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Balancing the Impact of City Infrastructure Engineering on Natural Systems Using Robots

MID-TERM REPORT 2018

"Working on this exciting project provides great opportunities to collaborate with other disciplines and institutes, which will suit my future in academia."

Mehran Eskandari Torbaghan, Research Fellow, University of Birmingham

WELCOME

Robots fixing potholes? Drones replacing lightbulbs? Automata repairing pipes?

Welcome to the Engineering and Physical Science Research Council (EPSRC) Grand Challenge project "Balancing the Impact of City Infrastructure Engineering on Natural Systems Using Robots". Our aim is to help develop the self-repairing cities of the future.

Over the last two years, we have brought together a world-class, multidisciplinary team to design autonomous systems – robots – that can help cities to heal themselves, avoiding intrusive and disruptive streetworks, preventing waste of material, reducing carbon emissions and making infrastructure a safer place to work.

This is not just about technology. We understand concerns about 'robots taking our jobs' and so the team includes social and environmental scientists, working out how deploying autonomous systems would affect the people, the economy and the environment in our cities. We are working towards a win-win situation where better jobs are created, taxpayers' money is used more efficiently and our air, water and wildlife are protected.

We've produced this brochure to help you learn about our team, research motivations, demonstration projects, public engagement, and future plans. It is exciting for me to share with you what we have achieved and how these achievements will shape the future, moving towards our "Grand Challenge" aim of zero disruption from streetworks by 2050.

Achieving our aim will require more collaboration with other academics, industry, media and the public, both across the UK and from further afield. If you think you could help us make the cities of tomorrow safer, greener and less disrupted places for everyone to live, work and thrive, contact me or one of the team to get involved.

P. Purnell

Prof Phil Purnell

Achievements so far:

- A pipe inspection robot that can operate autonomously in a 1-inch pipe, with wireless power transfer for charging.
- A drone with a 3D polymer printer that can provides customised plastic 'patches' for cracks in roads and the technology to 3D printed asphalt that performs better than traditional asphalt.
- A drone system that can control and co-ordinate the movements of trucks on a construction site.
- A drone that can autonomously land on a lamppost and perform tasks using an attached manipulator arm.
- Designed and started a 'horizon scanning' exercise to determine the likely ecological effect of operating robots in the natural environment.
- Simulated how simple, cheap 'disposable' robots with control systems based on the brains of nematode worms can efficiently locate potholes or other defects in roads.

PROJECT OVERVIEW

Between now and 2050, the United Nations' Department of Economic and Social Affairs estimates that 86% of the UK population will live in cities.

This is part of a worldwide trend, as cities and mega-cities become home for most of the world's population. Quality of life in cities is critically dependent on infrastructure systems that provide water, gas, electricity, transport etc. and the social systems that own, regulate and are supplied by them. These interact with the natural systems that provide clean air, biodiversity, waste disposal, recycling, and other associated ecosystem services.

The quality of life for future citizens will be critically affected by the engineering innovations and policy decisions of the next ten years that will shape these technical, natural and social systems.

Today's methods of updating infrastructure are resource- and labour-intensive. Much infrastructure is either buried or elevated along our roads and streets. Heavy vehicles in cities produce socially and environmentally damaging air, noise and waste pollution; earth excavation causes transport delays and displaces animal and plant life; maintaining systems 'at height' (lighting, gantries) involves multiple health and safety challenges. Yet often the basic physical demands of individual maintenance tasks are quite small (requiring few parts, simple tools and low forces). It is the involvement of humans that makes them expensive, time consuming and disruptive.

A 4-tonne vehicle might carry 3 people several tens of km just to replace systems weighing less than 30 g (e.g. a cherry-picker to change a street light); we dig metre-scale holes in roads to repair millimetre-scale defects in water or gas pipes; humans work at height in dangerous locations (e.g. motorways) to perform simple visual inspections. We are using sledgehammers to crack nuts. These are imbalances between the engineering responses used to manage city infrastructure and the needs of individual maintenance tasks.

- **Energy** imbalances: the total amount of energy used for actions not essential to the task is order-of-magnitudes greater than that required for the basic task;
- **Resource** imbalances: the scale and cost of engineering equipment, human and material resources, and waste generation are far greater than is necessary;
- **Risk** imbalances: the risks to human health and wellbeing, and natural ecosystems, are significantly greater than they need to be.

OUR VISION

Our vision is of a city where infrastructure is autonomously maintained and dynamically responsive to secure the health and wellbeing of its citizens, contribute to flourishing and sustainable natural systems, and create positive economic and societal outlooks. Cities of the future will be more like urban forests, unobtrusively looking after themselves and providing a sustainable ecosystem for their inhabitants in harmony with nature. Towards this vision we propose a Grand Challenge to rid our cities of the socially and environmentally damaging air, noise, light and waste pollution that occurs from infrastructure maintenance, in particular that associated – directly or indirectly – with roads.

We propose to tackle the Grand Challenge through the use of Robotics and Autonomous Systems (RAS) to creatively disrupt current engineering infrastructure approaches. Therefore, the aim of this project is the development and application of advanced RAS technology to rebalance the energy, resource and risk undertaken in street infrastructure maintenance and modernisation.

THE OBJECTIVES THAT WILL ACHIEVE THIS AIM ARE:

1. Minimally Invasive Sensing and Repair: To develop technologies for autonomous defect detection and diagnosis compatible with new and existing infrastructure.

2. Robots in Complex City Environments: To develop robotic platforms, control strategies, sensing and communication systems to autonomously undertake minimally invasive infrastructure management in complex city environments.

3. Robot – Human – Natural Systems Interfaces: To understand and manage the interactions between our technology, our society and the ecological environment.

In close collaboration with industry, we have identified seven technological challenges we are addressing within this project. However, technical solutions to these challenges must evolve in conjunction with understanding and addressing the social and ecological impacts of such technologies.

Zero disruption
from streetworks in UK cities by
2050

Fire and Forget
Robots designed to operate indefinitely, performing inspection, repair, metering and reporting tasks (e.g. robots operating in live water mains)

Perceive and Patch
Swarms of vehicles for autonomous inspection, diagnostics, repair and prevention of defects (e.g. potholes)

Perch and Repair
Remote inspection and maintenance of structures at height (e.g. bridge inspection).

Construct and Confirm
Coordination of robot teams to build/print, finish and certify infrastructure from CAD models using environmentally friendly building materials.

Plunge and Protect
Autonomous robots with the ability to perform underwater or underground infrastructure inspection, repair, and preventive defect maintenance

Dismantle and Dispose
Advanced manipulation in extreme environments to manipulate, cut, separate, and unfasten structures (e.g. nuclear de-commissioning).

Data and Decisions
Create, process and interpret data for effective, verifiable and trustworthy operation of robots interfaced through advanced communications with the smart city (e.g. robots to remotely augment building information models through the cloud).

HIGHLIGHTS

PEOPLE & PARTNERS

33 RESEARCHERS

04 UNIVERSITIES

14 INDUSTRIAL PARTNERS & COLLABORATORS

OUTPUTS

15 PUBLICATIONS

£ 29m FURTHER FUNDING

ENGAGING WITH OTHERS

22 PUBLIC ENGAGEMENT EVENTS
Over 60,000 visitors at events, activities attended by over 5500

24 INDUSTRIAL ENGAGEMENTS

15 CONFERENCES, WORKSHOPS AND EVENTS

04 POLICY RELEVANT
Two white papers, and input into Department for Transport consultation and Science Advisory Council

55 BROADCAST, WEB AND PRINT MEDIA

BROADCAST:
BBC One Yorkshire
BBC 4
BBC Newsnight
EuroNews
BBC World Service
BBC Radio 4

PRINT & ONLINE REPORTS:
Financial Times
The Economist
Guardian
New Scientist
The Conversation

Robots for Resilient Infrastructure: International Robotics Challenge Event 27-28 June 2017

OUTPUTS

89 TOTAL NUMBER OF ATTENDEES

69% SECTOR REPRESENTED: ACADEMIC

5% SECTOR REPRESENTED: PUBLIC SECTOR

26% SECTOR REPRESENTED: INDUSTRY

MEDIA COVERAGE

NEWS REPORT:
Made in Leeds TV,
27 & 28 June,
Average daily viewing figures 114,000

PRINT & ONLINE REPORTS:
Yorkshire Evening Post
The Engineer
Robotics Tomorrow
University of Leeds web

SOCIAL MEDIA COVERAGE

Facebook: 19,805 PEOPLE REACHED; 119 LIKES; 15 SHARES; 4,900 VIEWS

YouTube: OVER 1,800 VIEWS; 11 VIDEOS

LinkedIn: 64 LIKES

Twitter: 390 ENGAGEMENTS; 14,675 IMPRESSIONS

THE TEAM

Core Leadership Team

The project is overseen by a Core Leadership Team consisting of representatives from each academic partner: Prof Phil Purnell (Leeds), Prof Mark Miodownik (UCL), Prof Chris Rogers (Birmingham), Dr Stephen Prior (Southampton), Prof Rob Richardson and Dr Raul Fuentes act as operational directors for the project, leading on robotics and infrastructure respectively.

