Briefing: UK-RAS white paper in robotics and autonomous systems for resilient infrastructure

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This paper presents an extended briefing of the recently published UK-Robotics and autonomous systems (RAS) network White Paper in RAS for resilient infrastructure. It aims at setting out a vision of what RAS systems will be able to deliver in infrastructure, what are the current barriers and challenges to achieve that vision and what can the UK Government do to ensure that the UK remains at the forefront in this field.

1. Introduction

The infrastructure sector supports the entirety of the national GDP, without which, there would be no economic activity. The UK Government has recognised this and committed to spend over £500 billion on high-quality infrastructure projects by 2020–21 alone (HM Treasury and Infrastructure and Projects Authority, 2016). Outside the UK, as an illustration of the scale of the problem, the US road network requires US\$134 billion per year to maintain according to Chinowsky *et al.* (2013).

Our economic infrastructure system of systems is composed of the dense networks of energy, transport, water, waste, telecommunications and flood defences that provide the essential services on which people depend. Those networks are elderly and under heavy pressure as society demands ever-increasing levels of service from existing facilities. They are also highly interdependent, adding more complexity to the system (Eusgeld *et al.*, 2011; Kröger, 2008; Thacker *et al.*, 2017).

Key priorities of the infrastructure engineering sector include the affordability of deploying new facilities and reducing the cost of maintaining and improving existing systems. Upgrade of infrastructure can be driven by changing patterns of demands, such as the growing and ageing population or the introduction of new infrastructure technology.

An additional pressure is the need to mitigate and adapt infrastructure to the effects of climate change, which include decarbonisation of all aspects of infrastructure provisions, as well as adapting facilities to deal with the consequences of climate change, such as increased flood defences. To show the scale of the problem,

Chinowsky *et al.* (2013) noted that the road infrastructure in the US will require US\$2.8 billion more than currently thought by 2050 if prices are not discounted in order to adapt to climate change. This is a significant increase that will mean even more efficiencies will need to be sought to optimise expenditure.

These ever-increasing complexity and demands of infrastructure are driving a trend toward automation of all parts of infrastructure provision and operation with significant opportunity for robotic solutions. In this paper, the authors understand automation as the process of developing activities or processes automatically, without human intervention in the field. Robots are the physical agents that are deployed to enable automation to occur in combination with other machines (e.g. PCs, wireless communication systems, and sensors) and software.

Robots have the benefit of being able to operate across the full range of infrastructure engineering (see Figure 1), for example, inspection, maintenance and repair task working in the air, on the ground, in water and underground. They also bring a number of distinct potential advantages over traditional human-based practices.

- Greater accuracy: Precise and repeatable operations beyond the capability of humans are achievable.
- No uncertainty of human factors: Repetitive and mundane operations can be delivered with greater repeatability.
- Faster operation: Activities can be performed in a shorter period of time.
- Improved safety: Humans do not need to undertake risky activities.

Figure 1. Standard tasks undertaken as part of infrastructure engineering

- Improved efficiency and higher productivity: The input energy and materials needed to create the same outcome are less, resulting not only in financial gains but also the environmental benefits of lower energy consumption and fewer wasted materials.
- Better jobs for humans: To free humans from the need to undertake dirty, dull and dangerous jobs.
- Proactive action: Robots can undertake more frequent inspections of difficult-to-access locations, catching defects early and preventing escalation of damage.
- Low-cost: The same outcome can be delivered with less cost using robots.

The convergence of robotics and autonomous systems (RAS) with Smart Infrastructure and its ability to embed intelligence into assets, extract intelligence from big data and the development of new materials and processes have begun to create a platform to overcome some of the complex engineering challenges associated with installing and maintaining infrastructure networks. The companies that successfully deploy and exploit RAS will be at the forefront of the fourth industrial revolution. In addition to providing an unparalleled customer experience, it is likely that these firms will unlock value chains that generate completely new economic activities.

This paper summarises the main points shown in the recently published UK-RAS white paper in robotics and autonomous systems for resilient infrastructure (Richardson *et al.*, 2017). It provides a vision of how infrastructure will look like in the face of widespread robotic solutions. It also presents the current barriers for full deployment and provides some recommendations for the full exploitation of robotics in infrastructure in the UK and, by proxy, to the rest of the world.

2. Vision

The vision the white paper sets the scene for the rest of this paper and presents a new aspirational paradigm in the field of construction. This is one where infrastructure engineering is undertaken with zero disruption to human activity and zero environmental impact.

