Robots and Autonomous Systems for Nuclear Environments

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Nuclear decommissioning and the safe disposal of nuclear waste is a global problem of enormous societal importance. Decommissioning the legacy waste of the UK alone, represents the largest environmental remediation project in the whole of Europe, and is expected to take over 100 years to complete, with estimated clean-up costs as high as £220billion [1]. The quantities of UK legacy nuclear waste are vast, with the UK Nuclear Decommissioning Authority (NDA) estimating there is 290,000 m^3 of intermediate level waste (ILW) alone [2].

Much of the legacy nuclear waste is very old. Nuclear operations in USA and UK began in the 1940s, and greatly accelerated in both countries following the first USSR atomic bomb test in 1949. The UK pioneered peaceful use of atomic energy, with the world's first industrial scale civil nuclear power station coming online at the Sellafield site in 1956. Many of the UK's nuclear facilities, including test reactors, storage areas and fuel re-processing plants, are now in urgent need of decommissioning, with the UK Nuclear Decommissioning Authority (NDA) describing some facilities, particularly the ponds and silos at the Sellafield site in Cumbria, as intolerable risks.

Human access to such facilities is often not possible and where it is possible, such as alpha-contaminated zones, Personal Protective Equipment (PPE) is needed, including air-fed plastic suits, leather overalls to protect the plastic suit from punctures, and several pairs of gloves. Workers must handle power tools to cut contaminated lab equipment and place it in storage containers. Working in such conditions is stressful, physically demanding and poses risks to human safety.

Record keeping in the early days was not rigorous by modern standards, and there exist legacy waste storage containers with unknown contents or contents of mixed contamination levels. At the Sellafield site alone, 69,600 m^3 of legacy ILW waste must be placed into 179,000 storage containers [2]. To avoid wastefully filling intermediate-level containers with low-level waste, many old legacy containers must be cut open, and their contents “sorted and segregated” [3]. This engenders an enormous requirement for complex remote manipulations.

Perhaps surprisingly, there has been remarkably little use of robots in the nuclear industry. The vast majority of remote manipulation is performed by an aging workforce (mean age 55 in UK [4]) of highly skilled experts, using mechanical Master-Slave Manipulators (MSM). Such devices date back to at least 1949 [5] and have changed little in design since the 1960s. Where robots have been deployed, these have predominantly been directly tele-operated in rudimentary ways [6, 7]. Such robots, widely trusted in the nuclear industry due to their ruggedness and reliability, do not have encoders, and no inverse-kinematics solving is possible to enable Cartesian work-space control via a joystick. The operator looks at the robot through a 1.2 m thick lead-glass window, with very limited situational awareness or depth perception. They control each joint directly while guessing the inverse kinematics from experience. Such control methods may seem very strange to lab-based academic robotics researchers, but are standard and common in the nuclear industry.

Given how robotics has transformed the manufacturing industry, one naturally asks why nuclear environments remain so reliant on manual labour. Unlike industries, such as automotive, where operations are highly repeatable and the environments contain no uncertainties, a common factor of decommissioning environments is that they are typically highly unstructured and uncertain.

Legacy facilities, often closed off for many decades, are often poorly understood, with inventory records and design drawings incomplete, erroneous or unavailable. Hence, modern robotic solutions are often unsuitable [8].

In addition to the decommissioning of legacy facilities, the UK plans to build new nuclear power stations, a geological disposal facility and is investing significant resources in to nuclear fusion technology. To ensure the successful operation of each of these facilities and to avoid the creation of complex decommissioning challenges for future generations, it is vital that new robotics technology be developed and deployed across the nuclear industry.

Despite recent advances, there remain significant barriers preventing robotic and autonomous system (RAS) deployment in the nuclear industry. While many RAS advances required to overcome these barriers could help other domains, the nuclear industry is unique in the diversity and severity of its challenges. For example:

- Highly unstructured, uncertain and cluttered environments (many not fully characterised).
- High consequence environments, with extreme radioactive, thermal and chemical hazards.
- Limited access, with entry often only available through narrow ports.
- Thick concrete walls introducing significant communication difficulties that necessitate increased requirements for autonomy, currently unavailable to industry robots.
- The need to inspect, grasp, manipulate and dismantle a huge variety of objects and materials.
- Exploration, mapping and modelling of unknown or partially known extreme environments.
- Requirement for multiple sensing modalities, including radiological, chemical and thermal.
- A variety of locomotion methods are needed: underwater vehicles; airborne vehicles; and ground-based vehicles which must navigate complex terrains and complex 3D installations.
- Powerful, precise, multi-axis manipulators needed with complex multimodal sensing capabilities.
- Need for variable robot supervision, from tele-immersion to autonomous human-robot teamwork.
- Critically damaging effects of radiation on electronic systems.

