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Fuentes, R orcid.org/0000-0001-8617-7381, Chapman, T, Cook, M et al. (3 more authors) (2017) Briefing: UK-RAS white paper in robotics and autonomous systems for resilient infrastructure. Proceedings of the Institution of Civil Engineers - Smart Infrastructure and Construction, 170 (3). pp. 72-79. ISSN 2397-8759

https://doi.org/10.1680/jsmic.17.00013

Briefing: UK-RAS White Paper in Robotic and Autonomous Systems for Resilient Infrastructure

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Keywords: robotics, infrastructure, RAS, Government, investment

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 $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 we 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 aging 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 includes 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 provide the scale of the problem, (Chinowsky et al. 2013) showed that the road infrastructure in the US will require $2.8billion 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.

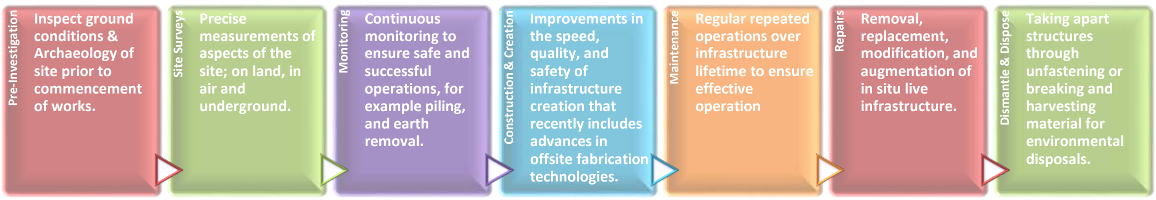

Figure 1. Standard tasks undertaken as part of infrastructure engineering.

This ever-increasing complexity and demands of infrastructure are driving a trend towards automation of all parts of infrastructure provision and operation with significant opportunity for robotic solutions. In this paper we 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, sensors, etc) and software.

Robots have the benefit of being able to operate across the full range of infrastructure engineering (see Fig. 1) – e.g. 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.

• Improved efficiency and higher productivity: The input energy and materials are less to create the same outcome, resulting 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 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 has 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 key points shown in the recently published UK-RAS White Paper in Robotic 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. Future Vision

The future vision the White Paper conveys sets the scene for the rest of this paper and presents a new aspirational paradigm in 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 health state of different assets and act upon this information.

Current state-of-the-art and applications have focussed 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 2017, 2015; 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 Cities, EP/N010523/1 n.d.) Self-repairing city project.

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), BIM (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, robotic science and technological challenges, and socio-economic. 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 approximately three-fold increase on the values from previous years and almost two times pre-crisis levels in 2007 (see Figure 2).

