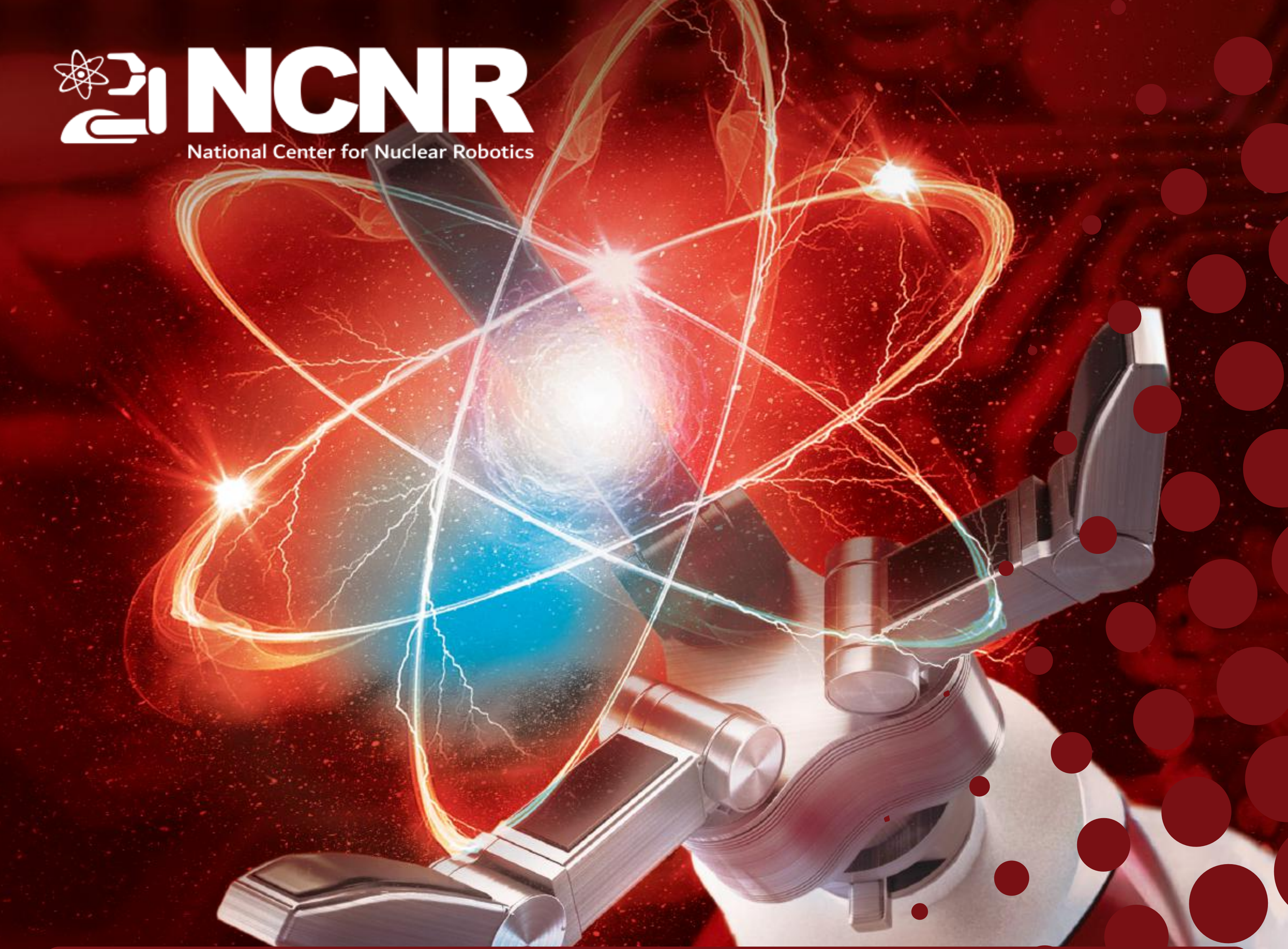
NCNR

National Center for Nuclear Robotics

Taking humans out of harm



"The National Centre for Nuclear Robotics, established in 2018, is a consortium of eight universities and affiliated partners tasked with finding fresh solutions to the well-established problem of nuclear waste. Nuclear decommissioning and the safe disposal of nuclear waste is a global problem of enormous proportions. The UK alone contains 4.9 million tonnes of legacy nuclear waste. The need to retrieve and dispose of contaminated materials while protecting the natural world and minimising radiation exposure has never been more pressing.

NCNR members have responded to this need by developing groundbreaking techniques for monitoring nuclear sites and disposing of radioactive material without endangering human life. Research into remote-controlled robots has taken centre stage in the NCNR's ambitious project. The challenge is to develop a new generation of autonomous, self-healing robots capable of carrying out complex tasks in contaminated environments while an operator oversees their work from a safe distance.

As a result of the inspirational work of consortium members and partners over the past four years, significant advances have been made in remote interventions using robotics. Many NCNR projects are making excellent progress through the UK's Technology Readiness Levels (TRLs), and have already completed TRL Level 3 (proof of concept). Some research has reached as far as TRL 7, meaning the system adequacy has been validated in the relevant field.

Thanks in no small part to the work described in this report, there seems little doubt that we are on the cusp of a new era in nuclear decommissioning, where state-of-the-art robotics and AI methods are standard in solving the problems presented by the nuclear industry."

- Professor Rustam Stolkin

Chair of Robotics, University of Birmingham

Royal Society Industry Fellow, National Nuclear Laboratory Ltd

Director, UK National Centre for Nuclear Robotics

Chair, International Expert Group on Robotics and Remote Systems, OECD-Nuclear Energy Agency

400+

peer reviewed scientific papers in four years!

200+

engagement, collaboration and exchange activities with external stakeholders.

£8million

leveraging from industry,

£10million

institutional investment and additional funding

Training of **60+**

early career post-doc and PhD researchers
in advanced robotics for industrial applications.

Worldwide impact on policy,
regulation and guidance to governments, nuclear agencies and operators.

National and international education outreach

in schools to inspire the next generation of engineers and roboticists.

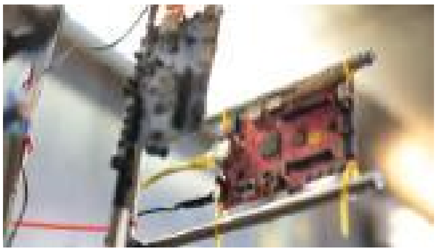
Innovation, technology transfer and commercialisation
impacts across nuclear and other industries.

World first AI-controlled robot arm in live radioactive environment.

World-first deployments of autonomous drones at **Chernobyl** and **Fukushima**.

Machine learning of complex dynamics for precision control of heavy-duty hydraulic manipulators.

Radiation-resilient electronics, self-monitoring and self-healing systems on chip, and novel "radiation hardening by software" for resilient COTS processors.



3D semantic SLAM for autonomous robotic scene understanding. Multi-sensor fusion of radiation sensing with computer vision data for characterisation.

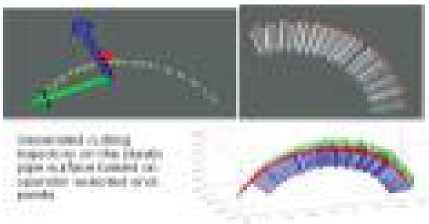
Gazebo simulation of THORVALD planning and tracking a path toward a user-given target location under the autonomous navigation framework

Virtual, augmented and mixed-reality interfaces, with state-of-the art haptic exoskeletons for immersive human interface system.

An intuitive, fast, and reliable bi-manual teleoperation system with Franka Panda arms

Combining human-in-the-loop with state-of-the-art AI and autonomy, via human-supervised-autonomy, variable autonomy, and shared control semi-autonomous systems.

Decommissioning UK's nuclear legacy - AI-controlled robotic laser cutting of contaminated waste in radioactive hot cell.



The National Centre for Nuclear Robotics is led by the University of Birmingham in collaboration with seven leading UK universities and the Royal Institution, London. Additional partners from academia and industry have joined the NCNR through its £2.6 million 'flexible partnership' fund. The team is also working with researchers from renowned organisations in the USA and Asia.

> **Collectively, this multi-disciplinary group offers world-leading expertise spanning radiation resilient systems, novel sensors, robotic vision and perception, autonomous navigation, advanced robotic manipulation, human-robot interfaces and human-centred design, as well as engineering, science education and outreach.**
> **- Professor Rustam Stolkin, NCNR Director**

UNIVERSITY OF BIRMINGHAM

Researchers at the University of Birmingham are developing fully autonomous robotic grasping and manipulation methods, where the robot arm is controlled by AI and guided by robotic vision systems. The team is also exploring how AI and humans can collaborate to control a remote robot via shared control systems.

University of BRISTOL

The University of Bristol is researching areas that include nuclear pipeline inspection, Unmanned Aerial Vehicles (UAVs, or drones) for site monitoring and emergency response, and autonomous robotic scanning methods for inspecting ageing nuclear waste packages. The team's activity will take advantage of strategic partnerships and collaborations established through the South West Nuclear Hub.

THE UNIVERSITY of EDINBURGH

The University of Edinburgh provides expertise in the dynamics and control of robot arms and the legs of complex walking robots. This work will allow robots to navigate autonomously through cluttered environments, such as disaster zones and legacy nuclear cells.

University of Essex

The University of Essex is investigating the effects of radiation on the electronics of robotic systems. It is also developing new methods to increase the resilience of the hardware and software of electronics systems. This work is an active collaboration between the University of Essex, and its partners and long-term collaborators at Caltech's NASA Jet Propulsion Laboratory. The university also contributes expertise in Computer Vision.

brl Bristol Robotics Laboratory

The University of West England provides the facilities of Bristol Robotics Lab, the UK's largest co-located robotics centre. Here, researchers work on human-centred design, human factors and human-robot interaction using multi-modal interfaces.

Lancaster University

Lancaster University contributes research on mobility and navigation, and grasping and manipulation. It also focuses on the integration, standardisation and modularity of the technologies it develops. In addition, the Lancaster team investigates low-level control problems of hydraulic actuators. Their methods extend to other control problems, such as stability in UAVs.

