UK Atomic Energy Authority

RACE

# LongOps Project Report

NDA

TEPCO

UKRI Innovate UK

1st edition October 2025

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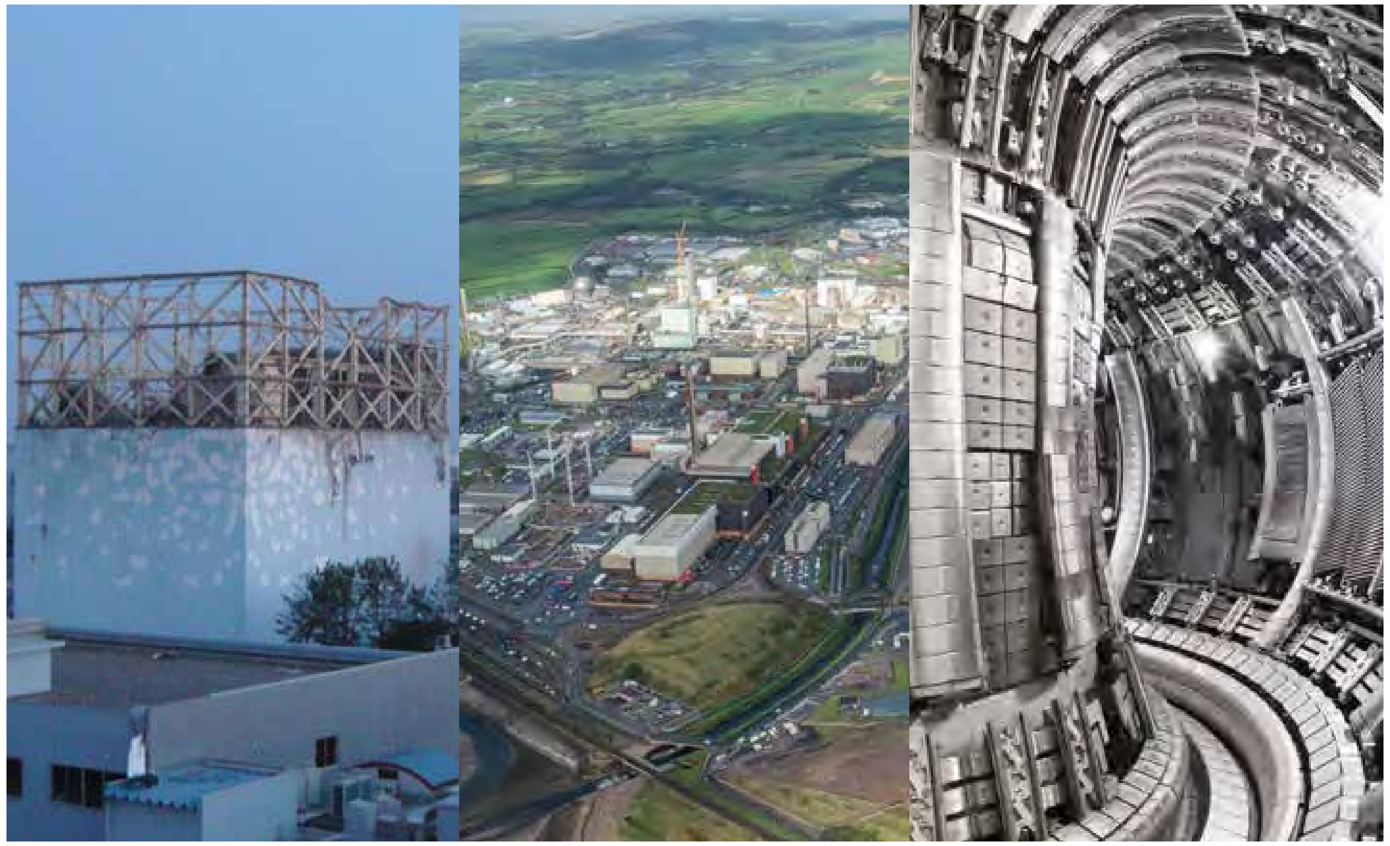
# Introduction



**Britain and Japan signed the LongOps research and development collaboration to consider how advances in robotics can deliver faster and safer fission and fusion decommissioning.**

**The £12M project, called "LongOps", focused on three long-term uses cases. From Japan, the focus was decommissioning the Fukushima Daiichi reactors owned by Tokyo Electric Power Company Holdings (TEPCO). In the UK, the focus was Windscale Pile 1 at the Nuclear Decommissioning Authority's Sellafield site and the JET fusion machine at the UK Atomic Energy Authority's (UKAEA) Culham site. The three-and-a-half-year project was funded equally by UK Research and Innovation (UKRI), the Nuclear Decommissioning Authority (NDA) and TEPCO. The collaboration was led by the UKAEA's centre for Remote Applications in Challenging Environments (RACE) which provides critical capability to the JET decommissioning programme.**



The challenge of decommissioning of both fission and fusion facilities creates complex long-term operational programmes. A common feature of these programmes is the inability for people to access high-hazard areas and this drives the need for remotely operated tools including long reach robots. LongOps is named accordingly: Long Term Operations using Long Reach Robotics.

A central component of the LongOps project has been the development and demonstration of sophisticated Digital Mock-Up technologies. These software tools use virtual models that pair the digital and physical worlds to enable four types of beneficial activity: planning and optioneering; operator training; rehearsal and monitoring of real operations; and the collection of data, that then inform further planning. These tools will enable continuous improvement and a managed response to a dynamic set of environmental conditions and constraints as the decommissioning progresses. As a result of developments in gaming technology and associated computing power these tools are becoming widely used across other sectors. In the nuclear sector, the rapid maturation of robot systems, including drones and quadruped walking machines, enables sensors to be carried into hazardous environments to collect data that can be used to create detailed digital representations. Within LongOps, breakthrough progress has been made with digital haptics which enables an operator to feel interactions within a digital world. A digital mock-up offers the potential to increase confidence and accelerate programme delivery by providing key stakeholders including operators, managers and regulators with access to detailed information about an asset and its decommissioning plans.

This report details the work conducted and the considerable progress made. Another feature of this report is the feedback provided by those involved. This focus on people reflects the fact that decommissioning requires people to make difficult decisions on a daily basis. In preparation for this, we need to reach a consensus regarding best techniques, including the assessment of emerging technical capability that can improve mission delivery. LongOps has enhanced our ability to consider these future challenges and offers a route by which we can deliver safer, faster and more cost-effective decommissioning.

# Preface


**LongOps was born from an agreement between Prime Ministers Theresa May and Shinzo Abe in 2019 to invest in UK-Japan robotics collaboration. £4M of UK funding was provided by UKRI, who had previously invested in the 'Robots for a Safer World' programme which included a successful investment in the Robotics and AI for Nuclear (RAIN) hub. Due to my role in RAIN and the rapid expansion of RACE, I was encouraged to convert the political will into a deliverable programme. The first challenge was to find a group of partners who had similar need, schedule, budget and capacity to work together. Building on two short-term secondments from TEPCO to UKAEA in 2018, after six months of intense national and international discussion, we signed a four-way collaboration agreement between UKRI, NDA, TEPCO and UKAEA.**

To my deep satisfaction, I have witnessed people coming together from diverse backgrounds and cultures to achieve considerably more than any one party expected or even hoped for. It has been a pleasure to host 14 TEPCO secondees during LongOps. We have become friends – for life. I hope we will support each other for years to come as we embrace the complex engineering challenges ahead.

Perhaps we got lucky? I don't think so. We were in the right place at the right time. We also knew what we wanted to do and trusted each other to make it happen. We were bold and persistent.




We formed an end-user led collaboration focused on helping our three organisations: the Tokyo Electric Power Company (TEPCO), owners of the damaged Fukushima Daiichi reactors; the Nuclear Decommissioning Authority (NDA), the arm's length body responsible for the UK's £178 billion legacy fission liability; and the UK Atomic Energy Authorly (UKAEA) with its world leading fusion mission.

We all recognised the opportunity to improve our mission performance by becoming intelligent customers for emerging robotics technology and more specifically digital mock-ups. The premise of the work was for the new generation of visualisation tools to assist in four ways: accelerating evidence-based decision-making for complex interventions into hazardous places; planning operations and training operators; monitoring and controlling in-situ operations; and finally, collating and curating data for review and for future planning, closing the continuous improvement circle.

The success of LongOps has already contributed to significant developments that will have impacts for many decades. In the UK, we have established RAICo, the Robotics and AI Collaboration, and UKAEA and TEPCO are in a discussion about the next LongOps project.

My challenge to you as you read this report is to consider how these technologies can accelerate your mission delivery.

**Prof Rob Buckingham** FREng OBE
Executive Director, UKAEA
LongOps Senior Responsible Officer

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# TEPCO

## Tokyo Electric Power Company

**It has been 13 years since the Fukushima Daiichi (1F) accident on 11 March 2011. Tokyo Electric Power Company (TEPCO)'s 1F decontamination and decommissioning was carried out initially on an emergency response basis, but we have entered the stage of taking on challenges in unchartered territory such as Fuel Debris Retrieval (FDR).**

**TEPCO recognises that the robotics and remote-control technology is one of the most important key success factors for the FDR project and needed to develop our inhouse technical capabilities for system and software designs, and the operation relevant to these technologies. Thus, we partnered with UKAEA, NDA/Sellafield Ltd, and UKRI to tackle the challenge jointly and despatched secondees to UKAEA.**

Specifically, we had to achieve its four objectives:

- → Developing a digital twin technology, taking the situation of Fukushima Daiichi into account
- → Learning robotics, remote-control and digital technology
- → Learning R&D management
- → Acquiring related information from UK and European capabilities

Through the project we have successfully developed the prototype of the Next Generation –Digital Mock-Ups (NG-DMU) which enable operators in charge of fuel debris retrieval to verify the operation procedure within a virtual environment and also supports the operation itself by providing path plans used for the long-reach manipulator and a realistic awareness of the harsh environment. These functions will help the operation to be more safe, secure and efficient.

We are now in a position to further develop our technical skills, continuously utilising the knowledge acquired through LongOps, aiming to build the digital mock-up to be used in the large-scale fuel debris retrieval.

On behalf of TEPCO, I would like to congratulate the successful completion of the project and express my sincere gratitude to everyone related to the LongOps project for their dedication and professionalism. It was a true international collaboration working towards the collective critical mission, and the teamwork displayed was nothing short of inspiring, resulting in the crucial achievements.

**Nobuhiro Ishii**
Group Manager
Large-Scale Fuel Debris Retrieval Consideration Group
Fuel Debris Retrieval Program Department
Fukushima Daiichi NPS
Tokyo Electric Power Company Holdings

# NDA

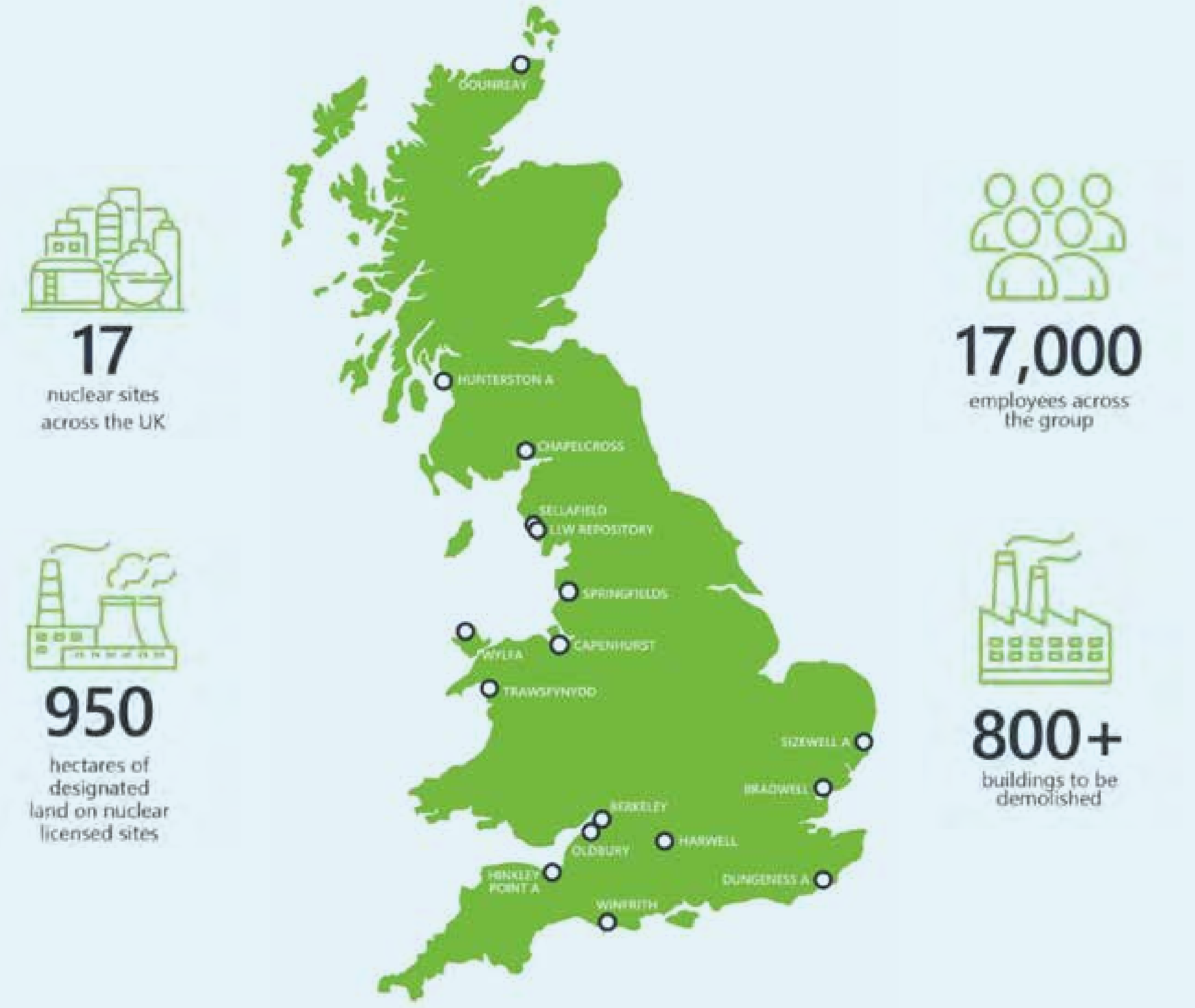
## Nuclear Decommissioning Authority

**The Nuclear Decommissioning Authority (NDA) is responsible for decommissioning the UK's oldest nuclear sites, dealing with some of the most complex and hazardous environments in the world, that require the development of first of a kind engineering and design solutions.**

**Through this international partnership we are developing new automation and robotic capabilities, applicable to cutting-edge fusion research and fast and safe decommissioning, protecting our people and leaving a more sustainable legacy for generations to come.**

I became involved in the LongOps project back in mid-2020. From my background and experience in Research & Development (R&D) for the defence sector, it was clear to me that there could be great benefit from such an international collaboration and the enthusiasm of the people involved was inspiring. We had similar technical problems to solve and working together would allow us to share knowledge and experience, providing mutual benefit both in terms of solutions and value for money for the taxpayer.

The first six months of the project focused on establishing relationships and sourcing end-user case studies to help bring the technical theory into real-life problem solving. These scenarios provide a focus to the technical direction and make it clear that there are synergies which will make the R&D more cost effective.




On LongOps, the technical progress has been good and aligned to pre-agreed milestones, despite noting that there always needs to be a degree of managed flexibility in R&D.

As well as the technical developments, a key success for LongOps is the involvement of the supply chain. The level, quality, and diversity of supply chain involvement, particularly SME's (small to medium enterprises), both from existing nuclear backgrounds and new entrants has been impressive.

The collaboration involved has been great to see – across the NDA group, internationally from experts at TEPCO in Japan, as well as supply chain, investors, and the potential end-users.

In summary, LongOps has exceeded our original expectations in delivering a strong pathway into the future potential use of robotics and demonstrating how different organisations can work together for a common purpose to solve similar real-life end-user problems.

**Alan Hutchison**
NDA Commercial Manager

# Sellafield Ltd

**Sellafield, nestled in the picturesque Cumbrian landscape, has witnessed decades of nuclear activity. The complex site has housed nuclear reactors, fuel reprocessing facilities and their associated treatment and storage plants. Several iconic events have now come to complete over recent years and the environmental restoration mission has now become the focus and priority.**

**Sellafield is one of the principal sites across the NDA group with a significant amount of highly complicated and technical challenges. Sellafield is home to a range of high hazardous environments that our teams work tireless to risk reduce, including a scope of construction, waste management and decommissioning challenges. There are a range of environments that humans cannot safely enter, this means that robotics and digital infrastructure have a huge part to play to undertake remote operations.**

The UK-Japan intercontinental collaboration emerged forming a four-year unique and jointly funded research project, LongOps. The technological developments scoped under LongOps were essential in the delivery of our missions, bridging cultures and technical expertise.

My involvement in LongOps was initiated when I came into role in 2020 to lead and manage robotics and AI capability development and deployments across Sellafield and NDA group. The project had scoped a number of use cases that had applicable use cases across Sellafield utilising cutting edge long-reach robotics in extreme environments. I was surrounded by some of the most genuinely excited and talented people who were proactively driving the work from strength to strength – this passion spread through the team!

The benefits of LongOps are monumental in scale and will leave a lasting legacy. When Sellafield entered the project, we were enthused about the ambitious research targets with focus on safety and the customer need at the core of the project. The breadth and depth of the development work would be extending the state-of-the-art in capabilities that were of huge interest to both fission and fusion decommissioning, and had the potential enable our mission of safer, faster, and cheaper and more efficient decommissioning. Beyond the research, a range of high readiness technologies have been made visible to our stakeholders and can be immediately utilised to make a difference on the Sellafield site and elsewhere across the NDA group.

By far, the most exciting prospect of the project was the opportunity to collaborate with our colleagues, internationally and domestically - including a cross section of the supply chain. It has been a privilege to work alongside such a diverse and talented team. LongOps also laid the foundations for the newly established RAICo (Robotics and Artificial Intelligence Collaboration) programme, which will continue to deliver great value and technical advancement for the nuclear industry through with collaboration between UKAEA, the NDA, University of Manchester and Sellafield.

Sellafield will look back fondly on the LongOps project and the significant opportunities it has established for the nuclear industry. The technologies and networks established will prove invaluable over the coming years, and the collective contributions of all parties have led to brilliant results in advancing robotics and artificial intelligent technologies.

**Rav Chunilal**
Head of Robotics and AI,
Sellafield Ltd.

# UKRI

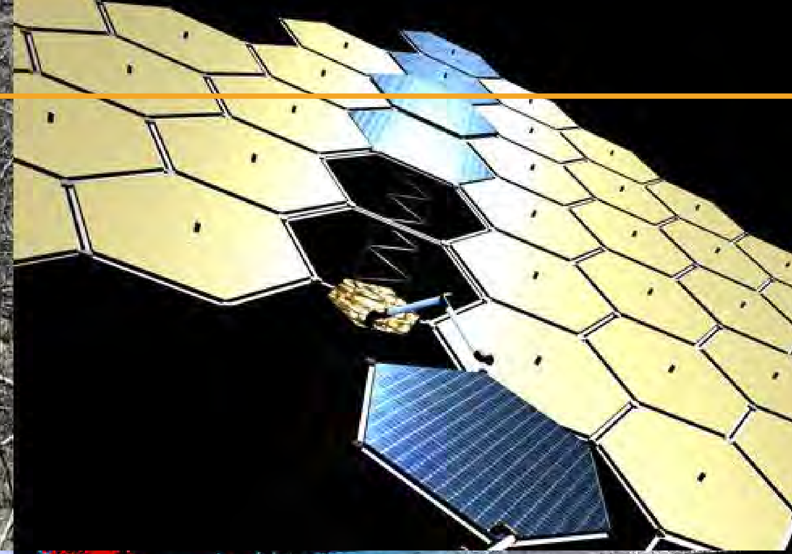
## UK Research and Innovation

© UK Research and Innovation

**We increasingly operate in extreme environments, some places are too dangerous or uncomfortable for people to work in effectively, or at all. Robots and artificial intelligence (RAI) offer huge potential for safer and easier working in these environments.**

**In 2017 the ISCF Robots for a Safer World challenge was launched, a £93m 4-year Challenge delivered by Innovate UK, part of UK Research and Innovation (UKRI). I was appointed Challenge Director and was tasked with accelerating the market readiness of RAI technologies in hazardous environments and to build a UK led robotics supply chain. We set out to increase the volume of research & test facilities for extreme environments; increase connection between the research base, industrial developers and end-users, and; ensure leverage of current investments and spill-over benefits flow back into other sectors.**

The task of decommissioning nuclear facilities is a collaborative one, where no one organisation can solve its issues alone. Following an announcement by Japanese PM Shinzo Abe and Prime Minister Theresa May in 2019, an agreement was made to collaborate on pioneering innovation and the LongOps project was born, with equal investment from Innovate UK, NDA and TEPCO for an ambitious £12m programme.



The rapid development of technologies, such as haptic controls and simulation using digital twins in LongOps has been impressive. Alongside which, the level of international collaboration has meant new skills and partnerships have been formed. It was agreed the majority of funds would go to the supply chain, specifically SME's. LongOps has enabled new companies to enter the nuclear supply chain and engage directly with Sellafield Ltd, TEPCO and UKAEA as end-users. The academic community has also applied its knowledge and demonstrated value. The University of Manchester is now leading an academic consortium to support Sellafield's new Robotics and Artificial Intelligence Centre of Expertise extending the UKRI investment.

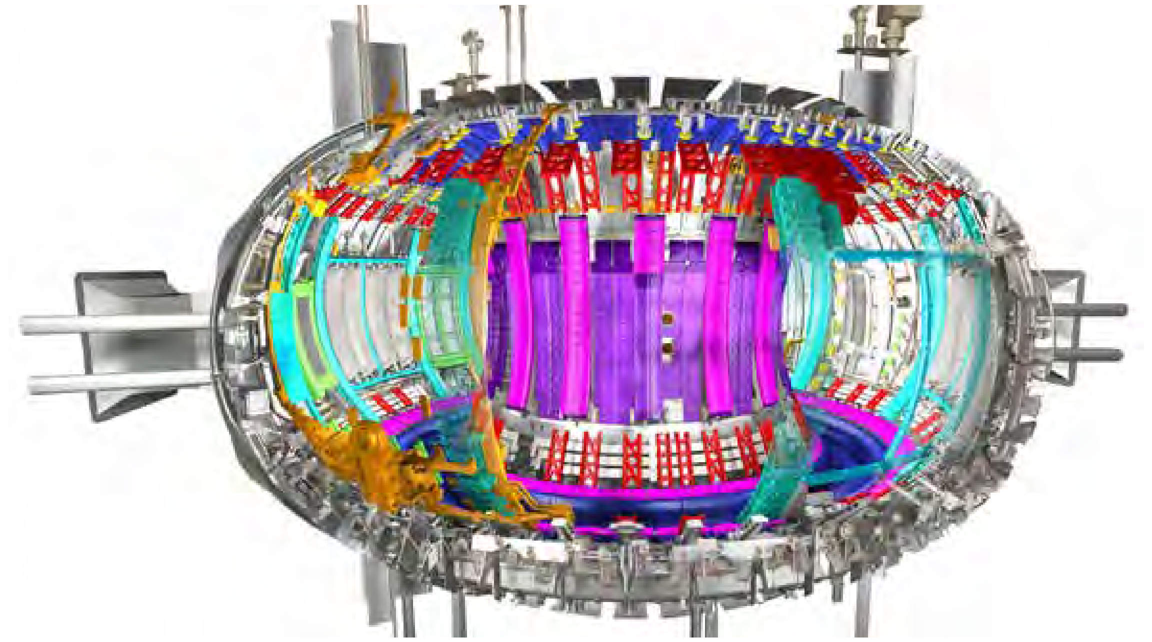
The aims of Innovate UK's work, through the ISCF Challenge Fund, has been to reduce human exposure to hazardous environments, so saving lives and reducing serious accidents; to develop efficient maintenance and decommissioning of infrastructures. The LongOps project has demonstrated what can be delivered in a short period of time and encapsulates everything I envisaged the RAI challenge would be at its outset. I am proud to have been associated with it.

**Andrew Tyrer**
Robots for a Safer World
Challenge Director

UK Atomic Energy Authority

# JDR

## JET Decommissioning and Repurposing



**As Director of JET Decommissioning and Repurposing (JDR) I find myself in an exciting place. JDR is a world-first programme harnessing high-end engineering and ground-breaking science. It is a great, multidimensional jigsaw, the completion of which will help the UK Atomic Energy Authority (UKAEA) complete its strategic mission to lead the delivery of sustainable fusion energy and maximise scientific and economic benefits.**

**As a large, UK government-funded programme, JDR has specific instructions from the Department of Energy Security and Net Zero (DESNZ) to consider. The programme must be delivered in a manner that is cost-effective and innovative, which develops and implements new technologies to position the UK for future international markets. JDR must consider Value for Money in the short-term (using resources efficiently) and in the long-term (undertaking activities that demonstrate the commercial viability of the future fusion power plant industry).**

JDR is dependent on UKAEA Divisions such as RACE, the centre of expertise for robotic development and delivery - RACE will be designing and implementing technologies that could have a significant impact in the commercial marketplace. JDR also provides inputs to other UKAEA programmes such as LIBRTI (Lithium Breeding Tritium Innovation), which forms part of Fusion Futures initiative. JDR will also influence the design and operations of STEP, the prototype fusion powerplant to be built in north Nottinghamshire, just a few miles from my family home.



In early summer 2024 JDR will be delivering its first practical projects. JET's remote handling capabilities have been significantly upgraded and we will be ready to start extracting and analysing samples from inside the tokamak. These are significant steps at the start of a 15+ year programme, meaning there is still plenty of room for further development and innovation, and because of that, we are delighted to be working closely with the LongOps team.

I expect LongOps to be a critical partner for JDR: providing the capability to train multiple new remote handling operators on digital simulators (at the same time as current operations are being delivered); turning design concepts for new tools into reality in a simulated environment where Techniques Tactics and Procedures can be tested and honed; and quickly adapting the virtual workplace to plan for unforeseen circumstances.

The technologies developed through LongOps will help JDR demonstrate the cost efficiencies and innovation required by DESNZ and will help showcase UKAEA's ability to deliver sustainable fusion energy. JDR can provide a real-world case study for the capabilities developed through LongOps and facilitated by RAICo – an opportunity to present cutting-edge technology to new customers, in the fusion or fission sectors, or wherever the intelligent use of robotics can provide tangible benefits. Indeed, these are exciting times.

**Zac Scott**
Director of JET Decommissioning & Repurposing (JDR)

# The LongOps Story

THE BEGINNING →

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# The Beginning

**The Joint European Torus (JET) fusion experiment has been in operation at Culham in the UK since the 1980s. Because of the hazards present in the machine, robotic systems have been developed and operated to upgrade and maintain the machine over several decades. Because of this need, significant experience has been developed around the operation of long-reach robotics for use in hazardous environments, including a unique Remote Operations team, with experience of planning, rehearsing, and delivering remote operations.**

Since the early 1990s at JET, virtual reality and digital twin mock-ups have been used to help with planning operations, training robotic operators, and the provision of additional supporting views and information during live operations. At UKAEA, remote operations capability had been developed over many years by operating robot- and remote handling tools in sophisticated mock-ups of parts of the JET tokamak, prior to the eventual deployment in the JET reactor. This use of mock-ups allowed the team to build capability in a safe environment, gradually decreasing the risk of operation in the real environment. A particular emphasis was given to the use of digital mock-ups for training and task development.

Following the 2011 disaster at Fukushima Daiichi, UKAEA took part in several workshops bringing together UKAEA, NDF, and TEPCO, to share experience on the use of physical and digital mock-ups and how these mock-ups can help with planning operations and building team capability. The LongOps project was developed following these workshops to explore the development of operational and technological capability, sharing knowledge and best practice between the UK and Japan on digital tools to de-risk remote operations.

# The Vision

**LongOps set out to build capability, knowledge, and relationships around technologies related to the de-risking of decommissioning operations including through the use of digital mock-ups. The flagship activity being an integrated Next-Generation Digital Mock-up prototype showing how innovative R&D in a range of related topic areas could be integrated to aid in the solution of decommissioning challenges over long timescales and involving long-reach manipulators.**

We defined three exemplar use cases – representative examples of the problems needing to be solved at each of the end-user's sites: JET, Sellafield, and Fukushima Daiichi respectively. This would explore how capability could be developed in the context of supporting decommissioning of accident-struck nuclear reactors, as well as the decommissioning of an end-of-life fusion experiment. The concepts of learning together, becoming "intelligent customers", and working collaboratively with industry and universities were built into the project design. The ambitious project was intended to engage with unsolved challenges that had a risk of failure.

We intended to act as facilitators, building links between problem owners, and innovative solution delivery organisations by making connections, facilitating workshops, and through regular demonstrations of the technological developments as they progressed through the project.

A part of the vision was to learn by doing, aiming to work in a collaborative mode with the suppliers for mutual benefit. The end goal was to create capability in people – teams with expertise, experience, confidence, and connections to be able to take on further innovation and engineering in support of remote operations at Fukushima Daiichi, the NDA estate, and for fusion devices.



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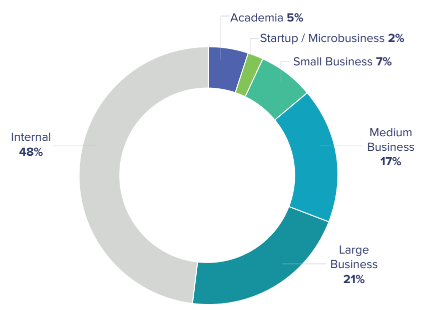
# The Achievements

**The LongOps project worked towards three main objectives:**

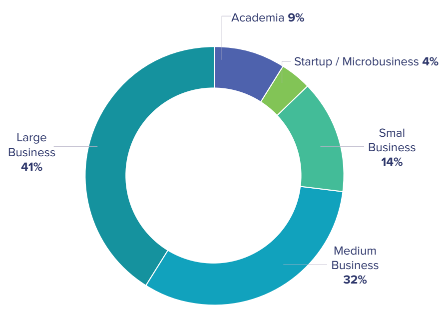
- ⟶ To strengthen the international relationship between Japan and the UK through knowledge and capability transfer.
- ⟶ To strengthen the relationship between the nuclear decommissioning sector and the supply chain.
- ⟶ To support innovation and development of nuclear decommissioning technology within the supply chain.

## PROJECT SPEND DISTRIBUTION



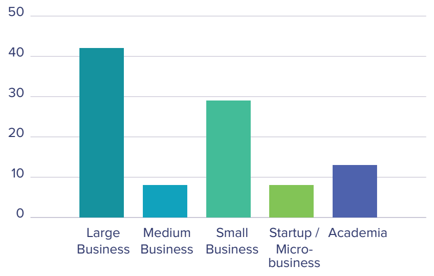

**Project Spend Distribution**
In support of the development of the supply chain, LongOps created a target for the project -to put at least 50% of the budget into the supply chain and UK industry. This ambitious goal was achieved through a variety of engagements, including international tender processes and SBRI contracts. The result involved over **40** contracts with over **20** suppliers from **4** different countries.

## EXTERNAL SPEND DISTRIBUTION




**External Spend Distribution**
Within this external spend, it was also important to LongOps and our stakeholders to engage with a variety of businesses and institutions that range in size from Large Business to Startups and Academia. The diverse procurement routes employed by LongOps allowed us to establish contracts representing over **53%** of the external spend with SME businesses and **5** separate contracts involving academic institutions.

