City, heal thyself

Leeds is pioneering a multi-million-pound research project to develop next-generation autonomous robots that can detect problems in urban infrastructure and fix them without human intervention. Here, **David Smith** meets the people behind the 'self-repairing city' vision and asks, can it really be done?

The city of Leeds – once at the heart of the Industrial Revolution – is the setting for a futuristic robotics project unlike anything attempted before. Dr Rob Richardson, director of the National Facility for Innovative Robotic Systems at Leeds University, plans to make Leeds the first "self-repairing city" in the world within 20 years. Richardson envisages a city where divisions of autonomous robots crawl through utility pipes performing smart repairs, and where drones patrol the city's skies spotting damaged infrastructure, changing the bulb on a streetlight or landing to patch a pothole.

Considering the scale of their ambitions, the Leeds team is up against the clock. Five years from the official start date in January 2016 Richardson intends to put on a spectacular show in Leeds city centre involving flying robots. By that stage, he hopes to have developed robot designs and technologies in all the main research areas for underground robots and drones. Further ahead, the intention is to make Leeds the first self-repairing city in the world by 2035. At that point the city will behave like a living thing. The robots will act like white cells that identify viruses and attack them. But the ultimate goals reach way beyond one city. By 2050, Richardson wants all British cities to possess the same capabilities. "It's a unique and revolutionary goal," he says.

The self-repairing city concept was a response to the £21m Engineering Grand Challenges issued by the Engineering and Physical Sciences Research Council (EPSRC). For an idea to be considered, it had to have the potential to be a game-changer. The Leeds project secured £4.2m in funding, and further industry investment will raise the total to around £8m. Leeds University is leading the project, but Richardson will need all the help he can get and the team also includes researchers from universities in Birmingham, Southampton and London (UCL), with Nottingham, Sheffield, Oxford and Imperial also taking part. Southampton's Dr Stephen Prior, who is leading the research into drones, says: "This project will stretch everyone involved to new levels – trying to do things we have never done before. It will be challenging, but rewarding when we pull it off, which we have to do."

How many drones does it take to change a lightbulb?

Self-repairing cities would naturally function much more smoothly and efficiently than the ones we live in today. The underground robots will "live in the pipes", carrying out surgical, preventative maintenance on water, gas and electricity infrastructure. For instance, they could stop lots of little cracks from turning into water leaks that lead to bigger problems like sink holes.

"Just imagine the energy difference if robots fix infrastructure compared with using a big truck that drives from a depot into the heart of the city so the workmen can dig a big hole," says Richardson. "You get all the delays from the road works and all the pollution from the fumes. Using robots will also make life less stressful for car drivers who won't be beset by delays."

Streetlamp repairs are often just as disruptive and inefficient. "Two men in a van drive up, blocking a lane, and cordon off an area so no one can get close to it," says Stephen Prior, an expert in unmanned air vehicles. "Then they put down ramps and raise a crane to change a light bulb weighing 200 grams. We're trying to do away with the expense and disruption by making these things almost invisible."

To fulfil his ambitions, Richardson will have to build on robotics innovations of recent years. And as it turns out, robots for pipe-repairing are actually a little old hat. Last year the London Borough of Camden piloted them in repairing more than 50 gas mains joints for the National Grid using one small hole in the carriageway, rather than digging 50 separate holes. The robot was called CISBOT, a name derived from its designation as an "Internal Cast Iron Joint Sealing Robot", and was manufactured by US firm ULC Robotics. ULC claims its CISBOTs have repaired thousands of joints for gas companies in the northeastern United States. For National Grid, the advantage is clear: it says there are around 17,000 excavations of Camden's roads per year, so the robot interventions could prevent thousands of disruptions.

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> Stephen Prior, University of Southampton

But Richardson will also have to hunt for new ideas. To this end, one of his key advisers will be the British roboticist Wez Little, innovations director of Harrogate-based firm Synthotech, who has built award-winning robots to repair pipes. Little says the big leap for Leeds will be making the robots fully autonomous, as opposed to them needing an operator to control them remotely. "There is already enough technology to make the robots move around the pipes and there's enough technology to do the repairs," he says. "But those things are the robotics of the present. When it comes to automation, Richardson will be working on the robotics of tomorrow and may have to go to the four corners of the earth to find the ideas he needs."

Not so new: In 2014 the London Borough of Camden piloted the use of robots to repair more than 50 gas mains joints for the National Grid

ULC Robotics

Aren't you a clever little bot

It's already clear how some of the autonomy required for the Leeds robots could be achieved. Artificial intelligence and 'machine vision' are key ingredients. Maps of the infrastructure are available from utility companies. As Building Information Modelling (BIM) is deployed in future infrastructure build-outs, even more accurate pictures of underground networks could be available. Once equipped with their infrastructure 'maps', the robots could use machine vision to search for deviations.