UNIVERSITY OF LINCOLN

The University of Lincoln contributes an expertise in the autonomous navigation of robot vehicles. It also brings detailed knowledge in the use of machine learning to control robotic manipulators. Areas of expertise include learning-from-demonstration and advanced human-robot interaction.

Queen Mary University of London

Queen Mary University of London leads on the development of novel 'soft manipulators', which can be inserted through narrow entry ports and can bend around obstacles to conduct inspections in hard-to-reach spaces. The team is also developing opto-mechanical robotic sensors which will support the high-level autonomous manipulation work being done by other partners.

Flexible Partnership Fund (FPF) partners

Partner and industry Partner:	Title of work:
University of Bristol (Magnox)	An integrated radiation mapping crawler for deployment in the Winfrith pipeline
University of Bristol (Rolls Royce)	Market analysis for applications of robotics and automation for in-service nuclear power stations
University of Bristol (Thales)	Approaches to safety critical certification for RAI systems
University of Bristol (Chernobyl)	Aerial radiation mapping
University of Plymouth	Robot teaming for collaborative terrain traversability assessment of nuclear environments
Southampton	Underwater sensors
Queen Mary University of London (Prof Kaspar Althoefer)	Electroadhesion for anchoring robots in challenging environments
University of Leeds (Dr Giorgio Locatelli)	Bringing robots to nuclear sites: best practice and guidelines to overcome the innovation "valley of death"
University of Edinburgh (Prof Tughrul Arslan)	Hardware overlay support for reliable reconfigurable computing in nuclear robots
BRL-UWE (Dr Alex Smith)	Tactile internet: Smart wireless communication for haptic teleoperation in nuclear decommissioning.
University of Lincoln (Manolis Chiou)	Haptic-guided shred control of mobile manipulation task
University of Lincoln (Ayse Kucukyilmaz)	CoRSA: Co-manipulated Training and Skill Assistance for Telemanipulation in Nuclear Settings.
University of Essex (Shoaib Ehsan)	RICE: Visual Place Recognition for Robotics in Extreme Environments
QMUL (Miles Hansard)	Analysis of cluttered and occluded scenes from millimetre wave RF data
Lancaster University (Prof James Taylor)	Motion Planning and Trajectory Generation for a Robot Assisted Laser Cutting Manipulator
University of Birmingham	Human-robot object hand-over path planning

Extreme Robotics Lab

UNIVERSITY OF BIRMINGHAM | EXTREME ROBOTICS LAB

The National Centre Director and Principle Investigator: Prof. Rustam Stolkin
NCNR Project manager: Peter Brewer

Focus (or foci) of the group for NCNR:

The University of Birmingham Extreme Robotics Lab has established one of the largest and best-equipped robotics research facilities in the UK. This comprises a 1,000m2 academic lab on campus, and a large rig-hall space at Birmingham Energy Innovation Centre containing large-scale heavy-duty manipulators.

The ERL team is known internationally as leaders in the application of advanced robotics to extreme environment industrial challenges. The team are particularly well known for their work on autonomous robotic manipulation driven by computer vision, however the research portfolio spans a wide range of core robotics and AI technologies that include:

- Robotic manipulation, including autonomous motion planning and control for grasping, cutting and other tool use.
- Remotely operating robot vehicles and mobile manipulators.
- Advanced computer vision, and other perception modalities such as tactile sensing.
- AI, machine learning and neural networks.
- Human-robot interaction, including haptic exoskeleton interfaces and virtual, augmented and mixed Reality.
- Human-AI collaboration for controlling remote robots, including: human-supervised autonomy, variable autonomy and shared control paradigms.
- Landmark demonstrations at high TRL on nuclear industry sites.
- Applications to other domains, including recycling and circular economy, disaster response and others.

“Significant advances are needed, beyond the technologies currently available, to develop robotic systems that can carry out complex tasks in hazardous environments, remote from human operators. In such cases situational awareness may be limited and communications difficult, requiring robots to have greater on-board intelligence and autonomous control capabilities. Novel sensors and advanced machine vision and perception will be needed for robots to navigate their environment and do useful work. High consequence, safety-critical interventions may still need a human to be in control, however, but these may be too complex for familiar forms of tele-operation, e.g. joystick. This creates an opportunity for novel approaches where operators and AI collaborate, in real time, to control remote machinery in very challenging environments.”
- Professor Rustam Stolkin

Contact: r.stolkin@bham.ac.uk,
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D1.1 - Autonomous vision-guided grasping

UNIVERSITY OF BIRMINGHAM | EXTREME ROBOTICS LAB

Brief description of functionality/utility:

Fully autonomous grasping of arbitrary objects from random self-occluding heaps - Currently the world's most robust, generalisable and computationally fast autonomous grasping algorithms.

Advanced robotics technologies for handling hazardous nuclear waste are essential for cleaning up legacy nuclear waste. The ERL has developed fully autonomous machines that are able to grasp arbitrary objects from random heaps, where one part of an object is occluded by another part. Currently the world's most robust, generalisable and computationally fast autonomous grasping algorithms. For this technology to work,

- No prior knowledge of the object's appearance or shape is needed.
- No machine learning or training data is needed.

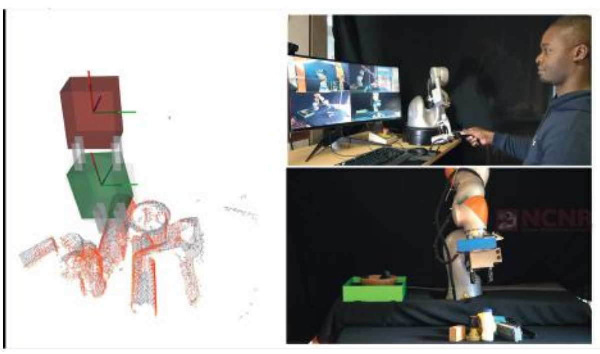
The shape of the object is acquired from partial datasets that have been obtained from the vision system, and is matched to the geometry of the robotic gripper and its fingers.

From a performance point of view (the speed of new grasps and reliability), this technology is second to none. The research team has ergonomically combined autonomous grasping with a haptic input device to enable a human operator to control the remote manipulator while being assisted by the AI.

These algorithms and control methods work with all types of robot arm and gripper. TRL 6+ (where the system adequacy has been validated in a simulated environment) has been demonstrated using large heavy-duty industrial manipulators on nuclear industry sites, under full nuclear safety and national security regulations.

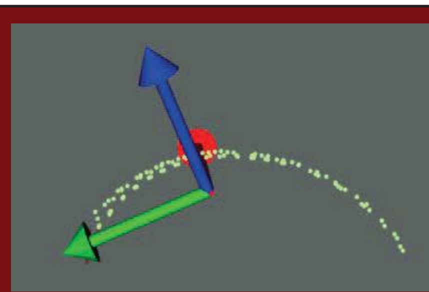
Arbitrary objects that are unknown to the robot, including deformable materials such as rubber gloves, hoses or cables, can be grasped from random, cluttered, self-occluding heaps.

- No machine learning is used, as we solve this purely as a 3D geometry problem with fully explainable, mathematically efficient methods. This may be more palatable to nuclear site operators than black-box learning based approaches.
- No training data is needed.
- The method thus extends to new objects, never seen before by the robot. In contrast, learning-based methods may struggle to extend to objects that greatly differ from those in the training dataset.



Link to demo video: www.NCNR.org.uk/bham/avgg

UNIVERSITY OF BIRMINGHAM | EXTREME ROBOTICS LAB



Brief description of functionality/utility:

ERL researchers have developed algorithms that allow a human operator to remotely control a robot as it autonomously cuts through contaminated metal. The operator uses a computer mouse to control the start and end points of the cutting tool path, with decisions being based on a 3D image of the object that has been captured by the robot and transmitted on a screen. The algorithm works even on metal objects that have an arbitrary shape.

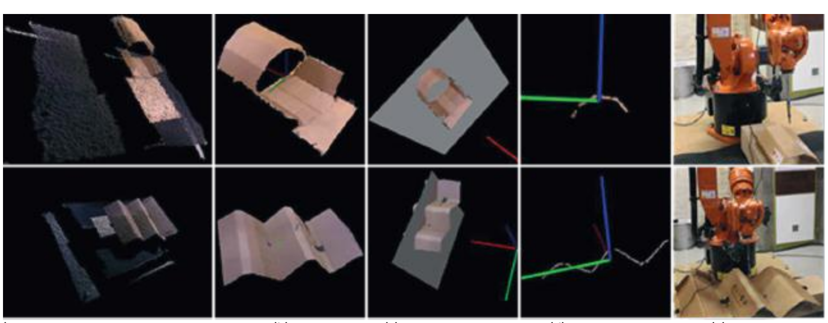
The cutting path can be automatically optimised to avoid obstacles on the surface. It can also be programmed so that disturbances or emergencies can be handled fast.

- The new algorithms work regardless of the type of robot or cutting tool adopted for the task.
- TRL 7 has been demonstrated in a live radioactive hot-cell environment at the Springfields nuclear site **- This is regarded internationally as currently world-leading in this domain. The autonomous cutting in an active cell remains unrepeated worldwide since our landmark demo with UK National Nuclear Lab.**

Decommissioning involves many cutting operations, in which arbitrarily shaped legacy structures and cell furniture must be dismantled. Conventional programming of robot motions involves standing near the robot while teaching a large number of tool positions which are then used as waypoints. This is only feasible in (say) manufacturing where exactly the same product is being assembled many times. It is not scalable in decommissioning scenarios where a new object, with new surface shape, may be encountered in each operation.

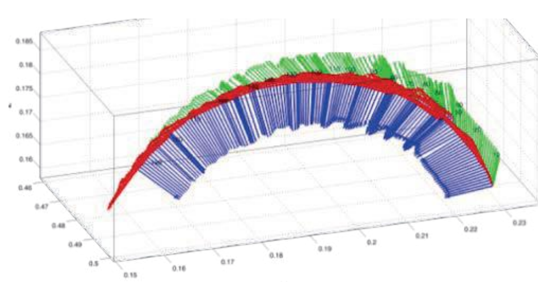
The Birmingham ERL team has demonstrated how:
Object surfaces, and their positions relative to the robot, can be accurately captured and modelled by advanced 3D computer vision systems. Advanced algorithms can automatically plan:

1) A correct trajectory for the cutting tool over the surface, maintaining the correct stand-off distance and orientation to the surface.
2) Trajectories for all joints of the robot, to deliver the tool along the cutting path, while avoiding obstacles and problematic robot configurations.