## SUPPLIER DISTRIBUTION




**Collaborations, not just contracts**
The LongOps project has always been considered a research project, aiming to push innovation and development of novel technologies within the supply chain. This greatly shaped the way we structured and managed the contracts with our suppliers. Rather than simply defining deliverables and holding the suppliers to them, the interaction between LongOps and our contracted suppliers was far more flexible than traditional procurement. Both scope and timelines were negotiated throughout the project in order to best serve the development and progress of each capability. Including, where appropriate, UKAEA researchers working with suppliers to deliver demonstrations, in some cases using UKAEA facilities and hardware.

*All sub-contract values are estimated



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## HIGHLIGHTS

Brought teams together from the UK and Japan to perform a **world-first full digital rehearsal of Fuel Debris Sample Retrieval** from a Fukushima Daiichi Unit, using the LongOps Digital Mock-Up.

Brought in expertise from the defence sector to engage with industry and develop a **unique set of standards** for the architecture of robotics systems in nuclear decommissioning.

Prompted the spin-out of **NavLive from Oxford University**, and facilitated demonstrations of new technologies in realistic mock-ups of nuclear decommissioning environments

Contributed to the **spin-out of HEROBOTS from the University of Naples Federico II** (UNINA) and the development of their flexible manipulator characterisation and control platform

Created a **first-of-a-kind simulator for training** and rehearsal on force-feedback manipulators

Deployment of collision avoidance control algorithms on TARM, a **multi-tonne 10-meter articulated manipulator** housed at RACE

Performed a first of a kind benchmarking study of two **multi-million-pound, best-in-class commercial force feedback tele-manipulators**

Developed a **training course** for the Responsible Officer role within TEPCO's remote handling team, who will **go on to perform fuel debris retrieval** from the damaged units at Fukushima Daiichi.


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# Project Overview

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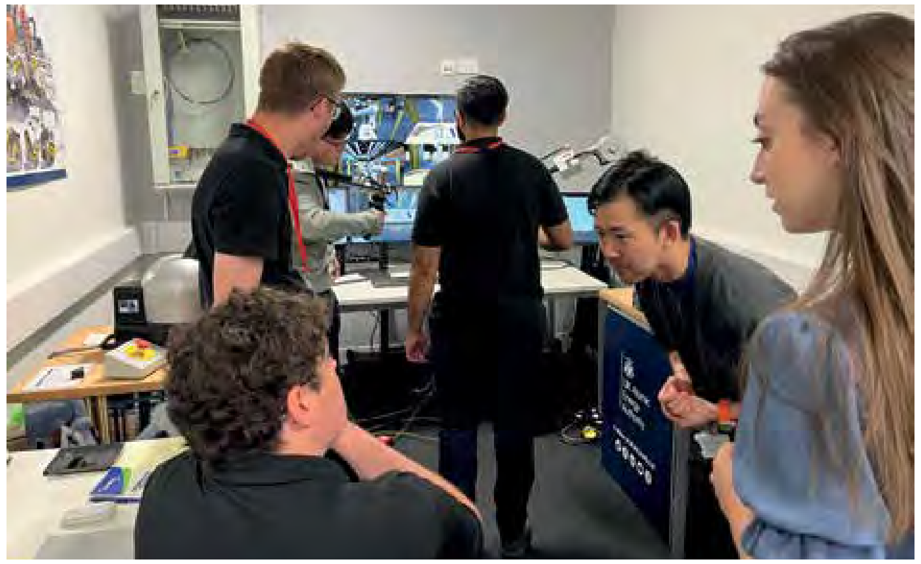
# Knowledge Capture

The primary goal of this task is to acquire and organise knowledge about challenges in various operational contexts. This initiative has two purposes: to help teams understand the challenges better and to prioritize research and development (R&D) efforts. We use workshops to engage with diverse stakeholders, challenge proprietors, and end-users to extract valuable information directly from primary sources.

Our overarching vision is to establish a comprehensive knowledge base that will inform future activities and guide the prioritization of LongOps' R&D initiatives. The conducted workshops are instrumental in acquiring and collating pertinent information essential for the enrichment of this knowledge base.

This methodological approach has many merits. It equips LongOps with the capability to gain profound insights into prevailing challenges and allows for the precise calibration of technological interventions. Notably, this initiative transcends the confines of the nuclear domain, facilitating effective communication of identified challenges to external entities, encompassing industry and academic spheres. Simultaneously, it engenders the cultivation of meaningful connections with stakeholders and end-users, establishing a foundational framework for enduring collaborations and reciprocal engagements. In essence, this initiative epitomizes a proactive strategy, endeavoring not only to address extant challenges but also to fortify collaborative pathways for sustained problem-solving endeavours in the long term.





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# Research

The purpose is to advance the state-of-the-art in the realm of nuclear applications through a two-fold approach: the development of novel technologies and the strategic adoption of existing solutions. This initiative is geared towards pushing the boundaries of current capabilities, fostering innovation, and ensuring that cutting-edge technologies are harnessed to enhance nuclear applications. By marrying the creation of pioneering technologies with the judicious incorporation of proven solutions, the aim is to propel the field forward, achieving advancements that contribute to the evolution and efficiency of nuclear applications.

The strategic approach involves the development of research activities at low and mid Technology Readiness Levels (TRL) with a focus on collaboration through public procurement and the Small Business Research Initiative (SBRI). This entails engaging with a diverse spectrum of entities, including academia, small and large companies, as well as startups. Notably, two robotics startups, NavLive (a University of Oxford spin-off) and HERObots (a University of Naples spin-off), have been successfully funded as integral components of the research procurement initiatives within the project.

The strategic framework incorporates in-house research efforts, integration activities, and direct engagement with end-users. During the project's lifecycle, specific emphasis has been placed on facilitating collaboration and knowledge exchange. Notably, the establishment of a collaborative environment is exemplified by the secondment of six researchers from Tokyo Electric Power Company (TEPCO) to the Remote Applications in Challenging Environments (RACE) facility for a period of three years. This initiative serves a dual purpose: enhancing the research capabilities through direct involvement in the project and simultaneously fulfilling an objective of on-the-job training for the secondees.

Additionally, the strategic initiative encompasses the establishment and funding of startups during the programme's duration. NavLive and HERObots, both originating from prominent academic institutions, stand as tangible outcomes of this collaborative and forward-looking strategy, emphasising the project's commitment to nurturing innovation and fostering partnerships across various sectors.

The overarching vision entails the pursuit of game-changing research within strategically significant technology domains. This involves the integrated demonstration of a diverse portfolio comprising small-scale research and development (R&D) studies. A pivotal aspect of this vision is the showcasing of proof-of-concept for the Next-Generation Digital Mock-up (NG-DMU), signifying a commitment to advancing cutting-edge technologies.

Central to this vision is the facilitation of knowledge exchange, emphasising the importance of disseminating insights, expertise, and discoveries across relevant sectors. The goal is to not only contribute to the scientific and technological landscape but also to foster collaboration and innovation through the sharing of ideas and advancements. By amalgamating groundbreaking research, diverse R&D demonstrations, and the tangible manifestation of forward-looking concepts like NG-DMU, the vision seeks to position the initiative as a trailblazer in strategic technology areas, catalysing transformative advancements and influencing the broader technological landscape.

The benefits derived from this initiative are multifaceted. First and foremost, there is a tangible enhancement of capabilities both within the internal framework and the broader supply chain. This development is not only crucial for the sustenance and growth of the initiative but also contributes to the overall strengthening of the industry's proficiency.

Secondly, the project serves as a practical problem-solving platform for real-world decommissioning challenges. By addressing these challenges head-on, the initiative becomes a catalyst for practical solutions, potentially revolutionizing the decommissioning landscape.

Furthermore, the development of a high-risk proof-of-concept for the Next-Generation Digital Mock-up (NG-DMU) stands as a notable benefit. This represents a significant leap in technological innovation, showcasing the initiative's commitment to pushing boundaries and exploring new frontiers in digital representation within the nuclear domain.

Lastly, the project's approach of de-risking technology areas by incorporating state-of-the-art solutions is a pivotal benefit. By adopting proven solutions from other industries and integrating them into nuclear applications, the initiative not only mitigates risks but also accelerates the pace of technological advancement within the nuclear sector. This approach contributes to the overall resilience and adaptability of the industry, positioning it at the forefront of technological innovation.

# Capability Transfer

**Purpose**
To share knowledge between LongOps project stakeholders to develop organisational and technical capability.

## Strategy

Share knowledge and experience captured and documented through workshops and sessions focussing on use cases from each stakeholder. Explore cases in more detail to support the aims of each partner.

Disseminate the output of the research activities. This will be done through regular demonstrations and user participation.

In addition to this, RACE will prepare a training course for TEPCO operators. This course will be based on the RACE RH operations training method. The course will capture and package the training and experience gathered over decades of preparing people to remotely maintain the Joint European Torus (, JET,) fusion device.

## Vision

LongOps stakeholders will develop and increase their capability to carry out safe and efficient remote handling operations in their own domains. This will be achieved through sharing their knowledge, experience and best practice developed over decades of work.

As areas of interest are identified, further focused workshops, demonstrations and training can be organised.

Specific training courses for areas of interest were identified at the start of and during the LongOps project.

All of this will stimulate collaboration between stakeholders and improve access to their specialist supply chains.

## Benefits

All stakeholders will benefit from knowledge captured, allowing them to develop and deploy technologies, techniques and best practice at an accelerated rate, making use of lessons learned over decades of work by all.

Stakeholders are kept up to date at regular intervals. User participation allows end-users to influence the direction of research activities. Researchers receive feedback from ends users ensuring that their output is applicable to real world applications, increasing the likelihood of integration and deployment of LongOps technologies.

Training provided to TEPCO operators will directly impact the work they are doing now. It will allow the TEPCO RH operations team to develop their own policies, procedures and processes.

# Knowledge Capture

USE CASE AND TASK ANALYSIS →

# Use Case and Task Analysis

**The LongOps programme focuses on the Research and Development (R&D) of Long Reach Remote Handling systems built around three international nuclear operations use cases: decommissioning in the UK (NDA/SL), decommissioning of the Fukushima Daiichi reactors in Japan (TEPCO), and fusion remote operations (UKAEA).**

**The initial task within LongOps was to capture existing knowledge from stakeholders to guide the research. This work was conducted using systems engineering methods and using hierarchical task analysis to understand the risks and requirements for unique decommissioning interventions. The end-user understanding of the requirements changed over time and this exercise was repeated throughout the program.**

The programme has developed LongOps Knowledge Base Models for the three use cases:
**1. Sellafield Windscale Pile 1** – LongOps Knowledge Base Model: A model developed in Enterprise Architect (EA) including diagrammatic representations of relationships between tasks, equipment and personnel.
**2. JET decommissioning and ITER remote maintenance** – LongOps Prototype Knowledge Base Model (LPKBM): A model developed in Enterprise Architect that includes the diagrams for JET and ITER use cases: use case definitions, equipment trees, organisation charts, equipment relationship diagrams, personnel diagrams, activity diagrams, concept design equipment, and equipment mapping.

The purpose of the knowledge bases is to create a universal model that can provide insights into relevant activities. Inputs to these models include end-users from across government, industry and academia, who present a variety of common purposes in relation to challenging nuclear environments. These include, but are not limited to:
**1. Suppliers** – The model aims to act as a single repository for RACE requirements, with clear linkage between the need, the function and the physical. Suppliers working from this common set of requirements for physical and digital solutions would be informed about how technologies are considered to integrate, roadmap technology maturity, and timescales. The model can support the identification of market gaps or exploitation in other demanding environments.
**2. LongOps stakeholders** – The model can act as a focal point for decision making about the prioritisation of R&D, future training needs and the viability of technology concepts.
**3. RACE developers and engineers** – This model can provide a set of common archetypes to identify common functions and systems.

Working with the supply chain, several task analysis studies have been conducted within the three use cases. Candidate process flows, architectures and tooling data has been captured from subject matter experts, lead technologists and end-user representatives. After each set of use case workshops a set of system engineering artefacts were produced to document the findings for future use. These include:
- Tepco Unit 3 use case:
  - o Hierarchical Task Analysis (HTA)
  - o Task flow model
  - o Operational challenges
  - o Operations risk assessment and mitigations.
- Sellafield Ltd. use case: Windscale Pile 1:
  - o Hierarchical Task Analysis (HTA) and Detailed Task Analysis (DTA)
- ITER Neutral Beam Maintenance use case:
  - o Initial task analysis (ITA), including equipment and operator knowledge capture.
- JET in-vessel component removal:
  - o ITA, including equipment and operator knowledge capture
- JET ex-vessel component removal:
  - o ITA, including equipment and operator knowledge capture


**TEPCO Responsible Officer (RO) Training**
The LongOps programme has also developed a training programme for TEPCO's Remote Handling team. This is the team that will undertake remote handling operations to retrieve fuel debris from the Primary Containment Vessels (PCVs) at Fukushima Daiichi.

Under LongOps, TEPCO requested a bespoke training programme designed around the role of Responsible Officer (RO). This role in RACE's JET Remote Handling Operations team has been replicated in TEPCO's Fukushima Remote Handling Operations team. The RO performs key functions including task planning in anticipation of operations and running the control room during operations.

To ensure accurate capture of every element of the RO role, a Systematic Approach to Training (SAT) has been employed. Utilising a structured and systematic approach the team were able to identify the responsibilities and corresponding knowledge, skills and attitudes obtained by a competent Remote Handling RO. The application of the SAT process was performed by ELS, a third-party training provider who specialise in training analysis and production, rooted in experience in the defence sector.

Based on analysis of the RO role in RACE's Remote Handling Operations team, RACE and ELS have developed a body of training material that includes learning specifications, lesson plans and course timetables. A complete written summary of key principles has also been produced to support the training programme. These materials will be used to deliver the training course in the UK. They are also intended to have continued use as a reference document by the TEPCO team, who are building long-term capability in order to perform a series of remote operations.

The training programme can be summarised into five main topic areas:
1. Remote Handling Systems
2. Task development
3. Task execution
4. Task supervision
5. Training and Team Development

An additional sixth topic is Safety, a 'golden thread' that runs throughout the other five.

The output of this work with ELS is a detailed analysis of the RACE Remote Handling Responsible Officer role. Training needs have been identified and documented, for the basis of the training course that has subsequently been design developed and delivered (training material) to the TEPCO operator team. The operators will receive the training from the RACE instructors in the near future.

The course provides structured training in the skills and competencies required to prepare and conduct remote handling operations in hazardous environments. The detailed lessons are not widely available or accessible to specialist teams carrying out long term remote handling activities. The 30 years of experience that RACE has in the field is now documented and accessible to others carrying out similar work or preparing to.


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# Research

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# Architecture and Standards

Decommissioning challenges in nuclear sectors require the integration of multiple pieces of software and hardware, often from multiple suppliers. Over decades, the maintenance and upgrade of these systems becomes expensive, mostly because of development effort. Standards, benchmarks, metrics and guidelines – like those developed under LongOps – will ensure modularity, reconfigurability, and reusability, ultimately reducing the lifetime cost of operating facilities.


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# Interoperability Standards

University of Sheffield
AMRC Advanced Manufacturing Research Centre

## IMPACT SUMMARY

**WORK:** In this work, an assessment method is developed to systematically evaluate software on multiple metrics: Scalability & Extensibility, Maintainability and Interoperability.

**NEED:** Robotic systems used in nuclear environments are often used over several decades. Over time, hardware may be added or replaced, to account for obsolescence or new operational requirements. software used within these systems must therefore be able to account for these changes flexibly.

**BENEFIT:** Use of this evaluation will allow system designers to make informed decisions about software – ensuring longevity, making integration of new equipment efficient, and improving safety and reliability through robust software communications protocols.

**IMPACT:** Ultimately this serves to reduce lifetime costs and improve operational agility in nuclear facilities which use remote equipment to perform maintenance, inspection or decommissioning.

The systems intended for maintaining, inspecting, operating, and decommissioning nuclear facilities, such as Fukushima Daiichi, ITER, and DEMO, are anticipated to integrate a multitude of systems from diverse suppliers. These systems are expected to have a long operational lifetime spanning several decades, during which requirements evolve, and effective obsolescence management becomes crucial.

Current networked and cloud-based technologies, encompassing robotics, digital twins, and tools, encounter significant challenges. These challenges include issues related to interoperability, heterogeneity, security, multi-robot management, common infrastructure design, maintainability, extensibility, quality-of-service (QoS), and standardisation. These challenges are particularly pronounced in the context of nuclear operations, where tasks extend over decades, necessitating real-time communication among a variety of robotic systems, often in critical applications. The inherent safety considerations and extended timescales underscore the importance of robust communication network properties from the outset of a mission.

For effective deployment, robotic systems must possess several key characteristics:

→ Scalability and Extensibility: Systems should be easily expandable to accommodate evolving requirements over many years of deployment.

→ Maintainability: Systems should be modifiable to reflect changes in system requirements over time.

→ Interoperability: Systems should effortlessly interact and communicate with other systems, ensuring seamless integration.

Evaluating software interoperability is a critical aspect, and despite the abundance of software evaluation methods, there is currently no established approach for assessing software interoperability, the goal is to characterise the protocol landscape using well-defined metrics. These metrics aim to be applicable across the entire system stack, addressing the communication requirements specific to nuclear operations. Additionally, they strive to cover both the concrete properties outlined in a protocol specification and properties present in abstracted representations of protocol communication.

The culmination of this effort involves a meticulous development and presentation of the breakdown for each metric identified. This detailed breakdown is a crucial component, providing a thorough and nuanced understanding of the interoperability landscape. By delving into specific properties outlined in protocol specifications and those present in abstracted representations of protocol communication, this breakdown offers a comprehensive overview of the system's interoperability capabilities.

Following this comprehensive analysis, an interoperability score is meticulously assessed and assigned. This score serves as a quantifiable measure, offering a precise evaluation of the systems' proficiency in seamlessly communicating and interacting within the intricate and demanding context of nuclear operations. This represents a groundbreaking methodology, as no such systematic approach to assessing software interoperability has been employed in the past.

This pioneering work, therefore, stands as a milestone in the assessment of software interoperability. The introduction of a quantifiable metric and a detailed breakdown mechanism represents a paradigm shift, providing a standardised and objective means of evaluating the efficacy of systems in complex and evolving operational environments.

The significance of this achievement extends beyond its novelty. The systematic evaluation and scoring mechanism introduced here are poised to make substantial contributions to the development of nuclear facility systems. By emphasising robustness, adaptability, and interoperability, these metrics become integral tools in ensuring the longevity and safety of nuclear facilities. This approach not only sets a new standard in assessing software interoperability but also reinforces the commitment to advancing technology in a manner that aligns with the unique and stringent requirements of nuclear operations.

# Generic Nuclear Robotic Architecture (GNRA)

## IMPACT SUMMARY

**WORK:** This work involved the development of an open standard to standardises the design, development, and integration of robotic equipment for nuclear applications.

**NEED:** Standards in defence applications, such as the UK's Generic Vehicle Architecture (GVA) and NATO's NGVA, are used to encourage maintainability, extensibility and modularity, to improve integration efficiency and operational agility. Various open standards exist in adjacent sectors for commercial and industrial robotics to reduce Through life costs.

**BENEFIT:** The draft Generic Nuclear Robotic Architecture (GNRA) developed in this work is a starting point provides the equivalent benefits for the nuclear sector.

**IMPACT:** Application of this standard not only reduces development and integration costs, it also maximises supply-chain efficiency and accounts for the strict safety and security requirements in the nuclear sector.

The primary objective of this work is to research, design, and draft an open standard for nuclear robotics, aiming to standardise the design, development, integration, interoperability, and overall through life capability management of technologies, devices, and platforms for robotic systems used in nuclear fusion and decommissioning operations.

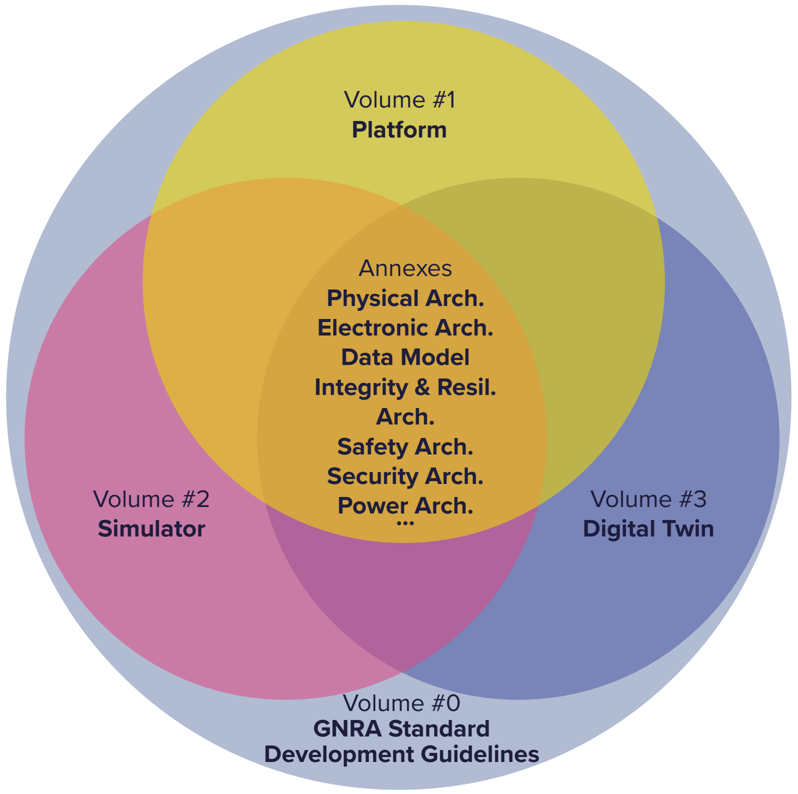
The commercial robotics industry has achieved great advancements in the past decade, but despite the exponential increase of capability, it is not easy to apply such technologies on a large scale directly to sensitive sectors, such as nuclear, due to their strict design, operation, and safety and security requirements. The increasing complexity of the devices, systems, system-of-systems integration, and proprietary/black-box designs make it even more difficult to cost-effectively achieve the desired requirements of the fully integrated system. Reduced capability, risk retention, and exponentially higher costs are often accepted when there is an urgent need for a solution, as evidently seen in defence with the use of urgent operational requirement contracts. In defence, the use of standardisation and encouraging inherent modularity and interoperability in the supply chain has been identified as the most effective solution to overcome these issues. It is considered, with a high level of confidence that the same would apply to nuclear robotics.

The creation process of such a standard for nuclear robotics could follow similar design steps of standards developed for military or defence applications, such as the UK's Generic Vehicle Architecture (GVA) and the NATO Generic Vehicle Architecture (NGVA). A nuclear robotics open standard would inherently improve software maintainability, extensibility, modularity, integration efficiency, and operational agility whilst reducing development and integration costs and maximising supply-chain efficiency.
The standard would cover communication (network interfaces, protocols), high-integrity & deterministic operation (networking, operating systems, applications), interoperability (system internal, system external, system-of-systems), Human-Machine Integration, rapid development & integration (middleware, data model), etc. One of the biggest challenges is future-proofing long-lived nuclear solutions which often require integration and interoperability between the existing legacy systems and future system designs. Therefore, futureproofing should lie at the core of this standard.

Currently there is no open standard tailored for nuclear robotics available to organisations and industry for use in operations, development, testing, and other activities. However, various types of open standards and technologies do exist in adjacent sectors such as commercial and industrial robotics, robotics-related technologies and devices supply, deterministic/high-integrity/safety critical systems interoperation and control, high-integrity teleoperator communication.

Industrial automation has made great advancement in robotic technologies, autonomous/semi-autonomous operations, centralised and remote managed operations, but it is believed that their design, development, and operational methodologies have not been advanced, tested or approved for the high-criticality and hazardous operational requirements of the nuclear robotics sector.
Security is also becoming an increasingly important requirement for highly connected robotics that operate in hazardous and critical environments, but current industrial and commercial robotics do not inherently provide the security protections that nuclear robotic operations would require to protect against serious threats from foreign State and Non-State Actor threats and terrorism activities.

Developing an open standard might be considered as a simple task due to its 'open' nature, but in reality it is a highly complex process that requires strategic organisation, targeted development activities, and long-term agile management. The technical elements of an open standard need to be simultaneously generic enough to support multiple technologies and designs to ensure that there is a high availability of a wide supporting product range and industry investment, while at the same time also be strict enough to ensure simplified and low-overhead interoperability and to protect against over specialisation where vendors develop solutions that indirectly lock-in the customers to a specific single-sourced product. In addition, the national and/or international political and commercial aspects need to always be an integral decision-making factor as each nation participant inherently tends to advocate for their own national government and industry interests. Failure to do so can result in an open standard that is well developed, widely available, but rarely used. The benefit of this work has been identifying the potential issues and the advantages associated with the challenges above.




**Architecture and Standards** - Generic Nuclear Robotic Architecture (GNRA)

# Teleoperation Manipulator Evaluation

The evaluation of industrial manipulators, particularly standalone unilateral usage such as industrial robotic arms, has been extensively studied and standardised. However, the same level of scrutiny and standardisation has not been achieved in the evaluation of telerobotic systems. In particular, bilateral teleoperation systems—those that provide force feedback to the operator—require evaluation on two primary measures: position tracking and force reflection. Despite their critical importance, there is currently no standardised method for experimentally assessing these aspects of bilateral telerobotic systems.

This project aims to address this gap by establishing benchmarking protocols for the evaluation of telerobotic systems. To achieve this goal, we conduct a comprehensive survey of existing assessment methodologies and approaches. Subsequently, we design and execute experiments aimed at capturing key performance metrics.

Bilateral teleoperation systems represent human-in-the-loop electromechanical setups. Consequently, during the evaluation process, we analyse performance criteria from two perspectives: objective and subjective measures. Objective measures include quantifiable characteristics such as accuracy, repeatability, force reflection, back-drivability, sensitivity, stiffness, and the presence of limit cycles and vibrations. These metrics will be assessed using various test equipment, with captured data presented in the figures opposite.

Overall, this project seeks to establish a standardised framework for evaluating bilateral telerobotic systems, thus facilitating advancements in this crucial field of robotics.





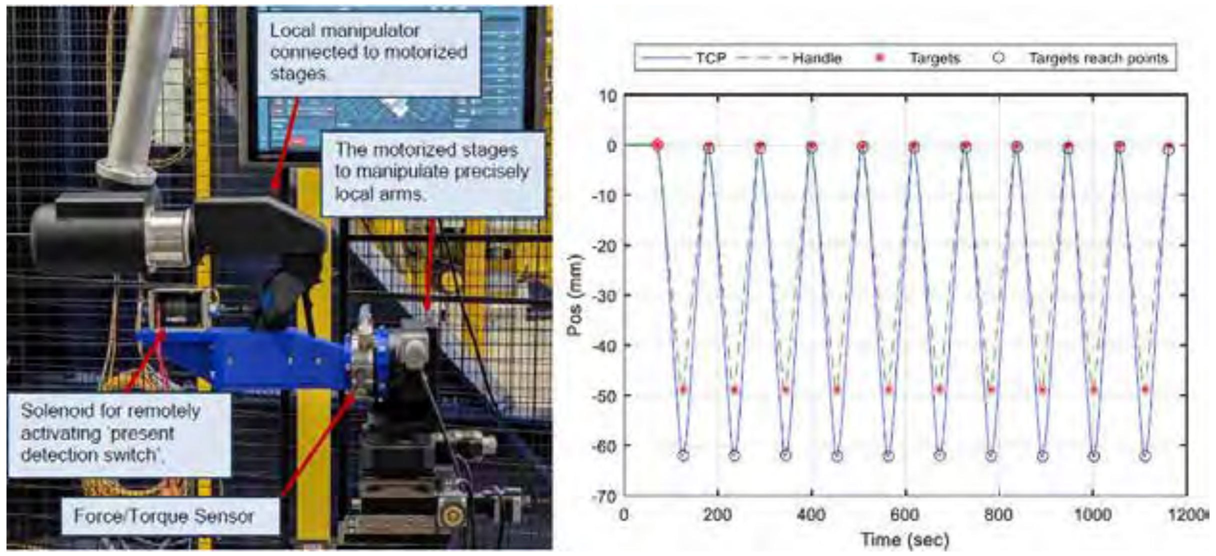



**Figure 1: Left motorized stages and force/torque sensor mounted to the local arm for remotely carrying out tests. Right: the handle and tool-centre-point (TCP) positions during bilateral accuracy tests.**

The latter aspect involves gauging the overall operator satisfaction and perception of the robotic system's operational capability, which encompasses factors such as task difficulty and handling quality. To capture this subjective feedback, conducting a user study is essential. During this study, various parameters can be observed and recorded, including the user's gaze (as depicted in the figure below), the motion of remote manipulators, and their performance across different tasks. This assessment involves both single and dual-hand devices to comprehensively evaluate the tele-manipulator system.

