RAIN

ROBOTICS AND AI FOR NUCLEAR

YEAR FOUR REPORT

Developing robotic and AI technology to solve challenges faced by the nuclear industry.

RAIN

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www.rainhub.org.uk

RAIN has been invaluable.

Melissa Willis
Robotics and Artifical Intelligence Integrated Research Team Lead, Sellafield Ltd
(at RAIN Big Meet Nov 2021)

OPENING WORDS

It is now over 4-years since RAIN was established and I think we can look back over that time with a sense of pride and satisfaction, as well as a desire for the work and the relationships to continue.

At its outset, RAIN aimed to address some of the complex research challenges that were limiting the deployment of robots in nuclear environments and to demonstrate to the nuclear sector what benefits robotic systems could bring to them. RAIN has been responsible for deploying a range of first-of-a-kind robots into active facilities at UK facilities, including Sellafield and Dounreay, as well as at international locations including Chernobyl, Fukushima and the Franz-Josef reactor in Slovenia. These deployments have led to more than 50 follow-on projects with industry, some of which have resulted in the development of commercial robots. Research completed within RAIN has led to the publication of several hundred articles in leading journals and conferences, helping to establish the UK as an international lead for robotics in extreme environments.

One of the most important outcomes from RAIN is the strong community that has been built up over the last 4.5 years. Within RAIN we have tried to encourage collaboration, with industry and between academic partners. In addition to the strong connections we have made between the partners involved in RAIN, we have, in partnership with researchers from ORCA, FAIR-Space, NCNR and elsewhere, established collaborations with researchers in several other sectors.

Looking forward it is particularly satisfying to know that the research and communities that have been established in RAIN are not going to disappear overnight. RAIN has had a transformational impact on the nuclear decommissioning sector, which has led to the creation of the Robotics and AI Collaboration Laboratory (RAICo) in West Cumbria. RAICo is a joint initiative between Sellafield, UKAEA, NNL and RAIN that, with a greater focus on delivering commercial robotics technology to sites within the Nuclear Decommissioning Authority's estate, will continue and extend the research that we have begun. We'll keep you informed as this programme progresses.

BARRY LENNOX

RAIN DIRECTOR

The Robots for a Safer World challenge completed in March 2022 and has invested over £112m since its inception in 2017.

During those 5 years the use of innovative robotic technologies in the nuclear industry has accelerated and looks likely to gain further pace. From new and innovative sensing and mapping technologies to the development of autonomously controlled platforms, robotic technologies are proving critical to how we utilise and then safely decommission our nuclear facilities here in the UK and further afield.

As one of the four Academic led, Industry inspired Hubs, RAIN has worked to establish a national asset and that has significantly strengthened the links between academic led research and industry driven use-cases. It has completed the first ever autonomous radiometric surveys of a former alpha laboratory on the Sellafield Ltd site and the JET Torus Hall at Culham. Using different and heavily customised platforms for each mission, the surveys mapped for radioactive contamination from fixed or migrating sources.

It has also collaborated with the Japan Atomic Energy Agency, designing a small underwater vehicle that been designed to survey and monitor hazardous environments, ensuring a more efficient decommissioning process and protecting human workers from harm, for deployment at sites such as the Fukushima Daiichi nuclear plant following the 2011 tsunami.

Despite the inevitable disruption caused by the Covid-19 pandemic, RAIN has continued to deliver excellent research and is able to both demonstrate innovative science and showcase technological developments they have worked so hard to produce over the past five years. Furthermore, RAIN have been working with other industry and Government stakeholders (Sellafield Ltd, NDA, NNL and the UKAEA) to take the learning from the past five years and apply it to the development of the RAICo incubator facility situated in Whitehaven, West Cumbria. RAICo is set to open in early 2022 and will focus initially on decommissioning, with Sellafield as its first use case, it will develop RAI technologies able to address the NDA's 'grand challenge' aim: "A 50% reduction in decommissioning activities carried out by humans in hazardous environments by 2030" and bring about benefits of cost and schedule reduction to the UK taxpayer.

ANDREW TYRER

CHALLENGE DIRECTOR – ROBOTICS INDUSTRIAL STRATEGY RESEARCH FUND

RAIN: THE STORY

In recent years the superhero genre has become not only a more prominent fixture in movies and popular culture but the film industry offers insight into how to strategise in the short and long term while also developing a successful and inviting community.

Hollywood film makers can easily attract crowds and rouse interest in make-believe characters that can do wondrous things and invent amazing contraptions.

Imagine if the same creative drive was applied in a community where real engineering and science excellence existed.

The ambition of RAIN was to bring together its own team of experts with the desire to create something amazing but also with the potential conflicts of any superhero squad.

However, the desire to underplay achievement and behave in a low-key manner is a stereotypically British trait and luckily with the variety of cultural backgrounds participating in RAIN we kindled enough fire to really start to take advantage of what went well and where we could improve.

RAIN WAS ESTABLISHED TO SATISFY THREE KEY AIMS:

- **To increase the volume of research in the RAI in Nuclear field**
- **To enhance the connectivity between research and industry, and**
- **To transfer people and skills from academia into industry.**

Those aims required dedication, the creation of a caring community and a drive to pursue the ambitions while overcoming any challenges to progress.

From the outset, RAIN was described as Phase One. Not only because it helped to wrap up the expected scope of work into a single package but also because it piques curiosity. It immediately suggested – deliberately – that RAIN wasn't expected to be a one hit wonder.

The growth of the Hub between Phase One and Two in terms of membership and number of Working Groups is testament to the belief and commitment that has been shared with RAIN from academia, industry and government. The dream that challenges could be tackled, while inspiring enthusiasm and attracting talented people, became reality.

The real human connections that have been made across the nuclear sector in fission decommissioning, new build and fusion development have not only been vital but gratefully received. It cannot be understated just how much value RAIN has placed in the people involved in the programme.

RAIN was structured as a community whereby varied contributions were required, and contributors' lives could be made a little bit better by being part of it. Hopefully this report expresses the wonderful achievements and the pride of what has been done so far.

Over the page you will see a few highlights since the inception of RAIN up until the end of Phase Two in March 2022.

KEY EVENTS

OCT 2017
RAIN Phase One Programme begins

JAN 2018
Working Groups established for:
Remote Handling
Remote Inspection
Safety Case

JUN 2018
AVEXIS trialled at Fukushima

JUN 2018
First RAIN community meets for RH and RI Working Groups

MAR 2019
RAIN Open Day Manchester event

SEPT 2019
RAIN hosts Energus event

OCT 2019
RAIN welcomes Leeds, Reading and Newcastle as partners

OCT 2019
First Chernobyl deployment

WINTER 2019
First RI deployments at UKAEA waste store

APR 2020
RAIN Webinar series begins

AUG 2020
First DSRL inspection deployment

MAR 2021
RAIN Phase Two Programme begins

'Safety Case' WG becomes 'Autonomy & Verification'. 'Standardisation' WG begins

MAY 2021
First ever deployment of autonomous inspection robot at JET Torus Hall

JULY 2021
RAIN publishes White Paper on Assurance and Autonomy

SEPT 2021
RAIN RH+ HRI livestream demo

JAN 2022
RH+HRI and RI Demo event

MAR 2022
RAIN Phase Two Celebration and Demo Events

JAN 2017 | JAN 2018 | JAN 2019 | JAN 2020 | JAN 2021 | JAN 2022

NUCLEAR GLOVEBOX CONTEXT

Nuclear gloveboxes are designed primarily to contain the materials within and secondly to allow human operators to undertake tasks in that contained environment.

As part of safety management, the glovebox volume is comparatively small. Often the working space is cluttered and, due to the non-adjustable nature of glovebox access ports, operator access can be challenging. In addition to this, due to the design of nuclear gloveboxes the operator is in close proximity to hazardous and radioactive materials. While working, the operator can be carrying out industrial as well as scientific tasks; the risks associated with these are clearly heightened due to the constraints mentioned.

Current gloveboxes rely directly on human operators. In terms of being able to handle dangerous materials the operator generally has two options; reduced dexterity via thick protective gloves requiring direct contact with the materials, or reduced dexterity via long-reach tele-operation arms with simplified grippers that distance the operator further from radioactive harm.

Working within a nuclear glovebox is tough work. The required base level of personal protective equipment (PPE) is not quick to put on or remove. While working arrangements are implemented in a way to minimise risk to the operators, proximity to radioactive materials is always a concern – particularly when PPE fails.

Implementing robotics into a nuclear glovebox has the potential to mitigate many of the risks posed to humans, though implementation is not straightforward.

Existing commercial off-the-shelf (COTS) systems are the immediate point of reference for developing glovebox-suitable robotic options. The differences in operating environment post challenges when trying to transfer COTS equipment into the glovebox environment.

Industrial robots have been operating in many sectors for many decades. Compared to the operating environment for nuclear gloveboxes, the industrial systems are comparatively bulky, tend to operate in open environments, often run on pre-programmed autonomous routines, are not subject to nuclear radiation, and have a smaller risk consequence if something were to go wrong.

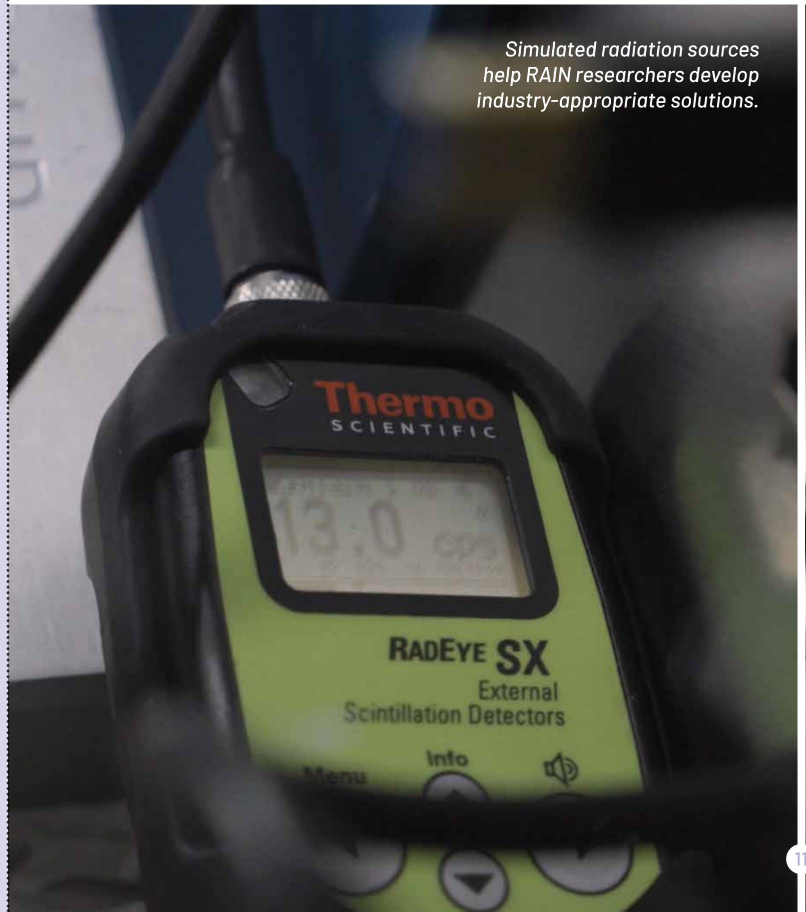
Nuclear robotic gloveboxes must provide the same, if not improved, level of safety and functionality as current human-centric operations, while exploiting the additional bonuses of reducing risk exposure to the operators and improving the operator experience too.