PHILIP PURNELL

Professor of Materials and Structures. He leads interdisciplinary research into infrastructure systems, ranging from microstructure of composite materials to applying economic theories to the provision of infrastructure.

(University of Leeds)

CHRIS ROGERS

A civil engineer researching future cities, the infrastructure systems that support them, streetworks and structural performance of buried infrastructure.

(University of Birmingham)

MARK MIODOWNIK

Director of Institute of Making, which links materials science to the arts and humanities, medicine, and society. He is also a broadcaster and writer.

(UCL)

STEPHEN PRIOR

A reader in Unmanned Air Vehicles and founder of the Autonomous Systems Lab, working on defence-related aerial robotic technologies.

(University of Southampton)

A robotics engineer researching a new generation of physical robotic systems, applied to the domains of infrastructure and to explore difficult to access locations.

(University of Leeds)

ROBERT RICHARDSON

RAUL FUENTES

Associate Professor in Infrastructure Engineering and recipient of a Royal Academy of Engineering/Leverhulme Senior Fellowship to develop infrastructure robotics.

(University of Leeds)

National Leadership Team

The National Leadership Team acts as an external advisory board, tasked with conducting performance reviews and ensuring the project remains cutting edge and relevant. In addition, they have the broader role of working with funding bodies, business and regulators to form a coherent and world class spectrum of activity. Current members include:

David Baker, Academic Channel Partner and BDM Manager, National Instruments

Michael Cook, Head of Transformation, Kier Services - Large Utility Services

Tom Knowland, Head of Sustainable Energy & Climate Change, Leeds City Council

Wez Little, Innovations Director, Synthotech

Heather Macklyne, Portfolio Manager, Infrastructure, EPSRC

Elaine Massung, Portfolio Manager, Robotics, EPSRC

Andrew Powel, Technical Assurance, Office of the Chief Scientific Adviser

Rob Shaw, Asset and Operations Enablement Manager, Anglian Water

THE TEAM

Research Team

Our research team spans across disciplines, partners and career stages, making the perfect melting pot to develop innovative ideas and approaches.

Mohamed Abdellatif

University of Leeds
Specialises in computer vision and robotic systems that can help in the automatic inspection and monitoring of structure health.

Muhammed Basheer

University of Leeds
Works on methods for assessing and improving the durability of concrete structures, including prediction of their service life.

Arpita Bhattacharjee

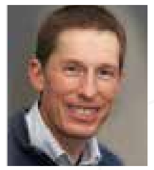
University of Leeds
Is looking into potential future outcomes of robots replacing human labour and what that implies for the wider socioeconomic landscape.

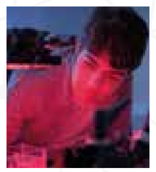
Jordan Boyle

University of Leeds
Works primarily in the field of biologically-inspired robotics, focusing on the minimalist solutions used by simple invertebrates.

Andrew Brown

University of Leeds
Researches key developments in economy and society, including job quality/satisfaction, wellbeing, infrastructure economics and ICT.

David Chapman

University of Birmingham
Is a civil engineer researching the interaction between the ground and buried infrastructure such as pipes and tunnels.

Netta Cohen

University of Leeds
Uses insight from locomotion and navigation based behaviours in animals to inform the design and control architectures for robots.

Anthony Cohn

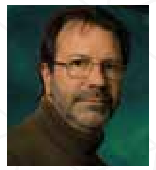
University of Leeds
A computer scientist with interests across AI and robotics, including activity recognition from video, and Decision Support Systems.

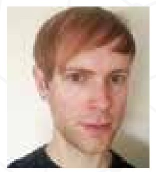
Martin Dallimer

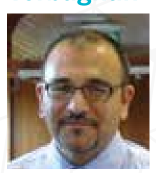
University of Leeds
Is interested in the sustainable management of natural environments in a human-dominated world experiencing rapid technological innovation.

Abbas Dehghani-Sanij

University of Leeds
Researches bio-robotics including bio-inspired system design and development e.g. enhancive robotic exoskeletons for heavy duty tasks.

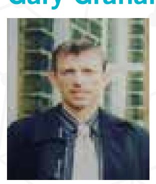
Gary Dymski

University of Leeds
Researches discrimination, financial exclusion, and community economic development, covering inequality, finance and productivity.

Nick Castledine

University of Leeds
Is developing a multi-modal soft robotic manipulator for collecting litter items in urban environments using soft robotic solutions.

Mehran Eskandari Torbaghan

University of Birmingham
A civil engineer investigating the use of autonomous systems to manage infrastructure, including utilities and roads.

Mark Goddard

University of Leeds
Is investigating how changes in pollution (air, noise, light) and increased automation will affect urban biodiversity and ecosystem function.

Gary Graham

University of Leeds
Researches smart cities, big data and social inclusion.

Richard Jackson

UCL
Works on 3D printing & the printing of novel materials, soft composite manufacture and processing, and nanomaterials, nanotechnology, microfabrication.

Bilal Kaddouh

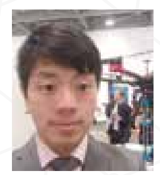
University of Leeds
Has expertise in UAV control and mission management, and is designing aerial robotics systems for autonomous inspection and maintenance.

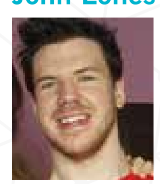
Jongrae Kim

University of Leeds
Is developing optimal estimation algorithms using multiple sensors to improve the navigation accuracy of mobile robots in urban areas.

Chang Liu

University of Southampton
Is a research fellow with expertise in control strategies for small remotely piloted aircraft. Now moved on from the project.

Jason Liu

University of Leeds
Is a research fellow specialising on the design and manufacturing of aerial and ground robots.

John Lones

University of Leeds
Researches biologically inspired control systems, looking at emergent behaviour and adaptation to complex and dynamic environments.

Shan Luo

University of Leeds
Works on machine learning and computer vision with applications in robotics, e.g. object recognition and localisation. Now moved on from project.

Natasha Merat

University of Leeds
An experimental psychologist interested in the interaction of road users with new technologies, including highly automated vehicles.

Nicole Metje

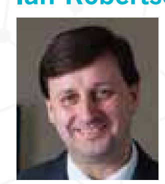
University of Birmingham
Specialises in quantum sensing technologies, tunnelling and underground space, buried utilities and streetworks operations.

Leo Pauly

University of Leeds
Is developing robotic visual perception system for detecting cracks in pavements using computer vision and deep learning techniques.

Harriet Peel

University of Leeds
Is researching robotics for bridge bearing inspection, and using deep-learning and computer vision for crack detection and monitoring.

Ian Robertson

University of Leeds
Research interests in high frequency electronics, such as wireless communication and power transfer for robotic applications.

Nutapong Somjit

University of Leeds
Focuses on microsystems technology including micro-sensors, systems integration, and wireless communications.

Industrial and Non-academic Partners

We are delighted to work with world class industrial partners who help shape our vision, contribute to our technical understanding and work with us to navigate the legal and regularity challenges to ensure our creations can be applied for positive impact in the real world.

- ASCE Construction Institute
- Anglian Water
- Balfour Beatty
- Creative Science Foundation
- DNV GL Software
- Elgin
- EUA Utility Networks
- Ferrovial Agroman
- Future Cities Catapult
- International Association for Automation and Robotics in Construction (IAARC)
- Kier
- Leeds City Council
- National Grid Electricity Transmission
- Northern Gas Networks
- Perth and Kinross Council
- Scoutek Ltd
- Severn Trent Water
- Synthotech
- UK Society for Trenchless Technology
- Yorkshire Water

FIRE AND FORGET

Robots in cities in the future will need to operate continuously, providing and collecting data in real-time.

