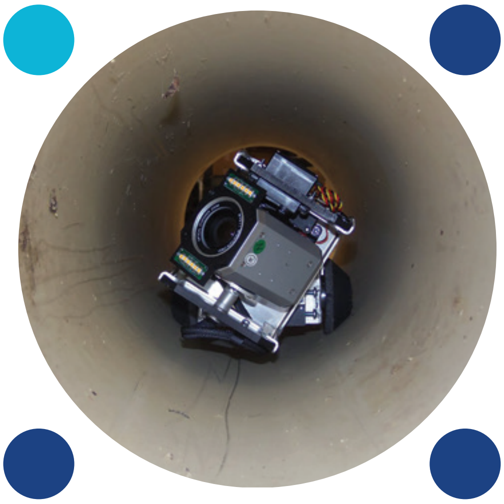
TWENTY65

Robotics and Autonomous Systems (RAS) for buried pipe infrastructure and water operations

Issy Caffoor



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1. Executive Summary

This report explores the opportunity for the use of Robotics and Autonomous Systems (RAS) in the Water Industry, specifically for use in underground infrastructure and more generally in all operational activities in water.

It discusses the applicability of the next generation RAS to water industry applications and the enablers required to fully exploit RAS technologies within the water sector. It concludes that RAS opportunity has clear global drivers, significant benefits, is diverse, exciting and potentially lucrative. The UK is in a strong position to develop an international lead in RAS market if it is proactive and willing to enable and embrace disruptive change in the market and business processes. We see an opportunity for the UK to differentiate itself in the digital industrial revolution that will inevitably take place. The water sector as a whole has the vision and ambition to address the challenge. However the water sector has unique technical and financial pressures which will require a different approach to RAS innovation. What is required is deep cultural change in organisations, governance, regulation and certification. It also requires the development of new skills and co-working approaches, open standards,open access to big data, and changes in customary practices, behaviours, expectations, processes and relationships. The real challenge is to achieve such change while maintaining public trust and confidence in the sector. Forecasting this type of impact and the way markets will change is challenging, but by pro-actively engaging stakeholders through direct measures, including academia and other technical experts, market specialists and end users, it is possible to exploit this transformation potential. It is clear that the technical needs of the water industry are specific and it is therefore incumbent on it to help define and develop the market through R&D investment, definition of technical specification and standards, help with the certification and approval processes and provide SME's assurances on the market size, scope and needs. Without such support to SME's it is likely that development of RAS will be constrained to small, low risk niche applications providing incremental benefits only. The current approach of the water industry to high risk R&D is to be a "fast follower". Given this it is almost inevitable that change will be incremental and based on clear unambiguous winners. In the first instance this is likely to be centred on mapping and condition/performance assessment in underground infrastructure. This will ultimately transition to a full "find and fix" solution in the future which integrates with other city transport and utility systems. The financial benefits of such a transformation are massive and estimated to be an order of magnitude or more greater than using current methods.

2. Introduction

This report explores the opportunity for the use of Robotics and Autonomous Systems (RAS) in the Water Industry, specifically for use in underground infrastructure and more generally in all other water operational activities. Robots are widely used in other industrial sectors and the significant development of Artificial Intelligence (AI) and Machine Learning techniques will result in a rapid growth of Robotics and Autonomous Systems which will have a deep impact on nearly all market sectors within the next decade. This economic impact is not just related to an expansion in the market for robotics technology but to the deep impact robotics technology will have on competitiveness and service provision across all economic sectors from utilities, manufacturing to healthcare. The early signs of this impact are visible in manufacturing, utilities, agriculture, transport, logistics, energy supply and healthcare; where robotics and autonomous systems are already deployed in niche applications. Wherever RAS impacts it will have a disruptive effect [1]. Adapting to these changes will be critical to the translation of disruption into growth. It is clear from the RAS development opportunities that commercial robots will no longer be largely confined to use within manufacturing, consumer and niche applications but environmental and utility applications will also play a significant part in the growth of RAS. Robotics will extend its impact into almost every human activity [1].

Robotics and autonomous systems are differentiated from other machines by their ability to perform physical tasks autonomously. They have the potential to enact a wide range of individual tasks without direct human supervision. These tasks consist of a combination of the three generic physical processes listed here: [1]

Manipulation and processing

RAS can interact with objects and materials directly, remotely or collaborating with co-workers within an Augmented Reality or Virtual Reality environment. It recognises, selects, grasps and manipulates raw materials, objects and parts. It can assemble or disassemble them, apply processing or interact with them even with flexible materials and soft objects; bending, shaping, fitting, cutting, polishing, grinding, drilling holes, cleaning, etc.

Data gathering and monitoring

RAS systems are used to observe and inspect a process, infrastructure or system, assess performance, identify failures or features, or simply provide status data and create system warnings. These monitoring operations can be carried out on people or pipes, land, farm animals, on bridges, roads and harbours, or on industrial plant and historic buildings.

Sorting and storage

RAS systems are used to sort, pack, unpack and store goods, raw materials and parts. These systems are responsible for the correct identification of parts and of keeping track of where each item is. The items being sorted and stored might be analytical samples in a laboratory, packages in a delivery chain, or parts in a store.

The justification for adopting RAS is subject to debate but there are numerous drivers for change which are common to numerous market sectors and these have significant impacts and benefits to society as illustrated in Figures (1) & (2).