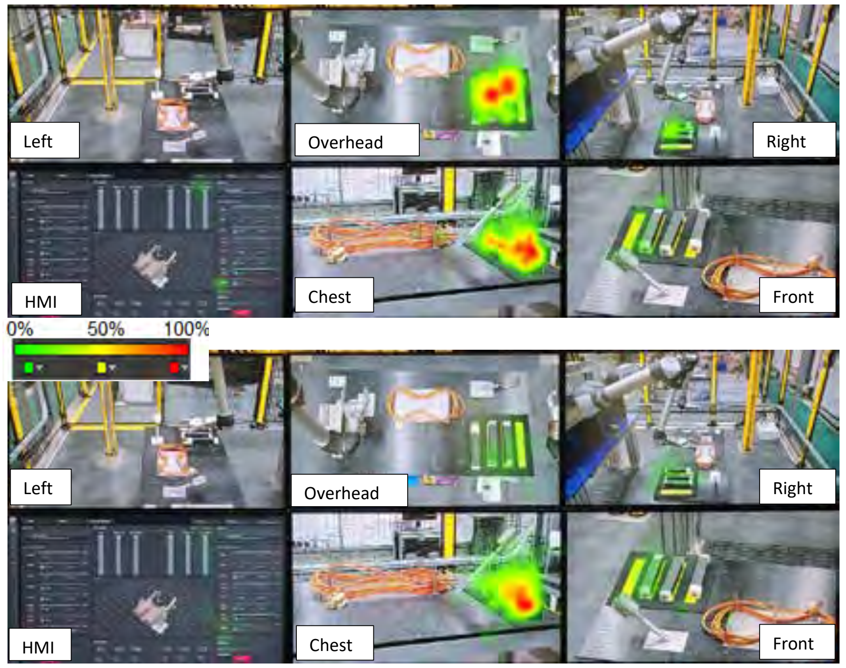



**Figure 2: Gaze heatmap of one of the tasks in the real system: top expert and bottom novice.**

A graphical representation illustrating operator opinions, recorded via questionnaires upon completing the experiments, regarding the tele-manipulator system is provided here:

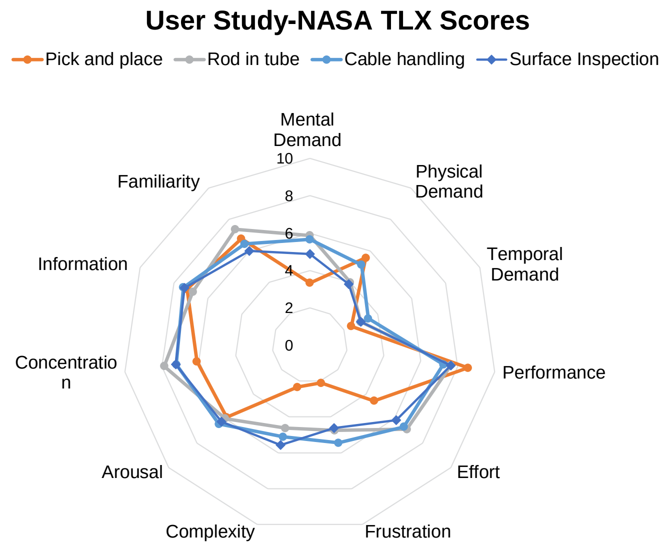



**Figure 3: Participants' response to the questions.**

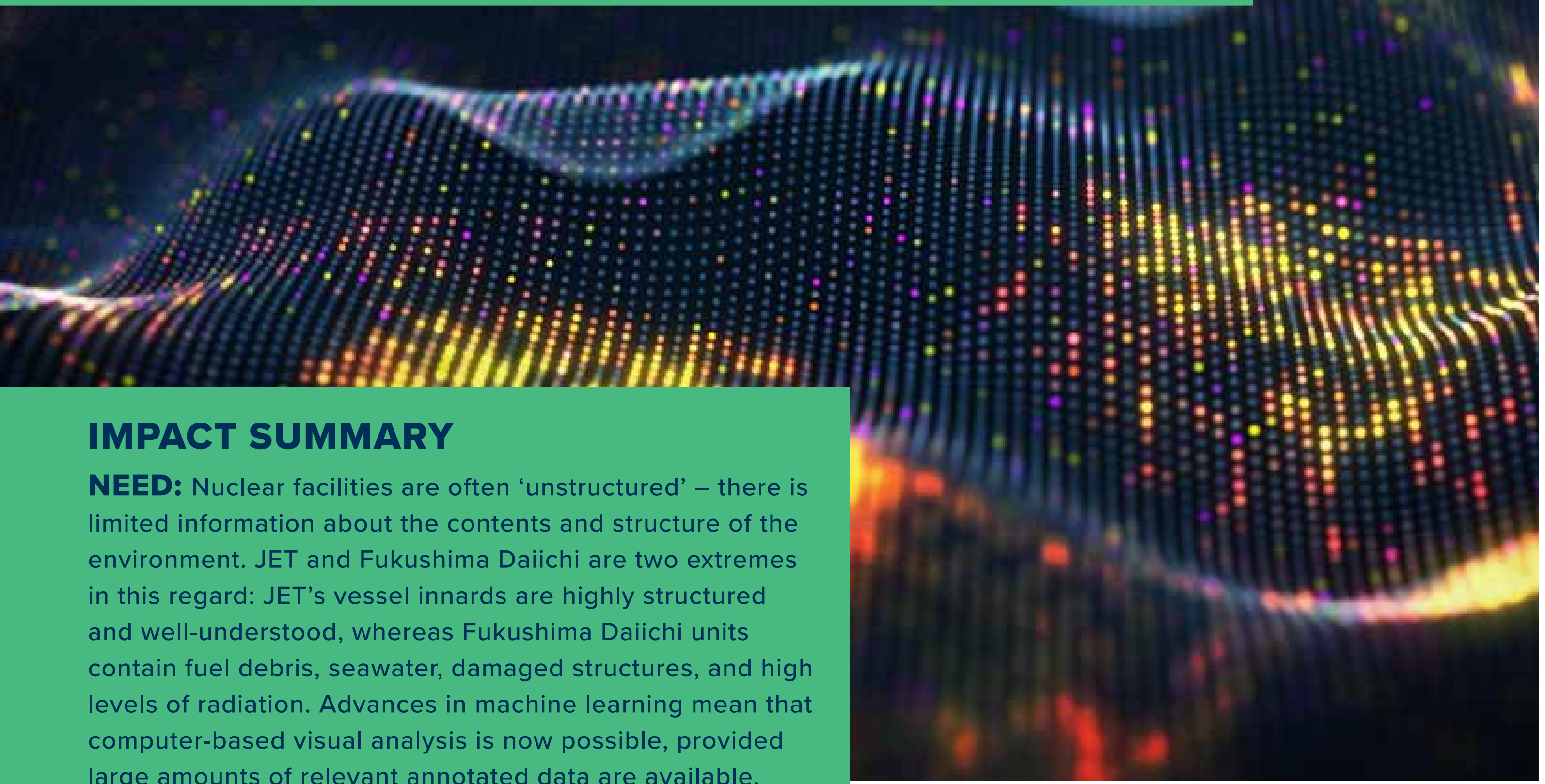
# Sensing and Perception

In nuclear environments, operators often deploy remote equipment with very limited information about the current state of the environment. In this work we apply some of the latest advancements in machine learning, sensor fusion, visualisation, simulation, and computer vision to nuclear decommissioning challenges. Providing this data to operators, using high-quality visualisation software, allows informed decisions to be made based on simulations and live condition monitoring. This ultimately serves to reduce risk when deploying remote equipment into unknown environments.

# Datasets for the Development and Testing of Sensing Techniques

Jacobs

mtc Manufacturing Technology Centre



## IMPACT SUMMARY

**NEED:** Nuclear facilities are often 'unstructured' – there is limited information about the contents and structure of the environment. JET and Fukushima Daiichi are two extremes in this regard: JET's vessel innards are highly structured and well-understood, whereas Fukushima Daiichi units contain fuel debris, seawater, damaged structures, and high levels of radiation. Advances in machine learning mean that computer-based visual analysis is now possible, provided large amounts of relevant annotated data are available.

**WORK:** In this work, a pipeline for data preparation consisting of analysing and generating relevant datasets for remote inspection tasks based on data from JET and Fukushima Daiichi. This software pipeline was used to collect archive data, perform analysis and annotation of useful data, pre-process data into datasets, apply machine learning to these datasets, and finally verify the model's results using unseen data.

**BENEFIT:** Application of machine learning principles to high-consequence environments could help operators at JET and Fukushima Daiichi extract increased meaning from visual data collected during remote inspection. This is particularly valuable for monitoring aspects like corrosion detection within the damaged Fukushima Daiichi units, where corrosion accelerated by the reactors' exposure to seawater, should be carefully monitored.

**IMPACT:** The application of AI for tasks like object detection and condition monitoring can provide facility managers in nuclear decommissioning with better tools to manage risks and changes as they occur.

The main aim of this work is to develop a data-based decision support tool based on artificial intelligence capable of identifying objects to de-risk operations in structured and unstructured environments, JET, Fukushima Daiichi, and support training in teleoperated decommissioning tasks. Due to its sensitivity, Sellafield's data was not considered for this work, but the scenarios used are representative of the their requirements and use cases. To develop the artificial intelligence-based object detection tool, a complete software pipeline is being developed which consists of, but is not limited to, the collection of archive data from JET and Fukushima Daiichi, analysis, and annotation of useful data, pre-processing of data by the development of datasets, applied machine learning on the prepared datasets and analysed the artificial intelligence-based model's results on unseen data.



**Contract/sub-work package.** The contract for this work package was awarded to Jacobs as the main contractor and MTC as sub-contractor. The annotation of data for both JET and Fukushima Daiichi has been completed with the support of Jacobs and MTC. However, building datasets, training of applied machine learning models and analysis of models has been performed in-house.

**Benefits and impacts.** With rapidly advancing capabilities emerging from the field of artificial intelligence/machine learning, it is becoming possible to develop improvements in terms of visual characterisation, scene understanding, and sensory perception to support various robotic tasks, including reactive trajectory planning, adaptive grasping, cutting optimisation, and tool selection. However, the development of machine learning and any other learning-based models requires significant volumes of relevant, high-quality annotated data to achieve adequate levels of performance.

Within legacy nuclear facilities, the exact contents and location of items within rooms, vessels and isolators/gloveboxes are not necessarily known. In disaster sites, the contents and structure of the environment is unknown due to limited data being available following the catastrophe and subsequent activities. JET and Fukushima Daiichi are two extremes in terms of characteristics, with JET having low levels of dust in the air, low radiation levels in vessel during maintenance and shiny metal surfaces, and Fukushima Daiichi having both dry and underwater reactors with significant levels of particulates of fuel debris, areas having significantly damaged structures inside the reactors and high levels of radiation.

Object detection has been conducted on both datasets, namely JET and Fukushima Daiichi, as illustrated in Figures 1, 2, 3, and 4, respectively. Within the JET dataset, Figure 1b reveals the identification of Mushroom Tiles utilising Figure 1a as input, while Figure 2b highlights the detection of LHCD Antenna, Defect in LHCD Antenna, and A2 Antenna from Figure 2a. Similarly, the Fukushima Daiichi dataset showcases the identification of CRD Housing Support and electrical cables in Figure 3, along with the recognition of build up / fuel debris in Figure 4. Moreover, emphasising the significance of condition monitoring, particularly in the context of corrosion detection within Fukushima Daiichi, becomes imperative due to the reactors' exposure to seawater, which has the potential to induce a substantial and exponential increase in corrosion.

By performing the object detection and condition monitoring, the research work can provide support in the following tasks:

- Choose appropriate tools on the manipulator for any maintenance/ removal operations.
- Precisely position any tools on the robot end-effector with respect to the component for maintenance/ removal operations.
- Reduce human effort and potential for human error when positioning tools on components.
- To reduce human effort and potential for human error in the process of inspection of components.
- Detection of structures and engineering elements such as beams, grids, bolts, fuel element remainders.
- Check for safe robot navigation ability during exploration.
- Develop strategies for the deconstruction and removal of components.

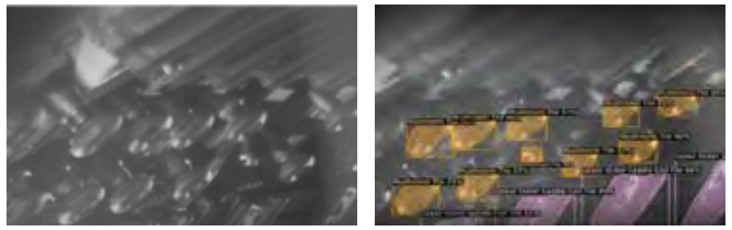


Figure 1: Detection of Mushroom Tiles in JET: a) original raw image and b) prediction results after analysis with trained deep learning model.

Figure 1: Detection of Mushroom Tiles in JET: a) original raw image and b) prediction results after analysis with trained deep learning model.

Figure 3: Detection of CRD Housing Support and Electrical Cables in Fukushima Daiichi: a) original raw image and b) prediction results after analysis with trained deep learning model.

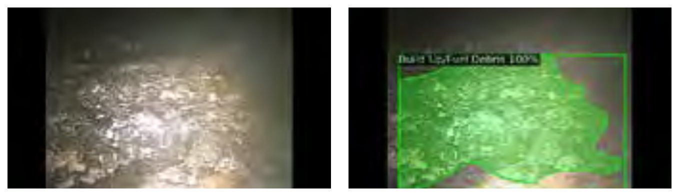


Figure 4: Detection of build up / fuel debris in Fukushima Daiichi: a) original raw image and b) prediction results after analysis with trained deep learning model.

# Incorporating Live Sensor Data into Digital Twins

## IMPACT SUMMARY

**NEED:** Decommissioning tasks at legacy nuclear facilities may involve the deployment of robotics and remote equipment into poorly understood environments, often relying on various types of sensors for information about the environment.

**WORK:** The focus of this work is the development of a digital platform that incorporates live sensor data from multiple sources into a digital mock-up. This included the development of a modular data pipeline, designed to use both real and simulated sensor data as input and process the data, including data validation and data fusion.

**BENEFIT:** The output of this pipeline was use-case tailored data augmentations displayed on a dashboard, presenting pertinent information and 3D visualisations to operators. This is designed to provide operators with more relevant and tailored information about the status of both the environment and the remote equipment being deployed.

**IMPACT:** Remote operations may involve large amount of data of different types, and operators are required to process and acting upon this information. Software assistance can reduce the cognitive burden on the operator, allowing them to maintain focus for longer and to make more informed decisions during their work.

The focus of this work is the development of a digital platform that would allow the incorporation of live sensor data into a digital mock-up. This included the entire data pipeline from the selection of the sensing devices, set up and calibration of the raw sensor input, and processing of the data including data validation, data fusion, and visualisation.

**Contract/sub-work package**

The contract for this work package was awarded to Jacobs as the main contractor, with MTC and PA Consulting as sub-contractors. Throughout the development of the project, weekly meetings were held among the three contractors and the LongOps team to discuss progress and steer the development in the right direction.

**Benefits and impacts**

The LongOps use cases present a range of environmental conditions, from low levels of radiation in a structured environment like JET to highly radioactive, highly unstructured, and partly submerged conditions in Fukushima. Hence, the platform is intended to be system and sensor-agnostic, and therefore a wide range of sensors, technologies, and sensor integration concepts were evaluated. This included practical tests of sensors and data acquisition, which were carried out in support of the development of a targeted perception pipeline (see Figure 1). The pipeline was designed in a highly modular fashion, which will offer great flexibility in the development of a Next Generation-Digital Mock Up (NG-DMU) to be used for a broad range of potential applications at Fukushima, RACE and Sellafield.

The project integrated a significant number of sensors to provide data into the pipeline deployed on a robotic arm mounted on a mobile manipulator and linear rail (see Figure 2). Besides sensor data, the pipeline integrated simulated radioactive sources which were overlayed into the real environment. Monitoring data and health indicators of the different software and hardware elements of the system provided means of system self-awareness, demonstrated by fault injections in the form of synthetically generated radiation-induced effects and blur in images or device disconnection. An image filtering pipeline improved image quality when these faults occurred. Filters were applied to point cloud data to reduce bandwidth allowing faster delivery to operators. Detectors for corrosion, objects and line features were implemented using various methods from classic computer vision to machine learning. These detections were located in a virtual volumetric map generated by the pipeline using simultaneous localisation and mapping. A broad spectrum of data was visualised, partly in 3D and partly in a dashboard.

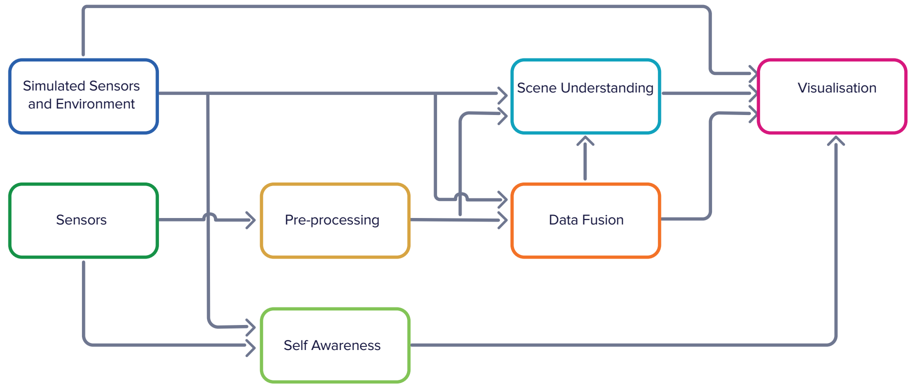


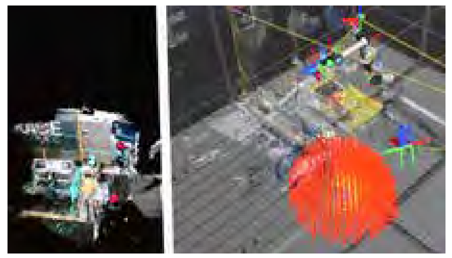

**Figure 1. High-level overview of the perception pipeline.**

Feedback from operators has been generally positive, with engagement on how to improve the system. Follow-up work bringing all the LongOps research work together, has already incorporated elements of this platform into the NG-DMU to be developed further.

a) Robotic arm mounted on a mobile robot used to deploy sensor rig.

b) Robotic arm mounted on an actuated rail to deploy sensor rig.

**Figure 2. Different configurations and mounts for the sensor rig: a) on a mobile platform and b) on an actuated rail**



a) Radiation simulation overlayed in the virtual representation of the sensed data

b) System monitoring dashboard

**Figure 3. Radiation simulation and monitoring dashboard.**

Sensing and Perception - Incorporating Live Sensor Data into Digital Twins

# Automated Change and Anomaly Detection

## IMPACT SUMMARY

**NEED:** In nuclear decommissioning tasks, remote equipment is used to deploy sensors and gather information about an environment. Data is captured periodically to assess the condition of a nuclear site before and during its decommissioning.

**WORK:** A novel methodology was developed for change and anomaly detection. This technique can be performed during inspections. Using a scanning device deployed on a robotics platform, are used Simultaneous Localisation and Mapping (SLaM) techniques to create an 3D model of a site, enhanced with capabilities that support the decision-making process.

**BENEFIT:** The main output of this work is the development of an automated technique which can compare point clouds – data representations of 3D scans of an environment – to detect changes in geometry i.e. positions of items or changes in structure of an environment. Changes in other properties can also be mapped onto the point cloud: in demonstrations temperature was used but this could be extended to properties like radioactivity. These changes are highlighted in a 3D visualisation of the environment.

**IMPACT:** Visualisations created using this technique can be used to efficiently identify changes in an environment, and therefore make informed decisions about maintenance and decommissioning in nuclear facilities.

The aim of this work consisted of the research and development of novel methodologies for change and anomaly detection while conducting inspections and data surveys from the various use cases among our stakeholders. This work is driven by the requirement to capture data periodically to assess the condition of a nuclear site before and during its decommissioning. To carry out decommissioning activities safely, it is important to have an up-to-date, informed model of the site enhanced with capabilities that support the decision-making process. Such capabilities were identified and tackled in this work as geometrical and physical change detection. For the former, novel techniques related to geometrical, multi-scale change detection were developed, implemented and tested, for the former, thermal change detection using a thermal camera was integrated into the sensing system.

**Contract/sub-work package.** This project was awarded to NavLive with support from Jacobs for field test locations, customer insight, and access to their digital twin portal. The final internal demonstration for this project occurred on the 13 December 2023 at the Jacobs Integrated Innovation for Nuclear Decommissioning (IIND) test facility in Warrington, England. Three previous demonstrations were conducted in the same test facility throughout the project.

**Benefits and impacts.** The use cases identified during LongOps require an up-to-date condition model in advance in order to plan its decommissioning as well as periodical assessments while decommissioning. This requires the deployment of sensors to capture geometrical and physical/radiometric information from a site. The main benefit of this work consisted of the development of an automated, marker-free geometrical and thermal change detection tool capable of informing operation planners. An overview of the system architecture developed can be observed in Figure 1. Further, the captured data is loaded into a cloud BIM for storage, remote visualisation and analysis.

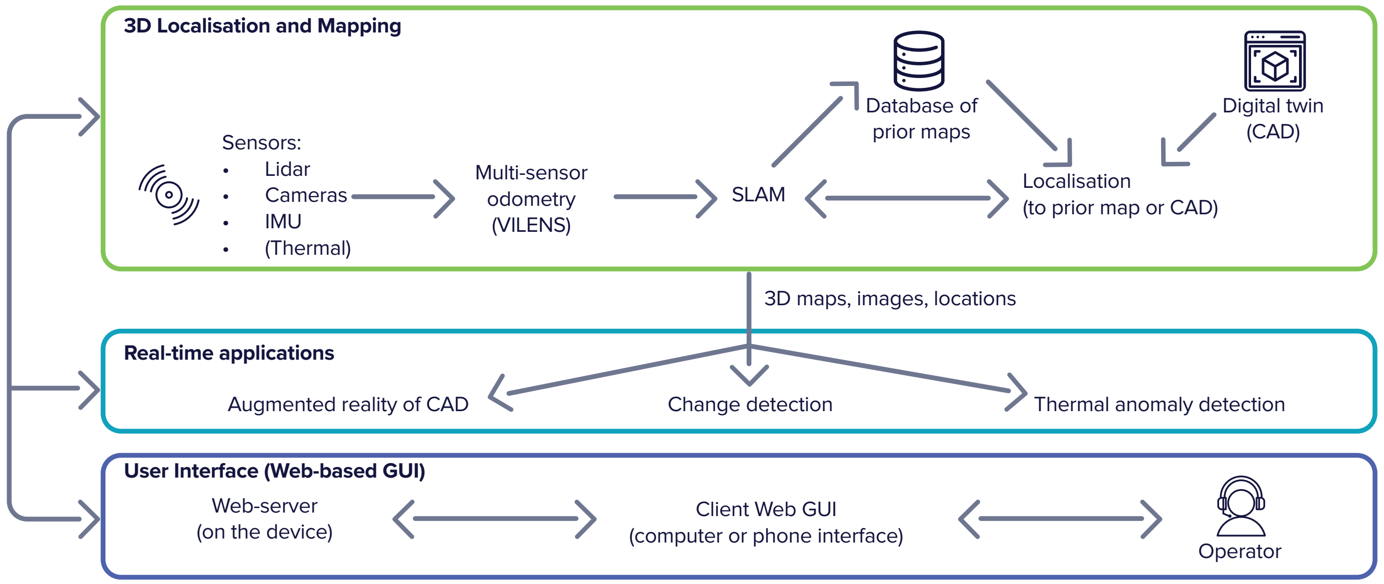



**Figure 1. An overview of the system architecture. The user interacts with either the 3D scanner or a cloud-based platform.**





Sensing and Perception - Automated Change and Anomaly Detection

The experiments took place in a location representative of a decommissioning site named IIND cell, located in Warrington. The scanning device captured data using a hand-held configuration as well as mounted on a remotely operated vehicle (ROV). Also, for the sake of demonstration and to test reliability of use in vibrating platforms, the sensing equipment was also mounted on a long boom manipulator as shown.

a) Frontier scanner mounted on a mobile robotic platform.

b) Hand-held version of the scanner.

The sensor fusion approach is based on proprioceptive and exteroceptive sensor data allowing it to behave robustly even on vibrating/shaking scenarios, a common situation faced in remote operations.

To carry out change detection, multi-session mapping was carried out (see Figure 3). This was required to baseline the condition of the site and identify changes.

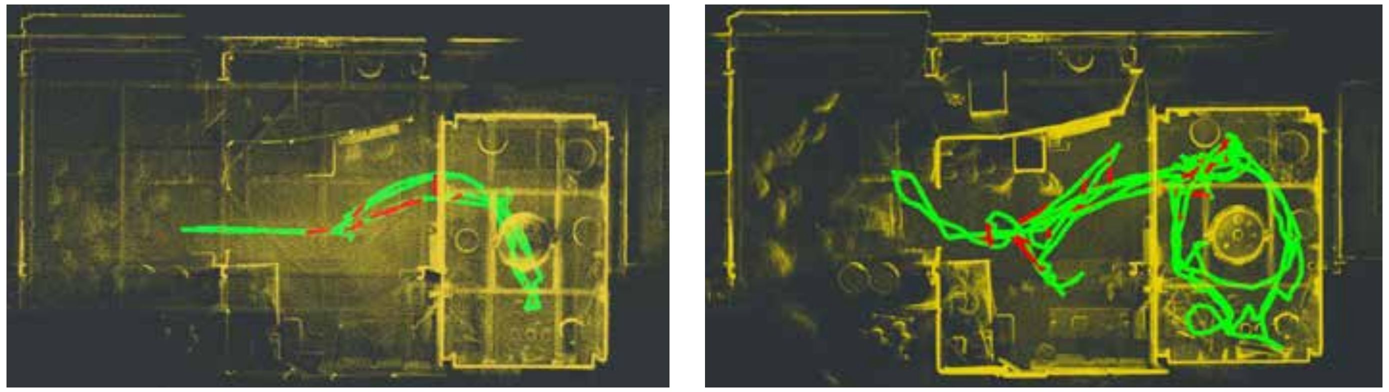


**Figure 2. Two examples of multi-session mapping combining the "before" and "after" maps. The green lines represent the sensor trajectory from two different missions, the red lines represent loop closures between.**



**Sensing and Perception** - Automated Change and Anomaly Detection

In Figure 3, the output of change detection is shown. The blue points represent parts of the scene that have not changed. Red denotes points that have changed between scenes (within a 5cm margin).

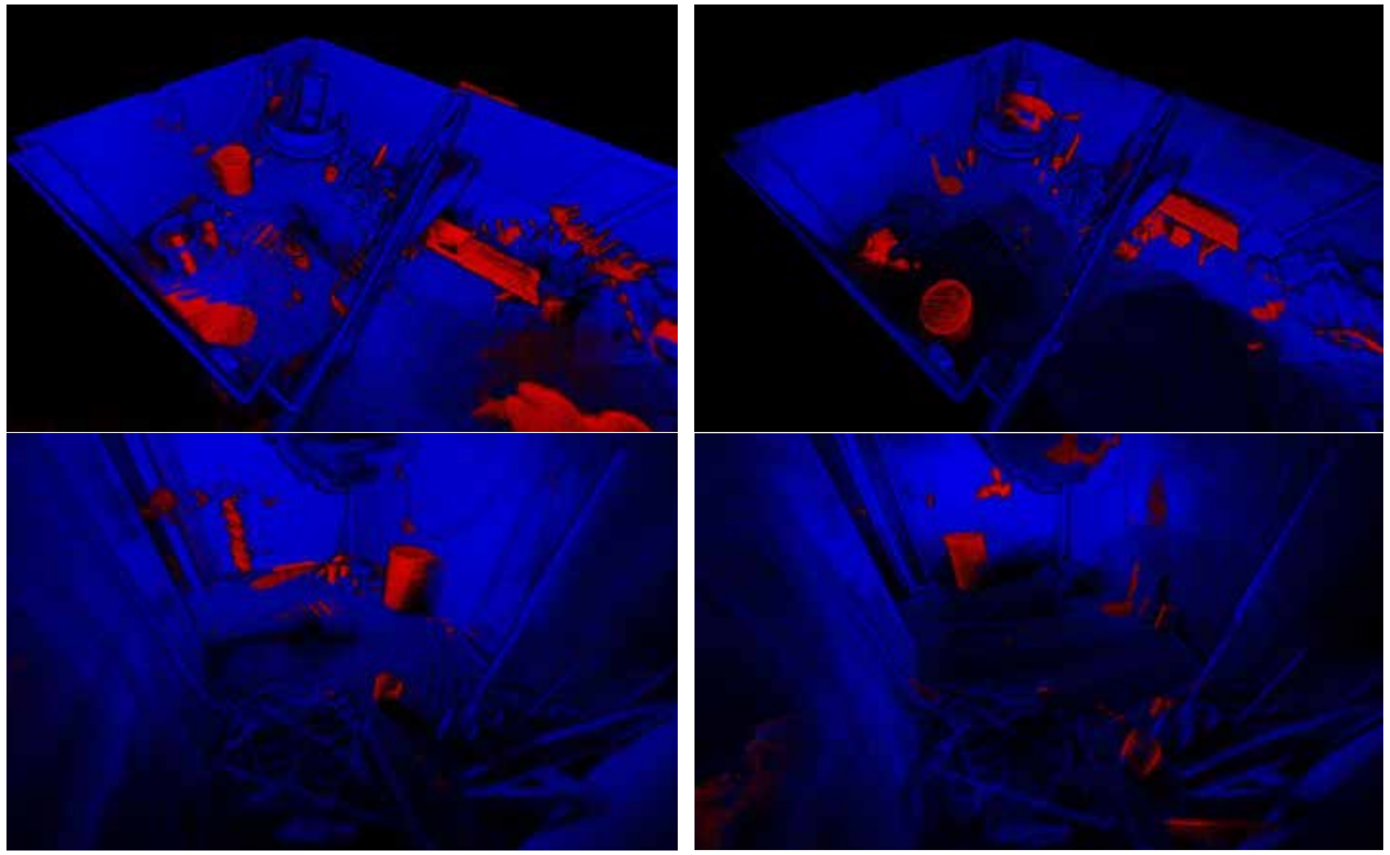
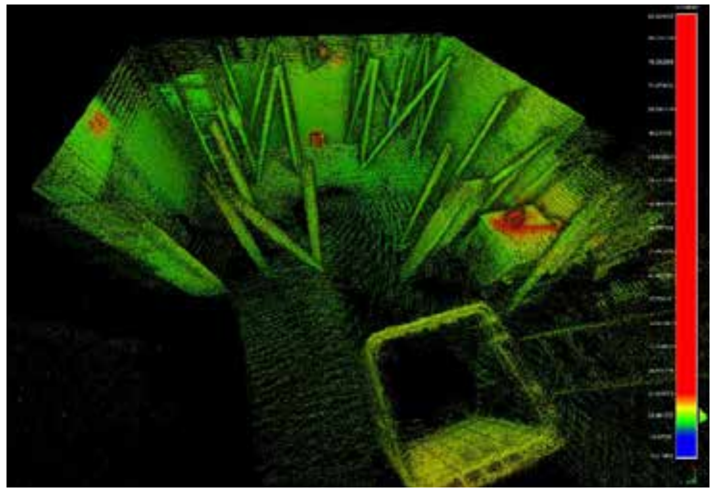


**Figure 3. An example of change detection: The Left images show the "before" scene and the Right images show the 'after' scene. The blue points represent parts of the scene that have not changed. The red points presents points that have changed between scenes.**

To perform thermal change detection, a thermal camera was integrated into the sensing system and mapped to the point cloud. In the test cell, some surfaces were heated and hot elements were introduced. The output is shown in Figure 5.



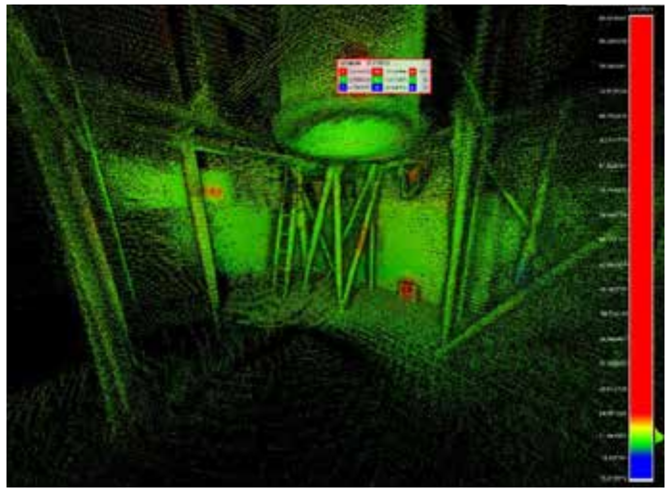


**Figure 4. Thermal differences overlayed in the point cloud.**

# Long-Reach Manipulators

Long-reach robotic manipulators enable remote operations in challenging environments in nuclear environments. In this work we tackle some of the most fiendish challenges associated with flexible long-reach equipment: predicting deformations under gravity, reducing vibrations caused by movements, and planning movement through highly constrained environments. The main capability generated by this work is the ability to reduce the likelihood of collisions between the robots and the environments they are deployed into.



