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***Abstract*—Increased population growth and continued urbanisation will necessitate novel, bold, and revolutionary approaches to infrastructure inspection, maintenance, and repair. This will likely be done by swarms of autonomous robotic systems. The University of Leeds is quickly establishing itself as a leader in the field by taking part in two ambitious infrastructure robotics projects - Self-Repairing Cities and Pipebots. Here we present an overview of these projects, as well as two outputs from them - an Asphalt 3D Printing drone, and a wirelessly powered pipe inspection robot.**

Keywords—Robotics, Autonomous System, Wireless Power Transfer, 3D Printing

I. INTRODUCTION (*HEADING 1*)

In a recently published White Paper by the UK's Robotics and Autonomous Systems Network, [1], the authors make a compelling case for the future vision of a society where infrastructure engineering, repair, and maintenance is undertaken with zero disruption to the everyday lives of people, and with zero environmental impact.

This is a bold and ambitious vision that requires significant research and development efforts, at various Technology Readiness Levels (TRLs), in order to become reality.

In pursuit of this vision, academic and research staff at the University of Leeds is undertaking two large, five-year research projects, in the broad field of infrastructure robotics.

These combine experience and expertise in multiple fields of engineering, science, and humanities.

In this paper, these projects are briefly summarised, including their envisioned contribution to the UK-RAS White Paper. Examples of the novel work undertaken and results achieved by the team are also presented and discussed.

II. SELF REPAIRING CITIES OVERVIEW

The first project that will be discussed is the Balancing the impact of City Infrastructure Engineering on Natural systems using Robots, or "Self-Repairing Cities" for short [2]. The grand vision of this project is that of a city where infrastructure is autonomously maintained and dynamically responsive, focused on: securing the health & well-being of its citizens; contributing to flourishing and sustainable natural systems in the city; and creating positive economic and societal outlooks.

To this end, there are several possible avenues for autonomous robotic systems to achieve this vision. These are organized in separate distinct themes, illustrated in Fig. 1.

Out of these, the main focus of the project is on the following three:

- Perch and Repair: Remote maintenance and modernisation of lighting columns to promote their use as multifunctional platforms for city communication nodes
- Perceive and Patch: Swarms of flying vehicles for autonomous inspection, diagnostics, repair and prevention of highway defects (e.g. potholes)
- Fire and forget: Hybrid robots designed to operate indefinitely within live utility pipes performing inspection, repair, metering and reporting tasks

Out of these, the team at the University of Leeds has expended considerable efforts into bringing the Perceive and

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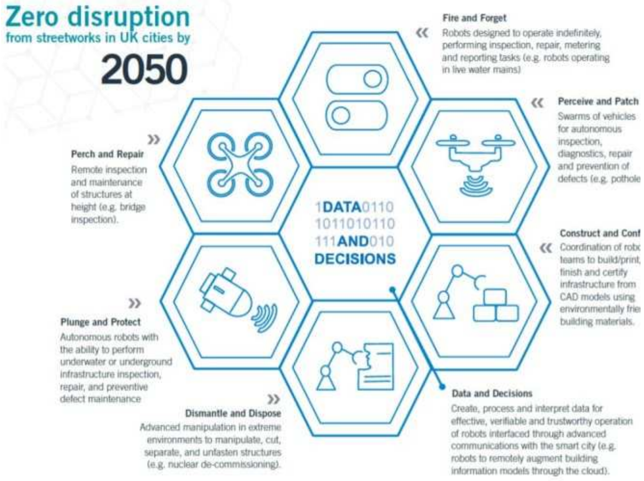


Fig. 1 Different themes of Self-Repairing Cities project.

Patch demonstrator to reality. Combining our individual expertise in aerial robotics, computer vision, and automated control, together with the invaluable contribution of our project partners in the field of civil engineering and material science, we have come up with the idea of an Asphalt 3D Printing Unmanned Aerial Vehicle. Details of this demonstrator are presented in the following section.

III. SELF REPAIRING CITIES DEMONSTRATION

A flagship demonstrator of the Self-Repairing Cities is the Asphalt 3D Printing Drone. It directly fulfils the “Perceive and Patch” aspect of the project, by autonomously detecting cracks in the road surface during flight, landing on top of them, and filling them using a novel asphalt extruder [3].