Due to the inherent risks of handling nuclear material, all RAIN remote handling work has been conducted in workshop or digital environments. This allows the technology and techniques to be proven out before exposing the equipment to radiation risks.

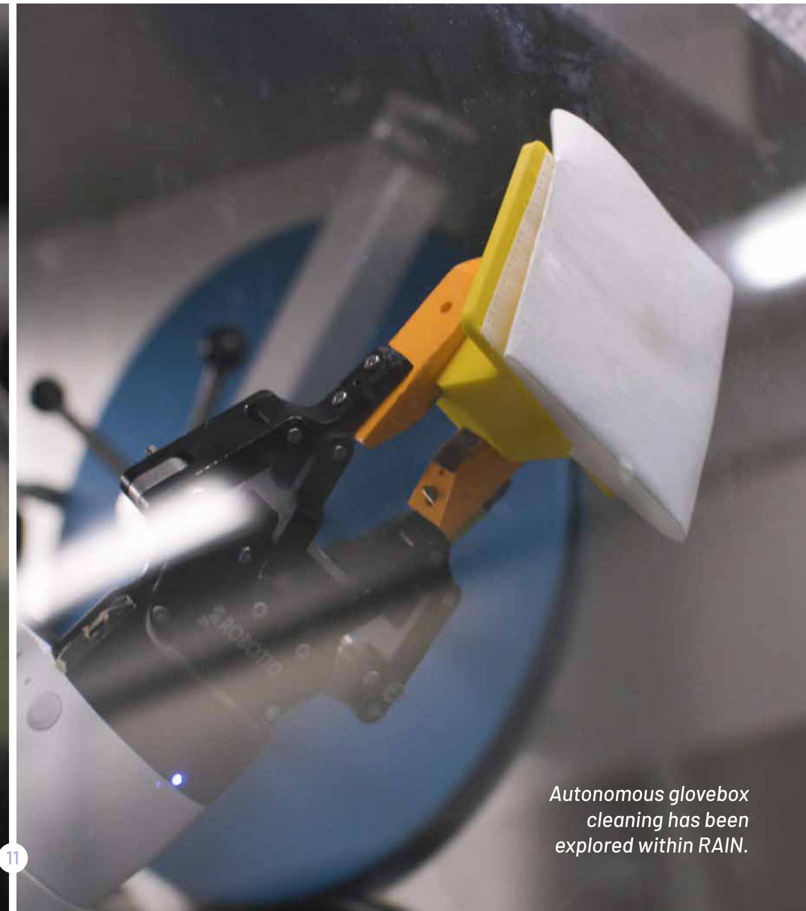
The field of nuclear robotic gloveboxes is relatively new, and so RAIN has linked the Remote Handling and Human Robot Interaction Working Groups to draw in existing operator and regulator expertise to research and develop options for future glovebox operators and their working environment. Perhaps the term 'glovebox' will be replaced by a new term as human entry won't be assumed as the default position.

The following pages highlight some of the specific challenges that RAIN has begun to address, with further narrative on the status of the developments.

Trained glovebox operators are an integral part of the RAIN development ethos.



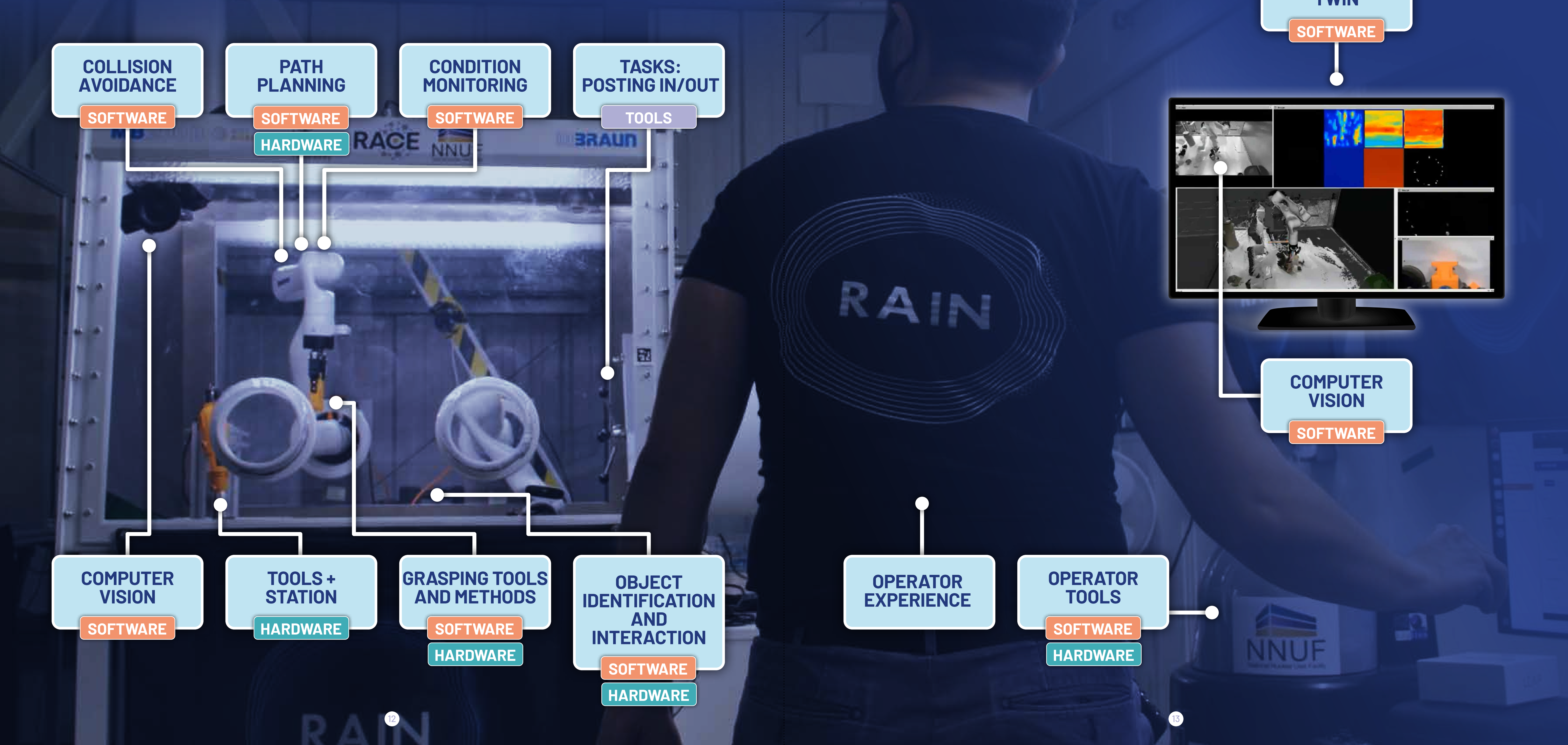
Simulated radiation sources help RAIN researchers develop industry-appropriate solutions.



Autonomous glovebox cleaning has been explored within RAIN.

NUCLEAR GLOVEBOX

HANDLING ENVIRONMENT



WORKING GROUP SUMMARIES

REMOTE HANDLING

Guy Burroughes

Back in the lab, this year the Remote Handling team has been more hands on with the robots and experiments.

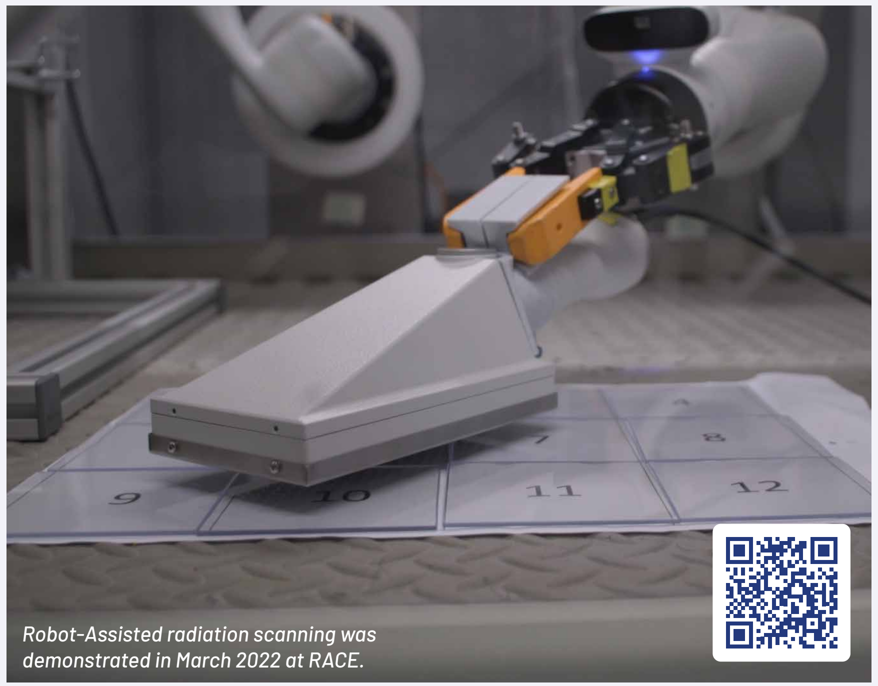
Still focusing on the Glovebox robotics research, the RH theme paired with the HRI theme to accelerate each other's work. The groundwork invested on digital tools, during the pandemic, has helped to smooth the path to practical deployment for the robotic glovebox hardware.

Coming into September the whole team was able to come together (with 2 metre gaps), for a week-long hackathon, culminating in a live streamed demonstration. 4 robot manipulators, 3 robot snakes, 4 different input devices, 8 cameras, VR, control systems, and dozens of pieces of interacting software and AI. This significant accomplishment brought together many elements contributed by the teams into a unified integrated system and highlighting the direction of travel for future research.

Since September, the team has focussed on extending and utilising this work: with focussed user studies supported by the HRI theme, to measure the performance and flaws in the systems; new input devices developed, demonstrations of new snakes, and much more.

The progressive strategy used in RAIN has allowed separate technologies to be tested, then integrated, then trialled with glovebox operators. This method of operator engagement provides measurably more valuable feedback than isolated system testing feedback or commenting solely upon research results. The operators also appreciate the ability to trial something that is in a state that is near-to-deployable condition as it removes the need for guess work or filling in the gaps of a system that has incomplete performance.

The research foundations and industrial working relationships developed by RAIN have allowed genuine industry use cases to be explored and options conveyed. While Phase Two is coming to an end, it is hoped that the collaborations with continue, and grow, for some time.

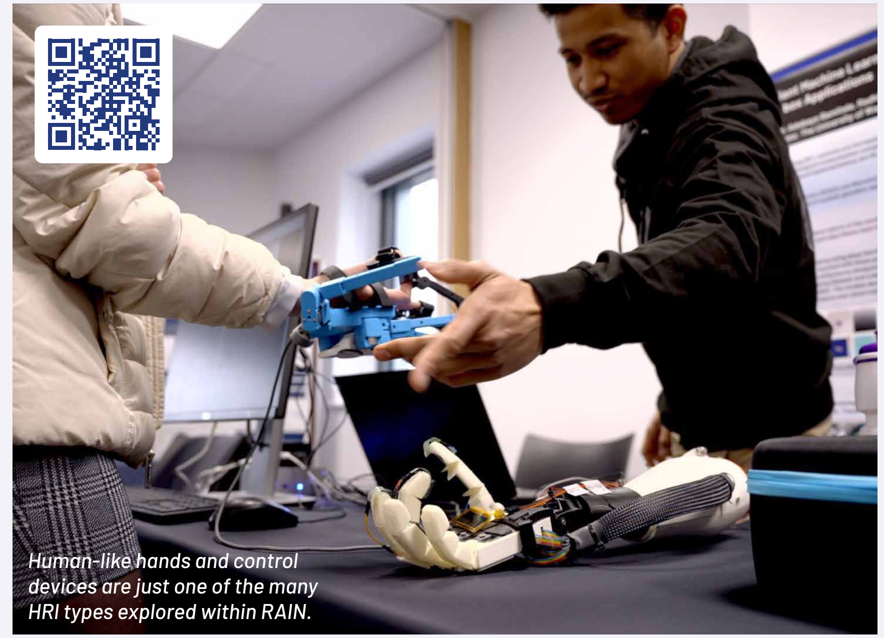


Robot-Assisted radiation scanning was demonstrated in March 2022 at RACE.

