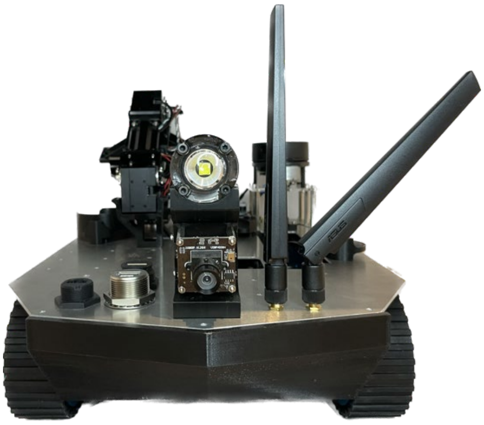

POTENTIAL USE OF ROBOTIC SYSTEMS IN THE UNITED KINGDOM'S GEOLOGICAL DISPOSAL FACILITY

September 2023

ABSTRACT

Designing the UK's proposed geological disposal facility (GDF) such that it is fully automated, requiring minimal human entry, is an attractive proposition for improving operational reliability, efficiency and reducing the risk related to the hazardous materials it will contain. This report discusses some of the opportunities, and the challenges, that robotics and autonomous systems may present in the operation of the GDF.

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Potential Use of Robotic Systems in the Geological Disposal Facility

Summary

Designing the UK's proposed geological disposal facility (GDF) such that it is fully automated, requiring minimal human entry, is an attractive approach to improving operational reliability, efficiency and reducing the risk related to the hazardous materials it will contain. This report discusses some of the opportunities, and the challenges, that robotics and autonomous systems (RAS) may present in the operation of the GDF.

Evidence across a range of industries indicates that with careful consideration of the operational requirements of the GDF and the capabilities and limitations of modern automation systems, it is credible that the GDF could be designed to operate in a highly automated manner. It is, however, recognised that this may require the deployment of a range of first-of-a-kind technologies, which could introduce significant cost implications. An additional challenge to a highly automated GDF would be if any high-level, automated decision making were required to accommodate, for example, unexpected variations in the size and shape of waste packages or the locations where these packages are to be moved to or from.

Although there are a growing number of automated storage facilities able to cater for significant uncertainties in operations, such as the customer fulfilment and storage centres operated by the likes of Ocado and Amazon, where goods of many different shapes and sizes are successfully handled using automated technology, these centres tend to be low-risk environments, with failures or accidents having limited consequences. Consequently, these centres are not subject to the same regulatory constraints and safety requirements that will govern the operation of the GDF, allowing technology, with rates of failure that would be considered unacceptable in a GDF, to be deployed.

It is not essential for any automated systems used within the GDF to utilise RAS, however, if human entry is to be minimised, then it may be necessary for such systems to be used for a range of tasks within the GDF. This report provides a brief overview of the state of the art in RAS technology, relevant to the GDF, and describes how RAS could potentially be used within the GDF and what its limitations might be.

The primary use cases for robots within the GDF are expected to be the following:

- Inspection and Surveillance: Robotic vehicles, which could include aerial, or flying platforms and ground-based robots, could be used to perform routine surveillance of surface and underground facilities, providing condition monitoring of waste packages and emplacement equipment. Robots could also be used for inspection tasks, such as measuring the integrity of equipment and facilities.
- Maintenance and Repair: If equipment is unable to leave a hazardous environment, then robots could be used to inspect, maintain and repair electrical and mechanical components within the GDF.

There are expected to be considerable benefits if any robots used in the GDF were able to function autonomously and the implications of this type of operation, and its challenges, are discussed in this report.

Whilst the operation of the GDF will share many similarities with other large-scale industrial facilities, the GDF has many unique features and requirements that will need to be considered if RAS is to be successfully deployed within it. For example, the GDF will need to remain operational for many decades with radiation dose rates high enough, in some parts of the facility, to restrict or even prohibit human access. This will have a considerable impact on how any equipment within the GDF, including any robots, can be inspected, and maintained. Furthermore, if the levels of radiation in

some areas of the GDF are sufficiently high, then electronic systems that are deployed into it, may be damaged. It is feasible that the likelihood of electronic systems being damaged by radiation can be determined in the pre-concept design stage, where learning can be taken from current, above-ground storage facilities.

The report highlights a range of important issues that should be considered if RAS is to be utilised within the GDF. These issues can be summarised as follows:

1. **Maintenance:** The GDF will need to be designed such that any mechanical or electronic equipment located within it, can be maintained and / or repaired. Remote handling, using RAS, could enable such tasks to be performed in-situ. However, remote handling of objects where uncertainties exist remains a challenge for RAS technologies. For example, if an object is to be grasped and its size and shape are not fully known, or if an unexpected event occurred whilst it was being grasped, then it may not be possible to rely, with certainty, on an automated grasping / handling system. Consideration of this during the design of the GDF can reduce, but not eliminate the problem.
2. **Inspection:** Mobile RAS offer an attractive solution for the deployment of a range of sensing technologies for routine inspection and surveillance of a GDF. However, the risk of using a mobile system, in terms of the potential for the equipment to become damaged, is likely to be higher than for a fixed inspection system, such as cameras or other fixed sensors. RAS based mobile inspection systems should therefore only be considered when fixed systems are unsuitable.
3. **Retrieval of failed robots:** Operational strategies can be developed to ensure that equipment failures and their impact are minimised. However, there will always remain the possibility that a robot will fail. To accommodate such failures, it is essential that, where necessary, processes and equipment are developed to enable failed robots to be repaired or retrieved. Without this ability, operations within the GDF could be limited with the risk that mobile robotic equipment could block essential access routes.
4. **Radiation damage:** The radiation dose rate in particular areas of the GDF may be sufficiently high that materials and electronic systems are damaged over the prolonged lengths of time the facility is operational. This could limit the types of RAS that can be deployed, or it may introduce a requirement for shielding or radiation tolerant electronics to be used. The latter would increase costs significantly, whilst the former may not always be feasible. Analysis of operational experience in current, above-ground storage facilities, during the pre-concept design should allow the risks associated with radiation damage to electronic systems to be assessed.
5. **Futureproofing:** The GDF will be operated over many decades and it will be important that it is designed in such a way that both hardware and software systems can be updated throughout its lifetime, without the introduction of significant operational difficulties and costs.
6. **Regulatory approval:** It will be necessary to work closely with regulators to ensure that any RAS can be approved for use in the GDF. It is anticipated that systems relying on non-transparent decision making, such as those made using machine learning techniques, would introduce significant, and potentially insurmountable challenges related to verification and substantiation. This is a recognised problem that the nuclear industry, as a whole, is facing and engagement, at the appropriate time, with, for example, the NDA, UKAEA and relevant regulators, would allow informed decisions to be made as to whether it is feasible for such systems to be of benefit in the GDF.

Robotics and AI are rapidly evolving technologies, and it is recommended that those involved in the development of the GDF maintain a watching brief on developments in both academia and industry in this field. There are several working groups and expert panels that have been set up within the nuclear industry to progress these topics. These include the Regulation of AI in Nuclear Expert Panel, established by the Office for Nuclear Regulation (ONR), and Sellafield Ltd’s Central Robotics and AI Centre of Expertise Forum. Furthermore, the Robotics and AI Collaboration (RAICo) has been created, in Cumbria, as a collaborative programme and facility involving Sellafield Ltd, the UK Atomic Energy Authority, the Nuclear Decommissioning Authority and the University of Manchester, with the aim of supporting the development and deployment of RAS technology in the nuclear decommissioning and waste management sector. It is recommended that these groups have representation from the GDF community or that a route is established to translate relevant information to Nuclear Waste Services.