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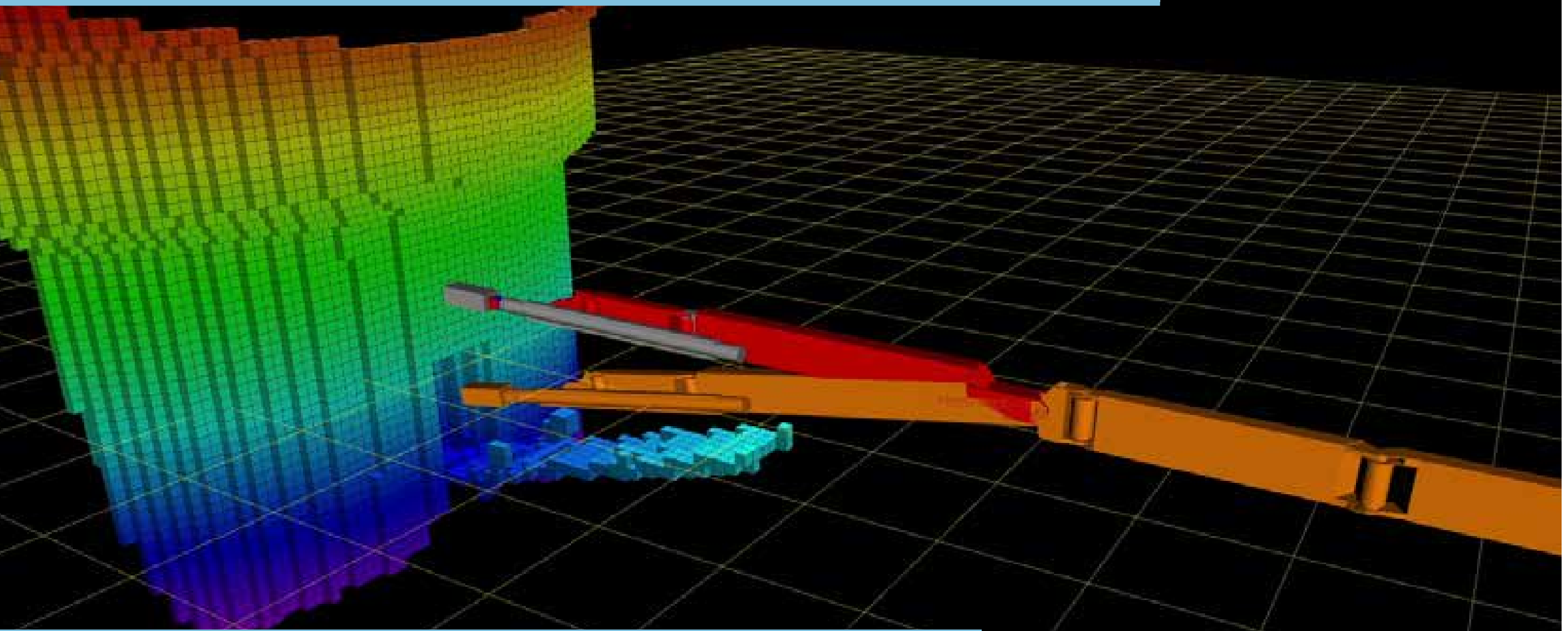
# Planning Tools for Long-Reach Manipulators



## IMPACT SUMMARY

**NEED:** Long-reach robotic systems are used to reach deep into environments which preclude human access. But long, slender manipulators are often excessively flexible, leading to deformation and vibration, making them difficult to manoeuvre. In such high-consequence environments, collision avoidance is imperative, and as a result operations are often slow to plan, rehearsal, and perform.

**WORK:** In this work, an automated motion planning system was developed to provide optimum safe motions, based on pre-known and online measured conditions.

**BENEFIT:** This tool can create an optimised robot trajectory according to various safety metrics selected by operators. It provides additional risk warning functions to enhance safety in operations, for example, by monitoring clearance between the manipulator and environment. The simulation can also be used to rehearse novel tasks, and even the effects of sensor noise or failure.

**IMPACT:** These tools allow operators of robotic equipment to plan, evaluate and reduce risk efficiently and safely in tasks involving long-reach equipment in confined environments. This is based on the needs of operators performing manipulation using long-reach systems in applications like fuel debris retrieval at Fukushima Daiichi and through wall operations at Sellafield.

The mechatronic designs of long-reach manipulators are very different from typical industrial or domestic robots. As such, there are currently no path-planning systems developed which can plan motions of long-reach systems effectively for demanding decommissioning missions, where operators may need to adjust and plan motions accordingly to the varying operation and environmental conditions, such as fuel debris retrieval at Fukushima Daiichi or post-operation clean out at Sellafield. Planning a manoeuvre in tight spaces with a long-reach system (prone to deformation under its own weight, as well as oscillation during movement) is a mentally exhausting task for operators, so semi-automated or automated path planning is a critical technical gap for future decommissioning work on essential demand for improved safety and efficiency.

**Contract/sub-workpackage**

As part of work package 3.3.1, AtkinsRéalis and University College London (UCL) have developed a software platform that allows for considering environmental data and sensor measurements to plan motions of long-reach manipulators via instructed way points in a semi-or-fully automated manner.

**Benefits and Impacts**

This project has achieved the following key contributions.

→ A modular software framework is developed and tested capable of planning long-reach manipulators' motions using the state-of-the-art techniques.

→ A multiobjective-optimisation-based motion planning function has been developed, so the system can plan motions based on different optimisation criteria and constraints.

→ The motion planning system can manage and take into consideration of different environmental data sets and use the data to automatically plan motions.

→ Operators can online adjust, plan, visualise, and execute motions of a long-reach manipulator

The motion planning system has been proven applicable to plan motions in practice, by testing and demonstrating the motion planning capability of controlling the telescopic articulated remote mast (TARM) at UKAEA. This system will be helpful to improve efficiency in planning decommissioning operations and enhance the safe awareness of planned motions.

Efficiency in planning operations can be significantly improved by using the motion planning system. The system allows the automatic suggestion of a sequence of safe motions by defining waypoints. Such a planning process was typically carried out by manual adjustment that is laborious and time consuming. Now, different missions can benefit from the results of this project, as the developed system is designed to be easily modified.

The motion planning system is built on a simulated environments, so it can be easily used as an operation training system. Different configurations can be applied and modified to retrofit the planning system to enable different use cases. For instance, sensor noises or even different types of failure events can be simulated, so the system can be used for investigating the impact on particular operations caused by any specific problem.

The developed motion planning system can provide additional information and monitor online data, so it can warn the occurrence of risky motions. GUIs are facilitated, providing the user interfaces to the implemented functions. Improvement on safety is another important contribution. The system allows for monitoring different safety-related metrics, such as manipulator-environment inter-distance. This gives operators an additional evaluation on whether the robot will be in a safe posture. Also, it can be used as an optimisation criterion to provide suggestions of safe motions.

**Figure 1 - Path planning and physical obstacle avoidance tests using TARM at UKAEA RACE.**

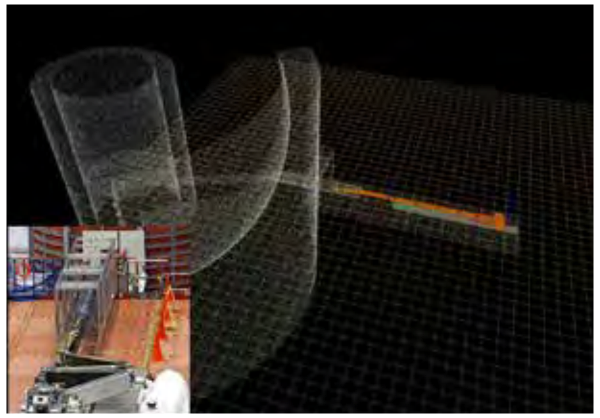


**Figure 2 - Simulation tests demonstrating capabilities for generating path planning solutions for Fukushima Daiichi Robot Manipulator.**

**Figure 3 - UKAEA, Atkins, TEPCO and UCL project team**

# Planning Tools for High Degree of Freedom Manipulators

## IMPACT SUMMARY

**NEED:** Long-reach manipulators are used in the nuclear industry to perform tasks which involve moving through constrained environments containing obstacles. Generating reliably safe motion plans is very challenging, particularly with manipulators with a large number of joints.

**WORK:** In this work, an algorithm has been developed which generates viable trajectories for moving robots through complex environments. This includes state-of-the-art techniques to achieve object avoidance and smooth motion, and introduces novel techniques that minimise radiation doses to the robot, and maximise the robot dexterity.

**BENEFIT:** This first-of-a-kind algorithm can automatically provide operators with optimum solutions for reducing the burden of planning complex manoeuvres. Multiple valid options are generated at a time, so teams can examine solutions and factor in additional considerations.

**IMPACT:** This algorithm has been developed in a generalisable way so that it can be applied to any tasks involving long-reach manipulators, including LongOps' core use cases at Fukushima Daiichi and JET.

Long-reach manipulators are typically designed with hyper-redundancy, enabled by a high degree of freedom design, to realise great dexterity. This allows the long-reach manipulators to access constrained and complicated decommissioning environments where there is usually no clear access to operation positions. However, the hyper-redundant design results in the computational challenge of finding possible manipulator motions that avoid collisions between any part of the robot and surrounding objects from infinite possible numerical solution spaces. Little previous work has been done on motion planning algorithms for high degree of freedom manipulators. The state-of-the-art only permits to plan motions of high degree of freedom manipulators by avoiding obstacles and optimising motion smoothness. There is no algorithm yet that allows for motion planning considering multiple operation factors, such as minimising radiation dose accumulated throughout the motion or maximising the robot-obstacle clearance.

To fill such a technical gap, this project develops an algorithm that computes candidate manipulation trajectories that safely guide a long-reach manipulator moving along target waypoints. After the operators select a desired trajectory, a smooth motion sequence is generated avoiding jerks and minimising radiation exposure, utilising a multi-objective optimisation method. The capability of the algorithm was shown via a demonstration test rig, which integrates two industrial manipulators as one system, yielding a 5 m long robot with 13 degrees of freedom. The algorithm was tested in two simulated environments, including the test rig in a mock-up scene and a long-reach system (with 9 degrees of freedom) in the JET vacuum vessel at UKAEA.

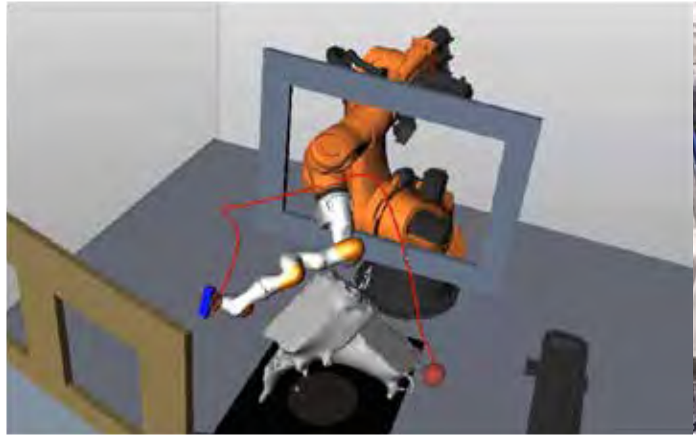
The developed algorithm is the first-of-its-kind that can potentially be applicable to nuclear decommissioning practice, as well as other safety-critical engineering sectors. In detail, this is the first theoretical framework that builds multi-objective optimisation function by design. The embedded multi-objective functionality allows for taking into account different operational considerations in a customisable way. Considerations, such as the exposure to radiation at certain components or the distance away from specific hot spots, are way beyond the scope of pure academic research.

The algorithm can automatically provide optimum solutions, so as to relieve operators from excessive load of task planning. This permits to automate the motion planning process, implying significant time reduction for task planning in practice. As a result, the motion planning algorithm enables a core function suitable for any motion planning system, that is to generate optimum safe manipulation motions at a fast speed.

The project demonstrates the algorithm at a middle-range technology readiness level, showing the potential to be completely applicable to Fukushima Daiichi, Sellafield and Magnox sites, where long-range high degree of freedom manipulators can provide side access to confinement areas. Also, the algorithm is developed in a generalisable way that permits it to be tailored to custom-built long-reach systems.

This algorithm is purposely designed to generate multiple valid solutions by giving certain optimisation criteria. It can display different solutions in a digital twin before execution. This is an important feature in assisting the operation team, who may need to verify each robot motion prior to execution. The operations team can examine and confirm the best choice should there be any operational consideration that is not built into the planning algorithm. This design is particularly suitable for the safety-critical operations in the nuclear sector.

Beyond the primary focus, the demonstration includes a general task that firstly inspects a fallen structure and then reaches a position avoiding such obstacles. An industrial 3D scanning camera has been introduced to scan and generate 3D models of the unknown fallen structure. It directly proves the planning algorithm can cope with new inspection results, as the inspection progresses within a completely unknown environment.



# Modelling and Control for Flexible Long-Reach Manipulators

## IMPACT SUMMARY

**NEED:** Slender, long-reach equipment is seen in various settings in the nuclear decommissioning sector, where access is required to areas deep inside constructions via narrow ports. These systems are inherently flexible, leading to oscillations that are challenging to control during in tasks that require high accuracy and repeatability.

**WORK:** This project successfully developed a methodology realising a complete workflow to measure, analyse, and model flexible long-reach systems. A physics engine was developed to precisely predict the deformation and vibration of flexible manipulators in real time. It also provides an open-loop vibration control method that allows operators to move long-reach equipment with minimal vibration effects.

**BENEFIT:** This methodology has been demonstrated to provide simulations of three flexible manipulators: a small-scale test rig, a 10-meter heavy-duty articulated manipulator, and the prototype 22-metre manipulator for fuel debris retrieval at Fukushima Daiichi. Digital twins of these long-reach systems are developed accordingly.

**IMPACT:** This methodology provides guidance for engineering practice to understand complicated flexibility of long-reach systems. It shows that establishing good dynamics models can improve both accuracy and speed of positioning long manipulators. Operators can therefore perform tasks more safely, with higher confidence, and in a fraction of the time. The success of this method implies that deformation and vibrations in long-reach manipulators at JET, Sellafield and Fukushima Daiichi can finally be understood systematically to lower risks in practical deployment.

In the nuclear sector, decommissioning sites usually feature areas with small access ports and intricate geometry. To be able to comply with these constraints, manipulators used for internal remote operations often have a slender design, making this class of system inherently flexible and subjected to non-negligible oscillations during motion. This poses a big challenge for the engineers having to use these manipulators for high-accuracy tasks. To enhance the performance of long-reach systems, it is necessary to tackle these problems and provide modelling and control strategies that can help engineers and researchers improve the dynamic performance of long-reach flexible systems.

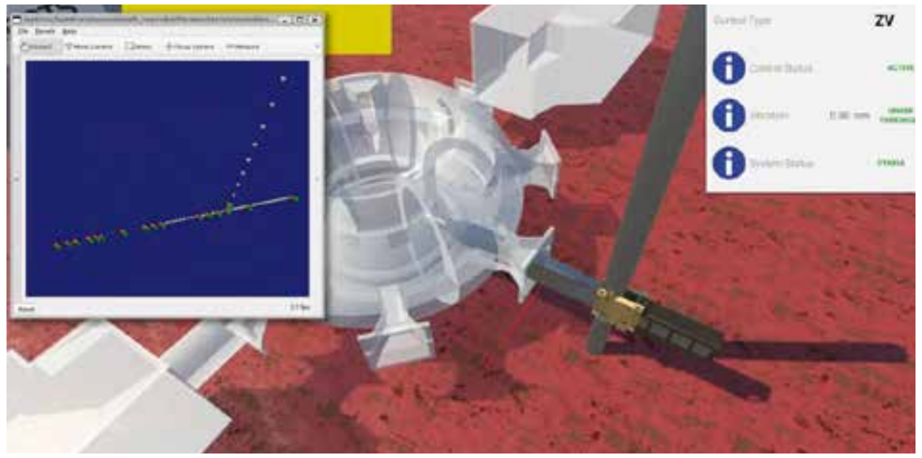




This project addressed a key technical gap, which is the absence of methodologies to model the complicated dynamics behaviours of flexible long-reach manipulators. A small-scale test rig with significant flexibility has been developed to validate the modelling methodology and, later, an open-loop vibration control method. The methodology is implemented using a physics engine, which can simulate the flexible dynamics, causing deflection and vibration, of long-reach manipulators. Specifically, the methodology has been used to create simulations of three flexible manipulators, including the small-scale test rig, a heavy-duty articulated manipulator over 10 m in length at the UKAEA, and the prototype 22-metre-long manipulator for fuel debris retrieval at Fukushima Daiichi.

This project successfully developed a modelling methodology, which has been a very challenging open question itself, applicable to long-reach manipulators. Significantly, the modelling methodology has been validated in practice. The success implies that the deformation and vibrations of long-reach manipulators, for example at Sellafield and Fukushima Daiichi, can finally be understood systematically and therefore support analysing risks in practical deployment.

Importantly, the project illustrates a complete workflow of identifying, modelling, and validating the complex dynamics of flexible manipulators. The developed workflow paves a generic way of modelling different long-reach systems, and it exceeds the typical research and development that is commonly just applicable to a specific system. As a result, it gives the possibility of properly estimating the time and financial cost needed for testing a bespoke long-reach manipulator, for operation preparation.



A novel physics engine has been invented achieving a middle-range technology readiness level. This physics engine can precisely predict the deformation and vibration of flexible manipulators in real time. This intuitively permits us to create an accurate digital twin, providing a visual 3D representation of flexible manipulators. The operators can visually assess and avoid risks, which cannot be analysed without such a model, using the digital twin in operations.

Nevertheless, the physics engine can be embedded as a core function in a digital mock-up system. It allows for simulating the flexibility of joints and bodies in long-reach systems. In contrast, common commercial-off-the-shelf physics engines are developed for simulating simple physical interactions, and they are not capable of simulating flexible dynamics. For the first time, a digital mock-up system can effectively represent dynamic behaviours of flexible long-reach manipulators.

In addition, the project utilises an input-shaping control algorithm that can compensate for the vibrations of flexible manipulators. The demonstrated control method is an open-loop approach suitable for controlling long-reach systems for limited operations, e.g., inspection, that does not interact with environments or objects. Furthermore, it gives great confidence in utilising the methodology and the physics engine to develop other advanced control algorithms, which are robust enough for practical deployment and capable of other remote operations. Hence, the advanced control can significantly improve the positioning speed and accuracy of long-reach manipulators, therefore, achieving the same operation quality using a fraction of the time needed at present.

# Vibration Compensation for Flexible Long-Reach Manipulators

## IMPACT SUMMARY

**NEED:** Long-reach robotic manipulators are used in nuclear environments to provide access with tools and sampling equipment into hazardous areas. However, these long, slender designs have inherent flexibility which leads to vibration. Control algorithms are critical for safely and accurately moving and positioning these devices.

**WORK:** In this work control methods were developed that use a model of a long-reach robot's dynamics to reduce vibrations. This is achieved in two ways. One feedforward control method is adjusting a manipulator's motions to minimise vibrations in contrast to nominally planned motions without considering vibration presence. The other method is to control the joint motions at a fast speed to counteract vibrations using a feedback control algorithm.

**BENEFIT:** During testing, the experiments show the ability to reduce vibration of a long-reach deployment robot for decommissioning at Sellafield using the feedforward control. Also, the feedback control can effectively compensate for artificially induced vibrations, which simulates unknown external impacts. This achieves reducing the duration of vibrations by two thirds.

**IMPACT:** This work demonstrates how advance control techniques can significantly improve the positioning performance of long-reach equipment, like that used in nuclear facilities, and so enhance operation safety against abnormal events. It also shows advanced control methods will help safely stabilise long-reach system into a safe status, against unexpected impacts.

In the applications of long-reach manipulators, the vibrations caused by flexible dynamics result in uncertainties in positioning performance, imposing potential risks in operation practice. Giving a particular long-reach manipulator, suitable control algorithms are essential techniques that realise fast and precise positioning performance by exploiting its hardware capabilities. Assuming a long-reach system can be precisely modelled, this project aims to explore practically applicable control methods that can supress vibrations and reduce the associated risks in decommissioning operations.

This project proposes two complimentary control methods to reduce vibrations, after the flexible dynamics of a long-reach system are studied. The first approach is to shape the motion profile of each joint in a flexible manipulator, according to a given motion profile, before operation. The other feedback control method is to utilise a multi-input-multi-output robust control algorithm to compensate for vibrations in real time. These two different methods have been tested using a flexible long-reach system, which is prototyped for through wall manipulation at Sellafield, in practice.

The control methods allow for controlling vibrations of a long-reach system developed for nuclear decommissioning for the first time. After an unexpected impulse is applied to the long-reach system, the duration of the resulted vibration can be reduced by two thirds. This clearly demonstrates that advanced control can significantly improve the positioning performance in practice and enhance operation safety against abnormal events.

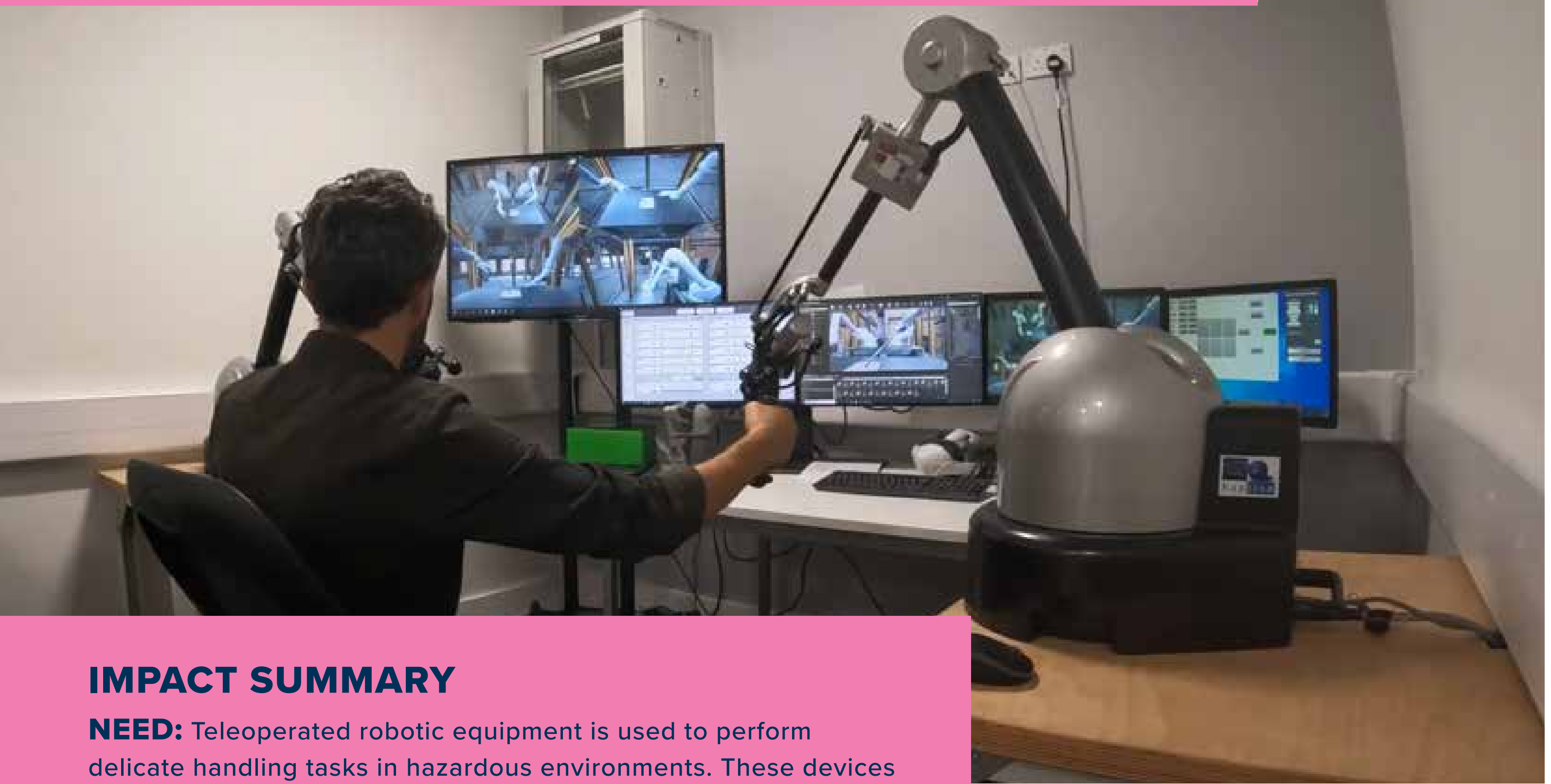
The success of this project indicates the importance and necessity of understanding long-reach systems' flexible dynamics. Both the motion reshaping method and the robust control method need system identification and dynamics models to achieve considerable vibration suppression performance. This clearly addresses the demand for the work of the "Modelling and Control of Flexible Long-Reach Manipulator", which develops a systematic methodology to identify, model, and validate flexible dynamics for long-reach manipulators.

This project shows the potential performance improvements, in terms of speed, accuracy and safety, of long-reach manipulators for nuclear decommissioning. Advanced control algorithms, such as adaptive control, passivity control, etc., have been suggested for future development. These control methods will enable absolute stability in changeable environments and adaptability to varying operation conditions, such as payloads or interactions with objects, so as to realise safer remote manipulation.

# Haptic User Interfaces

In nuclear facilities where human entry is prohibited, teleoperated manipulators may be used to perform delicate handling tasks. Highly sensitive force feedback is common in these devices, allowing the operator to feel forces through the input device that compliments the visual information they receive through camera views. In this work, a haptic training simulator is developed, modelled after flight simulation for pilot training. This allows operators to train in parallel, in a low-cost manner, and quickly switch between training tasks at the click of a button.

# Haptic Training Simulator



## IMPACT SUMMARY

**NEED:** Teleoperated robotic equipment is used to perform delicate handling tasks in hazardous environments. These devices are often 'force reflecting', providing operators with a haptic sense. Training new operators is time consuming because of the physical skills required, and expensive due to the high cost of haptic enabled devices. There is a need for representative training simulations, similar to those used in medical robotics and in air pilot training.

**WORK:** In this work a Haptic Training Simulator has been developed. This brings together software – a physics simulation with haptic rendering – with commercially available haptic-enabled input devices. This can quickly and cheaply simulate various tasks, where the training tasks, robots, and environments can be changed at the click of a button.

**BENEFIT:** This innovative approach can provide operations teams with practical experience and proficiency, without the need for physical prototypes, exposure to actual hazardous conditions, or risking damage to real robotic equipment.

**IMPACT:** This tool gives the potential for operations teams at JET, Fukushima Daiichi, and Sellafield to develop proficiency in navigating novel, complex scenarios, reducing risk and cost in training proficient remote operations teams.

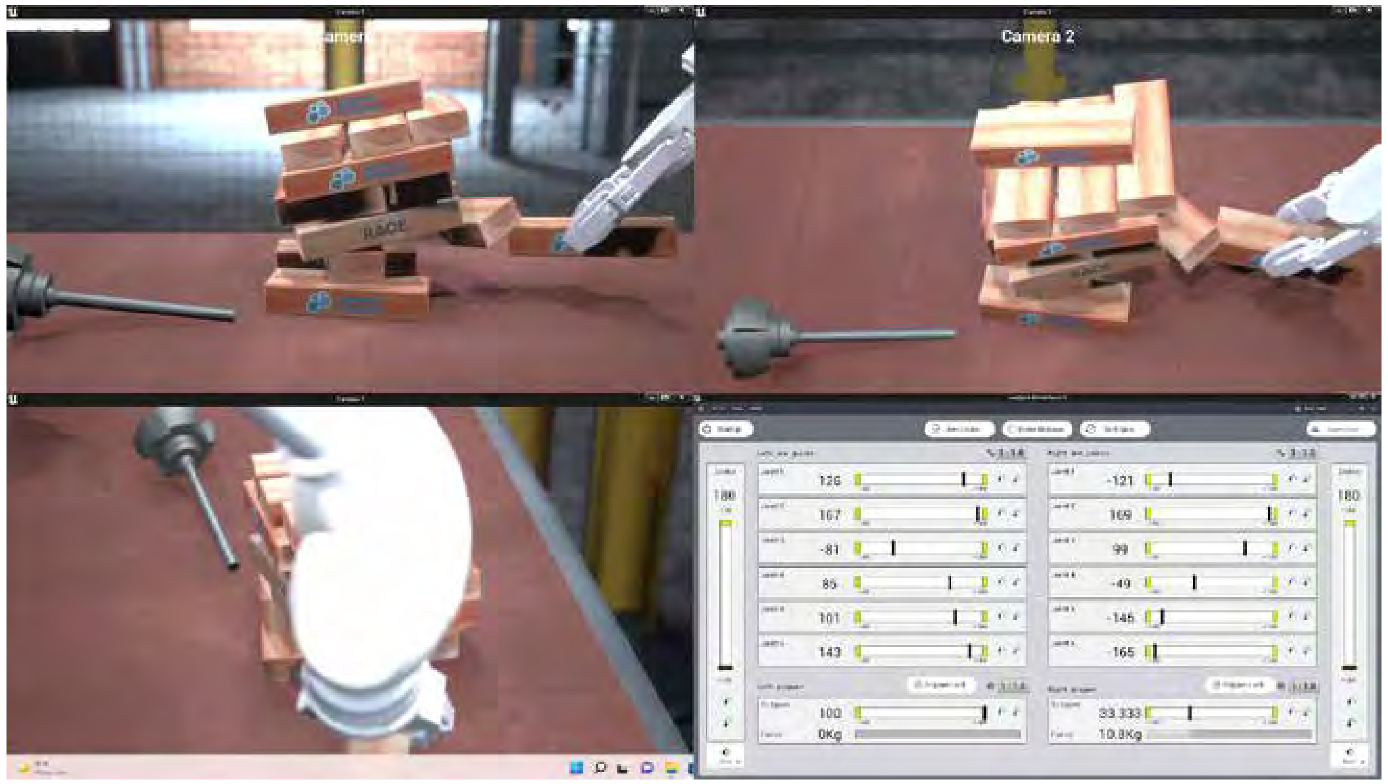
Robotic manipulations in contaminated environments often pose challenges that make full autonomy impractical for decommissioning or clean-out processes. As a result, remote robotic systems, where a human operator is actively involved in direct control and decision-making, are commonly utilised. In the nuclear industry, bilateral teleoperation systems play a crucial role by enabling remote manipulation of delicate materials in hazardous conditions, providing high dexterity, and offering sufficient force feedback to enhance operational safety.

However, the successful operation of such complex robotic systems requires operators to undergo extensive training. For instance, the maintenance of the Joint European Torus (JET) tokamak, a highly structured process, necessitates approximately six months of training for operators. Training becomes even more challenging when preparing operators for the demanding conditions imposed by contaminated environments or post-disaster scenarios, where factors such as low visibility, restricted motions in confined spaces, and limited interaction force come into play. Creating physical mock-ups for training may not always be feasible due to uncertainty about the actual operating conditions, while the use of bespoke robotic systems is often restricted by tight maintenance schedules and limitations on the number of available systems.

In operational conditions of this nature, a Haptic Digital Twin (HDT) emerges as a crucial solution. This comprehensive system integrates physics simulation, haptic rendering, and local haptic devices, playing a significant role in preparing operators to remotely manipulate hazardous materials in an economic manner. The HDT acts as a highly effective tool by simulating a diverse range of tasks, robots, and environments within the hazardous setting. The incorporation of a Haptic Digital Twin addresses the challenge of training operators in a manner that is both time- and cost-effective, offering a virtual platform for skill development. This innovative approach enhances the overall readiness of operators, providing them with practical experience and proficiency without the need for physical prototypes or exposure to actual hazardous conditions.

The HDT contributes to increasing the operational readiness level of operators by simulating diverse representative failure scenarios, such as actuator or sensor malfunctions and task setbacks. Additionally, the virtual platform allows for the development, verification, and validation of different remote manipulation tasks. This approach not only facilitates the efficient training of operators but also ensures their preparedness for unforeseen challenges in contaminated environments.

The Haptic Digital Twin (HDT) exhibits extensive applicability across diverse decommissioning processes, encompassing the robotization of nuclear gloveboxes and the Post-Operational Clean-Out Process (POCO). Its specific value shines through in the context of cleaning out the Fukushima-Daichi power plant, especially during the intricate fuel debris retrieval process. Operators can effectively harness the capabilities of the Haptic Digital Twin to develop proficiency in navigating complex scenarios without relying on physical prototypes or exposure to real hazardous environments. This streamlined training process significantly contributes to heightened safety and efficiency in nuclear industry operations.



