UK Atomic Energy Authority

RACE

LongOps Project Report

EXECUTIVE SUMMARY

NDA

TEPCO

UKRI Innovate UK

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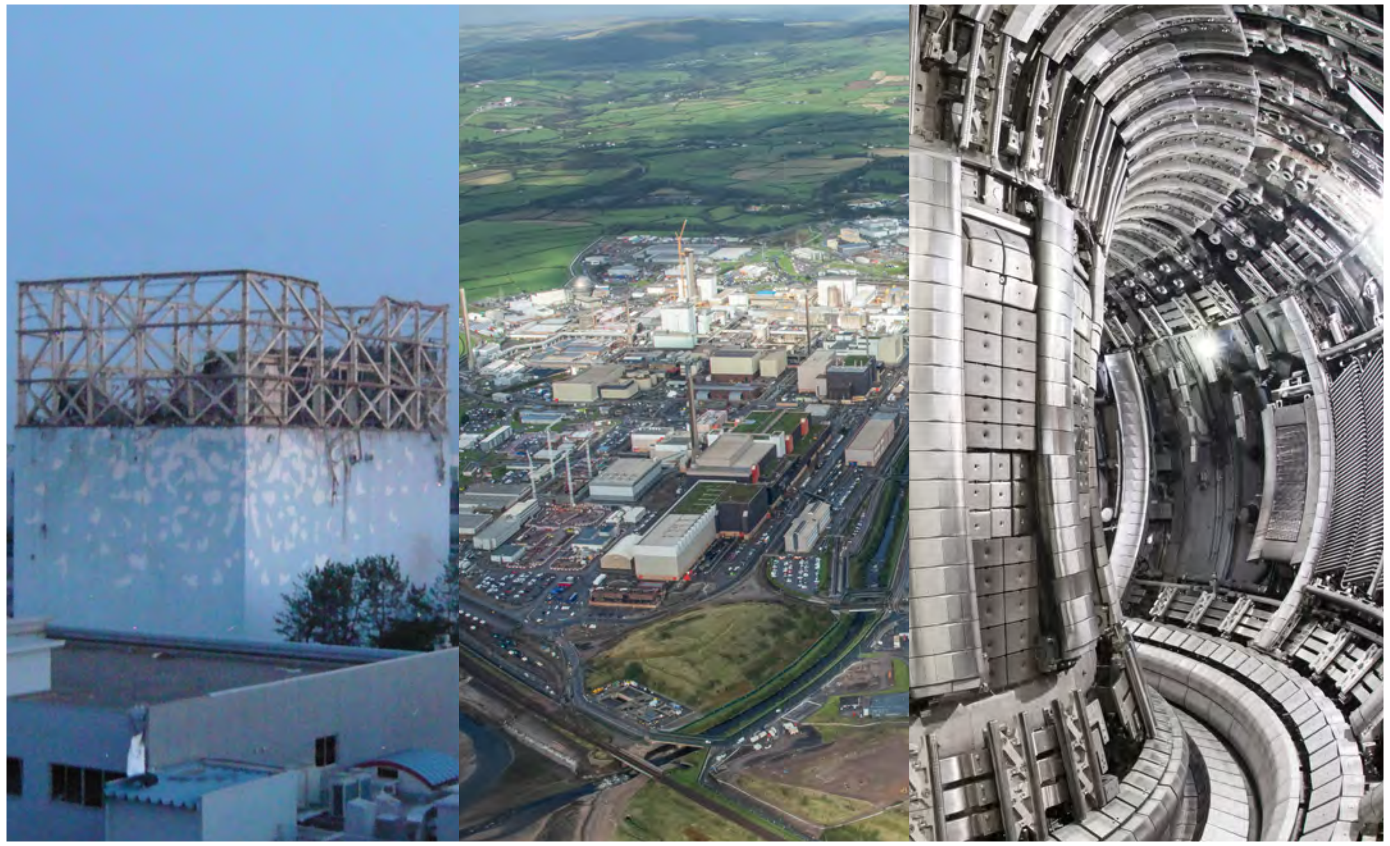
Introduction