Machine vision is already used in modern robotics. It uses the physical geometry of objects to teach a robot to distinguish between them. It can be programmed, for example, to tell the difference between apples, bananas and pears based on their shape. A typical system might consist of structured lighting, a camera with a lens, a processor and vision software. "The Leeds robots would have a database of what the pipes should look like, then they would spot the differences," says Little. "If they found a leak, they would determine the cause by referring to a second database of potential causes."

But machine vision and artificial intelligence would not be quite sufficient to grant the robots enough autonomy to live underground for several years. To achieve that, they would need to be able to create more precise maps of the infrastructure as they move around. "This requires an element of self-learning, which is possible now that computers have become so powerful," says Little.

Impressive advances in 'self-learning robots' have been achieved at MIT's Computer Science and Artificial Intelligence Laboratory. The MIT robots are able continuously to update 3D maps of their environment based on a technique called SLAM, short for Simultaneous Localisation and Mapping, which allows a robot to locate itself using a low-cost Kinect-like camera. As the robot travels through an unexplored area, the Kinect sensor's visible-light video camera and infrared depth sensor scan its surroundings, building up a 3D model of the walls of the room and the objects in it. When the robot passes through the same area again, the system compares the features of the new image with previous ones. At the same time, it constantly calculates the robot's motion using on-board sensors. The visual information is combined with the motion data, to determine the robot's exact position.

University of Leeds

A "bore-hole deployable robot", made by the University of Leeds, can enter a 40-mm-diameter hole and then reconfigure into a U-shape for better mobility. Applications include search and inspecting disused mines

Quest for power

However, even if the Leeds robots understand how to upgrade the maps of their environments, they will also need a continuous source of power to keep moving for years. Roboticist Wez Little says there are solutions available. "There could be charging stations built into the infrastructure that eliminate the need for later excavations. They'd be similar to ones used for electric vehicles today. A robot would drive around and when it was coming to the end of its charge it would return to base," says Little. "Or, the robots could be recharged by other vehicles like military airplanes on long missions refuelled in mid-air by other planes. A recovery robot could do that as long as a robot low on charge continues to emit an on-board signal. We see something similar with the Pipetel robots – if one gets stuck another robot is sent to rescue it."

Richardson is also considering inductive charging. The process was first used by Nikola Tesla in 1901 to transfer electromagnetic energy wirelessly. Tesla's basic technique is now employed in any situation where batteries are being charged without physical contacts. It is used to recharge electric toothbrushes and shavers and various methods of inductively charging electric cars have been developed, though they are not widely deployed yet. In the world of robotics, Intel has used near-field magnetic resonance charging to repower a 'swarm' of robots. One method could be to inductively power charging mats which then transfer energy to the Leeds robots.

Another potential recharging solution being considered is to use the energy from the flow of water through the pipes. The robots would become like mini hydroelectric power stations converting the water's kinetic energy into electrical energy. "As long as we can find a way of making the robots stationary while the water flows over them, this method could work," says Richardson.

We kind of did it in Egypt

The Leeds robotics team has been wrestling with complex robotics problems for years. In 2011, they designed the 'Djedi' robot that sent back the first images of ancient Egyptian markings from a tiny chamber of the Great Pyramid of Giza. The story of their little Indiana Jones robot caught imaginations around the world. Last year, the team went further with a new robot, which crawled into the pyramid's tunnel, then used its flexible "micro snake" camera to see around corners. It brought back images of 4,500-year-old hieroglyphs written in red paint, and carvings in the stone. "There are similarities between the two projects," says Richardson. "The pyramid robots had to climb in square, or round, shafts, which are basically like pipes. They employed lots of cameras to navigate and sensors that detected how thick the walls were. Of course, a major difference is that the Giza robots didn't have to be autonomous."

More inspiration can be sought in Japan, where robots are being used to explore one of the three Fukushima nuclear reactors wrecked in the 2011 earthquake and tsunami. Although an earlier robot failed to survive inside the reactor, researchers have high hopes for a second one. Developed by the Universities of Tokyo and Tsukuba, and the International Research Institute for Nuclear Decommissioning (IRID), the remotely-controlled robot will use 360-degree cameras and lasers to create a 3D map of the reactor buildings.

Though unlikely to be blasted by nuclear fallout, the drones in Leeds will face a battering from the elements in Northern England, which can be severe enough. "The drones will have to work night and day, and in the wind, rain, snow and sleet," says Southampton's Stephen Prior. "We'll design them to withstand any conditions so they'll even be capable of surviving sandstorms. They'll also have to be protected from security dangers. There are lots of issues to consider and we're just at the tip of the iceberg in terms of our understanding of what it will take to pull it off."

The security question is an interesting one. Robots that are inaccessible in underground pipes could be an tempting target for malicious re-programming – to make the robot to drill a hole in a gas pipe to cause an explosion, for instance. Richardson is aware of the dangers. "We're collaborating with people across the UK on safety verification systems to make sure the robots are safe to operate autonomously and can't be hacked," he says.