RAS	Drivers	Sectors	Impacts
Global Competition Jobs Growth Aging Society Aging Infrastructure Food Security Transport Consumer Demand Living Well Climate Change Environmental Protection Urbanisation Sustainability	Economic → Societal → Market Needs → End Users →	Manufacturing Healthcare Agri-food Energy Utilities Environment Transport Cities Consumer	→ Avoid Health & Safety Risks Improved Productivity Improved Asset Management Beyond Human Skills Enhanced Capability Improved Resource Utilisation Improved Manpower Utilisation Corporate Image

Figure (1) – Global Drivers, Sector applications, and potential impacts of RAS – Adapted from [1]

Impacts		Benefits
Avoid Health & Safety Risks	→	Avoid exposure to harsh or hazardous environments
Improved Productivity	→	Continuous processing / Rapid performance assessment / Speed
Improved Asset Management	→	Multiple autonomous processes / Less downtime / Improved geo-locational accuracy / Optimise use of assets
Beyond Human Skills	→	Dexterity / Precision / Complex and specialised skills / Direct interface to sensors /IT / Speed of retraining / Machine learning
Enhanced Capability	→	Remote handling and manipulation / Aerial/Aquatic capability / AI / Immediate value mapping / Interface to city and third party systems
Improved Resource Utilisation	→	Optimise resources / Reduce waste
Improved Manpower Utilisation	→	Amplifying physical capability / Co-working / Reduce indirect costs / New advanced skills / Logistical flexibility
Corporate Image	→	Competitive advantage / Business growth / Enhanced corporate value / Enhanced environmental performance / Good place to work

Figure (2) – Impacts and potential benefits of RAS applications – Adapted from [1]

Such disruptive technical advances do not occur in isolation, they impact on society and on our economy (see Fig. 2). This will occur over a broad range of market sectors and the total size of this impact will be significantly greater than the size of the RAS sector itself [1]. Robotics and Autonomous Systems (RAS) were identified by the UK Government in 2012 as one of the 8 Great Technologies that support the UK government's industrial strategy [7]. It has been estimated that the global market for RAS products and technology will be in the order of £70bn by 2020-2025 and that if the UK optimised its current RAS technology it would raise manufacturing productivity by 22%. Tractica, a market intelligence firm, has forecast that the industry will grow from $28.3 billion worldwide to $151.7 billion in 2020 [8]. The Boston Consulting Group states that robots currently perform about 10% of all manufacturing tasks, but in 2025 that will jump to 25% [8]. Business Insider Intelligence reports that there will be a $1.5 billion market for consumer and business robots by 2019 [8].

Across these sectors strong cross cutting themes exist that can be used to drive synergies to more rapidly build technical capability and market opportunity [1]. Within those sectors that will benefit the most from robotics and autonomous systems technology the potential for disruptive innovation and the need to respond to change through the development of new regulations and business models is now obvious [1]. Robotics and autonomous systems do not work in isolation. They will require testing, regulation, standards, innovation, investment and skills together with technical progress and strong collaborative partnerships in order to fully realise the opportunity [1]. The UK has a unique opportunity to engage with robotics and autonomous systems, to exploit existing research, development and commercialisation expertise within the UK and explore its potential. The current deployment of RAS applications in the UK is no different from the other major developed economies engaging with RAS [1]. The disruptive nature of many RAS applications means that they will reshape the market and its business models. Forecasting this type of impact and the way markets will change is challenging, but by proactively engaging stakeholders through direct measures, including academia and other technical experts, market specialists and end users, it is possible to exploit this transformation potential.

As well as impacting on socio-economic challenges such as transport, food security, global competition etc. (see Fig. 1&2), RAS offers the potential to reduce government expenditure in critical areas such as security, healthcare, environmental protection, and management and decommissioning of infrastructure. Investment has seen incremental growth attracting investment by governments and private corporations in isolated and uncoordinated pockets. This investment has resulted in competitiveness and productivity in the UK and, when applied in manufacturing to date, has resulted counter-intuitively in a net gain in jobs over time [1]. RAS has enabled the societal benefits of technology to be delivered to the public at large through public services such as the NHS and through private providers. The future market for RAS is currently wide open; key markets are yet to be defined, standards set, value and supply chains created. Embracing this opportunity will deliver various benefits (see Fig. 2):

- Increased manufacturing competitiveness and increased volume of UK manufacturing.
- Improved, and lower cost service delivery in both public and private sector such as utilities, transport to healthcare.
- Improved safety and reduced risk in hazardous or constrained environments (e.g. underground pipes) and on the roads.
- Reduced waste and improved utilisation of resources from chemical usage, mines to farmland.
- More efficient inspection and maintenance of key infrastructure such as pipes and plant.

Analysis of trends, opinions and historical precedents has confirmed that RAS will have a significant impact on all sectors within the UK economy. It will increase business competitiveness, provide effective solutions to societal problems and give greater freedom and choice to individuals [1].

3. RAS – Potential opportunities in the water sector

There are a number of potential opportunities and challenges for the application of RAS in water. These can be broadly grouped under the following headings:

- Underground infrastructure
  - » including transit and transportation within pipes
  - » mapping, condition assessment and rehabilitation within underground pipe assets
  - » security, surveying and mapping of pipe assets from above ground
- Water operations (above ground)
- Water and cities – Providing an integrated approach to city services

These are discussed in the following subsections.