Recommendations

Whilst continuing the analysis of how the GDF should be designed and operated, the following recommendations, related to the deployment of RAS within it, are made.

1. Maintain an awareness of the technologies that have been developed, and are being developed, for applications such as nuclear inspection, warehouse logistics and automated manufacturing and processing and identify technologies that may be of relevance to the GDF. When appropriate, demonstrations and feasibility studies of technologies, such as automated package tracking systems, should be explored, with a specific focus on determining the potential for them to deliver benefits to the operation of the GDF.

2. It is recognised that expected radiation dose rates within the GDF will be determined and areas where human access will be prohibited will be identified. As the design of the GDF moves beyond concept stage, the requirements for any remote inspection, surveillance, maintenance, and repair systems within the GDF should be identified, addressed and appraised, to enable any gaps in existing technology to be identified and addressed. The design of the GDF should consider access for robotic systems and practicalities related to their use and retrieval.

3. Consider whether current, above-ground facilities, such as the waste storage facilities on the Sellafield site, might be appropriate for prototyping and testing of new technologies for potential deployment into the GDF and for assessing the impact of radiation on electronic systems.

4. With knowledge of the radiation dose rates within the GDF, the locations of any remote operating equipment and operational experience from current, above-ground storage facilities, the impact of radiation damage on the operational lifetime of any electronic equipment deployed in the GDF should be determined, allowing its potential impact on subsystems within the GDF to be identified.

5. The ONR and if necessary, other regulators, should be engaged with, at the appropriate stage in the design process, to specifically discuss the potential use of robotics and AI in the GDF. It is suggested that Nuclear Waste Services be represented on the ONR’s Regulation of AI in Nuclear Expert Panel.

6. Nuclear Waste Services should determine whether the standardisation of robotic equipment is of significance in the GDF and, if necessary, and at the appropriate time, engage with Sellafield Ltd on their Standardised Robotics initiative and potentially the UK Atomic Energy Authority, who are also working in this area.

7. Robotics and AI is a rapidly developing area and a watching brief should be maintained on developments in this field and their potential impact on the future design and operation of the facility. Furthermore, developments in the field of radiation tolerance of electronic systems should be monitored, particularly in application areas such as space and at facilities including CERN and fusion reactors.

1. Introduction

The IAEA state that the protection of people and the environment against radiation hazards is the overriding concern at each decision point in the design and operation of a GDF (IAEA, 2011). Therefore, with the advances that have been made in the field of RAS in recent years, it is feasible that such systems could feature extensively during the operational phase of the UK's proposed GDF. They could also feature in the construction of the GDF, but that is not considered in this report. Whilst the operation of the GDF will share many similarities with other large-scale industrial facilities, which are becoming increasingly automated, and in many cases, reliant on robotic technologies, the GDF has many unique features and requirements that will need to be considered if RAS is to be successfully deployed within it. For example, the GDF will need to remain operational for many decades with radiation dose rates high enough, in some parts of the facility, to restrict or even prohibit human access. Furthermore, the levels of radiation may be sufficiently high to damage any electronic systems that are deployed into it, over long periods of time. To address this, equipment may need to be maintained remotely, electronic systems may need to be shielded from radiation sources and hardware and software systems may require future proofing to enable them to be used and maintained over the long periods of operation of the GDF.

This report begins by describing some of the assumptions that have been made in this work regarding the design and operation of the GDF and lists some definitions related to robotics and artificial intelligence (AI) that are relevant to this work. Following this, section 3 discusses the state-of-the-art in robotics, focusing on technologies that may be of use in a future GDF. Following this, section 4 describes other issues which may need to be considered if robots are to be used within a GDF. Section 5 discusses how robotics and AI may evolve in the future and finally, section 6 provides some conclusions from this work.

2. Assumptions and Definitions

Definitions

To provide clarity on the robotic systems described in this report, robots can be operated in several ways:

- Tele-operated: The robot is directly controlled by a human through some form of input device, or human-robot interface (HRI), such as a joystick.
- Full autonomy: The robot uses sensory measurements and some form of artificial intelligence (AI) to gain situational awareness, and then makes operational decisions without human input.
- Partial, or semi-autonomy: The robot would typically provide some low-level autonomy, but a human would be responsible for any complex or important decisions that are taken. For example, a robot may have low-level autonomy that allows it to automatically grasp an object, but a human operator would decide which object to grasp and where the object should be moved.

Industrial processes are often described as being partially or fully automated. Whilst automation of such processes may be achieved using robots, autonomous decision making may or may not be required. For example, automated car parks typically operate by a vehicle, matching a pre-defined size, arriving at a prescribed location. On exiting the vehicle, the driver operates an interface to confirm that the car is empty, together with any other relevant information, and a series of lifts and conveyors move the car into a vacant space for storage. Such a system might make use of robotic, or electro-mechanical devices, but no autonomous decision making is required.

Commercial pressures have meant that processes and operations have become increasingly automated. However, until recently such operations were typically restricted to environments that are referred to as being ‘highly structured’. This means that the environments are well understood, the location of all objects in the environment is known and there are few, if any, uncertainties. Unstructured environments, which contain uncertainties, represent a much greater challenge for RAS and automation, and it is only in recent years that robots have begun to impact these environments. Warehouses, such as large-scale customer fulfilment centres, operated by businesses including Amazon and Ocado, are good examples of unstructured environments. Following significant investment, many of these facilities have begun to be automated, with RAS being used to handle and transport packages of uncertain dimensions in environments that contain dynamic obstacles (e.g. people). This is discussed further in section 3.1.

Assumptions Regarding the Design and Operation of a GDF

The GDF has not yet been designed and so when considering how RAS may be used within it and what issues should be considered in its operation, various assumptions have been made when completing the analysis summarised in this report. These include the following:

- No decision has yet been made as to whether RAS will be used in the GDF or where within it human access will be permitted once it has become operational.
- The GDF will be constructed in several phases, with some sections of it operational, before building has begun on other sections.
- Over the operational phase of the GDF, it is expected that it will be subjected to relatively small land movements. This may result in slight changes to the internal layout of the GDF. These changes may not be relevant to humans accessing the facility, but could be relevant to RAS.
- All waste packages that arrive at the facility for subsequent storage will be of a size and weight that are known a-priori.
- The GDF will operate in a highly automated manner, consistent with that envisioned by Nuclear Waste Services in their video, produced in 2017: (https://www.youtube.com/watch?v=QCRT7DlP2PU)

The GDF video produced by Nuclear Waste Services shows a series of fully automated operations that take delivery of a waste package and transport it around the GDF using various cranes and vehicles. Figure 1 and Figure 2 show specific scenes from this video. Figure 1 illustrates a waste package, located in the centre of the image, being moved into place by a crane and Figure 2 shows the same package being moved into a vault. It is anticipated that transportation of waste packages would not require any autonomous decision making as there are few, if any, uncertainties in such tasks. For example, the waste packages will be of a pre-determined size, they will arrive at and be delivered to pre-specified locations and there will be no unexpected objects that the package will need to be manoeuvred around. Hence a series of automated operations can be followed to successfully handle all waste packages.