The University of Manchester is leading two major collaborative projects, funded by the UK government to try and address some of these challenges. The Robotics for Nuclear Environments (RNE) project is focused on fundamental research of key enabling robotics technologies (Technology Readiness Levels (TRL) 1 – 3 [9]), whilst the Robotics and Artificial Intelligence for Nuclear (RAIN) Hub aims to demonstrate and showcase robotic platforms and technologies in representative environments, up to and including real-world active deployments (TRL 4 – 6). Both projects have very strong engagement with key stakeholders and end users such as Sellafield Ltd., the National Nuclear Laboratory, EDF Energy and the Atomic Weapons Establishment (AWE).

Robotics for Nuclear Environments (RNE)

The RNE project, funded by UK Research and Innovation (UKRI), is a collaboration between the Universities of Manchester, Birmingham and West of England and the National Nuclear Laboratory (NNL), with the aim of enabling step changes to be made in the capabilities of industrial robotic solutions for use in the nuclear industry. Starting in 2017, the project has three key research themes: low-level system design for robust operation, collaboration and cooperation and advanced autonomy for robotic perception, navigation and manipulation. A few highlights of the research are presented below:

Autonomous Surface Vehicle (ASV) – The MallARD ASV was developed for an International Atomic Energy Agency (IAEA) Robotics Challenge on the inspection of spent fuel storage ponds by the University of Manchester. The MallARD was successfully deployed by the IAEA in a storage pond in Finland in February 2019. This was the first known deployment of a surface vehicle in an active nuclear storage pond. A significant amount of research has been conducted on this platform with a focus on the development of robust localisation and positioning techniques that can be applied without the need for additional infrastructure. Robust sensor fusion techniques using Kalman filters and model predictive control techniques have allowed the vehicle to be positioned with an accuracy of <1 cm within a storage pond, which meets the requirements for deployment into facilities operated by Sellafield Ltd [10].

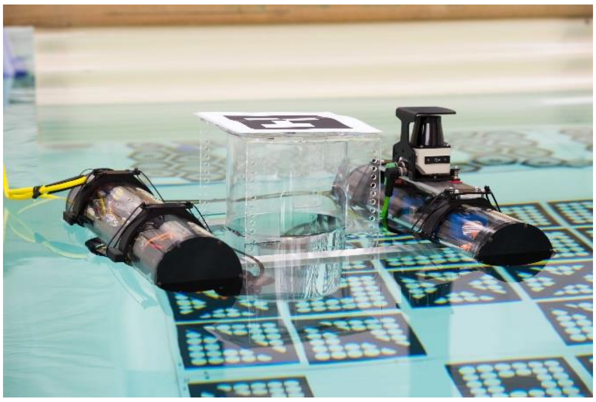

Figure 1 - The MallARD ASV in a test pond in Brisbane, Australia

Communications – A novel architecture for a wireless sensor system capable of operating in nuclear decommissioning environments has been developed. The architecture is based on an asymmetric communication system, where there is a relatively low-complexity wireless sensor node (located in the active area) and a relatively high-complexity base station (located in an inactive area). The benefit of utilising a low-complexity system in the active area is that it is simpler to design it such that it can have higher radiation tolerance. Preliminary wireless signal propagation loss measurements have been taken by the University of Manchester from two buildings on the Sellafield site [11] and initial designs for the communication systems have been developed and tested, demonstrating that communication through representative infrastructure is feasible.

On-line Behaviour Risk Assessment – The University of West of England's Bristol Robotics Laboratory (BRL) is investigating how to design, implement and test the architecture for robots to assess, at runtime, the risks associated with their own actions and the robots and humans around them in the context of their current mission tasks. As the first step in this work, the team at BRL is investigating how the decision making process of the robot needs to be designed to maximise the trust of the human operator controlling the robot. In parallel with the study of risk strategies, the use of simulation-based internal models is also being explored [12] to allow a robot to estimate the risk (to itself) of each of its next possible actions.

Characterising nuclear and extreme environments – A large body of work has been successfully developed at the University of Birmingham that uses advanced computer vision methods to achieve semantic-level understanding of nuclear environments. In addition to 3D geometric reconstruction and SLAM, methods which can recognise semantic information such as the categories of objects and materials in scenes have been developed and this semantic information can be used for pixel-wise segmentation and semantic labelling of 3D scene models.

To provide sufficient training data for learning-based methods, a nuclear waste objects' dataset has been developed and also a virtual camera system for generating synthetic ground-truthed images to augment the data for learning. Semi-supervised methods have been developed to overcome the need for large human-annotation of training data that has been typical in other computer vision applications where much larger online benchmark datasets are more commonly available [13, 14].