Short battery life presents a significant obstacle to long-term operation. It either requires redundant units that can replace each other whilst the other one is charging, or be capable of on-the-move charging. In the first approach, charging can happen in docking stations by retrieving the robots and recharging them. In constrained spaces, where space for charging stations or retrieval is undesired or difficult, on-the-move charging is preferable. We have been investigating doing this by wirelessly recharging a pipe robot with microwaves.

CASE STUDY:
WIRELESS RECHARGING PIPE ROBOT

Bilal Kaddouh

Wireless power transfer in metal pipes is a promising alternative to tethered exploration robots, with strong potential to enable longer operating times. Using the metal pipe as a wave guide drastically reduce the losses compared to free space and allow the use of higher transmit powers.

A prototype gas pipe inspection robot with wireless power receiver functionality was developed in collaboration with SWIFT project (EPSRC EP/N005686/1) that focuses on wireless power transfer technologies.

The pipe inspection robot is designed to fit a 1-inch pipe with sensors, microcontroller, wireless power transfer module and

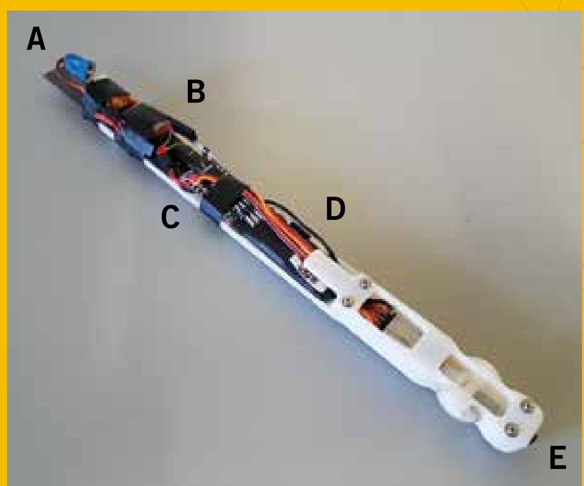


Figure 1: Gas inspection pipe robot.
A: WPT module; **B:** Backup battery;
C: Microcontroller;
D: Video recording and transmission;
E: Camera with night vision

back-up batteries on-board. The design is fully 3D printed using variable stiffness materials, and is fully operational straight out of the 3D printer. The current and previous revisions of the robot were printed in the EPSRC National Facility for Innovative Robotic Systems at Leeds. The robot is equipped with a night vision camera, with the ability to extend longer to accommodate additional sensors. It has the potential to include infrared and ultrasonic sensors depending on the inspection needs. The robot uses an encoder to measure distance travelled allowing preprogramed inspection routines and data logging.

Experiments on electromagnetic propagation in a metal pipe, as well as wireless power transfer for powering and charging of a prototype robot have been conducted[1]. The experiments successfully demonstrate Radio Frequency-to-Direct Current rectification with up to 23% efficiency at the end of a 2 metre long gas pipe, which can be used to extend the operating lifetime of an autonomous inspection robot. The best performance (23%, 18 mW direct current power, PDC) was obtained at a frequency of 12 GHz and 19 dBm of Radio Frequency power at the input of the rectifier.

The ability to transfer power wirelessly through the pipe allows the robot to operate for extended periods of time. This paves the way for future robots that remain in the pipeline system indefinitely while being charged wirelessly. Ultimately, this technology reduces the cost of pipe inspection and allows detection of anomalies and cracks that facilitates preventive proactive maintenance.

[1] Doychinov, V, Kaddouh, B, Mills, G et al. (3 more authors) (Accepted: 2017) Wireless Power Transfer for Gas Pipe Inspection Robots. In: To be confirmed. The UK-RAS Network Conference on Robotics and Autonomous Systems: robots working for and among us, 12 Dec 2017. (In Press)

PERCIEVE AND PATCH

Asphalt composites are the most common material used in surface roads. Its success is due a combination of factors: it creates a safe and robust road surface; road surfacing can be done quickly and without complex machinery; it has good acoustic properties; and it is repairable, indeed it self-repairs to a certain extent.

However asphalt composites degrade over time due repeated loading, temperature, oxidation, and various other factors. This degradation leads to increased stiffness and brittleness of the road surface. Cracks form and can quickly deteriorate into pot-holes. Increasing the life of asphalt roads could reduce the social and environmental costs associated with road closures and the congestion they cause. Increasing the life of roads could also reduce the annual cost of re-surfacing, estimated to be more than £1 billion per year in the UK alone.

We are working to radically change the way asphalt composite roads are repaired by developing a technology to locate defects in the road surface, and deploy an automated robot to 3D print asphalt into cracks and potholes. In addition, we are developing low cost perception sensing and a decision support system for infrastructure condition assessment.

CASE STUDY:
3D ASPHALT PRINTING DRONE

Richard Jackson, Bilal Kaddouh, Jason Liu

Having identified road defects, it is important to be able to perform maintenance to prevent further deterioration. One approach taken in this project is to implement innovative asphalt 3D printing technology to fill-in cracks, before they become potholes.

The asphalt extruder, developed by UCL, is itself mostly 3D printed in high-temperature resistant acrylic based resin. This houses an aluminium tube enclosing a printed Archimedes screw attached to a stepper motor. Stacked stainless steel washers connect to the tube via conductive epoxy in order to supply heat to the extruder tip. Equidistant power resistors supply heat to the asphalt chamber, controlled via thermistor. This compact, lightweight extruder uses pelleted asphalt to 3D print under a range of environmental temperatures.

To be deployed, the 3D printing extruder needs to move to the correct location and then move to fill irregular cracks. The asphalt extruder was installed on a hybrid aerial-ground vehicle developed at the University of Leeds, consisting of an Unmanned Aerial Vehicle (UAV) fitted with tracks for ground manoeuvring. The bespoke tracks were designed to ensure the size was similar to the stock landing struts of the UAV and the weight minimal. They are easily removed for maintenance and are controlled with in-built control boards.

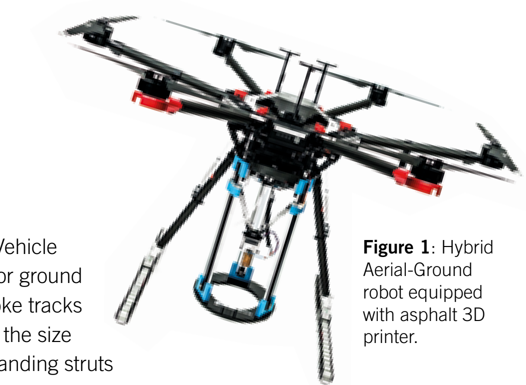


Figure 1: Hybrid Aerial-Ground robot equipped with asphalt 3D printer.

The UAV is commanded by an on-board computer that controls the tracks and the delta arm. The UAV is able to navigate autonomously on the ground so it can reposition itself once landed. It uses an on-board crack detection algorithm to locate the crack and position the nozzle. The UAV is also able to move while filling a crack when the crack size exceeds the operation area of the arm. The current fixing method utilises two one-point laser range finders with 1mm accuracy positioned on each side of the extruder nozzle. This allows the printer to accurately scan the area to be filled ahead of the nozzle during each pass.

The developed UAV provides an automated inspection and maintenance system for cities' infrastructures and offers a platform for further development of aerial maintenance robots.

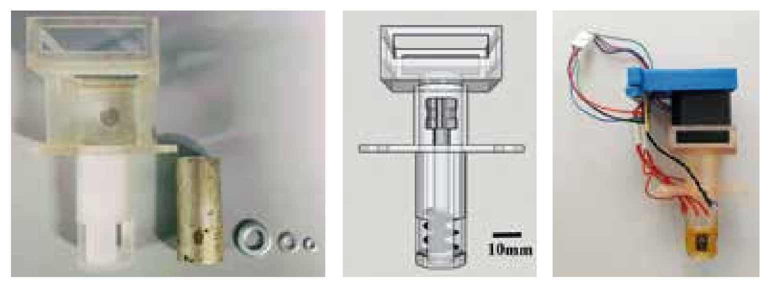


Figure 2: Asphalt extruder. Left to right - Components (Tip inset), Schematic, Fully Assembled.