# Haptic Interation of Rigid Materials with Fluids

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## IMPACT SUMMARY

**NEED:** Robots which provide operators with force feedback are used in an increasing set of scenarios. Beyond their historic use in tightly controlled industrial environments, these devices are now being used to perform tasks in highly complex environments. Incorporating these scenarios into a haptic training simulator can address the need for efficient, low-risk and low-cost operator training.

**WORK:** In this work, the haptic simulation developed earlier in LongOps was extended to include semi-rigid physics, including fluid physics. This is complex because of the need to include haptic feedback to operators in a realistic way.

**BENEFIT:** This research has bridged the gap between conventional simulations of rigid objects, extending it to scenarios found in more complex real-world environments, providing a more realistic and effective platform for training and rehearsal of tasks. Haptic rendering of fluid dynamics is a first-of-a-kind.

**IMPACT:** This ability to render haptic force feedback, bespoke for the complex needs of the nuclear sector, allows teams at Fukushima Daiichi and JET to train operators and rehearse tasks in a highly realistic manner – even tasks which have never been performed in the real world.

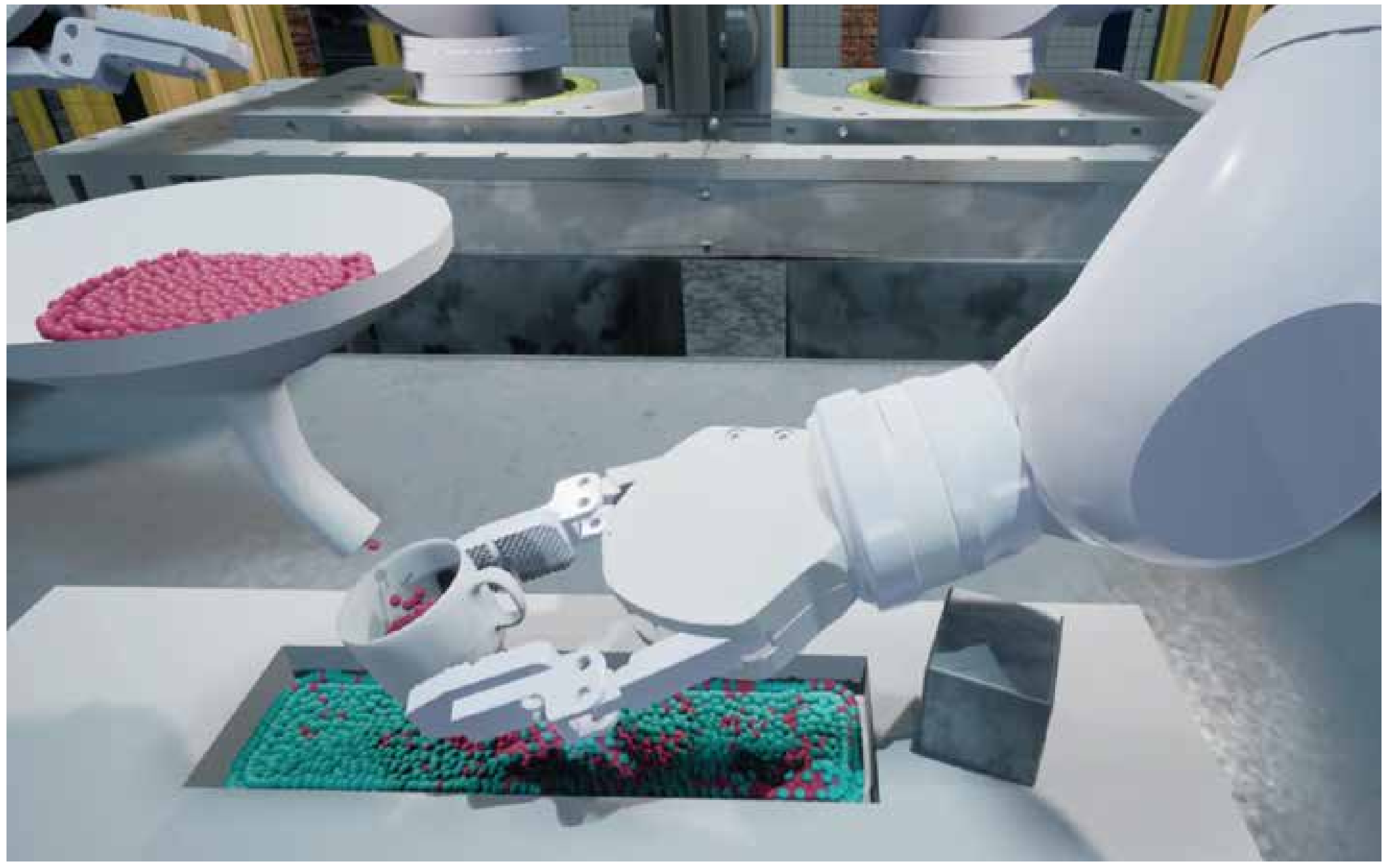
The earliest bilateral teleoperation works, operational mainly in industrial scenarios, focused on rigid environments, assuming tasks involving hard objects and minimal interaction deformation. However, the expanding applications of bilateral teleoperation robots in daily life, including nuclear, service, and collaborative robots, introduce more complex and non-rigid environments. The conventional haptic simulation research, based on rigid scenarios, may no longer effectively deliver satisfactory performance in these evolving and intricate real-world interactions.

One primary challenge in achieving physically realistic haptic simulation, distinct from tactile effects on mobile devices, lies in maintaining high update rates and low jitter. This is essential for the stability of control systems and staying above the haptic sensory threshold, where humans can detect tactile anomalies. In force-based simulation for realistic dynamic environments, this imposes limitations on the complexity and realism of virtual scenes. The need for quick and reliable updates to the scene is crucial to prevent adverse effects on user experience, potentially rendering a simulation unusable.

Historically, the push for haptically enabled virtual environments has favoured simplicity due to computational constraints, limiting scenarios to tightly defined situations. Yet, real-world applications requiring haptic technologies for training and rehearsal often involve inherently complex environments. The discrepancy between the ideal and practical simulation scenarios hinders the effectiveness of training simulations, as their complexity fails to align with the intricacies of real-world situations.

An illustrative example is the decommissioning of the Fukushima Daichii reactors, submerged under a large volume of water for cooling. When decommissioning begins, navigating the unique conditions of wet and potentially sludgy environments becomes a significant challenge. The interaction between solid objects like pipes and surrounding substances, including water, sand, and mud mixtures, greatly influences the handling and manipulation of the decommissioning process.

To address these challenges, this project aimed to enhance haptic simulation by introducing a single simulation environment that combines classical rigid/semi-rigid physics with particle-based dynamics suitable for haptic rendering. This research effort seeks to bridge the gap between conventional rigid-based simulations and the intricate dynamics of real-world environments, providing a more realistic and effective platform for training and operational rehearsal, particularly in complex scenarios like the decommissioning of nuclear facilities.



# Merging Haptic Rendering with Live Sensor Data

## IMPACT SUMMARY

**NEED:** The Haptic Training Simulator previously developed in LongOps enables robotics operators to efficiently train in unfamiliar scenarios. However, certain operational scenarios – such as those involving continuously changing conditions – are challenging to rapidly simulate in a virtual environment.

**WORK:** In this work the Haptic Training Simulator software was enhanced to rapidly generate virtual environments derived directly from real-world environments. Red-Green-Blue-Depth (RGB-D) sensors generate a point cloud that is used to make new virtual environments. Changes in the real environment are replicated in virtual environment live. Objects are segmented, and properties are replicated in the virtual environment, including moveability and rigidity.

**BENEFIT:** By integrating real-world scenarios derived from sensor data, the Haptic Digital Twin (HDT) streamlines the design process within the simulation platform, reducing time and costs while improving the training experience for robot operators.

**IMPACT:** Operators at JET, Sellafield and Fukushima Daiichi can use this type of software to interact with accurate, up-to-date virtual replicas of real environments, reducing the cost and risk associated with planning remote operations.

This project aimed to develop methods enhancing the creation of a Haptic Digital Twin (HDT) to aid in training operators for teleoperated robotic tasks in the nuclear sector. The project covered various aspects, incorporating live data from 3D cameras for visualisation and haptic information, along with robot simulations featuring kinematic constraints. The objective was to establish a virtual environment that improves the training experience for robot operators, with a primary focus on the nuclear industry. Furthermore, the developed methods hold potential applications in other industries, including medical robots.

The HDT is now playing a crucial role in bilateral teleoperation systems, particularly in aspects such as operator training and task validation/confirmation. However, creating training scenarios within an HDT often requires time-consuming and costly reconfiguration, primarily due to design expenses. This challenge can be addressed by incorporating real-world scenarios derived from sensor data, offering a solution to mitigate both time and cost associated with designing assets and scenarios within the simulation platform. Such sensor data includes both visual and geometric information, as to replicate the way a real-world assent or scenario looks and feels.

Studying tactile perception and its applications across various fields is a significant challenge in haptics. Over the past two decades, researchers have explored tactile, haptic, and multisensory interfaces for applications ranging from remote surgery in teleoperation to virtual environments. In the context of fundamental scientific research on human haptics, replicating haptic sensations artificially presents formidable difficulties, given the intricate nature of sensations experienced during interactions with physical objects.

Human sensory experiences, especially in response to proprioceptive and mechanical efforts, are inherently nonlinear, highly multidimensional, and direction sensitive. Factors such as magnitude and orientation play crucial roles. Applying constant or linearly scaled forces from a mechanical actuator falls short in replicating responses similar to real-world interactions. The computational model that calculates such forces to be experienced by a user is called haptic rendering. The diverse ways the hand interacts with objects correspond to distinct physical properties, requiring consideration of factors like texture, weight, hardness, volume, and shape in the haptic rendering process.

The core challenge in this research lies in integrating real-world sensor data into the HDT, encompassing both visual and haptic rendering. While visualisation tools for sensor data exist, unique challenges arise in visualising point clouds due to their substantial size. Crucially, the visualisation process must not interfere with the physics or other simulation procedures.

Haptic rendering involves intricate calculations to estimate forces applied by the haptic device, including collision detection and distance calculations. Ensuring a fast and consistent connection between the simulation and the haptic device in a visuo-haptic environment, where visual and tactile experiences are closely related, adds another layer of complexity. This complexity is heightened when haptic rendering is based on live 3D data, with sensor data and haptic feedback occurring at different rates and possessing distinct spatial properties.

Addressing these challenges, a technological solution emerged in the form of a successfully developed HDT. This innovative system integrates sensor data from a remote side, via point cloud data, into a local simulation, enabling the operation of any haptic device. The system architecture, illustrated in Figure 1, signifies a significant advancement in overcoming the complexities associated with real-world sensor data integration into haptic simulations.

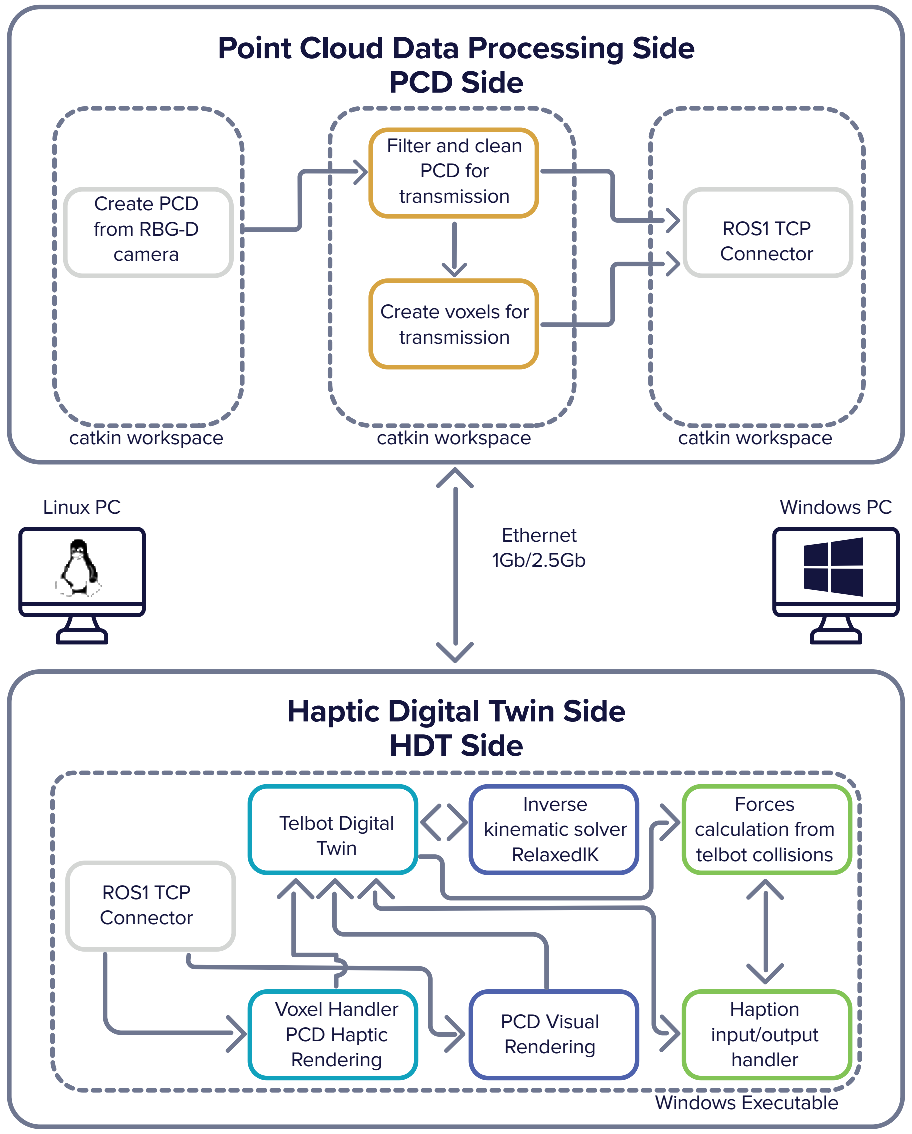



**Figure 1: General system architecture to integrate live sensor data for haptic rendering.**

# Next Generation Digital Mock-Ups

Digital Mock-Ups provide operators with the ability to visualise remote equipment in nuclear facilities. This most prominently provides operators with a live visualisation during task execution, but is also a core tool in planning, high-level decision-making, operator training and asset management. In LongOps, a ‘Next-Generation Digital Mock-Up’ (NG-DMU) has been produced which functions as a digital alternative to physical mock-up operations, providing an environment for technology validation, training, and demonstration.

# Integration into the Operational Lifecycle

## IMPACT SUMMARY

**NEED:** users want to be able to perform ‘digital rehearsals’ of operations, avoiding the expense of full physical mock-ups. In the LongOps programme there has also been a need to demonstrate various technologies to end-users from the project stakeholders.

**WORK:** These two needs were met using a ‘Next-Generation Digital Mock-Up’ (NG-DMU) nicknamed ‘The Grid’. This suite of software provides the ability for users to simulate the operators’ experience of performing a remote operation – without the use of physical robotic hardware. On top of this, the Grid also simulates how LongOps technologies can be applied to operations, including path planning, long-reach modelling, object recognition, incorporation of live sensor data, and simulated haptic teleoperation.

**BENEFIT:** This work extends the existing visualisation capabilities used in JET remote handling operations, allowing it to be applied to other scenarios, including fuel debris retrieval at Fukushima Daiichi and the Windscale Pile 1 clean up at Sellafield.

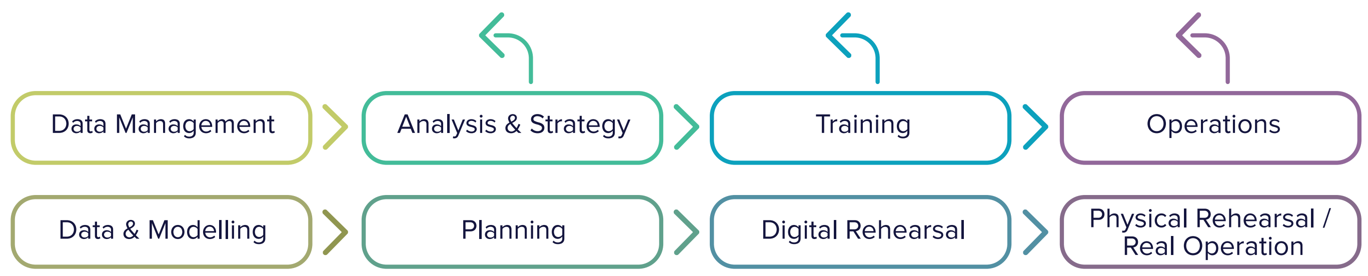
**IMPACT:** The NG-DMU has been used in LongOps to demonstrate to end-users how the technologies developed in the programme can be applied to their use cases. On top of this, the NG-DMU is a tool which can be used by operators to interact with virtual mock-ups of their operations, and make informed decisions when designing, planning and training on remote operations in high-consequence environments.

**NG-DMU Launcher – Integration into the operational lifecycle**

At the centre of the LongOps project was the concept of developing the “next generation” of digital mock-ups. Digital mock-ups are already an integral part of UKAEA’s development and planning of JET remote handling operations. Operators plan the moves of the remove handling equipment - the two large booms and MASCOT, our two-armed tele-operation manipulator - many months before the real operations are due to take place. These planned moves are loaded into an offline version of the operator’s Human Machine Interface (HMI) and visualised in 3D using models of the JET torus and the remote handling equipment.

While these visualisations or digital mock-ups are invaluable both during planning and online operation, they lack the simulation and interaction capability required to be used as an alternative to physical mock-ups, i.e. an environment in which operations can be performed in a way as close as possible to how they will be performed during real operations. The purpose of the Next Generation Digital Mock-up (NG-DMU) theme was to develop this capability and use it to demonstrate the technology produced by the various other themes within LongOps. The aim being to produce not only a simulation tool, but also a communications tool – allowing the stakeholders to see how these novel tools and capabilities could be used in their own applications.

From the very start, the NG-DMU was developed as an application agnostic tool. While the focus under




the LongOps project was certainly on the three stakeholder use-cases – Fukushima Daiichi reactors (TEPCO), Windscale Pile 1 (Sellafield, NDA), and JET (UKAEA) – the architecture of the NG-DMU was designed to be flexible and accommodate a wide variety of environments, operations, and hardware solutions. That being said, it was still important that the tool still be intuitive to use and facilitate the operations lifecycle established by 30 years of JET remote handling operations (see diagram), rather than try to redefine it. Therefore, the NG-DMU has been designed to support each major stage of operations and provide tools and capability accordingly.

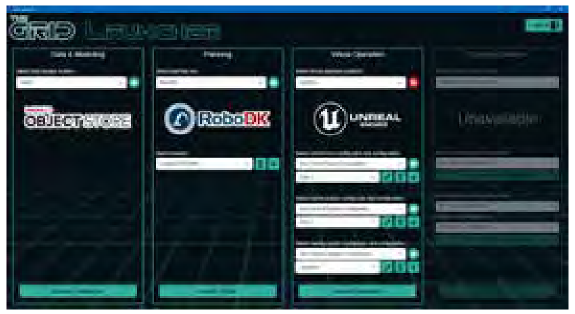
The first stage of operations development focuses on Data Management. This activity involves gathering together knowledge and information known prior to the development of the new operation. This can include: models of the environment, models of the available hardware and tools to be used in-situ (e.g. robots, grippers, cameras), characterisation and performance models of that hardware (e.g. payloads, mass, flex), radiation maps, control algorithms, etc. Some of this data may be available from manufacturers, but the majority is likely to have been gathered from previous operations or producing during the construction of the environment.

From a digital systems point of view, this stage is facilitated via the use of data storage and modelling software. Databases of available environments, robots, and tools, previously used configurations, and control solutions should be easily available to operators and engineers planning their next operation. The NG-DMU provides this capability via the use of produced databases and object storage services, presented to the user via an easy-to-use catalogue. The catalogue provides the user with various performance metrics of available robots and tools, and links with a database of models that maybe used in the later planning and digital rehearsal stages.

With a suitable amount of knowledge gathered, the next stage is to analyse this data in order to inform our strategy for the new operation. This is the beginning of planning and often includes the first steps of the development of the digital mock-up. Models of the environment (as it is currently known) can be combined with available tools and robotic hardware to outline early concepts of possible solutions. The use of known robot kinematics can also allow operators to start to planned moves and paths through the environment, and cameras and lights can be placed in locations operators feel they are likely to be needed.

The ability to visualise the environment and provide an interface through which operators can assemble a concept solution and plan an operation is essential for accurate and efficient operations development. The NG-DMU provides this capability through the use of third-party off-the-shelf software - RoboDK (though the flexibility of the architecture would allow other similarly capable software packages to be used). RoboDK has also been integrated with the NG-DMUs catalogue, allowing operators to import assets from the catalogue with a single button, facilitating the construction of the digital mock-up.

Once the operation has been planned to a required level of detail, the plan can be used to form the basis of training – the third stage of operations development. As previously mentioned, during the training of JET remote handling operations, visualisation of the operation is traditionally done using a digital-twin visualiser. However, in order to provide an interactive and realistic environment in which to operate, LongOps developed a simulator in which fully digital rehearsals can take place. This allows the operators to not only see the hardware in the environment but interact with it in a similar way to reality. The simulator also recreates the functionality of tools and sensors – LIDARs produce point clouds, cameras produce video feeds, and laser cutters bifurcate objects. This allows a number of the other capabilities produced within LongOps, such as object recognition and change detection, to make use of simulated sensor data and perform their intended function during a simulated operation.

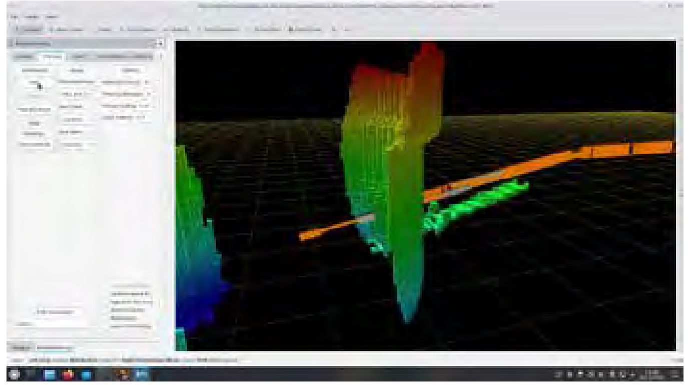


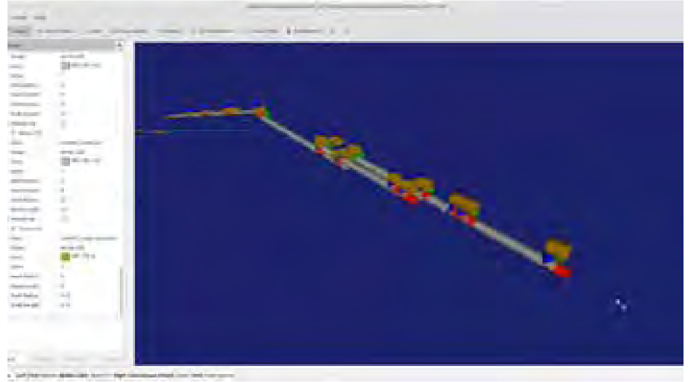

# Integration of the LongOps Technologies

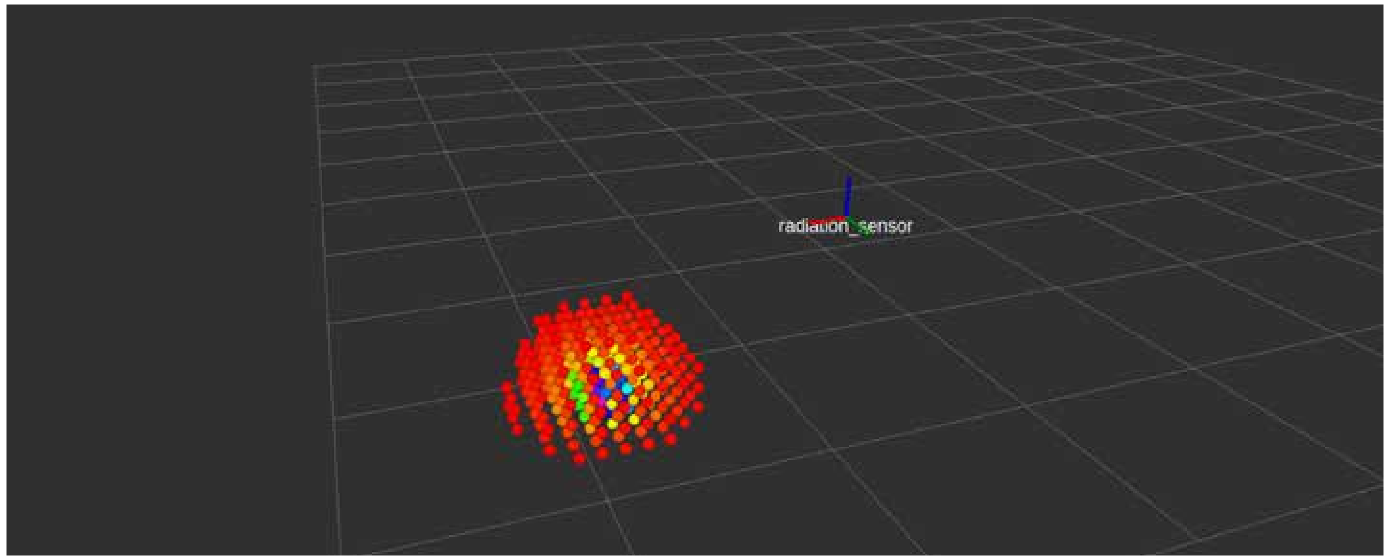
It is often difficult to relate the development of novel technology and capabilities to their intended application areas when demonstrated in isolation. It is also difficult to demonstrate their application when the intended environment is one of high cost and risk. Therefore, the original purpose of the NG-DMU theme was to provide a demonstration platform for the technologies developed within the other LongOps themes, that would illustrate their use and application in a simulated environment representative of the three selected use cases - Fukushima Daiichi, Windscale Pile 1, and JET.

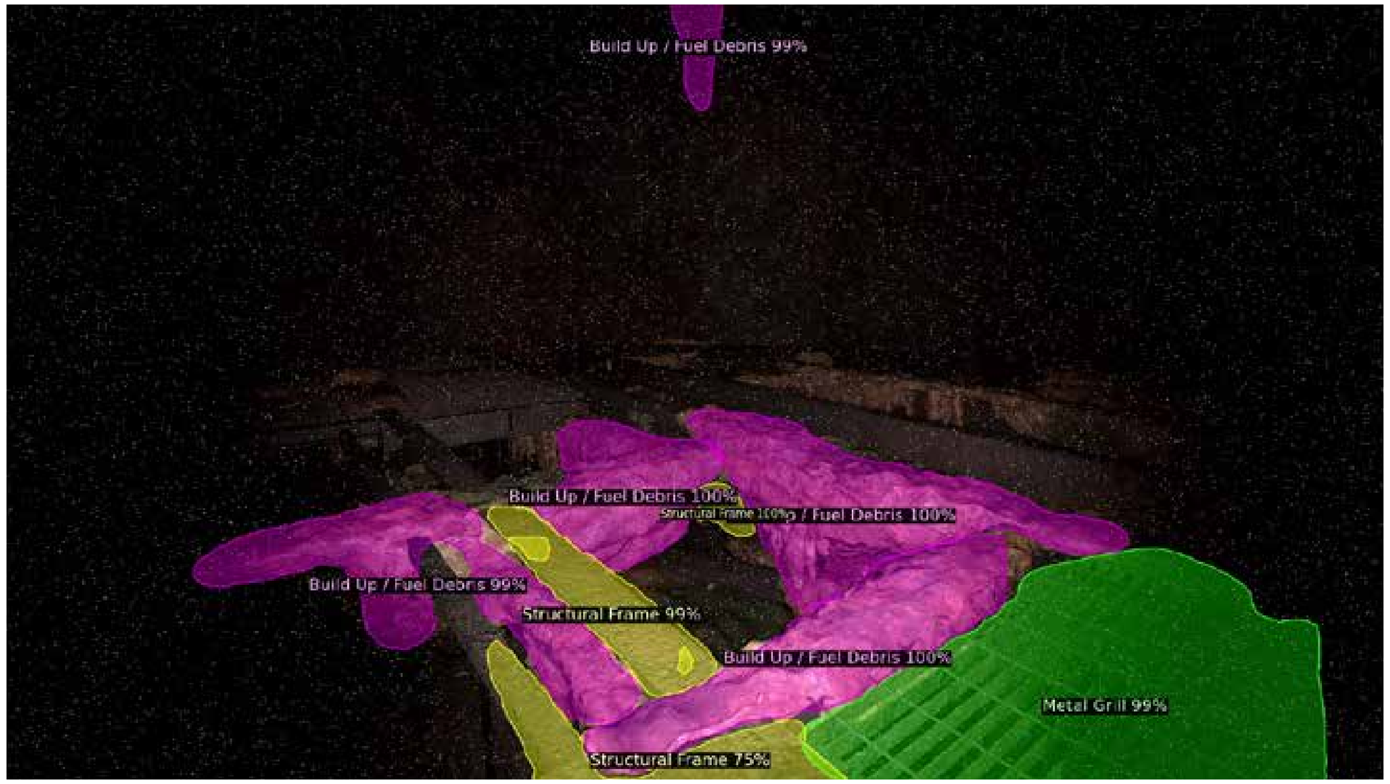
However, it quickly became clear how powerful the recreation of the environment and the operators' interaction with the decommissioning solution would be for solution development, planning, and training (see previous section). As a result, the scope of the NG-DMU expanded from not just illustration of other theme technologies and capabilities, but also their integration and operator interaction. In order to deliver both these functions, the NG-DMU needed to simulate both the **physical world** and the **digital world**.