A photo of the full system on the ground is presented in Fig. 2. It consists of a DJI hexacopter, a CoLiDo delta frame, custom designed and made tracks for ground mobility, and the asphalt extruder mentioned previously. In addition, a sophisticated on-board computer vision system is used to recognise cracks in the road surface.

One area where the multidisciplinary team at the University of Leeds and its partner institutions excel is the seamless integration of components and systems. In the case of the drone, the main contribution stems from making sure the on-board computer vision system can recognise and process cracks in the road surface, and output data in a way that is suitable for the control of the CoLiDo delta frame.

The integration is implemented in Python, with calls to a Matlab script to run the computer vision system. The output of that system is a list of X-Y coordinate pairs, which correspond to particular points, or “pixels”, of the crack. The control of the frame itself is through another custom Python script, which uses this output to carefully position the asphalt extruder above those points, depositing asphalt as it moves. A diagram showing this workflow is given in Fig. 3.

Finally, a photograph captured by the on-board camera, showing the system in action, is shown in Fig. 4. In that figure, the precision and accuracy of the developed solution can be clearly seen in that a very narrow and irregularly-shaped crack is neatly filled with molten asphalt. Experiments to test the quality of the repaired crack and its longevity are still ongoing.

IV. PIPEBOTS OVERVIEW

Another ambitious multi-institution project that the University of Leeds is taking an active part in is the Pervasive Sensing for Buried Pipes project, or “Pipebots” for short [4]. This project aims to address the worldwide issues of pipe inspection and rehabilitation, in particular pipes used for the transport of potable water and those used for drainage and sewerage. The ambition of the project is to adopt a truly interdisciplinary approach to this grand challenge and solve it by researching and developing a swarm of autonomous robots, which can be deployed and remain in the pipes indefinitely.

This approach is illustrated in Fig. 5, which shows a breakdown of the project into its constituent, yet interlinked, themes,

Crucial to achieveing the goal of indefinite deployment will be the ability to wirelessly recharge the on-board batteries of the individual “Pipebots”. To this end, initial experiments were carried out at the University of Leeds, to investigate the feasibility of using millimetre-wave wireless power transfer. Results and more detailed discussion follows in the next Section. Despite the use of a steel gas pipe, the findings will be applicable to similar metal pipes used in the water distribution network.

V. PIPEBOTS DEMOSTRATION

The use of high-power electromagnetic (EM) waves for Wireless Power Transmission (WPT) has been studied since the late 19th century [5], with arguably one of the most famous demonstrators being the ”Microwave Powered Helicopter” by W. C. Brown [6]. The two main modalities investigated by the research community are near-field non-radiative power transfer, such as magnetic, inductive, and capacitive coupling; and far-field power transfer through highly directional antennas [7], [8].

The near-field methods have successfully been adopted in commercial products for efficient charging of consumer electronics. With the increased popularity of Electric Vehicles (EV) concepts have been proposed for their continuous charging via capacitive coupling systems [9]. The main disadvantage of the near-field method of power transfer is the short maximum operating distance, which is on the order just a few centimetres [10]. On the other hand, far-field

Fig. 2 Asphalt 3D Printing Drone.

Fig. 3 Illustration of the automation process behind autonomous crack detection and filling.

systems suffer from large propagation losses through atmospheric attenuation and absorption, limiting the amount of power that can be delivered to a receiver [11]. Furthermore, regulations on transmitted power in the Industrial, Scientific, and Medical (ISM) bands further limit the potential deployments of such systems to low-powered Internet-of-Things sensors [12]–[14].

Recently, another mode of WPT has been proposed, and that is WPT in shielded metal pipes, which can potentially deliver higher power, on the order of several Watts, at distances up to tens of metres [15]. This is enabled by considering the pipes as circular waveguides, which support low-loss EM propagation [16]. This in turn opens up exciting opportunities for remote powering and charging of pipe inspection robots, eliminating the need for a tethered power connection.