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

Forewords
from our Stakeholders

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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

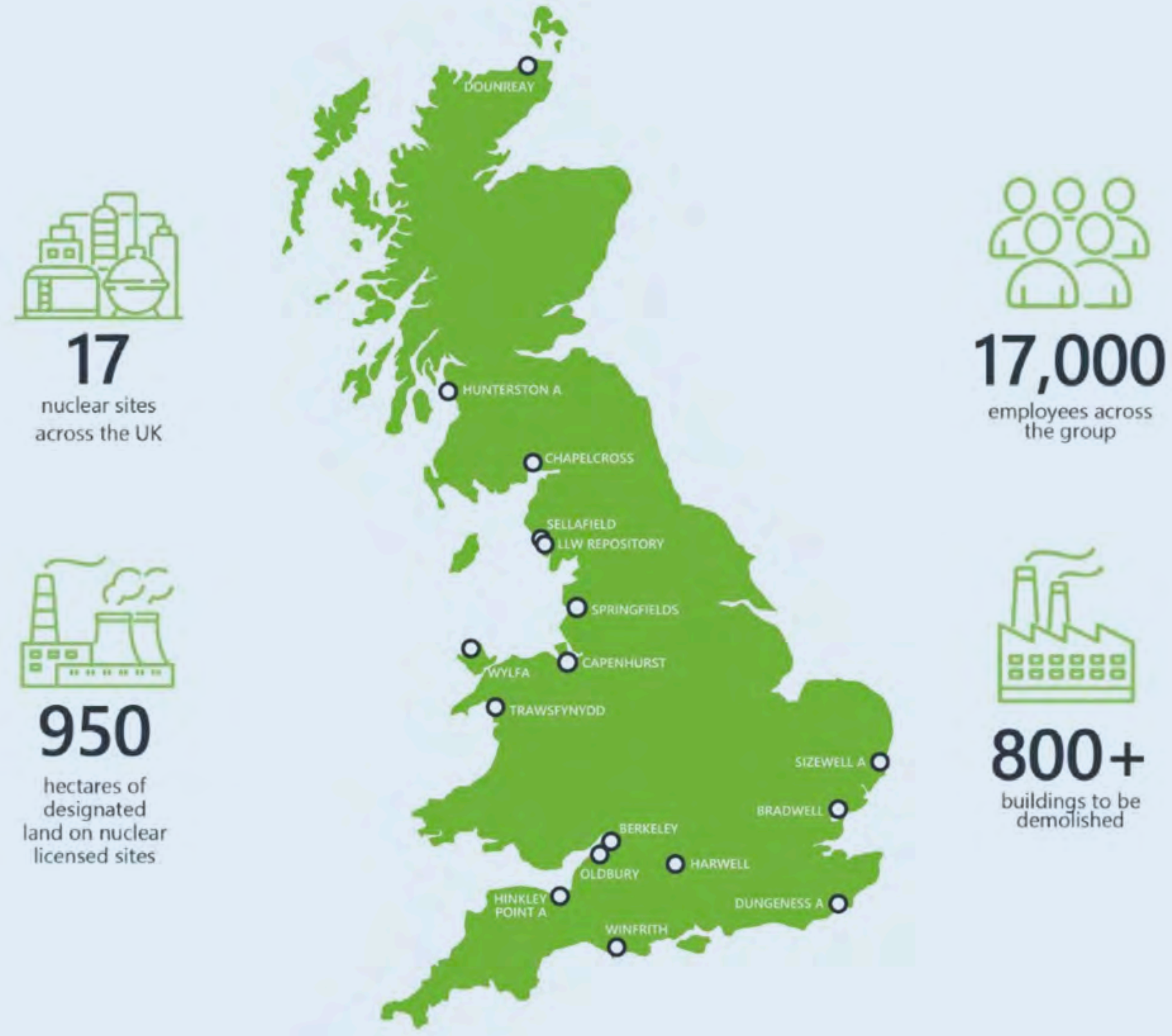
Nuclear Decommissioning Authority

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

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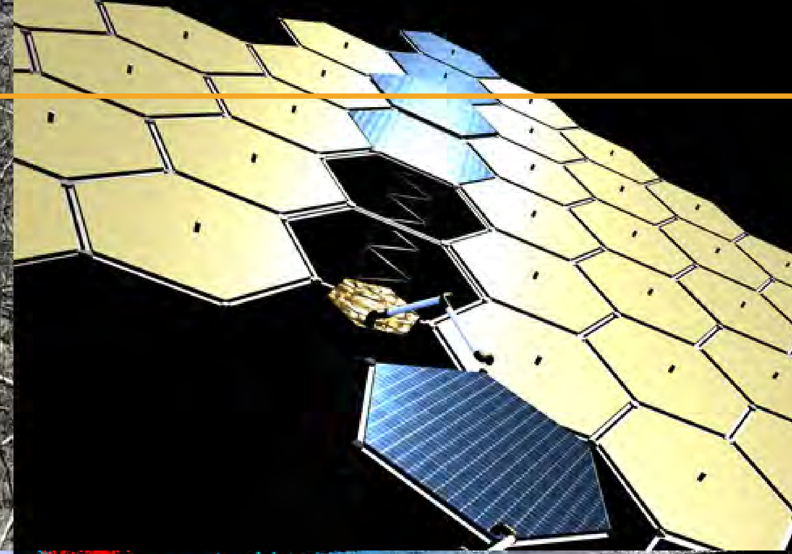
