

# Application of Robotic and Autonomous Systems for Road Defect Detection and Repair - A Position Paper on Future Road Asset Management

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# Smart Infrastructure and Construction

## A Position Paper on Robotic Systems for Road Asset Management

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<b>Abstract:</b>	<p>The ever-growing urban population faces challenges of ageing infrastructure. The process for renewing the infrastructure is costly, and current practices for maintaining and repairing are often ineffective and labour intensive. Road networks, for instance, which act as the arteries for cities, suffer from reoccurring potholes (in the UK, a pothole is filled every 21 seconds: Asphalt Industry Alliance, 2018).</p> <p>A more effective way of maintaining road networks is through a proactive approach, where condition assessment and intervention are conducted throughout the asset lifecycle. However, there are barriers to a proactive approach, including budget constraints and the lack of effective technology for early defect detection (followed by a cheap yet effective repair). This paper puts forward an automated system, currently in development, based on cutting-edge robotic technologies to address these barriers and help achieve an effective proactive infrastructure maintenance and repair system. Technologies developed include automated condition assessment measures to detect road defects and repair technologies using a novel 3D printing method to seal road cracks and potholes. Sealing small cracks by using 3D printing techniques has shown promising results by achieving superior mechanical properties.</p>
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## Abstract

The ever-growing urban population faces challenges of ageing infrastructure. The process for renewing the infrastructure is costly, and current practices for maintaining and repairing are often ineffective and labour intensive. Road networks, for instance, which act as the arteries for cities, suffer from reoccurring potholes (in the UK, a pothole is filled every 21 seconds: Asphalt Industry Alliance, 2018).

A more effective way of maintaining road networks is through a proactive approach, where condition assessment and intervention are conducted throughout the asset lifecycle. However, there are barriers to a proactive approach, including budget constraints and the lack of effective technology for early defect detection (followed by a cheap yet effective repair). This paper puts forward an automated system, currently in development, based on cutting-edge robotic technologies to address these barriers and help achieve an effective proactive infrastructure maintenance and repair system. Technologies developed include automated condition assessment measures to detect road defects and repair technologies using a novel 3D printing method to seal road cracks and potholes. Sealing small cracks by using 3D printing techniques has shown promising results by achieving superior mechanical properties.

ICE Keywords:

Roads & highways; Infrastructure planning; Maintenance & inspection

## Abbreviations

CNN Convolutional Neural Networks

GPR Ground Penetrating Radar

NDT Non-destructive Technologies

PWM Pulse Width Modulation

RAS Robotic and Automatic Systems

RFID Radio Frequency Identification

UAV Unmanned Aerial Vehicle

## 1 Introduction

Flexible pavement structures (i.e. asphalt pavements) are the most common type of road surfacing in UK urban areas. Its wide application is due to a combination of factors: it creates

1 a safe and robust (strong, stiff and resilient) road surface for driving; road surfacing can be  
2 carried out rapidly and without complex machinery; it has good acoustic properties; it is  
3 repairable and indeed can self-repair (García, 2012). However, flexible pavements deteriorate  
4 over time due to the effects of repeated dynamic loading (Cebon, 1986; Henning, 2008),  
5 environmental conditions (e.g. temperature; Cawsey and Massey, 1988), surface water and  
6 groundwater (Simonsen *et al.*, 1997; Werkmeister *et al.*, 2003), and interaction with other  
7 infrastructure systems (e.g. a leaking pipe; Vipulanandan and Liu, 2005; Balkaya *et al.*, 2012).  
8 The deterioration may lead to decreased stiffness and increased brittleness of the road surface,  
9 crack formation (thereby allowing water ingress to the lower unbound layers and the ground),  
10 loss of aggregate and/or localised softening of the ground, and may lead to the development of  
11 potholes (Schlotjes, 2013; Thom, 2013).  
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20 The current road inspection and maintenance regime is mainly based on visual inspections  
21 followed by a reactive or emergency maintenance which is normally applied when a serious  
22 defect has occurred or is reported, e.g. a pothole. This current practice is blamed for recurring  
23 and perennial road defects and progressively worsening road conditions (UK Parliament,  
24 2013). The degraded road condition caused by the reactive approach imposes huge extra direct  
25 and indirect costs on the road asset management systems and wider economy. For example, in  
26 2018 in England and Wales alone, £28.3 million (including staff costs) was paid in  
27 compensation for damage to people or vehicles as a result of poor road condition (Asphalt  
28 Industry Alliance, 2018). The Asphalt Industry Alliance (2020, page 13) stated “*Maintenance  
29 costs increase as the structure of the roads deteriorate(s) and we are now starting to see the  
30 consequences of delaying intervention. It has got to the point where full reconstruction is  
31 needed*”. The cost of filling a pothole as part of a reactive approach is reported to be 65% higher  
32 than a planned a maintenance (Asphalt Industry Alliance, 2020). Furthermore, there are other  
33 socio-economic issues associated with the current inspection and maintenance approaches. For  
34 instance, the current practice involves, 1) visual detection of road deterioration, with inherent  
35 subjectivity, 2) closing off roads during daylight hours for a long period of time (urban road  
36 maintenance activities are normally done during the daytime because of noise level restrictions  
37 during the night), sometimes without any maintenance activity, with associated disruption to  
38 the traffic flow, 3) employing a maintenance crew and heavy lorries to carry the equipment and  
39 material to conduct the maintenance, with the associated health and safety issues and costs.  
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57 The UK Department for Transport (2012) estimates that the costs of disruption caused by  
58 streetworks exceeded £600 million per year in 2011. Most critically, fourteen road workers  
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1 were killed and over 300 were seriously injured between 2006 and 2016 (RoWSaF, 2016).  
2 Congested traffic, such as that caused by streetworks, emits four times as much pollution as  
3 free-flowing traffic thereby contributing to the estimated 40,000 premature deaths caused by  
4 poor air quality every year (Local Government Association, 2017).  
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7 Early detection and repair of road defects, within a proactive approach, can significantly save  
8 costs while extending the asset lifecycle. It is hypothesised that, through the deployment of  
9 robotic and automatic systems (RAS), the current practices for road condition assessment and  
10 repair will be enhanced significantly. RAS has the potential to replace the lengthy process of  
11 visual condition assessment, to achieve remote and automated inspection making early defect  
12 detection possible. This can be achieved either via drone flights and photography, or swarms  
13 of miniature (cheap and dispensable) land-based robots working on temporarily closed lanes  
14 overnight, leading to multiple (economic and social) benefits. RAS has the potential to make  
15 routine, regular problem diagnosis affordable leading to proactive asset management  
16 approaches.  
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19 Furthermore, utilising robotic road repair – particularly to intervene frequently and with  
20 minimal material to fix nascent defects before they become serious, for instance to treat road  
21 cracks via a 3D printed asphalt from drone-mounted (a future vision which has been proved by  
22 the research team) or land-based tracked robots (prototypes being created and trialled). This  
23 has the potential to extend the life of the asset, and minimise the need for heavy lorries to carry  
24 the equipment and material thus reducing the environmental impact. This has the potential to  
25 make routine, regular early-stage maintenance affordable and avoid more serious deterioration  
26 (such as pothole formation). RAS can also have a significant positive Health and Safety  
27 implication for both inspection and maintenance activities. Moreover, RAS can address the  
28 issue associated with the limited adaptation of a pro-active road asset management. This limited  
29 adaptation is mainly attributed to the cost (UK House of Commons, 2019) affected by the  
30 difficulty of gaining access during daylight hours, and its associated lane rental cost (Moran *et*  
31 *al.*, 2017).  
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34 As part of the current reactive approach, road asset owners tend to react to significant, serious  
35 or ‘catastrophic’ failures, while neglecting to repair defects at early stages of development,  
36 such as small cracks (Figure 1). However, an ‘effective crack treatment’ at early stages of  
37 development is suggested to extend the life of a road by two to five years (Chong, 1990; Eacker  
38 and Bennett, 1998; Masson *et al.*, 2003). Effective road crack treatment is achievable when  
39 applied to pavements with low to moderate crack density, and with cracks with little or no  
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branching (FHWA, 1998). Masson *et al.* (2003) concluded that a failed sealant is unlikely to show any improvement compared to the road without sealant, showing the importance of having an effective sealing procedure in place. They also concluded that crack treatment needs to be repeated during the lifetime of the pavement, as there is only a two to seven year durability expectation from current sealants.