HUMAN-ROBOT INTERACTION

Guido Herrmann

The Human-Robot Interaction (HRI) Working Group has been closely working with the Remote Handling group to establish methods for specific autonomous and semi-autonomous task execution supported by different forms and modalities of human-robot interaction.



Human-like hands and control devices are just one of the many HRI types explored within RAIN.

This has been with focus on tele-operation systems for manipulator-augmented glovebox systems for post operation clean out (POCO).

RACE and the Universities of Manchester, Reading and Nottingham have been working closely to achieve various high technology readiness level outputs (TRL), yet publishable results in support of an overall glovebox tele-operation system.

For human-robot interaction interfaces on the primary side of the tele-operation system, we have advanced modalities of gesture input and force-feedback enabled haptic interfaces in connection with glovebox systems and their digital mock-up, i.e. also allowing for virtual reality. These are part of a suite of autonomous and semi-autonomous task results, allowing semi-autonomous object radiation scanning, autonomous grasping, and inverse-kinematics optimised manipulation on the secondary side of tele-operation. Formal tele-operation quality assessment approaches specifically for manipulator augmented glove box systems have been developed to allow for evaluation of the impact of robotics-enabled POCO in relation to the operator and the practical outcome.

Principal results from the project by Collins, Lopez & Taylor "Using LEGO® Serious Play® for Nuclear Decommissioning Risk Mitigation Extrapolation" have been summarised, i.e. investigations on challenges behind future integration of semi/autonomous systems and the changes it will bring to working practices in the nuclear sector.

These outcomes have been demonstrated in different demonstration events and further results with a focus on assessable semi-autonomous tele-operation will be provided in the final demonstration in at the end of Phase Two.

NUCLEAR GLOVEBOX

PROGRESS AND SOLUTIONS

CONDITION MONITORING

Operating robot equipment within a glovebox comes with the expectation that the kit will function as expected. Naturally there are myriad reasons why equipment may fall in its ability to perform. Using data output from the robot arms used in the glovebox, RAIN has developed a condition monitoring tool that highlights to the operator deviations from expected performance. The method uses colour-coded spheres attached to each joint in a digital twin of the robot arms to highlight the size of deviation to the operator.

COLLISION AVOIDANCE

The containment provided by a nuclear glovebox, and the containers within them, is a key safety function and must not be compromised. This requirement means that anything introduced to the glovebox should not increase the risk of containment breach / damage or unexpected material dispersal. RAIN research has explored techniques to ensure that the robotic manipulators deployed into gloveboxes can avoid collisions with objects in the glovebox as well as other robotic manipulators. One example uses a neural network machine learning technique to provide real-time in-motion collision avoidance which has been successful in digital simulations.

INVERSE KINEMATICS

Manoeuvring robotic arms within a glovebox must be simple to allow swift and safe work. Depending on the method of control, a robot may articulate itself in a peculiar orientation to allow the gripper to reach its destination. Such peculiar poses can lead to the robot 'locking up' by reaching its joint limits and colliding with obstacles. RAIN research into inverse kinematics has provided a solution that allows the operator to focus on carrying out tasks, while the algorithm does the work of orientating the robotic arm in such as way as to maximise the remaining movement available for the robot and avoiding obstacles.

OPTIMISED OBJECT GRASPING

Accurate, repeatable and dependable objects grasps are a key advantage to be exploited from the introduction of robotic manipulators into nuclear gloveboxes. RAIN research has investigated techniques to provide autonomous grasping options within the cluttered glovebox environment. This work integrates computer vision with Deep Learning and variational auto encoders to provide a system that can adapt to objects of different sizes and shapes while providing high reliability grasps.

TASK-BASED INTERACTION OPTIONS

Introducing robotics technology into gloveboxes will need to address the existing manual operations and progress towards semi-autonomy and perhaps full autonomy.

The initial RAIN research steps for semi-autonomy provides the operator with enhanced abilities or lower mental load compared to existing manual operations. RAIN research has investigated ways to provide operators with alternative input methods – gaming controllers, industrial controllers, hands-free control – to measure the improvement to operator experience and task performance based on real glovebox tasks. Such is the engagement with the nuclear industry that the RAIN techniques have been trialled with remote handling and glovebox operators.

INTEGRATION

The development of separate robotic glovebox technologies and techniques is beneficial. However, the full value can only be assessed when the separate elements can operate successfully as aspects of an integrated system. RAIN research has focused dedicated expertise on the integration of the handling and human interaction techniques to allow them to operate in the nuclear glovebox as a coherent whole. The task of integration highlights any issues regarding system stability, communication methods, reliability and operating speed. The key value of the RAIN integrated glovebox system is that the research outputs can be trialled with real operators for crucial feedback and guidance for future research.

INTENTION DETECTION

To truly enhance the working routines of a glovebox operator it is necessary to understand how the operator expects to work. This type of relationship can be developed between humans, as operators learn how each other works. In the realm of robotics, intention detection employs human analysis methods, such as eye tracking and gesture measurement, to predict what the operator plans to do next. With this information the robotic system can use machine learning techniques to augment predicted tasks while keeping the operator safe by limiting 'extreme' or accidental motions.

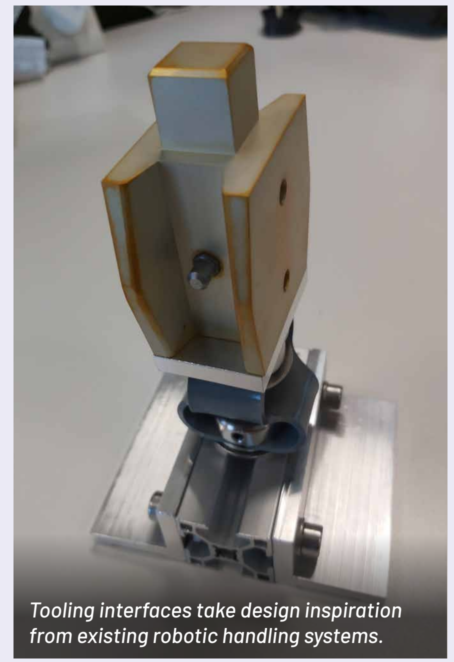
In collaboration with NNUF-HR, RAIN has developed a glovebox collaboration suite to demonstrate many tools and techniques.

OPERATIONS DIGITAL TOOLS

Predictability of operations in a nuclear glovebox lends itself to maintaining a safe working environment. RAIN has engaged with remote handling operators to utilise skillsets from non-glovebox telerobotics to enhance current manual glovebox operations. The Operations Management System (OMS), provides a step-by-step digital sequence for any defined task. Each step can be a fully manual, fully autonomous, or hybrid task to allow work to be done in a controlled manner. The OMS system has been trialled for radiation survey and cleaning tasks to prove out the applicability of this work control technique.

OPERATIONS HARDWARE TOOLS

In many instances robot manipulators possess different physical traits compared to a human operator, e.g. fewer fingers and greater range of movement across a greater number of joints. Quickly and predictably interacting with tools is a necessity, particularly when tasks are expected to be automated. RAIN research has investigated and produced options for tool interfaces to improve compatibility with COTS equipment and improve task execution.



Tooling interfaces take design inspiration from existing robotic handling systems.

NUCLEAR GLOVEBOX

The Matrix device provides an immersive experience which allows the user to interact with virtual objects as if they were real.

SHARPS DETECTION

Human operators possess abilities that are very challenging to mimic in machinery. However, some senses can be easily augmented to provide helpful information to the operator. A particular use case in this scenario is for sharps detection. RAIN has undertaken research in the nuclear glovebox by utilising supply chain technology to detect sharp edges on objects within the environment. This identification is valuable as part of the risk mitigation for preventing damage to protective equipment and the operator.

THE MATRIX

Developing advanced teleoperation techniques requires a platform within which performance can be measured. The Matrix device developed in RAIN allows researchers to explore the reactions to operators while modifying the virtual environment in which they operate. The VR-haptic system in which an operator can carry out tasks is precisely adjustable to allow in-depth and specific assessments. This psychological-engineering combination can inform future systems design useful for improving training regimes and operational methods.

TASK SPECIFIC ENHANCEMENTS

Radiation scanning - RAIN research has developed a technique to allow operators to undertake robot-assisted radiation scanning tasks which require precision, repeatability and stability. The technique maintains the in-glovebox use criteria (e.g. fixed distance from the item of interest) so that the operator can focus on selecting the areas of interest thus reducing the burden on the operator.

Brushing – brush cleaning debris while minimising dispersal is a challenge for robotic systems. While the task of brushing has been used as a research focus, the outcomes from it can be used to implement other tasks more easily. This ease comes from the familiarity with the process of data gathering mechanisms and observing measurable robotised outcomes and deploying this process for other tasks.

KEY DEMONSTRATIONS

LIVESTREAM EVENT

September 2021

On 22nd September 2021 RAIN presented a livestream demonstration of the glovebox technology developed within the Hub, hosted at RACE. The multi-system demo presented an integrated suite of technologies including:

- Digital Twins (inc. RHOVR)
- OMS (Operations Management System)
- Input devices (Leap motion control, Vive controller and Haption controller)
- Multi-Criteria Inverse Kinematics
- Condition Monitoring
- Modelling of manipulators
- Snake robot inspection
- Long distance teleoperation
- Data compression
- Computer vision
- Collision avoidance
- Soft (hand) robotics
- Tasks including; radiation scanning, sharps detection, automated tool changing, cutting and vacuuming

It was a fantastic achievement for the team to integrate their sub-systems and for those systems to function together for a live demo. A brilliant example of joyful and productive collaboration from RACE, University of Manchester and Nottingham.

HRI-RH DEMO

January 2022

The latest advances from the RH and HRI WG's in autonomous grasping, teleoperation and task-driven validation and design of HRI interfaces were shown, at RACE. This work helps promote the concept of robots performing tasks inside gloveboxes and helps open up the conversation about the wider challenges behind enabling such operations.

Some of the current advances showcased were: autonomous grasping of objects with different shapes, sizes and orientations using the Kinova robot wrist camera, accuracy has been increased to around 95% from the previous 80%. Teleoperation with different input devices (i.e., HTC VIVE controllers) using velocity and torque controllers, enabling smooth and reliable control. Task analysis around radiation surveying and interface design to enable the seamless operation to allow a robot to perform tasks with such reliability and flexibility as a trained operator.

RAIN PHASE TWO CELEBRATION AND DEMONSTRATION EVENT

On Wednesday 16th March 2022, RAIN hosted the RAIN Phase Two Celebration and Demonstration event at UKAEA, Culham.

The Glovebox challenges featured in the Handling and Digital zones at the event.

Stands were hosted to show;

- RACE-Manchester – Operator assistance
- RACE – Glovebox tooling
- Manchester – Operator Intention Detection
- RACE – Systems Integration
- RACE – Robot Hands
- RACE – Dual glovebox robot arm collision avoidance simulations
- Reading – The Matrix Device

With live demo's of the Integrated Glovebox featuring aspects of all RAIN glovebox systems and sub-systems.