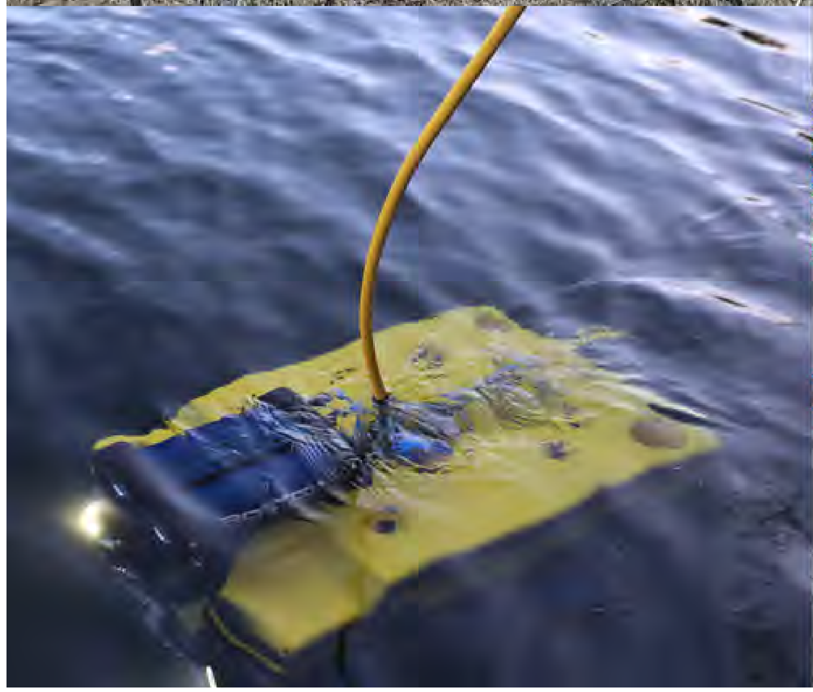
We increasingly operate in extreme environments, some places are too dangerous or uncomfortable for people to work in effectively, or at all. Robots and artificial intelligence (RAI) offer huge potential for safer and easier working in these environments.

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.