3.1. Underground infrastructure

The application of RAS to underground infrastructure is seen as a priority area in the water sector.

The replacement value of UK buried water and wastewater pipes, a network with a length of approximately 1M km, is between £300B and £600B [3]. For individual companies such as Severn Trent Water and Yorkshire Water, this equates to 93,000 km sewers, 49,000 km water pipes, and 60,000 km sewers and 30,000 km of water pipes, respectively. In terms of the wider market potential similar figures can be assigned to the gas supply network. None of these pipes are smart and currently their inspection is slow and labour intensive, analysis is subjective, and their deployment and rehabilitation disrupts customers and traffic. The condition and performance of the majority of this infrastructure is unknown, leading to reactive management to failure, greater costs and significant disruption. This lack of knowledge about the condition of buried pipes results in sporadic, unforeseen and creeping failures that may never be spotted. Locating and repairing these faults causes huge disruption to road traffic, pedestrians city logistics and local businesses. There are 1.5M road excavations per year in the UK causing full or partial road closures and an estimated loss in earnings to the UK of £5.5B per year [2]. Anecdotal evidence suggests up to 1/3 of water utility excavations result in 'dry holes', i.e. when the pipe is either not located or the fault is elsewhere. Without new technologies this situation will worsen as the infrastructure ages. The government Water White paper "Water for Life" published in Dec 2011 [9] noted that approximately 0.1% of public sewers were replaced or rehabilitated per annum and at that rate it would be about 800 years before the whole system was replaced ie. it's implied asset life. A similar estimate for water mains is 120 years. This compares to typical current age of pipes of 50-100 years that already have unacceptable high failure rates. The need for a radical solution has been articulated by major utilities and their subcontractors. In the round-table discussions at the EPSRC TWENTY65 "Bringing the Water Sector Together" conference in Manchester in April 2017 the industry stated that pervasive sensors delivered by miniature robots are the future for inspection and assessment of their buried pipe networks. The actual problem of failing buried pipes is global, providing an opportunity for the UK to develop radically new pipe inspection technology to market worldwide with a massive economic return. The UK Water Partnership estimate that the UK could increase its global market share in water technology innovation to at least 10% (£8.8 billion), providing 71,000 jobs and involving around 960 SMEs. They estimate the leakage minimisation and pipeline rehabilitation market to be $3-5 B [10] within the next 6 years.

A comprehensive journal review [6] of robots for pipeline inspection revealed that robots currently available are mainly laboratory prototypes designed for large diameter pipes, human controlled, heavy (tens or hundreds of kg) single devices suitable for a single short duration intervention. Examples of these robots are illustrated in Box 1.

Technical challenges and opportunities for RAS in underground infrastructure

A. Transportation and transit in pipework

Common to existing RAS systems used to convey items over a distance, the ability to navigate complex routes is a crucial capability for RAS operating in pipes. Autonomous vehicles within buildings, on roads, rail, aerial, or aquatic, which are already available, will become more prevalent and the crossover of this navigation technology into pipes will be accelerated. However, pipes carry their own technical challenges, not least the difficulty of communication within a subterranean environment with limited known points of reference, working in aquatic and sometimes pressurised systems and negotiating pipe blockages, unknown pipe artefacts and furniture.

B. Mapping and condition assessment of pipe assets

RAS can improve the mapping of legacy assets and installations, improve plant and infrastructure condition monitoring by providing early warning of deterioration, and improve the monitoring of widely distributed underground and above ground infrastructure. RAS has already been used off-shore and underground installation and maintenance and in live power line or under-pressure pipe inspection. In the distribution of domestic utilities RAS can help reduce the impact on highways, provide faster installation, reduce the impact on customers, improve leak detection and repair, and reduced contamination and intermittent flooding.

The actual problem of failing buried pipes is global, providing an opportunity for the UK to develop radically new pipe inspection technology to market worldwide with a massive economic return. The current methods using CCTV or tethered crawler inspection technologies are costly. If networks are going to be generally inspected it is believed that pervasive RAS systems could provide cost savings of an order of magnitude or greater compared to conventional systems. Mapping and inspecting pipes brings with it a series of challenges, not least recognising legal and illegal pipe furniture. Inspection and maintenance is expensive in the utilities sector because of the need to turn off, and sometimes excavate, valves, pipework and plant in order to safely inspect and repair. Extending "up-time" during maintenance will significantly reduce costs. RAS technology can reduce the time it takes to inspect infrastructure by not requiring excavation involving highway closure. It can reduce the time to repair because multiple autonomous platforms can work together and in conditions no human can access or endure, for example within small diameter pressurised pipe systems or within a sewer containing noxious gases. In some cases RAS can carry out regular inspections while plant, pipes are still running or pressurised, increasing the frequency of inspection. By building Big Data about each plant or network, RAS can more accurately spot early warning signs that might indicate damage, decay or fatigue. RAS will therefore reduce maintenance downtime and reduce risk and future liability by increased inspection. The UK has significant water distribution and wastewater collection assets distributed above and below ground. Water companies readily admit that the age and state of their networks make them unstable and it is only through "redistribution of costs and propping them up with OPEX expenditure do they remain serviceable. The urgent need is for find and fix technology that avoids catastrophic failures and enables preventative maintenance. Stopping interruptions to customers is a key driver and the need for "low interruption" "no dig" condition assessment and rehabilitation has been identified as a priority for the next Asset Management Plan (AMP). However, water companies have genuine concerns on the suitability of RAS for this driver. Not least the state of the network, the risk of contamination or blockage (eg. lithium power sources), presence of in-situ often unmapped pipe furniture, recovery of RAS technologies from the pipework, capability and expectation of RAS, and building the cost/benefits case. It is generally accepted that ideally a RAS system should be a find and fix solution. However, it is also recognised that this might be a staged evolution.

