing needed, and a decreased administration.

It must be said, however, that many decommissioning contractors have experienced significant problems with complex customised robotic systems and hence remain sceptical about their deployment. Whereas conventional industrial robots now have a mean-time-between-failures (mtbf) of 70 000 hours, a typical customised one-off solution has a mtbf of only 5-6 hours!

B. *Existing use of robots for decommissioning*

Current automated systems employ virtually no autonomy or even programmed motion. Invariably there is a human in the control loop, and this is expected to continue. This means that nearly all systems employ simply remote control, tele-operation or master/slave manipulation. Systems generally fall into one of four categories:

1. Relatively expensive customised solutions to specific problems
2. General purpose plant
3. Systems fabricated from off-the-shelf components
4. Automated process plant for packaging and waste processing.

Examples of the first three categories will be provided.

A customised solution was used for the DECON demonstrator project at **Windscale Advanced Gas Cooled Reactor** (WAGR) [8]. Immediate demolition of the reactor vessel would have resulted in dose exposure of 1 Sv/hr, which means that a worker would have reached their annual dose rate

Fig. 6. Decommissioning robot for WAGR reactor [8]

in 20 minutes. Fig. 6 shows the system used which consist of an extendable mast with a 6 degree of freedom manipulator at the end. Waste material is then transported out of the reactor containment vessel by overhead gantry crane and finally lowered through the floor into concrete storage vessels for disposal. The floor over the reactor was filled with lead shot to protect the workers above. Dose rates have been kept to a total of 17 mSv per worker over the six years of the project. It has produced 22 tones of Low Level Waste and 10 tones of Intermediate Level Waste. The total project has cost £80m so far, with the automated handling system alone costing about £8m.

An example of general purpose plant is the remote control Brokk as shown in Fig. 7. A remote operation pendant allows the operator to be at a safe distance from high radiation areas and hazardous or falling debris. The Brokk is rugged enough for demolition work and small enough to work inside buildings. They are often electrically powered, through an umbilical cable, to make indoor working easier. A wide range of end-effector tools is available for most demolition tasks. Such items of plant have become widely accepted throughout the decommissioning industry.

Fig. 7.Brokk remote controlled plant for demolition [9]

Fig. 8. LMF general purpose vehicle [10]

Another example of general purpose plant is the LMF vehicle. LMF is a remotely operated vehicle for contaminated environments and is used by KHG (Kerntechnische Hilfsdient Gmbh) in Germany for Post-accidental situations and tasks in the nuclear industry, designed by CYBERNETIX [10]

Three examples of off-the-shelf components that can be integrated into remote-controlled systems are shown in Fig. 9.

RODDIN is a crane deployed work platform used for pipe and metal cutting in decommissioning and was provided to FLUOR DANILE HANFORD, in Washington State, USA for deactivation activities, designed by CYBERNETIX [10].

Dual Arm Work Module (DAWN) was based on two Schilling Titan II hydraulic manipulators with 5 DOF base and are set up in master/slave configuration to perform standalone remote manipulation tasks in radioactive environments such as the mechanical dismantlement of reactors and bio-shield structures, pipe cutting and tank removal [11]. DAWN was used for dismantlement of the CP-5 reactor, located at Argonne National Laboratory (ANL) in Chicago, USA. A wide range of Schilling manipulators are well known in the offshore industry for sub-sea work.

ARTISAN, is a radiation tolerant tele-operator robot and has a heavy duty manipulator system designed by

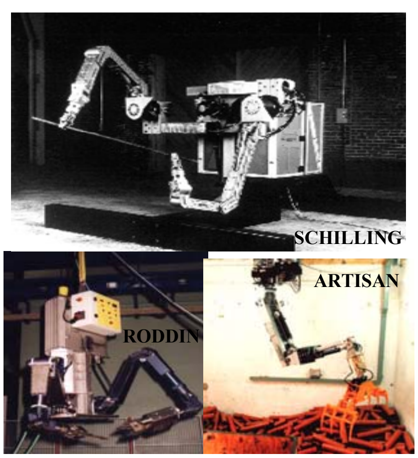

Fig. 9. Recently developed automated technology for decommissioning tasks

RWE NUKEM Limited in Germany and are specifically designed for nuclear decommissioning, waste handling and processing tasks such as waste retrieval and volume reduction and is shown here being used for retrieval of solid wastes from a storage container [12].

VII. Future Scope for Robotic Development

Robotics has become a key technology in the decommissioning of nuclear power plants for the reasons stated above. Further reductions in allowable radiation dose exposure will accelerate this trend towards the increased use of robots [13].