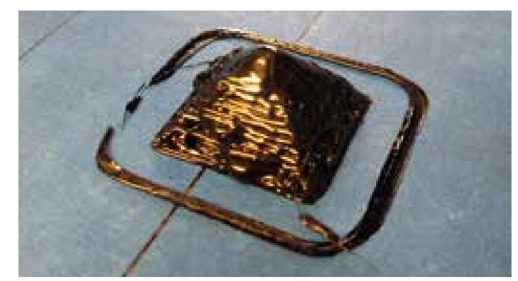


Figure 3: First print of simple object.

CASE STUDY: INSPECTION ROBOT WITH LOW COST PERCEPTION SENSING

Harriet Peel, Anthony Cohn & Raul Fuentes

Bridge bearings are a critical component of a bridge and require regular visual inspection to ensure its safe operation throughout its life.

However, they are often located in spaces that are difficult or hazardous to reach, which can limit how often the bearings are inspected. In addition, these spaces are small and offer significant challenges for tele-operation due to line-of-sight restrictions; hence, some level of autonomy is required to make robotic inspection possible.

We are developing a robotic solution to bridge bearing inspection, including approaches for determining the robot location at any given time as the first and most important step towards automation. Robot localisation has been performed in both lab and real bridge bearing environments. Adaptive Monte-Carlo Localisation has been used, which gave comparable results to existing approaches (e.g. Hector-SLAM), with all results less than a defined error threshold of 10 cm. A combination of both these methods is proposed to give a more robust approach, giving errors lower than this boundary in the real bridge. The experiments also show the need to provide an accurate starting point for each inspection within the bearing, for which we notionally suggest the use of a fixed docking station; this gives additional opportunities to improve autonomy, such as providing recharging. In addition, proof-of-concept approaches have been developed for visual inspection tasks, such as geometry changes and foreign object detection.

CASE STUDY: INFRASTRUCTURE CONDITION ASSESSMENT

Mehran Eskandari Torbaghan, David Chapman, Nicole Metje, Christopher Rogers

Efficient and reliable condition assessment of our infrastructure systems can inform an effective asset management policy, providing huge savings by optimising required interventions and prolonging the asset life.

Two of the most common traditional condition assessment methods are: 1. Destructive (e.g. coring), and 2. Visual assessment, both long criticised for their limited effectiveness and efficiency. Destructive condition assessment by its very nature causes damage, is time consuming and often disruptive. Visual assessment is prone to subjective human error and only provides a qualitative assessment.

Non-destructive technologies (NDTs) can address these drawbacks. Most of these techniques can be utilised without any disruption to infrastructure operation, and have the potential to become fully automated. In recent years there have been some exciting cases of utilising robotics and autonomous systems (RAS) for assessing concrete structures. However, the application of RAS to other types of infrastructure assessment such as buried utilities remain unexplored; an area this project is planning to investigate.

"We are supporting Self-Repairing Cities through access to city infrastructure to help deliver new innovations that can be scaled."

Tom Knowland, Leeds City Council

Each NDT has its own limitations; for example, high frequency ground penetrating radar (GPR) only penetrates a short distance into a structure. Therefore, in order to get a full picture of any existing defects associated with a particular infrastructure artefact, and to be able to make a reliable judgment on the main causes of any identified defect, it is essential to combine various complementary NDTs. As a result a decision support system is being developed, which can offer advice on the most appropriate systems to be utilised for different assets and determining their condition. Once developed, the system will be initially evaluated under controlled conditions using full-scale laboratory based testing.

CONSTRUCT AND CONFIRM

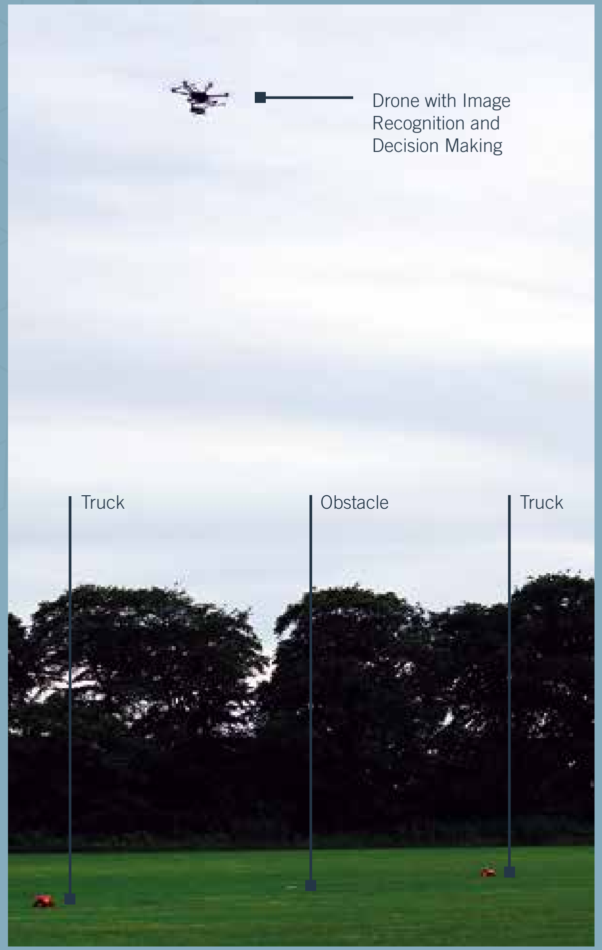
The construction industry is well-known for being notoriously slow to take up innovation. However, in the presence of revolutionary technology, such as robotics, this is rapidly changing.

Synergistic developments are occurring that are making the industry more receptive to potential robotics implementations, such as increased digitalisation (e.g. bridge information modelling, augmented and virtual reality), new sensing and monitoring technology, and off-site manufacturing and assembly (i.e. pre-fabrication of infrastructure components). Similar to 3D printing technology, robotic solutions are and will be implemented more as they provide better means to implement digital designs i.e. they will fabricate structures to better tolerances, measure as-built structure more accurately and provide feedback to the digital asset. Another development is the use of autonomous vehicles in construction to increase productivity and improve safety. The case study below presents the use of earthmoving trucks in collaboration with drones in large construction and mining sites.

CASE STUDY: AUTONOMOUS OPERATION OF EARTHMOVING TRUCKS FROM DRONES

Bilal Kaddouh, Jason Liu, Shan Luo & Raul Fuentes

Construction and earth moving sites involve the operation of large heavy machinery in a dynamic environment. This presents two problems: the site is very hard to manage due to its changing nature and the need for continuous map updates; and workers are confronted with safety hazards caused by the restricted awareness of heavy machinery operators.



To address these issues and to experiment with site management systems, we developed a scaled-down prototype system where earthmoving trucks are fully guided by a fleet of UAVs. The trucks follow simple operations with no obstacle avoidance sensors, receiving all their instructions from the airborne UAVs that can better monitor their position. The UAVs guide several trucks simultaneously and safely navigate them through detected obstacles including other trucks. The aerial view reveals obstacles and potential hazards that would be impossible to see from sensors on-board vehicles. This offers the ability to predict trajectories and identify any potential collision course.

All the information gathered by the UAVs is used to continuously update a map of the site. In parallel, the UAVs can receive requests from various parts of the site for earthmoving trucks that are then directed to these areas on demand. With the use of 3D modelling techniques, the volume of earth being moved can be tracked and automatically managed so that the flow of earth is maintained efficiently, reducing waste 'spoil'. This offers the ability to efficiently allocate and monitor resources, and efficiently manage the overall operation.

The system is designed to use multiple fully-instrumented collaborating UAVs, reducing the likelihood of system breakdown or failure. The need for sensors on ground vehicles is reduced making them cheaper and easier to integrate. The balance between ground versus aerial autonomy for optimising safety of the operation is currently under investigation. The system is versatile enough to incorporate static ground and/or elevated sensors and safely integrate with other human driven vehicles.

There is potential for such system to be used in autonomous maintenance operations, which could be carried out by ground maintenance robots transported to the location and overseen by a UAV.

Image: Scale mock-up system for autonomous earth moving site management and control from UAVs.