Inspection and repair to maintain capacity and extend operating life could be impacted by RAS. There are existing modular, robotic inspection systems that helps utilities screen their network for problem areas and gain a better understanding on the condition of their assets (Box 1). Machine learning can be used to spot irregularities in pipes. Robotic crawlers exist which are designed to easily transport sensors and tools through dewatered pipe, or while submerged in potable, raw water, or wastewater.

Box 1

Pipe Inspection Robots

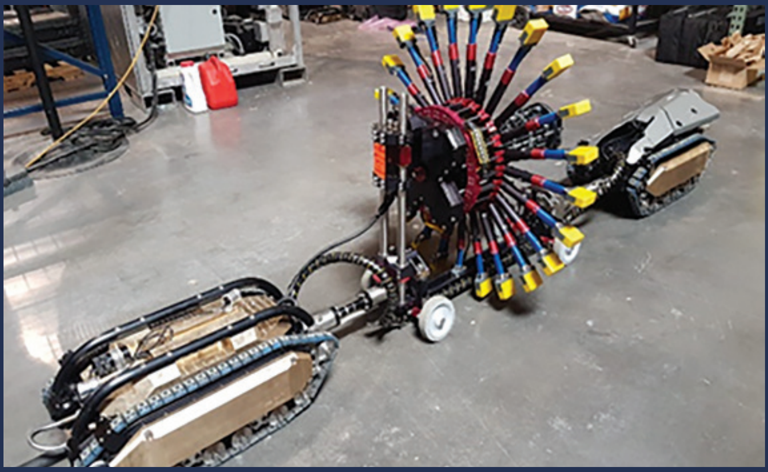
Ultrasonic Inspection Robots from INSPECTOR SYSTEMS have been specially developed for making detailed measurements of the thickness of pipe walls using ultrasonic techniques. [15]

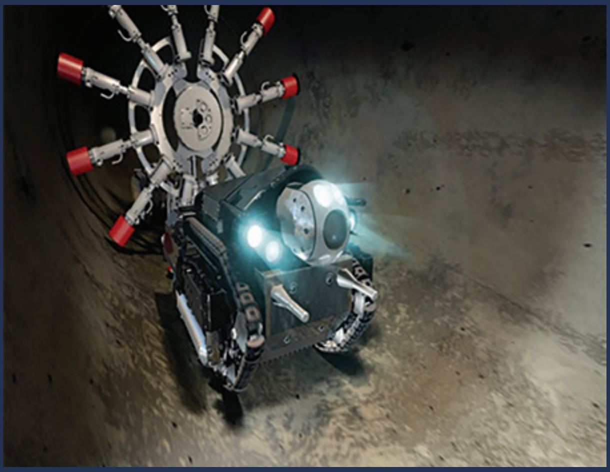
The tethered robots are able to travel both horizontal and vertical sections of pipe with a speed of 200 m/h. Even bends and turns with a diameter of 1.5 D are no obstacle. The robots are self-propelled and don't need to be pushed through the piping. Several hundred meters in length and pipe systems containing many bends and vertical sections can be inspected. The cable also transmits control commands as well as ultrasonic and picture data.

The actual ultrasonic element consists of a rotating ultrasonic sensor for measuring pipe wall thickness as well as a camera and a positioning unit.

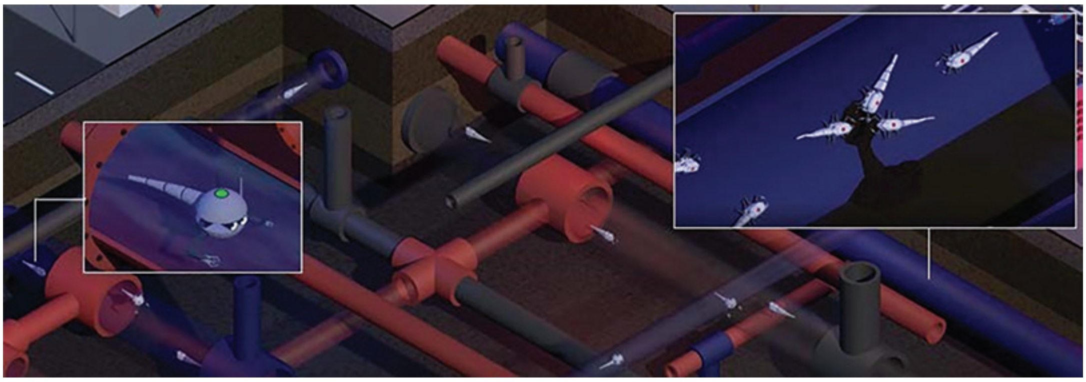
The ultrasonic inspection head is designed to either transmit the ultrasonic beam through water filled pipes into the pipe wall (the UT probes do not contact the inner pipe wall in this case) or as a second possibility the ultrasonic inspection probes are pressed against the inner wall of the pipe (the UT probes are in contact with the inner pipe wall in this case). Using an adaption unfilled pipelines can also be inspected [15].