NUCLEAR INSPECTION CONTEXT

When considering nuclear safety, data related to the status of a nuclear site and the materials within it, is inherently important.

The data supports regular site running including environmental assessments, operational support, and materials management. Further to this is the influence data, and data gathering tools, have upon decommissioning, dismantling, decontamination, and emergency response. The speed of decisions in all these circumstances relies upon reliable, robust, repeatable, complete and contextual data gathering methods to quickly acquire, process, and present information for review.

Nuclear facilities and sites rely primarily on human operators to gather data. This means that for every data point regarding a particular topic, there is a direct expenditure of human effort to acquire it. Some tasks require high dexterity and direct contact with other human operators, but others are repetitive and often not particularly kind to the human physiology. Some monitoring tasks send operators within proximity to radioactive materials and as such represent high risk activities.

Robotic inspection options can automate specific tasks, leading to repeatable missions to acquire reliable data. If these routines were fully automated there is the option for increased frequency of measurements and hence the ability to track changes more closely.

Additionally, robots can inspect zones that are inaccessible to humans, either from size or hazard constraints.

A key aspect to the success of robotic adoption is ultimately the proof that the technology and techniques can be relied upon in the actual environments they are expected to operate within.

This type of proof is possible due to the progressive nature of testing that has been used in RAIN. Initial trials are undertaken in lab-based environments. Second stage trials are carried out in industrial, non-nuclear, settings. Third stage trials are carried out in low-hazard nuclear site zones. Final stage trials are carried out in the actual area of operation on a nuclear site.

The mobile robotics sector has seen a period of focused development in recent years. Myriad commercial platforms exist, some of which are ideal as carrier units for bespoke robot-compatible sensor payloads; some of these platforms require 'nuclearisation' to allow them to be suitable for nuclear deployments.

Developing and trialling robotic solutions within RAIN has focused on three key areas:

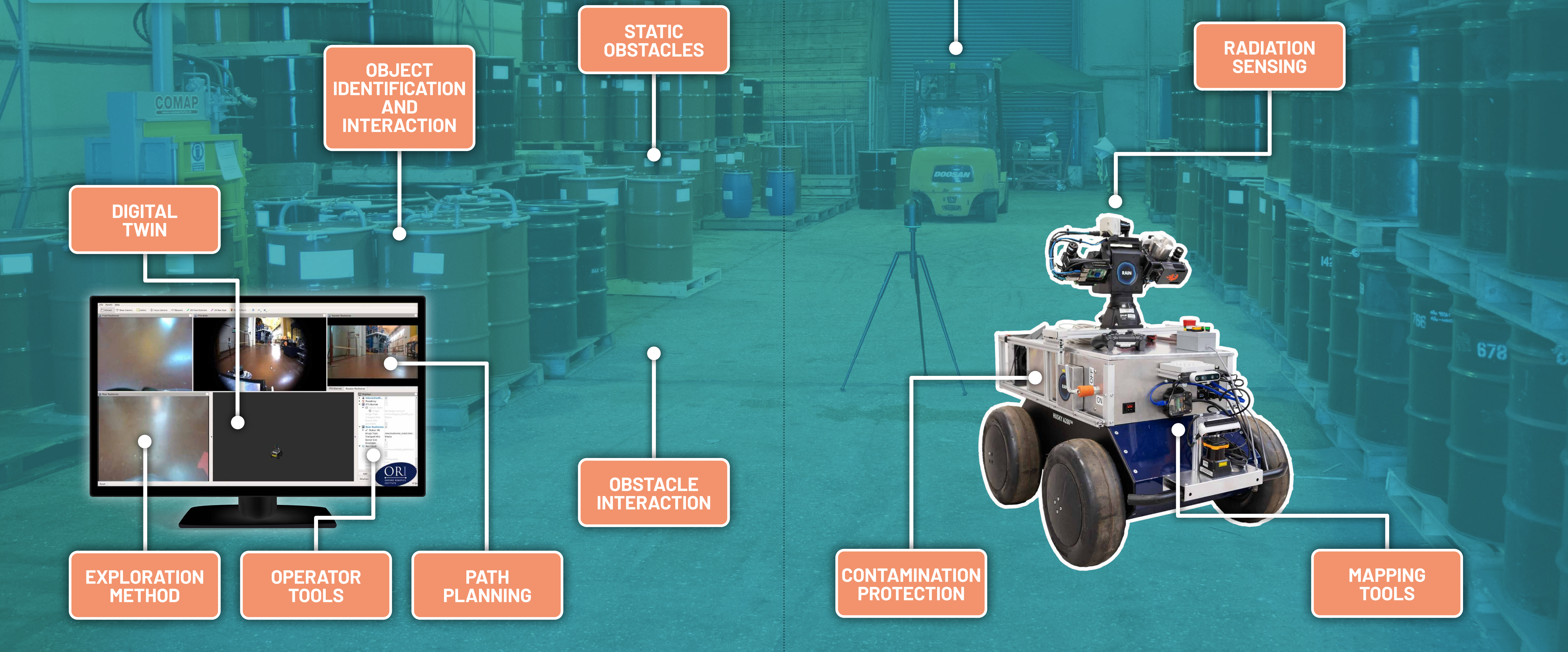
- Platform development; building and adapting physical hardware for nuclear inspection scenarios including radiation hardening.
- Sensing & perception; 3D mapping and localisation along with robot-compatible radiation sensing.
- Missions & autonomy; mission-level control and behaviour planning including verification of autonomous robots.

In the next section you will find details about how the Remote Inspection Working Group has begun to tackle some of the inspection challenges and the status of the developments.

MIRRAX provides high accuracy and manoeuvrable mapping tools in a package that can access via 6" access ports.

NUCLEAR INSPECTION

INSPECTION ENVIRONMENT



WORKING GROUP SUMMARY

REMOTE INSPECTION

Nick Hawes

This final year of RAIN has seen many of the strands from the Remote Inspection working group come together into demonstrators and trials of robots and AI at end-user sites.

To name but a few, members of the working group have supported Bristol's further trials of Spot and Oxford's 3D mapping tools at Chernobyl, alongside Bristol's own bespoke 3D radiation mapping device (YanDavos). Oxford have also worked with Createc to deliver remote inspection demonstrations using a Boston Dynamics Spot at Sellafield and Magnox sites. In the near future the team will be pushing this further to demonstrate fully autonomous inspection missions at Sellafield, and radiation-aware autonomous exploration and mapping at Culham. Manchester, working with ICE9, have also continued deployments of the low-cost Vega robot, with successful trials at Dounreay and Magnox.

This impressive range of deployments at end-user sites has only been possible because of the support provided by RAIN. The novel inspection and autonomy technologies being used in the activities above were developed by researchers supported by RAIN, and the relationships with companies in the supply chain were seeded by small projects funded by RAIN. The gradual but consistent increase in the capabilities of remote inspection technology we have been able to demonstrate over the life of the RAIN project has been matched by an increase in confidence in, and appetite for, this technology from users in the nuclear industry and beyond. Although the RAIN project is drawing to a close, all partners will be continuing to develop and demonstrate this work at high TRL, as well as going back to the lab to develop the next generation of AI and robotics systems for future inspection (and intervention) challenges in the nuclear industry.

Digital mapping helps operators understand the planned path of a robot as well as present a model of the explored zone.

Collaborating with COTS organisations means that RAIN can enhance existing products. Here, Boston Dynamics Spot carries bespoke RAIN mapping hardware – demonstrated at RACE in March 2022.

NUCLEAR INSPECTION

PROGRESS AND SOLUTIONS

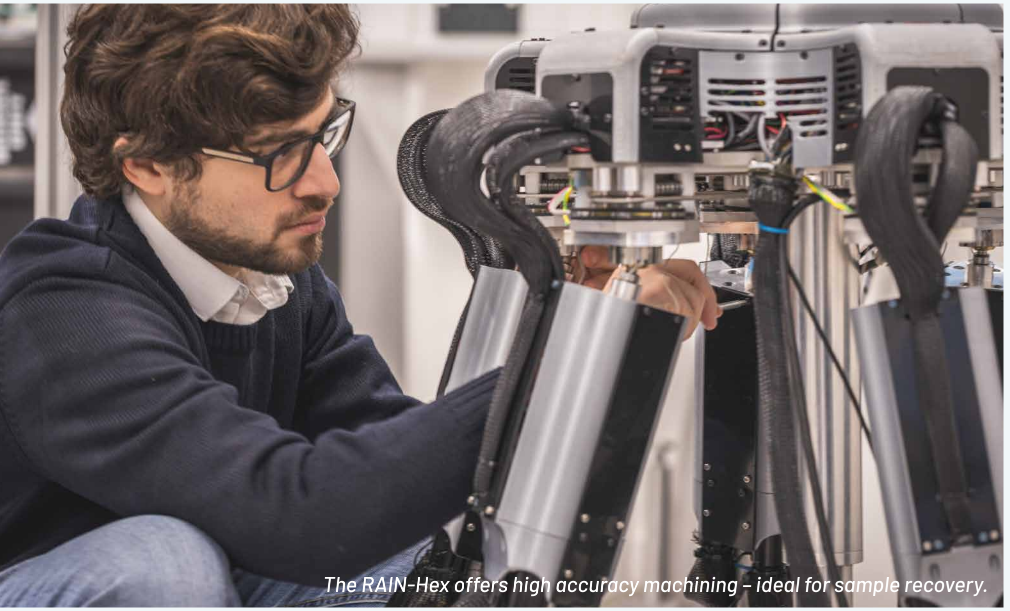
PIBAIR ROBOT

Inspecting small bore pipework is necessary to determine contamination and characterisation to inform decommissioning and maintenance. RAIN has continued development of the low-cost PIBAIR inspection robot, the first of its kind to navigate a two-inch pipe network traversing t-sections and ninety-degree bends. The platform is currently designed to explore a range of up to 50 metres while transporting a radiation measurement module. Improving stability and robustness has been a focus to develop a unit that is suitable for commercialisation.

ONBOARD RADIATION SENSING

Robot-friendly sensors aren't commonly available and as such RAIN has developed bespoke modules to allow detection of a range of nuclear measurements. These modules must; interface with robot-based software, operate on mobile robot power supplies and be suitably small so as not to breach payload carrying ability.

To verify the acquired data from onboard modules a series of tests have been undertaken to qualify the legitimacy of the RAIN-modules versus laboratory quality measurement kit. Findings are very positive and with easy deployment in mind the technology is ideal for commercialisation.



The RAIN-Hex offers high accuracy machining – ideal for sample recovery.

RAIN SNAKE

Access to confined environments requires slender platforms and tool-delivery capability. RAIN has developed the RAIN Snake continuum robot as a low-cost platform with such ability. At 9mm diameter this is the slenderest in the world, allowing inspection before heftier interventions. The snake allows close-up observation and delivery of small tools such as cameras and other measurement sensors. Control algorithms, feed mechanisms and coiling capabilities have been developed to allow a compact deployable system applicable for zones where external space is at a premium (e.g. deploying into a glovebox).

RAIN-HEX

Specific scenarios require simultaneous inspection and machining capability in a mobile platform. The RAIN Hex is designed to provide a mobile, adjustable and high-precision machining tool. Applications include sample site inspection and sample recovery. RAIN has developed a bespoke platform which successfully calibrates, walks and undertakes machining operations to 100-micron accuracy. More recently the work has undertaken to use three of the six limbs as legs, with three used for object manipulation. This work expands the capability of the kit for collection and transport of samples.