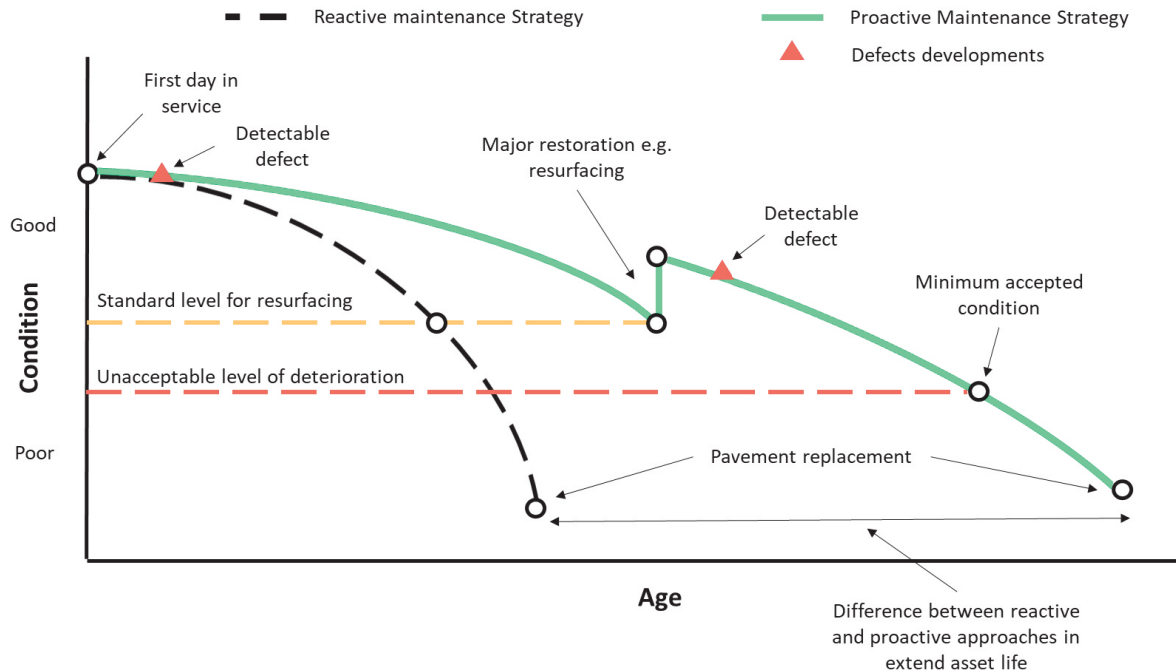


Figure 1: An illustration of differences between road reactive and proactive approaches

Crack repair is usually initiated based on the defected area or length, for instance in England a 0.5% to 5% wheel track cracking intensity are given as the lower and upper thresholds, respectively, for principal roads (Furness *et al.*, 2007). Most of the local authorities in the UK use a risk-based approach for categorising cracks, which is then used to prioritise them for associated intervention. For instance, Oxfordshire County Council (2011) uses a width of 30mm and a length of 300mm for cracks in minor carriageways as a threshold to classify a crack as a 'Safety hazard' prior to applying the risk assessment.

The methods and procedures for repairing cracks are not standardised in the UK and it is left to local authorities to decide whether to intervene and what method, material and procedure to use. Crack repair has been classified into two categories by Masson *et al.* (2003):

1. Crack sealing - rout and seal using hot mixture, normally used to treat cracks which open in winter and close in summer (called active cracks);

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2. Crack filling - no routing, both cold and hot mixture might be used, and can only be used to treat cracks that show little, if any, movement over time.

Crack sealing as a repair measure, when compared with the alternative method of crack filling, has higher installation costs, but is more cost effective (Masson *et al.*, 2003). The repair procedure can be affected by various factors, including the asphalt and the ambient temperature, the humidity, the crack size and the cleaning method, as well as the temperature and the heating time of the sealant, and its finish and protection (Masson *et al.*, 2003).

This position paper sets out the authors' vision on application of RAS in detecting road defects and cracks and repairing them, including a developed 3D printer for sealing cracks. The ambition is to radically change the way asphalt pavements are repaired by developing an automated system to locate defects (cracks and potholes) in the road surface while they are still relatively small, and deploy an autonomous robot to repair them before they become defects requiring streetworks intervention. This has the potential to revolutionise the way roads are maintained, while reducing road closures, risks to operators and indirect costs incurred by road users due to streetworks. Section 2 presents a review of RAS applications in the construction industry; Section 3 presents a developed robotic and automated road repair and 3D printing; discussion is provided in Section 4; and conclusions are drawn in Section 5.

## 2 Robotic and Automation in Construction Industry

In order to place the use of RAS for road condition assessment and repair into context, the recent applications of RAS in the construction industry are reviewed. This includes proof of concepts achieved in applications focusing on automated condition assessment and repair that informed the development of the automation aspect for the road inspection and repair RAS.

RAS has been utilised in the construction industry with various applications including tying steel reinforcements, bricklaying, welding and installation of steel frames, earthwork and excavation (Narasimha Prasad and Agrawal, 2019). RAS has been utilised to tackle the challenge of working in harsh conditions and environments (Lia and Leung, 2017). For instance, robots have been used for working at height to install window glass and steel modules, see Bogue (2018) for commercial and industrial developments. Choi *et al.* (2005) reported the development of a robotic platform equipped with pneumatic actuator which was trialled for assisting in the installation of heavy ceramic tiles (with the weight of 5 kg), alongside a human, with the potential to be utilised for installation of different materials.

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1 Pre-fabrication construction has huge potential for automation both during the construction, in  
2 a factory (Bock, 2008) and the installation on site, as the robotic system can deal with expected  
3 geometry and material. Kasperzyk *et al.* (2017) developed an automated robotic system to  
4 enhance flexibility in redesigning prefabrication during the installation phase, which was  
5 successfully demonstrated using small ‘Jenga’ blocks. Willmann *et al.* (2016) developed an  
6 automated installation system for timber structures, consisting of a robotic arm and a gantry  
7 robot, which was positively trialled to assemble a roof built of 48,624 timber boards at a  
8 maximum length of 3.17m.

## 15 2.1 RAS for Condition Assessment

17 For RAS to be successful, both the propulsion and data processing from a range of different  
18 sensors needs to be automated. Several kinds of sensors can be used to replace the current  
19 visual inspection process for road condition assessment. For instance, robotic platforms could  
20 be equipped with automated visual measurements using cameras working in the visible  
21 spectrum or other spectral bands, to capture digital images and identify anomalies using  
22 suitable algorithms. Similarly, road cracks can be detected using a combination of several basic  
23 algorithms that may include edge detection, image segmentation, texture analysis and 3D  
24 segmentation. Ouma and Hahn (2016) constructed an automatic recognition approach of linear  
25 cracks based on the wavelet-morphology and circular Radon transform methods, which was  
26 successfully tested and achieved an average crack detection of 83.2% with an average  
27 processing time of 125 seconds.

38 Recently, deep learning (e.g. Convolutional Neural Network, CNN) using different learning  
39 architectures has been used to automatically detect cracks in the road in images. In deep  
40 learning, the number of convolution layers, which consists of a filter to extract local contextual  
41 features (White *et al.*, 2017), is an important variable. Cha *et al.* (2017) described a method for  
42 the detection of concrete cracks through automated detection of the defect image features, using  
43 a deep architecture of CNN. They used four convolution layers and reported a robust  
44 performance of the method at detecting thin cracks under natural lighting conditions compared  
45 to two more complex traditional methods, namely Canny and Sobel edge. CNN has also been  
46 used within an automated crack detection method, for example, Zhang *et al.* (2016) created an  
47 automated road crack detection method by training supervised deep CNN to classify each  
48 image patch in the collected images. They used six convolution layers for binary crack  
49 detection on roads. A training set of 600k images and 200k for testing was used and achieved  
50 87% accuracy in detecting cracks. The results were compared with two different methods,  
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namely support vector machine and Boosting, which achieved accuracies of 81% and 73% respectively.