These types of robots tend to be multi-sensor platforms that carries a variety of condition assessment tools inside the pipeline in a single deployment that also provides live video that can aid in detecting anomalies within the pipe. These tend to be tethered tools which provide limited spatial and temporal resolution condition assessment, and require human intervention and service disruption.





This is a global problem and UK expertise can supply a global market for robotic find and fix technology. Fully maintained assets will reduce costs of failure and repair. A major £4M grand challenge consortium project led by the University of Sheffield called "TWENTY65" (www.twenty65.ac.uk) aims to develop 'silver baskets' of tailored solutions that have the potential to transform the UK (and the world's) water service provision. The research is organised in 8 themes, one of which is Robotic Autonomous Systems for Water Infrastructure Inspection and Rehabilitation. This theme will develop the framework for production and deployment of independent free moving co-operative RAS for collection and rehabilitation of water infrastructure. By 2065 it is envisaged that RAS are permanently deployed within water infrastructure to minimise human intervention, dramatically reducing costs and improving safety (https://www.youtube.com/watch?v=-9p3KOMeTVY&feature=youtu.be). A recently announced EPSRC Programme Grant of £7.2M awarded to the University of Sheffield (www.pipebots.ac.uk) and three other universities proposes "a radically new sensing technology platform" that will transform the way utilities map, locate and collect data on the condition of their buried pipes in real time, over the entire network using minimal human interaction. It is concerned with clean water, waste water and gas pipes. For these pipes the research will assess commonalities in pervasive inspection and develop tailored solutions specific to pipe material and type. This innovation will be the first of its kind to support deployment of swarms of miniaturised autonomous robots equipped with novel sensors in buried pipes of variable type.



Swarms of robots for pervasive pipe inspection

RAS is already being exploited in many parts of the energy supply chain. Most often in hazardous areas providing remotely driven services such as nuclear inspection. Operating in hazardous environments under the sea, within pressurised pipes, sewers filled with combustible gases or in nuclear reactors with remotely operated systems is an ideal RAS application with many crossover technologies which will accelerate the development of applications in water infrastructure. Adding autonomy and precision complemented by geo-locational accuracy enhances both inspection and maintenance operations and increases operator safety or reduces operator fatigue. Liability can be reduced simply by mapping and assessing asset condition, it is a huge benefit in its own right and should be regarded as the first stage towards a vision for a find and fix solution. The data that RAS would provide could be transformative in really knowing the networks. It would provide a detailed understanding of condition and therefore provide the opportunity to optimise investment where it was needed and exploit slack where it was apparent. It could also be used to support several KPIs from minimum pressure to CSO spills etc. RAS working could be integrated into the design of new build pipe assets and other types of buried infrastructure as "smart infrastructure" so that maintenance can become embedded, including asset tagging, automatic condition monitoring, self-healing pipes etc.

Box 2

Aerial Robots

There is significant learning to be had from the existing use of Unmanned Aerial Vehicles (UAV's).

UAV's can take-off, fly on a predetermined path and land autonomously, providing live feedback to a control centre. In times of critical emergencies a UAV can be deployed to the pre-set waypoint and provide real-time coverage, even before the emergency crews arrive. Real-time video link can also be fed to the relevant emergency departments to provide information on the severity of the hazard. This information can then be used to decide on the logistical reinforcements (such as the number and type of equipment and personnel required) to deploy. High resolution data collected by mapping drones in a dense point network can be further crunched in powerful GIS (Geographic Information Systems) and CAD software, allowing for extremely precise volume and area calculations for surveying resources, hazards and map changes or deterioration of features. There are significant parallels to incident management in water pipes or water resource survey.

C. Security, surveying and safety

Aerial robots (UAV's) are becoming more and more popular in security, surveying and safety applications (Box 2) and they offer some potential for use in the water industry.

Leakage is a major factor for unaccounted losses in every pipe network around the world (oil, gas, water). In most cases the deleterious effects associated with the occurrence of leaks may present serious economic, environmental and health problems. Therefore, leaks must be detected quickly, localised and repaired. Nevertheless, most state of the art leak detection techniques have limited applicability and are neither reliable nor robust; while other techniques depend on the experience of the operator. (Box 3) Often is the case with remote above surface monitoring that the leaked material is located but is some distance from the source of the leak arising in unnecessary excavation.

There are also passive in-pipe systems like the PURE Technologies SmartBall system which utilises an accelerometer and gyroscope technology to create a field generated X and Y map of a pipeline, which can be used to understand better the alignment of pipes relative to other critical assets, plan maintenance work more efficiently, reduce the likelihood of third party damage, conduct more accurate hydraulic modelling and detecting leaks on large diameter mains. Large, long run-time leaks have a significant impact on Non-Revenue Water as the volume of water lost with these leaks is often more than those of small diameter mains.