In this paradigm, cities will be proactively maintained by teams of autonomous robots that will generate and process information about the state of health of different assets and act on this information.

Current state-of-the-art applications have focused on inspection (e.g. Balaguer *et al.*, 2002; Bock, 2007; Jahanshahi *et al.*, 2009; Jiang *et al.*, 2005; La *et al.*, 2013; Lattanzi and Miller, 2015, 2017; Lee *et al.*, 2012; De Paiva *et al.*, 2006; Peel *et al.*, 2016) with fewer applications of repair due to technology development and, in particular, challenges in robotic object manipulation (e.g. Roth *et al.*, 1998). However, in the future, there will be no separation between sensing and repair; robot teams will be capable of performing both tasks seamlessly as researched in the self-repairing city project (Self Repairing Cities, EP/N010523/1 n.d.).

New infrastructure will be autonomously created by robots either built offsite and assembled in location operating as a manufacturing facility (e.g. Willmann *et al.*, 2016) or fully created on-site where only prototypes have been created to date (e.g. Augugliaro *et al.*, 2014; Bosscher *et al.*, 2007; Erdine *et al.*, 2017; Gardiner *et al.*, 2016; Keating *et al.*, 2017; Tay *et al.*, 2017; Więckowski, 2017).

Infrastructure robots will draw on data from smart cities and autonomous cars using advanced communication systems and cloud technology, undertaking reasoning using sophisticated artificial intelligence algorithms, in full integration with ongoing developments such as Smart Cities (e.g. Ampatzidis *et al.*, 2017; Ermacora *et al.*, 2016; Foina *et al.*, 2016; Huang *et al.*, 2016; Salmerón-García *et al.*, 2017), Building Information Modelling (e.g. Chuang *et al.*, 2011; Edenhofer *et al.*, 2016; Feng *et al.*, 2015; Lundeen *et al.*, 2017; Rausch *et al.*, 2017; Schlette and Roßmann, 2017; Vähä *et al.*, 2013), Big Data or the Internet of Things (e.g. Giyenko and Cho, 2017; Dos Santos *et al.*, 2016; Torras, 2016). This future will result in a healthier, happier and more productive society.

However, this vision will need to tackle and overcome a series of challenges related to the infrastructure ecosystem within which robots will operate and resolve robotic science and technological challenges and socio-economic challenges as well. These are covered below.

3. Infrastructure ecosystem challenges

In the UK, the Government has committed to spend over £100 billion by 2020–21 on infrastructure alone (HM Treasury and Infrastructure and Projects Authority, 2016). This is a significant step-change in the Government's previous proposals which on average means an investment of £20 billion per year from 2016: an

Figure 2. Trend of the construction industry's market size (HM Government, 2016)

approximately three-fold increase on the values from previous years and almost two times pre-crisis levels in 2007 (see Figure 2).

This increased Government investment is built around delivering improvements in four societal challenges (HM Infrastructure and Projects Authority, 2016), named below, to which robots and autonomous systems can contribute in different ways.

■ **Supporting growth and creating jobs**

The use of robotics in construction will have an impact on the labour market and in construction. However, its net effect is still unclear. Deloitte shows that out of 2 607 000 jobs in real estate and construction, 34% are high risk, 15.5% are medium risk and 50.6% are low risk (Smith and Bishop, 2016) in terms of being lost to automation, although the figure is 24% at high risk according to PriceWaterhouseCoopers (Berriman and Hawsworth, 2017). However, research also shows that robotics creates jobs as shown by the International Federation of Robotics (International Federation of Robotics n.d.). For example, the US automotive industry installed more than 60 000 industrial robots between 2010 and 2015 and the number of employees increased by 230 000 in the sector.

■ **Raising the productive capacity of the economy**

It has been shown many times that expanding productive capacity requires investment in research and innovation. Equally, robotics has been identified as one of the most obvious vehicles to increase capacity. For example, structures that were not possible in the past could be possible today.

■ **Driving efficiency**

Using the manufacturing industry as proxy, Boston Consulting Group (Sirkin *et al.*, 2015) shows that 'as a result of higher robotics use, average manufacturing labour costs

will be 33 percent lower in South Korea and to 25 percent lower in China, Germany, the US, and Japan than they otherwise would have been'. Similar efficiency benefits can be expected in the construction industry in the short to medium term, especially in sub-sectors like pre-fabrication, modular construction and off-site manufacturing where research and actual implementations are already underway (e.g. Bi *et al.*, 2015). In the mid- to long-term, in situ fabrication will also be much quicker (e.g. Erdine *et al.*, 2017; Keating *et al.*, 2017; Lundeen *et al.*, 2017; Tay *et al.*, 2017).