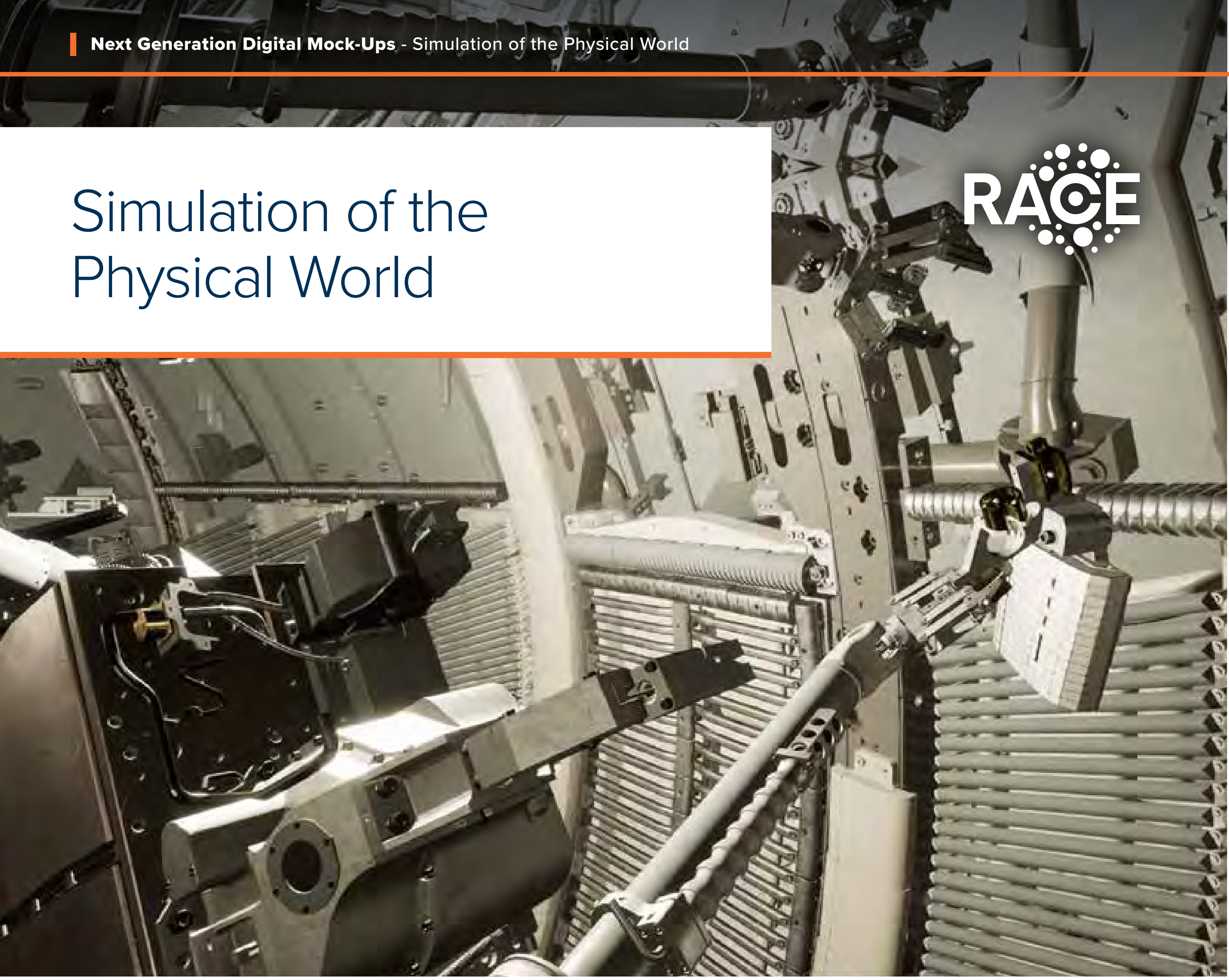






# Simulation of the Physical World




The simulation of the physical world is needed to recreate visual representations of the environment and operational hardware. This was achieved using Epic Games' Unreal Engine 5© - a games engine capable of producing close to photorealistic renders of 3D geometry, with an integrated programming environment capable of providing the simulated functionality we would require. UKAEA VR Engineers used a combination of pre-existing CAD and the creation of bespoke models to recreate environments, robots, and tools, which were then imported into the Unreal Engine, assembled, textured, and lit to produce highly realistic recreations of the 3 use case environments.

During the construction of the digital mock-up, the NG-DMU allows fixed and pan, tilt, zoom cameras to be placed in the environment. During digital rehearsal, the simulation provides live video streams from these simulated cameras using an open standard for network video streams called NDI© (Network Device Interface). This allows the use of off-the-shelf third-party applications to be used to both view and operate (pan, tilt, and zoom) the simulated cameras within the environment, providing a realistically limited interaction between the operators and the operational space.

Once the environments were populated, we then needed to recreate the physical behaviour and interaction between the operational hardware and the environment. For simplistic interactions (for example, general collisions and gravity), we were able to make use of the physics engine provided by the Unreal Engine. However, for the complex modelling and simulation of long-reach manipulators, we were able to integrate the capability provided by HEROBOTS (see 6.3.3) to recreate the bend, flex, and resulting oscillations of, in this case, the manipulator to be used for Fukushima Daiichi sample retrieval. This integration meant the manipulator in the NG-DMU simulation behaved much more realistically – recreating the droop due to gravity seen in many long-reach manipulators, and the oscillations produced from large accelerations – resulting in a far more accurate experience for operators than the rigid models previously used for training.

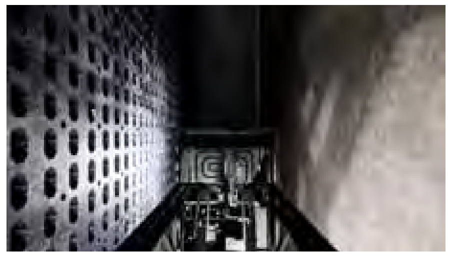
Similarly for teleoperation, the NG-DMU developers were able to integrate the technology provided by Generic Robotics to bring the capability of the haptic training simulator into the realistic environments of the simulator. As a result, the NG-DMU has been able to recreate both Dexter operations within the Fukushima Daiichi simulated environment, and UKAEA MASCOT operations within the JET vessel simulated environment, while providing operators with the haptic feedback they would expect from teleoperating within a physical environment.

Another physical property of the environment, particularly important to nuclear decommissioning operations, is radiation. Using capability produced by Jacobs the NG-DMU has integrated the ability to use simulated radiation sources and sensors, in order to simulate both the instantaneous and accumulated dose based on the proximity of a sensor to a defined source. This information can not only be useful to be provided to an operator, but can also be used to simulate other behaviours which would be effected by radiation.

One such example within the NG-DMU is the degradation of camera feeds. In addition to the live feed produced by cameras, additional functionality from Jacobs has been used to add simulated noise to the video feeds, in order to recreate the effects produced by received radiation. The noise varies in intensity based on the currently received simulated dose, which can also result in permanent damage, or even entire failure of the camera if the simulated accumulated dose passes a selected threshold. The addition of this camera noise is greatly beneficial during training - providing operators with a much more realistic experience of the distraction and limited viewing experience of working with radiation effected cameras.

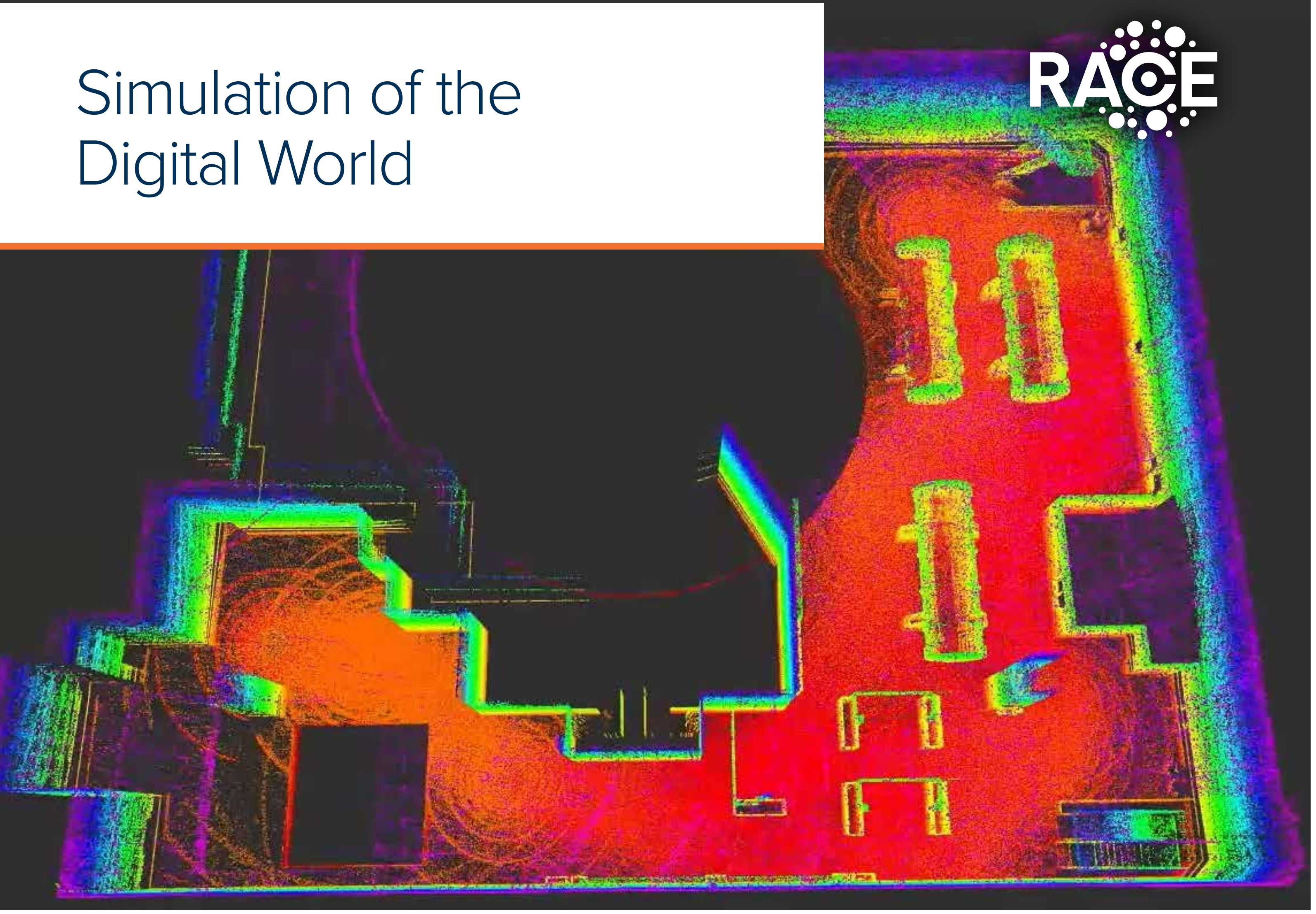
The final physical behaviour simulated within the NG-DMU is bifurcation – the ability to cut and separate parts of the environment using tools. Segmentation and size reduction are common activities during nuclear decommissioning – either for the purposes of separating differing levels of waste, or simply reducing the size of an object for transport and storage. However, in the case of deteriorated environments, for example due to a disaster (in the case of Fukushima Daiichi and Windscale Pile 1) or simply due to the passage of time (in the case of some Sellafield buildings), it can be required to cut and/or remove objects in order to simply reach places within the environment. With this activity being particularly applicable to all use cases, the development of the NG-DMU also included the creation of a simulated laser cutting tool. This tool is capable of cutting selected objects within the environment and separating them into separate pieces. This allows operators to perform operations including cutting tasks and see the environment behave as expected in real time, providing a much more realistic experience.



Next Generation Digital Mock-Ups - Simulation of the Physical World

# Simulation of the Digital World




In addition to the recreation of the physical world, it was just as important to recreate the digital world in the simulation – to reproduce the software interfaces that control systems and other software capabilities would use to provide further capability to operators.

The first interface was to provide control over the robots and tools within the environment. The NG-DMU provides a generic interface for controlling the joints of the robots using both an open-source communication interface – ZeroMQ – and an open standard – JSON. This control system agnostic interface has enabled the NG-DMU to integrate with control system solutions based on ROS1, ROS2, CorteX (UKAEA's in-house communications and control system solution), and bespoke third-party applications.

One implementation of this interface was the integration of the path planning software developed by Atkins and UCL, and the previously mentioned long-reach manipulator modelling by HEROBOTS, with additional input-shaping capability. The integration of these capabilities (developed entirely separately) together with the NG-DMU, has allowed operators to use autonomous path planning to control the Fukushima Daiichi manipulator within a 1F reactor environment, and see the resulting realistic motion (including droop due to gravity and oscillations) in real-time, through the use of environmental cameras.

As a result, TEPCO secondees were able to perform a simulated operation representative of sample retrieval within a Fukushima Daiichi reactor, many months before the hardware designed to perform this operation in reality will be ready.

Further use of the camera feeds (including simulated radiation noise) was integration with object recognition capability using Jacobs' datasets. This capability, produced by UKAEA, allowed live feeds from simulated cameras to be passed through an image recognition system based on annotated data sets produced by Jacobs. This capability provides operators with annotated displays of live camera views, highlighting components, recognised materials, and elements of the environment. In the case of the Fukushima Daiichi environment, the system was capable of recognising objects in extremely low light through high levels of radiation induced noise – objects which were near impossible for a human operator to recognise given the same video feed.

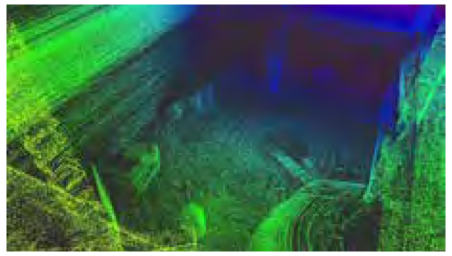
The final piece of digital simulation was the reproduction of a sensor rig developed by NavLive. In order to integrate the change and anomaly detection capability provided by NavLive, the NG-DMU simulation had to provide the same digital information as their software would expect from their physical sensor rig – made up of four cameras, a LIDAR, and an IMU. UKAEA therefore developed a simulated LIDAR capable of producing a point cloud of the simulated environment in real-time. Although the resolution of the simulated LIDAR is limited in its resolution, the point cloud produced, combined with the simulated camera views and IMU data, was still detailed enough to allow NavLive's change detection software to produce a map of changes in a simulated environment.

This is just one example of how point cloud data can be used during an operation and is vital for many other mapping and localisation technologies, such as Jacobs' object detection. The ability to produce point clouds from within the simulated environment, opens the door to a wide range of external software and capabilities to be integrated with the NG-DMU.

**Boston Dynamics' Spot**
Although the three main LongOps use cases – Fukushima Daiichi reactors (TEPCO), Windscale Pile 1 (Sellafield, NDA), and JET (UKAEA) – were demonstrated within the NG-DMU, over the course of the project, both Sellafield and TEPCO deployed Boston Dynamics Spots on their respective sites. It was therefore felt appropriate to also develop a Spot based simulation that could be demonstrated in both a Sellafield and Fukushima Daiichi representative environment, as part of the final LongOps demonstrations.

These demonstrations included the integration of a simulated Spot controller, produced in collaboration with RAICo (***www.raico.org***), capable of controlling a simulated Spot in a mock-up of a Sellafield building and a Fukushima Daiichi turbine hall. Both these demonstrations made use of the simulated LIDAR, which was mounted on the back of the quadruped robot and was used to produce large point clouds of the environments.

The NG-DMU demonstrations clearly showed the level of realistic visualisation and interaction that can be created using a simulation, and how valuable it is not only as a training tool, but also as a communications tool for solutions development and planning.



# Assessment

# NG-DMU Evaluation


## IMPACT SUMMARY

**NEED:** Under LongOps, a prototype Next-Generation Digital Mock-Up (NG-DMU) was created, to demonstrate how LongOps software tools could be incorporated into a remote handling control room setting. As a core part of the LongOps strategy, it was important to have an objective evaluation metric.

**WORK:** In this work, the NG-DMU was evaluated, to ensure that it meets design requirements, is intuitive to use, and aligns with the task development and execution lifecycle for remote handling operations.

**BENEFIT:** The NG-DMU provides software tools that support each major stage of remote handling operations, based on 30 years of experience operating remote equipment in JET. This design choice reflects a commitment to building on existing operational knowledge, derisking nuclear operations.

**IMPACT:** Effective validation ensures that all requirements have been appropriately met, so that the NG-DMU aligns with stakeholders' needs and future aspirations.

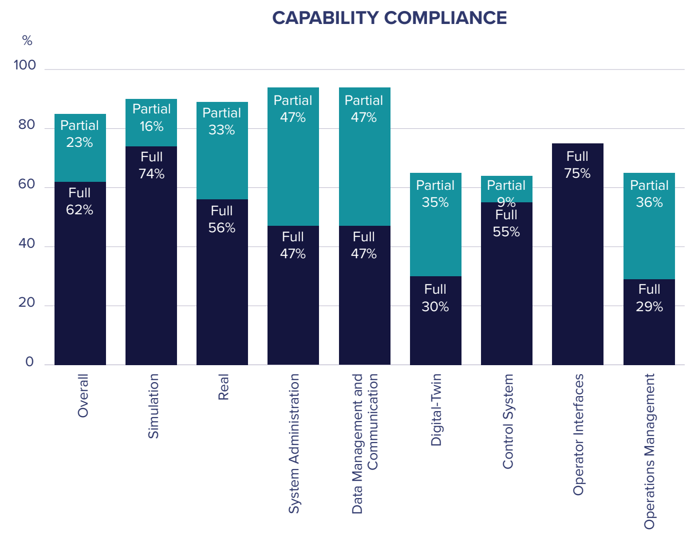
The Next-Generation Digital Mock-Up (NG-DMU), as described in section 6.5, is a tool that is developed with a focus on being application agnostic, meaning it can be used in various contexts. The LongOps project emphasised three specific stakeholder use-cases: Fukushima Daiichi reactors (TEPCO), Windscale Pile 1 (Sellafield, NDA), and JET (UKAEA). Despite this focus, the NG-DMU was designed to be flexible and adaptable to different environments, operations, and hardware solutions.

The architecture of the NG-DMU was created with the intention of accommodating a wide range of scenarios. It is highlighted that the tool aims to be intuitive to use, and it aligns with the established operations lifecycle, particularly drawing from the 30 years of JET remote handling operations.

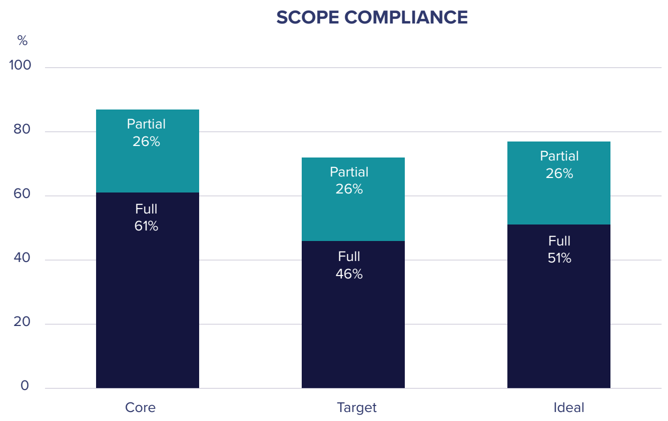
The NG-DMU has been tailored to support each major stage of operations, providing tools and capabilities that align with the operations lifecycle established by JET remote handling operations. This design choice reflects a commitment to building on existing operational knowledge rather than redefining it, derisking nuclear operations.

Requirements capture and validation are integral processes in the development of complex systems, such as the NG-DMU. Capturing requirements ensures a comprehensive understanding of the diverse needs of stakeholders, such as TEPCO, NDA, and UKAEA, enabling the development team to tailor the NG-DMU to meet specific operational challenges. Validation ensures that these captured requirements align with the intended functionality and purpose of the tool. It serves as a crucial step in verifying that the NG-DMU not only meets the individual needs of stakeholders but also functions cohesively in the broader operational context. Effective requirements capture and validation are paramount to delivering a solution that is not only technically sound but also aligns closely with the operational workflows, ensuring successful integration and usability in real-world scenarios.

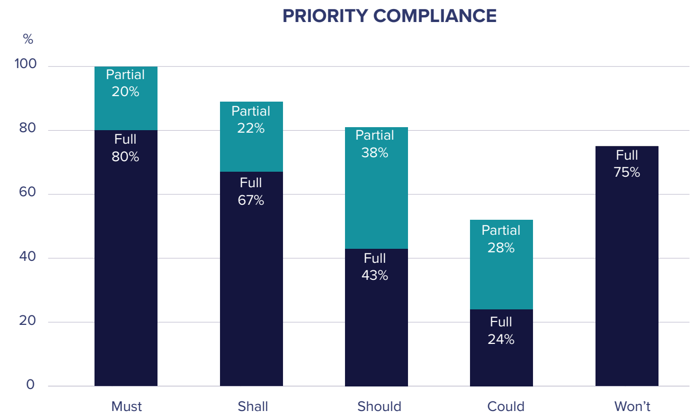
In addition to the importance of requirements capture and validation, diverse scopes such as core, ideal, and target have been employed throughout the NG-DMU development process. The core scope encompasses fundamental requirements essential for the tool's functionality, ensuring full compliance is achieved. Ideal scope represents additional features or capabilities that, while desirable, are not strictly necessary for baseline functionality. Requirements falling within the ideal scope may have partial compliance, offering flexibility in implementation. The target scope outlines aspirational features or advancements for future iterations, setting a visionary direction. Effective validation ensures that each requirement, whether core, ideal, or target, is met with either full or partial compliance, ensuring a balanced and adaptable NG-DMU that aligns with stakeholders' needs and future aspirations while maintaining operational integrity.




**Requirements were gathered across a broad range of capabilities from which a "Next Generation Digital Mock-Up" could provide benefit.**




**The requirements were grouped into 3 categories. Core – fundamental capabilities, Target – novel capabilities, and Ideal – cutting-edge capabilities**




**The requirements were also given a priority to allow for agile development of scope.**


**Across the full range of requirements, the NG-DMU was able to deliver 80% of the total proposed scope to either Full or Partial compliance.**

# TRL Evaluation

## IMPACT SUMMARY

**NEED:** Several technologies have been identified and developed in the LongOps project. This work recognises a need to track progress for these against an objective scale.

**WORK:** In this work, the LongOps research project was broken down into its component technologies. The development of each technology was assessed and tracked through the course of LongOps using the Technology Readiness Level (TRL) scale. This scale was aligned with industry standards including the TRL definitions used by the Nuclear Decommissioning Authority (NDA), and was verified by external experts.

**BENEFIT:** TRL scales allowed LongOps researchers and stakeholders to communicate about progress in a common language. TRL levels act as a metric to showcase the increased trend in the development and maturation of technology areas.

**IMPACT:** Use of a structured and transparent approach to reporting progress guided the LongOps program toward its vision more effectively, giving end-users greater confidence in the technologies being developed.

The LongOps project envisions the development of groundbreaking low-to-mid Technology Readiness Level (TRL) research in strategic technology areas, concurrently with the de-risking of high-stake technologies for market integration. Recognising the pivotal role of TRL assessment in demonstrating progress towards our goals, we have adopted a strategic approach. We utilise TRLs as a metric to showcase the increased trend in the development and maturation of technology areas, effectively indicating a reduction in the inherent risks associated with each technology.



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Integral to the project's success has been the development of an approach to capture, mitigate, and report maturation risks consistently and coherently over time. To achieve this, we implemented a systematic process. Firstly, we established a system product breakdown structure, providing a comprehensive framework for our assessments. Agreement on TRL definitions within the team, aligned with industry standards such as Nuclear Decommissioning Authority (NDA)'s TRL definitions, ensured a common understanding.

Internal reviews with research leads followed, capturing current TRL assessments, maturation risks, fallback options, and forward maturation plans. These assessments were cross-verified with external experts, providing a robust validation process with evidence-based documentation of developments. Subsequently, we created a comprehensive database to track progress, incorporating contextual, environmental, and testing provenance for all Research and Development (R&D) elements within the project.

To ensure effective communication and control, we established a periodic reporting cycle within the project team and with external stakeholders. Through these collective efforts, a common language for defining and assessing TRL levels across the program was achieved. Moreover, control over the R&D baseline was established, providing a structured and transparent approach to guide the LongOps program toward its vision.

| Phase | TRL | Stage | Description |
|---|---|---|---|
| **Operations** | TRL9 | Operations | The technology is being operationally used in an active facility. |
| **Deployment** | TRL8 | Active Commissioning | The technology is undergoing active commissioning. |
| | TRL7 | Inactive Commissioning | The technology is undergoing inactive commissioning. This can include works testing and factory trials but it will be on the final designed equipment, which will be tested using inactive simulants comparable to that expected during operations. Testing at or near full throughput will be expected. |
| **Development** | TRL6 | Large Scale | The technology is undergoing testing at or near full-scale size. The design will not have been finalised and the equipment will be in the process of modification. It may use a limited range of simulants and not achieve full throughput. |
| | TRL5 | Pilot Scale | The technology is undergoing testing at small to medium scale size in order to demonstrate specific aspects of the design. |
| | TRL4 | Bench Scale | The technology is starting to be developed in a laboratory or research facility. |
| **Research** | TRL3 | Proof of Concept | Demonstration, in principle, that the invention has the potential to work. |
| | TRL2 | Invention and Research | A practical application is invented or the investigation of phenomena, acquisition of new knowledge, or correction and integration of previous knowledge. |
| | TRL1 | Basic Principles | The basic properties have been established. |

**NDA Technology Readiness Level Scale**

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| | Technology Readiness Level | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Base | Q7 | Q8 | Q9 | Q10 | Q11 | Q12 | Final | Goal |
| **Control System** | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 4 |
| System Health | 2 | - | - | - | - | - | - | - | - |
| Condition Monitoring | 2 | - | - | - | - | - | - | - | - |
| Collision Avoidance | 1 | 1 | 1 | 1 | 1 | 3 | 4 | 5 | 4 |
| Constraint Management | 1 | 1 | 1 | 2 | 2 | 3 | 4 | 5 | 4 |
| Autonomous Acutation | 2 | - | - | - | - | - | - | - | - |
| Semi-Autonomous Acutation | 2 | - | - | - | - | - | - | - | - |
| Autonomy Override | 2 | - | - | - | - | - | - | - | - |
| Haptic Controller | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 |
| Long Slender Manipulator Control Systems | 1 | 1 | 2 | 2 | 3 | 4 | 4 | 5 | 4 |
| **Sensors** | 3 | 3 | 3 | 3 | 4 | 5 | 5 | 5 | 5 |
| Sensor simulation | 3 | 3 | 3 | 3 | 4 | 5 | 5 | 5 | 5 |
| Rad Hardening | - | - | - | - | - | - | - | - | - |
| Sensor calibration | 3 | 3 | 3 | 3 | 4 | 5 | 5 | 5 | 5 |
| Raw data preparation | 3 | 3 | 3 | 3 | 4 | 5 | 5 | 5 | 5 |
| **Data Processing** | 2 | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 5 |
| Noise Reduction | 3 | 3 | 3 | 3 | 4 | 4 | 5 | 5 | 5 |
| Real-time Storage Management | 2 | - | - | - | - | - | - | - | - |
| Communication Standards | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 5 |
| Imagery Analysis | 3 | 3 | 3 | 3 | 4 | 4 | 5 | 5 | 5 |
| Point Cloud Analysis | 2 | 2 | 2 | 3 | 4 | 5 | 5 | 5 | 5 |
| **Simulation** | 1 | 2 | 2 | 2 | 3 | 4 | 4 | 4 | 4 |
| Virtualisation | 2 | 2 | 2 | 2 | 3 | 4 | 4 | 5 | 5 |
| Data Sets | 2 | 3 | 3 | 3 | 4 | 5 | 5 | 5 | 5 |
| Model Asset Management | 2 | 2 | 2 | 3 | 4 | 4 | 4 | 4 | 5 |
| Haptic Simulation | 1 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 |
| **Robots** | 1 | 1 | 1 | 1 | 2 | 2 | 3 | 3 | 3 |
| Manipulators | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 |
| Tooling | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 |
| Long Reach Deployment | 1 | 1 | 1 | 1 | 2 | 2 | 3 | 3 | 3 |
| Manipulator Evaluation | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 4 | 4 |
| **Visualisation** | 2 | 2 | 2 | 2 | 2 | 3 | 4 | 4 | 5 |
| HMI Standards | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 5 |
| Control HCI | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 5 | 5 |
| Digital Twin Visualisation | 2 | 3 | 3 | 3 | 4 | 4 | 5 | 5 | 5 |
| Visual Augmentation | 2 | 2 | 2 | 2 | 2 | 4 | 5 | 5 | 5 |
| Auditory Augmentation | 2 | - | - | - | - | - | - | - | - |
| Haptic HMI | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 5 |
| **Planning** | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 4 | 3 |
| Strategic Goal Planner | 1 | - | - | - | - | - | - | - | - |
| Task Sequencer | 1 | - | - | - | - | - | - | - | - |
| Path Planner | 1 | 1 | 1 | 1 | 2 | 3 | 5 | 5 | 3 |
| Path Optimiser | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 4 | 3 |
| **Fusion** | 2 | 2 | 2 | 2 | 2 | 3 | 4 | 4 | 5 |
| Video Fusion | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 |
| Model Fusion | 2 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 |
| Multi-Sensor Fusion | 3 | 3 | 3 | 3 | 3 | 5 | 5 | 5 | 5 |
| Fault Detection | 2 | 2 | 2 | 3 | 4 | 5 | 5 | 5 | 5 |
| Deformation Predication | 2 | 2 | 2 | 2 | 3 | 4 | 4 | 4 | 5 |
| Criticality Detection | 2 | - | - | - | - | - | - | - | - |
| Object Detection | 2 | 3 | 3 | 3 | 4 | 5 | 5 | 5 | 5 |
| Estimation | 2 | 2 | 2 | 2 | 2 | 3 | 4 | 4 | 5 |



| | Technology Readiness Level | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Base | Q7 | Q8 | Q9 | Q10 | Q11 | Q12 | Final | Goal |
| **Architecture & Standards** | | | | | | | | | |
| Interoperability Standards | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 5 |
| Generic Nuclear Robotic Architecture (GNRA) | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 5 |
| Teleoperation Manipulator Evaluation | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 4 | 4 |
| **Sensing and Perception** | | | | | | | | | |
| Datasets for the Development and Testing of Sensing Techniques | 2 | 3 | 3 | 3 | 4 | 5 | 5 | 5 | 5 |
| Incorporating Live Sensor Data into Digital Twins | 2 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 |
| Automated Change and Anomaly Detection | 2 | 2 | 2 | 3 | 4 | 4 | 5 | 5 | 5 |
| **Long-Reach Mechanisms** | | | | | | | | | |
| Planning Tools for Long-Reach Manipulators | 1 | 1 | 1 | 2 | 2 | 3 | 5 | 5 | 4 |
| Planning Tools for High Degree of Freedom Manipulators | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 5 | 4 |
| Modelling and Control for Flexible Long-Reach Manipulators | 1 | 1 | 1 | 2 | 3 | 4 | 4 | 4 | 5 |
| Vibration Compensation for Flexible Long-Reach Manipulators | 1 | 1 | 1 | 2 | 3 | 4 | 5 | 5 | 5 |
| **Haptic User Interfaces** | | | | | | | | | |
| Haptic Training Simulator | 1 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 5 |
| Haptic Interation of Rigid Materials with Fluids | 1 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 5 |
| Merging Haptic Rendering with Live Sensor Data | 1 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 5 |
| **Next Generation Digital Mock-ups** | | | | | | | | | |
| Development and Build | 2 | 3 | 3 | 3 | 4 | 4 | 5 | 5 | 5 |

## SUMMARY

The quarterly review of TRL across the range of capabilities within the LongOps scope provided the project with a clear view of progress and potential opportunities for improvement. Together with the list of requirements discussed in the previous section (NG-DMU Evaluation), these heatmaps highlighted areas of capability where scope should be further developed and provided strong goals for the project.

This steer was reflected in both the approach to the NG-DMU and the engagement with suppliers, guiding which capabilities should be integrated together and how they should be demonstrated to stakeholders. As a result, the project achieved an average TRL increase of between 2 to 3 levels across the full range capabilities. In some cases, taking a TRL 1 capability through to TRL 5. Furthermore, a review by stakeholders highlighted that our evaluation may have been a little conservative and some capabilities my even be considered as high as TRL 6.

These maps also serve as a piece of a capability roadmap, which can be used to inform future opportunities for technology development and when deployments and engagements with stakeholders would progress TRLs beyond TRL 5 and through TRL 7-8. Consequently, this process can now be employed by UKAEA, NDA, and TEPCO to refine capability / technology roadmaps across projects and programmes to better shape the future of fusion and nuclear decommissioning capability.