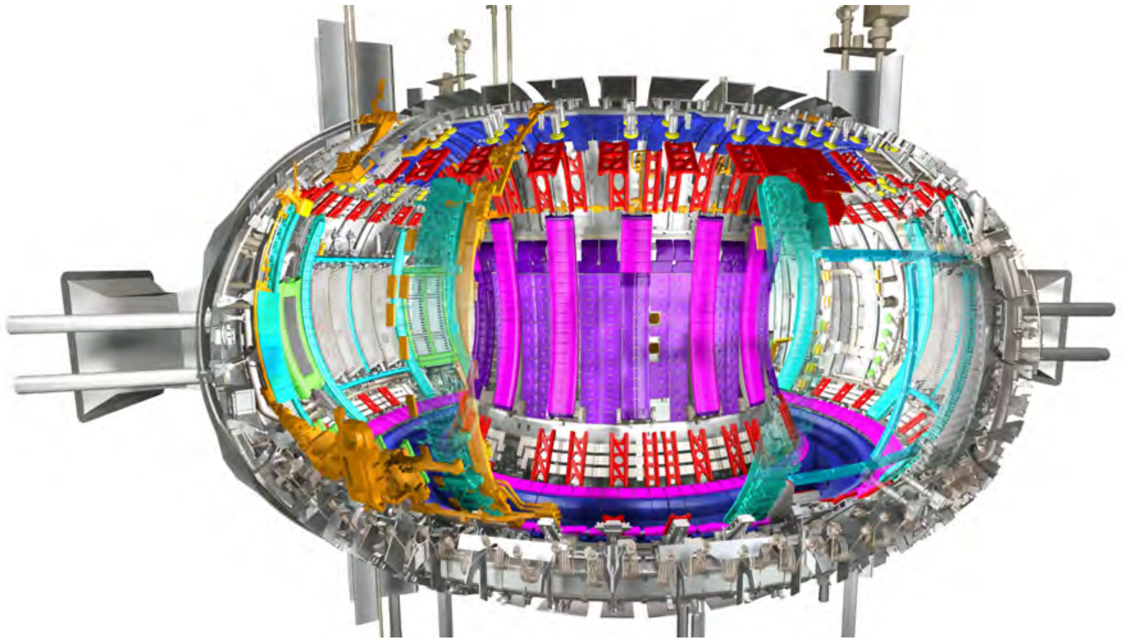
The aims of Innovate UK's work, through the ISCF Challenge Fund, has been to reduce human exposure to hazardous environments, so saving lives and reducing serious accidents; to develop efficient maintenance and decommissioning of infrastructures. The LongOps project has demonstrated what can be delivered 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 →

THE VISION →

THE ACHIEVEMENTS →

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.

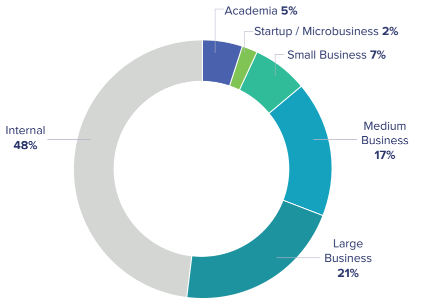
A part of the vision was to learn by doing, aiming to work in a collaborative mode with the suppliers for mutual benefit. The end goal was to create capability in people – teams with expertise, experience, confidence, and connections to be able to take on further innovation and engineering in support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

The Achievements

The LongOps project worked towards three main objectives:

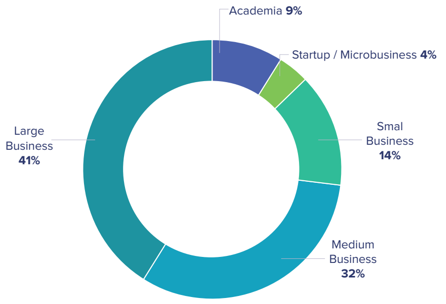
- ⟶ To strengthen the international relationship between Japan and the UK through knowledge and capability transfer.
- ⟶ To strengthen the relationship between the nuclear decommissioning sector and the supply chain.
- ⟶ To support innovation and development of nuclear decommissioning technology within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