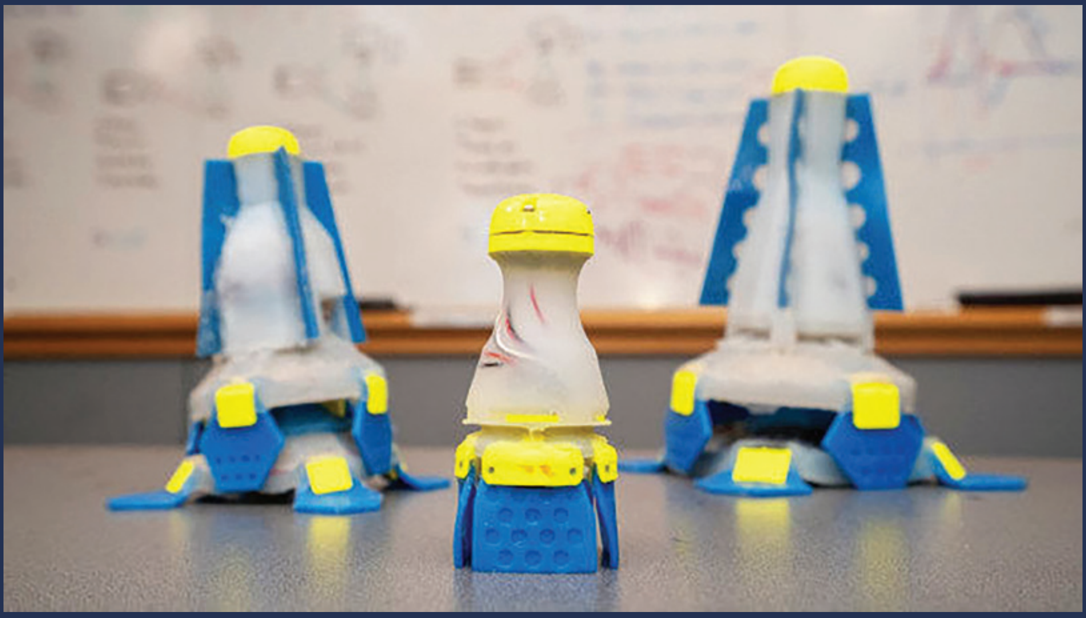
Autonomous systems can be used to inspect pipe network and identify leaks. For example, [4] MIT and stakeholders in Kuwait have tested a prototype propulsion module which allowed an ellipsoidal swimming robot to manoeuvre inside pipe networks with a flexible sensor module allowing the sensor to operate inside pipes with significant irregularities inside. The swimming robot made navigation through complex pipe network possible. In the power industry many urban cable installations are laid in tunnels, conduits, or pipes, which makes them also accessible for inspecting robots. There are also learning points from reported applications from the autonomous mining and construction industries in tunnel and underground environments as applied to critical large diameter utility infrastructure [5]. In this application a self-contained inertial navigation system was developed for the positioning and mapping of underground infrastructures using tunnel profiling, 3D referencing and gyro/laser surveying. The underground positioning relied on a network of satellites placed to surround an area of interest, with a range of up to 2km through soil or rock with accuracy better than 3%, enabling accurate positioning of underground assets. The robotic system had the capabilities to map tunnels, pipes and conduits in detail and sequentially transfer the data collected into engineering CAD systems. A specialized military grade inertial referencing system (IRS) linked to multiple scanners provided high precision profiling while measuring roughness, deflection, ovality and positioning.

Box 3

Leakage Inspection Robots

Severn Trent Water (STW) are trialing a robot for leak detection called Lighthouse.

Lighthouse is shaped like a large badminton shuttlecock with flexible membrane flaps which allow it to flow through the pipes, recording the positions of leaks as it goes. STW aim is to get a dozen or so trial robots that can hand out to engineers in 'real world' situations to see how they perform. The developer from Massachusetts Institute of Technology claims it is 10 times more sensitive to leaks than current technologies, which can only identify large breakages losing at least 10 gallons of water per minute approximately twice the flow of a typical shower. Lighthouse is claimed to spot cracks as small as four millimetres across, losing just one gallon of water per minute [14]. The device can be inserted into the water system through any fire hydrant. It then moves passively with the flow, logging its position as it goes. It detects even small variations in pressure by sensing the pull at the edges of its soft rubber skirt, which fills the diameter of the pipe. The device is then retrieved using a net through another hydrant, and its data is uploaded. No digging is required, and there is no need for any interruption of the water service. In addition to the passive device that is pushed by the water flow, the team also produced an active version that can control its motion.



3.2. Water operations – (above ground)

RAS will impact on both water supply and waste treatment and collection. Not by replacing the water engineer or technician but by enhancing and augmenting their skill, reducing complexity of data, increasing safety and improving customer service.

RAS will also help in reducing rehabilitation impact on other services and in auxiliary tasks such as mapping, condition assessment and problem identification. This will largely be achieved through cooperative human RAS working.

The delivery of efficient and effective water service provision depends on accurate and timely data and on the quality of their interpretation. RAS devices can collect and communicate that data augmenting it with an interpretation of context. They will be an invaluable source for "Big (Water) Data" where data volumes are prohibitive for rapid and timely collection and contextualisation and interpretation by current systems. It is here where the benefits of one of the eight great technologies "Artificial Intelligence (AI)" [7] will come into its own. Ethical data use and privacy will need to be embedded at the core of the system.