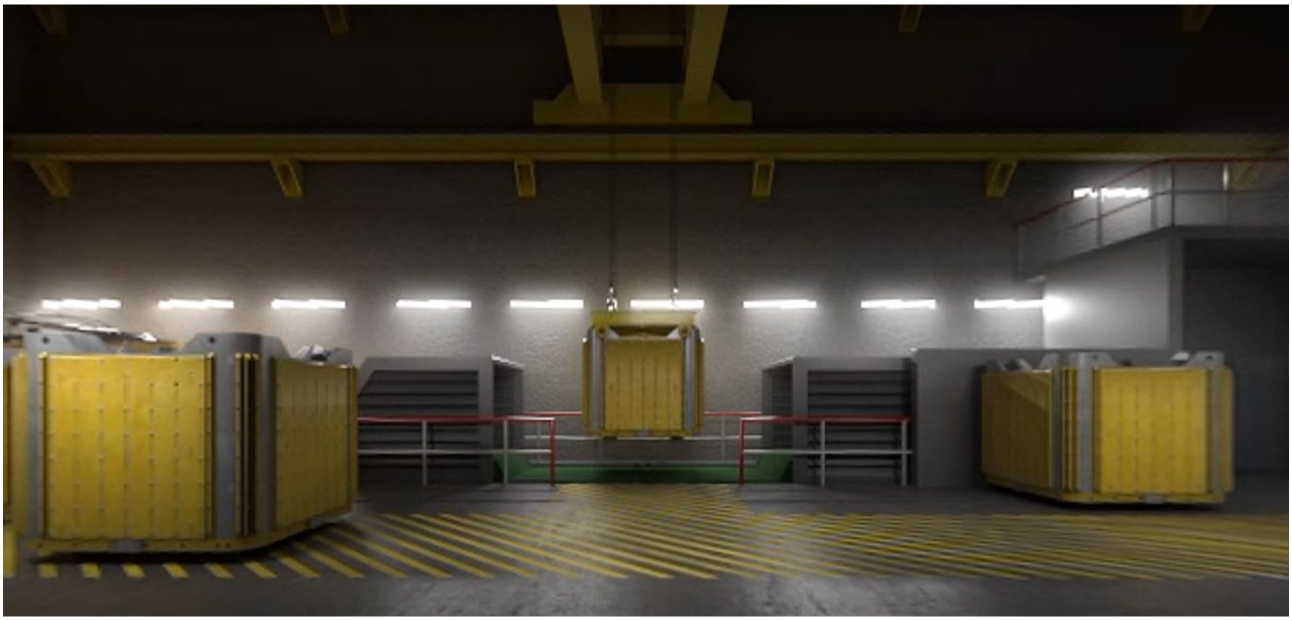

Figure 1: Schematic of a Fully Automated GDF as Envisaged by Nuclear Waste Services (© Nuclear Waste Services)

The feasibility of performing operations, like those expected in the GDF, using automated technologies, has been demonstrated across numerous industries. For example, the automobile industry has benefited considerably by designing their manufacturing facilities such that they are fully automated. These facilities make extensive use of robotic manipulators to lift objects into place and then perform tooling operations on them, such as drilling, joining, and paint spraying. The robots used in these facilities are typically not required to make any autonomous decisions and operations are often repetitive. However, an important advantage that industries, such as manufacturing, have is that humans can access the facility to perform maintenance and repair operations, and this may not be possible within the GDF. Within the GDF, it may be that some equipment, such as the cranes, can be moved into safe areas for routine inspection and maintenance, however, there may be many repair, maintenance, surveillance, and accident recovery situations when RAS may be of benefit, and potentially essential. The following section describes the state-of-the-art in RAS, with a particular emphasis on the use of RAS in unstructured environments.

Figure 2: Image of a vault inside a GDF, as envisioned by Nuclear Waste Services (© Nuclear Waste Services)

State-of-the-Art in Robotics

Warehouse Logistics

The last two decades have seen significant advances in the capabilities and reliability of robotic systems, as well as the acceptance of this technology as a deployable tool to support industrial operations. This has resulted in more businesses being established to sell robotic solutions and the technology becoming more prevalent across a range of sectors, including automotive, social care and warehouse logistics. Robotic systems have led to many industries becoming more automated, with manufacturing and warehouse logistics gaining most benefit from the technology. A recent report by BEIS highlighted that, based on current projections, the total economic impact of RAS in UK warehouse logistics is estimated to be £4.4 billion by 2035 (BEIS, 2021). However, in other sectors, such as energy and infrastructure, the projected impact of RAS is expected to be only £0.6 billion. The same report highlighted that in energy and infrastructure, up to 39% of tasks could technically be automated by 2035, with a potential value to the sector of £23.4 billion. Risk aversion and the high consequences of failure in this sector was partially blamed for the lack of uptake and the authors of the report suggest that policy engagement may be necessary to promote the use of RAS in this sector. Given the particularly high consequences of failure of RAS technology within a GDF, it may be appropriate for the nuclear industry to be conservative with implementation of first-of-a-kind technology. However, the sector may wish to monitor developments and successful technology implementations in other industries and consider the deployment of tried and tested systems.

The take-up of RAS in the warehouse sector over the last decade or so has led to a transformation of the industry. Warehouse storage facilities were traditionally operated manually, with retrieval and distribution of packages relying almost exclusively on human workers, with the support of machinery, such as fork-lift trucks, when necessary. The shift to automating stores came as organisations tried to reduce costs and accelerate the fulfilment of customer orders. A major tool that enabled this was the Kiva robot, shown in Figure 3 and Figure 4.

Figure 3: Kiva Robot (© Amazon Robotics)

Figure 4: Multiple Kiva Robots Moving Mobile Storage Shelves Around a Warehouse Environment (© IEEE)

Kiva was designed to move shelving units containing packages of various sizes, around a warehouse, autonomously. To do this, Kiva identifies a path that it needs to follow to reach its desired location. Kiva then moves along this path and as it does, it uses various sensors to avoid colliding with obstacles, which will include the many other Kivas located within the facility. Amazon first used Kiva robots in 2012 and recognising how it might transform their business bought Kiva Robots in 2014 and set-up Amazon Robotics. Amazon now use more than 500,000 robotic units in their fulfilment centres worldwide. This has led to significant cost savings and reductions in the time taken to fulfil orders. An advantage that the warehouse industry has when deploying RAS tools, such as Kiva Robots, is that the consequences of failure or abnormal operation are relatively low.

Building on their success with the use of the Kiva robot, Amazon has developed robots that assist a range of operations that were traditionally performed manually. These operations include those that are most onerous to manual workers, such as lifting and transporting packages. These robots have exploited the many advances that have been made in robotic systems, such as automated grasping, increased battery power and improved sensors.