Despite the data processing being relatively time-consuming compared to the time required to collect the data (Zhang *et al.*, 2018), image processing has been utilised on RAS, for instance by Knyaz and Chibunichev (2016) who included photogrammetric techniques for generating a 3D model and to assess road conditions by including road features such as macro-texture, longitudinal and transversal evenness profiles, and also cracks and potholes. The technique was tested during an experiment on a test track using cameras mounted on an Unmanned Aerial Vehicle (UAV) and taking images from a height of 30m. Measurements associated with road surface deformation with an accuracy of 0.1mm and a resolution within 0.3mm for the 3D model were achieved. Image processing for identifying pavement distresses has also been utilised on robotic platforms, e.g. Tseng *et al.* (2011) and Li *et al.* (2016).

Wang *et al.* (2011) developed a prototype laser scanner for an automatic high-speed road assessment, which aimed to achieve 1mm resolution, under natural lighting conditions (day and night), and detect rutting and cracking. The proposed system claimed to have the following capabilities: identifying surface distresses, road profiling, transverse profile for identifying rutting and longitudinal profile for measuring roughness, measuring macro-texture, and roadway geometry, but it is only operative when the pavement surface is dry. However, due to budget limitations, the developed prototype was not fully tested. A similar system was developed by Yu *et al.* (2007), in which a video camera was also deployed. Li *et al.* (2020), also reported in Li *et al.* (2019), utilised a point laser system mounted on a vehicle to automatically detect road fretting. The proposed system used pre-processing algorithms to remove noise caused by the moving vehicle and a signal processing algorithm to identify changes in road surface texture. The data processed by the developed system was compared with a visual assessment survey for four road sections and achieved the same level of accuracy.

Inspections of concrete bridges and slabs (also known as rigid pavement) using robotic systems has attracted more attention compared to the flexible roads. This might be due to the fact that asphalt is a more complex structure compared to concrete as it consists of more layers and is less homogeneous. For instance, a robotic system called Rabbit (Robotics Assisted Bridge Inspection Tool) was developed in the USA for bridge deck condition assessment (Gucunski *et al.*, 2013; La *et al.*, 2013a; La *et al.*, 2013b). Rabbit used a number of non-destructive technologies (NDTs) to detect concrete defects, corrosion and delamination and also to measure concrete elastic modulus. These were cameras in the visual spectrum, ground

1 penetrating radar (GPR), impact echo, ultrasonic, capacitive resistivity, and laser scanner (La  
2 *et al.*, 2014). The robot, which covers a 1.83m width in each scan and is able to scan a distance  
3 of 53m within 50 minutes, has been tested during a number of field trials and the results have  
4 been presented in various publications (Gucunski, 2012; Gucunski *et al.*, 2013; La *et al.*, 2013a;  
5 La *et al.*, 2013b; La *et al.*, 2014), however, it seems that a deep analysis and interpretation of  
6 the results is missing from the publications.  
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11 In Germany a multi-sensor self-navigating robotic system, called BetoScan, was developed and  
12 utilised for condition assessment of concrete slabs in bridges and parking decks, looking in  
13 particular for corrosion (Cotič *et al.*, 2014). The following NDT sensors were deployed on the  
14 BetoScan (Wiggenhauser *et al.*, 2008; Reichling *et al.*, 2009):  
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- 19 a. Cameras in the visual spectrum and using image processing; for locating cracks and  
20 defected areas
- 21 b. Microwaves; for humidity distribution used to identify corrosion
- 22 c. Ultrasonic; for measuring voids and crack depth and layers thickness
- 23 d. Temperature probes;
- 24 a. Eddy current method (Electrical Resistivity method) and GPR; for locating rebars and  
25 measuring its cover
- 26 b. Electrochemical Potential sensors; for detecting and mapping corrosion
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35 This section showed the successful applications of RAS in condition assessment, while  
36 highlighting areas for further improvements especially on the automation of the data processing  
37 in order to make RAS useable routinely in practice. The next sections present applications of  
38 RAS in construction and repair.  
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## 42 2.2 Autonomous Movement

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45 Navigation of ground robots on a construction site and also harsh environment with various  
46 unpredicted obstacles might impose a serious risk and limitation to the wide deployment of  
47 RAS in construction (Davila Delgado *et al.*, 2019). Potential solutions, however, seem  
48 promising where UAVs have been used to control and navigate ground robots. Asadi *et al.*  
49 (2020) have developed a control algorithms and trialled it inside a building to simulate an  
50 indoor construction site. The trial successfully demonstrated autonomous navigation using the  
51 UAV to follow a manually controlled ground robot, so the UAV can indirectly follow human  
52 navigation orders as a demonstration of a scenario where autonomous robots and humans  
53 would work together on a construction site.  
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1 The concept of introducing highly automated machines to construct roads dates back to the  
2 1980s (Parker and Draper, 1998). Rupp *et al.* (1998) reviewed the state-of-the-art for automated  
3 road construction methods and Osmani *et al.* (1996) evaluated 25 different road maintenance  
4 techniques and evaluated the conceptual feasibility and cost benefits associated with  
5 automation. It was estimated then that over a 30 year period in the state of Texas, USA, the net  
6 present worth of automated crack sealing could be in the hundreds of millions of dollars  
7 (Osmani *et al.*, 1996).  
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12 Road maintenance systems that can identify and seal cracks have been trialled for example the  
13 Automated Crack Sealing Machine (ACSM) (Winters *et al.*, 1994; Bennett *et al.*, 2003) which  
14 used two-line scan cameras for crack detection and a Selective Compliance Articulated Robot  
15 Arm (SCARA) for the sealing operations, using a pressurised injection system for bitumen  
16 heated up to 200°C. The developed technology was successfully tested for filling cracks at a  
17 rate of 8 km/hr (Bennett *et al.*, 2003). Another crack sealing prototype was developed at  
18 Carnegie Mellon University, and The University of Texas at Austin (Hendrickson *et al.*, 1991;  
19 Haas *et al.*, 1992; Greer *et al.*, 1997) which developed perception and control methods to enable  
20 effective automation of routed pavement crack sealing. The system used laser sensors and  
21 video cameras for automated crack detection and was equipped with heated air torch and a  
22 nozzle to pour bitumen installed on a design x-y table (1.5m × 3m), similar to a 3D printing  
23 system (Haas *et al.*, 1992). The developed system was tested in both laboratory and field  
24 environments and led to a field prototype, however details of the experiments were not  
25 reported. The University of Texas at Austin (Haas, 1996) reviewed the evolution of an  
26 automated crack sealer alongside its design cycle, economic feasibility, and implementation.  
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41 The Tethered Mobile Routing Robot (TMRR) by Hong *et al.* (1997) focussed on mobility as a  
42 key feature to follow the irregular patterns usually found with road surface cracks. The repair  
43 process began with the equipped router cutting a channel in the path of the crack to allow for  
44 increased penetration of a pressurised hot thermoplastic sealant using the sealant applicator on  
45 a gantry system. The developed system was successfully tested in the laboratory environment  
46 and was able to detect and follow a crack in the form of a straight line rather than a natural  
47 irregular crack, with a width of 6.4mm.  
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54 The growth of 3D printing, also known as additive manufacturing or rapid prototyping, has  
55 steadily gained recognition (Gross *et al.*, 2014), and has been used in building construction  
56 (e.g. Bogue, 2018). The application of 3D printing technology for road repairs has been tested  
57 for spall damage repair by using printers to produce negative moulds of damaged spalls into  
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1 which concrete is poured, cured and finally glued to the damaged area (Yeon *et al.*, 2018). In  
2 contrast, Jackson *et al.* (2018) suggested that durable and efficient repairs could be conducted  
3 using screw extrusion-based 3D printing as this enables autonomous approaches to road repair.  
4 Similar proposals were made by Buswell *et al.* (2018) for other common infrastructure  
5 materials such as concrete. However, there is a wide range of material, environmental and  
6 situational variables for every road defect, as well as its individual or collective geometry,  
7 increasing the requirements significantly for true autonomy. These additive manufacturing  
8 techniques also invite the introduction of different material mixes that can have different  
9 properties at different points in the volume of the repair at different print times for more  
10 advanced and cost effective repair materials. Examples include a surface containing a more  
11 expensive but functionally superior nano- or microscale material than the bulk, as well as the  
12 preselection of a range of graded aggregate/ binder mix pellets to be added to the print  
13 feedstock at precomputed times based on the geometry of the structure to be manufactured, in  
14 order to mechanically grade larger repairs (or construction). Potential additions include self-  
15 repairing oil capsules (Al-Mansoori *et al.*, 2018), induction heated materials (Liu *et al.*, 2011),  
16 a wide variety of recycled materials such as polymers (Huang *et al.*, 2007), reclaimed asphalt  
17 (Oliveira *et al.*, 2013) and graphene (Yao *et al.*, 2016), as well as other nanoscale materials to  
18 influence material properties (Antonovič *et al.*, 2010).