DISMANTLE AND DISPOSE

Robotics could have a role to play in the end-of-life phase of infrastructure operation, especially in challenging situations such as radioactive environments, offshore installations, waste management systems, or at height.

This might include dismantling structures and harvesting materials/components either for reuse and recycling, or for safe environmental disposal. To do this will involve a combination of identification and classification (e.g. recognising materials/components and degrees of corrosion or damage), dismantling (e.g. unbolting, cutting) and manipulation (e.g. sorting and transfer to safe storage).

Using robots and autonomous systems (RAS) to recover resources from waste could reduce costs and increase the quality of secondary materials to the point where they can displace primary resources, helping us reduce our reliance on primary materials and carbon emissions associated with primary materials production.

This is particularly important for the construction sector – our biggest producers of waste. Combining RAS with emerging design and installation systems that encourage reuse and dismantling could massively reduce the carbon, material and waste footprint for new structures. It is also important in low-carbon energy infrastructure that use 'critical' materials – such as rare earth metals, cobalt and lithium, for which the UK is normally a 100% importer and for which supply is at risk due to market imbalances or geopolitical reasons – to ensure that materials security is maintained to reduce the risk of serious commercial impacts.

CASE STUDY: **LITTER COLLECTION ROBOT**

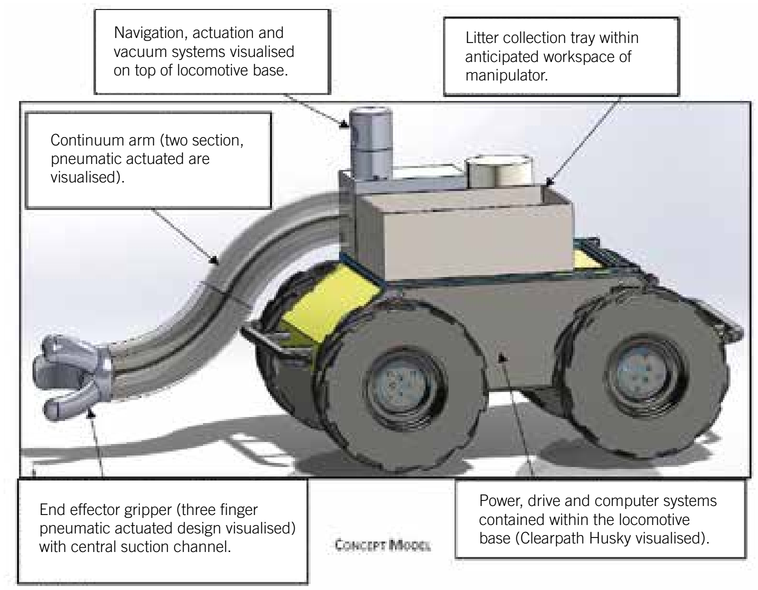
Nick Castledine, Jordan Boyle, Jongrae Kim

Refuse removal and disposal is a significant issue in urban spaces due to the money, energy and resources required to remove and dispose of it safely with minimal impact to the environment. This is essential to keep cities looking visually appealing, maintain certain levels of hygiene expected by their inhabitants and reduce the impact of litter on urban wildlife.

"The soft robotic manipulator will allow for three modes of manipulation - gripping with or without suction assist, and the capture of small litter items through the vacuum tube."

Nick Castledine, University of Leeds

As robotic platforms become more integrated and commonplace in public spaces, their adaptability and compliance to their environment become increasingly important. Cost and reliability are also factors to be considered, as lower initial capital costs and robust, reliable designs to reduce maintenance, give the technology a higher chance of being adopted by governments and businesses. The main objectives of this research include: identifying the key system requirements and challenges; developing, implementing and assessing manipulation hardware systems; developing, implementing and assessing low-level software systems (e.g. sensing and control); assembling a suitable robotic platform; and performing comprehensive field tests of the integrated robotic system.



PLUNGE AND PROTECT

In situations where infrastructure is only directly accessible by operating underground or underwater, robots have the potential to undertake detailed inspections and even repairs at large distances from a human observer.

These robots may be required to be resilient to high water pressures, high or low temperatures, and unpredictable environments. Urban infrastructure of this type includes canals, rivers, dams, large historical sewer networks, underground caves, wells, and voids created during construction processes.

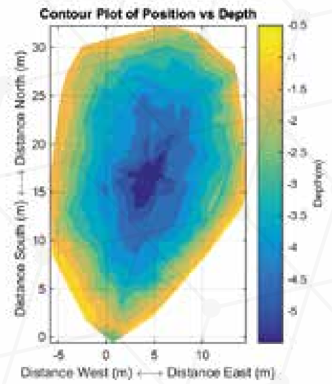
SURVEYING GLACIAL MELT-LAKES IN NEPAL

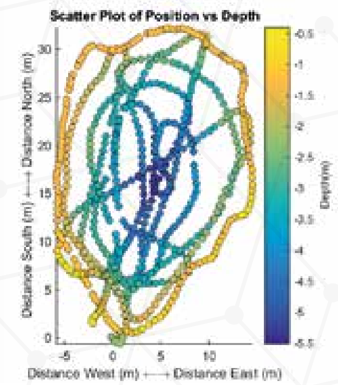
CASE STUDY

Robert Richardson

We are developing surface water vessels to survey beneath the surface of inland waterways to autonomously measure their depth and general condition.

As an extreme test of our technology, in collaboration with external researchers, we investigated the water storage and energy transfer roles of supraglacial lakes in Nepal, using a novel, backpack portable, autonomous water survey vessel. We obtained evidence of pool deepening, the presence of ice cliffs, characterisation of shape to hydrology, and a definitive linear relationship (doubling the data set) between surface area and water volume enabling greater use of satellite imaging.





PERCH AND REPAIR

The ability for robots to perch and repair is a game-changer which will revolutionise many previously difficult, dangerous and dull tasks.

Operations could range from adding sensors or cameras to high-rise structures to changing lightbulbs on lampposts. It would eradicate the safety risks inherently associated with operatives working at a high elevation, and remove the need for heavy machinery such as elevated work platforms. This would open up opportunities such as: surveillance, monitoring fly tipping, infrastructure repair, pollution control, real-time weather, traffic monitoring, etc. In order to achieve this, we need to develop real time kinematic position systems (cm resolution), permission to operate in urban centres and reliable Beyond Visual Line of Sight (BVLOS) protocols.

CASE STUDY

AUTONOMOUS UNMANNED AERIAL VEHICLE PERCHING AND MANIPULATION ON A STREET LAMPPOST

Chang Liu & Stephen Prior

The aim of this project is for the UAV to undertake object manipulation at the top of street lamps, both for direct maintenance and to promote their use as multifunctional platforms for e.g. robot charging, elevated monitoring platforms and city communication nodes.

An initial proof-of-concept perching and manipulation UAV system has been developed. The low-cost UAV system was put together using commercial-off-the-shelf components. It is capable of autonomously perching on the projection bracket of a street lamppost, and performing sensor/camera (un-)installation with its onboard robotic arm [1]. A video of the system in operation can be found in **https://youtu.be/NKEIrKbcBkk**. The resulting system was awarded the 'Greatest Potential for Positive Impact' prize at the 'Robots for Resilient Infrastructure: International Robotics Challenge Event' (Leeds. 2017).

In addition to the initial implementation, a novel perching mechanism has also been developed to allow perching on the vertical column of the street lamppost. The proposed mechanism does not require an actuator to produce perching force, but rather utilizes gravity itself via the rolling self-locking principle. The perching clamp was designed, manufactured and then installed onto a small UAV, which demonstrated successful perching stability.

Figure 3 - Perching clamp tested on mockup metal column.

[1] Liu, C, Paget, L, Turner, P, Erbil, M, Prior, S (2017) Autonomous Unmanned Aerial Vehicle perching and manipulation on a street lamppost. In 8th International Advanced Robotics Program IARP-RISE'2017: Risky Interventions and Environmental SurveillancE.

Figure 1 - Typical modern method to reach a lamppost.

Figure 2 - Initial implementation: Complete system in operation (Liu et al., 2017).

DATA AND DECISIONS

Robotic agents operating in infrastructure are doing so within an ecosystem that is increasingly dominated by data generation and capture.