(a) (b) (c) (d) (e)

(a) The robot moves the camera to multiple viewpoints, and reconstructs 3D model of the scene.
(b) The AI automatically segments the foreground object from background points.
(c) The human operator selects a cutting plane using two mouse-clicks.
(d) The AI automatically selects the points along the surface to be cut, and plans a trajectory for the laser, including desired laser stand-off distance and automatically maintaining laser axis orthogonal to the local surface curvature throughout.
(e) The AI automatically plans a collision free trajectory of the robot's joints to deliver the laser along the cutting trajectory.

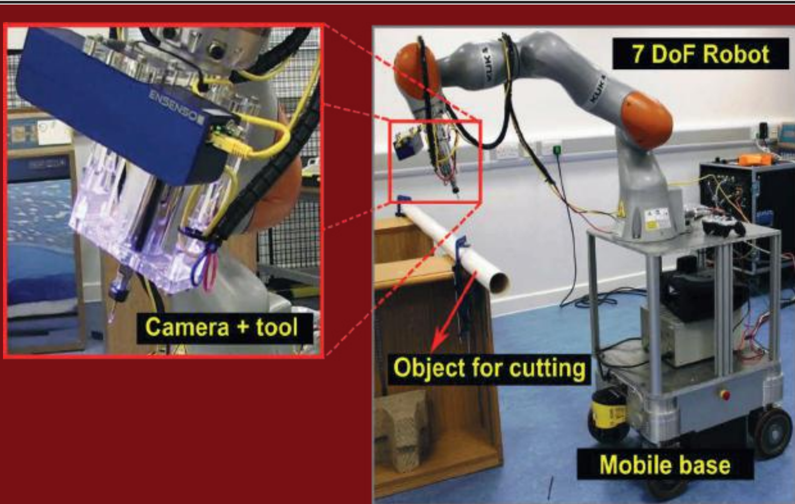


Link to demo video: www.NCNR.org.uk/bham/sarc

NCNR National Center for Nuclear Robotics

D1.3 - Advanced computer vision for characterisation, scene and object understanding:

UNIVERSITY OF BIRMINGHAM | EXTREME ROBOTICS LAB



Brief description of functionality/utility:

Mobile manipulation with vision-guided autonomous cutting of a pipe using rotary contact cutter. The arm behaves compliantly to respond dynamically to perturbing contact forces during cutting.

Link to demo video:
www.NCNR.org.uk/acv

Bristol Robotcs Lab

Lead Investigator: Manuel Giuliani

Focus (or foci) of the group for NCNR:

When it comes to making nuclear environments safe for humans, robot teleoperation – the ability for humans to remotely operate machines to physically interact with objects and environments – is key. To be effective, robot arms and end effectors must successfully navigate unknown spaces and interact with unknown objects, sending back dependable information to the human operator. All the while, the machine must remain safe for use.

The Bristol Robotics Lab has been tasked with analysing levels of robotic autonomy and control, and assessing how reliable robots are in their communication with human operators.

Topics investigated include:

- Levels of autonomy and variable levels of autonomy
- Enhanced remote viewing
- Human-robot interactions
- Robot teleoperation
- Reliable wireless communication

Prototypes developed for this project include:

- Mirrored teleoperation system with three levels of autonomy.
- Stereo remote viewing interface, including operator head tracking.
- A low-power, high-reliability, high-speed wireless communication interface for teleoperation.

Contact: manuel.giuliani@brl.ac.uk

D2.1 - Variable Autonomy control for mirrored teleoperation

brl
Bristol Robotics Laboratory

Brief description of functionality/utility:

A mirrored teleoperation setup for sorting waste, using two Franka Emika Panda Manipulators.

Three levels of autonomy have been established:

1. manual control with no feedback
2. manual control with virtual force fields for object avoidance
3. semi-autonomous mode with programmed movements

Smooth teleoperation using wireless communications has been developed together with Toshiba Telecommunications Research Lab.

TOSHIBA

Experiments have shown a reduction in cognitive loading for operators when using the semi-autonomous mode, with a small reduction in cognitive load when working with virtual force-fields. Software has been developed in a specific environment for the Panda arm, using a high-speed communication protocol developed especially for this task. The concept on the control is transferable to other remote robotic arm systems.
Currently at TRL 5, having been tested at small scale using industrial-relevant tasks and items for sorting.

Link to demo video:
www.NCNR.org.uk/brl/vamo

Bristol Robotics Laboratory

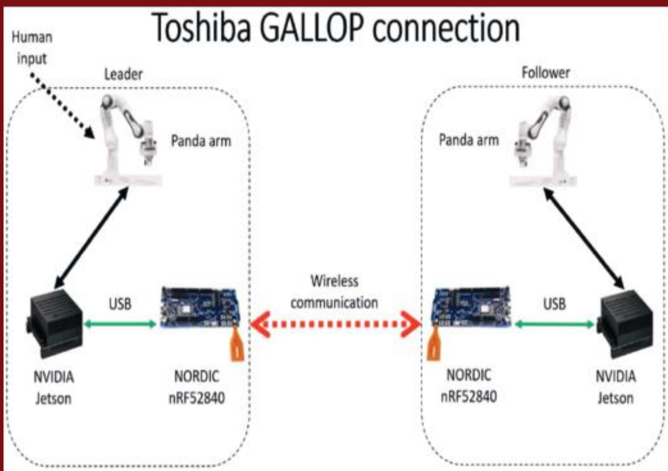
Brief description of functionality/utility:

Streaming video from a stereo camera mounted on the end effector of a robot arm in the remote scene to the Head-Mounted-Display (HMD) for the teleoperator.

- The teleoperator can move around and have different viewing angles/positions to maximise their situation awareness. The robot motion is synchronised with the operator's head motion.
- The current implementation is based on a Stereolab ZED camera and Franka Emika Panda arm, however, so long as similar equipment is used, with real-time video stream (camera) and real-time control (robot arm) the same algorithm can be implemented.
- The system is currently at TRL 5.

Link to demo video:
www.NCNR.org.uk/brl/mrsv

D4 - The NCNR-Toshiba project for reliable remote robotics control protocols



Bristol Research and Innovation Laboratory

Since its inception in 1998, the Bristol Research and Innovation Laboratory (BRIL) has been at the cutting edge of wireless and network systems research.

The NCNR-Toshiba project was carried out to investigate the use of wireless communication protocols for real time robot tele-operation. This is particularly important for scenarios where the use of a wired connection between the leader and follower robots is limited, difficult or impossible. Tele-operation was achieved by sending data packets between the leader and follower robots via different communication protocols. Joint positions and velocities of the leader robot were sent to the follower robot, while external torque of the follower robot was sent to the leader robot. Heuristic evaluation was carried out to compare the effectiveness of wired TCP/IP and wireless TCP/IP with Toshiba's low-power communication protocol called GALLOP. Send and receive times of data packets between the leader and follower robots were measured as well as position and velocity errors. Questionnaires were also completed by robotics experts who volunteered to take part in the evaluation. In the questionnaire, 5-point Likert scale ratings were used to request the experts' perceived smoothness, feeling of safety and responsiveness of the robot control for the different communication protocols examined.
Results showed that GALLOP is a reasonable replacement for wired connection, but more studies are needed to investigate the effect of radiation on wireless communication protocols examined. Journal and demo papers have been written on the tele-operation setup and results from the heuristic study.

Link to demo video:
www.NCNR.org.uk/toshiba

Lincoln Centre for Autonomous System - CAS

lncn.ac/ncnr

Lead Investigator: Amir Ghalamzan

Focus (or foci) of the group for NCNR:

Integrating autonomous mobile navigation with tele-operated manipulation for the purpose of cleaning up deposits outdoors

The University of Lincoln is known for producing groundbreaking research on long-term control systems for mobile robots working in difficult environments. In its work with the NCNR, the team at Lincoln has developed outdoor robots that can cope with rough terrain and autonomously map their environments. This allows the machines to be used efficiently and long term in dangerous environments, as they are capable of avoiding radiation sources or locating them more efficiently. Autonomous machines can also be used to deploy additional sensors or end effectors, such as robot arms, soft robotics or multirotor UAVs.

The Lincoln Centre for Autonomous Systems Research (L-CAS), the University of Lincoln's cross-disciplinary research group in robotics, specialises in technologies for perception, learning, decision-making, control and interaction in autonomous systems, especially those involving mobile manipulators. It also excels at integrating these capabilities in application domains including agriculture, nuclear robotics and space robotics, i.e., applications of robots in extreme environments. Among NCNR, L-CAS participates in a large number of collaborative research projects with other academic and industry partners, funded by the UK Research Councils, Innovate UK and Horizon 2020, among others. For instance, L-CAS is leading the £6.9m EPSRC Centre for Doctoral Training in Agri-Food Robotics, with the Universities of Cambridge and East Anglia, and co-leads a £6.3m award from the UK Government's Expanding Excellence in England (E3) Fund to create Lincoln Agri-Robotics, a global centre of excellence for agricultural robotics, in collaboration with the Lincoln Institute for Agri-Food Technology. L-CAS is one of the big robotics labs in the UK, a member of UKRAS and euRobotics.

UNIVERSITY OF LINCOLN

Brief description of functionality/utility:

This project set out to show that a mobile manipulator remotely controlled by a human operator could be tasked with removing dangerous items from a given area. The potential applications for a remote mobile manipulator extend beyond nuclear decommissioning tasks to any object-retrieval task at long distance.

To demonstrate the effectiveness of it's system, the team instructed a human operator to control both the mobile base and the robotic arm in various ways, using a web interface and a second robot arm acting as follower. The robot navigated autonomously through closed-loop teleoperation upon identification of the target area. Haptic-feedback teleoperation was used to retrieve items on the mobile platform. There remained the additional option of deploying an eversion robot for confined spaces.