19 The addition of materials that heat up when subjected to magnetic induction, such as steel  
20 fibres, offer better repair bonding than current cold mix methods for either direct printing or  
21 patching with prefabricated tiles (Obaidi *et al.*, 2017). Other material additions are able to offer  
22 more long-term, flexible and durable solutions for defect repair (Butt *et al.*, 2016). In addition,  
23 more advanced smart components such as radio frequency identification (RFID) tracking  
24 (Ergen and Akinci, 2007) could be introduced during a low temperature material extrusion,  
25 perhaps during (or at the end of) another type of repair, enabling a more proactive, and therefore  
26 more efficient, maintenance system. As well as screw extrusion of melted material, similar  
27 unheated systems could deliver pellets to a defect, which could then be inductively heated to  
28 conform and bond to the exposed surface (Obaidi *et al.*, 2018). Both of these material  
29 deposition methods would also go some way to increasing the energy efficiency of repairs,  
30 given the current energy costs of material transportation and heating (Zapata and Gambatese,  
31 2005). Combined with commensurate advances in computer vision, robotics and machine  
32 learning, repair of road defects via additive manufacturing promises a very capable solution  
33 that may also influence material composition and infrastructure design in the future.



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Having highlighted recent developments in RASs in the construction industry and the potential of automated defect detection using a range of sensors and the forthcoming potential additive manufacturing offers to repair defects, the Self-Repairing Cities research project ([www.selfrepairingcities.com](http://www.selfrepairingcities.com)) set out to exploit these advances. The following section briefly summarises the progress made to date.

### 3 Developed Robotic Repair and 3D Printing

The Self Repairing Cities project has implemented innovative asphalt 3D printing technology to fill-in cracks and potholes (Figure 2). This approach includes positioning an extruder nozzle in the vicinity of the cracks and then 3D printing the material to seal them. The extruded material proved to have superior mechanical properties by being more ductile and exhibiting the ability to deform under stress before failure (Jackson *et al.*, 2018). There is a challenge in getting the extruder nozzle into the correct location and using it to fill irregular cracks and potholes, which has been addressed by Self-Repairing Cities project using an image processing technique. To ensure a quick, autonomous response to the detected anomalies, the asphalt extruder developed by the University College London (Jackson *et al.*, 2018) is installed on a hybrid aerial-ground vehicle developed at the University of Leeds. The extruder houses an aluminium tube enclosing a printed Archimedes screw, which is attached to a stepper motor. Three equidistant power resistors supply heat to the asphalt chamber, controlled via a thermistor. This enables the additive manufacture of pelleted materials such as asphalt in a compact, lightweight package, and under a range of working temperatures.

The extruder is installed on a delta arm modified from a commercial 3D printer, retrofitted onto a UAV with tracks that allow for ground manoeuvring (Figure 3).