# Capability Transfer

TRAINING →

SECONDMENTS →

DEMONSTRATIONS →

DISSEMINATION →

# Training

TEPCO has a team of remote handling operators. They have a requirement to train staff for their roles in this team. During a six-month secondment in 2019 TEPCO staff experienced the RACE method of training Remote Handling Responsible Officers (RH RO) for JET RH operations. tepco wanted to capture and share this knowledge, to do this they asked RACE to develop a training course for their RH operators. The objective is to transfer the knowledge from the RACE Remote Handling operations team to the TEPCO operators to help them prepare and conduct RH operations.

Detailed information about the training needs of the role were collated and documented. This forms the basis of a structured course that is standalone and does not rely on JET RH hardware and resources. Creating RH based courses as a product for external organisations is not a something RACE has done before. The existing JET RH operations training has comprehensive lesson materials but does not have the training needs analysis fully documented.

The request from TEPCO was to create a training course based on RACE RH operations experience and current training methods. The course must be no longer than 3 months to fit with the TEPCO operator's work programme. The basis of the course will be the JET Remote Handling systems and methodologies. The course must be standalone and decoupled from the in-service JET RH systems and facilities. This is important to ensure the course is not impacted by availability of resources. A standalone course also allows TEPCO to use it in their own facility with minimal change.

A Structured Approach to Training (SAT) methodology has been used to produce the training course. This is based on the IAEA Nuclear ***IAEA NPP Personnel Training and Evaluation***. RACE engaged industry to support the commercialisation of RACE RO training. A company, Explosive Learning Solutions (ELS), specialising in training development and delivery, were selected to support the analysis of the training needs and review RACE documents. They also provided guidance on the design of course material and its delivery.

The SAT process we are using has five phases. The relationship and flow of tasks is shown in Figure 1.

- → Analysis Phase. Assess the training needs by analysing the people to be trained, the task they must complete and the role they have. the report will form the basis of the course design and content.
- → Design Phase. Produce the course structure, timetable and content based on the options available.
- → Development Phase. Create the module and lesson plans, the course material, instructor material and the trainee assessments.
- → Implementation Phase. Deliver the course to the trainees, capture data and information that will support the assessment of individuals.
- → Evaluation Phase. Create the training performance reports. Gather course feedback from all involved.

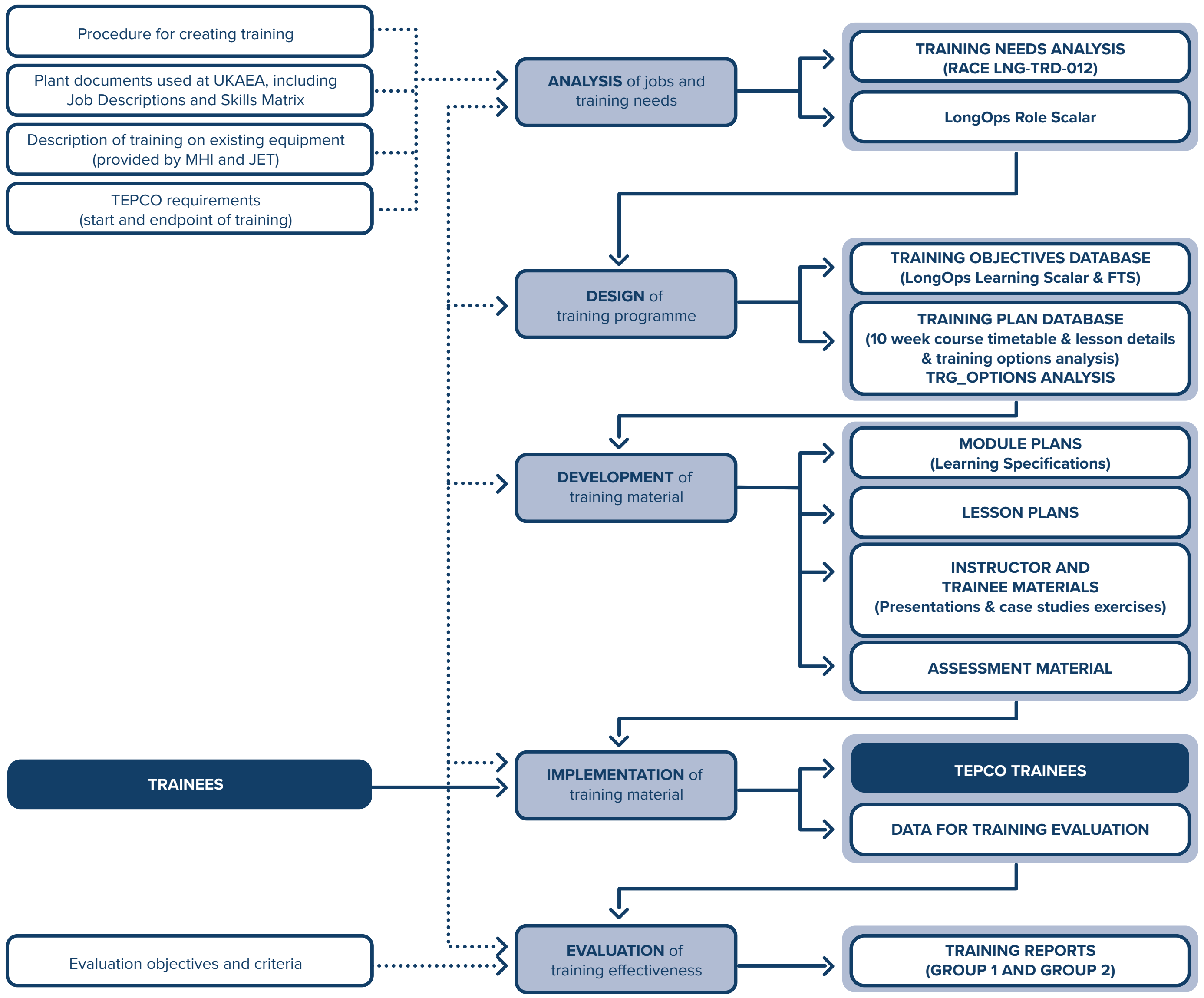



**Figure 1 Systematic Approach to Training (SAT) Flow Diagram**

The course will be delivered in the UK at RACE. It is supported using a JET-like Digital Mock Up (DMU) and hardware available in the RACE building (e.g. user interfaces, cameras, lighting, MASCOT, TARM, communications infrastructure etc), as well as hardware that can be brought from JET to RACE for short periods (e.g. tooling). The training course has been developed with three levels, covering topics in increasing detail:

**Level 1 - Basic**

This is level provides an introduction to remote handling at RACE. It provides the foundation for the whole course giving the students an appreciation of safe systems of work and RH principles. The students will be trained to use the digital tools that make up the training platform, these include RH equipment Human Machine Interfaces (HMI) and a JET-like DMU.

→ The basic level course will provide a functional and operational overview of operation of the training platform, a system representing the JET remote handling equipment and software.

→ This will give participants an understanding of the chosen systems, including how they integrate within the overall RH system. System functionality and operating principles: Safety, design integration, and use cases. Include simple hands-on practical familiarisation. Basic training exercises in a simulated environment, the DMU.

→ Attendees will gain a basic knowledge of the subject matter or topic area to allow understanding and familiarisation. Basic understanding of how the system integrates within the full RH system.

**Level 2 - General**

This level continues to build experience and knowledge of RH operations systems and processes. It is supported by practical demonstrations and exercises in a control room environment using simulated RH systems. The trainees will participate assuming the role of RO. The group will run through the output of exercises, reviewing and learning.

→ Attendees will be trained in the functionality and safe operation of the training platform.

→ The participants gain a greater understanding of what the system is and how it integrates within the overall RH systems. System functionality and operating principles: Safety, design integration, and use cases. Includes operation and exercises in a simulated environment (DMU). Where available, this will include the use of real hardware.

→ Attendees will be trained in the use of the selected RH equipment or application. Theory and practical assessment will be used to confirm a basic understanding of the system architecture and capabilities. They will achieve basic competence in the safe operation of the selected remote handling equipment or application.



**Level 3 - Expert**

This level will allow the trainees to demonstrate their knowledge through its application. Exercises are more complex with students expected to work with minimal supervision. Communication between students and the wider RACE team is encouraged.

→ Training in the advanced functionality and safe operation of the selected equipment or application and how it interacts with the full RH system. Develop in-depth expertise from the previous general course.

→ Advanced functionality and its application. Off-normal and recovery scenarios will be studied alongside advanced task development and optimisation. Team supervision, mentoring and development for junior personnel. Simulated operational scenarios, including working within a team environment.

→ Attendees will be trained in the advanced use of the selected RH equipment or application, including off-normal or recovery scenarios. Attendees will have a full understanding of the system architecture, operation and capabilities. They will have experience of working in/leading an operational team in either a simulated or real environment. Executing advanced and full operational tasks – Simulated or real.

TEPCO operators will gain the skills and competencies required to be responsible officers. They will be able to use this knowledge to develop their own operating practices and training. Applying what they have learned at RACE to their RH programmes and team development will help to accelerate their journey to delivering the safe decommissioning of Fukushima Daiichi power plant. RACE gains experience in preparing and delivering a structured training course to an external organisation. Moreover, others can benefit from the creation of this standalone training course, including Sellafield, ITER, European Spallation Source, and JET Remote Handling. The approach used to create the RO course is being applied to the JET RH training to make it a more complete the package.

The training will be delivered to the TEPCO trainees over 12 weeks at RACE, with two groups of three attending. Training will include 'homework' which will be conducted during the remaining time. 'Homework' may include use of the JET-like DMU and the Learning DMU. Each group of TEPCO trainees will be allocated an instructor and mentor. RACE will prepare a final trainee assessment and will provide TEPCO Project Manager with a confidential assessment of the trainee's activities and competence.
The course equips the trainees with the skills and competencies to work as RH responsible Officers based on RACE experience and knowledge. This does not qualify the trainees to work at Fukushima Daiichi 1F as RH ROs, further training specific to their equipment and environment is required.

# Secondments

A total of five secondees have joined LongOps from September 2021. TEPCO's objective for the secondments is developing technical skills regarding digital mock-up systems which are necessary for the fuel debris retrieval at Fukushima Daiichi NPS in the future. Sellafield Ltd also embed a secondee in the project to bring an enhanced knowledge of remote systems back to their team.

## Fumiaki Abe

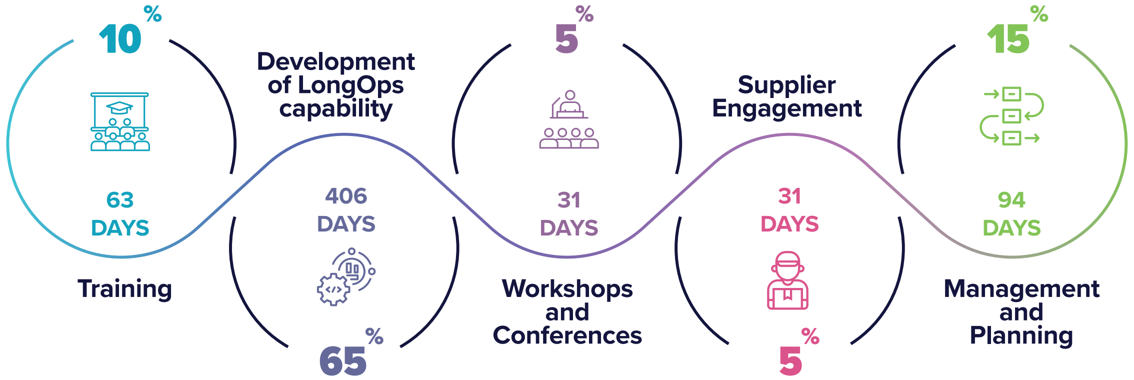
Engineer, Tokyo Electric Power Company Holdings, Incorporated

Alhough initially affiliated with the Japan Atomic Energy Agency (JAEA), which is a research institute in Japan that conducts various research and development related to nuclear energy, before joining LongOps, I was seconded to TEPCO. I had experience in the research and development of a robot simulator that provides operators with virtual training for remotely controlled robots. I have used my experience to support the development of technology within the Longops programme.

Firstly, I have experience and knowledge in robot simulation. In past projects, I developed autonomous navigation programs for mobile robots using a camera and distance measurement sensor. Additionally, I integrated motion planning frameworks for robot arms into simulations. In LongOps, we have collaborated with various suppliers in technology development. My experience and knowledge contributed to discussions as to whether the software implementation aligns with the TEPCO use case.

Secondly, I have experience in implementing technologies commonly used in robotics and information engineering into practical applications. Leveraging these experiences, I contributed to the development of programs for acquiring actual sensor data necessary to evaluate manipulator performance, as well as interfaces to integrate long reach boom simulation into NG-DMU.

Finally, I have supported the facilitation of smooth communication between the UK and Japan, where differences in language and the use of numerous terminologies could lead to misunderstandings. In such situations, I have utilised my skills to explain concepts words that the Japanese team can correctly understand. Additionally, I have conveyed questions from my Japanese colleagues to those from the UK, contributing to an improved mutual understanding.




## Masaki Sakamoto

Nuclear Engineer, Tokyo Electric Power Company Holdings, Incorporated

My background is in nuclear engineering. Robotics is challenging but interesting to me. I have been involved in the following on the LongOps programme:

- Internal research on manipulator evaluation.
- Haptic training simulator.
- Datasets for the development and testing of sensing techniques.

My primary responsibility lies in the development of the Haptic Digital Twin (HDT). The HDT has been developed in collaboration with RACE and Generic Robotics. My main tasks have included commissioning and conducting user trials. During commissioning, I focused on confirming the following functions:

- Ensuring various haptic devices, such as Haption Virtuose 6D TAO and Geomagic Touch, can connect with HDT.
- Ensuring Haptic force feedback functions properly through the connected haptic devices.

The user study of HDT involved ten operators. The completion time for each task was recorded in the user study for both novice and expert operators. Additionally, gaze heatmaps were created for several tasks, comparing novice and expert operators. The results of the commissioning and user study are summarised within the NG DMU Familiarisation Training report.
Two simulators have been developed as part of this scope:

- Haptic simulator merging rigid body with fluid modelling
- Haptic simulation with live sensor data

For the Haptic simulation with live sensor data, I conducted multiple tests with the connection of a Kinect v2 camera and Haption Virtuose 6D TAO. I provided feedback to each supplier, leading to the development of revised simulators.

Within the sensing and perception work package, a dataset for machine learning was created using information from Fukushima.

As part of my work on manipulator evaluation, I underwent operational training for both TELBOT and Dexter. I am now a certified operator capable of manipulating both TELBOT and Dexter. After obtaining the operator certification, my next task was to prepare teach files for TELBOT. This involved displacing TELBOT remote arms automatically for repeatability and accuracy tests. I delved into the inverse kinematics using Peter Corke's Robotics Toolbox. The Toolbox provides tools for representing the kinematics and dynamics of serial-link manipulators. The TELBOT models were added to the Denavit-Hartenberg (DH) directory of the robotics toolbox models. Subsequently, joint angles of TELBOT remote arms were calculated using Python scripts and written into teach files. Through several trial and error iterations, I revised the teach files. The repeatability and accuracy tests of TELBOT were then conducted using the revised teach files.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## Shu Shirai

Researcher, Tokyo Electric Power Company Holdings, Incorporated

My background is materials science. Robotics and digital are not familiar to me, but I am very interested in it. Participating in the LongOps Programme is a significant challenge for me, and I am happy to be part of this programme, especially given its focus on R&D for fuel debris retrieval at Fukushima Daiichi nuclear power station (NPS).

As part of the Longops programme I was responsible for the following three tasks.

**Selection, procurement, and evaluation of manipulators**
Due to the inaccessibility of the inside of the Fukushima Daiichi NPS reactors for humans, remote operation technologies such as robots and manipulators are essential. However, we, TEPCO, lack the knowledge and experience related to the selection and procurement of such robots. Therefore, I am acquiring these skills within this project to contribute to future debris extraction efforts. As a result, we can select suitable robots and manipulators for fuel debris retrieval operations and purchase them at appropriate prices. This is a crucial skill for us, as it can also contribute to reducing the costs associated with the decommissioning process at Fukushima Daiichi.

**Object recognition using AI**
As mentioned earlier, since humans cannot enter the reactor, we conduct inspections inside the reactor using cameras. However, the visibility inside the reactor is significantly compromised due to obstacles, camera noise from radiation, low light levels, and other factors. Therefore, we have developed object recognition using AI to easily evaluate what there is inside a reactor.

**Building a simulation environment using haptic devices**
We also have an insufficient number of remote operation operators, requiring a significant amount of training time and facilities. However, manipulators are expensive and prone to physical malfunctions, making efficient training challenging. To address this, we have constructed a simulation environment using haptic devices to enable more realistic training, contributing to the skill development of operators.



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## Tomoki Sakaue

Senior Researcher, Tokyo Electric Power Company Holdings, Incorporated

I am a senior researcher from TEPCO with an Electric and Electronic engineering background. Before the secondment, I was involved in R&D of remotely controlled robots which apply to Fukushima Daiichi decommissioning at the TEPCO Research Institute. In Fukushima Daiichi decommissioning, various types of robots were introduced, however, these robots had been developed with respective design policy and had no common interface. In order to develop decommissioning robots more efficiently and keep a sufficient quality, standardised architecture and interfaces should be applied. My objectives in LongOps were developing standardised architectures and interfaces used in decommissioning robots through integrating NG-DMU Architecture and Standards for Interoperable Robotics Software & Communication.

In the work of the development of standardised architectures, I learned how to configure the architecture of NG-DMU. The architecture was created based on requirements for the NG-DMU which satisfy Fukushima, Sellafield and JET use-cases. Our major task here was attempting to develop the NG-DMU architecture to an architecture which focusses on TEPCO's specific fuel debris retrieval use-case. This architecture is expected to be utilised as a basis for building an actual DMU system which is planned to be used at the Fukushima Daiichi site in the next 2 years.

In the work of Standards for Interoperable Robotics Software & Communication, I was involved in both of the sub-projects, Interoperability standards and Generic Nuclear Robotics Architecture (GNRA). We learned the background technology and knowledge each supplier has, such as the evaluation criteria of interoperability and the methodology of building GNRA, which are a set of standards. In addition, we worked together with RACE and suppliers to develop an improved demonstration scenario and standards framework taking user perspective into account. The interoperability criteria will be used in platform selection for the TEPCO's DMU for the objective evaluation.

I was also involved in De-Risking Flexible Device Motion Planning. The subject of this workpackage is developing vibration suppression technology which can be applied to the long-reach arm, with two suppliers bringing their unique control techniques. TEPCO secondees learned the control theories and their implementation within physical systems. We also built one of the control systems on the ROS2 platform by ourselves, then verified its effectiveness. Our experience and knowledge obtained in this work will be useful for designing and maintaining TEPCO's own systems even if the configuration of future robots' changes.


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## Wataru Sato

Nuclear Engineer, Tokyo Electric Power Company Holdings, Incorporated

Prior to being seconded to RACE, I was involved in tasks related to radiation management and nuclear reactor containment vessel investigation at Fukushima Daiichi Nuclear Power Plant. I primarily worked on sensing and perception and carried out tasks related to TEPCO's management in the LongOps programme.

As part of the construction of the object recognition dataset for the Fukushima Daiichi use case, I worked on building a dataset. A significant challenge of this task was the low quality of the Fukushima Daiichi data used, as it consisted of investigation footage from the accident reactor, that is to say it consisted of, low resolution camera footage within an extreme nuclear environment such as high radiation, low light levels and foggy. Determining what is shown in the footage required knowledge of nuclear reactors and a specific understanding of the Fukushima Daiichi situation. I leveraged my experience in investigation within the Fukushima Nuclear reactor to check the data annotated by the supplier for its accuracy. Since it serves as the training data for object recognition, accuracy is of the utmost importance! I also engaged in tasks such as creating and evaluating the object recognition trained model in WP 3.5.1 (Datasets for the development and testing of sensing techniques) and conducting system verification for data sensing in WP 3.5.2 (Incorporating live sensor data into digital twins). Regarding this, I lacked experience and knowledge, and I relied on guidance from the RACE team members throughout. I am not sure how much impact I had, but this experience provided me with valuable learning opportunities. I also provided RACE with the necessary TEPCO data for the LongOps programme at the initial stage. The exchange of data internationally and between organisations is highly complex, involving issues such as intellectual property and foreign exchange regulations.

Lastly, I believe that during this secondment the most significant contribution of the LongOps programme for the TEPCO secondees, including me, is becoming an engineer who understands the digital system and can integrate digital systems into Fukushima Daiichi decommissioning. Thank you for everything!




## Ryan Parker

Remediation Technical, Technology & Innovation (T&I), Sellafield Ltd

As a Mechanical Engineer in the Remediation Technology and Innovation Team at Sellafield. I have been involved with the LongOps programme since it kicked off in 2020, and have taken on a range of roles over that time. Initially I supported the Sellafield Lead by downselecting our potential use cases, resulting in the selection of Pile 1 and provided engineering input to the initial tranches of problem workshops.

As part of my graduate programme an opportunity arose for a secondment to UKAEA, as part of the LongOps team. While I was there, I got brilliant exposure to remote handling and robotic operations and spent a significant amount of time around real experts in this field – this included training on MASCOT. While at UKAEA I delivered a range of projects including a feasibility study into decommissioning JET, the design of a remote handling training platform and substantiation calculations for mechanical components of the TELBOT and Dexter testing cells. I speak very highly of my time at UKAEA, where I was stretched and supported brilliantly by RACE, which allowed me to bring a greatly enhanced knowledge of remote systems back to my team at Sellafield and a network of contacts with significant expertise.

Since returning from my secondment, I've had the privilege of being Sellafield's Lead for LongOps. I've worked closely with UKAEA and TEPCO colleagues to raise the profile of the programme within the NDA group, to ensure that the impressive work undertaken as part of programme is seen by stakeholders, and the opportunities it presents are understood. This has involved a range of presentations, webinars and interactive stakeholder demonstrations. I was also given the incredible opportunity to visit Fukushima as part of my role. While there, I provided insights into technologies that have been utilised in the UK that could assist TEPCO in their decommissioning mission.

I've thoroughly enjoyed working on LongOps and it has been very formative in my nuclear career – thank you to everyone that's contributed to the programme and congratulations on everything that's been achieved!

# Demonstrations

Demonstrations formed an invaluable part of the capability transfer and communication strategy for LongOps. Throughout the 3.5 years of the project, demonstrations were used to show concepts of things to come, progress of work, and the delivery of key milestones. Where possible, these demonstrations were provided in-person, but also included video demonstrations, and live-streams to NDA stakeholders across the UK or TEPCO stakeholders across the world.

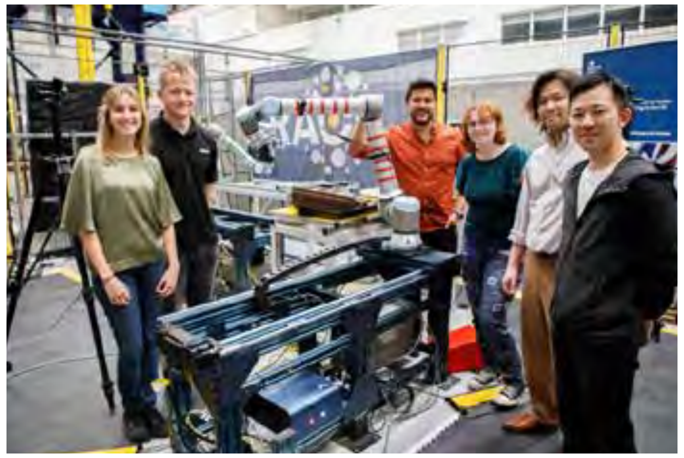
Demonstrations were found to be crucial in the communication of the capabilities being developed in the various themes, and for stakeholders to understand the benefit these capabilities would have in their own applications. Once capabilities were developed to an operable level of maturity, LongOps also held a number of “familiarisation sessions”, which allowed operators from UKAEA, NDA, and TEPCO to have “hands-on” experience with the tools and give feedback. This provided opportunities for operators to learn how the tools worked and how they can be applied to their operations, but in many cases also provided the suppliers with useful information and user testing to help refine their designs.

NavLive demonstration at Jacobs facility



Many demonstrations were held by suppliers at their own facilities, attended by representatives from NDA, TEPCO, and UKAEA. These demonstrations were very helpful throughout the duration of the various supplier contracts in order to report on progress and provide feedback if required. These visits provided a significant level of confidence in the approach and capability being demonstrated.

Atkins path-planning demonstration on TARM



Jacobs demonstration in UKAEA’s RACE workhall

Where possible, UKAEA also supported suppliers by providing representative nuclear hardware on which to demonstrate. This included the use of RACE’s 10-metre long TARM manipulator, which was used with great success to demonstrate automated path-planning with obstacle avoidance. This gave stakeholders the opportunity to not only see the capability produced, but also see it demonstrated on real-scale nuclear hardware, gaining further confidence in its capability and application.

An NG-DMU live-stream demonstration

NG-DMU demonstration at Fukushima Daiichi

The NG-DMU and its virtual operations control room at UKAEA’s RACE facility was used throughout the project to demonstrate various LongOps developed capabilities within simulations of the stakeholder use-cases. This room was specifically designed to deliver demonstrations both in-person and to stakeholders that wished to join remotely, providing the ability to stream any display in the room (and the room itself) to an online audience.

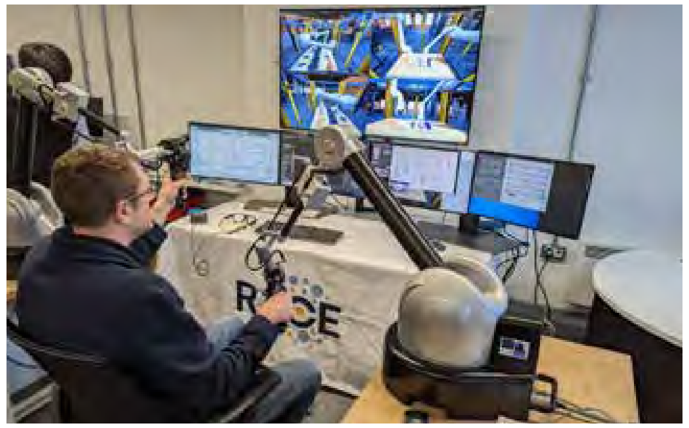
NG-DMU demonstrations have also been delivered in Japan to large TEPCO audiences.

**Familiarisation Sessions**
In addition to regular demonstrations, “familiarisation sessions” were held throughout the LongOps project, giving operators from TEPCO, Sellafield Ltd, and UKAEA the opportunity to gain hands-on experience with the digital capability developed within the project. These sessions gave stakeholders and potential end-users the chance to provide feedback on what it was like to use the technology from a non-technical perspective and steer the direction of development.

**NG-DMU familiarisation day at RACE**

In order to facilitate stakeholder and end-user engagement, familiarisation sessions were held at all 3 use-case locations – Oxford & Cumbria in the UK, and Tokyo & Fukushima Daiichi in Japan.

**Haptics familiarisation session in Tokyo, Japan**



**Haptics familiarisation session in Cumbria, UK**



**Digital rehearsal familiarisation**

**Tele-manipulator familiarisation**

Sessions included hands-on experience with both digital and physical systems. Allowing operators and end-users to experience how the technology works together for the benefit of their particular applications and challenges.

**A group of 11 operators and end-users from Sellafield Ltd joined the LongOps team at RACE for a full day of familiarisation, feedback, and demonstration sessions.**

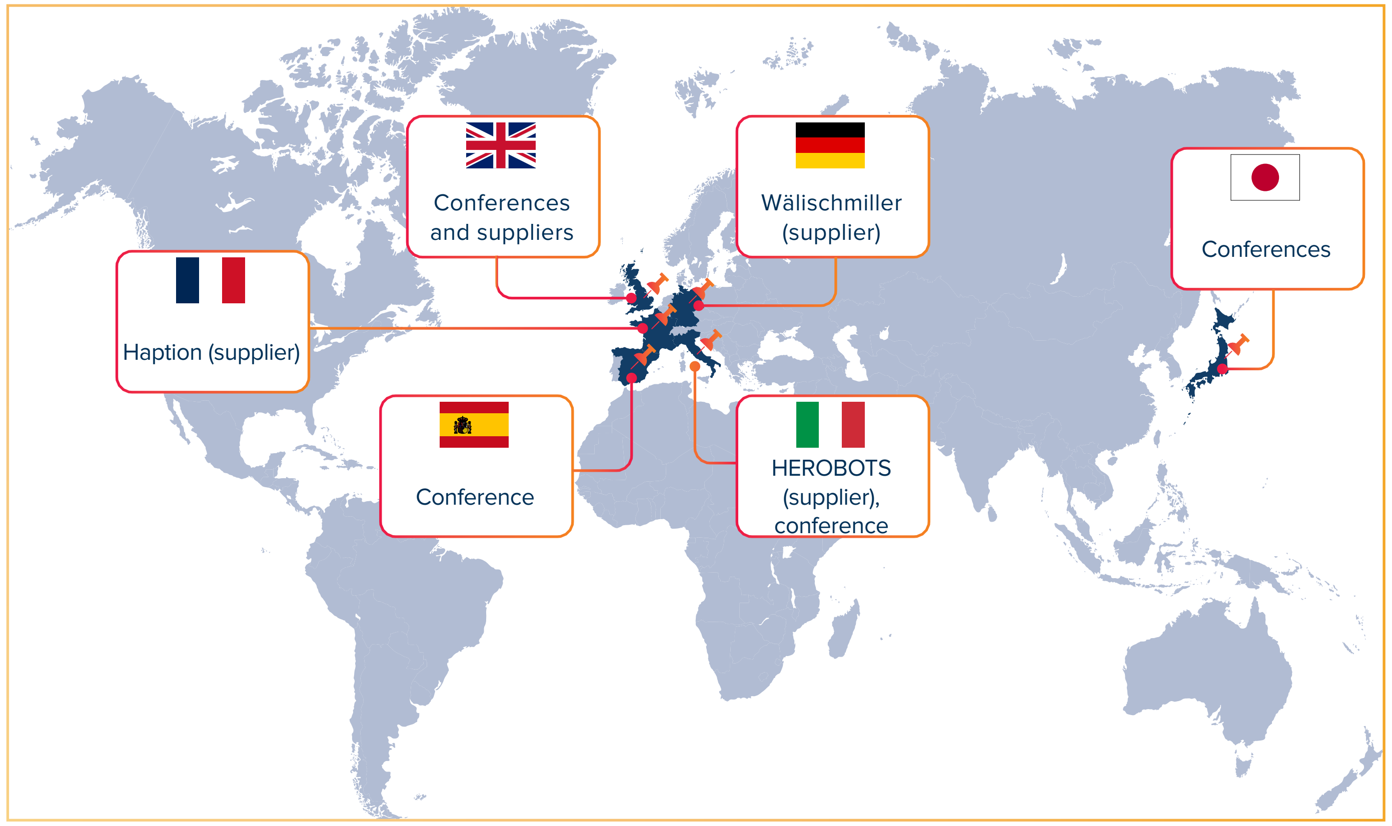
Providing stakeholders and end-users with the opportunity to see and use the technology as it was being developed throughout the LongOps project, greatly facilitated the communication of the progress that was being made, and heavily contributed to the confidence in the pace and direction of the research.

# Dissemination

**Knowledge dissemination was a key objective of the LongOps project. The project team, including the TEPCO secondees, shared knowledge with the international robotics and technology community to accelerate technology exploitation, and engaged with the public to raise awareness of our shared challenges and inspire future engineers and scientists.**

## INTERNATIONAL REACH

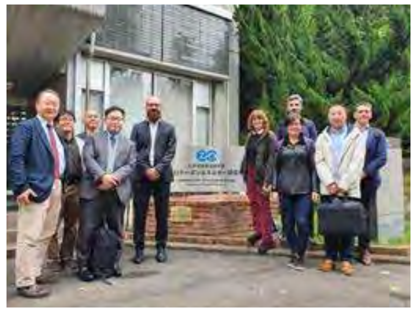
The project's knowledge and capabilities have been sourced from and disseminated around the world.