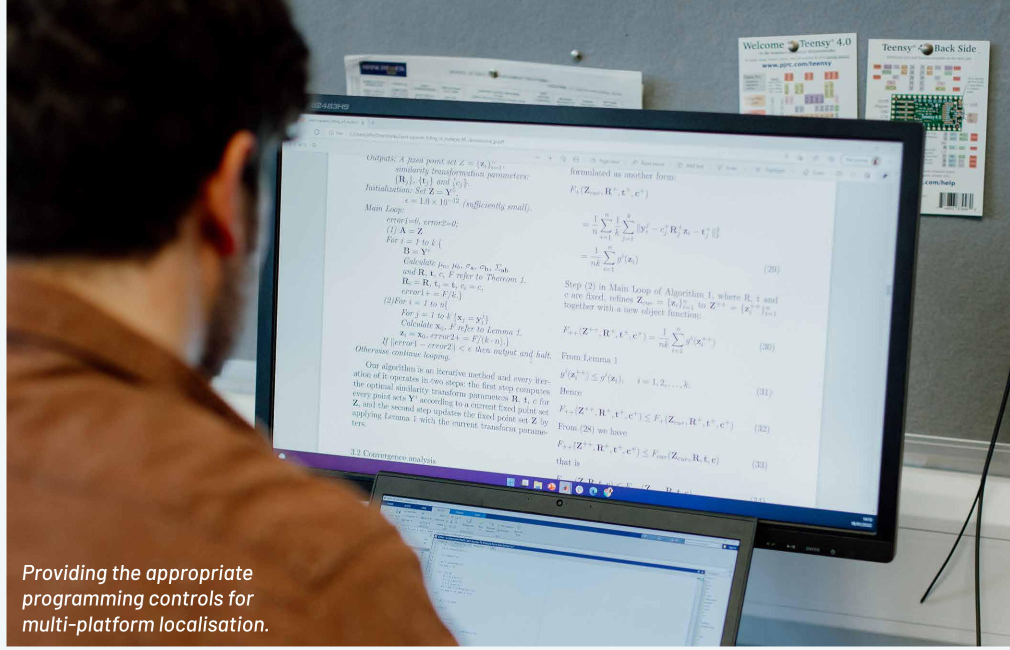
MULTI-PLATFORM LOCALISATION

Vision-based localisation of robot teams is necessary in data collection tasks of complex environments, especially when the platforms need to operate in air, on land or in water.

The need is heightened in poor or GPS-denied environments, such as shielded buildings or underwater operations. RAIN has developed a low-cost system, primarily using COTS equipment, to provide an easy and quick to deploy method of tracking multiple mobile robots in the designated zone of operation. The technique is cheaper and faster than full motion capture and is expected to be trialled in nuclear facilities to prove out the system strengths against the challenges of those environments.

MIRRAX

Circumstances often call for a small-port access platform with mobile and data gathering abilities. RAIN has developed the hardware and software maturity of the MIRRAX platform for data gathering in restricted access, cluttered environments. The platform is suited for geometric and radiometric characterisation. The control techniques have been improved to provide more reliable and more complex operating motions which enhance the capability of the platform.



Providing the appropriate programming controls for multi-platform localisation.

AQUATIC SMART TETHER

Aquatic exploration often involves the use of tether systems to allow transfer of data, power and control. Entanglement of the tether represents a challenge which can compromise mission success. RAIN has developed a smart tether which connects to a ROV to control the shape and position of the tether. This level of control aims to maximise mission success and reduce inspection time. The system has applicability for the inspection of nuclear materials in storage ponds as well as in the offshore oil and gas sector.

RISK AWARE MISSION PLANNING

Extending the life of robotic inspection platforms is a valuable strategy, especially where a platform has the ability to reduce its own exposure to radiation. RAIN has developed such a technique where an inspection robot can autonomously explore unknown areas while adjusting its route upon encountering radiation sources. Developed for deployment on nuclear sites, guarantees of performance and safe operation are intrinsic components. This level of autonomy relieves the burden on the operator of planning contribution and provides valuable radiation mapping data while maximising robot capability.

RELIABLE QUADRUPED LOCOMOTION

Reliably manoeuvring a legged robot requires advanced control to allow each footstep to provide progress rather than instability. RAIN research has focused on control of legged robots for enhanced mobility in industrial settings. A platform agnostic framework has been developed incorporating reinforcement learning and optimal control. This has been proven to allow reliable locomotion on complex, uneven unstructured terrain. Furthermore, the technique adapts to changes in payload so that robot locomotion routines can be flexible in the field.

KEY DEMONSTRATIONS

JET MONITORING

May 2021

RAIN completed a major field trial at JET (the Joint European Torus), at the UKAEA site in Culham. In a collaboration between Oxford Robotics Institute, RACE and Lancaster University, the trial involved the remote operation of a heavily customised Clearpath Husky ground robot in the JET Torus Hall. The first-of-a-kind trial involved the robot entering this nuclear environment, scanning for radiation at fixed locations, and returning to base hours later.

RAIN INSPECTION DEMO

January 2022

On January 26, a team of Oxford researchers went to the RACE site at the Culham Science Centre to demonstrate their approach for autonomous radiation-aware safe exploration and mapping.

The demo consisted of having a Spot robot safely explore and map an area that was fully unknown a priori. The environment was setup to mimic an industrial outdoor setting, including mock radiation sources.

The robot was able to create a map of the surrounding area whilst maintaining itself far from the radiation sources. To the best of our knowledge, this was the first example of autonomous exploration and mapping that considered radiation, ensuring that the robot never attempted to navigate to dangerous areas. The RACE trials were crucial to assess the feasibility of the approach in real-life.

RAIN PHASE TWO CELEBRATION AND DEMONSTRATION EVENT

On Wednesday 16th March 2022, RAIN hosted the RAIN Phase Two Celebration and Demonstration event at UKAEA, Culham.

The Remote Inspection solutions featured in the Inspection and Digital zones at the event.

Stands were hosted to show;

- Nottingham – COBRA continuum robot
- Manchester – Computer vision
- Lancaster – Radiation sensors and sensing techniques
- Newcastle – Aquatic Active tether
- Leeds – Pipe inspection robot
- Manchester – Inspection platforms
- Oxford – Frontier, rapid 3D point cloud mapping
- Bristol – Tales from Chornobyl
- Manchester – Long distance remote ops of mobile inspection robot

With live a live demo of the Spot-based autonomous mapping and exploration system developed by Oxford Robotics Institute.

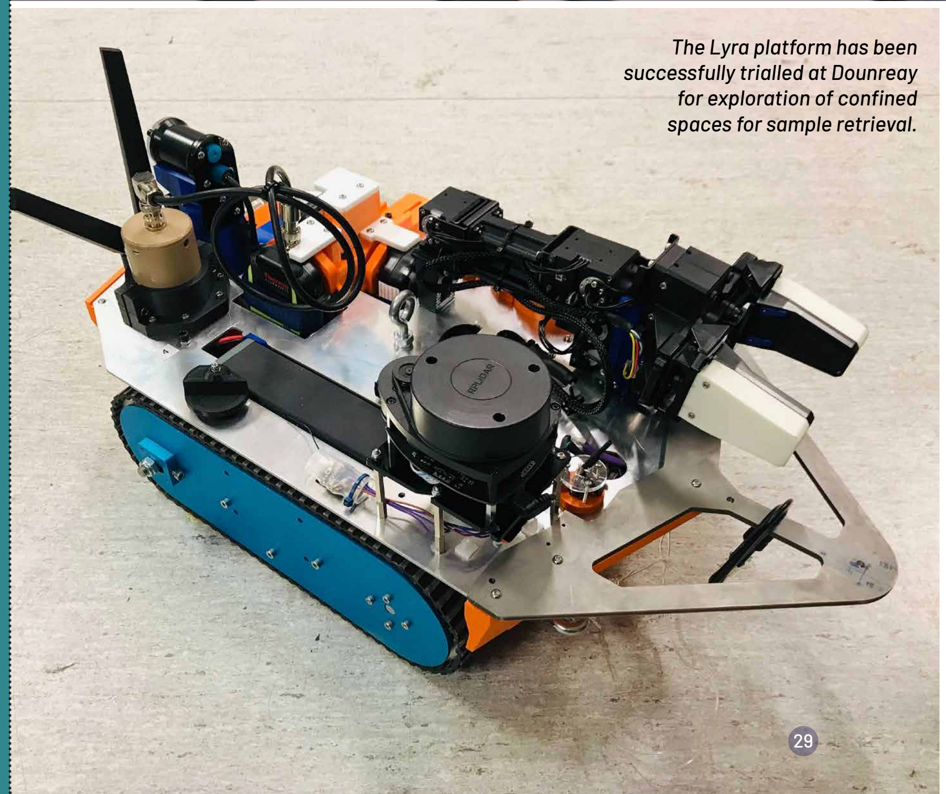
VEGA EVOLVES INTO LYRA

The Vega robot had undertaken multiple successful trials at the Dounreay nuclear plant to conduct inspection surveys of an underground drain. RAIN identified that Vega would be ideal to perform essential radiation surveys in areas which are unsafe for humans. The robot successfully undertook visual and radiological surveys in an underground duct not otherwise easily accessed.

Building on results of the deployment, RAIN has further upgraded Vega, creating the Lyra platform to enable longer deployment missions to capture more data and support the decommissioning planning of the underground duct.

Lyra has traversed 140m of duct from a single-entry point and provided operators with detailed radiological characterisation information that can now be used to help plan safe and efficient decommissioning of the laboratories.

The Spot robot carries bespoke mapping tools, as demonstrated in Jan 2022 at RACE.



The Lyra platform has been successfully trialled at Dounreay for exploration of confined spaces for sample retrieval.

RAIN has both significantly modified a Husky robot and developed bespoke mapping equipment to explore the JET Torus Hall.

WIDER NUCLEAR CONTEXT

Nuclear robotic deployments naturally rely upon functional equipment. However, there are wider aspects to consider for a deployment to be allowed and to be repeatable.

The Remote Handling, Remote Inspection and Human Robotic Interaction Working Groups in RAIN address technologies and techniques that operators will be using. Behind the scenes there are other aspects to be considered.

A key benefit of robotic solutions is the ability to leave them to do tasks in an unsupervised capacity. In comparably low consequence environments this can be a relatively easy thing to do. Given the potential for high consequence outcomes from poorly interacting with nuclear material, the path to long-term autonomous nuclear deployment is a little more complex.

For this reason, RAIN has been able to deploy remote inspection robots on nuclear sites, but remote handling has not yet interacted with nuclear materials; observing is simpler than handling.

Autonomous capabilities need to be suited to the target applications. In some cases, this may mean that a pre-defined routine could be programmed and left to run. In other circumstances the system may have a greater need for variability within the autonomous operations; for example, the use of machine learning.

As with existing human-driven operations, there must be appropriate qualification in place to allow a nuclear operation to be undertaken. This qualification is embodied in the 'safety case' document which describes the design, through-life operations and associated procedures and processes that ensure safe and predictable outcomes.

Guidance is provided on such matters by the UK nuclear regulator, the Office for Nuclear Regulation (ONR).

Given that most safety cases rely upon human operators, the transition to reliance upon machine-based decisions is one that is important and sensitive.

The Autonomy and Verification Working Group has focused upon the qualification aspects to support the long-term deployability of robotic solutions. The relations fostered with the ONR have been gratefully valued by RAIN.

In the broader context of ease of contribution and longevity is the theme of standardisation.

Here the value is in the ability for experts to participate in shared virtual environments that can allow multi-user engagement for nuclear scenario testing. Such environments allow for performance measurement and improvement using metrics that are easy to interpret for given applications.