Here we present experimental results of WPT to a small robot, designed to fit in and inspect 25.4 mm diameter gas pipes. Details of the robot prototype are given, as well as measurements of the electromagnetic propagation environment within the pipe used for these tests. Finally, a short discussion on the WPT module performance is included.

A. Scenario Description and Robot Prototype

A photograph showing the experimental setup is given in Fig. 6a. The pipe used is a decommissioned 2 metre long cast iron pipe. A Keysight E8267D Vector Signal Generator is used to provide the EM signal, which can then be coupled to the pipe through a standard gain horn antenna, as shown in Fig. 6b.

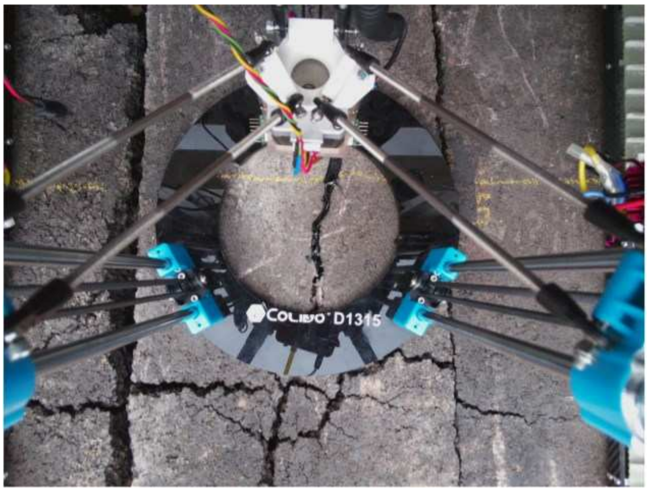


Fig. 4 Close-up view of a filled crack.

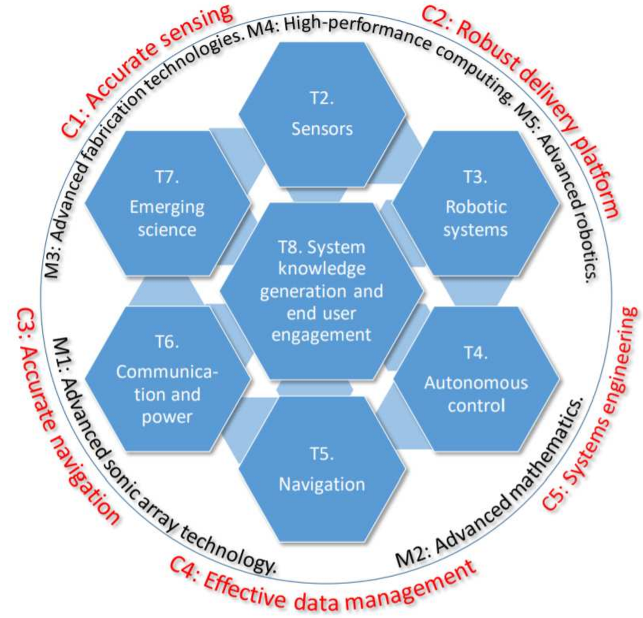


Fig. 5 Different themes of Pipebots project.

In this scenario, the aim is to deliver as much power as possible when the robot is at the far end of the pipe, with input RF power limited by the capabilities of the E8267D.

The details of the robot prototype are presented in Fig. 7a and Fig. 7b. The body of the robot is 3D printed as a whole using a Stratasys Objet1000 Multi-Material 3D printer, and houses the MCU (Pololu Baby Orangutan), a single brushed DC motor, backup batteries (2 x 3.7 V 100 mAh LiPo), as well as a night-vision camera. The robot also includes the PT module, which is discussed in Section V-B.

B. Pipe Propagation Measurements and WPT Module

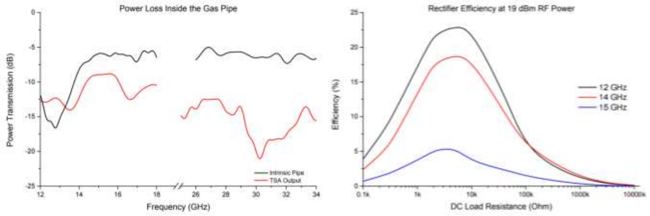
As mentioned earlier, metal pipes act as circular waveguides from an EM propagation point of view. The lowest cut-off frequency, i.e. the frequency below which propagation in the waveguide cannot occur, is an important parameter of any waveguide, and is dependent on its diameter. For the pipe used in this experiment, this was found to be 6.922 GHz [17].