Whilst not robotics, a particularly useful technology that Amazon have developed, which is relevant to the GDF, is the Amazon Robotics Identification System. This system uses cameras and AI to automatically scan and track packages as they are moved around the warehouse. This technology may be of relevance in the tracking and logging of package locations within the vaults of the GDF. With fixed cameras located within the vault and elsewhere in the GDF, the system would be able to track and log waste packages as they are moved around the GDF and into position within the vault. A system such as this would be able to provide a geometric map of the vault, showing the location of all packages within it and the size of any gaps between them. Rapid advances are being made with vision-based systems like this, and within a GDF environment, the location of packages could be determined to within several centimetres using existing technologies. The accuracy is primarily dependent on the image resolution provided by the cameras and the image processing techniques that are employed. As these technologies improve so too does the location accuracy.

Ocado have also had considerable success with the development of automated fulfilment centres for its grocery deliveries. Figure 5 shows an image from an Ocado fulfilment centre. Following significant investment, Ocado's distribution warehouses, used as part of their domestic delivery service, are heavily automated with little requirement for human interaction. Human interaction is typically limited to the packing of items that are soft and could be damaged by robotic handling systems or have unusual shapes and are difficult for a robotic system to grasp.

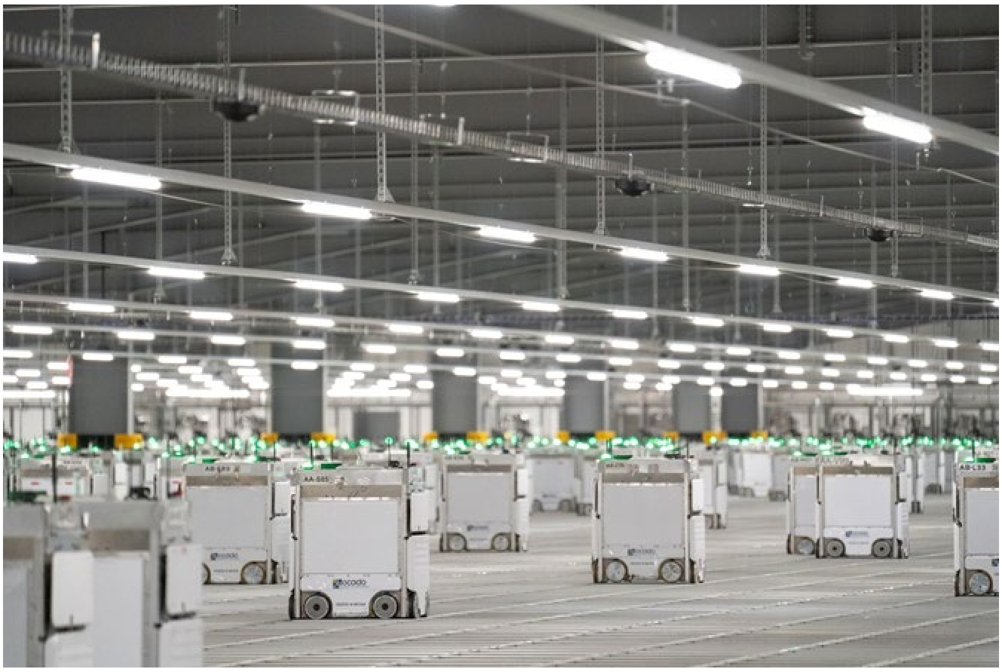

Figure 5: Robotic vehicles in use at one of Ocado's automated warehouses (© Ocado)

Recommendation 1: Maintain an awareness of the technologies that have been developed, and are being developed, for applications such as nuclear inspection, warehouse logistics and automated manufacturing and processing and identify technologies that may be of relevance to the GDF. When appropriate, demonstrations and feasibility studies of technologies, such as automated package tracking systems, should be explored, with a specific focus on determining the potential for them to deliver benefits to the operation of the GDF.

RAS for Inspection and Surveillance

If human access is to be minimised within the GDF then robotic systems may be required to perform inspection, surveillance and maintenance tasks. The nuclear industry has a long history of utilising robots and early examples include the deployment of the Pioneer remote operated vehicle (ROV), developed by RedZone Robotics, to inspect the structural integrity of the sarcophagus that was built around unit 4 of the Chernobyl Nuclear Power Plant in 1997. More recently, robots have been deployed to characterise nuclear facilities in the UK. For example, robots have been deployed to characterise the Magnox reprocessing facility on the Sellafield site (Cheah et al, 2022) and an underground ventilation duct at Dounreay (Nancekievill et al, 2023). Characterisation robots have also been used extensively at the Fukushima Daiichi Nuclear Power Plant. For example, the PMORPH and Scorpion robots were deployed through 100 mm access ports into the primary containment vessels of Units 1 and 2 respectively, where they were able to measure radiation dose rate and collect video footage (TEPCO, 2017). The use of robots at Fukushima Daiichi, and elsewhere, has not been without its problems, with several robots at the Fukushima Daiichi site failing, and in some case blocking important access routes. Many more examples of robotic systems being deployed in the nuclear industry are described in Tsitsimpelis et al (2019) and a report on the potential use of robot in nuclear decommissioning and waste management has been produced by the Nuclear Energy Agency (2023).

The majority of mobile robots that have been deployed into active nuclear facilities have used tracks or wheels and have been tele-operated. In contrast, the CARMA robot, developed to scan for alpha contamination on large floor spaces, and deployed at the Sellafield site (Bird et al, 2019) is fully-autonomous and its use demonstrates that fully autonomous, routine inspection of facilities, such as the GDF, is feasible. The illustrative geometry of the GDF's vaults suggest that aerial, or flying vehicles might be an attractive tool for routine inspection and surveillance. Aerial vehicles are being deployed with greater frequency in the nuclear industry for inspection and surveillance operations. The majority of these deployments have been in outdoor environments, with the risk of crashing into walls and other objects, limiting their use in indoor and particularly congested environments. The RISER aerial vehicle, which has been deployed at Sellafield and Fukushima-Daiichi (Owen et al, 2018) has however demonstrated that it is feasible to deploy fully autonomous aerial vehicles to inspect and survey indoor nuclear facilities and routine deployments of aerial robots at sites such as Sellafield are now taking place. As aerial robotic technology continues to improve, it might be expected that by the time the GDF is operational, aerial vehicles would be able to provide reliable surveillance and routine inspection of vaults and other areas within the GDF.

Wheeled and tracked robots are often restricted on the terrain that they can be deployed into and for rough and uneven terrain, legged robots can provide attractive alternatives. Figure 6 and Figure 7 show two examples of legged robots, both developed by Boston Dynamics. These robots, Atlas and Spot, have exploited the many advances made in areas such as power management, motors, sensors, computing, and AI, together with the significant investment made by Boston Dynamics into this technology. Spot was released as a commercial product in 2019 and is considered one of the most advanced commercially available robots in the world. During 2022, Spot has been deployed in nuclear facilities including Sellafield and Culham, in the UK, as well as internationally at Chernobyl and Fukushima-Daiichi. In these deployments it has been used as a sensor platform, transporting radiation detectors and cameras into difficult to access areas and there are future deployments plans to use Spot to retrieve relatively small amounts of waste at Sellafield. Spot has also been tested by Andra (French National Radioactive Waste Management Agency) as a potential tool for performing inspections of the Industrial Centre for Geological Disposal (Cigéo) during its construction and operation. Whilst Spot is sold as a tele-operated robot, it has low-level autonomy to maintain balance and ensure that it does not walk up or down very steep steps or over large amounts of rubble that might cause it to fall. Spot is also equipped with a manipulator, which allows it to perform operations, such as lifting objects, opening doors or locating sensors in confined spaces that the body of the robot may not be able to access.