Improved sensing technologies are being developed and incorporated not only into robots, but also distributed among private vehicles, public transport, personal communication devices, air quality monitoring stations etc. Exploiting this proliferation of data could greatly improve urban decision-making and robot deployment, but it requires the development of radical data curation, manipulation and aggregation techniques and data security protocols. In this area, artificial intelligence and data analytics will play a key role. The case study below showcases this.

CASE STUDY

NEMATODE WORM INSPIRED ROBOTIC MODEL FOR POTHOLE DETECTION

John Lones, Anthony Cohn, Netta Cohen

Animals navigate complex and varied environments, but often use only limited sensory information. Inspired by the sensory model and navigation strategy of the microscopic nematode worm C. elegans, we have developed a control architecture suitable for low-cost, low-power autonomous robots for the application of finding road damage such as potholes.

The work focused on pothole and crack finding in roads by single – and small populations, or 'swarms' – of wheeled ground robots with minimal sensing (low speed, low resolution camera for vision, and low-cost infra-red sensors for object avoidance). We considered sensor specifications and sensory-motor control for efficient target finding (pothole) in unknown, unconstrained environments, or in environments with limited sensory cues (e.g. poor visibility). This is a regime of operation in which classical control algorithms are typically sub-optimal and may benefit from insights from animal behavioural strategies.

In particular, we investigated the control problem from a holistic systems level perspective (integrating sensors, processing unit actuation, and robot-body architecture). The initial algorithms developed and tested were informed by the salt navigation circuit of C. elegans that give rise to a hybrid deterministic-stochastic search strategy. Using a simulation framework, and satellite road images as input, it was demonstrated that the algorithm that embeds decision making in the robot sensors gives rise to robust, efficient pothole finding in a range of environments and outperforms a number of popular area search algorithms [1]. The algorithms were tested on a number of off-the-shelf and bespoke robots simulations, and are currently being implemented in physical robots for testing and integration with the project.

[1] Lones J, Cohn AG and Cohen N, Proceedings of Workshop on Worm's Neural Information Processing, NIPS 2017.

CITY AND SOCIETY

In considering the work of the Self-Repairing Cities project, it is tempting to be transfixed by the sheer technical challenges – robots crawling through the pipes, perching drones fixing street lights, miniscule cracks in asphalt fixed before they do structural damage: a fixed-life fragile system altered to become a flexible, dynamically adjusting mechanical organism.

But beyond these technical transformations, our project represents an overall assault on the traditional boundaries of machine/human interaction. What then, we might think, is there for humans to do? An obvious answer is to attain advanced skills so they can continue to find meaningful work. Evidence already shows that new avenues are opening, but achieving this transition will require re-engineering some key aspects of society as we have known them. Finding empirical evidence that can support some of the major steps in these transformative processes will be crucial as we move forward.

As well as the human population, cities are home to many plants and animals that, in turn, can provide valuable ecological services. The light, noise and air pollution currently endemic to cities undoubtedly have negative impact on natural systems. A future city maintained by robots could dramatically reduce polluting factors to the benefit of natural systems, but we have no evidence of the impact autonomous robots themselves might cause.

Balancing these social and natural impacts is at heart of Self-Repairing Cities, not an afterthought or an adjunct.

CASE STUDY

CHALLENGES ASSOCIATED WITH REPLACEMENT OF HUMAN WORK

Arpita Bhattacharjee & Gary Dymski

Technological change always causes disruption in its wake – the quintessential Schumpeterian creative destruction.

The Robotics and AI revolution is posed for just the same. Except this time, many experts are rather pessimistic about the dire consequences. In the past, every industrial revolution has seen existing jobs become obsolete, labour being replaced with machines, and yet new tasks have emerged that acted as a counterbalance to the displacement of workers. Similar to the past, the robotics and AI revolution is set to displace a large proportion of the current workforce. But the concern this time is that if robots/AI can learn most of the new tasks, the creation of new jobs may not be a sufficient counterbalance for the loss of obsolete ones.

With uncertainty writ large over this revolution, it will be the responsibility of the State to safeguard the interest of all members of society and make sure that those who stand to lose the most from impending disruptions do not fall through the cracks. Institutions will play a key role in the distribution of the productivity gains in a post-robotics society – hence it stands to reason that strengthening the institutions that enable individuals to lead a meaningful life is imperative in the face of disruptive technologies. The key areas of focus for this work are:

1. Education – moving from "factory-model" of education to a more "personalised" system, based on acquiring the set of skills complementary to the emerging technological frontier. Need to focus on encouraging innovations that complement human work and not "replace" it.
2. Democracy and Political Participation – make sure that all members of society are well-represented in decision making processes. The Robotics/AI revolution will have "big winners" and many "losers", and those at a disadvantage because of these emerging technologies will require safety-nets and representation.
3. Sustainable Development Goals (SDGs) – with the recent commitment to SDGs, every country needs to step up the efforts to move to environmentally friendly processes and work out sustainable livelihood options, as well as safeguard against technologies that threaten to accelerate degradation of the environment.

CASE STUDY

ECOLOGICAL IMPLICATIONS OF ROBOTICS AND AUTONOMOUS SYSTEMS

Martin Dallimer & Mark Goddard

As cities continue to expand, urban environments increasingly have to be managed for the benefit of both people and biodiversity in order to meet global sustainability goals. Cities can, and do, support important populations of many species.

Indeed, human dominated regions can be of greater value for biodiversity than the intensively farmed landscape. When envisioning a future city maintained by autonomous robots it is important to understand the ecological impact they themselves might cause – both positive and negative. There are three main aspects in the Self-Repairing Cities project that address this question:

1. A 'horizon scanning' exercise in collaboration with experts from various sectors will identify the emerging impacts of robotics and autonomous systems (RAS) on urban biodiversity and ecosystem function.
2. A review of the published literature will seek to quantify the current state of knowledge on the impact of light, noise and air pollution on urban biodiversity and ecosystem function.
3. We will carry out biodiversity surveys across gradients of light, noise and air pollution in and around West Yorkshire in order to model the possible changes in biodiversity which might be associated with reduced pollution associated with RAS operating in cities.

MAKING AN IMPACT

An important part of our vision is to understand how the technologies and knowledge we develop will be incorporated into real industrial practice, to provide better cities for everyone.

Once implemented in the real world, these technologies have the potential to provide economic returns and fiscal savings, but will also cause positive and negative societal and environmental impacts.

We are actively engaging across our stakeholders groups to communicate and present the outcomes of the Self-Repairing Cities project. We are: arranging and attending events to link academic researchers and industry; co-developing with industry two white papers that explore the potential for robotics to enhance the resilience of infrastructure and for use in infrastructure under extreme conditions; and we have undertaken multiple activities to engage with the general public both directly and via print, spoken, broadcast, social and online media.

WHITE PAPERS

Our white papers provide a quick and accessible introduction to robotics in infrastructure that outline background information, the current state of the art, and future recommendations. Part of the UK-RAS series, 'Robotics and Autonomous Systems for Resilient Infrastructure' (lead by Richardson) and 'Extreme Environments Robotics' (Richardson co-author) were released in 2017.

The first white paper built the case for further UK investment in infrastructure robotics; in particular the need for investment in training, the need for real world test facilities and the importance of constructively engaging in discussions regarding concerns within the infrastructure sector on loss of jobs to robots and potential solutions. The second highlighted the need for: a fast-track for research organisations to obtain regulatory permissions for aerial robotics activities; creation of an autonomous systems specialist advisory group in the UK; increased government help to SMEs in the area; and for a streamlined approach to allow academics access to government and military land for aerial robot testing.

Both white papers are free to download at:
http://hamlyn.doc.ic.ac.uk/uk-ras/white-papers

"It's about getting exposure for your technology to industry and academia, and being exposed to the problems that those people have that really can shape the future of your research."

Dr Nick Hawes, University of Oxford, Robots for Resilient Infrastructure Robotic Challenge Event, 2017.

ROBOTS FOR RESILIENT INFRASTRUCTURE: AN INTERNATIONAL ROBOTICS CHALLENGE EVENT

"In the air, on the ground and underground – robots to create, inspect, repair and maintain the physical infrastructure of our everyday lives"

A two day robotics challenge event was organised by the Self-Repairing Cities project (27th & 28th June 2017, Leeds) as part of the UK Robotics Week 2017, to showcase the current state-of-the-art of robotics for infrastructure through a packed programme of talks and demonstrations. The challenge was primarily supported and funded by an EPSRC investment in capital equipment, and received the support of the International Association for Automation and Robotics in Construction (I.A.A.R.C.), Kier and AEROWORKS.