Furthermore, the assumption for low loss is dependent on the surface roughness of the inside of the pipe being low [18]. In the case of the cast iron pipe used in this paper, this was found to not be the case, due to corrosion and material buildup on the inside surface of the pipes. The propagation loss inside the pipe was then measured using a Keysight N5247 PNA-X, resulting in Fig. 8a. Loss results are shown both for the pipe on its own, as well as a composite loss when a Tapered Slot Antenna (TSA) [19] is used at the receiver end. The frequency ranges for which data is presented correspond to those for which horn antennas were available at the time of the experiments.

Once the total propagation losses are known, and the RF input power level can be calculated, an RF-to-DC rectifier can be designed. It has been shown that the efficiency of a rectifier is a function of input power level, frequency, input impedance, and DC load resistance [20]. It is also dependent

(a) Top side of prototype robot (b) Bottom side of prototype robot

Fig. 7 Pipe inspection robot prototype.



(a) Electromagnetic propagation loss (b) Rectifier efficiency

Fig. 8 Overview of the electromagnetic performance of the measurement setup.

on the type of semiconductor element used, i.e. a diode or a transistor, as well as overall circuit topology [11], [20].

For the WPT receiver used with the prototype robot, an 8-stage voltage doubler topology was thus selected, using commercially available low-barrier Schottky diodes (Avago HSMS-286C). The circuit was implemented on a low-loss PTFE substrate (Duroid 5880), with a TSA used to couple the incoming EM energy to the rectifier. The output of the rectifier can then be connected to a voltage regulator and a battery charging circuit, although physical space might become an issue. Details of the rectifier circuit are included in Fig. 7a and Fig. 7b.

The rectifier, as well as the TSA, were designed with dual-band operation in mind, with the bands being Ku-band (12 GHz – 18 GHz) and Ka-band (26.5 GHz – 40 GHz). Rectification efficiency, defined as $\eta = P_{DC} / P_{RF}$, was found to be better for lower frequencies, with best performance (23%, 18 mW P_{DC}) obtained at a frequency of 12 GHz and 19 dBm of RF power at the input of the rectifier. A comparison between several frequencies in the Ku-band for different DC load resistances is presented in Fig. 8b

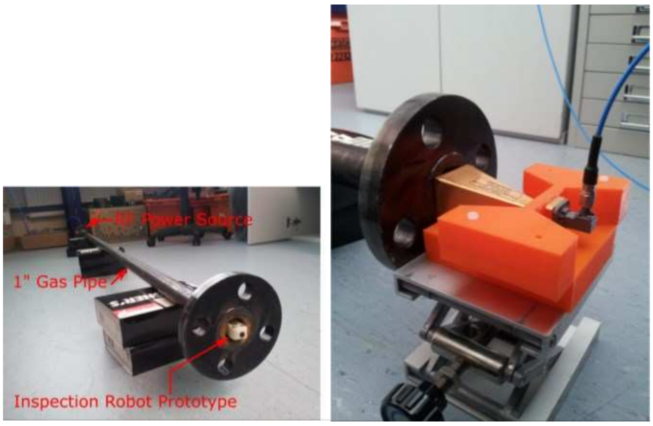


Fig. 6 Pipe measurement setup, including method of supplying RF power.

C. *Conclusion*

Experimental results on EM propagation in a metal pipe, as well as WPT for powering and charging of a prototype robot have been presented and discussed. We have successfully demonstrated RF-to-DC 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.

VI. DISCUSSION

The field of autonomous and large-scale deployments of infrastructure robotics is a nascent one, however it holds a lot of promise to improve the quality of life for everyone. The projects and research discussed in this contribution are just two ways in which this can be achieved. However, they both hold great promise and the potential to completely revolutionise the ways in which infrastructure in modern day cities is maintained and repaired

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