■ **Boosting international competitiveness**

The UK is a research power both in robotics and infrastructure subjects. For example, the Government has recently invested £138 million to increase infrastructure research capacity in the UK through the UKCRIC programme (UKCRIC - UK Collaboratorium for Research on Infrastructure and Cities n.d.). In the industrial sector, UK consultancies are among the biggest and most successful around the world. Jewell and Flanagan (2012) show that Construction Professional Services account for £4.01 billion (fourth of all service exports). However, UK contractors, compared to others in Europe, are less successful in exporting. Robotics presents an opportunity to provide a competitive advantage to contractors, while maintaining and enhancing the global standing of research institutions and consultancies alike.

A particular challenge of the construction industry is its fragmented taxonomy (see Figure 3 for details of the UK), and this is a worldwide phenomenon that acts as a barrier to innovation (Dulaimi *et al.*, 2002; Häkkinen and Belloni, 2011). Most companies are very small SMEs that comprise the most significant financial share of the market, while only very few large companies

Figure 3. Fragmentation of the UK construction industry (HM Government, 2016)

employing more than 1200 employees exist and have a market share lower than 20%. However, equally, small and medium-sized enterprises (SMEs) have the least financial prowess to invest in disruptive technologies such as robotics, placing them at a disadvantage. This is partly because the business models to date are not capable of capturing the potential benefits of these technologies, therefore making it harder to attract the necessary finance. There are new approaches to quantify the financial benefits of these investments. For example, Bi *et al.* (2015) carried out research showing and justifying how SMEs should invest.

Hence, to achieve the UK Government's intended benefits and to roll out robotics widely within the construction industry, significant investment will be required at all technology readiness levels (TRLs) spanning from fundamental research to maintain the UK's strong position to commercial enterprises. This will need to include public and private sectors, SMEs, large construction companies and universities.

Focus must be placed on maintaining and enhancing research in infrastructure robotics, where the UK is currently world-leading, while developing new construction robotics technologies that will give UK contractors a competitive advantage internationally. Additionally, substantial funds will need to be spent on training and making sure that the fragmented supply chain, consisting of small SMEs, is not left behind and can benefit from it as well. New business models will be needed to implement this future at

industry level, which will require either significant internal investment or, more likely, pump-priming public money to promote this change.

4. Robotic, scientific and technological challenges

Seven robotic technological barriers are identified in the white paper (see Figure 4) that currently restrict the wider adoption of robotics technology for infrastructure delivery. They are termed here as *Perch and Repair*, *Perceive and Patch*, *Construct and Confirm*, *Dismantle and Dispose*, *Plunge and Protect*, and *Fire and Forget* and build on the Self-Repairing Cities project's initial proposal (Self Repairing Cities, EP/N010523/1 n.d.).

Application of these core robotic technologies is dependent on *Data and Decisions* (see Figure 4) obtained and processed locally or accessed remotely through, for instance, data 'cloud' technology with examples that were already provided (e.g. Chuang *et al.*, 2011; Ermacora *et al.*, 2016; Huang *et al.*, 2016; Salmerón-García *et al.*, 2017).

These challenges are the technological building blocks for the future of infrastructure robotics. Alongside technological challenges, it is also important to address the wider issues of openness and sharing; assurance and certification; security and resilience; and of public trust, understanding and skills (Lloyd's Register Foundation, 2016).

Figure 4. Technological challenges in infrastructure robotics

5. Socio-economic challenges

Humans, by nature, fear the unknown, especially when they see it as a threat to their livelihood and the comfort of the status-quo (Rotman, 2013). These fears are fuelled by the predictions of senior figures; the Governor of the Bank of England's was reported as predicting the loss of 15 million jobs to robots (Haldane, 2015). However, when it comes to technology advances, this fear is often based on false and uninformed constructs of reality and the future (Fuentes, 2016), although some authors suggest that this time, things may be different (Campa, 2015; Ford, 2015). This fear is not new, as exemplified in Brontë's quotation below, from the Industrial Revolution era, when the steam locomotive, the telegraph, the sewing machine or Edison's light bulb were invented and rapidly spread throughout the land.