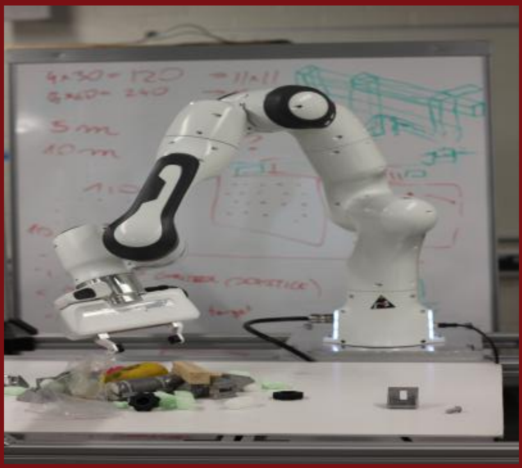
The demo was performed while using two Franka-Emika arms and a Thorvald robot from Saga robotics, which had been extended with a custom frame for supporting one of the arms.

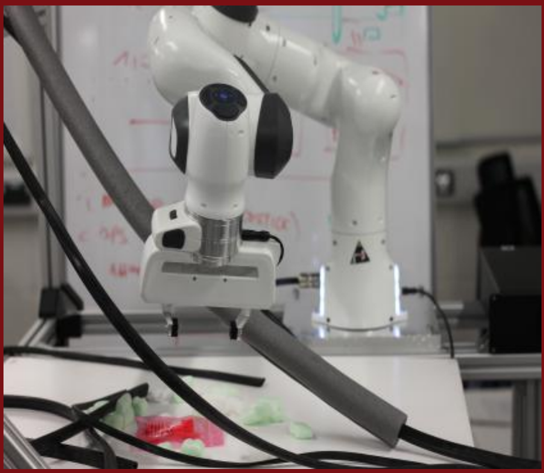
The objective of this demo is to show a mobile manipulator remotely controlled by a human operator to clean a specific area out of dangerous items. The human operator is located somewhere else at distance and controls both the mobile base and the robotic arm in various ways, through a web interface and a second robot arm acting as leader, respectively. In this way, space can be decontaminated without putting the operator at risk. The application can be useful not only for nuclear decommissioning tasks but for any object-retrieval task at long distance (e.g., over the network. The demo is performed while using two Franka-Emika arms and a Thorvald robot from Saga robotics, which has been extended with a custom frame for supporting one of the arms.

Upon identification of target area, the mobile platform robot can navigate there autonomously to deploy a mobile manipulator using closed-loop haptic teleoperation to retrieve an item or interact with the environment.

Link to demo video:
www.NCNR.org.uk/lincoln/omm

UNIVERSITY OF LINCOLN





Brief description of functionality/utility:

When grasping and manipulating dangerous and potentially fragile materials, it is vital for a robot's contact forces to be regulated with high precision: too much force and the material might rupture. The team at Lincoln set out to use the dexterity of the human hand to control the contact forces of remote robotic hands. For this project, bilateral teleoperation was achieved using Franka Emika Panda Arms. (2 arms!

The torque-controlled robotic arms were programmed to generate feedback forces such
that the machine would mimic a haptic device and enhance the user experience of the human operator while performing a teleoperation task.

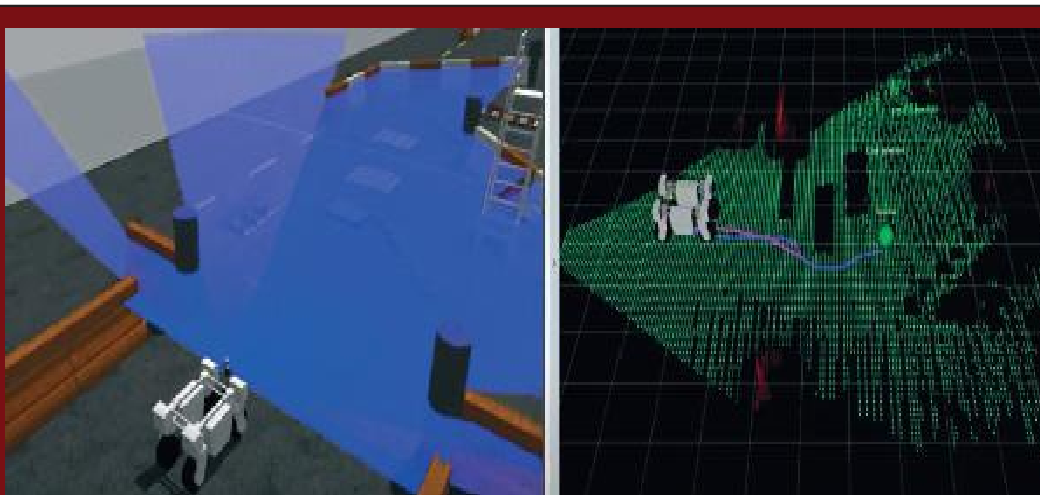
A method was developed to incorporate robot trajectories learned from human demonstrations and dynamically adjust the level of robotic assistance based on how closely the detected intentions matched these trajectories.

Another method was developed to enable real-time control with less communication latency. This was tested and verified for long-distance teleoperation tasks.

Link to demo video:
www.NCNR.org.uk/lincoln/fgt

D3.3 - Radiation mapping

UNIVERSITY OF LINCOLN



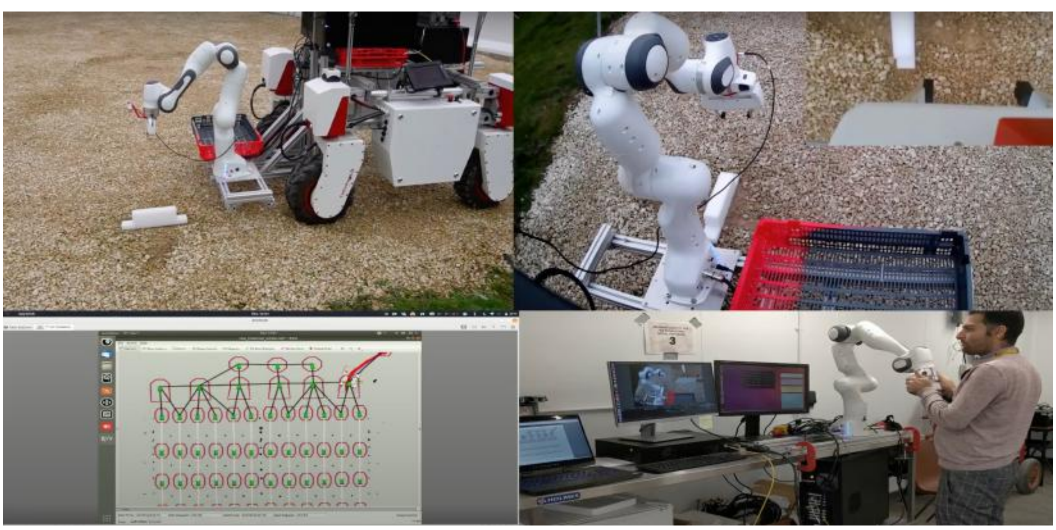
Brief description of functionality/utility:

There are obvious challenges to surveying an outdoor site remotely to reveal radiation sources and localise them autonomously. This project set out to improve existing solutions. The team used a wheeled robot that could autonomously traverse challenging terrains. A probabilistic radiation map was incrementally built, and sensing points were automatically chosen to drive the autonomous exploration of the robot.

A hybrid digital twin-real-world system was deployed to facilitate experimentation with simulated radiation sources in controlled positions, while researchers tested navigation and movement behaviours in the real world under realistic conditions.

Robot navigation was performed through the use of a topological map: a graph-based representation that exploits the structure of the environment. The robot path planning was performed by Next-Best-Sense, a framework for combining multiple criteria and expressing the preference of one above others. Kriging method (also known as Gaussian Process regressor was used for interpolating sensor readings and building two maps (mean and covariance of where the radiation sources were located.

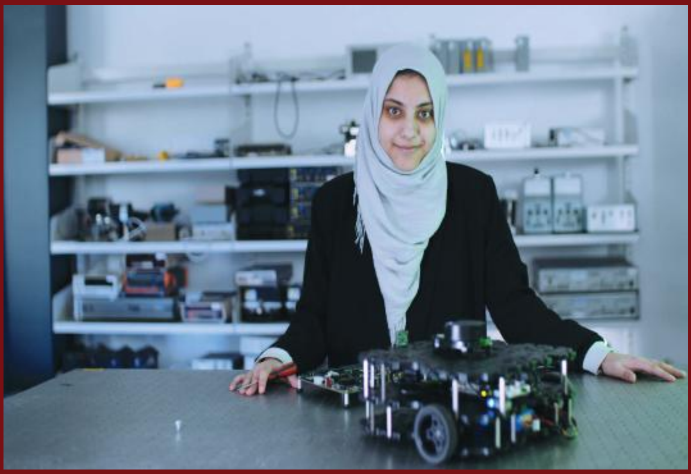
Link to demo video:
www.NCNR.org.uk/lincoln/rm



Embedded and Intelligent Systems Laboratory

Lead Investigator: Prof. Klaus McDonald-Maier, Dr Shoaib Ehsan & Dr Xiaojun Zhai

University of Essex



Focus (or foci) of the group for NCNR:

For its work with the NCNR, the University of Essex has focused on measuring and modeling the effects of radiation on the sensors and hardware used in robotics. It has also investigated how firmware and software are affected.

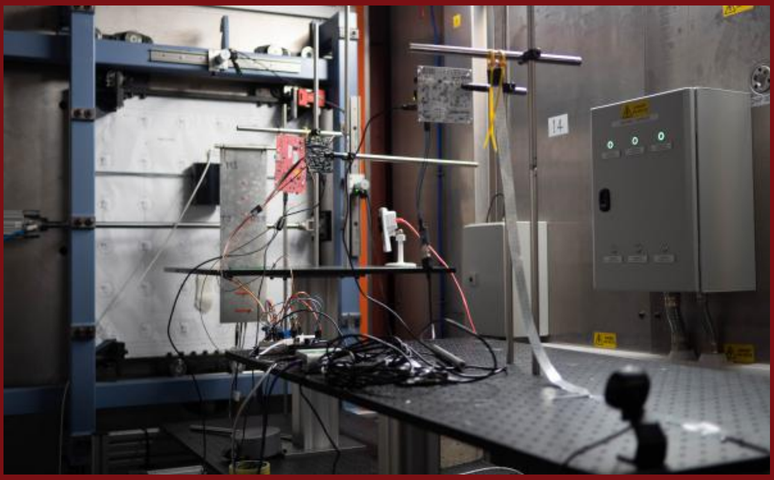
The team measured radiation effects on a number of readily available cameras, sensors and control electronics to identify how these components can be used effectively in radioactive environments. Using equipment that is easy to come by can reduce the cost of robotics hardware and improve the lifespan of what will become consumable equipment. The degradation models produced in Essex can also be used by high-level perception algorithms that filter, or compensate for, the noise and degradation on sensors and cameras.

