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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

--Manuscript Draft--

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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 a safe and robust (strong, stiff and resilient) road surface for driving; road surfacing can be carried out rapidly and without complex machinery; it has good acoustic properties; it is repairable and indeed can self-repair (García, 2012). However, flexible pavements deteriorate over time due to the effects of repeated dynamic loading (Cebon, 1986; Henning, 2008), environmental conditions (e.g. temperature; Cawsey and Massey, 1988), surface water and groundwater (Simonsen *et al.*, 1997; Werkmeister *et al.*, 2003), and interaction with other infrastructure systems (e.g. a leaking pipe; Vipulanandan and Liu, 2005; Balkaya *et al.*, 2012). The deterioration may lead to decreased stiffness and increased brittleness of the road surface, crack formation (thereby allowing water ingress to the lower unbound layers and the ground), loss of aggregate and/or localised softening of the ground, and may lead to the development of potholes (Schlotjes, 2013; Thom, 2013).

The current road inspection and maintenance regime is mainly based on visual inspections followed by a reactive or emergency maintenance which is normally applied when a serious defect has occurred or is reported, e.g. a pothole. This current practice is blamed for recurring and perennial road defects and progressively worsening road conditions (UK Parliament, 2013). The degraded road condition caused by the reactive approach imposes huge extra direct and indirect costs on the road asset management systems and wider economy. For example, in 2018 in England and Wales alone, £28.3 million (including staff costs) was paid in compensation for damage to people or vehicles as a result of poor road condition (Asphalt Industry Alliance, 2018). The Asphalt Industry Alliance (2020, page 13) stated "*Maintenance costs increase as the structure of the roads deteriorate(s) and we are now starting to see the consequences of delaying intervention. It has got to the point where full reconstruction is needed*". The cost of filling a pothole as part of a reactive approach is reported to be 65% higher than a planned a maintenance (Asphalt Industry Alliance, 2020). Furthermore, there are other socio-economic issues associated with the current inspection and maintenance approaches. For instance, the current practice involves, 1) visual detection of road deterioration, with inherent subjectivity, 2) closing off roads during daylight hours for a long period of time (urban road maintenance activities are normally done during the daytime because of noise level restrictions during the night), sometimes without any maintenance activity, with associated disruption to the traffic flow, 3) employing a maintenance crew and heavy lorries to carry the equipment and material to conduct the maintenance, with the associated health and safety issues and costs.

The UK Department for Transport (2012) estimates that the costs of disruption caused by streetworks exceeded £600 million per year in 2011. Most critically, fourteen road workers were killed and over 300 were seriously injured between 2006 and 2016 (RoWSaF, 2016). Congested traffic, such as that caused by streetworks, emits four times as much pollution as free-flowing traffic thereby contributing to the estimated 40,000 premature deaths caused by poor air quality every year (Local Government Association, 2017).

Early detection and repair of road defects, within a proactive approach, can significantly save costs while extending the asset lifecycle. It is hypothesised that, through the deployment of robotic and automatic systems (RAS), the current practices for road condition assessment and repair will be enhanced significantly. RAS has the potential to replace the lengthy process of visual condition assessment, to achieve remote and automated inspection making early defect detection possible. This can be achieved either via drone flights and photography, or swarms of miniature (cheap and dispensable) land-based robots working on temporarily closed lanes overnight, leading to multiple (economic and social) benefits. RAS has the potential to make routine, regular problem diagnosis affordable leading to proactive asset management approaches.

Furthermore, utilising robotic road repair – particularly to intervene frequently and with minimal material to fix nascent defects before they become serious, for instance to treat road cracks via a 3D printed asphalt from drone-mounted (a future vision which has been proved by the research team) or land-based tracked robots (prototypes being created and trialled). This has the potential to extend the life of the asset, and minimise the need for heavy lorries to carry the equipment and material thus reducing the environmental impact. This has the potential to make routine, regular early-stage maintenance affordable and avoid more serious deterioration (such as pothole formation). RAS can also have a significant positive Health and Safety implication for both inspection and maintenance activities. Moreover, RAS can address the issue associated with the limited adaptation of a pro-active road asset management. This limited adaptation is mainly attributed to the cost (UK House of Commons, 2019) affected by the difficulty of gaining access during daylight hours, and its associated lane rental cost (Moran *et al.*, 2017).