Figure 6: Atlas (© Boston Dynamics)

Figure 7: Spot (© Boston Dynamics)

Atlas is a highly capable robot, with the ability to perform complex manoeuvres including jogging, jumping and even backflips. However, it remains several years away from being able to be deployed reliably in industrial environments to perform maintenance tasks. Humanoid robots that can be operated reliably are challenging to design as they remain limited by the power to weight ratios of the motors, the size of battery that can be accommodated and the difficulties that large batteries and motors introduce when balancing the robot. The main argument for their development tends to be that they can be used in spaces that are designed for humans. This argument is important when considering the decommissioning of legacy nuclear environments, which were designed for human access, however, the GDF can be designed so that wheeled, tracked or multilegged vehicles can access all necessary areas and hence the requirement for bipedal robots may be limited.

Despite all the improvements that have been made to robotic systems, within the GDF it is recommended that fixed sensors, such as cameras, temperature sensors and radiation detectors, be deployed as permanent fixtures whenever possible. The reason for this is that when using a robot to deploy sensors, there will always be the risk that the robot will fail, which might introduce additional problems.

RAS for Maintenance and Repair

The use of RAS to provide maintenance and repair capabilities is a greater challenge than inspection and surveillance. This is because maintenance introduces uncertainties. For example, bolts that require loosening, may corrode over time and require greater torque than expected, and equipment that needs to be repaired, may be unusually orientated, which introduces additional grasping and manipulation challenges. The difficulties of performing routine maintenance tasks were clearly illustrated in the Defence Advanced Research Projects Agency (DARPA) series of robotics challenges between 2012-2015. The aim of the final DARPA challenge was to design robots able to complete complex tasks in dangerous, degraded, human-engineered environments. During the competition robots were required to perform a series of tasks that included: driving a vehicle; opening a door; entering a building; and locating and closing a valve. All tasks were simpler than what might be expected in a real industrial environment and whilst some of the robots did successfully complete all the tasks, the performance of the robots highlighted that robotics remains challenging and that none of the robots could be deployed, with confidence, in a real, high consequence environment.

The UKAEA has had considerable success in remote maintenance and repair of the Joint European Torus (JET) fusion reactor over the last few decades. As human access is highly restricted in the reactor, UKAEA designed a boom system, shown in Figure 8, that allows Mascot, shown in Figure 9, to be deployed into the reactor. Mascot has two arms that can be used to perform multiple tasks within the reactor. Mascot makes use of a tooling station, which is deployed on a second boom, also shown in Figure 8. Mascot has been extremely successful over its lifetime, performing multiple operations, including changing all the internal tiles of the reactor. Mascot itself is tele-operated and it does require significant training to become a competent operator. Whilst the use of booms may not be possible within the GDF's vault, it is feasible that a robot similar in operation to Mascot could be deployed from above or below, although it is recognised that this would introduce significant design challenges.

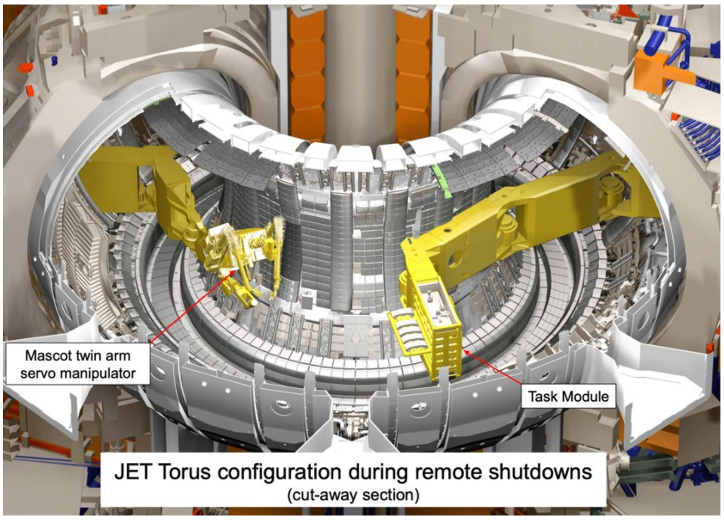

Figure 8: Booms in operation within the JET fusion reactor © UKAEA

Figure 9: Mascot © UKAEA

Veolia Nuclear Solutions have developed a similar robotic arm, shown in Figure 10. This robot has been designed to be deployed through a small access port into the Fukushima-Daiichi reactors to analyse and retrieve fuel debris. A related style of robot that has received attention in the nuclear industry is the snake, or continuum robot. Figure 11 shows Laser Snake 2, which was deployed at Sellafield and Winfrith to size reduce objects located in a radioactive cell. The 'snake' is articulated using numerous wire tendons connected across the length of the robot. These tendons are tensioned and relaxed to apply a torque at various points along the length of the snake, changing the shape of the robot and providing it with considerable dexterity. Tools such as lasers and plasma torches can be deployed through a hollow shaft running through the centre of the robot, along with radiation detectors, photonic equipment, and cameras. Continuum robots have proven to be of considerable use in the nuclear industry with Laser Snake 2 successfully size reducing an active dissolver cell in the first generation reprocessing plant on the Sellafield site. However, the technology does have its limitations. For example, considerable space is required outside the facility for deployment and extraction, and maximum payloads are relatively small.

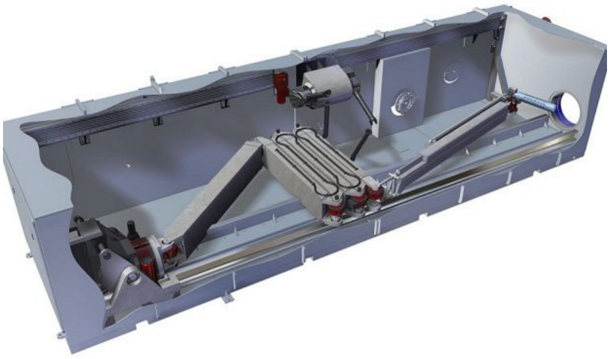

Figure 10: Veolia arm developed for deployment at Fukushima Daiichi (© Veolia)

Figure 11: Laser Snake 2 – size reducing manipulator using a laser cutter (© The Welding Institute, TWI)

For complex maintenance and repair, it is likely that objects, such as tools and equipment, will need to be grasped and manoeuvred. Whilst it is feasible to grasp objects using tele-operated robotic manipulators, this type of operation does require considerable training. Automated grasping is therefore attractive, but it is a complex challenge and despite the investments made, it has not been completely solved, with the likes of Ocado using manual techniques to grasp objects that have complex shapes in their customer fulfilment centres. Gu et al (2021) provide a comprehensive review of techniques that utilise vision to enable robots to automatically grasp objects and Tokatli et al (2021), discusses automated grasping, specifically related to the remote operation of nuclear gloveboxes. It remains a significant challenge.

To simplify the process of automatically grasping objects, the UK Atomic Energy Authority have designed a ‘gripper block’ that is attached to many of the objects that need to be grasped within the JET fusion reactor, which is entirely remotely operated and maintained. The block has holes and grooves in it which enables the object to be grasped securely, by a regular two-finger end-effector. Figure 12 shows the interface block and how it can be attached to regular items, in this case a paint brush, to enable them to be grasped with greater ease and security.