The novel systems developed allow firmware, operating systems and hardware to physically reallocate resources to unaffected areas. This maximises the lifetime and reliability of mission-critical remote equipment and also allows detailed remote monitoring of the hardware and software at a very low system level.

For its NCNR work, Essex has also developed reconfigurable embedded platforms supporting a variety of AI and machine-learning edge computing models. The team has also made significant contributions to novel visual place recognition methods for challenging environments.

Contact: kdm@essex.ac.uk, sehsan@essex.ac.uk and xzhai@essex.ac.uk

University of Essex



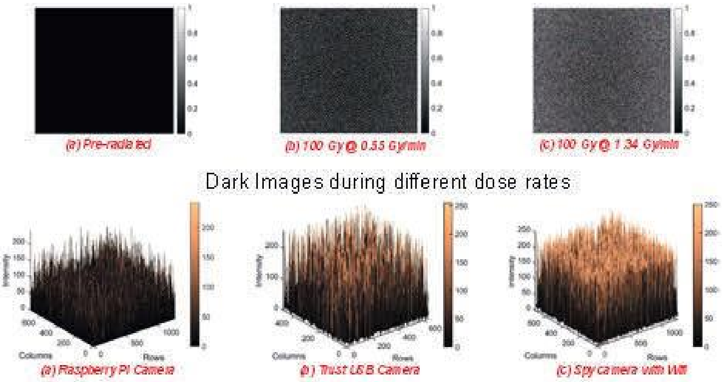
Brief description of functionality/utility:

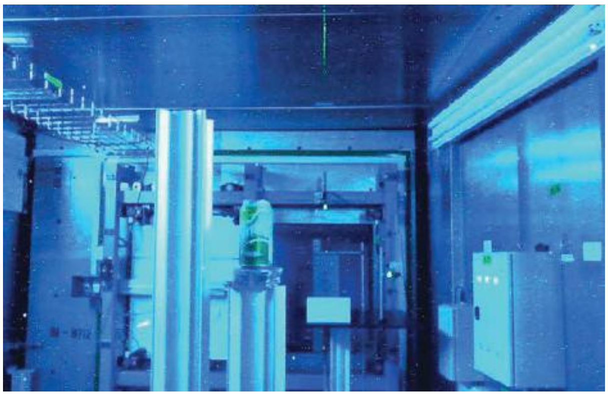
It is essential for robotic sensors and cameras to be reliable in the information they transmit from environments affected by radiation. It is also important for human operators to know when a sensor is failing, and how to compensate for degradation when it happens.

For this project, the Essex team tested a range of highly available sensors. They measured and modelled the effects of radiation on sensors and systems for neutron and
gamma radiation. Radiation effects were measured and modelled for:

- Robots and off-the-shelf sensors (e.g. cameras)
- Novel sensor technologies
- General purpose embedded systems
- Robot and sensor communications
- Specialised system-on-chip units

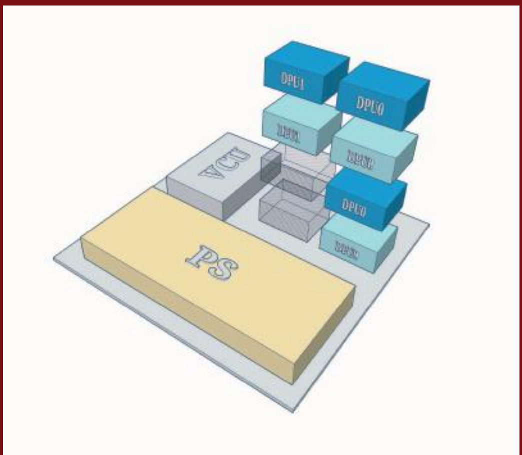
In addition, the team built machine-learning models to predict how long a sensor/robot/processor would last. They also identified the critical point for system failure. Their noise/degradation models can be fed to high-level perception algorithms.

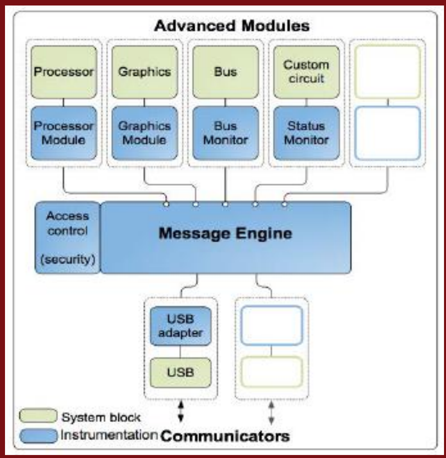


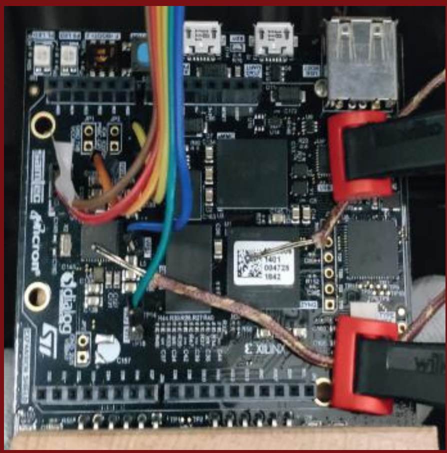


Link to demo video:
www.NCNR.org.uk/essex/rdm

University of Essex







Brief description of functionality/utility:

Self-healing radiation hardening design

There are obvious advantages to designing electronic components and circuits that are resistant to damage or malfunction triggered by exposure to high levels of radiation. The team at Essex has focused on self-healing designs that allow damaged components to be updated in real time, thereby maximising a robot's lifespan and reliability.

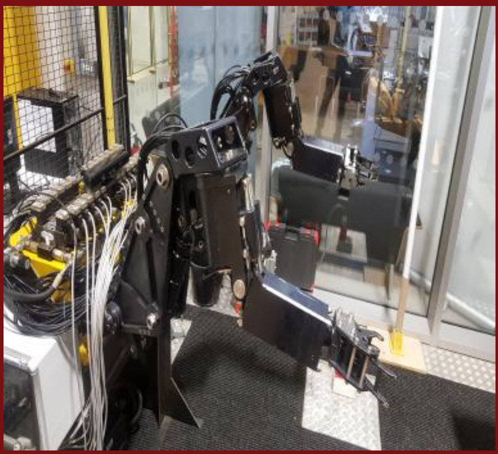
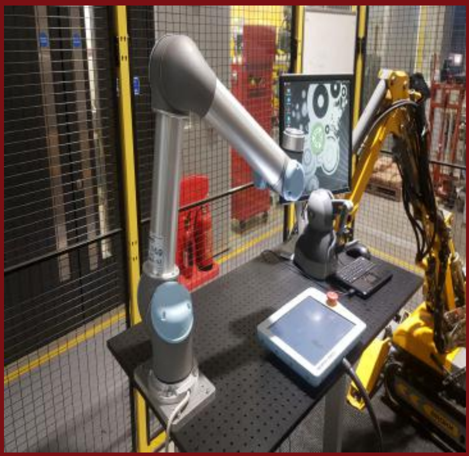
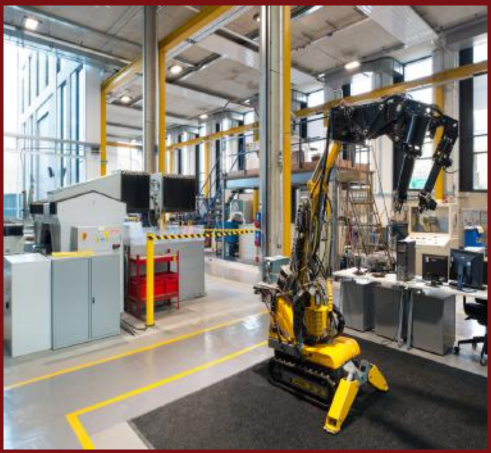
The novel designs allow:

- Adaptation of hardware and operating systems
- Self-healing dynamic recovery via reconfiguration
- Cross-layer resilience across system hardware and software
- The use of commodity processors and systems with improved performance
- Seamless real-time reconfigurable regions for updating the damaged blocks
- Remote monitoring and assessment of hardware/software

Link to demo video:
www.NCNR.org.uk/essex/rred

Nuclear Science & Engineering group

Lead Investigator: Prof. James Taylor
Contact: c.taylor@lancaster.ac.uk (please CC a.montazeri@lancaster.ac.uk)

Focus (or foci) of the group for NCNR:

Robots involved in nuclear operations often operate in conditions that are less than optimal. As a result of radiation, machines can deteriorate, they can return incomplete information from their remote locations, and they can be governed by nonlinear systems that yield data which appears chaotic or unpredictable. Lancaster is involved in developing nonlinear robust and adaptive algorithms designed to improve the modelling and control of robots operating with such uncertain parameters.