Autonomous manipulation – A novel autonomous grasp planning algorithm has been developed at the University of Birmingham, which can reliably grasp objects (with no prior knowledge or object models) from random, cluttered, self-occluding heaps, imaged with partial point-clouds [15]. Given that grasp planners can propose multiple possible stable grasps on each object, a variety of work has been completed on how to select optimal grasps to achieve collision-free manipulation pre and post grasping [16], selecting grasps to maximise safety in the event of collisions and work on bi-manual manipulation has also been undertaken [17]. It has also been shown how to combine vision-based tracking work with grasping to achieve autonomous grasping of moving objects [18].

Robotics and Artificial Intelligence for Nuclear (RAIN) Hub

The RAIN Hub, also funded by UKRI, is a collaboration between the Universities of Manchester, Bristol, Lancaster, Liverpool, Nottingham and Oxford and the UK Atomic Energy Agency Remote Applications in Challenging Environments (UKAEA RACE). Starting in 2017, the project has three key themes: remote inspection, remote handling and safety case studies. A few highlights of the research are presented below:

AVEXIS – A collaborative project between the Universities of Lancaster and Manchester equipped neutron and gamma detectors onto an AVEXIS ROV (Figure 2) [19], which was then deployed into the TRIGA nuclear research reactor in Slovenia, providing, for the first time, radiation measurements taken from a robot as it manoeuvred around an operational reactor. AVEXIS has also been deployed at the Naraha research facility, close to Fukushima Daiichi, to demonstrate how the same technology could be used to locate melted fuel within the reactor vessels. The work is now continuing with a joint project with the Japan Atomic Energy Agency (JAEA) and the National Maritime Research Institute (NMRI).

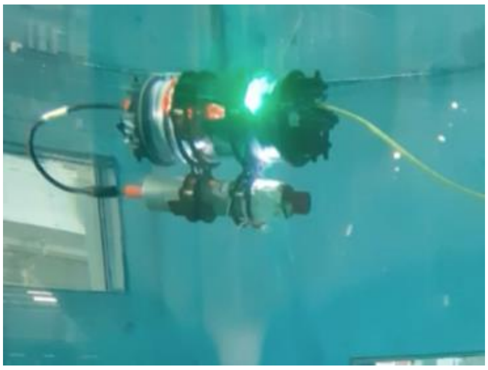

Figure 2 - The AVEXIS ROV at the Naraha Test Facility, Japan

CARMA - Designed to map radiation in large floor spaces, the CARMA robot (Figure 3) became the first fully autonomous robot to be deployed on the Sellafield site in December 2017 and was deployed for a second time in May 2019 [20]. This work has progressed with further Sellafield deployments planned in 2019. A commercialisation project has been initiated with Nuvia to develop a commercial version of this platform.

Figure 3 - The CARMA Robot

MiRoR Photonics - Researchers from the University of Bristol have successfully installed their Raman photonics device on to the continuum robot developed by the University of Nottingham [21] and used it to analyse unknown materials. The combined system allows materials, such as corrosion oxides to be identified in highly constrained and difficult to reach areas and if necessary, repairs and maintenance to be carried out.

Hands-out of Gloveboxes - Following concerns regarding safety, there is a major effort underway in the nuclear industry to develop remotely operated gloveboxes. In collaboration with the Italian Institute of Technology (IIT) and the University of Sheffield, demonstrators have been developed at RACE and Manchester that illustrate how robotic manipulators can be used to replace humans. These demonstrators use state-of-the-art virtual reality and sensor technologies [22].

The Unknown Room - An extremely low-cost, purpose built ground-based vehicle was integrated with a radiation detector to characterise a sealed gamma source at the Atomic Weapons Establishment (AWE), UK. This demonstrator was developed by the Universities of Bristol and Manchester and is the first stage of a research programme that aims to deploy a robot into an AWE facility. Commercialisation opportunities are being explored through a company, Ice-Nine, which has been established by one of RAIN's researchers and an active deployment is being planned on the Sellafield site.

JET Fusion Reactor – RACE were able to map the inside of JET with an Oxford Robotics Institute (ORI) LiDAR and stereo camera was conducted in 20 minutes rather than 1.5 days with the current manual approach, achieving 0.5mm accuracy with respect to the CAD model and identifying a component that was not in the digital model.

Verification & Validation – The University of Liverpool is leading research to develop the necessary Verification and Validation (V&V) techniques that will be required if robotic systems are to be deployed within the highly conservative safety culture of the nuclear industry and to use these techniques to assure safety, assess long-term reliability, and provide both evidence for regulators and confidence for operators [23].

Conclusions

The UK government has invested a significant amount of money over the last 3 years to make the UK a world leader in robotics for extreme environments, with particular focus on the nuclear sector. Prior to the RNE and RAIN projects, there were around 10 researchers working on nuclear robotic projects in the UK. There are now over 100 researchers in 10 world leading institutes undertaking coordinated and focused research to solve real-world, end-user driven nuclear robotics challenges. Several technologies have already been successfully demonstrated in nuclear environments and are being translated into commercially viable systems.

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Web links
https://rainhub.org.uk/
https://nuclearrobots.org/

Bios

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