Recommendation 2: It is recognised that expected radiation dose rates within the GDF will be determined and areas where human access will be prohibited will be identified. As the design of the GDF moves beyond concept stage, the requirements for any remote inspection, surveillance, maintenance, and repair systems within the GDF should be identified, addressed and appraised, to enable any gaps in existing technology to be identified and addressed. The design of the GDF should consider access for robotic systems and practicalities related to their use and retrieval.

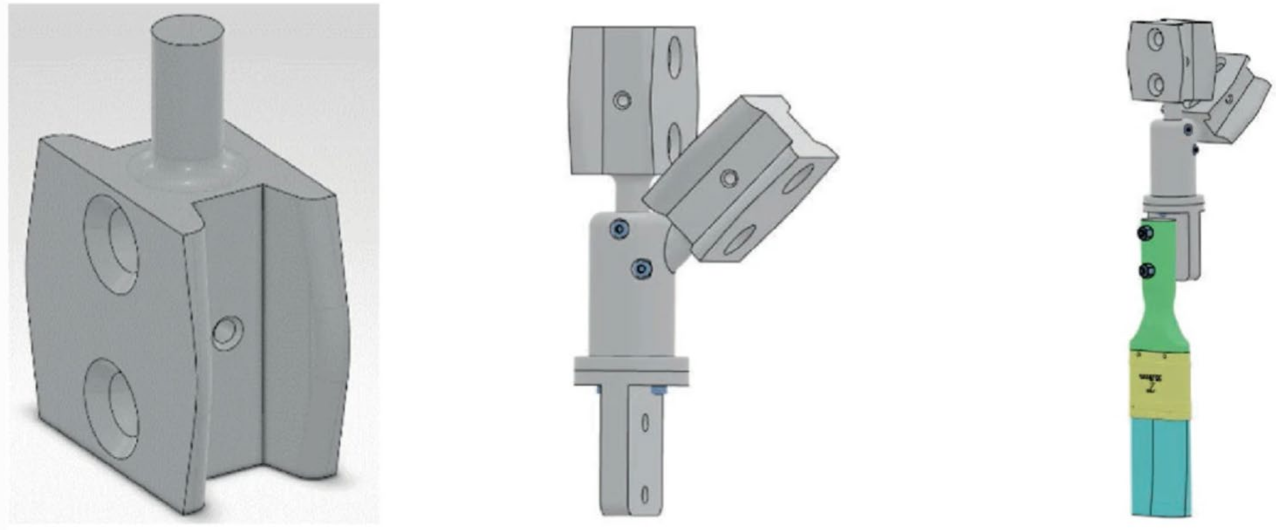

Figure 12: a) UKAEA Gripper Interface block; b) Interface block with two connection points; c) Interface block attached to a regular paint brush (Blake et al, 2022).

Other Factors to Consider When Utilising RAS within a GDF

In this section several important factors that may need to be considered if RAS technologies are to be utilised within the GDF are discussed. These factors include the potential for ionising radiation to damage the robot and gaining regulatory approval to enable the robot to be deployed.

Radiation Damage to Electronic Systems within a GDF

Gamma radiation will affect the materials used in the construction of the electronic systems and the materials used in the fabrication of any robot deployed into the GDF. Evidence from existing above-ground storage facilities suggests that gamma dose rates are not sufficiently high for any resulting effects to impact the operation of electronic systems, however, there is the potential for electronic systems to be deployed for longer lengths of time in the GDF, which could introduce operational problems.

Recommendation 3: Consider whether current, above-ground facilities, such as the waste storage facilities on the Sellafield site, might be appropriate for prototyping and testing of new technologies for potential deployment into the GDF and for assessing the impact of radiation on electronic systems.

The general effect of radiation on electronic systems is relatively well known and can be divided into three categories: single event effects (SEE); displacement damage (DD); total ionising dose (TID). SEE are caused by single particle strikes, typically involving high energy particles. DD is the effect of the physical interaction between ionising particles and the crystal lattice of the electronic device as the particle passes through the device. TID is the cumulative damage resulting from prolonged exposure to ionising radiation, which causes a charge to build up in the oxide layer of electronic devices, eventually leading to component failure. In nuclear environments, the primary concern for electronic components is TID resulting from gamma radiation. TID can be a concern even in environments with low levels of ionising radiation, as the effect is cumulative and hence long-term exposure to low-levels of ionising radiation can damage electronic systems.

There is no definitive method for determining the TID that an electronic device can withstand as the effect is partially stochastic. However, standards have been developed, such as MIL-STD-883 that can be used to assess the tolerance of electronic components. With the recent growing interest in developing robotic solutions for nuclear environments, several tests have been reported on relatively standard robotic components. These tests have shown that individual commercial, off-the-shelf devices, commonly used on robotic systems begin to fail after being exposed to approximately 50-100 Gy (see for example Bird et al, 2021).

Practical methods may be applied to protect RAS devices from radiation fields. For example, when not in use, mobile robots can be moved to areas of low radioactivity, or the sensitive components can be designed to be modular and replaced when necessary. Alternatively, the sensitive electronic components on the robot can be shielded by high density materials, such as lead or tungsten. This latter approach was adopted on the Juno spacecraft that has spent several years in orbit around Jupiter. Juno was designed with a tungsten lined 'vault', which contained all the sensitive electronic components. The radiation environment in space is very different to that in a nuclear facility and whilst the Juno spacecraft required the tungsten vault to be approximately 10 mm thick for deployment over many years, a recent study suggested that a single board computer would require 6.3 mm of tungsten to increase its TID resilience to approximately 1 kGy, which would allow it to withstand approximately 100 hours within the primary containment vessels at the Fukushima-Daiichi nuclear power plant (West et al, 2022). The same study found that increasing the radiation resilience to 10 kGy would require 17.4 kg of tungsten, which highlights that the use of shielding to protect electronic systems for long periods of time can become infeasible as the weight of the shielding increases rapidly.

To address the sensitivity of electronic systems to ionising radiation, it is possible to design them such that they are more tolerant to radiation environments. For example, Osborn et al (1998) identified that using modern electronic devices can be an effective strategy, as modern devices have become more tolerant to gamma radiation, as a consequence of using thinner oxide gates. III-V compound semiconductors, such as GaAs and GaN devices, have been shown to offer greater tolerance to gamma radiation than silicon semiconductors. However, the technology is not as mature or prevalent as silicon semiconductors and electronic systems using this technology will be considerably more expensive and potentially one or two generations behind state-of-the-art (Houssay, 2000). The design of radiation tolerant devices is an area of active research, as it impacts the operation of fusion reactors and CERN, and some devices, such as DCDC converters, are now commercially available (see https://www.magics.tech for example).

An alternative approach to designing a radiation tolerant robot is to design the robot such that all electronic systems are kept out of the radioactive environment. A good example of this is Laser Snake 2, shown in Figure 11, which does not require any electronic systems along its length. Instead, all sensitive electronics are located at its base, which can be kept out of the radioactive environment. Laser Snake 2 can be deployed into radioactive facilities through a relatively small hole in the wall. Once deployed, the motors and other electronics are located on the non-radioactive side of the wall and hence the robot is tolerant to environments with high levels of ionising radiation. Mascot, discussed in Section 3.3, is similar, in that much of its functionality can be designed such that few electronic systems are required to be deployed into the active area. Any electronic systems that do need to be deployed into the active facility can be designed to be modular, so that they can be replaced with ease when necessary.