As part of the current reactive approach, road asset owners tend to react to significant, serious or ‘catastrophic’ failures, while neglecting to repair defects at early stages of development, such as small cracks (Figure 1). However, an ‘effective crack treatment’ at early stages of development is suggested to extend the life of a road by two to five years (Chong, 1990; Eacker and Bennett, 1998; Masson *et al.*, 2003). Effective road crack treatment is achievable when applied to pavements with low to moderate crack density, and with cracks with little or no 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.

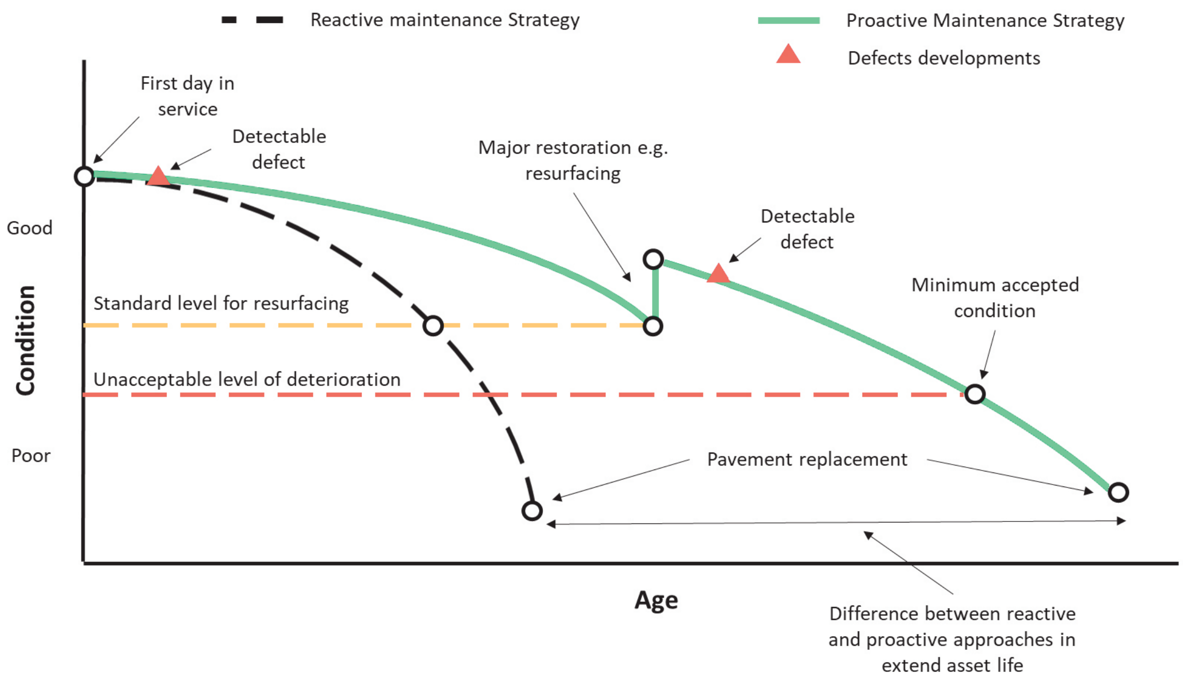

Figure 1: An illustration of differences between road reactive and proactive approches

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);

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.

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

2.1 RAS for Condition Assessment

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

Recently, deep learning (e.g. Convolutional Neural Network, CNN) using different learning architectures has been used to automatically detect cracks in the road in images. In deep learning, the number of convolution layers, which consists of a filter to extract local contextual features (White *et al.*, 2017), is an important variable. Cha *et al.* (2017) described a method for the detection of concrete cracks through automated detection of the defect image features, using a deep architecture of CNN. They used four convolution layers and reported a robust performance of the method at detecting thin cracks under natural lighting conditions compared to two more complex traditional methods, namely Canny and Sobel edge. CNN has also been used within an automated crack detection method, for example, Zhang *et al.* (2016) created an automated road crack detection method by training supervised deep CNN to classify each image patch in the collected images. They used six convolution layers for binary crack detection on roads. A training set of 600k images and 200k for testing was used and achieved 87% accuracy in detecting cracks. The results were compared with two different methods, 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 Rabit (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). Rabit 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 penetrating radar (GPR), impact echo, ultrasonic, capacitive resistivity, and laser scanner (La *et al.*, 2014). The robot, which covers a 1.83m width in each scan and is able to scan a distance of 53m within 50 minutes, has been tested during a number of field trials and the results have been presented in various publications (Gucunski, 2012; Gucunski *et al.*, 2013; La *et al.*, 2013a; La *et al.*, 2013b; La *et al.*, 2014), however, it seems that a deep analysis and interpretation of the results is missing from the publications.