"... these sufferers hated the machines which they believed took their bread from them: they hated the buildings which contained those machines; they hated the manufacturers who owned those buildings."

From *Shirley: A Tale*, by Charlotte Brontë, 1849

The introduction of any new technology, let alone one as radical as RAS, will always change the distribution of jobs in a sector. However, this need not be for the worse overall. In the

infrastructure sector, many current jobs are dirty, dull and dangerous. Maintaining our buried infrastructure of pipes, cables and wires involves working in deep excavations; upgrading our electricity, communications and street lighting networks means working at heights; looking after our roads and railways can put people in the path of live traffic. All these activities put operatives and the public at risk of injury or worse. The time taken to finish many maintenance tasks is often dominated by routine preparatory or remedial work (i.e. digging holes and filling them back in), which either wastes the time of skilled workers or creates low-quality jobs that do not give workers the chance to become skilled. It is these jobs that robots should replace, freeing up our workforce to tackle the more complex, creative and challenging issues facing our ageing infrastructure. The infrastructure industry is desperately short of workers, particularly at higher skill levels across the world. For example, Tateyama (2016) highlights this in Japan and presents robotics as part of this solution. Additionally, reducing the unskilled workload will give the industry the opportunity to retrain existing workers rather than be forced to recruit internationally.

The design, manufacture, commissioning, supervision and maintenance of infrastructure robots will create a new industry

with new jobs, as will adapting the infrastructure people have now to make it easier for the robots to navigate and operate. Research should tackle social issues head-on alongside technical research in collaboration with policymakers through bodies such as the Institute for Civil Engineering and the Royal Academy of Engineering in the UK.

It is important to consider environmental issues as part of the value of adopting RAS for infrastructure engineering. Proactive maintenance has the potential to identify and repair defects, quickly minimising damage and the scale of subsequent repair and allowing infrastructure assets to be kept in service for long. By increasing the reliability and resilience of infrastructure, it also minimises the environmental pollution caused by, for example, traffic congestion as a result of street works or the displacement of animals and materials from large excavation works. Improved resilience of pipe networks will help to conserve fresh water and prevent pollution of our natural environment by fugitive sewage.

6. Recommendations

The UK-RAS white paper builds the case for infrastructure robotics investment, developing a world-leading UK robotics sector that can assist the government in achieving its key strategic priorities: supporting growth and creating jobs; raising the productive capacity of the economy; driving efficiency; and boosting international competitiveness.

For its realisation, three key action priorities are proposed to accelerate the uptake of robotics within infrastructure engineering.

- Investment in interlinked basic research and technology transfer is required to pull advanced robotic technology into infrastructure engineering; only a small amount of UK Government-funded robotics research has been allocated to develop infrastructure robotics. Investment into the whole infrastructure supply chain will be needed to support uptake, training and new business models to accommodate the autonomous future.
- Industry and universities should work together to develop test facilities where infrastructure robots can be allowed to gracefully fail and be evaluated and improved. Current test facilities are small-scale, fragmented and uncoordinated and the industry will need financial and commercial incentives to share, operate and manage test facilities that advance the development of robust robotic solutions for the benefit of the sector. This will need to happen at three levels.
 - **Lab scale:** Specific elements of real infrastructure should be recreated in research lab environments (e.g. a pipe, a bridge bearing and wind turbine) incorporating some elements of the real operational environment, for example perturbation in temperature and wind conditions.
 - **Prototype scale:** 1:1 large-scale testing facilities in dedicated research areas that are designed to stress test

prototype systems in close to operational conditions, but under tightly controlled conditions enabling specific failure modes to be investigated (e.g. strong winds).

- **Real-world scale (Living lab):** Robots would be deployed on real assets under human-accessed controlled conditions to allow their operational performance to be stressed to graceful failure.
- Infrastructure robotics should be developed in partnership with the general public and community organisations to tackle perceived challenges around loss of jobs. Programmes should be put in place to train the next generation of robot-savvy infrastructure engineers, including advanced apprenticeships, degree programs and doctoral training schemes.

7. Conclusions

This paper is a summary of the findings of the UK-RAS white paper. It presents a vision of robotics in infrastructure and to reach that vision, shows the identified actions needed in seven main areas. It also provides a summary of recommended actions to the UK Government (as the target audience of the white paper) to implement in order to lead the way in infrastructure robotics.

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