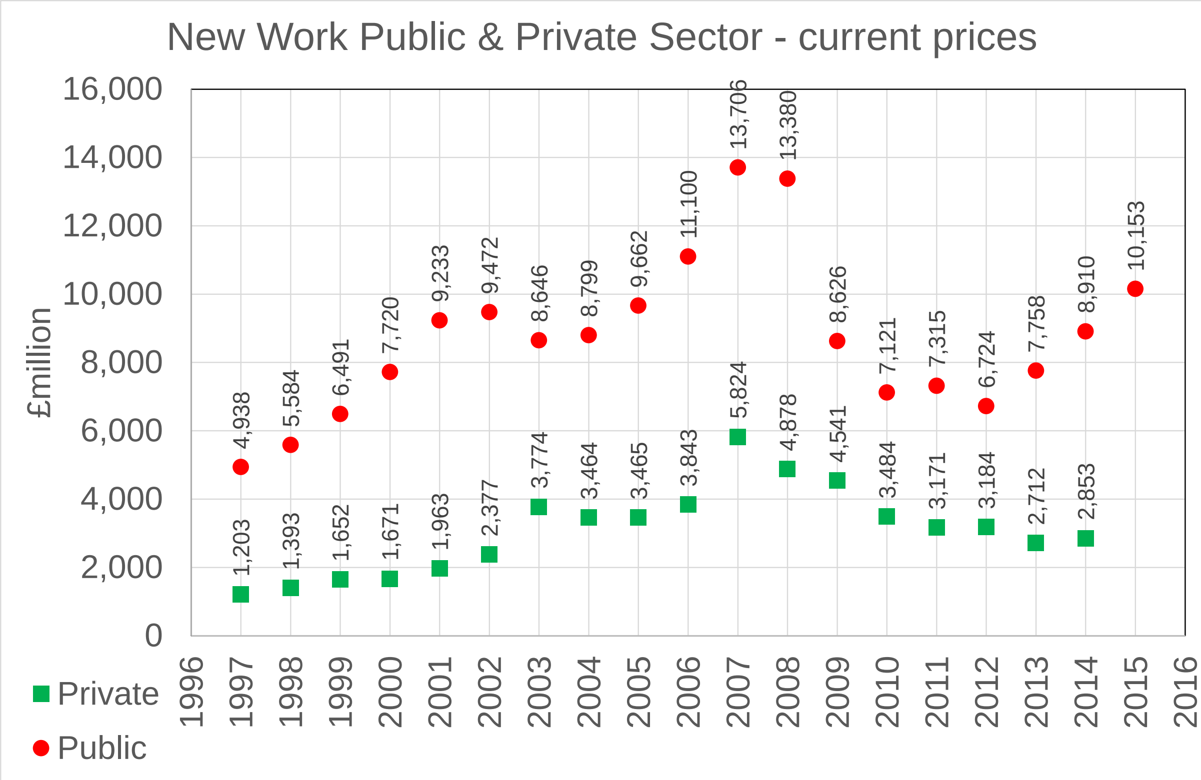

Figure 2. Trend of construction industry market size (HM Government 2016)

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:

1. ***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% medium-risk and 50.6% are low-risk (Smith and Bishop 2016) of being lost to automation, although the figure is 24% at high-risk according to PriceWaterhouseCoopers (Berriman and Hawksworth 2017). However, research also shows that robotics create 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.
2. ***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 before will be
3. ***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 be also much quicker (e.g. (Erdine et al. 2017; Keating et al. 2017; Lundeen et al. 2017; Tay et al. 2017)).

4. ***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 amongst the biggest and most successful around the World. (Jewell and Flanagan 2012) shows 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, whilst maintaining and enhancing the global standing of research institutions and Consultancies alike.

A particular challenge of the construction industry is its fragmented taxonomy (see Fig. 3 for details of the UK) and this is a World-wide 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, whilst only very few large companies employing more than 1,200 employees exist and have a market share lower than 20%. However, equally SMEs have the least financial prowess to invest in disruptive technologies such as robotics placing them at disadvantage. This is partly because the business models to date are not capable of capturing the potential benefits of these technologies and therefore, makes it harder to attract the necessary finance. 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.