Furthermore, in the context of longevity, is the ability for robotic systems to maintain performance over time. As is known with computer systems, the software and hardware lifecycle can be rapid and thus it is advantageous for nuclear robotic systems to accommodate such changes.

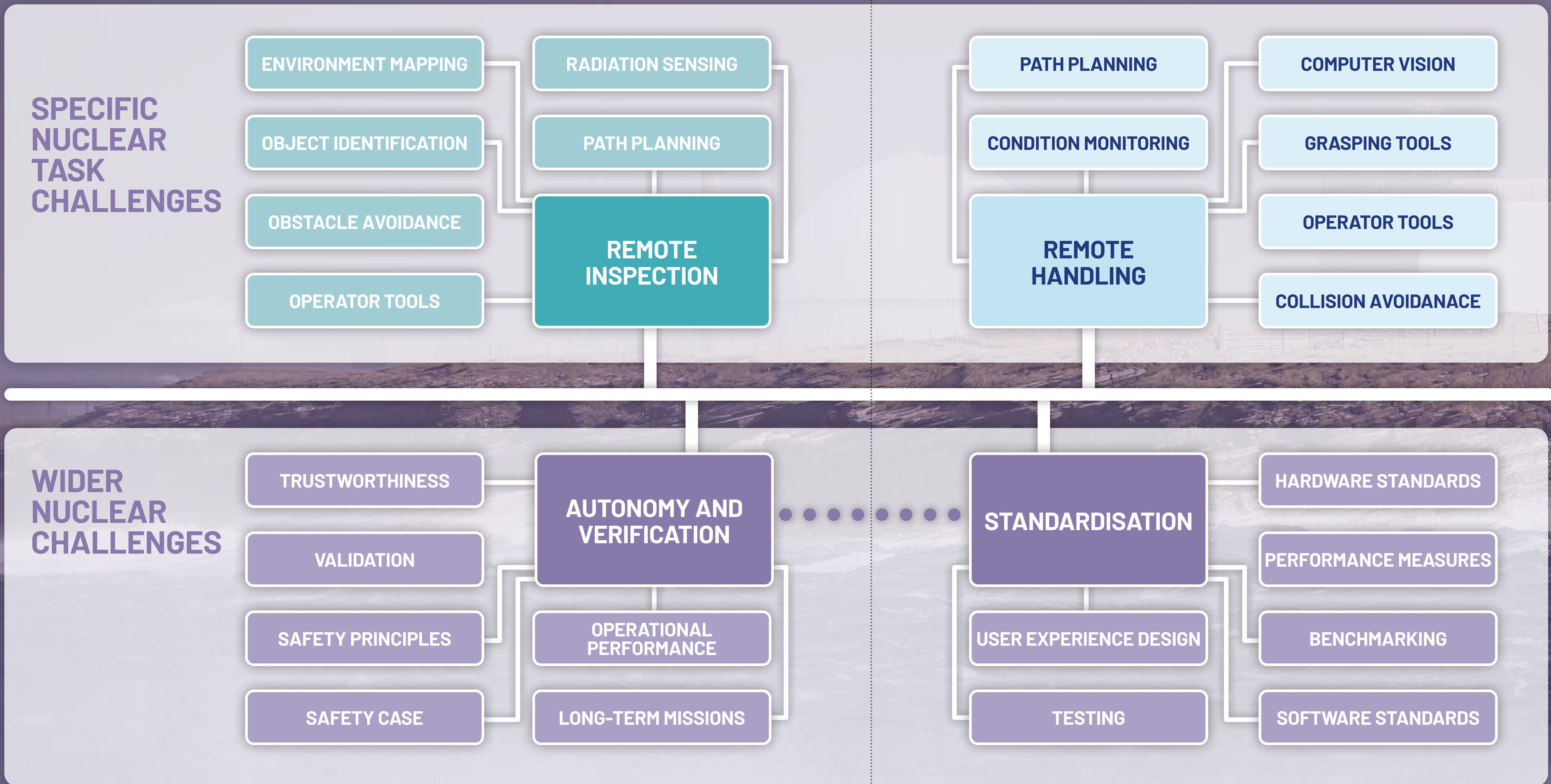
The RAIN perspective is not one simply of deploy and forget, but one of long-term through-life support and development to ensure that technology and techniques are not only reliable but also adaptable.

The Standardisation Working Group has begun to set foundations for a standard framework in nuclear robotics; developing the CorteX system at RACE, creating baselines for HMI's and performance evaluation for teleoperation.

Overleaf you will find helpful highlights from the Working Group leads for the topics introduced here.

The concepts explored in RAIN can affect the fundamental design, manufacture and assembly of robotic tools. Early integration of such concepts ensures easier integration, easier operation and simpler verification.

WIDER NUCLEAR ENVIRONMENT



WORKING GROUP SUMMARIES

AUTONOMY AND VERIFICATION

Louise Dennis

The Autonomy and Verification Working Group has focused on identifying the regulatory barriers to the deployment of autonomous robots in nuclear environments and identifying routes forward

In July, we published a White Paper on Principles for the Development and Assurance of Autonomous Systems for Safe Use in Hazardous Environments. This was joint work by members of the working group and employees from the Office for Nuclear Regulation (ONR).

We are currently working on a sample safety case for deployment of the Autonomous Aquatic Inspection and Intervention (A2I2) underwater survey robot in a nuclear decommissioning context. This sample safety case will aim to show both what existing technology might allow in terms of deployment of autonomous robots in nuclear environments as well as pointing to ways forward, and possible directions that could be taken to develop autonomous robots in a way that integrates with the safety case process.

Work has continued on the development of verifiable modular robotic architectures; the relationship between fault recovery and verifiability; and on the potential impact of explainability technology on the deployment of autonomous robots in nuclear environments. As part of this work we've collaborated with a number of other projects most notably the Trustworthy Autonomous Systems Verifiability node, and the FAIR-Space Robots for a Safer World hub.

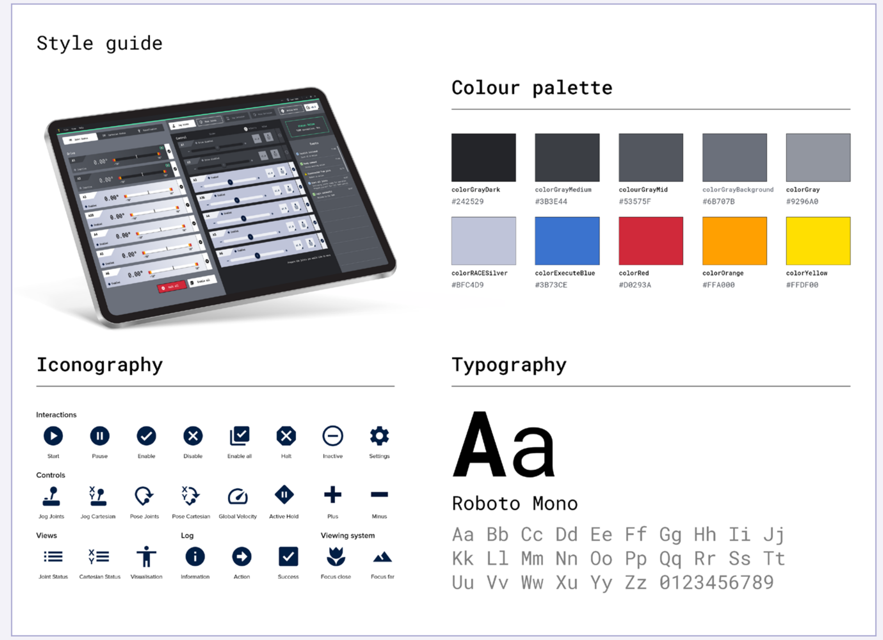
During the RAIN Programme, as both the Safety Case WG and now the A&V WG, we have fostered relations to build real working connections between nuclear end users, suppliers, regulators and researchers. These connections are vital to convert the enthusiasm from seeing robot demonstrations into tangible methods to realise the daily, reliable and trustworthy use of nuclear robotics.

Designing for autonomy and verification is a helpful mindset.

STANDARDISATION

Ipek Caliskanelli

The Standardisation working group focused on bringing academic and industrial experts to create new baselines in specific areas such as operator-facing human-machine interfaces (HMI), extensible modular software systems, and nuclear tele-manipulation systems.



Our first workshop was held online in June 2021 on HMI standardisation. Nuclear end users are experts in their field of operation, and the operational parameters are often high risk and stressful. Therefore, the nature of the user interaction requires a specific set of guidelines for the design of the graphical-user interface of telerobotic systems which at present is not well defined in the industry. This work aims to contextualise the modern design guidelines and discuss the creation of a standard of design guidelines for graphical human-machine interfaces in telerobotics. A report describing the motivation for selecting and adapting modern guidelines to suit the specific needs of telerobotics operators has been released.

A second workshop on Standardised software frameworks for robotics in nuclear took place in conjunction with IROS 2021 in September. The aim of the IROS workshop was to raise awareness on nuclear challenges, and to attract academics for their research expertise. The essence was to create a nuclear community around this topic to help solve these problems together. Further information is available on request via the special journal edition which we have edited.

Last but not least, we are working on performance evaluation methodologies for bilateral teleoperation systems. The goal of this is to evaluate the adequacy of the exciting techniques, defining objective performance benchmarks, that can be quantitatively measured for the manipulators for individual usage (unilateral) and for bilateral mode, and proposing methodologies to capture operators' perception about the bilateral teleoperation systems. A detailed report on our findings is available upon request.

WIDER NUCLEAR

PROGRESS AND SOLUTIONS

DYNAMIC MODELLING

RAIN has used the process of dynamic modelling to create digital models of given manipulators which possess sufficient physical characteristics as to allow technical assessment. Such a model will be used to assess the stress or strain on the manipulator in a virtual environment to prove out either the suitability or highlight any task modifications to allow safe operations. The slender glovebox robot arms, and their digital twins, have been used by other programmes to allow dynamic modelling systems to be developed and trialled. This basis can then be transferred to much larger handling systems compatible with fission and fusion reactors.

INTEROPERABILITY

Hardware integration to create one-off research platforms is useful for investigating specific outcomes. However, for industry adoption the systems should be able to interface with differing hardware and software in the long-term. Such flexibility and standardisation would allow the swift integration of different manipulators and input devices to accommodate operator / task preferences and newer technology. RAIN research has investigated the use of the CorteX software architecture developed at RACE for application in the RAIN nuclear glovebox. This is to set the foundation for extensibility into use of other technologies for the varied glovebox challenges.