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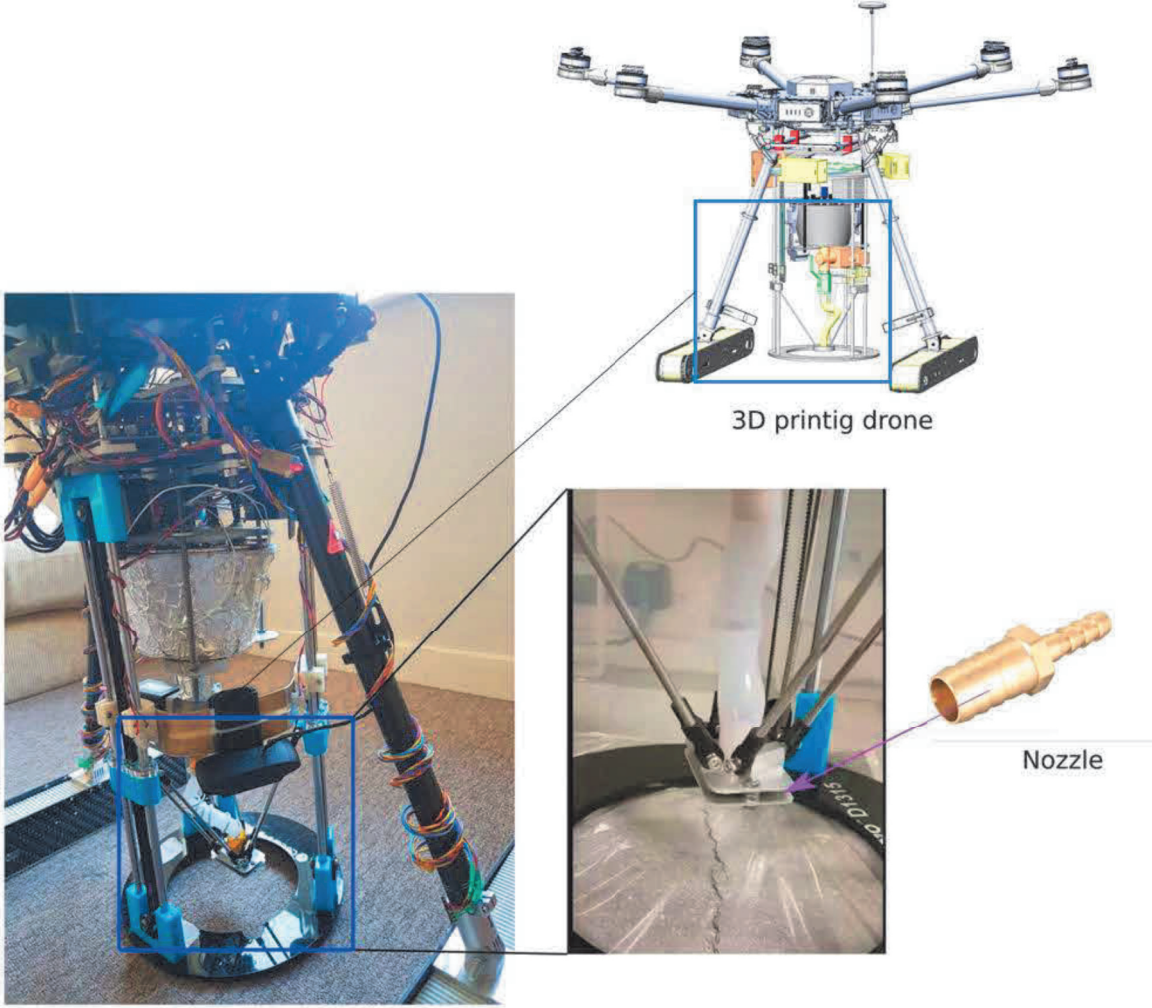
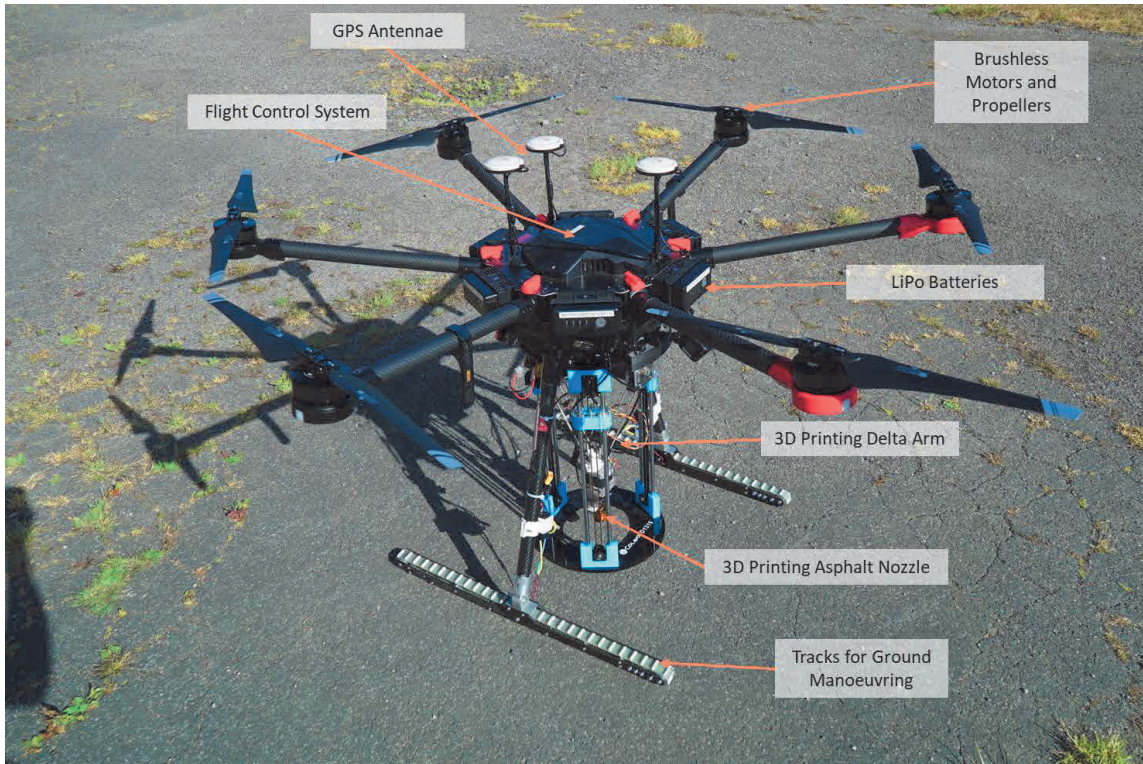
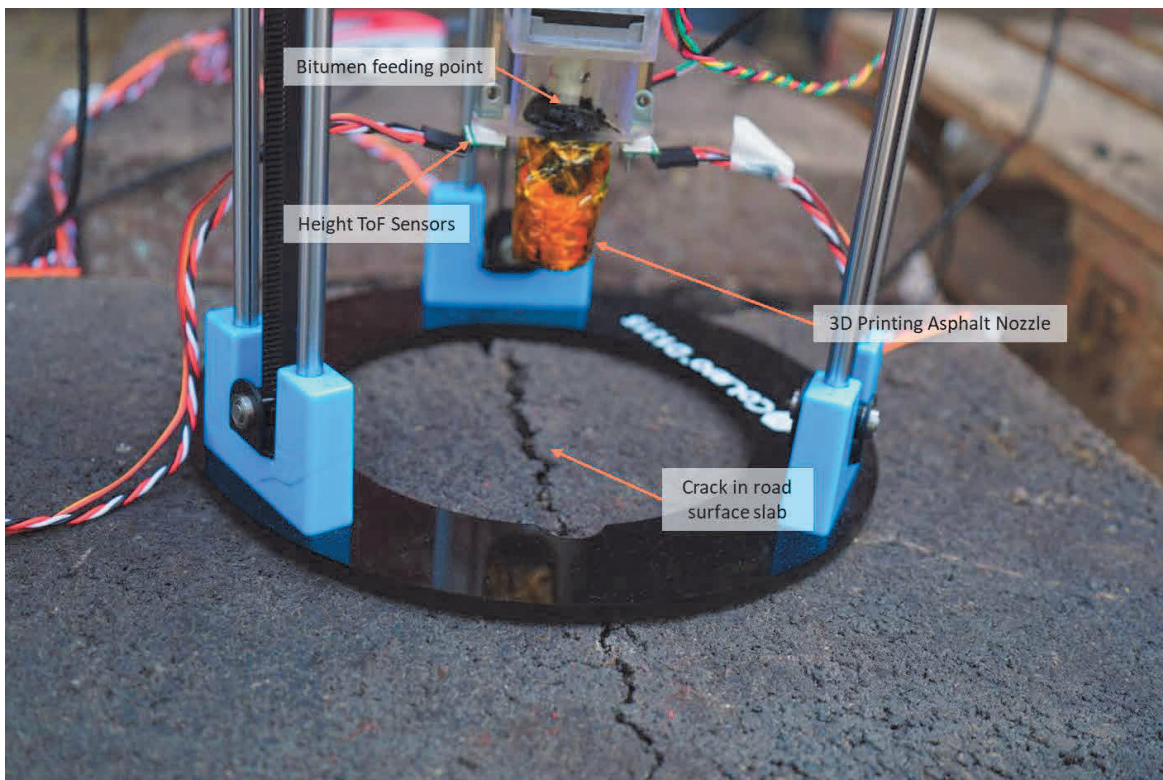


Figure 2: 3D asphalt drone



(a)



(b)

**Figure 3: (a) 3D printing asphalt UAV, (b) detailed view of the printing arm**

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The UAV is a modified hexrotor DJI M600 Pro with a payload capacity of 6.5 kg and nearly 20 minutes of flight time at full payload. It relies on a redundant system composed of 6 motors,

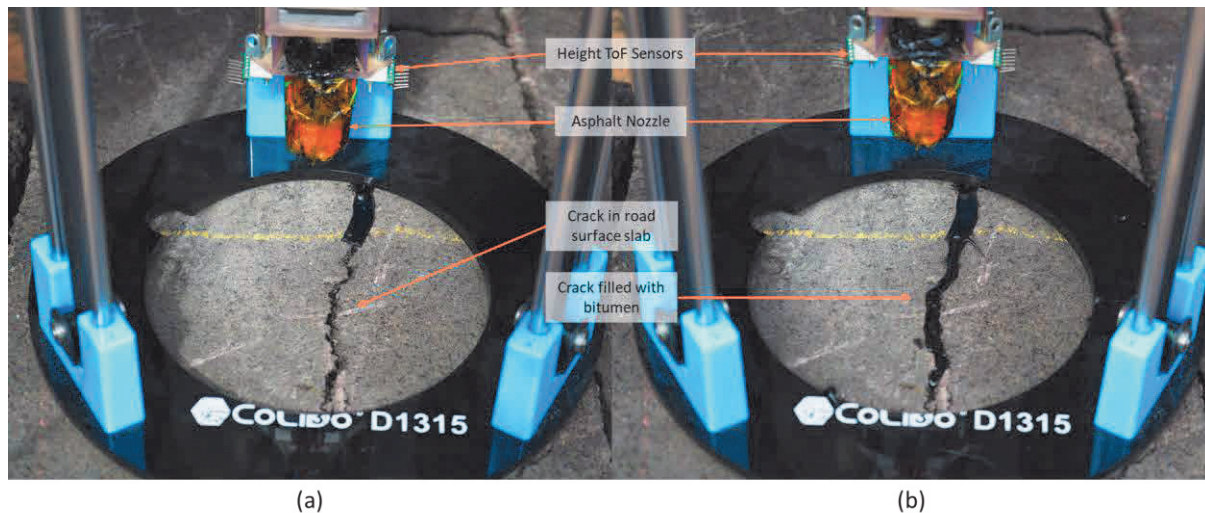
1 6 batteries, 3 IMUs and 3 GPS antennae in order to provide more reliability to the autonomous  
2 flight operation. The UAV's flight controller is commanded by an Intel Nuc companion  
3 computer that is responsible for autonomous navigation in the air as well as autonomous  
4 driving on the ground and control of the repair system. The UAV receives a list of prioritised  
5 crack locations in the form of GPS coordinates and an estimation of the material required to  
6 fill those cracks. Once released from its base station with the repair material on-board, the UAV  
7 flies autonomously to the first crack location and lands within 2m of the crack coordinates. The  
8 on-board companion computer is responsible for running a crack detection neural network to  
9 find the cracks in the vicinity of the aircraft once it has landed. The companion computer  
10 controls the tracks in order to navigate the UAV to the nearest crack, position it over the crack  
11 and begin the repair process. A downward facing camera detects the crack and generates an  
12 appropriate tool path for the 3D printing nozzle to follow. The volume required for extrusion  
13 is estimated from the size of the crack and factored into the 3D printing process. The UAV is  
14 able to move while filling a crack or pothole when their size exceeds the operation area of the  
15 printing arm. The current design allows for 2.5kg of repair material to be carried by the UAV,  
16 i.e. approximately 2.5 litre of pure bitumen. Considering two sizes of cracks, 3mm and 5mm  
17 wide cracks, and assuming 60mm depth, this volume is enough to seal 13.8m of 3mm cracks  
18 and 8.3m of 5mm cracks. The use of the UAV repair system is beneficial in areas where there  
19 are relatively small cracks that are geographically dispersed. The system is envisioned to be  
20 used in a team of heterogeneous robots that maximise the advantages of each individual robotic  
21 system.