PROJECT SPEND DISTRIBUTION



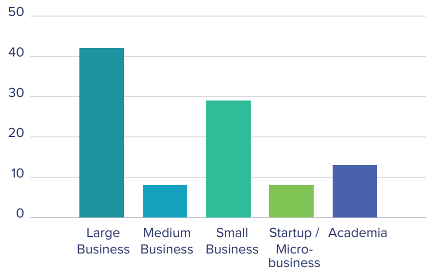
Project Spend Distribution
In support of the development of the supply chain, LongOps created a target for the project -to put at least 50% of the budget into the supply chain and UK industry. This ambitious goal was achieved through a variety of engagements, including international tender processes 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

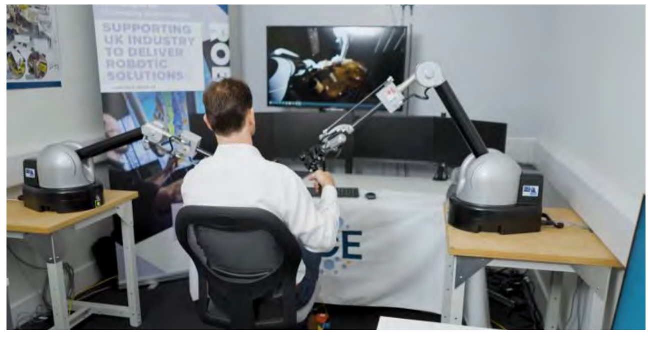
HIGHLIGHTS

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.

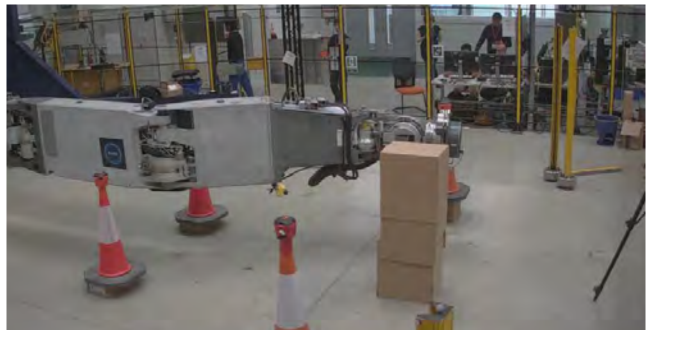
Brought in expertise from the defence sector to engage with industry and develop a **unique set of standards** for the architecture of robotics systems in nuclear decommissioning.

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

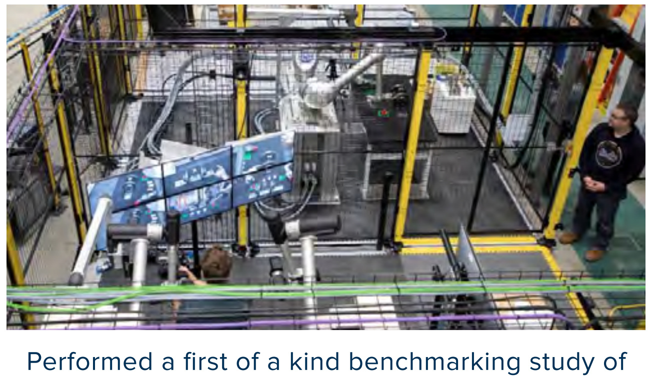
Contributed to the **spin-out of HEROBOTS from the University of Naples Federico II** (UNINA) and the development of their flexible manipulator characterisation and control platform



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.