SAFETY CASE

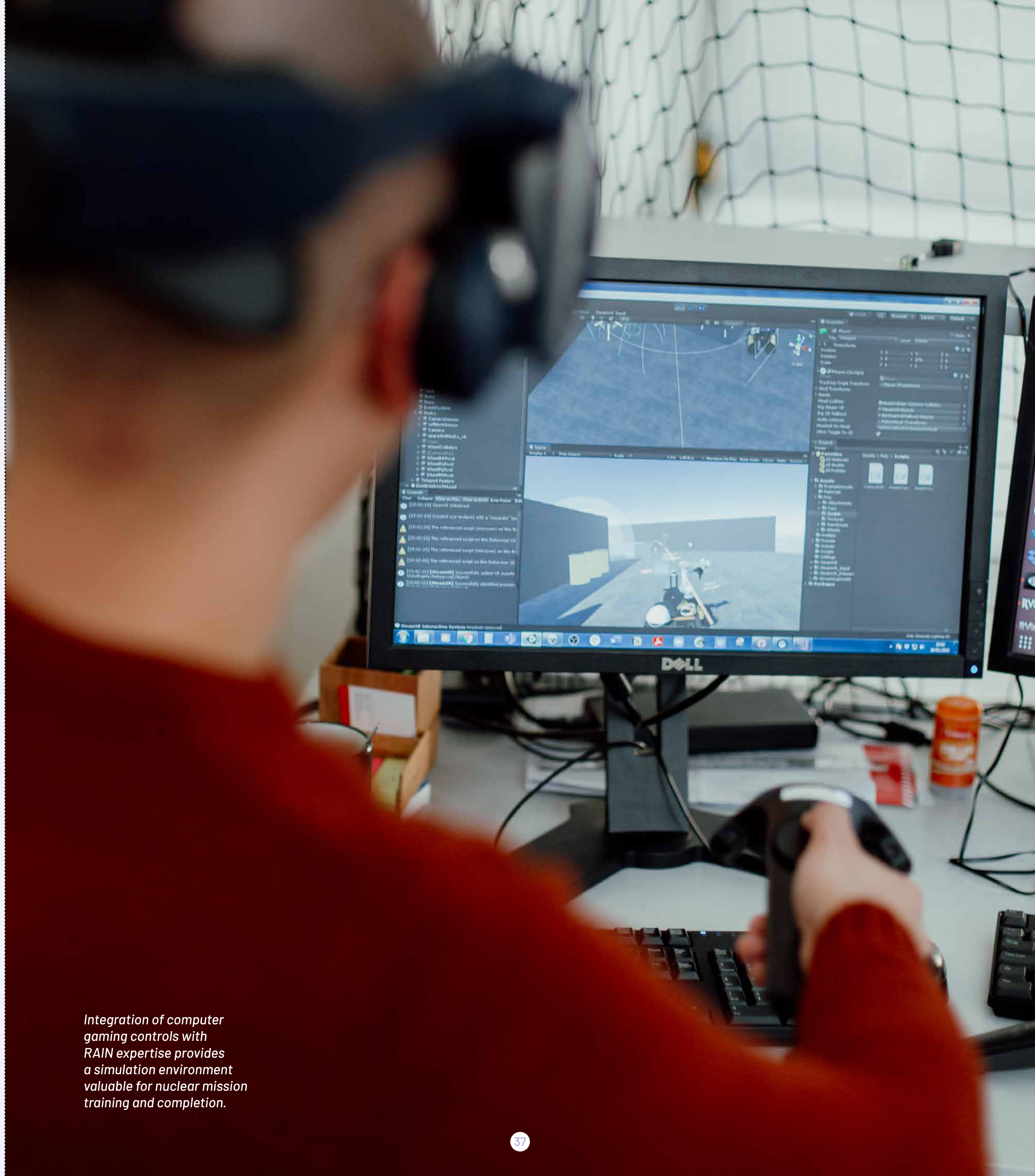
Safety is a paramount criterion for nuclear operations and as such it has been a focus in RAIN. Research has explored the creation of an exemplar safety case, using AI technology, for a robotic use case. Such an approach lends itself to principles preferred by the ONR such as traceability for substantiation. The technique is evolutionary, using approaches already trusted in the nuclear sector but formulating content in a way that is suitable for robotic deployments. Such a method will be valuable to minimise time to generate safety case documentation and highlighting areas for additional scrutiny.

DIGITAL TWIN

Prototyping and trials have long been engineering steps to work towards success. Digital prototyping allows platforms to be assessed in isolation or in a mission context for operator familiarity or general assessment. RAIN has developed a digital environment to lead the way towards standardised digital operation and evaluation. This adds value to design and development activities as well as pre-deployment practice. The ability to also include a variety of immersive control methods along with actual geometric data gathered from proposed mission environments will help hone operator skills.

RESILIENT MACHINE LEARNING

Machine learning is a widespread technique in general industry but less so in nuclear. Challenges around trustworthiness and resilience need to be assured prior to deployment. RAIN has explored the application of ML in the nuclear sector and has proposed a benchmarking scheme for determining resilience. Such work is valuable to promote safe and secure adoption to gain the benefit from defence options against adversarial attacks thus preventing damage and safeguarding assets.



Integration of computer gaming controls with RAIN expertise provides a simulation environment valuable for nuclear mission training and completion.

KEY OUTCOMES

RAIN HUB AND ORCA HUB LAUNCH ROBOTIC KNOWLEDGE INVENTORY

As part of a joint initiative between the RAIN Hub and ORCA Hub, RAIN has developed a Robot Knowledge Inventory called Robotki. Our vision is to try and make robotics engineers lives as easy as possible by providing a single portal to find robotics resources such as simulation environments, CAD models, code, datasets and tutorials.

Robotki does not host any material directly, instead it collates it from around the world into a single, easily navigable environment that anyone from aspiring undergraduate robotics engineers through to experienced practitioners can use.

The first version has just gone live and can be found here: robotki.github.io

ONR WORKSHOP

November 2021

Representatives of Sellafield Ltd (SL), the Office for Nuclear Regulation (ONR), UKAEA, NNL and the University of Manchester (UoM), representing RAIN, met to discuss how the safety of applications containing Artificial Intelligence (AI), and particularly Robotics and AI (RAI) can be justified, to help assist in the translation of this technology on to nuclear sites.

The three-day session covered optioneering studies in safety cases, outline RAI strategies, CE/UKCA marking, and the benefits and challenges surrounding the topic.

RAIN PHASE TWO CELEBRATION AND DEMONSTRATION EVENT

On Wednesday 16th March, RAIN hosted the RAIN Phase Two Celebration and Demonstration event at UKAEA, Culham.

The Glovebox challenges featured in the Handling and Digital zones at the event.

Stands were hosted to show;

- Warwick – Cyber security
- RACE – CorteX
- Manchester – Digital Twins
- RACE – RHOVR (Remote Handling Operations in Virtual Reality)

With an in-person workshop discussing the outcomes and perspectives on the safety case work developed in RAIN.

NUCLEAR ROBOTICS WHITE PAPER PUBLISHED

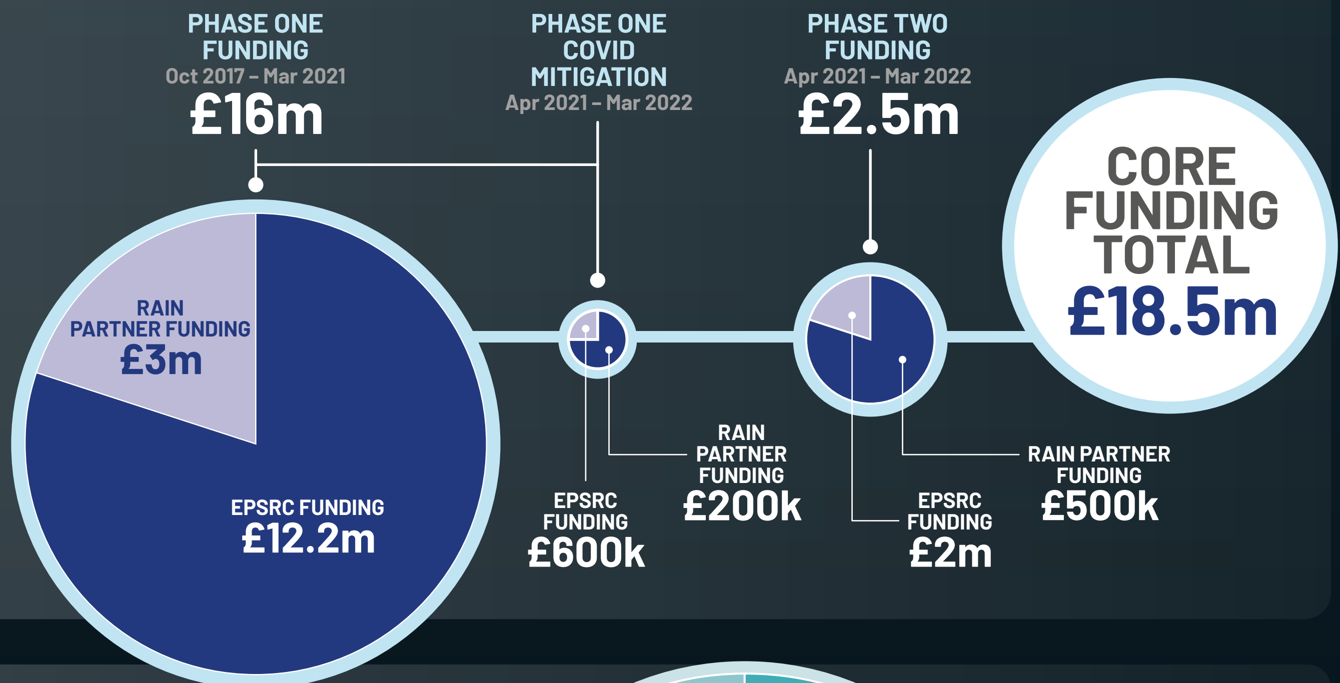
July 2021

RAIN collaborated with partners at the UK's nuclear regulator, the Office for Nuclear Regulation (ONR) and together produced a white paper entitled "Principles for the Development and Assurance of Autonomous Systems for Safe Use in Hazardous Environments".

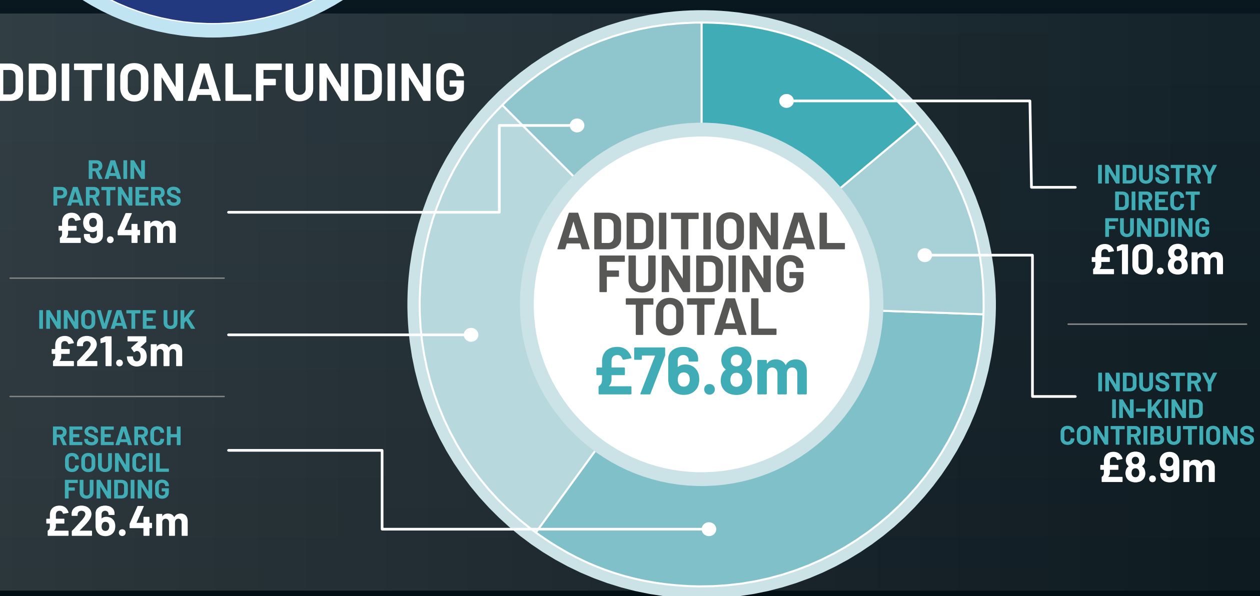
The white paper provides guidance on designing and assuring autonomous systems used in hazardous environments, such as in the nuclear industry. This guidance is to be considered alongside existing standards and regulations aimed at, for example, robotics, electronic systems, control systems, and safety-critical software.