Big data and a new generation of modelling tools for its interpretation and transformation into actionable information and even knowledge can ensure consistency in operational procedures and integrate physical information during complex operational management activity to guide operational decision making processes. RAS combined with resilient data communication and collection systems, adaptive mathematical tools, decision support systems and effective re-programming and operator training systems will all improve accuracy and service outcomes robotics assisted tools are a paradigm shift for water engineers.

There are numerous minor procedures that are carried out every day by water engineers, from taking water samples, process changes, and checking water chemistry to changing valve positions, leak detection and fitting boundary boxes. Many of these repetitive procedures can be partly automated. For example, through site identification, or by sensory extension such as the overlay of outflow data, or faster more accurate data collection, interpretation and actuation than is humanly possible. RAS can provide operational tools that transform service outcomes.

Water companies are complex distributed organisations where critical decisions are made every day. Many have a strategic vision to undertake a digital transformation of their operations which will impact directly on the composition of their workforce. Currently information accuracy and efficiency in service delivery generally uses sensors and other technology such as telemetry which underlies good decision making. However, the scale, complexity and uncertainty of the vast infrastructure means the volume of data they provide is tiny in comparison to the size of the problem. Some companies have a declared intent to have "open data" going forward, whereby some data will be made available in the public domain, which will release a potential for third party RAS applications and help transform the scale of data collected within the city system as a whole. RAS will impact on all the non-engineering and engineering functions in a water company, from the delivery of chemicals to the testing of quality, changing of valves and delivery of water samples and sludge. RAS will enhance this capability through seamless and autonomous interchange between technologies. Sometimes it will provide for cognitive assistance to workers albeit through autonomous methods sometimes combined with other advanced systems such as Augmented Reality (AR) or Virtual Reality (VR). This will provide immediate access to all and relevant autonomously collected data, providing conformity of decision making based on this data, traceability of decisions based on this data, the deployment of best practice and the avoidance of employee and public health risk.

RAS can be deployed on long term monitoring of the oceans, rivers, groundwater sources reservoirs outfalls. RAS systems able to transition between land, water and air can monitor resources, track pollution or record plant and animal life. This long-term provision of data will inform decision making across many areas of activity from resource availability, flood risk, environmental measurement, to pollution targets.

The demand for new skills within the industry is increasing. There are severe economic constraints to enabling a work-life balance for staff wishing to modify their working practices, retraining new staff with the right skills, and the logistics of staff deployment, particularly to remote sites. RAS can assist technicians to work from home or covering a larger area by remote engagement with RAS technology at remote sites, increase their independence, enhancing their role and interest levels, detect if a field worker is unwell or unsafe such as through the use of wearable technologies and deliver improved social and technical interaction and communication by freeing up time (see Box 4).

This does raise considerable responsible innovation, human resource and ethical issues. It would need robust and failsafe centric design of systems, engagement from the workforce, customers and management and responsible ethical design and innovation processes. Site visits can be reduced by RAS technology applied to monitoring and water and waste treatment. For rehabilitation and treatment RAS can automate routine procedures that currently need a technician visit. RAS can automate self-recovery when processes show signs of failing while monitoring progress and the effect of remedial actions. Automatic delivery of remedial action becomes possible with RAS technology.

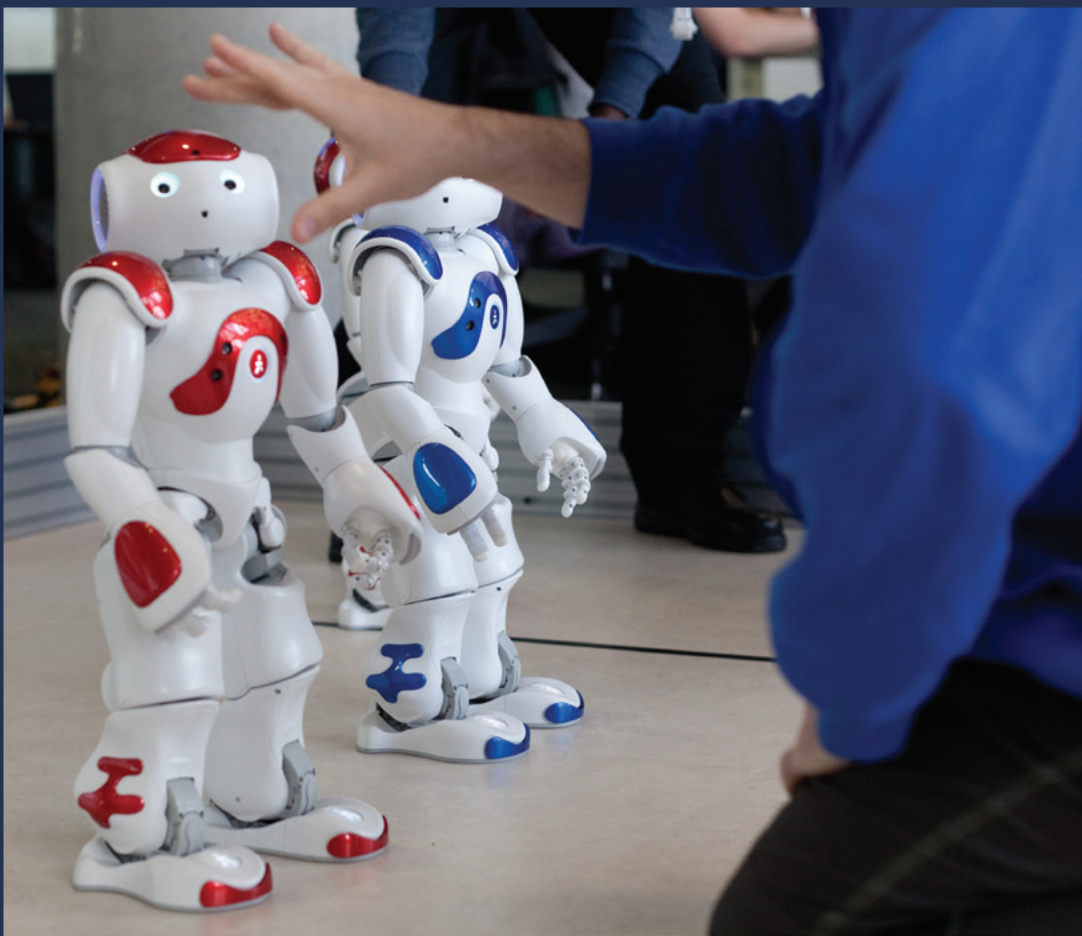
Health and safety of the operational workforce and of the general public is of paramount important. H&S risk is prevalent in every operational activity from handling chemicals, to cleaning pipes and tanks, to deploying current inspection systems and excavation of roads. RAS has the potential to lessen the exposure of humans around higher risk activities. Among the many justifications for using robotics, the most important is to shield people from working in dangerous environments and from handling hazardous materials. From dealing with chemicals that are explosive to handling radioactive substances, robots are routinely used to perform tasks that would kill or maim people. The analogy in water operations would be for example: chlorine dosing equipment, noxious gases from sewage sources, sludge handling (see Box 5).