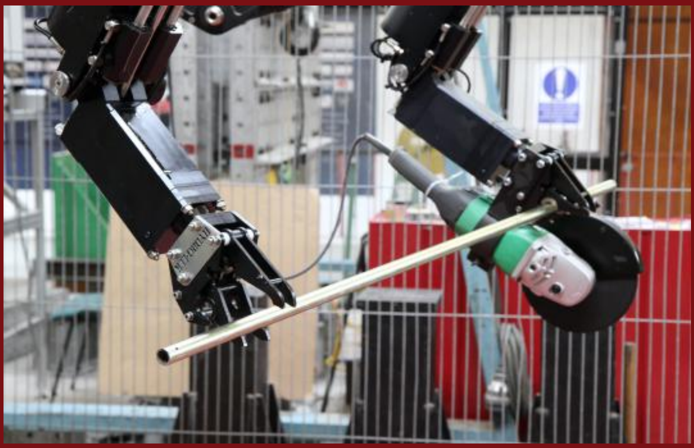
Algorithm development falls broadly into two main areas: mobility and navigation, and grasping manipulation. Laboratory prototypes developed by the group include:

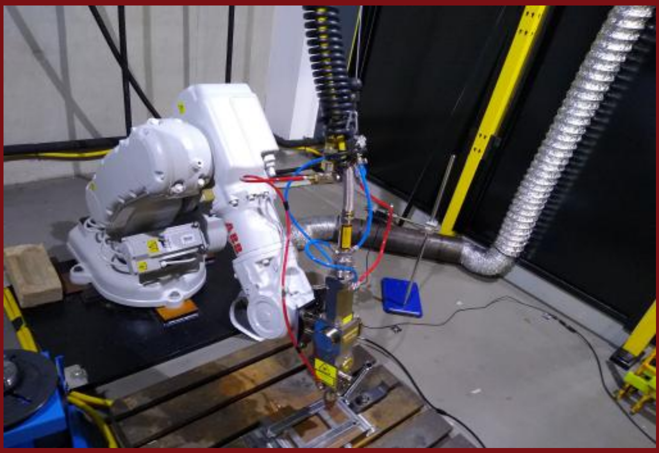
- Heavy-duty hydraulic manipulator control systems, with cutting that uses a reciprocating saw
- Adaptive control of a four-rotor unmanned aerial vehicle (i.e. a drone)

https://www.lancaster.ac.uk/engineering/research/nuclear/

D6.1 -Resilient navigation and adaptive control of underactuated robots:

Lancaster University





Brief description of functionality/utility:

The Lancaster team has developed a system that can be paired with a drone to accurately locate and map a contaminated area when large external disturbances are experienced, for instance during bad weather.

The system uses a cascaded two-stage modified fast simultaneous localisation and mapping system (SLAM). The technology was developed for resilient and autonomous navigation by a single drone in an unknown and environment where GPS does not work.

This new navigation system allows the robot to operate reliably over a long period of time when it is sent to a sensory degraded environment, such as a highly contaminated radioactive environment. It has been evaluated and tested in a realistic simulation environment using the ROS platform (TRL 2), and implemented on an open-architecture drone system (designed and built fully at Lancaster University) for laboratory testing (TRL 3). Preliminary work to extend the results to cooperative robots is ongoing with the support of the National Nuclear Lab.

System key points include:

- High-performance manipulator positioning controllers based on data-driven, stochastic state-dependent parameter models.
- Addresses uncertainty arising from sensor degradation, material inconsistencies, device nonlinearities, etc.
- Illustrative case study – dual manipulator, semi-autonomous pipe cutting with reciprocating saw.
- Suite of widely applicable algorithms for adaptive control, inverse kinematics, planning and robot parameter estimation.
- Additional illustrative case study
    - identification and control of aerial vehicles with unknown inertia parameters.

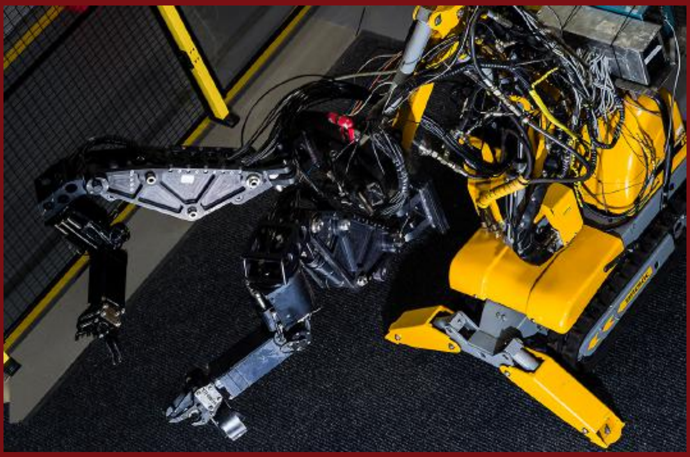
Link to demo video:
www.NCNR.org.uk/lancaster/rcur

D6.2 An integrated design procedure and high-performance robust control algorithm for robotic manipulators with

Nuclear Science & Engineering group

Lead Investigator: Prof. James Taylor
Contact: c.taylor@lancaster.ac.uk (please CC a.montazeri@lancaster.ac.uk)

Lancaster University



Brief description of functionality/utility:

This project focused on developing an integrated design procedure and high-performance robust control algorithm for robotic manipulators with uncertain and nonlinear dynamics.

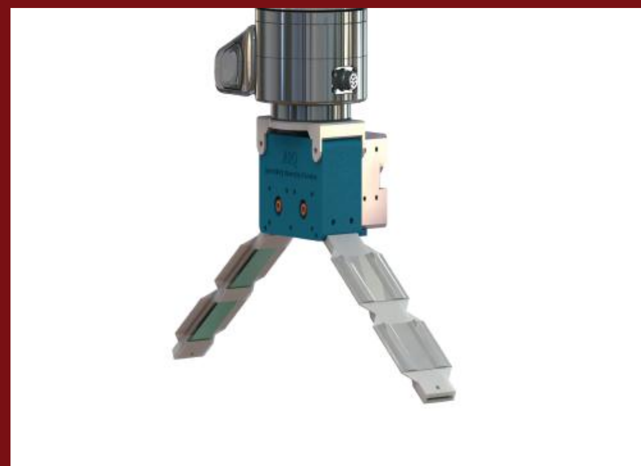
- An integrated, state-dependent design procedure for input signal calibration, nonlinear system identification and robust adaptive control system design.
- The technology has been developed by the NCNR for either tele-operation (low-level control of joint angle for faster, smoother movement) or semi-autonomous control (including computer vision and optimisation module for decision-making) of manipulators.
- Straightforward recalibration when dynamic characteristics of the robot have changed or the actuators have deteriorated due to age or contamination.
- This technology has been developed and evaluated within the NCNR for heavy duty hydraulic manipulators, as relevant to nuclear decommissioning (TRL3: laboratory evaluation for dual manipulator BROKK system with semi-autonomous cutting of aluminium pipes) and civil construction.
  (TRL 5), and other industries that sometimes require high power-to-weight ratios.
- The underlying technology is based on state-dependent parameter models in which the model coefficients are identified as functions of measured variables, hence the algorithms developed are also applicable to other types of robotic actuators (pneumatic, electrical) and nonlinear control problems more generally.

Link to demo video:
www.NCNR.org.uk/lancaster/idp

D7 - Queen Mary University London

Team Robotix, Centre for Advanced Robotics

Lead Investigator: Kaspar Althoefer
Contact: Ivan Vitanov i.vitanov@qmul.ac.uk



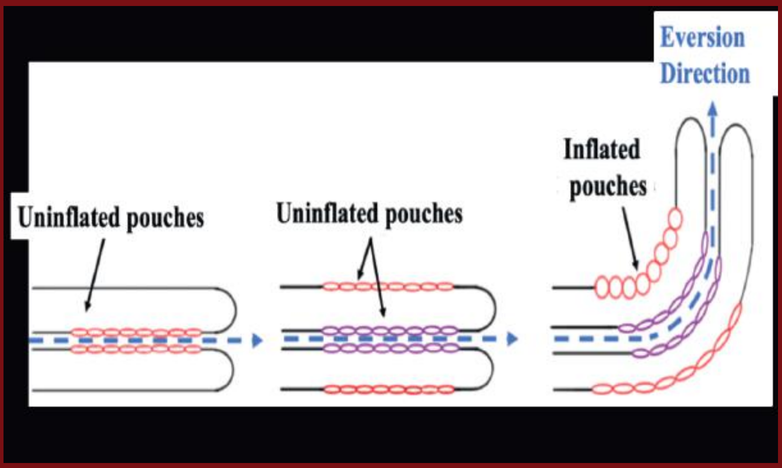
Focus (or foci) of the group for NCNR:

Dexterity is important when robots are sent to remote locations to handle nuclear waste. The team at Queen Mary focused on developing soft robotics, including eversion robots (where the robot can turn inside out) to enable smart machines to access to extreme environments and deliver essential information to their operators.

Project achievements include:

- Soft robotics, such as soft fabric-based inflatable grippers, to handle objects of different shapes
- Tactile perception, especially using nuclear radiation-immune optics methods, for integration with robotic grippers and hands
- Camera-based intelligent object detection
- Visuo-tactile perception for autonomous robotic manipulation (e.g. grasping)
- Computer vision and machine learning
- Sensor delivery with reinforcement learning-based mapless navigation in unseen environments
- Single picture-based policy learning for reaching objects
- Autonomous robotic grasping and manipulation based on visual and tactile input
- Software framework to ease integration of software and hardware components
- Teleoperation of collaborative robot and dexterous robot hands with haptic feedback
- Human-robot interaction for virtual reality (VR) interfaces
- Haptic feedback systems
- Soft grippers with variable stiffness hinges for dexterous grasping of objects
- Electro-adhesive (EA) pads for anchoring on objects, to assist grasping using soft gripper

Queen Mary University of London



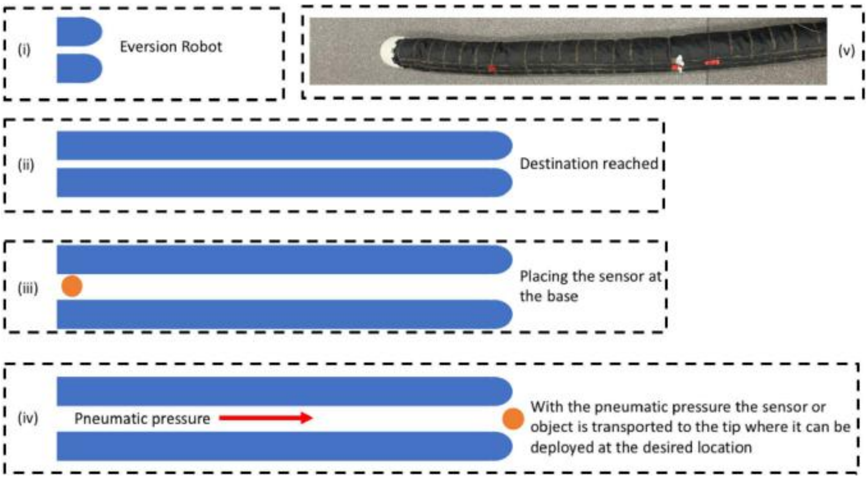
Brief description of functionality/utility:

Gaining access to otherwise inaccessible spaces through narrow openings is essential when it comes to cleaning up nuclear wate. The team at Queen Mary has made significant progress in this area, by:

- Developing a system to move robots by up to 20 metres in realistic environments
- Increasing the manoeuvrability of robots using integrated actuation pouches
- Developing the remote operation of vision sensors
- Developing initial robot models and control strategies to assist human teleoperators

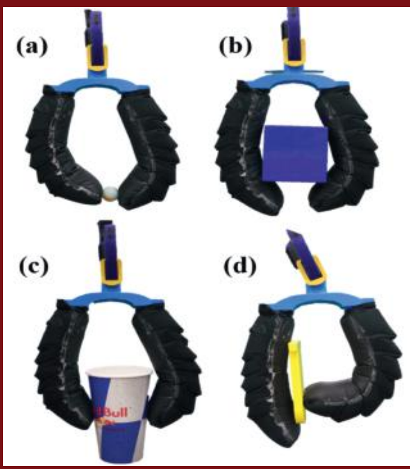
In terms of accessibility and manoeuvrability, robot performance has proven state-of-the-art using this technology. User-friendly and intuitive teleoperation software is now being developed to enable a human operator to steer and control the remote robot. The interface to a mobile robot platform (Lincoln) is also being developed.