RAIN IN NUMBERS

CORE FUNDING



ADDITIONALFUNDING



28 STUDENTSHIPS
PHD SUPPORT PROVIDED FOR RAIN

12 ACADEMIC APPOINTMENTS

90 RAIN WEBINAR PRESENTATIONS

100+ TECHNOLOGY DEMONSTRATIONS

1000+ ENGAGEMENT ACTIVITIES

363 PUBLICATIONS

31 FURTHER FUNDING

20 AWARDS & RECOGNITION

29 COLLABORATIONS & PARTNERSHIPS

10 INFLUENCE ON POLICY, PRACTICE, PATIENTS & THE PUBLIC

9 NEXT DESTINATION

21 RESEARCH DATABASES & MODELS

9 SOFTWARE & TECHNICAL PRODUCTS

1 SPIN OUTS

OTHER BENEFITS

CAREER DEVELOPMENT

The RAIN Hub has provided a unique environment in which to develop career aspirations.

With a range of ambitions it was necessary for the Hub to be structured akin to a small business. This provided a structure within which it was possible for participants to progress their career across many disciplines; particularly in the research roles. In fact, many of the researchers have moved from academia into industrial positions which helps spread the research ethos into industry.

MINDSET

Bringing together academia, suppliers and end users in the RAIN programme has naturally drawn together different characters in participating organisations. The variety of perspectives, from sectoral to personal, has helped form a 'nuclear research mindset'. This mindset is one that fosters curiosity, while recognising industrial demands and urgency along with limits on time and resources. The ethos is also one of stirring up sufficient enthusiasm and awareness with industrial partners so that they can 'pull' technology and techniques through to deployments, rather than relying solely on research 'push'.

SHARING RESEARCH VALUE

At its core, the RAIN Hub is a research engine. The ability to explore new techniques is valuable and that value is increased several times by sharing the progress and outcomes with a wide audience. Alongside the traditional route of publishing research papers and journal articles RAIN has hosted in-person events, including workshops, showcases and hackathons along with online sessions via the RAIN webinar series. In each of these engagements it is an opportunity to share the value of the research or tailor the direction so that it has further community relevance. This 'listen and adjust' dynamic has served RAIN well.

COMMUNITY GROWTH

The nuclear community is a niche collection of wonderfully skilled and diverse individuals. Serving their needs meant that the behaviours in the Hub needed to be aligned with an understanding of the existing community. However, the RAIN ambition has always been to foster positive change and to do so requires the support of the folks with existing experience.

RAIN has helped to foster genuine growth across the community. Observers will have seen industrial companies initiating or rapidly growing their robotics departments as a result of RAIN's existence. In addition, RAIN events have provided varied options for experts to come together and share desires, offerings and opportunities.

COMMUNITY PREPAREDNESS

Each robotic deployment requires multiple aspects of preparation. Some of the elements are akin to using industrial equipment, however some relate specifically to robotics. For example, the means of control for autonomous operations. Since deploying robotics on nuclear sites is still comparatively new, each deployment is not only valuable for the specific mission outputs but also in building familiarity with the processes required to assure safety and outcomes. RAIN is enormously grateful for the myriad people involved across nuclear sites for helping prepare and deploy robots in real industrial scenarios.

> ***Now the characterisation survey is complete we have built up a very comprehensive picture of the duct, which will help us make informed decisions on how the duct should be decommissioned.***
>
> ***Jason Simpson***
> ***Project Manager, DSRL***
> *(ref: Lyra Deployments at Dounreay 2022)*

> ***It's really exciting to see the kind of progress from right at the beginning to the culmination today.***
>
> ***James Kell***
> ***Robotics Technical Director,***
> ***Jacobs Clean Energy***
> *(at RAIN Phase Two Celebration Event Mar 2022)*

ENGAGEMENTS HIGHLIGHTS

WEBINARS

Started in April 2020, the RAIN webinar series continued to attract audiences spanning the academic and industrial sectors. With topics including resilient machine learning, acoustic sensing and enhanced wireless control, the sessions helped to continue engagement while in-person contact was still challenging.

VR SCHOOLS ENGAGEMENT

RAIN has worked on a collaborative project to create a VR-headset-based experience to share what it's like to be a robotics researcher. The experience, developed for schools, allows the wearer to fly drones and control mobile robots to complete missions. This exciting experience changes how outreach activities can link up to a wider community and aims to inspire future scientist and engineers. A hands-on experience of the kit was hosted at the Phase Two Celebration Event at UKAEA, Culham.

Robotics engagement for schools will help foster interest for technologists of the future.

RAIN HOSTS INTERNATIONAL GUESTS

In January 2022 RAIN demonstrated handling and inspection technology to international visitors.

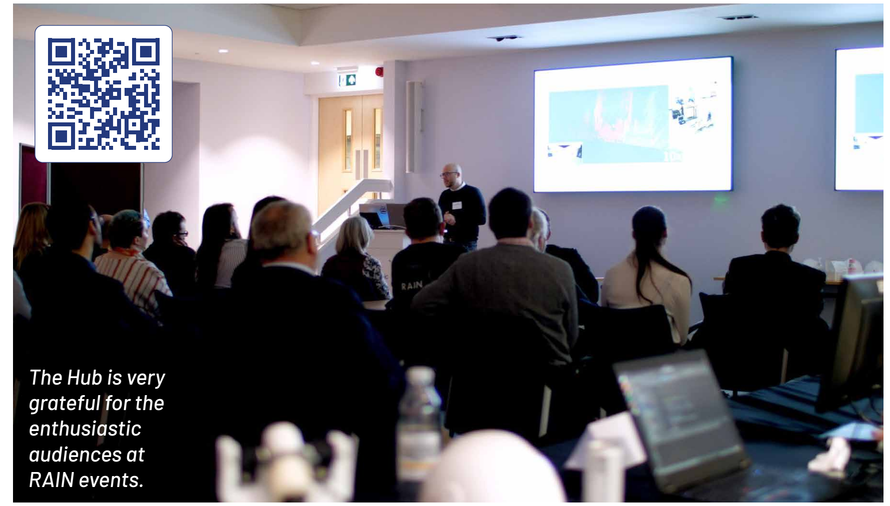
ISCF BROCHURE

RAIN is proud to have received its initial funding from the UKRI Challenge Fund and has been part of a fantastic cohort. The 2022 ISCF Challenge Fund Brochure features a wonderful two-page spread on the RAIN programme.

PHASE TWO CELEBRATION AND DEMO EVENT

March 2022 – Culham

An opportunity to showcase the achievements of Phase Two was not to be missed! Hosting more than twenty separate stands, the institutions in RAIN – spread across three technology zones – demonstrated their work. The one-day celebration provided an in-person opportunity to enthuse audiences from fellow academics, the supply chain and nuclear end users. It was fantastic to see non-nuclear attendees being equally delighted.



The Hub is very grateful for the enthusiastic audiences at RAIN events.

MAGNOX VIRTUAL SHOWCASE

A RAIN Virtual Showcase was held share with a decommissioning and engineering audience at Magnox to share the status of RAIN research. The two-way knowledge exchange allowed RAIN to understand more about the Magnox estate challenges and Magnox to identify how RAIN research related to their work. Of particular value was the focus on deployment opportunities. During the session various deployment options were identified and subsequently explored.

ROBOTS FOR A SAFER WORLD CELEBRATION

March 2022 – Bristol

The official culmination of the RAIN Phase Two programme was hosted at We The Curious in Bristol, UK on 29th March 2022. The day brought together all four Hubs along with representatives from the various projects and programmes in the >£112m Challenge Fund. The four RAIN stands welcomed many enquiries and members of the Hub presented talks and compered the live link to the official opening of RAICo in Whitehaven. The Celebration Event was a lovely way to round off Phase Two of RAIN.

RAIN is privileged to be amongst the 212 organisations involved in the Robots for a Safer World challenge.

WHAT NEXT?

While RAIN has made good headway, the nuclear robotics challenges are not yet solved. There is still plenty of value that can be added across the fission and fusion sectors through further research and collaboration.

RAIN has helped to strengthen the foundations of the nuclear robotics research community and shed light upon the potential enhancements that could be achieved. There is a tangible and vibrant enthusiasm across the research, supplier and end user organisations which will serve to benefit not only nuclear but wider sectors.

As described earlier in the RAIN Story, RAIN always had a long-term view; it's somewhat necessary with the current longevity of nuclear challenges. RAIN has fostered a sense of curiosity and ambition which has manifested in further initiatives, some of which you may already be familiar with, others are only just starting and one or two are yet to be announced (watch this space).

Examples of those that are now up and running include the National Nuclear User Facility Hot Robotics programme (http://hotrobotics.co.uk), which provides equipment and facilities to support and promote research into nuclear robotics, and the Robotics and Artificial Intelligence Collaboration (RAICo) initiative. RAICo, which has its home in Whitehaven, Cumbria, is a collaboration between RAIN, the UK Atomic Energy Authority, Sellafield Ltd, the Nuclear Decommissioning Authority and the National Nuclear Laboratory that is focused on delivering robotics innovation to Sellafield, Dounreay and other legacy nuclear sites, to accelerate and reduce the cost of decommissioning and minimise risk. Finally, Oxford Robotics Institute have secured funding from EPSRC for the 'From Sensing to Collaboration', which will deliver improvements to robotic and autonomous systems across all sectors.

The drive to make nuclear robotics useful, fun and trustworthy has relied upon a whole host of people. Which brings us onto a 'thank you'.

THANK YOU

As you're reading this – and clearly a brilliant fan of RAIN – hopefully we've made it abundantly clear that we have been utterly grateful for the support that you have given to RAIN.

We know that lots of different people have helped in very different ways. Some were there in the beginning. Some joined as our work grew. Some have been in the front and centre of research and demonstrations.

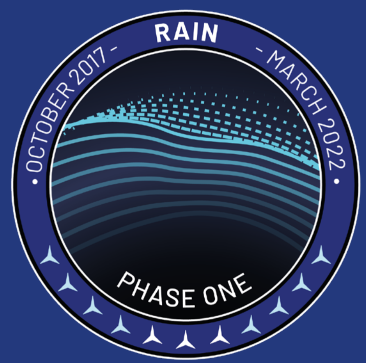
Some have been behind the scenes, putting things in place so that we could all do our things together. The breadth of skills and characters in the RAIN community has made it a fun place to be. We hope you have enjoyed the experience so far.

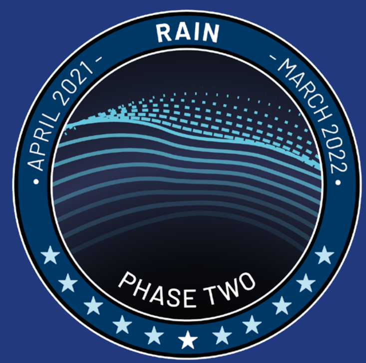
This is a brief moment to reflect and celebrate your contribution. Your participation, curiosity and enthusiasm have been the fuel we needed to tackle challenges.

It has been wonderful to see the collaborations and friendships that have developed across the research, supply chain and end user sites. Some folks were sceptical that such links could be made. But it's amazing to see what can be done if you get people together and give them the opportunity and support to make amazing things happen.

Perhaps that's what it boils down to.

Thank you for helping us make amazing things happen.





The RAIN Hub: facilitating change to existing nuclear programmes and initiatives.

The RAIN Hub's objectives are to overcome the challenges facing the nuclear industry. Through applying our scientific knowledge and understanding we can improve safety and efficiency in the nuclear sector, benefiting the UK economy and creating a safer working environment.

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