22 The bespoke tracks were designed and manufactured for the UAV to ensure the size remains  
23 similar to the stock landing struts of the UAV and the weight is minimal to not exceed the  
24 UAV's payload capacity. These are also easily removable for maintenance and can be  
25 remounted on other UAVs as required. These are each controlled with in-built control boards  
26 receiving the common Pulse Width Modulation (PWM) signal alongside a 3–4 cell LiPo  
27 voltage range. They allow the 16.5kg UAV to move on the ground with speeds of up to 0.5m/s.

28 The current fixing method utilises an additional camera aimed towards the printer workspace  
29 to identify and compute a work path for the printer nozzle. The nozzle will follow the direction  
30 of the crack and extrude asphalt material at a temperature that allows the asphalt to flow into  
31 the crack and therefore filling it in a single pass. The ideal speed and temperature for this  
32 process are still to be identified and will depend on the external environment. Irregular crack

1 shapes or pothole forms can now be fixed. Figure 4 shows an irregular crack autonomously  
2 detected and filled with asphalt by the Self-Repairing Cities system.  
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4 The developed UAV plays a key role in the automated inspection and maintenance system of  
5 city infrastructures, and offers a platform for further development of aerial maintenance robots.  
6 The developed 3D printing system, ultimately, will be utilised along with a crack detection  
7 process to inform an automated decision making on the required material to be carried around  
8 and to ensure that there is no shortage or excess of material.  
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Figure 4: (a) Irregular crack to be filled (b) Crack autonomously filled with asphalt.

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4 Discussion

37 The presented UAV concept is an autonomous means of crack repair for bituminous roads that  
38 drastically reduces road closure time and associated traffic congestion. It also provides the  
39 benefit of being able to cover a larger area with dispersed detected defects in less time  
40 compared to a ground vehicle. The UAV concept reduces the repair cost, through early  
41 detection and repair of defects and hence extension of an asset's lifetime (Figure 1), while also  
42 reducing the risk to road workers and the maintenance operation time by eliminating or  
43 minimising the need for a road closure setup. CO<sub>2</sub> emissions are reduced due to low energy  
44 consumption, mainly through removing the need for large vehicles to conduct the inspection  
45 and repair while achieving efficient heat delivery to melt the bitumen and the reliance on  
46 electricity.  
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56 Other means of autonomous crack repair are under investigation such as using electric  
57 autonomous ground vehicles equipped with an array of bitumen 3D printing arms combined  
58 with the ability to detect cracks. The autonomous ground vehicle is envisioned to detect and  
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1 seal cracks while driving which allows larger stretches of roads to be covered and minimizes  
2 effects on traffic flow. Such a vehicle will have the advantage of being able to operate  
3 throughout the night, when traffic is low, eliminating the risk of people working at night on  
4 dangerous roads.  
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7 In addition to the technological aspect of RAS in road condition assessment and repair, Self-  
8 Repairing Cities is investigating the interactions between technology, society and the  
9 ecological environment to make sure this technology will enhance balancing our resources for  
10 a more sustainable future (Raul *et al.*, 2017).  
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14 Despite the aforementioned positive aspects of deploying an UAV for automated road crack  
15 sealing, some questions over its practicality and effectiveness might be raised. For instance,  
16 the speed of 3D printing asphalt mounted on an UAV for sealing a longitudinal crack might  
17 seem slow when compared to an operator or other automatic techniques (e.g., an autonomous  
18 vehicle). To increase the UAV operational speed on the ground, it has currently been equipped  
19 with tracks. At the same time, it should be noted that the developed successful 3D printing  
20 mechanism can be utilised on ground robots, an ongoing research, which can be deployed  
21 independently or along with the UAV system based on the working condition. This has the  
22 potential to speed up the repair operation.  
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32 While landing an UAV on the road pavement might be regarded as more dangerous than the  
33 visual inspection process, it should be noted that this road or lane closures are envisaged to  
34 reduce the risk. However, the size of the UAV will allow minimising disruption to the road  
35 (both the required time and space) when compared to the current operation, while eliminating  
36 the existing risk to the street works operators.  
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42 The required energy to heat small amounts of material may also raise questions over the  
43 efficiency and efficacy for UAVs when compared to the large quantities of bitumen used within  
44 current practices, the success of the proposed method, therefore, depends on the insulation  
45 efficiency of the system. The energy efficient system will just carry small quantities of asphalt,  
46 supplied by a central station with larger capacities, with minimum energy required to just  
47 maintain the temperature. Ongoing research is working on improving the efficiency of the  
48 system. Moreover, a whole systems cost analysis is required to include the improved road  
49 condition and thus reduced maintenance cost and reduced labour costs.  
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57 The risks associated with the 3D printing UAV autonomously flying above residential areas  
58 should also be investigated, identifying measures to mitigate or control the associated risks.  
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1 The other aspects of the proposed system, which should be investigated in order for industry  
2 to adopt the technology, are its reliability, safety and cost-effectiveness. Large-scale trials are  
3 underway to investigate the reliability of the system compared to the current practices. This  
4 will also enable to assess the cost-effectiveness of the system taking a whole systems approach.  
5 The research question for the trials is how effective the 3D printing would be in preventing  
6 further developments of the cracks when compared to the current practices.  
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## 10 11 **5 Conclusions**

12 Early detection and repair of road defects have been identified as an effective cost saving  
13 approach for cities. However, as discussed in this paper, current common practices are typically  
14 unable to detect defects at an early enough stage. Furthermore, the current practices are costly  
15 and disrupting the traffic while putting workmen life in danger. RAS equipped with the right  
16 technologies has not been utilised for assessing the condition of asphalt pavement and  
17 autonomously repair the detected defects, and these are the main objectives of the Self-  
18 Repairing Cities Project. This will allow early detection and repair of defects within a proactive  
19 asset management strategy.  
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28 The 3D printer developed by the Self-Repairing Cities project has been presented as a method  
29 to more effectively seal cracks at their early stages, using the benefit of an in-house RAS  
30 system. Utilising such an automated system has the potential to prevent pothole formation with  
31 the associated huge economic, social and environmental benefits for the society.  
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## 38 **6 Acknowledgements**

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40 Science Research Council (EPSRC) through the grant EP/N010523/1 (Balancing the Impact of  
41 City Infrastructure Engineering on Natural Systems using Robots).  
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## 47 **7 References**

- 48 Al-Mansoori, T., J. Norambuena-Contreras and A. Garcia (2018). "Effect of capsule addition  
49 and healing temperature on the self-healing potential of asphalt mixtures." Materials and  
50 Structures **51**(2).  
51  
52 Antonovič, V., I. Pundiene, R. Stonys, J. Česniene and J. Keriene (2010). "A review of the  
53 possible applications of nanotechnology in refractory concrete." Journal of Civil Engineering  
54 and Management **16**(4): 595-602.  
55  
56 Asadi, K., A. Kalkunte Suresh, A. Ender, S. Gotad, S. Maniyar, S. Anand, M. Noghabaei, K.  
57 Han, E. Lobaton and T. Wu (2020). "An integrated UGV-UAV system for construction site  
58 data collection." Automation in Construction **112**: 103068.  
59  
60  
61  
62  
63  
64  
65

1 Asphalt Industry Alliance (2018). Annual Local Authority Road Maintenance (ALARM).  
2 Bristol, UK. 20.

3 Asphalt Industry Alliance (2020). Annual Local Authority Road Maintenance (ALARM).  
4 Bristol, UK. 20.

5  
6 Balkaya, M., I.D. Moore and A. Sağlamer (2012). "Study of non-uniform bedding due to voids  
7 under jointed PVC water distribution pipes." Geotextiles and Geomembranes **34**: 39-50.