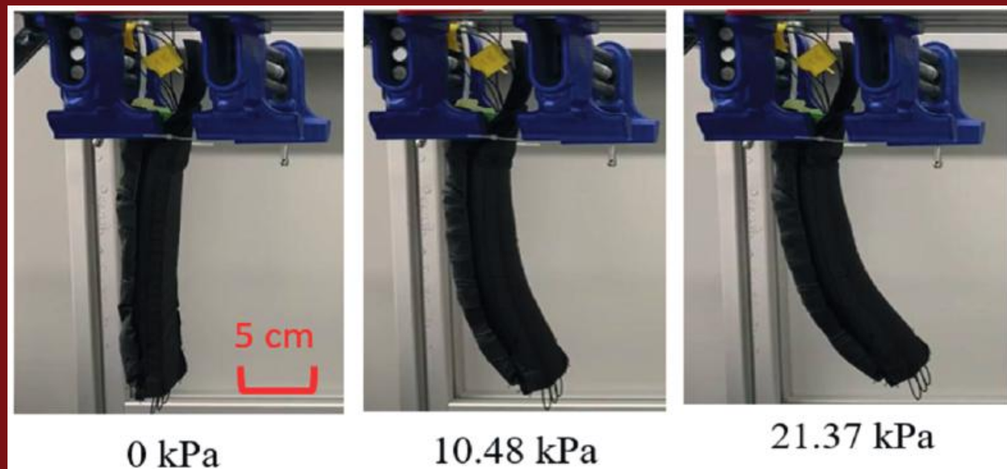
The hardware and software developments of this project are at TRL3+.



Link to demo video:
www.NCNR.org.uk/qmul/ais

Queen Mary
University of London

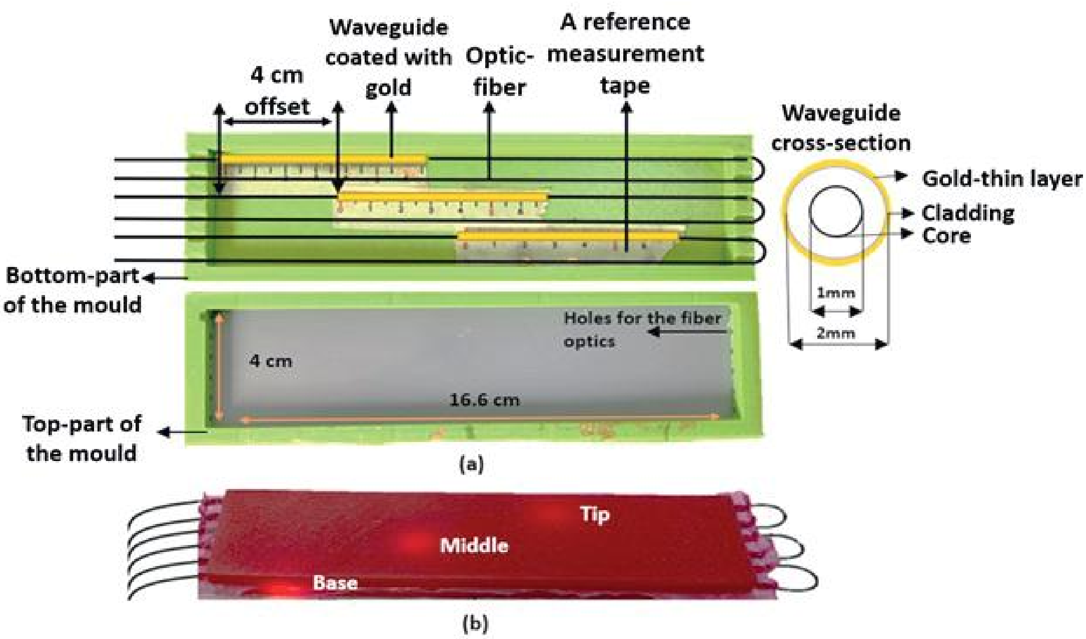




Brief description of functionality/utility:

Researchers at Queen Mary's have found a way to inflate fabric-based robot fingers and to combine these fingers to form resilient grippers. Fingers are made of airtight structures and are pleated on one side. As a result, they bend when air pressure is applied. Maximum payload achieved: 10Kg.
The team has also developed grippers that are able to grasp a range of differently shaped objects that are unknown to the robot. Very little control or navigation strategies are needed to achieve a reliable grasp.

An interface to attach grippers with Franka and UR5 robots is currently being developed, and tactile sensing is being integrated. This project has reached TRL 3, meaning it has been demonstrated in a lab environment.



Link to demo video:
www.NCNR.org.uk/qmul/ifgd

NCNR
National Center for Nuclear Robotics

D8 - Bristol University

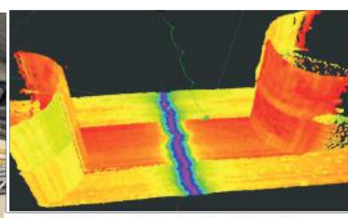
Lead Investigator: Tom Scott

University of BRISTOL

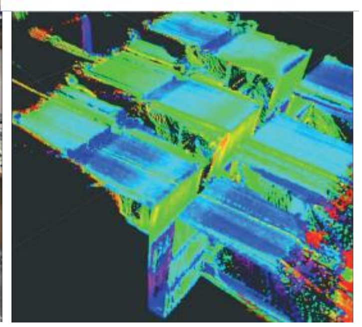
Focus (or foci) of the group for NCNR:

The University of Bristol has expertise in the development, deployment and analysis of radiation sensors for characterisation and mapping of contaminated environments, both indoors and outdoors. Work has included drone surveys at Fukushima and Chernobyl. A suite of sensors has also been developed for radioactive waste storage buildings at Sellafield.

D8.1 – ’suitcase’ multi-sensor inspection system.

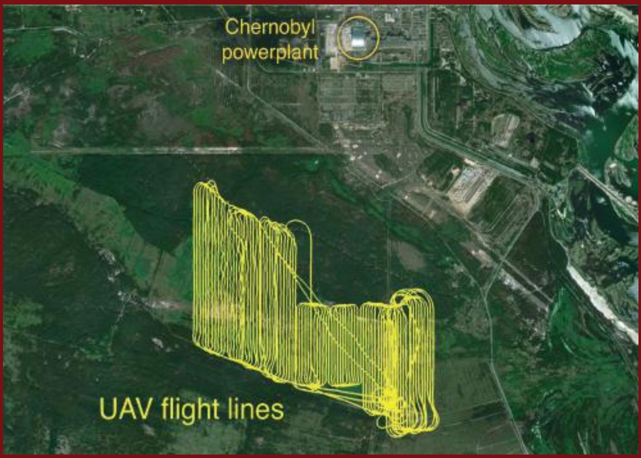


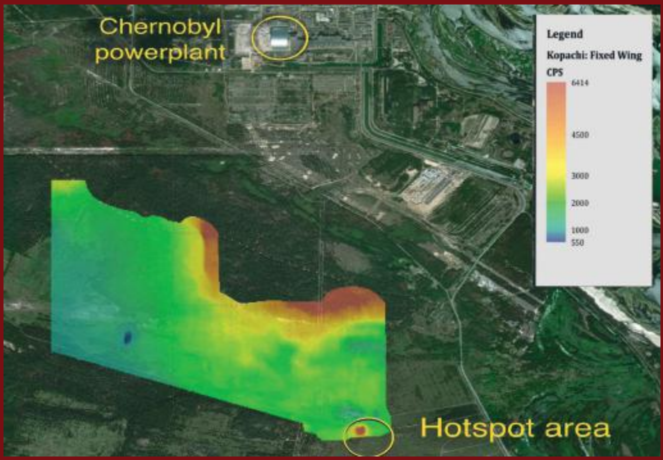
Live 3D data scanning output from the suitcase



Over 18 months of work between the Bristol NCNR team and Sellafield has culminated in a successful 'white' demonstration of the integrated ’suitcase’ inspection system.
Designed for deployment in ILW stores at Sellafield via the overhead gantry crane systems, this multi-sensor unit can map radiation, 3D structures and environmental data all in real time.
Phase 2 is now complete. Phase 3 will include active deployment at Sellafield and a serial production run of up to 20 units.

University of BRISTOL





Brief description of functionality/utility:

A methodology has been developed for rapidly surveying large areas. First, fixed wing drones are used to conduct a low-resolution (higher altitude) survey of a large area. Hotspots and areas of interest are then scanned at a higher resolution by multi-rotor drones, at lower altitudes. The radiation data can be used to annotate 3D models of the terrain. These models are built from camera images from the drones. NCNR has funded the University of Bristol team to carry out pioneering drone surveys at the Fukushima and Chernobyl disaster sites. Similar approaches have been used to map the radiation on waste objects (e.g. spent fuel rod skips) by deploying radiation sensors on a robot arm which moves the sensors around the objects, annotating a 3D object model with radiation data.