YouTube videos of demonstrations have collectively been watched over **1800** times

It brought together academics, industry, policy makers and stakeholders to explore the future use of robots in the creation, inspection, repair and maintenance of critical infrastructure.

Attendees heard from Prof Hajime Asama (University of Tokyo), Prof Phil Purnell (University of Leeds), and Prof Mark Miodownik (UCL). They also heard from industry, government and academic speakers cutting across the construction, nuclear, local government, energy, and even space and farming sectors. The event was successful in bringing together key players from across these diverse areas to talk about developments, applications and future challenges in the use of robotics for resilient infrastructure.

Attended by **89** delegates, of which **26%** were from industry and **5%** from public sector

Ten teams from across the UK came to compete, demonstrating their systems across the two days. International video-only entries were also received. The teams were judged on the best technical implementation, the greatest potential for positive impact in infrastructure engineering and also for the best presented video. The entries were expertly judged by: Mr Michael Cook (Kier Utilities), Prof David Hogg (University of Leeds), Dr Ana MacIntosh (Sheffield Robotics, University of Sheffield) and Dr Jakob Sprickerhof (Engineering and Physical Science Research Council). Prizes were sponsored by Kier Utilities.

Facebook live streaming of demonstrations received **4,900** active views

Best Technical Implementation

- First Prize: Metamorphic walker, King's College London
- Runner Up: Lucie, autonomous safety guard, STRANDS project (Universities of Birmingham & Leeds).

Event reported in local press, online and on Made in Leeds TV news (average viewing figures **114,000**)

Greatest Potential for Positive Impact

- First Prize: Grasping and manipulation system using robust shared autonomy and continuous scene monitoring, University of Edinburgh
- Runner Up: Aerial vehicle perching and manipulation on a street lamppost, University of Southampton (part of Self-Repairing Cities project).

Best Video

- First Prize: BALLU, Buoyancy Assisted Lightweight Legged Unit, UCLA
- Runner Up: Q-Bot remote underfloor-foam insulation installation, Q-Bot.

Further details and videos of the challenge entries and winners are available on the challenge review on the **Self-Repairing Cities website**.

Lucie, autonomous safety guard, STRANDS project.

THE FUTURE OF DRONE REGULATION

The Universities of Leeds and Southampton are collaborating with the UK city councils of Bradford and Southampton as part of Nesta's Flying High Challenge.

This challenge, supported by Innovate UK, aims to explore the potential of drones within cities. In early 2018, five UK city regions (Bradford, London, Preston, Southampton and the West Midlands) were selected explore how drones could meet the specific challenges of their city.

"We continue to support the development of new technologies to support Southampton becoming a smarter city fit for the future, where we see the use of drones as having great potential."

Pete Boustred (Southampton City Council)

The challenge aims to:

- Shape city plans on the future of drones in UK cities, exploring specific applications of drones within cities and hazardous environments.
- Identify and address key complexities such as technology, infrastructure, law, regulations, safety and privacy.
- Detail technical and economic plans that unlock market opportunity through regulatory testbeds, open innovation technology challenges and live, real-world demonstrations.

These cities will create, and later implement, a route map to deploy the technology. The current and future technology capability, the needs of cities and people, the potential impact and integration challenges will all be considered as part of the route map creation process. These in turn will help to inform regulations to enable exploitation of technology whilst minimising risk.

SKILLING THE NEXT GENERATION

TRAINING FOR SUCCESS

The success of our project is only possible if our people are also successful. As such, we take pride in training not only those involved in the project directly, but also undergraduate and post-graduate students.

Three examples of how we achieve this are shown here:

1. Project-based teaching of 50 MSc students at UCL on the MSc Engineering & Finance and MSc Engineering and Innovation & Entrepreneurship degrees. Students assembled into groups and were tasked with designing and building a prototype aligned with Self-Repairing Cities. The projects took 9 months and prototypes included: window cleaning robots, road marking robots, plastic waste collecting robots, and solar cell array cleaning robots.

2. PhD student Nick Castledine's research is to design and develop a multi-modal manipulator with the goal of collecting common items of litter scattered around urban spaces. The manipulator would be attached to an untethered locomotive platform and may work as part of a swarm of similar robots to achieve a unified goal of litter clean up and collection. Soft robotic solutions have been chosen due to their adaptability to un-structured environments; their versatile ability to grasp a wide range of geometries and compliance to external collisions while working in public spaces. Mechanical designs and control systems in this field will be explored and tested to develop a novel solution to this problem.

3. Dr Shan Luo joined the Self-Repairing Cities project at the University of Leeds shortly after finishing his PhD at Queen's Mary University. During his almost two years here, he was funded to attend The International Computer Vision Summer School in Italy, a 3 month stay at MIT in the USA, and a 1 day course in High Performance computing in Leeds. Dr Luo has now progressed into a Lecturer position at the University of Liverpool, starting January 2018, after spending 6 months at Harvard University following his departure from Leeds. Although, no longer officially involved he continues to collaborate with the team in papers.

Pictured right: Litter picking robot designed by UCL MSc students.

PUBLIC ENGAGEMENT

One of the major impacts of the Self-Repairing Cities project so far has been to raise awareness among the public, both of the use of robots in infrastructure, and infrastructure in general.

The project has caught the imagination of the world's press, and the team has carried out dozens of international TV, radio, online and print media interviews and features over the past two years. These have ranged from local radio stations to international outlets such as the BBC World Service, Financial Times and Newsnight (see key broadcast, radio/podcast and print outputs to the right). This has been has been augmented by our own series of engagement events (e.g. working with post-16 students at University Technical College) and invitations to events such as the Cheltenham Science Festival. More specific impacts will emerge as the technical and social science aspects of the work combine; a recurring theme in media engagement is the 'what about our jobs' question and we have recently started our socio-technical analysis in this area.

Broadcast

- **BBC One Yorkshire (23/06/2017, 7.30-8.00pm) 'Invented in The North'**
  The programme focused on the regions' role in the history of flight and looked forward to its future. As part of this, Prof Rob Richardson and Dr Bilal Kaddouh (University of Leeds) demonstrated their drone, developed for Self-Repairing Cities, which is capable of delivering and controlling other robots. The programme was previewed on BBC One Yorkshire 'Look North' earlier in the evening (23/06/17, 6.43pm), featuring the drones being develop at the University of Leeds.
- **BBC Newsnight (27/11/2017)**
  Interview with Prof Rob Richardson (University of Leeds) discussing the Industrial Strategy Challenge Fund strategy and demonstrating various robots including from Self-Repairing Cities.
- **EuroNews (18/09/2017)**
  News report: 'Superfast broadband speeds for a brave new gigaworld'. Featured Dr Raul Fuentes (University of Leeds) talking about Self-Repairing Cities, including footage of robots from the project and from the 'Robots for Resilient Infrastructure: International Robotic Challenge Event' (June 2017, Leeds).

Radio and Podcasts

- **BBC Radio 4 (30/6/2016)**
  Interview with Prof Phil Purnell (University of Leeds) talking about a robotic future, including research into self-repairing cities and the possibilities of using robots to repair roads.
- **BBC World Service (16/12/2016)**
  Interview with Prof Phil Purnell (University of Leeds) discussing the Self-Repairing Cities project and how by using robots small problems in infrastructure can be identified and fixed become they become a significant issue.
- **Podcast for Guardian Technology (17/2/2017)**
  "Chips with Everything" show 'How do you build a self-repairing city?' Tech podcast presented by Leigh Alexander discussed the Self-Repairing Cities project, asking how close we are to the end of potholes and road works, and whether Leeds could become the first city to repair itself using new robot technology.