Recommendation 4: With knowledge of the radiation dose rates within the GDF, the locations of any remote operating equipment and operational experience from current, above-ground storage facilities, the impact of radiation damage on the operational lifetime of any electronic equipment deployed in the GDF should be determined, allowing its potential impact on subsystems within the GDF to be identified.

Regulatory Acceptance

The introduction of RAS as a tool within a GDF will require close collaboration with the Office for Nuclear Regulation (ONR) and potentially other regulators. Gaining approval for the deployment of tele-operated robots in nuclear environments will not be significantly different to the processes required for other automation technologies. Some concerns that relate to the use of robotic systems, include the following:

- *Security*: There is a risk that third parties could access the transmission of sensitive information, such as images or the location of radioactive materials. Furthermore, it is feasible that unauthorised users could gain control of robotic devices.
- *Unauthorised Data Transmissions*: Vulnerabilities have been identified in the software systems used to operate some commercial robots. This has raised concerns that some robotic systems could be designed to transmit sensitive data, such as photographic images, to unauthorised locations.
- *Software Systems*: The use of software modules, developed by third parties and frequently available for no charge in on-line repositories, raises security implications if this software is not open to examination and its operation not fully understood. Automated software updates also introduce concerns as this raises the potential for unvalidated software to be installed.

The above concerns can be addressed, and have been already in the deployment of automation and control systems in nuclear and other industrial sectors. For example, programmable logic controllers and SCADA systems introduce security implications, as does the wireless transmission of instrumentation measurements, but all have been approved for use on nuclear sites after appropriate security measures have been put in place.

The integration of robot autonomy using AI raises additional and more complex challenges for gaining regulatory approval, particularly if machine learning is utilised. AI typically makes its decisions by collecting sensory measurements and then processing these measurements appropriately. Sometimes these decisions are made in an interpretable manner, such that a human can understand the reasoning behind any decision. For example, the AI may use a series of if/then statements to determine an action that is dependent on various conditions. Such decisions are transparent, which allows the software and the behaviour of the robot to be verified.

Many of the advances that have been made in AI, such as the ability to classify images and process natural language, have been based on deep learning, which is a subfield of machine learning, which itself is a subfield of AI. In the case of image classification, deep neural networks are presented with multiple images, which are used to teach the network to recognise what the images are of and what action might be performed based on this image. Deep neural networks are highly complex, containing many thousands of functions, making them difficult to interpret. This presents a significant problem because if a robot utilises a deep neural network to make any decisions, the robot cannot be guaranteed to act in a desired manner in untested situations. For example, if the robot encountered a situation that its response hadn't been tested for, then its behaviour will be unpredictable. The sensitivity of deep neural networks has been demonstrated in attempts to 'fool' the networks into incorrectly classifying images. For example, changing a single pixel on an image of a green traffic light was shown to make a deep neural network classify the image as a red light (Huang et al, 2020). Whilst this was a carefully designed adversarial attack, it demonstrates that it is possible for AI systems to give unexpected outputs with very minor changes to the scenario. Addressing his challenge is the subject of intense research.

The complexity of the challenge, with regard to gaining approval for robotic systems that utilise AI will be dependent on how the robot and AI are to be used. There are broadly three ways in which AI can be used:

- Advisory: The AI provides information to an operator. For example, it could analyse images of a scene and indicate to the operator if the image shows an abnormal situation.
- Supervisory: The AI enables the robot to perform low-level actions, such as automatically grasping an object, or suggesting a new location to move to. However, the behaviour of the robot is supervised by a human operator, who has overall control of the robot's actions.
- Control: The AI enables the robot to perform its tasks completely autonomously, with no human supervision.

In the nuclear sector as a whole, the use of AI in a 'control' capacity will introduce the greatest challenge in gaining regulatory approval, particularly in situations where incorrect decisions can have significant consequences. The problem is exacerbated because there remain very few use cases of robotics and AI in the nuclear industry, and in other related industries, and therefore regulatory good practice does not yet exist. This is expected to change in the future as the ONR have established an expert panel on the Regulation of AI in Nuclear, which aims to investigate how AI technology can be used within the nuclear industry[1].

Recommendation 5: The ONR and if necessary, other regulators, should be engaged with, at the appropriate stage in the design process, to specifically discuss the potential use of robotics and AI in the GDF. If possible, there should be representation from the GDF on the Regulation of AI in Nuclear Expert Panel.

RAS Maintenance

It is to be expected that over time any RAS deployed within a GDF will require maintenance, replacement and other interventions. Experience at the Fukushima-Daiichi power plant has highlighted the difficulties that this can introduce when such interventions are unplanned. However, in contrast to Fukushima Daiichi, operations within the GDF should have little uncertainty and hence, with appropriate maintenance strategies in place, there should be an operational aim to avoid in-service failure of RAS. To enable this, intervention methods to extract any RAS equipment from the facility should be considered during the design phase. Furthermore, access routes within the GDF should be designed such that they are suitable for any RAS that might be required. Legacy sites at Sellafield, for example, have many facilities with highly restricted access or were designed for human access only, which introduces considerable challenges when attempts are made to deploy modern RAS.

A major reason for the success of the Kiva robot at Amazon was that this device could be refined over many iterations and tested extensively in live environments, improving its reliability and reducing its cost. Care needs to be made to ensure that any RAS is thoroughly tested in realistic environments prior to its deployment in the GDF. This may be possible using above ground storage facilities operating at sites such as Sellafield.

Future Proofing

With an operational phase of several decades, there will be challenges introduced as to how any RAS hardware and software, used within the GDF, are future-proofed, such that they can be maintained, upgraded, replaced and operated over long periods of time. This will be a consideration not just for RAS, but for any automated system in use in the GDF. Maintenance of legacy hardware systems has introduced problems previously in the nuclear industry. For example, following hardware failures,

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[1] https://www.onr.org.uk/external-panels/artificial-intelligence.htm

legacy robotic systems have had to be entirely re-designed and replaced on the Sellafield site because of a lack of replacement parts. Furthermore, Sellafield Ltd have, in the past, had to procure legacy computing equipment from the National Museum of Computing to replace damaged hardware, which can be extremely costly.

To address the issue of future-proofing robotic systems, Sellafield Ltd have initiated a Game Changer[2] programme to develop a standardised software architecture that will allow their robotic systems to be agnostic to the precise robotic hardware that is used. This would allow damaged or legacy hardware to be replaced by a similar piece of hardware, potentially from a different manufacturer, without the need to change and re-validate the software systems. Sellafield Ltd are currently investigating whether CorteX, which is under development by UKAEA (Caliskanelli et al, 2020) and IRIS, which is being developed by Createc Robotics Ltd.[3] would be suitable software architectures for this. A similar software architecture may offer benefits in the operation of the GDF. An alternative is the ROS Military, or ROS-M[4], software architecture that has been developed in the USA, to support greater collaboration, re-use of code and improve reliability of RAS.

Recommendation 6: Nuclear Waste Services should determine whether the standardisation of robotic equipment is of significance in the GDF and, if necessary, engage with Sellafield Ltd on their Standardised Robotics initiative.