8  
9 Bennett, D., X. Feng and S. Velinsky (2003). "Robotic machine for highway crack sealing."  
10 Transportation research record **1827**(1): 18-26.

11 Bock, T. (2008). Construction Automation and Robotics.

12 Bogue, R. (2018). "What are the prospects for robots in the construction industry?" Industrial  
13 Robot: An International Journal.

14  
15 Buswell, R.A., W.R. Leal de Silva, S.Z. Jones and J. Dirrenberger (2018). "3D printing using  
16 concrete extrusion: A roadmap for research." Cement and Concrete Research **112**: 37-49.

17  
18 Butt, A.A., B. Birgisson and N. Kringos (2016). "Considering the benefits of asphalt  
19 modification using a new technical life cycle assessment framework." Journal of Civil  
20 Engineering and Management **22**(5): 597-607.

21  
22 Cawsey, D.C. and S.W. Massey (1988). "In service deterioration of bituminous highway  
23 wearing courses due to moisture-susceptible aggregates." Engineering Geology **26**(1): 89-99.

24  
25 Cebon, D. (1986). Road damaging effects of dynamic axle loads. Proceedings, International  
26 Symposium on Heavy Vehicle Weights and Dimensions, Kelowna, British Columbia.

27  
28 Cha, Y.J., W. Choi and O. Büyüköztürk (2017). "Deep learning- based crack damage detection  
29 using convolutional neural networks." Computer- Aided Civil and Infrastructure Engineering  
30 **32**(5): 361-378.

31  
32 Choi, H.-S., C.-S. Han, K.-y. Lee and S.-h. Lee (2005). "Development of hybrid robot for  
33 construction works with pneumatic actuator." Automation in Construction **14**(4): 452-459.

34  
35 Chong, G.J. (1990). "Rout and Seal Cracks in Flexible Pavement- A Cost-Effective Preventive  
36 Maintenance Procedure." Transportation Research Record **1268**(1990): 8-16.

37  
38 Cotič, P., E. Niederleithinger and M. Stoppel (2014). Unsupervised fusion of scattered data  
39 collected by a multi-sensor robot on concrete. DGZfP-Jahrestagung Potsdam, Germany,  
40 Deutsche Gesellschaft für Zerstörungsfreie Prüfung (DGZfP): 1-8.

41  
42 Davila Delgado, J.M., L. Oyedele, A. Ajayi, L. Akanbi, O. Akinade, M. Bilal and H. Owolabi  
43 (2019). "Robotics and automated systems in construction: Understanding industry-specific  
44 challenges for adoption." Journal of Building Engineering **26**: 100868.

45  
46 Department for Transport (2012). Street Works (Charges for Unreasonably Prolonged  
47 Occupation of the Highway) (England) Regulations 2011.

48  
49 Eacker, M.J. and A.R. Bennett (1998). Bituminous Crack Filling Test Section on US-10 Near  
50 Ewart. Michigan Department of Transportation,

51  
52 Lansing, Michigan.

53  
54 Ergen, E. and B. Akinci (2007). An Overview of Approaches for Utilizing RFID in  
55 Construction Industry. 2007 1st Annual RFID Eurasia.

56  
57 FHWA (1998). Techniques for pavement rehabilitation - Reference manual, 6th edition.  
58 Washington, DC, F.H. Administration.

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64  
65

Furness, G., S. Barnes and A. Wright (2007). Crack Detection on Local Roads—Phase 2.

García, Á. (2012). "Self-healing of open cracks in asphalt mastic." Fuel **93**: 264-272.

Greer, R., Y.-S. Kim and C.T. Haas (1997). Telerobotic Control for Automated Pavement Crack and Joint Sealing, Transportation Research Board.

Gross, B.C., J.L. Erkal, S.Y. Lockwood, C. Chen and D.M. Spence (2014). Evaluation of 3D printing and its potential impact on biotechnology and the chemical sciences, ACS Publications.

Gucunski, N. (2012). "Comprehensive Condition Assessment of Concrete Bridge Decks by Multiple NDE Technologies." HDKBR INFO Magazin **2(2)**: 3-9.

Gucunski, N., A. Maher, B. Basily, H. La, R. Lim, H. Parvardeh and S. Kee (2013). "Robotic platform robot for condition assessment of concrete bridge decks using multiple nde technologies." HDKBR INFO Magazin **3(4)**: 5-12.

Haas, C. (1996). "Evolution of an automated crack sealer: a study in construction technology development." Automation in construction **4(4)**: 293-305.

Haas, C., C. Hendrickson, S. McNeil and D. Bullock (1992). A field prototype of a robotic pavement crack sealing system. Proceedings of the 9th International Symposium on Automation and Robotics in Construction (ISARC), Tokyo, Japan.

Hendrickson, C., S. McNeil, D. Bullock, C. Haas, D. Peters, D. Grove, K. Kenneally and S. Wichman (1991). Perception and control for automated pavement crack sealing. Applications of Advanced Technologies in Transportation Engineering, ASCE.

Henning, T.F.P. (2008). The development of pavement deterioration models on the state highway network of New Zealand. PhD, University of Auckland.

Hong, D., S.A. Velinsky and K. Yamazaki (1997). "Tethered mobile robot for automating highway maintenance operations." Robotics and Computer-Integrated Manufacturing **13(4)**: 297-307.

Huang, Y., R.N. Bird and O. Heidrich (2007). "A review of the use of recycled solid waste materials in asphalt pavements." Resources, Conservation and Recycling **52(1)**: 58-73.

Jackson, R.J., A. Wojcik and M. Miodownik (2018). "3D Printing of Asphalt and its effect on Mechanical Properties." Materials & Design.

Kasperzyk, C., M.-K. Kim and I. Brilakis (2017). "Automated re-prefabrication system for buildings using robotics." Automation in Construction **83**: 184-195.

Knyaz, V.A. and A.G. Chibunichev (2016). Photogrammetric Techniques for Road Surface Analysis. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Prague, Czech Republi, Copernicus Publications. **XLI-B5**: 515-520.

La, H.M., N. Gucunski, K. Seong-Hoon, J. Yi, T. Senlet and N. Luan (2014). Autonomous robotic system for bridge deck data collection and analysis. 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems.

La, H.M., R.S. Lim, B. Basily, N. Gucunski, J. Yi, A. Maher, F.A. Romero and H. Parvardeh (2013a). Autonomous robotic system for high-efficiency non-destructive bridge deck inspection and evaluation. Automation Science and Engineering (CASE), 2013 IEEE International Conference on, IEEE.

La, H.M., R.S. Lim, B.B. Basily, N. Gucunski, J. Yi, A. Maher, F. Romero and H. Parvardeh (2013b). "Mechatronic systems design for an autonomous robotic system for high-efficiency

1 bridge deck inspection and evaluation." Mechatronics, IEEE/ASME Transactions on **18(6)**:  
2 1655-1664.

3 Li, S., C. Yuan, D. Liu and H. Cai (2016). "Integrated Processing of Image and GPR Data for  
4 Automated Pothole Detection." Journal of Computing in Civil Engineering **30(6)**: 04016015.

5  
6 Li, W., M. Burrow, N. Metje and G. Ghataora (2020). "Automatic Road Survey by Using  
7 Vehicle Mounted Laser for Road Asset Management." IEEE Access **8**: 94643-94653.

8  
9 Li, W., M. Burrow, N. Metje, Y. Tao and G. Ghataora (2019). "A novel processing  
10 methodology for traffic-speed road surveys using point lasers." IEEE Transactions on  
11 Intelligent Transportation Systems.