In Germany a multi-sensor self-navigating robotic system, called BetoScan, was developed and utilised for condition assessment of concrete slabs in bridges and parking decks, looking in particular for corrosion (Cotič *et al.*, 2014). The following NDT sensors were deployed on the BetoScan (Wiggenhauser *et al.*, 2008; Reichling *et al.*, 2009):

a. Cameras in the visual spectrum and using image processing; for locating cracks and defected areas
b. Microwaves; for humidity distribution used to identify corrosion
c. Ultrasonic; for measuring voids and crack depth and layers thickness
d. Temperature probes;
a. Eddy current method (Electrical Resistivity method) and GPR; for locating rebars and measuring its cover
b. Electrochemical Potential sensors; for detecting and mapping corrosion

This section showed the successful applications of RAS in condition assessment, while highlighting areas for further improvements especially on the automation of the data processing in order to make RAS useable routinely in practice. The next sections present applications of RAS in construction and repair.

2.2 Autonomous Movement

Navigation of ground robots on a construction site and also harsh environment with various unpredicted obstacles might impose a serious risk and limitation to the wide deployment of RAS in construction (Davila Delgado *et al.*, 2019). Potential solutions, however, seem promising where UAVs have been used to control and navigate ground robots. Asadi *et al.* (2020) have developed a control algorithms and trialled it inside a building to simulate an indoor construction site. The trial successfully demonstrated autonomous navigation using the UAV to follow a manually controlled ground robot, so the UAV can indirectly follow human navigation orders as a demonstration of a scenario where autonomous robots and humans would work together on a construction site.

The concept of introducing highly automated machines to construct roads dates back to the 1980s (Parker and Draper, 1998). Rupp *et al.* (1998) reviewed the state-of-the-art for automated road construction methods and Osmani *et al.* (1996) evaluated 25 different road maintenance techniques and evaluated the conceptual feasibility and cost benefits associated with automation. It was estimated then that over a 30 year period in the state of Texas, USA, the net present worth of automated crack sealing could be in the hundreds of millions of dollars (Osmani *et al.*, 1996).

Road maintenance systems that can identify and seal cracks have been trialled for example the Automated Crack Sealing Machine (ACSM) (Winters *et al.*, 1994; Bennett *et al.*, 2003) which used two-line scan cameras for crack detection and a Selective Compliance Articulated Robot Arm (SCARA) for the sealing operations, using a pressurised injection system for bitumen heated up to 200°C. The developed technology was successfully tested for filling cracks at a rate of 8 km/hr (Bennett *et al.*, 2003). Another crack sealing prototype was developed at Carnegie Mellon University, and The University of Texas at Austin (Hendrickson *et al.*, 1991; Haas *et al.*, 1992; Greer *et al.*, 1997) which developed perception and control methods to enable effective automation of routed pavement crack sealing. The system used laser sensors and video cameras for automated crack detection and was equipped with heated air torch and a nozzle to pour bitumen installed on a design x-y table (1.5m × 3m), similar to a 3D printing system (Haas *et al.*, 1992). The developed system was tested in both laboratory and field environments and led to a field prototype, however details of the experiments were not reported. The University of Texas at Austin (Haas, 1996) reviewed the evolution of an automated crack sealer alongside its design cycle, economic feasibility, and implementation.