Project Overview

KNOWLEDGE CAPTURE →

RESEARCH →

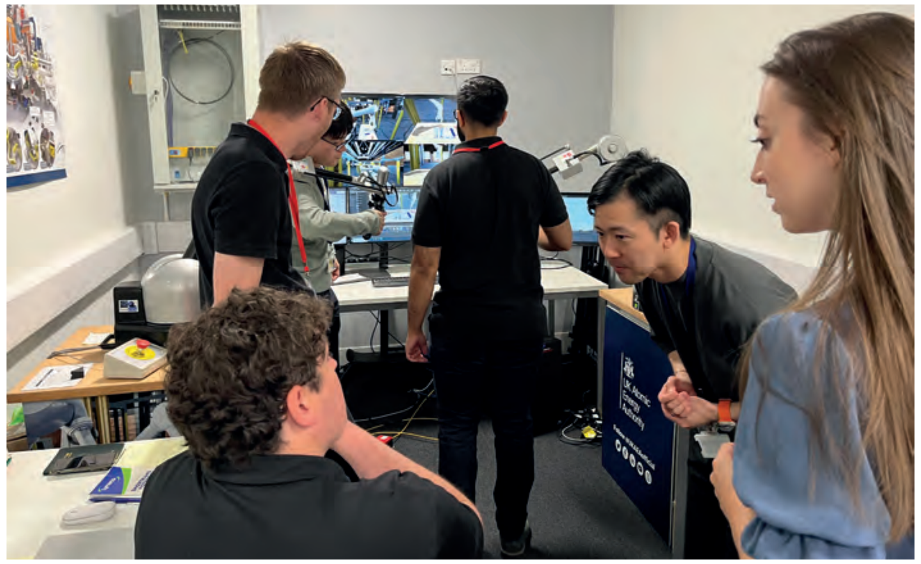
CAPABILITY TRANSFER →

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.



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 project'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.

Research Themes

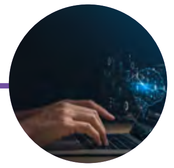
LongOps's research was carried out under six themes including Architecture and Standards, Sensing and Perception, Long-Reach Manipulators, Haptic User Interfaces, Next Generation Digital Mock-Ups and Assessment.

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.

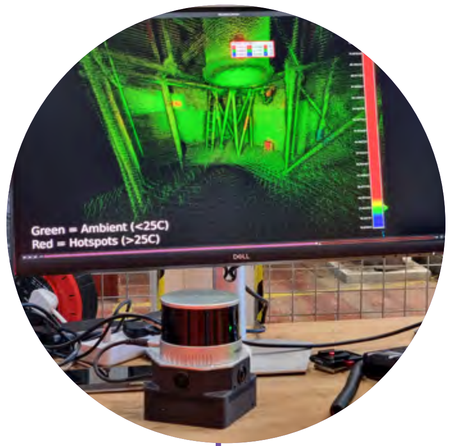
WORKPACKS

Interoperability Standards



Generic Nuclear Robotic Architecture (GNRA)

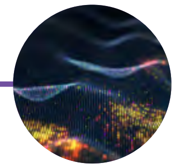
Teleoperation Manipulator Evaluation



Sensing and Perception

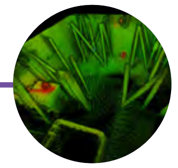
In nuclear environments, operators often deploy remote equipment with very limited information about the current state of the environment. In this work we apply some of the latest advancements in machine learning, sensor fusion, visualisation, simulation, and computer vision to nuclear decommissioning 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.

WORKPACKS



Datasets for the Development and Testing of Sensing Techniques

Incorporating Live Sensor Data into Digital Twins

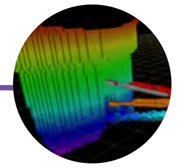


Automated Change and Anomaly Detection

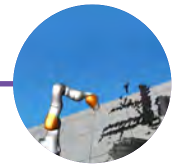
Long-Reach Manipulators

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.

WORKPACKS



Planning Tools for Long-Reach Manipulators



Planning Tools for High Degree of Freedom Manipulators

Modelling and Control for Flexible Long-Reach Manipulators

Vibration Compensation for Flexible Long-Reach Manipulators

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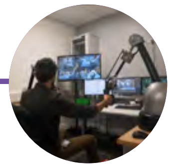
Haptic User Interfaces

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.