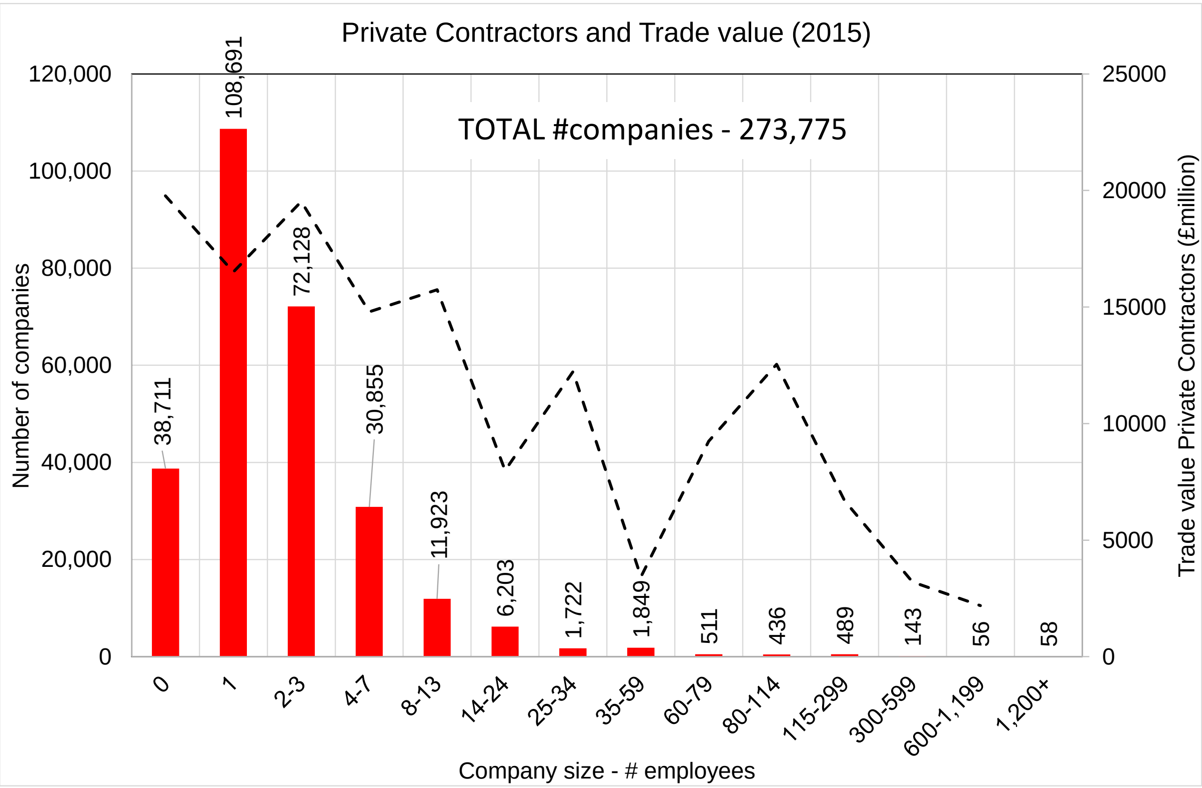

Figure 3. Fragmentation of UK Construction industry (HM Government 2016).

Hence, to achieve the UK Government's intended benefits and to roll-out robotics widely within the construction industry, will require significant investment 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, whilst developing new construction robotics technologies that will give UK Contractors a competitive advantage abroad. Additionally, substantial funds will need to be spent on training and to make sure that the fragmented supply chain consisting of small SMEs are 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 Fig. 4) that currently restrict the wider adoption of robotics technology for infrastructure delivery. They are termed here: *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 Fig. 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

6 Socio-economic challenges

Humans by nature fear the unknown, especially when they see it as a threat to their livelihoods 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 this time things may be different (Campa 2015; Ford 2015). This fear is not new as exemplified in Bronte'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 Bronte, 1849*

The introduction of any new technology, let alone one as radical as RAS, will always change the distribution of jobs in a sector. But 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 from abroad.

The design, manufacture, commissioning, supervision and maintenance of infrastructure robots will create a new industry with new jobs, as will adapting the infrastructure we 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 policy makers through bodies such as 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. Pro-active maintenance has the potential to identify and repair defects quickly minimising damage, the scale of subsequent repair, and allowing infrastructure assets to be kept in service for longer. By increasing the reliability and resilience of infrastructure, it also minimises the environmental pollution caused by e.g. traffic congestion as a result of streetworks, 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.

7 Recommendations

The 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; boosting international competitiveness.

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

1. 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.
2. 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 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 (i.e. a pipe, a bridge bearing, wind turbine, etc.) 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 (for example 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.

3. 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 doctorial training schemes.

8 Conclusions

This paper is a summary of the findings of the UK-RAS White Paper. It presents a future vision of robotics in infrastructure and shows the perceived challenges to reach that vision in three 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.

9 Acknowledgments

The authors are grateful to the UK-RAS for their support in preparing the White Paper. Equally, an immense thank you to all the contributing authors named in the White Paper and the EPSRC funding the Infrastructure Grand Challenge 'Balancing the impact of City Infrastructure Engineering on Natural systems using Robots' (Self Repairing Cities, EP/N010523/1 n.d.).

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