The Tethered Mobile Routing Robot (TMRR) by Hong *et al.* (1997) focussed on mobility as a key feature to follow the irregular patterns usually found with road surface cracks. The repair process began with the equipped router cutting a channel in the path of the crack to allow for increased penetration of a pressurised hot thermoplastic sealant using the sealant applicator on a gantry system. The developed system was successfully tested in the laboratory environment and was able to detect and follow a crack in the form of a straight line rather than a natural irregular crack, with a width of 6.4mm.

The growth of 3D printing, also known as additive manufacturing or rapid prototyping, has steadily gained recognition (Gross *et al.*, 2014), and has been used in building construction (e.g. Bogue, 2018). The application of 3D printing technology for road repairs has been tested for spall damage repair by using printers to produce negative moulds of damaged spalls into which concrete is poured, cured and finally glued to the damaged area (Yeon *et al.*, 2018). In contrast, Jackson *et al.* (2018) suggested that durable and efficient repairs could be conducted using screw extrusion-based 3D printing as this enables autonomous approaches to road repair. Similar proposals were made by Buswell *et al.* (2018) for other common infrastructure materials such as concrete. However, there is a wide range of material, environmental and situational variables for every road defect, as well as its individual or collective geometry, increasing the requirements significantly for true autonomy. These additive manufacturing techniques also invite the introduction of different material mixes that can have different properties at different points in the volume of the repair at different print times for more advanced and cost effective repair materials. Examples include a surface containing a more expensive but functionally superior nano- or microscale material than the bulk, as well as the preselection of a range of graded aggregate/ binder mix pellets to be added to the print feedstock at precomputed times based on the geometry of the structure to be manufactured, in order to mechanically grade larger repairs (or construction). Potential additions include self-repairing oil capsules (Al-Mansoori *et al.*, 2018), induction heated materials (Liu *et al.*, 2011), a wide variety of recycled materials such as polymers (Huang *et al.*, 2007), reclaimed asphalt (Oliveira *et al.*, 2013) and graphene (Yao *et al.*, 2016), as well as other nanoscale materials to influence material properties (Antonovič *et al.*, 2010).

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

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) 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).