## CONFERENCES

Held a workshop at the International Topical Workshop on Fukushima Decommissioning Research 2022 (FDR2022) on 14-16 October 2022 in Naraha, Fukushima, Japan. The topical workshop promoted a broad global exchange of information on technologies, operations, management and safety for the Research and Development activities on decommissioning and dismantling of the Fukushima Daiichi Nuclear Power Station.


**University of Tokyo & Tokyo Tech**



**Quantum Science & Tech Research (QST)**

Exhibited at the 2023 IEEE International Conference on Robotics and Automation (ICRA), one of the most prestigious events in the robotics calendar, with attendees from companies and institutions from across the globe. It was held from 29 May to 2 June in ExCel London and attracted over 6000 attendees.

Participated in the 22nd World Congress of the International Federation of Automatic Control held on 9 – 14 July 2023 in Yokohama, Japan.

## PUBLIC ENGAGEMENT

Demonstrated the Haptic Training Simulator at the New Scientist Live - a festival of ideas and discoveries. We reached over 23,000 audience consisting of 44% adults and 56% children on 12–14 October 2023.

Demonstrated the Haptic Training Simulator at the Festival of Speed held on 13–16 July in West Sussex, letting the audience discover the revolutionary new ideas, inventions, concepts and innovations of tomorrow.
**www.goodwood.com/motorsport/festival-of-speed**

Introduced our innovative remote handling technology to Prime Minister Rishi Sunak and then Secretary of State for Energy Security & Net Zero, Grant Shapps in March 2023.

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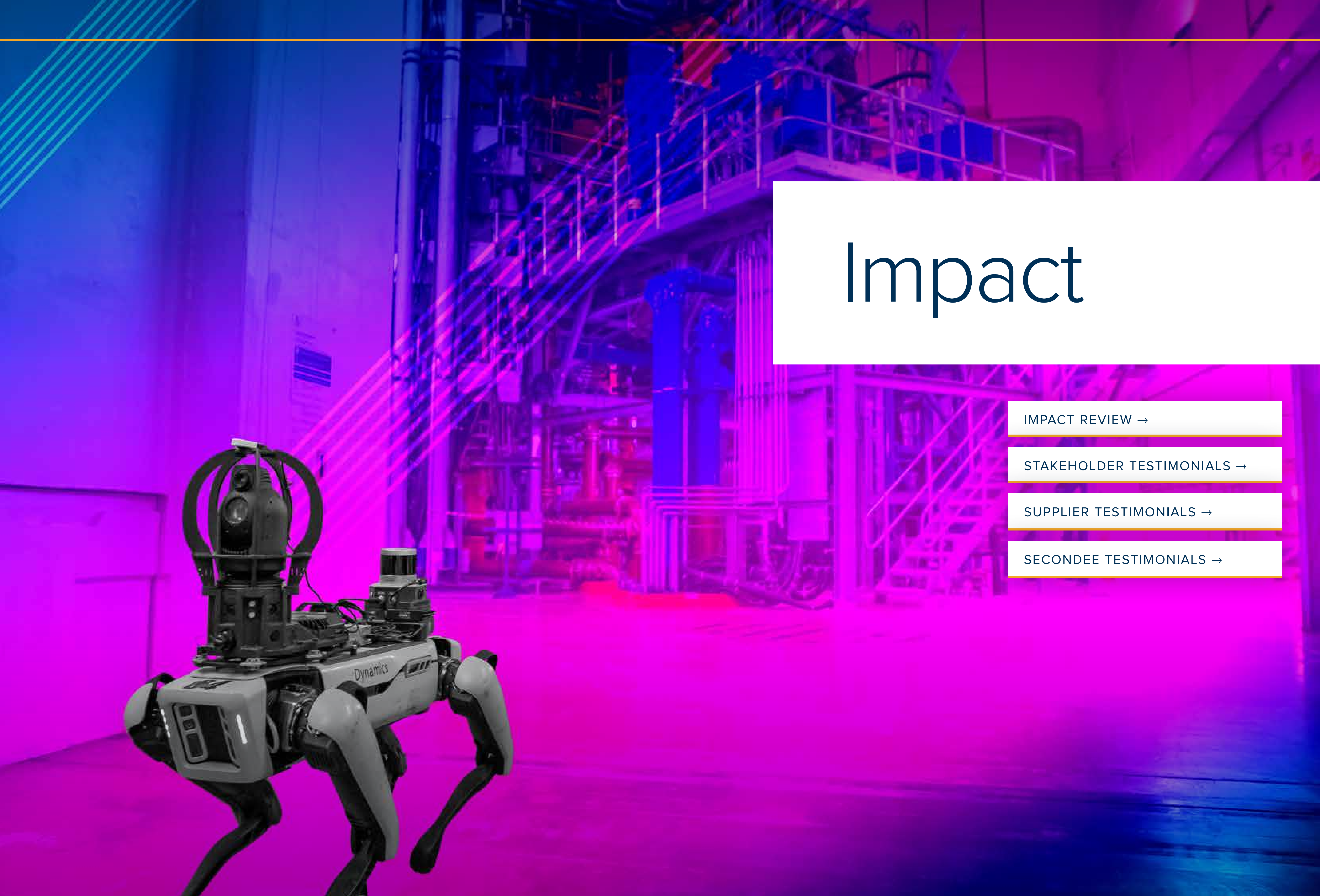


# Impact





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# Impact Review

Over the last four years we have initiated a new international collaboration, agreed scope and arranged for 14 secondees from Japan to the UK to help deliver a 3.5 year £12M jointly funded project of research into robotics and artificial intelligence focused on digital twins.

The key to the success of the project has been aligned self-interest. The NDA Group, including Sellafield Ltd, TEPCO and UKAEA are all end users who own substantial missions and associated liabilities that cannot be transferred to third parties. These end users recognise the vital role of suppliers in the rapidly developing field of robotics and digital twins. UKRI co-invested in LongOps in order to build up supply chain capability. On completion LongOps has involved 20 suppliers and 5 academic institutions from 4 countries with 53% of £6M external funding going to innovative SMEs.

We recognised at the outset of the project that this could be the start of a long-term relationship between NDA, UKAEA and TEPCO since they all have multi-decadal projects that will rely on international agreement regarding best practice and risk reduction. By working together, we have avoided duplication and learnt faster. In the UK, the NDA and UKAEA have joined forces to establish the Robotics and AI Collaboration (RAICo) based in Cumbria to build on progress made under LongOps.

The output of the project has been shared with hundreds of interested parties culminating in a series of workshops that included representation from beyond the nuclear sector. The purpose of sharing this information is to build agreement amongst many end users so that the ecosystems servicing many sectors can grow for the benefit of all.

Collaborations are based on recognising the value of working with the other parties. The NDA recognises the challenges faced by TEPCO with the decommissioning of the Fukushima Daiichi reactors and has supported the Japanese efforts since 2011. The NDA also recognises the value in learning with UKAEA from parallel developments in fusion remote operations. TEPCO recognises their need to learn about setting up teams capable of delivering long term decommissioning using remotely operated machines. UKAEA recognises the opportunity to learn from the realities of nuclear fission decommissioning to inform the design of future fusion power plants.

In the technical space, the primary achievements of LongOps have included:
First, we have integrated a range of software tools from in-house and external suppliers into a suite of software called the prototype next-generation digital mock-up. We have built models of three uses cases, one each for NDA, UKAEA and TEPCO and operated a variety of robots within these digital environments. We have developed digital haptics that enable an operator to both see (tele-vision) and feel (tele-force) the interactions of robot and environment in the digital space.  And, we have started to use machine learning techniques to enhance an operator's awareness of the environment.



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Second, we have procured, commissioned and conducted comparative assessment of two state-of-the-art industrial manipulators at RACE. These systems are now in regular use for training and operational rehearsals in an open environment. For the first time we have been able to quantify the strengths of each system and understand more about expert operator performance.

Third, we have developed standards for digital architectures which could pave the way for decades of obsolescence management and upgrade.

Perhaps more significantly we have felt part of a controlled experiment that has worked well. We have seen the level of knowledge and confidence of UK and Japan engineers grow in design of and use of this next generation of software tools. Many conversations indicate that there is agreement that these digital tools will play a central role in delivery of NDA, UKAEA and TEPCO missions.

Our shared view is that a digital twin has four primary operational impacts. Firstly a digital twin is a communication tools that enable many parties to agree strategy and plans. Second, many can be trained in parallel in many different environments using many robots without the huge expense of creating physical mock-ups. At the UKAEA we have moved from 100% of training conducted in a full-size mock-up to less than 20% immediately prior to commencing real operations. Third, a digital twin can be used during operations by collecting real-time data from the robot and environmental sensors to monitor and improve outcomes. Using machine learning techniques to automatically identify materials and components within both simulated and real environments shows a route to 24-7 automated intervention. Fourth, we have created a time machine. Within a digital world it is possible to review past action for audit or continuous improvement, conduct real time operations and run multiple future scenarios. The final demonstration involved rehearsing fuel debris retrieval from the Fukushima Daiichi reactors.

Initial benefit analysis indicates that there is considerable potential for these digital tools to save "billions and decades" at a national level. One specific outcome is the JET Senior Responsible Owner has mandated the use of a digital twin for the duration of decommissioning the JET reactor as partial mitigation for known schedule and cost risk.

The LongOps team now recommends that NDA and TEPCO replicate the prototype software across their organisation and increase robotic environmental data collection to enable the widespread, managed development and sharing of strategy and plans.

LongOps was established an international collaboration between organisations. It has become a collaboration between individuals. The task ahead is long and complex. There will be unexpected challenges ahead. Digital twin technology can reduce this risk and increase confidence levels that will enable regulators to sanction and operational leaders to initiate planned interventions.

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# Stakeholder Testimonials

## Thomas Cross
Nuclear Counsellor, British Embassy Tokyo

LongOps has been very positive for the bilateral relationship with Japan in nuclear. It is an example often quoted by stakeholders in Japanese and UK governments, including by senior civil servants and by Ministers, as a great example of UK-Japan cooperation. Beyond achieving excellent results in its technical goals, by bringing together a number of scientists and engineers from both countries to work closely together for an extended period, it has helped create enduring ties between our organisations that will continue to give mutual benefits to both our countries into the future.

## Tomoki Sakaue
Senior Researcher, Tokyo Electric Power Company Holdings, Incorporated

TEPCO In Fukushima Daiichi decommissioning, the remote control and robotics are essential technology for not only fuel debris retrieval but also preparation works such as clearing and cleaning due to the high radiation environment inside the reactor buildings. Going forward, it is assumed that the duration of the operations conducted by remotely controlled robots become longer, and the operation becomes more sensitive in hazardous areas. This condition must need operators' attentiveness. All the technologies developed in LongOps can support the operation because of their universality. For instance, manual operations can be replaced by the path planning and the motion control, and the haptics increase operator awareness. Moreover, state-of-the-art sensing techniques help operators' decision making by providing rich information of the operation environment. It is obvious the standardised architecture can be commonly used within various type of remote systems. The final deliverable of LongOps is still a prototype of NG-DMU, however, it shows potential of a future digital mock-up system apply to any remote operations in Fukushima Daiichi.

In addition to the technical aspects above, the human resources development is another contribution of LongOps. 6 R&D secondees and 3 of System Integrator secondees were dispatched for 2.5 years and 0.5 year, respectively. These UK based secondees have acquired a lot of technical skills and knowledge through working in RACE. They are expected to play active roles in building an actual DMU in the near future.

## Ryan Parker
Remediation Technical, Technology & Innovation (T&I), Sellafield Ltd

Across Sellafield there are areas that are not safe for people to enter, or activity levels mean they cannot stay for very long. These include highly shielded and complex environments, such as reactor cores and vast reprocessing cells. Robotics are invaluable to enable decommissioning operations in these areas, to make progress towards our goal of a fully remediated site – but the unstructured and sometimes unknown environments do not always lend themselves well to these missions.

Windscale Pile 1, the Sellafield LongOps use case, is a great example of a complex and unstructured environment. Following a fire in 1957 an area of the reactor's core has been left damaged, making retrieval of the last of the fuel complex. While it is safely within the core for now, the fuel must be removed before decommissioning can take place – as such, long reach robotics will need to be used.

The tools and capabilities developed through LongOps could be invaluable to our robotics challenges. The broad scope of the project has pushed the state-of-the-art in a significant number of areas, and enabled the supply chain to bring innovative solutions to a range of challenging problems. The outputs of the project will de-risk operations, and also enhance the opportunities to train and rehearse in more realistic environments.

The collaboration opportunities that LongOps established will be invaluable moving forwards. Connecting an international network of experts to enable the sharing of learning will have drastic effects on the use of technology in decommissioning. At Sellafield, we're very exited to continue to nurture the collaboration in future projects.

## Eddie Pennington
Development Engineer, Fusion Technology, UKAEA

The Jet Decommissioning & Repurposing (JDR) programme exists to safely and cost effectively decommission the Joint European Torus (JET) following the cessation of plasma science operations in 2023. This is a highly complex programme and a first of its kind in the UK, and indeed the world.

Delivery of this programme will necessitate the handling of hazardous waste materials from within the tokamak, requiring extensive use of robotics and remote handling technologies throughout.

New waste processing facilities, compatible with remote handling, are also expected to be designed and implemented as part of the JDR programme to detritiate JET components, thereby efficiently and effectively minimising the amount of Intermediate Level Waste extracted during the decommissioning process.

Digital capabilities developed under LongOps, specifically the Next Generation Digital Mock Up (NG-DMU), can add significant value to JDR in this area. Specific use cases include task development for complex remote handling operations (e.g., disassembly of beryllium first wall tiles) and rapidly prototyping concept layouts for new facilities. This will greatly benefit the programme by de-risking novel operations prior to physical implementation, reducing overall development risk and associated costs.

NG-DMU will also facilitate operator training and task familiarisation when the physical remote handling systems are in use (for example during decommissioning operations). This is key to maintaining a team of fully trained remote handling operators over an extended, 10+ year decommissioning campaign, ensuring operational readiness throughout.

Moving forwards these digital capabilities developed under the LongOps can continue to support JDR and ultimately contribute to decommissioning activities on future fusion power plants.

# Supplier Testimonials

## Generic Nuclear Robotic Architecture (GNRA)

Participating in the LongOps programme has enabled us to work with RACE/UKAEA and understand first-hand the operational requirements of the atomic energy robotics sector. This achievement would have been challenging to accomplish organically as a new R&D supplier to the nuclear sector. Consequently, we were able to bring in 20+ years of defence R&D expertise and in collaboration with the RACE experts draft the first ever Generic Nuclear Robotics Architecture (GNRA) standard, a significant milestone that marked the initiation of a new technology standardisation programme.

Standardisation and through-life capability management has been evident in significantly improving the whole development and supply-chain life-cycle of high-criticality systems and platforms in complex environments, such as defence. The GNRA programme now aspires to extend these proven benefits to the development of robotic systems and platforms tailored for nuclear decommissioning (structured and unstructured) and other applications within the atomic energy sector.

**Periklis Charchalakis - Vetronics**

## Automated Change and Anomaly Detection

The LongOps project has made a big impact on NavLive. This was our first project as a spinout from the University of Oxford and provided the funds and opportunities for us to grow and demonstrate our technology in a realistic environment. From a technology point of view, the LongOps project allowed us to improve our 3D mapping technology, and develop new capabilities in change detection, thermal mapping, and BIM visualisation (augmented reality) which are crucial to our future business opportunities. With UKAEA, TEPCO, and Jacobs, we have shown how this type of technology could help to solve some of the key challenges in nuclear inspection and decommissioning. This includes remote inspection, detecting changes in the environment, and bridging the divide between the digital twin and reality.

More broadly, this LongOps project was an enabler for us to raise our seed round of venture capital investment in mid-2023 and is hopefully the beginning of future projects within the nuclear industry and beyond. The networks, technology, and skills we gained will be very valuable for us in the future.

**NavLive**

## Interoperability Standards

The AMRC's objective on the LongOps programme was to develop a data model to quantify and assess the interoperability of communication protocols and architectures used in robotics systems. This mechanism builds upon the latest findings in the landscape to evaluate captured metrics against its relevancy and suitability specific to nuclear applications.

LongOps has been of immense value to the AMRC in also advancing our understanding of interoperability quantification and its importance across other sectors whilst directly applying it within the nuclear domain. The programme has delivered a framework for system definition and evaluation to address the challenge of quantifying the affects and changes in system design or architecture to assess potential improvement as a feedback mechanism. This will be available open source following a publication, which both AMRC and RACE will use for future system design.

The RACE project team have been invaluable in fostering the horizontal innovation, adapting our main sector expertise into their domain. This built on AMRC's main domain knowledge within manufacturing and aerospace to produce the quantifiable analysis mechanisms of the data model within nuclear decommissioning environments from both safety-critical domains. The regular support and communication throughout the project developed a strong supportive culture from both sides to deliver the best value to all involved.

**Jack Raspin – University of Sheffield AMRC**

## Vibration Compensation for Flexible Long-Reach Manipulators

Participating in the LongOps project has been an incredibly enriching experience. The professionalism and dedication of the research team were evident at every stage, ensuring the highest standards of quality and accuracy. What stood out to me the most was the collaborative spirit that permeated the project. Working alongside academics and engineers from diverse backgrounds (Jacobs, UKAEA, TEPCO, Sellafield) fostered a dynamic exchange of ideas and perspectives, enhancing the depth and breadth of our research outcomes. The innovative approach to mitigate vibration directly by controlling the manipulator dynamics has the potential to revolutionise engineering practice, offering valuable insights and solutions to complex challenges.

The team is confident that the findings from the LongOps project will not only advance the field of nuclear robotics but also make a tangible difference in real-world applications like mobile robots and long-reach manipulators. This research has led to further funding and recognition in international events and media. We are grateful for the opportunity to have contributed to such impactful work and look forward to seeing its continued influence in the industry.

**Erwin Lopez Pulgarin, Joaquin Carrasco, Alexander Lanzon, and Guido Herman - University of Manchester**

## Planning Tools for High Degree of Freedom Manipulators

Long-reach, many-jointed robot arms will be needed to reach inside damaged reactor cores at the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident site. Other kinds of long-reach arms will be needed for servicing and decommissioning UKAEA's experimental nuclear fusion torus, and there is potential to use such manipulator robots for inspection, characterisation and decommissioning operations in complex or hard-to-reach environments at Sellafield and other legacy facilities.
LongOps had benefitted the University of Birmingham Extreme Robotics Lab (ERL) team by:

- → providing funding to enable us to explore a complex and exciting robotics research challenge;
- → enabling us to demonstrate our technologies and capabilities to important stakeholders in the national and international nuclear sectors;
- → enabling us to learn about a new industrial challenge from these stakeholders, and target our research efforts at industrially relevant applications;
- → giving us the opportunity to engage in a rich cultural exchange experience by working with colleagues from Japan.

We are keen to work with the LongOps stakeholders to scale up this technology and implement it a higher Technology Readiness Levels. It will assist TEPCO, Sellafield and UKAEA to use these methods for their long-reach manipulators in nuclear fusion applications.

There is also potential to use these technologies in other extreme environments, such as space and sub-sea operations. Closely related computational problems arise in motion planning for high-value manufacturing, in which robot arms are combined with multiple additional motion axes in tasks such as inspection, welding or additive manufacturing.

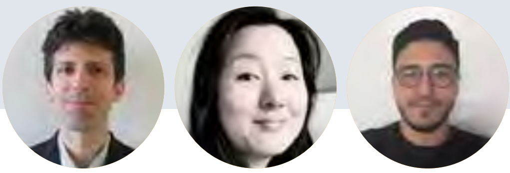
**University of Birmingham**

## Planning Tools for Long-Reach Manipulators

The main drive for the involvement in LongOps was to build on our extensive experience in industries with hazardous and challenging environments with a high safety focus. This project specifically allows operators to plan robotic operations and tasks safely in the digital environment and evaluate the impacts and risks of movements and operations before deployment and operation in the real environment. This reduces the stress on human operators and lowers the chances of human error. It also allows for partial automation of routine tasks.

- → Our involvement in LongOps allowed us to work within multidisciplinary teams from different backgrounds and research institutions, enhancing our ability to work with non-commercial supply chain and continue our contribution to drive technology forward.
- → This project has benefited our understanding of the challenges and needs on this type of work, including the constraints of current technologies and resource skills. It did also helped us to understand better the skills required to manage the interface between design and system integration work with research activities and use of open source evolving tools.
- → Moving forward, we are keen to further our involvement in projects of research nature with potential of commercialisation, working with the brightest minds within our own organisation and supply chain from all backgrounds, academic, research and commercial. Our role lies in integrating teams, delivering to challenging specifications and delivering exciting advancements in technology.

**AtkinsRéalis**



## Datasets for the Development and Testing of Sensing Techniques / Incorporating Live Sensor Data into Digital Twins

The UKAEA LongOps programme has benefitted Jacobs in terms of our technology development as the design of an initial overall software architecture for a NGDMU involving the existing NVEC architecture has enabled us to extend the applicability of NVEC which is expected to be useful for future projects. The integration of radiation simulation codes in the robotics pipeline has enabled us to progress ideas towards a flexible modelling framework supporting remote operations, whilst the development of software modules to handle and display 3D radiological data fields has enabled us to use radiation simulation results in new ways which will be useful for future applications.

Developing the perception pipeline in LongOps has provided insights of the state of the art and new tools which are already benefiting our robotics capability, to the point that some of the modules developed and used in LongOps are currently being used in client projects.

The projects have allowed us to learn and apply development processes and modular system architectures which will impact how new projects will be organised and designed. The work we performed in LongOps aligns well with CRADLE (Centre for Robotic Autonomy in Demanding and Long-lasting Environments) which is a collaborative research centre being ran by Jacobs and the University of Manchester delivering novel and transformational Robotics and Autonomous Systems (RAS) technology for demanding environments, such as space, nuclear, energy generation and urban infrastructure, allowing the benefits promised by this technology to be realised across wide sectors of UK industry. Working with our partners and UKAEA has been beneficial to understand the way of working of each organisation and we look forward to future collaborations.

**Jacobs**

## Merging Haptic Rendering with Live Sensor Data

The LongOps program has had a positive impact on our research and general outputs. The LongOps program has benefited us greatly, as it provided us with the time, resources, and technical input to create a technological demonstrator that integrates different cutting-edge technologies. This platform has allowed us to extend our research for further funding, achieve dissemination of our work in local events and social media, and to create recognition and links in international events such as IROS 2023.

This platform was developed wanting to overcome most of the limitations previously experienced when developing Digital Twins: slow or unfeasible point cloud rendering from live data feed, and the impossibility of using it for physics-based calculations and applications such as haptic rendering. Besides using more powerful and expensive computers with more powerful CPU, GPU and RAM specifications, there was no solution to these problems, which are severe if using a Digital Twin for teleoperation. In applications with limited bandwidth, such as distance teleoperation using an internet connection, point clouds could not be used at all.

Our next steps are to improve and extend our platform for both research and industrial applications. We will improve our mathematical models to make our voxel-based renderer more stable and will integrate eye-tracking data into our point cloud processing pipeline. We will also extend our platform to be the intermediate layer between the user controlling a real robot, particularly for applications such as robots performing glovebox operations for nuclear decommissioning.

**Erwin Lopez Pulgarin, Joaquin Carrasco, Alexander Lanzon, and Guido Herman - University of Manchester**

## Planning Tools for Long-Reach Manipulators

The inception of LongOps was driven by the need to address complex challenges in remote operations and hazardous environments. By being part of a multi-disciplinary team of talented industry experts, the experiences gained has significantly benefitted our understanding in best practices for innovation delivery and uplift current approaches in research engineering.

- → Technological Development: Focusing on advancing our research results in robotic path planning and simulation, LongOps has allowed us to translate the work further towards industry application that otherwise wouldn't be possible. The lessons learnt has helped us to advance more quickly towards our aim in becoming market leaders in the field and attracting follow-on investment from other industries keen on adopting our solutions.
- → Management Enhancement: Our involvement in LongOps has tested and enabled change in how we manage operations to better handle high risk translation projects. The project's demands has led us to evaluate and streamline current approaches to aid industry collaboration. This includes more support for fostering in-depth relationships that requires engagement across multiple stakeholders.
- → The Future Trajectory: Looking ahead, LongOps has helped us refine our technological solutions and management approaches to achieve impact across a broader set of applications. The versatility of the technology developed makes it adaptable to various challenging environments, promising a future where our solutions not only contributes to industrial efficiency and optimisation but also environmental conservation.

The journey with LongOps has been transformative, and we are enthusiastic about the future prospects and impact of the technologies we have developed.

**University College London, The Bartlett School of Sustainable Construction**

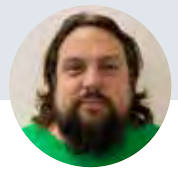
## Haptic Training Simulator

LongOps was a unique opportunity in technology R&D and a niche area like robotics, it is rare to have access to high-level complementary expertise yet a broadly free rein to explore the necessary paths to reach a particular goal. This process has resulted in a new technology stack that, to our knowledge is unique in the sector, yet fit for purpose and evaluated against real-world needs. Consequently, this has mean we hit the ground running at the end of the project commercially speaking, with a clearly defined and proven USP, even if there remained significant technology development left to move the new platform though to a commercially exploitable TRL. The UKAEA relationship was equally beneficial in making connections to potential clients/customers who would have otherwise been hard to access.

The robotics sector lacked tooling and more broadly a general platform for real-time robotic simulation, that is, the ability to quickly deploy realistic simulation of robotic systems which can be operated in real-time whilst still behaving in a physically plausible manner and responding to controller or human inputs in real-time. Many comprehensive off-line simulation platforms exist, as do some vendor specific real-time platforms, but little has ever been available that can be generalised to arbitrary robotic systems and applications, especially where haptic control is concerned which takes the real-time element to a very technically challenging level

Were in the process of commercialising the technology with two main activities: further developing the robustness and capabilities; and building partnerships and potential clients. We have a small number of clients using the platform for R&D and demonstrative purposes and are about to ship the first implementation for a directly commercial application

**Alastair Barrow (CEO) and Tom Smith (CTO) - TOIA**



# Secondee Testimonials

TEPCO

### Fumiaki Abe

LongOps has been an opportunity to explore various technologies I have not dealt with before. It was challenging until I got used to it, but it was also enjoyable.

I am going to return to my former employer, Japan Atomic Energy Agency (JAEA), and start research and development of technologies for the decommissioning of Fukushima Daiichi Nuclear Power Plant. Path Planning for robotic arms is one of my research themes and I would like to conduct a more in-depth study on the challenges revealed in LongOps. Specifically, I will focus on generating paths that allow robots to move while ensuring safety in complex and unpredictable environments. As well as a user-friendly interface enabling users to operate digital tools in an intuitive way.

### Masaki Sakamoto

When I joined LongOps, I was unfamiliar with robotics, haptics, and digital mock-ups. During my time at LongOps, I acquired knowledge in fundamentals such as Haptic Digital Twin (HDT), machine learning datasets, forward/inverse kinematics, and the operation of TELBOT and Dexter. These activities proved challenging yet intriguing to me.

Now, as I return to my original position at TEPCO Systems (TEPSYS) after completing my secondment at LongOps, I will apply the experience and knowledge gained to contribute to the development of a digital system for Fukushima with TEPCO.

### Shu Shirai

At the beginning of my participation in LongOps, I had no background in digital technology. However, through this project, I was able to acquire knowledge in digital technology, especially a foundational understanding of manipulator mechanisms, evaluation methods for selecting manipulators, practical manipulator operation techniques such as TELBOT and Dexter, basic knowledge of AI, programming skills, and haptic simulation. With these acquired skills, I aspire to contribute to the future fuel debris removal at Unit 1, Fukushima Daiichi, ensuring safety and reliability in the decommissioning operations.

### Tomoki Sakaue

Apart from digital related technologies, what most impressed me was Technology Readiness Level (TRL). TRL is considered an objective tool to measure the technology level before and after the R&D, and the relevant people can predict how long further R&D will take, and how difficult it is before its commercialisation. If we use a subjective measurement tool for technology levels, there could be a misunderstanding between the research group and the stakeholder, and the project may not succeed. I would like to apply TRL to R&D projects conducted in our company and increase the outlook accuracy after going back to TEPCO.

### Wataru Sato

When I first came to RACE, I had no prior experience or knowledge about robots and digital systems. Through the two and half years of secondment on the LongOps project, I gained insights into robot and digital systems and became a person capable of applying them to Fukushima Daiichi. Upon returning to TEPCO, I am going back to Fukushima Daiichi hopefully, and I aim to implement the digital system into Fukushima decommissioning. The first step is to implement the NG-DMU system in Fukushima! Through these activities with RACE, I hope to contribute to the widespread adoption of digital systems in Fukushima decommissioning and lay the foundation for TEPCO to become an intelligent customer.

# Conclusion

**The LongOps project has been an unqualified success. The project has met, and in many cases, exceeded the expectations of everyone involved.**

Over the course of three and a half years, the relationship between NDA, Sellafield Ltd, TEPCO and UKAEA has deepened. We have combined knowledge and efforts across our organisations to build an improved understanding of our shared challenges.

We have enabled many stakeholders to see and explore their assets, sometimes for the first time, by creating a mission control room which allows operators and observers to interact with a realistic virtual digital representation of their real work sites.

We now have the ability to collect data from hundreds of facilities, using robots, in order to build 'as is' models of inaccessible hazardous spaces. By combining this data with available design drawings and human knowledge we can create multi-layered augmented-reality models with the potential to improve training and rehearsal of decommissioning operations and improve operational accuracy, reducing the time people need to work in harmful environments.

Furthermore, this type of technology is relatively low-risk, low-cost and scalable. By reducing the reliance on expensive, one-off physical mock-ups we can conduct much more work in parallel. This provides opportunities to increase the number of qualified remote operators and allow them to train in physical-risk-free environments. The digital mock-up technology also allows us to demonstrate specific challenges to decision makers and regulators, offering opportunities to make better informed decisions, faster. And for the future, the data we are collecting will be invaluable as we establish how to use emerging artificial intelligence capability to support our activities.

The development of UKAEA, NDA and TEPCO as 'intelligent customers' of digital mock-up technologies also increases opportunities for intelligent suppliers. The capability produced under the LongOps project would not have been possible without the numerous collaborations with our suppliers. The range of innovations and capabilities produced over the project's 12 separate contracts is a testament to the talent of the suppliers involved. LongOps has shown not only how collaborations of this nature can increase technical maturity across a wide spectrum of capabilities, but also how they can be integrated and applied to achieve real-world operational benefits beyond the bounds of a laboratory environment.

We have reached consensus that digital mock-ups will be a feature of our programmes for the coming decades. For example, the JET Decommissioning and Repurposing Senior Responsible Owner has mandated the use and development of a digital twin technology as mitigation against schedule creep and consequent cost increases. We have also formed new collaborations including the Robotics and Artificial Intelligence Collaboration (RAICo) between the NDA, Sellafield Ltd, the University of Manchester and UKAEA to continue working together with a new dedicated facility opened in Whitehaven. TEPCO and UKAEA have extended parts of LongOps and are seeking to broaden the operational impact at Fukushima Daiichi. LongOps has enabled us to lay the foundations for long-term collaboration between Japan and the UK for the benefits of both countries for the decades to come.

**Thank you for reading.**

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