12  
13 Lia, R.Y.M. and T.H. Leung (2017). Leading safety indicators and automated tools in the  
14 construction industry. ISARC. Proceedings of the International Symposium on Automation  
15 and Robotics in Construction, IAARC Publications.

16  
17 Liu, Q., Á. García, E. Schlangen and M.v.d. Ven (2011). "Induction healing of asphalt mastic  
18 and porous asphalt concrete." Construction and Building Materials **25(9)**: 3746-3752.

19  
20 Local Government Association (2017). A country in a jam: tackling congestion in our towns  
21 and cities: How councils are dealing with congestion and how they could do more London,  
22 UK.

23  
24 Masson, J., S. Boudreau and C. Girard (2003). Guidelines for sealing and filling cracks in  
25 asphalt concrete pavement: A best practice. National Guide to Sustainable Municipal  
26 Infrastructure, National Research Council Canada, Canada.

27  
28 Moran, J., M. Eskandari Torbaghan and M.P.N. Burrow (2017). "Estimating the Benefits of  
29 Joint Occupation for Street Works." Infrastructure Asset Management **4(4)**: 115-127.

30  
31 Narasimha Prasad, K.N. and V.M. Agrawal (2019). "Automation and Robotics in the  
32 Construction Industry-A Review." i-Manager's Journal on Future Engineering and Technology  
33 **14(3)**: 49-55.

34  
35 Obaidi, H., B. Gomez-Meijide and A. Garcia (2017). "A fast pothole repair method using  
36 asphalt tiles and induction heating." Construction and Building Materials **131**: 592-599.

37  
38 Obaidi, H., B. Gomez-Meijide and A. Garcia (2018). "Induction-Heatable Asphalt Pellets as a  
39 New Material in Road Maintenance." Journal of Materials in Civil Engineering **30(11)**:  
40 04018300.

41  
42 Oliveira, J.R.M., H.M.R.D. Silva, C.M.G. Jesus, L.P.F. Abreu and S.R.M. Fernandes (2013).  
43 "Pushing the Asphalt Recycling Technology to the Limit." International Journal of Pavement  
44 Research and Technology **6(2)**: 109-116.

45  
46 Osmani, A., C. Haas and W.R. Hudson (1996). "Evaluation of road maintenance automation."  
47 Journal of transportation engineering **122(1)**: 50-58.

48  
49 Ouma, Y.O. and M. Hahn (2016). "Wavelet-morphology based detection of incipient linear  
50 cracks in asphalt pavements from RGB camera imagery and classification using circular Radon  
51 transform." Advanced Engineering Informatics **30(3)**: 481-499.

52  
53 Oxfordshire County Council (2011). The little book of highway defects; a guide to the  
54 identification of common problems, Wilson Pym May Limited: 142.

55  
56 Parker, L.E. and J.V. Draper (1998). "Robotics applications in maintenance and repair."  
57 Handbook of industrial robotics **1378**.

58  
59  
60  
61  
62  
63  
64  
65

1 Raul, F., C. Timothy, C. Michael, S. Jim, L. Zhibin and R.R. C (2017). "Briefing: UK-RAS  
2 white paper in robotics and autonomous systems for resilient infrastructure." Proceedings of  
3 the Institution of Civil Engineers - Smart Infrastructure and Construction **170**(3): 72-79.

4 Reichling, K., M. Raupach, H. Wiggenhauser, M. Stoppel, G. Dobmann and J. Kurz (2009).  
5 "BETOSCAN—An instrumented mobile robot system for the diagnosis of reinforced concrete  
6 floors." Restoration of Buildings and Monuments **15**(4): 277–286.

7  
8 RoWSaF (2016). RoWSaF Strategy 2015.

9  
10 Rupp, T., H. Volz and T. Cord (1998). "Automated and Robotics-Based Techniques for Road  
11 Construction." IFAC Proceedings Volumes **31**(3): 515-520.

12  
13 Schlotjes, M.R. (2013). The development of a diagnostic approach to predicting the probability  
14 of road pavement failure. PhD, The University of Auckland and University of Birmingham.

15  
16 Simonsen, E., V.C. Janoo and U. Isacsson (1997). "Prediction of temperature and moisture  
17 changes in pavement structures." Journal of Cold Regions Engineering **11**(4): 291-307.

18  
19 Thom, N.H. (2013). Principles of Pavement Engineering, ICE Publishing.

20  
21 Tseng, Y.-H., S.-C. Kang, J.-R. Chang and C.-H. Lee (2011). "Strategies for autonomous  
22 robots to inspect pavement distresses." Automation in Construction **20**(8): 1156-1172.

23  
24 UK House of Commons (2019). Local roads funding and maintenance: filling the gap.

25  
26 UK Parliament (2013). Managing a valuable asset: improving local road condition. London,  
27 UK.

28  
29 Vipulanandan, C. and J. Liu (2005). Sewer pipe-joint infiltration test protocol developed by  
30 Cigmat. Pipelines 2005: Optimizing Pipeline Design, Operations, and Maintenance in Today's  
31 Economy, Houston, Texas, ASCE.

32  
33 Wang, K.C., W. Gong, T. Tracy and V. Nguyen (2011). Automated survey of pavement  
34 distress based on 2D and 3D laser images.

35  
36 Werkmeister, S., R. Numrich, A.R. Dawson and F. Wellner (2003). "Design of Granular  
37 Pavement Layers Considering Climatic Conditions." Transportation Research Record: Journal  
38 of the Transportation Research Board **1837**: 61-70.

39  
40 White, C., H.D. Ismail, H. Saigo and D.B. Kc (2017). "CNN-BLPred: a Convolutional neural  
41 network based predictor for  $\beta$ -Lactamases (BL) and their classes." BMC Bioinformatics  
42 **18**(16): 577.

43  
44 Wiggenhauser, H., M. Stoppel, G. Dobmann, J. Kurz, M. Raupach and K. Reichling (2008).  
45 BETOSCAN - An instrumented mobile robot system for the diagnosis of reinforced concrete  
46 floors. Concrete Repair, Rehabilitation and Retrofitting II, CRC Press: 255-256.

47  
48 Willmann, J., M. Knauss, T. Bonwetsch, A.A. Apolinarska, F. Gramazio and M. Kohler (2016).  
49 "Robotic timber construction — Expanding additive fabrication to new dimensions."  
50 Automation in Construction **61**: 16-23.

51  
52 Winters, S., D. Hong, S. Velinsky and K. Yamazaki (1994). A New Robotic System Concept  
53 for Automating Highway Maintenance Tasks. Proceedings of the ASCE Conference on  
54 Robotics for Challenging Environments.

55  
56 Yao, H., Q. Dai, Z. You, M. Ye and Y.K. Yap (2016). "Rheological properties, low-  
57 temperature cracking resistance, and optical performance of exfoliated graphite nanoplatelets  
58 modified asphalt binder." Construction and Building Materials **113**: 988-996.

59  
60  
61  
62  
63  
64  
65

1 Yeon, J., J. Kang and W. Yan (2018). "Spall damage repair using 3D printing technology."  
2 Automation in Construction **89**: 266-274.

3 Yu, S.-J., S.R. Sukumar, A.F. Koschan, D.L. Page and M.A. Abidi (2007). "3D reconstruction  
4 of road surfaces using an integrated multi-sensory approach." Optics and Lasers in Engineering  
5 **45(7)**: 808-818.

6  
7 Zapata, P. and J.A. Gambatese (2005). "Energy Consumption of Asphalt and Reinforced  
8 Concrete Pavement Materials and Construction." Journal of Infrastructure Systems **11(1)**: 9-  
9 20.

10  
11 Zhang, L., F. Yang, Y.D. Zhang and Y.J. Zhu (2016). Road crack detection using deep  
12 convolutional neural network. IEEE International Conference on Image Processing (ICIP),  
13 2016, Phoenix, AZ, USA, IEEE.

14  
15 Zhang, R., G. Zhou, J. Huang and X. Zhou (2018). Real-time ortho-rectification for remote  
16 sensing images. Fifth recent advances in quantitative remote sensing. J.A.S. Rodríguez.  
17 Valencia, Spain, Universitat de València: 460-464.  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
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