Landing on a lamppost

Another fundamental challenge is to make the navigation systems precise enough so the drones can locate items that need repairing. "GPS will generally be as good as plus or minus two metres, which is no good when you're trying to land on a lamppost," he says. "If the drone gets it wrong by two centimetres, it'll fall off. It's unusual to require such a high degree of accuracy. Even crop sprayers don't need such precision. If some of the spray lands on the next field no one cares. Even when our drone lands on its target, it will need to manipulate something accurately, which is another level of complexity. That's what makes this such a unique and fascinating challenge."

Military GPS possesses an accuracy measured in millimetres, but universities are barred from accessing encrypted channels. The EU's 5bn Galileo satellite system will provide greater precision from 2016, but it still won't be enough. Prior says the answer will be a 'course-to-fine' strategy. "We can use GPS to tell the drone where the lamppost is to plus or minus two metres, then use a laser mechanism to take it to the next level of accuracy. There are laser altitude metres and laser range finders and scanners that could recognise the outline of the lamppost structure," he says.

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> Rob Richardson, University of Leeds

Although Prior wants his 'very practical' team at Southampton to build the drones for Leeds, he will consult widely. He is an admirer of the world-renowned EPFL's Laboratory of Intelligent Systems in Switzerland. EPFL drones have mapped environments at an unprecedented level of detail. In one study, two EPFL spin-offs, senseFly and Pix4D, modelled the Matterhorn mountain in the Alps in 3D after taking high-resolution pictures at 4,478m altitude for six hours. Bespoke software assembled the images into a 300-million-point 3D model. In addition, the EPFL drones are autonomous. They require only a computer-conceived flight plan before being launched by hand. "No one does it all and everyone is leaning on everyone else's shoulders," says Prior. "There's a lot of information in open-source papers and books. We'll borrow ideas, but build things in our own way. We like to think that at Southampton we're the world's leading expert in efficient rotor propulsion systems."

A complicating factor for the drone designers is that the British regulator, the Civil Aviation Authority, places restrictions on flying unmanned aerial vehicles. Drones can travel up to 400 feet from the controller but they aren't allowed to fly 'non-line-of-sight' unless they possess sense-and-avoid capability. But they're working on that, too. Says Prior: "We're negotiating with the CAA and selling them our ideas in the hope they'll let us fly in the city centre. We'll have to equip the drones with map sensory capability so they can recognise obstacles in their flight path, such as birds."

The technology has to be foolproof because a malfunctioning drone could endanger passers-by. "It's a whole different category to underground robots. If one breaks down in a pipe, it's unlikely anyone would notice, whereas a damaged drone could drop on someone's head and they might feel aggrieved." Despite the exceptional challenges, Prior is hopeful of success. "What we're trying to achieve is not a million miles from drone deliveries of Amazon parcels which they say they will be doing in a couple of years."

But will robots take over?

When they hear about the Leeds project many people find it hard to envisage robots and mending infrastructure autonomously. But Wez Little says this pessimism is largely a result of misconceptions about robotics. Modern robots are often the product of the multi-disciplinary field of 'mechatronics', which integrates electronics with mechanical design to create intelligent systems. "People still think of robots as humanoid replacements so they can't imagine them working underground, but that's not the way robotics is going. It's more about creating task-specific robots," says Little. "When I show pictures of robots the first thing people say 'it doesn't look like I thought it would'. People assume they will be shaped like R2-D2 in Star Wars rather than round and small enough to fit inside pipes. It's certainly a misconception to think Leeds will see loads of robots wearing hard hats and high-visibility jackets digging holes at the side of the road."

The misunderstanding of the nature of robotics has provoked widespread fear about robots replacing humans in the workplace. "A recent report said anyone earning less than £20,000 would see their job replaced by a robot in the next 20 years. But that's nonsense. Even low-paid jobs would not be cost-effective to automate. You'd need staggering volumes of robots to stand behind every counter at McDonald's and Subway, or collect everyone's bins," Little says.

"The Leeds project will be about finding a balance between things worth automating and things not worth doing. Defining the parameters carefully will be the best way to meet the 2035 deadline. What will they need to be able to do? Glue, drill and weld? Will they cover distances of 3km or 10km? Will they start in the mains then go off exploring smaller pipes? How far will they need to travel from the incision point and how many bends will they need to go around? What diameter will they have to be? Once Richardson has defined the parameters, designing the robots to meet them will be relatively easy."

The vision is clearly very ambitious, and will not be realised overnight. Richardson hopes to reach a 'tipping point' in 10 years time when the Leeds team will have demonstrated the technologies and the project will gather unstoppable momentum. "Everyone will see that the benefits are so great that it simply has to happen," he says. "Municipalities around the world will appreciate the logistical and environmental benefits and businesses will want to invest. There are lots of question marks before we reach that point, but I'm confident we can work our way through the field of unknowns and find all the answers." ❑