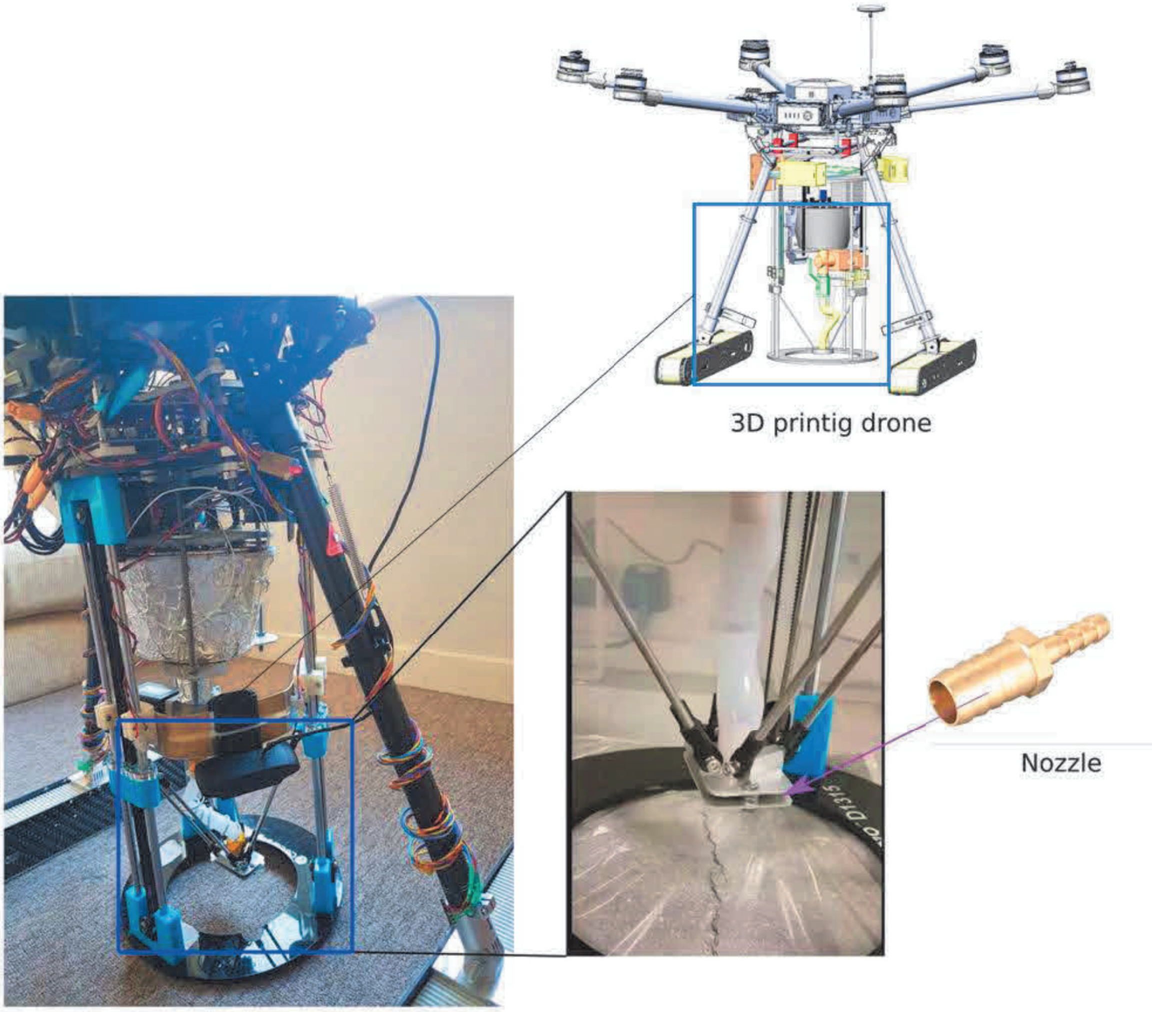

Figure 2: 3D asphalt drone

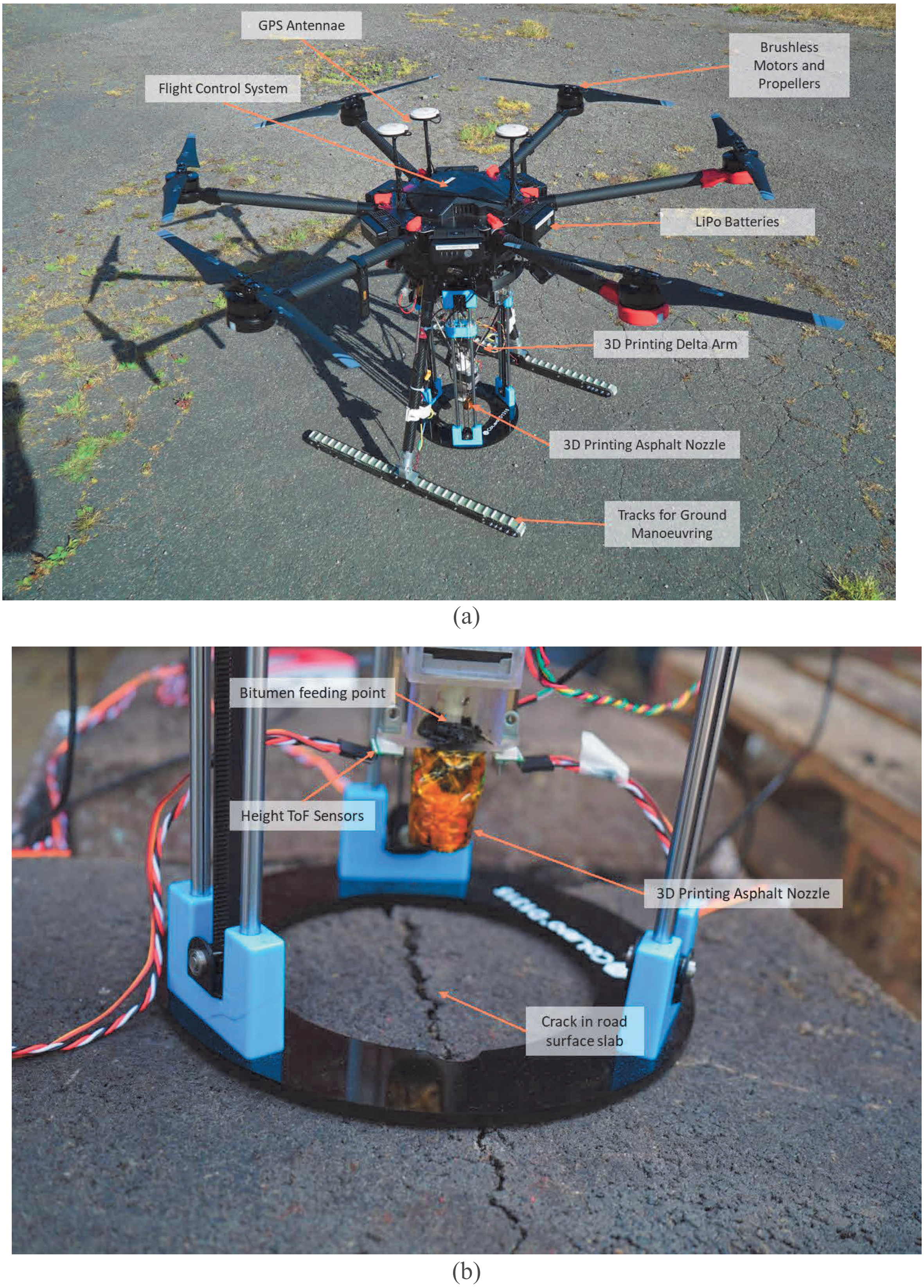

Figure 3: (a) 3D printing asphalt UAV, (b) detailed view of the printing arm

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

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

The current fixing method utilises an additional camera aimed towards the printer workspace to identify and compute a work path for the printer nozzle. The nozzle will follow the direction of the crack and extrude asphalt material at a temperature that allows the asphalt to flow into the crack and therefore filling it in a single pass. The ideal speed and temperature for this process are still to be identified and will depend on the external