A key issue for future developments is the degree to which autonomous functions will be acceptable to the industry. Fig. 10 shows the relationship between environmental variability and the level of human responsibility for three different types of robotic systems: autonomous robots, supervised robots and tele-operated robots [14]. When variability is low, autonomous robots are efficient and human involvement is at the level of strategic decision making.

When variability is high, human sensing and decision making are more important and the human operator has more responsibility.

Work in hazardous environments in the nuclear industry is particularly dependant on two aspects of the work environment - **variability** and **accessibility**. Currently autonomous robots are unable to function efficiently in many dynamic or variable environments, which require either completely human control or tele-operator solutions.

As stated earlier, robotic solutions are often found in environments with low human accessibility owing to physical constraints or danger. Where accessibility is low but variability is high, tele-operators are usually applied. However, until significant progress is made with autonomous systems, close human supervision of robotic systems will continue where environmental variability is high.

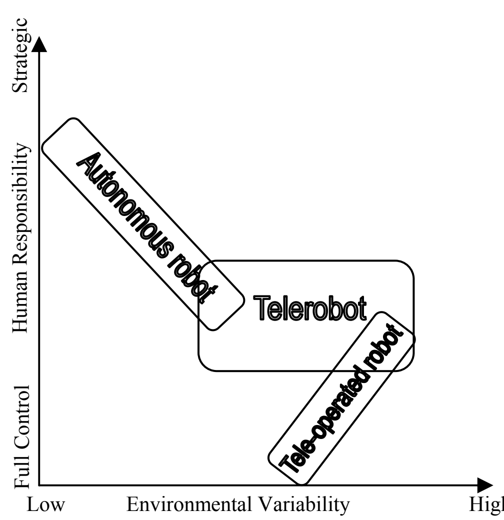

Fig. 10. Relationship between environmental variability and Human input responsibility [14]

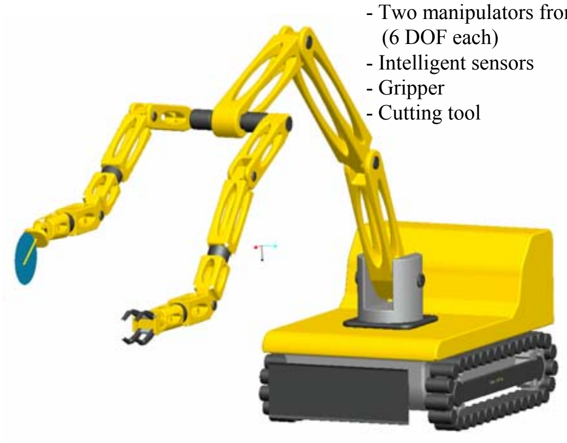

Fig. 11. Dual Arm Robot

Current research work in robotics at Lancaster is concerned with advancing semi-autonomous tele-operated robots for D&D tasks. In this project, the aim is to combine artificial intelligence, computer vision, improved sensors, on-board intelligence and multi-manipulator robotics for complex disassembly tasks**.** An example of this type of research is the development of improved hardware and software systems such as Robotic Platform (an open software control platform) which combines hardware interfacing, servo control, trajectory generation, task level programs, 3D simulation, a graphical user interface, and a math library. The robotic Platform implements all these components in a homogenous architecture that utilizes a single hardware platform (a standard PC), a single programming language (such as C++) and a single operating system (possibly the QNX Real-Time Platform) [15]. This design will lead to an open architecture that is less complex, easier to use and easier to extend. Two-arm robot is being developed for specific decommissioning tasks such as cutting pipes as shown in Fig. 11. The primary aim of the research is to develop intelligence in the robot that is similar to the cooperation and communication between the human brain and its two arms, hence the human body is adopted as the starting point to establish the size and functionality of the proposed system.

VIII. CONCLUSION

Nuclear decommissioning provides a particularly fruitful sector for the advancement of automation and robotics. Earlier generations of nuclear facility have now been closed and many are waiting effective decommissioning. There is a multi-billion dollar world-wide market for companies who have the skills and technology to engage with the task. In addition to traditional hazards such as asbestos and PCBs, the key hazard is obviously the presence of significant quantities of radioactive waste material. It is the effective management of this waste which is the crux of nuclear decommissioning.

Many projects have been successfully completed and valuable lessons learned. A current trend is for the nuclear industry to demonstrate that it can clean-up quicker (DECON), which means dismantling before significant radioactive decay. This is a great driver for the further use of automation and robotics in order to reduce the radiation dose to which workers are subjected.

However, many contractors have suffered negative experiences with advanced robotics because of expensive development and reliability problems. In many cases they have failed to deliver the promised benefits. It is a challenge to the robotics community to demonstrate that advances in robotic technology can enable safe and economic nuclear decommissioning.

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