The M600 UAV conducts an automated grid survey at an altitude of 30m and then 15m to obtain a higher spatial resolution radiation map of the hotspot area to pin-point its exact location.

Link to demo video:
www.NCNR.org.uk/bristol/rdrm

Mistry Group

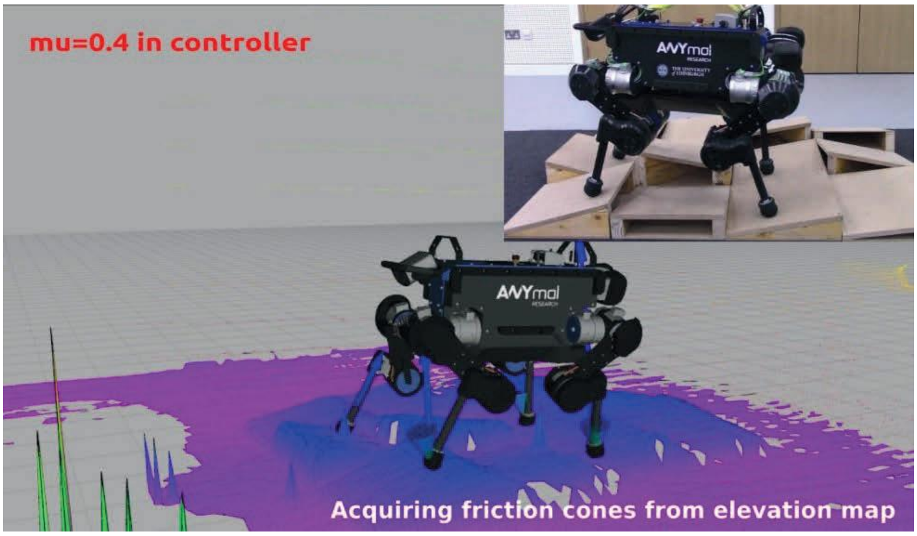
Lead Investigator:Professor Michael Mistry

Focus (or foci) of the group for NCNR:

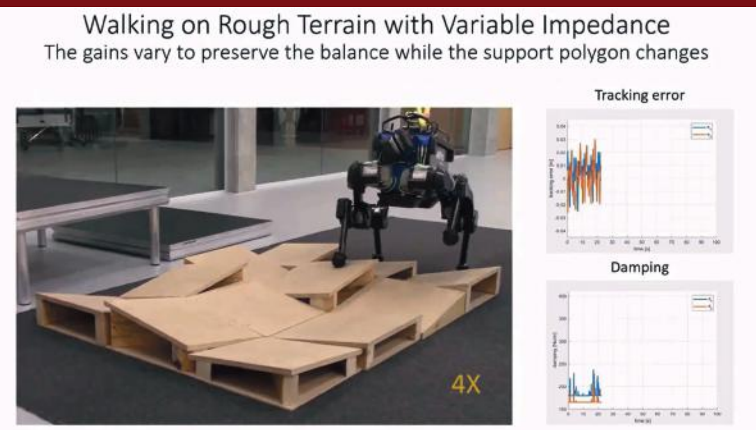
The University of Edinburgh is leading the way in systems designed to control walking robots. The challenge is to create robot legs that can autonomously adapt to surfaces that are neither straight nor flat (for instance, bumpy paths and entrances to contaminated areas) in unknown environments. As part of this work, the group has designed legs that are able to interact with, and change, their environment (for instance, by performing manipulation tasks). They have also developed tactile leg sensors that can build maps to deepen human understanding of a robot's extreme environment.

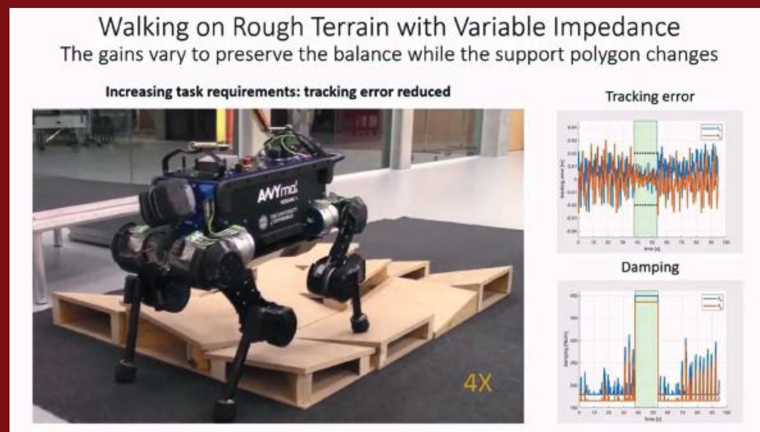
The team's systems have been tested with information delays of up to 1 second and a communication bandwidth as low as 10Hz. The system's teleoperation architecture allows two human operators to cooperate virtually. This is possible thanks to the system's ability to switch online between admittance and impedance behaviours.

contact: michael.mistry@ed.ac.uk



THE UNIVERSITY of EDINBURGH





Brief description of functionality/utility:

Research in haptic exploration by the Edinburgh team has focused on safe teleoperation in difficult circumstances, such as when robots are sent to unknown or challenging environments. One aim has been to maintain robust communication between operator and machine even when there are delays in communication, or communication bandwidths are low.

Other objectives include:

- Teleoperation via robot legs
- Increase scalability due to decoupled stability between the arms
- Quadruped locomotion and interaction in extreme environments
- Dynamics model-learning for safe control
- Use of leg actuators as end effectors (arms)
- Flexibility of exploiting the body to perform manipulation tasks

Link to demo video:
www.NCNR.or.uk/edinburgh/hedt

Closing summary from professor Rustam Stolkin - NCNR Director

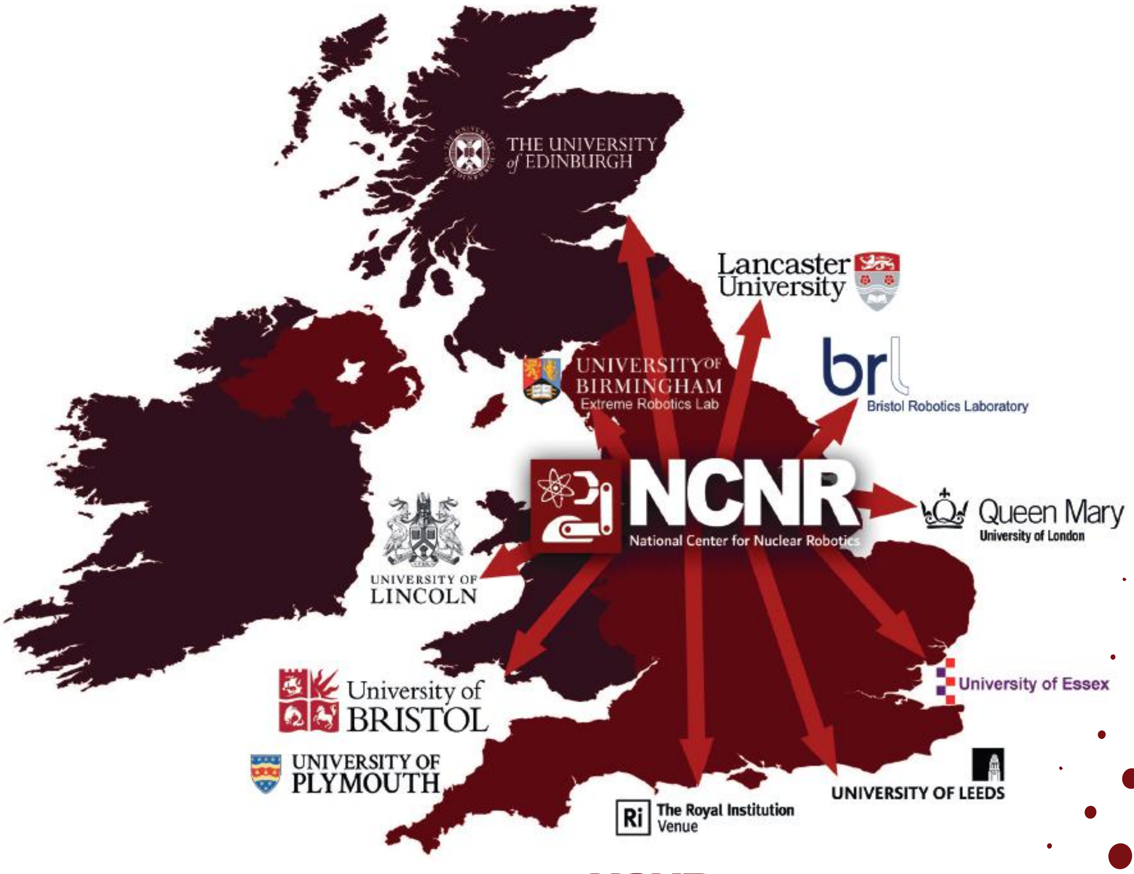
"In four and a half years of funded activity, the National Centre for Nuclear Robotics has delivered arguably the most productive project in the history of UK robotics research. As a result of this activity, over 400 novel, peer-reviewed scientific papers have been published, and high TRL has been delivered (following demonstrations and deployments on prominent nuclear sites in the UK and internationally). In addition, NCNR researchers have liaised with national and international nuclear agencies worldwide, and further collaborations have been forged between NCNR members and researchers from non-nuclear industries. Outreach work resulting has impacted school children and the wider public, and training programmes have boosted the work prospects of early-career roboticists.

This work has established the UK as a global leader in the development of advanced robotics for nuclear and other hazardous environments, placing UK in a strong position as the expanding decommissioning market opens up to these highly disruptive technologies. The consortium will continue to liaise and function as a body moving forward, providing a key national resource of expertise for nuclear and other industries seeking advice or assistance on advanced robotics."

- **Professor Rustam Stolkin** - NCNR Director

"**We would especially like to thank National Nuclear Laboratory Ltd, Sellafield Ltd, KUKA UK, and the numerous other companies, small and large, nationally and internationally, that have provided an impressive level of commitment in terms of active collaboration, access to key industry sites and facilities, direct funding and in-kind support. We also thank the EPSRC and the Industrial Strategy Challenge Fund for providing the grant resource to enable the academics to undertake this work**"

- **Mr Peter Brewer** - NCNR Project Manager



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