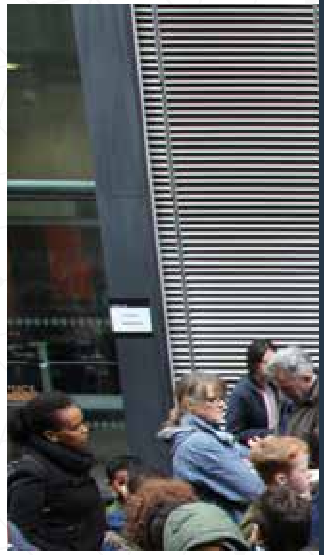
Print

- **Financial Times (28/03/2018)**
  Article: 'No more potholes: when cities can repair themselves' Prof Mark Miodownik (UCL) on how smart materials could transform our infrastructure, giving details of the work being undertaken on the Self-Repairing Cities project.
  https://www.ft.com/content/9870fa7a-314d-11e8-b5bf-23cb17fd1498
- **Guardian (21/9/2016)**
  Feature article on 'The automated city: Do we still need humans to run public services'. The article covered the automation of municipal services and mentions the Self-Repairing Cities project. Prof Phil Purnell (University of Leeds) is quoted saying that putting road workers out of work is absolutely not the objective of the exercise.
  https://www.theguardian.com/cities/2016/sep/20/automated-city-robots-run-public-services-councils
- **New Scientist (12/01/2016)**
  Article: 'Self-repairing cities will maintain their own roads'. The future possibilities of research by Prof Phil Purnell and Prof Rob Richardson (University of Leeds) into self-repairing city robots are explored.
  https://www.newscientist.com/article/2072761-self-healing-cities-will-fix-their-own-potholes
- **New Scientist (18/10/2017)**
  Article: 'Journey to the city of tomorrow'. It included Mark Miodownik (UCL) talking about how autonomous vehicles could help with road repairs, mentioning Self-Repairing Cities and their collaboration with Leeds City Council.
  https://www.newscientist.com/article/2150487-journey-to-the-city-of-tomorrow
- **The Economist (11/6/2016)**
  Article: 'Fixing potholes – the hole story'. Research by Prof Phil Purnell and Prof Rob Richardson (University of Leeds) is referenced, regarding the automation of the inspection and maintenance of infrastructure using robotics.

CASE STUDY

PUBLIC ENGAGEMENT AT THE INSTITUTE OF MAKING

Mark Miodownik is Director of the Institute of Making which is physically located in the heart of London. It contains a multidisciplinary workshop and a materials library, open to all disciplines and occupations. The idea is to very visibly showcase materials science as a creative and active force at the heart of society.



Through public open days, master classes and workshops, the Institute puts into practice something that Mark has been championing for more than fifteen years; that hands-on making is one of the most effective ways bring new talent into materials science and engineering. This has provided a very effective platform to show-case the Self-Repairing Cities technology and allow the public to play with it and to discuss it. At the summer open day more than 1300 members of the public took part.

Mark recently presented a TV programme called Secrets of the Super Elements which examined how dependent modern cities have become on a number of key materials and how important it is to understand this complexity. He followed this up by giving public talks in Sheffield, Birmingham, New Scientist Live, Cheltenham Science Festival, as well as giving many school talks (total audience more than 5000). Mark is also active in influencing policy of the role of public engagement. He is the chairman of the Ingenious Grants Committee of the Royal Academy of Engineering and a member of the Cheltenham Science Festival Advisory Group. In these capacities he works to influence how politicians, funding council representatives, academics, and companies appreciate the challenges of sustainable city infrastructure.

ROUTE MAP FOR THE FUTURE

Technology and Engineering: We're looking forward to advancing our research and finding new infrastructure applications, focussing on five research challenges which cut across our seven technical infrastructure challenges (see figure on page 5):

- Novel robot configurations and manufacturing: techniques involving minimal human assembly to create complex, multi-functional robots, miniaturised to tackle challenging locations and problems. Perch & Repair – 3D printing of robots; Fire & Forget – wireless energy transfer for pipe robots; Dismantle & Dispose – minimally invasive robots to inspect damaged/disused structures; Plunge & Protect; fast, portable "robot boats" for infrastructure inspection.

- Swarms and autonomy: algorithms that minimise the sensor data, processing power and computer hardware required for robust operation and autonomously collaboration between small and large robots. Fire & Forget – robot swarms to inspect inside metal pipes; Construct & Confirm – UAVs for collaborative manipulation and mobility; Data & Decisions – bio-inspired robotic search approaches and sensor-based infrastructure mapping and analysis.

- High speed multi-link systems: commercial legged robotic systems for infrastructure tasks, and high speed multi-linked systems to form manipulators for robots and drones. Perch & Repair – design and control of lightweight manipulators for UAVs; Perceive & Patch – multi-linked hybrid climbing robots to work under bridges; Construct & Confirm – "armed and legged" robots for construction; Dismantle & Dispose – urban litter collection.

- Autonomous additive and subtractive processes: new processes for applying materials to repair damaged infrastructure, and robots to remotely sample soil and install services without digging trenches. Perceive & Patch – 3D printing and/or spraying of advanced materials for infrastructure repair; Plunge & Protect – burrowing robots that collect soil and install e.g. underground pipes and cables.

- Air and ground interaction control: 'real-world' control algorithms for UAVs and ground vehicles that enable forces to be applied whilst maintaining stability including rotary UAVs that can pick/place objects, and precision landing of fixed wing and rotary UAVs. Perch & Repair – precision landing on infrastructure; Perceive & Patch – ground robots with extending masts for bridge underside inspection.

Jobs and people: The most pressing concern that people have over introducing robots into workplaces is the potential for lost jobs. Up to now, economic evidence has always shown that the jobs displaced are replaced by new jobs as new goods and services are developed. However, the ability for robots to learn new tasks, changing the human-machine interaction, throws into question whether this will continue. We will work towards providing the evidence for how robots will affect infrastructure jobs, and help legislators draw up policies, via existing initiatives such as the Industrial Strategy and National Infrastructure Plan, that encourage those displaced (from the tedious, repetitive jobs for which we will use robots) to learn new skills and participate in the new robotic economy. We will also investigate how robots will affect the wider economy – i.e. the creation, appropriation and distribution of value and resources – and help people to engage in the political process to ensure that all citizens, not just a privileged few, will benefit. New technology needs to be primarily shaped by the needs of society, not vice versa.

The business case: The commercial rationale for introducing robots into infrastructure needs to be more sophisticated than just cutting costs. Our global infrastructure is a parlous state, and people with the higher-level skills are in short supply. The benefit of robots will not be to reduce infrastructure budgets, but to allow those budgets to be more efficiently spent by redeploying workers currently engaged in low-value, reactive tasks – pothole repair, digging holes, changing light-bulbs – towards the more complex technical problems that require proactive, creative human input such as increasing infrastructure resilience to climatic, economic and societal change. We will explore what this will mean for education, outlining systems that can react more quickly to create bespoke skill-sets on demand as technology advances, rather than the current 'one size fits all' model. We will also quantify the ability of robots to reduce fatalities and injuries, increase resource productivity and reduce carbon emissions; all of which contribute to the 'triple bottom line'. As an early mover in infrastructure robots, we will also explore the potential for the sector to gain an advantage with regard to export of technological, financial and educational products across the world to benefit UK plc.

The city, environment & ecology: We know that robots have the potential to reduce waste, noise, light, dust and carbon pollution, but we don't know by how much. We also need to explore the potential for impacts, both positive and negative, on other ecosystem parameters such as biodiversity. These could form an important part of the overall business case for robots. We will combine our 'horizon scanning', literature review and survey evidence to analyse and present the case for robots and autonomous systems as a key part of achieving a circular economy (in which materials retain their highest value function for as long as possible and the ecological impacts of their use, reuse, recycling and disposal are minimised) and the UN Sustainable Development Goals. The potential for robotic systems to greatly enhance our ability to recover resources from waste by better identification, sorting, and reprocessing of waste streams is an exciting part of this effort. We will also start to re-imagine the built environment of the future. At the minute, we must design robots that can cope with existing infrastructure, but it will make much more sense to design infrastructure that can cope with robots as well; or more correctly, that future infrastructure and robots should co-designed.

It is important for us to point out here that our job is to provide 'proof-of-concept'; to demonstrate prototype technologies, policies and systems that show the way towards a self-repairing city future. As we move towards the end of the project, we will work closely with cities, industry and policy makers to turn these prototypes into the products, new regulations, educational syllabi and institutions that will populate the streetwork-free city of the future. We hope that we are on our way.