environment. Irregular crack shapes or pothole forms can now be fixed. Figure 4 shows an irregular crack autonomously detected and filled with asphalt by the Self-Repairing Cities system.

The developed UAV plays a key role in the automated inspection and maintenance system of city infrastructures, and offers a platform for further development of aerial maintenance robots. The developed 3D printing system, ultimately, will be utilised along with a crack detection process to inform an automated decision making on the required material to be carried around and to ensure that there is no shortage or excess of material.

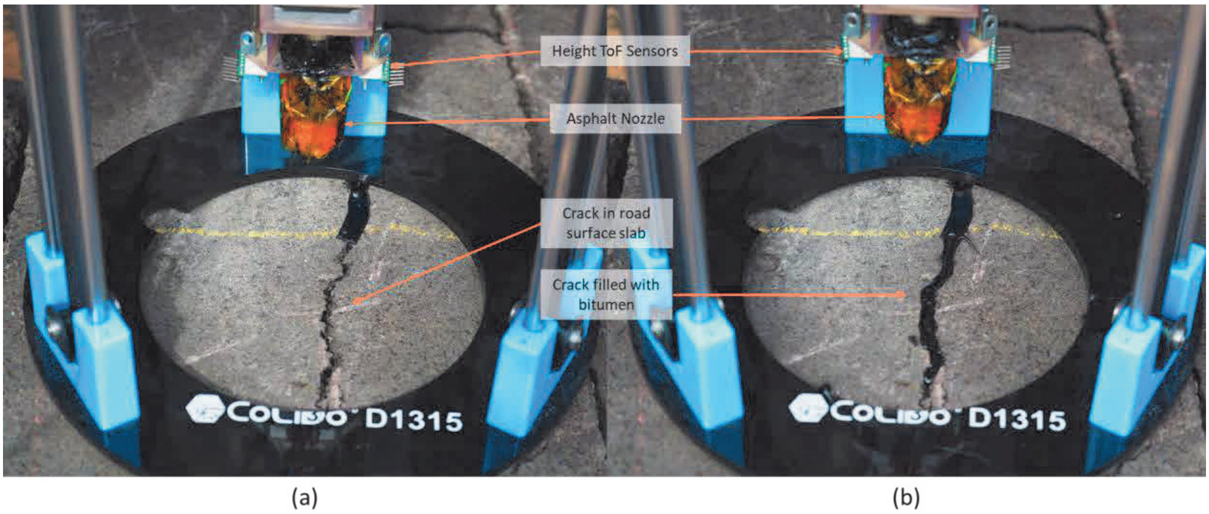

Figure 4: (a) Irregular crack to be filled (b) Crack autonomously filled with asphalt.