WORKPACKS



Haptic Training Simulator

Haptic Interation of Rigid Materials with Fluids

Merging Haptic Rendering with Live Sensor Data

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.

WORKPACKS

Integration into the Operational Lifecycle

Integration of the LongOps Technologies

Simulation of the Physical World

Simulation of the Digital World

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.

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

	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.

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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.

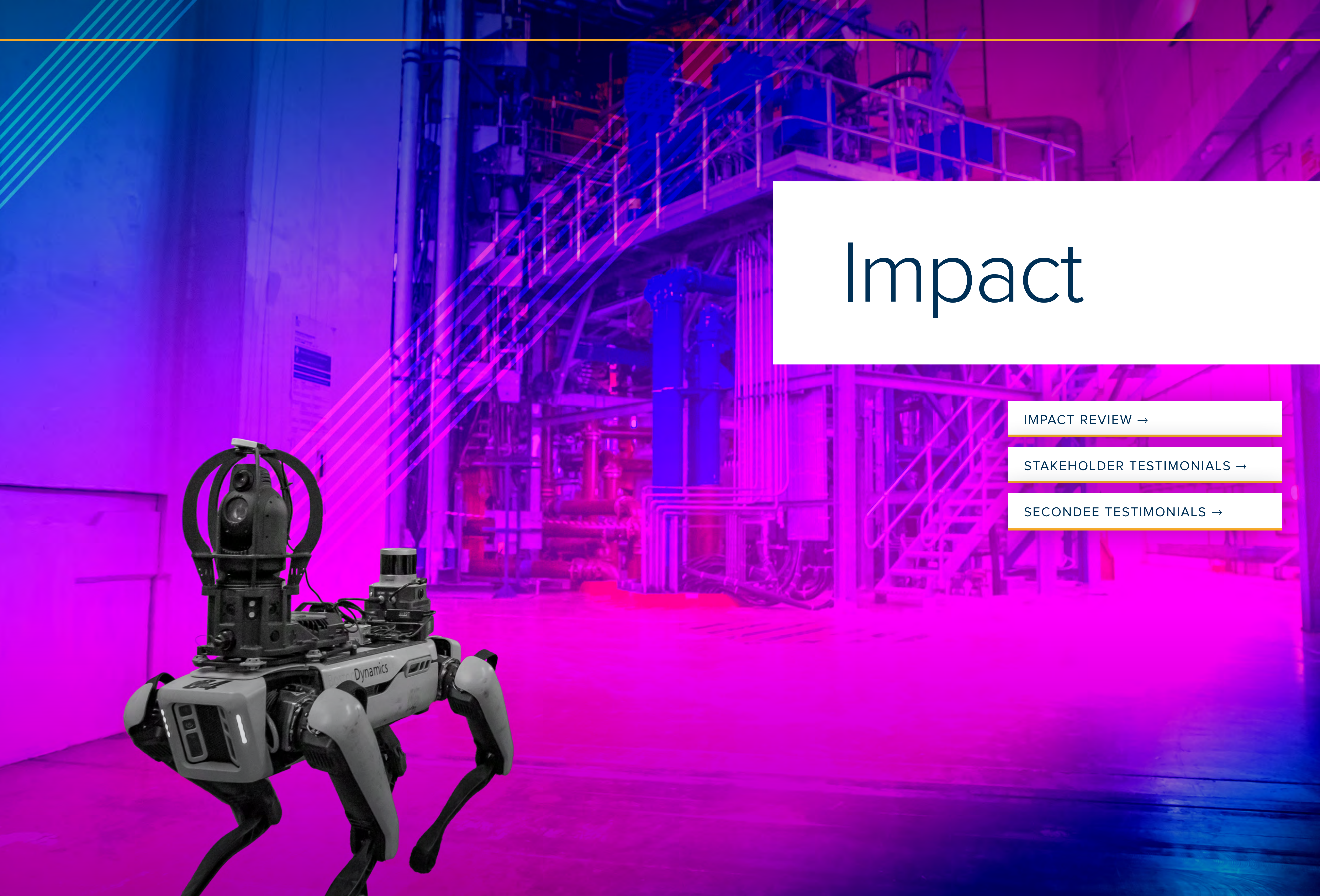
Specific training courses for areas of interest were identified at the start of and during the LongOps project.