Bespoke Design

Given the unique characteristics of the GDF it is to be expected that either robotic systems will need to be designed specifically for the facility, or commercial systems will need to be modified to enable them to be fit for purpose. This raises significant issues in relation to the reliability of any robotic systems that are developed. Whilst the operation of a robot can be tested prior to deployment, it is often not possible to test it in conditions that are entirely realistic of the real environment. For example, it may not be possible to reproduce the precise radiation conditions that would be experienced within a vault. It is also not possible to test the reliability of such systems over the many years that the GDF is operational. Difficulties in testing could introduce problems for any bespoke robotic equipment as engineering systems can be prone to early failures. Such failures can be reduced by performing comprehensive testing in environments that are as realistic as possible, which may be possible in, for example, the intermediate level waste stores on the Sellafield site, where significant learning and operational experience could be acquired.

Power Management

Any RAS used in the GDF will require power. If the robot is tethered then this offers simplicity in terms of power management, but the long lengths of tether, which may be required, can create problems as tethers can become tangled, a problem experienced in the storage ponds on the Sellafield site for example, and they can also create blockages in access routes. Battery powered robots have the benefit of not requiring a tether, but instead they would need the ability to recharge. The Kiva robots, which are used by Amazon for example, automatically return to a base station to recharge, but this introduces the risk that any failures in charging could mean that robots run out of power and fail to return to the base station. Wireless charging is a relatively new technology, but it may offer a suitable method for charging robotic systems by the time that the GDF is constructed. Cheah et al (2019) provides an overview of current limitations with the wireless charging of robots. Whether a robot is tethered or untethered also has an impact on the type of communication that might be used between a base station and the robot, i.e. wired or wireless.

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[2] https://www.gamechangers.technology

[3] https://createcrobotics.com

[4] http://rosmilitary.org

Whilst any communication system will contain electronics that could be damaged by gamma radiation, it is unlikely that the actual transmission of radio signals within an environment would be affected by radiation.

Socio-Economic Impact of RAS

The widespread adoption of RAS is expected to have a significant impact on society, and this is likely to be seen in the locality of the GDF. The Future of Jobs Report 2020 (World Economic Forum, 2020) estimated that by 2025, 85 million jobs may be displaced by the introduction of machines, which includes automation technologies and RAS. However, the same report also estimated that 97 million jobs may emerge that are related to these new technologies. The more recent Future of Jobs Report 2023 (World Economic Forum, 2023) recognised that digitalisation, and AI and machine learning, had the fastest growing impact on jobs and that the growth in the take-up of automation technologies had slowed slightly. However, it is clear that the impact of digitalisation, robotics, AI and automation will be significant. Of particular relevance to the GDF is that the jobs that are created in new technologies are often in different locations and require different, and often higher-level skills.

Future Trends in Robotics and AI

Robotics Technology

Current plans envisage that the construction of the GDF won't begin until the 2040s and that it will be operational for many decades, with some parts of the facility being operational whilst others are still being designed and constructed. With such long timescales, it is sensible to consider what developments there will be in robotics over the coming years and how these might impact the GDF. Robotic systems have improved considerably over the last two decades and it is anticipated that they will continue to evolve rapidly. It is difficult to predict what advances will be made over the next 20 years, but it is possible to look back at progress made over the last 10 to 20 years to see what advances are possible in such time periods.

Figure 13 shows an image of Big Dog, a quadruped robot that was funded by the US military. Big Dog was developed by Boston Dynamics and eventually led to the creation of Spot. There are approximately 15 years between Big Dog and Spot and significant differences can be seen in the robots and their capabilities. Spot has made use of advances in battery technologies, for example, that means it does not require the onboard, two-stroke engine that Big Dog relied on. Other improvements have been made to the camera systems, motors and materials of manufacture, which have enabled control systems to be developed that provide improved stability. Spot is also a commercial product, with similar products becoming available from other manufacturers, including Unitree and Ghost Robotics, whilst Big Dog was a demonstration platform only. The commercialisation of Spot has led to competition in the market, reductions in cost and improvements in capability, making the technology more attractive to industry.

Figure 13: Big Dog (© Boston Dynamics)

Figure 14: KUKA Titan KR1000 (© KUKA)

Comparing Atlas, shown in Figure 6, with the bipedal robots that took part in the 2015 DARPA Robotics Challenge Finals in 2015, shows that bipedal robotics technology has improved considerably over the last 8 years, although the technology remains several years away from commercialisation. It is similar with industrial manipulators. The capabilities of modern manipulators, an example of which is shown in Figure 14, have improved considerably over the last few decades. However, they are not unrecognisable from manipulators in use 20 years ago, although their lifting capacity has increased, as has the precision of their movement and their reliability. If developments over the last 20 years are projected forward 20 years then we might expect commercial robots to be significantly more capable than those available today, but they are unlikely to be unrecognisable from robots that might be found in modern research laboratories.

AI Technology

AI has developed rapidly over the last decade or so with a variety of applications that have begun to have a transformational impact across a range of industries. The technology developments over the last decade, and particularly those related to machine learning, would have been difficult to predict and so too might the advances over the next decade. However, there are reports that progress in AI is beginning to slow down, with a lack of sufficient computing power reportedly holding the technology back. Limited ability to ensure the safety and trustworthiness of AI systems is also a factor that has slowed the application of the technology in certain industries. However, trustworthy AI is an area of research that is receiving increasing attention, with techniques such as neuro-symbolic AI, which attempts to combine the capabilities of neurologically inspired techniques, with more transparent 'symbolic' AI tools to create interpretable AI systems, one of several new technologies that are being investigated. It is therefore feasible that there will be breakthroughs in this field in the next decade which may have an impact on the deployment of RAS solutions in hazardous environments, such as those found in the nuclear industry.

Recommendation 7: Robotics and AI is a rapidly developing area and if there is potential for such systems to feature within the GDF then a watching brief should be maintained on developments in this field and their potential impact on the future design and operation of the facility. Furthermore, developments in the field of radiation tolerance of electronic systems should be monitored, particularly in application areas such as space and at facilities including CERN and fusion reactors.

Conclusions

This report has provided a brief overview of some of the opportunities and implications of using robotic systems within a GDF. Some of the challenges that might be faced if the decision was made to operate the GDF with minimal human entry have been highlighted. Whilst it is feasible that the general operation of the GDF could be automated, as there should be limited if any uncertainties in its operation, requirements to monitor, maintain and repair equipment in the GDF raises significant complications if robotic systems are to be relied upon. A summary of latest state-of-the-art robotic systems, particularly those deployed in recent years in nuclear environments, has been provided and their current limitations identified. Difficulties related to the use of AI within any autonomous robot deployed into a radioactive environment, where incorrect decisions could have significant implications, have been identified and this may limit any use of fully autonomous systems in the GDF in the foreseeable future.

Robotics and AI are rapidly evolving technologies and it is recommended that those involved in the development of the GDF maintain a watching brief on developments in both academia and industry in this field. There are several working groups and expert panels that have been set up within the nuclear industry to progress these topics, such as the Regulation of AI in Nuclear expert panel, which has been established by the ONR and Sellafield's Central Robotics and AI Centre of Expertise Forum. It is recommended that these groups have representation from the GDF community.

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