4 Discussion

The presented UAV concept is an autonomous means of crack repair for bituminous roads that drastically reduces road closure time and associated traffic congestion. It also provides the benefit of being able to cover a larger area with dispersed detected defects in less time compared to a ground vehicle. The UAV concept reduces the repair cost, through early detection and repair of defects and hence extension of an asset's lifetime (Figure 1), while also reducing the risk to road workers and the maintenance operation time by eliminating or minimising the need for a road closure setup. CO_2 emissions are reduced due to low energy consumption, mainly through removing the need for large vehicles to conduct the inspection and repair while achieving efficient heat delivery to melt the bitumen and the reliance on electricity.

Other means of autonomous crack repair are under investigation such as using electric autonomous ground vehicles equipped with an array of bitumen 3D printing arms combined with the ability to detect cracks. The autonomous ground vehicle is envisioned to detect and seal cracks while driving which allows larger stretches of roads to be covered and minimizes effects on traffic flow. Such a vehicle will have the advantage of being able to operate throughout the night, when traffic is low, eliminating the risk of people working at night on dangerous roads.

In addition to the technological aspect of RAS in road condition assessment and repair, Self-Repairing Cities is investigating the interactions between technology, society and the ecological environment to make sure this technology will enhance balancing our resources for a more sustainable future (Raul *et al.*, 2017).

Despite the aforementioned positive aspects of deploying an UAV for automated road crack sealing, some questions over its practicality and effectiveness might be raised. For instance, the speed of 3D printing asphalt mounted on an UAV for sealing a longitudinal crack might seem slow when compared to an operator or other automatic techniques (e.g., an autonomous vehicle). To increase the UAV operational speed on the ground, it has currently been equipped with tracks. At the same time, it should be noted that the developed successful 3D printing mechanism can be utilised on ground robots, an ongoing research, which can be deployed independently or along with the UAV system based on the working condition. This has the potential to speed up the repair operation.

While landing an UAV on the road pavement might be regarded as more dangerous than the visual inspection process, it should be noted that this road or lane closures are envisaged to reduce the risk. However, the size of the UAV will allow minimising disruption to the road (both the required time and space) when compared to the current operation, while eliminating the existing risk to the street works operators.

The required energy to heat small amounts of material may also raise questions over the efficiency and efficacy for UAVs when compared to the large quantities of bitumen used within current practices, the success of the proposed method, therefore, depends on the insulation efficiency of the system. The energy efficient system will just carry small quantities of asphalt, supplied by a central station with larger capacities, with minimum energy required to just maintain the temperature. Ongoing research is working on improving the efficiency of the system. Moreover, a whole systems cost analysis is required to include the improved road condition and thus reduced maintenance cost and reduced labour costs.

The risks associated with the 3D printing UAV autonomously flying above residential areas should also be investigated, identifying measures to mitigate or control the associated risks.

The other aspects of the proposed system, which should be investigated in order for industry to adopt the technology, are its reliability, safety and cost-effectiveness. Large-scale trials are underway to investigate the reliability of the system compared to the current practices. This will also enable to assess the cost-effectiveness of the system taking a whole systems approach. The research question for the trials is how effective the 3D printing would be in preventing further developments of the cracks when compared to the current practices.

5 Conclusions

Early detection and repair of road defects have been identified as an effective cost saving approach for cities. However, as discussed in this paper, current common practices are typically unable to detect defects at an early enough stage. Furthermore, the current practices are costly and disrupting the traffic while putting workmen life in danger. RAS equipped with the right technologies has not been utilised for assessing the condition of asphalt pavement and autonomously repair the detected defects, and these are the main objectives of the Self-Repairing Cities Project. This will allow early detection and repair of defects within a proactive asset management strategy.

The 3D printer developed by the Self-Repairing Cities project has been presented as a method to more effectively seal cracks at their early stages, using the benefit of an in-house RAS system. Utilising such an automated system has the potential to prevent pothole formation with the associated huge economic, social and environmental benefits for the society.

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