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.



Impact

IMPACT REVIEW →
STAKEHOLDER TESTIMONIALS →
SECONDEE TESTIMONIALS →

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 programmes 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.

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.

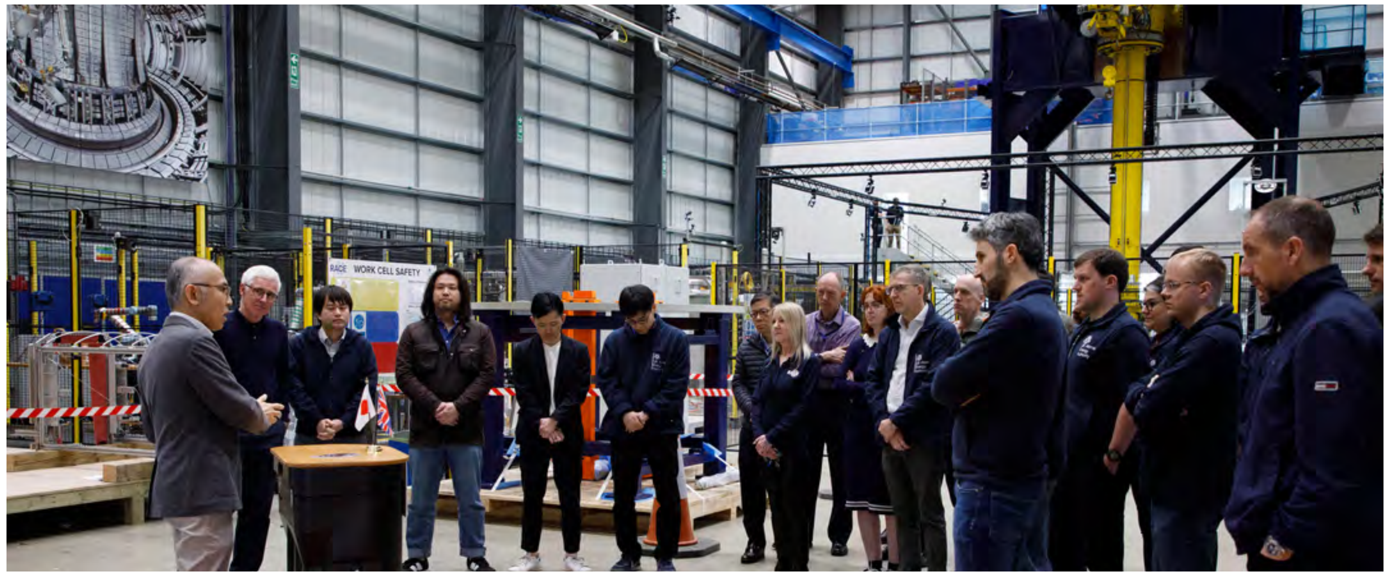
Perhaps more significantly we have felt part of a controlled experiment that has worked well. We have seen the level of knowledge and confidence of UK and Japan engineers grow in design of and use of this next generation of software tools. Many conversations indicate that there is agreement that these 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.



Stakeholder Testimonials

British Embassy Tokyo

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.

TEPCO

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.

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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.

UK Atomic Energy Authority

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.

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Secondee Testimonials

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.

The UK Atomic Energy Authority's mission is to lead the delivery of sustainable fusion energy and maximise scientific and economic benefit

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