Box 4

Robots Responding To Human Emotions

Researchers at MIT's Computer Science and Artificial Intelligence Laboratory claim that emotions can be detected remotely using a device that emits wireless signals to help it measure heartbeat and breathing.

The new device, named "EQ-Radio," is 87 percent accurate at detecting whether a person is excited, happy, angry or sad — all without on-body sensors or facial-recognition software. Remote emotion monitoring could eventually be used to diagnose or track conditions like depression and anxiety [12].



Box 5

Processing Robots

Processing robots are extensively used in manufacturing, nuclear, processing and in the food industry.

Robots have excelled in such applications and in constrained environments, but there is a demand for faster and more agile machines able to provide faster operations on individual processes and products. Research from within both academia and industry has developed a broad range of end effectors able to grasp the vast majority of process mechanics and products found in the process industry.

Stanford engineers have developed an electronic glove containing sensors that could one day give robotic hands the sort of dexterity that humans take for granted [13].

Public health in water supply, drainage and treatment operations are a key performance indicator. Automated monitoring and treatment of potential public health failures has the potential to reduce infection or public health incidences as well as retaining trust in the sector. Combined with smart sensors automated and autonomous systems able to sense and clean RAS will impact on key performance indicators. RAS could enhance capability in chemical delivery, site security, site cleaning and maintenance including recreation and amenity sites and public education. This could serve to improve public safety and make contact with water companies a more engaging and fulfilling experience.

As is done already to a lesser or greater extent, RAS could be used to autonomously control water production based on up to date demand data, energy and raw material costs, risk and raw water supply, thus reducing waste and increasing productivity.

Managing the flow of water and sewage samples to a central testing laboratory and their sequencing within it is a complex logistics problem. Greater levels of automation in both delivery and testing will result in more efficient and timely services.

3.3. Water and cities – providing an integrated approach to city services

Autonomous systems across cities will become significant data generators for Big Data and the agents of action in the Internet of Things. It is important that communication protocols are developed that account for autonomy. Not only with respect to interconnection between RAS devices and "cloud" services but also to drive actions based on data from the "cloud" or other utility systems. Establishing integrated transport utility service delivery within cities will critically depend on the bidirectional flow of information between vehicles and the systems of systems that manage traffic and road usage patterns and utility services. There will be a need to deliver greater capacity as urbanisation and demographic change escalates, as well as the need to meet traffic management, customer impact, environmental, energy and water resource usage targets. City services and inhabitants will benefit from improved safety, infrastructure and transport network utilisation as well as reduced utility service downtimes and travel times.

The management of infrastructure, waste and traffic will benefit from RAS carrying out services in the city invisible to the operation, that is the utopia of find and fix without road closure detailed in the TWENTY65 Programme. RAS will enable us to maximise the capacity of existing infrastructure, proactively detect deterioration and to increase safety and to reduce downtime of city infrastructure and generate data to drive better maintenance and investment models. City "Big data" will become a valuable commodity. RAS coupled to big data will revolutionise the urban environment both physically and in terms of its utility. Integrating city wide data from transport and utility services and using this to dynamically route and prioritise utility work, traffic flows and will decrease average journey times and optimise the utilisation of capacity and interconnections as well as reducing utility customer impact.

Progressive levels of autonomy will enable new transport and utility delivery models where ownership is replaced by more cost effective on-demand and point of use services and here again the TWENTY65 Programme aims to deliver a basket of solutions for point of use services. The long term data gathered will inform infrastructure investment/development and set control and planning parameters. Robotised maintenance and rehabilitation will enable significant advantages.

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4. RAS enabling new business models, disruptive and integrated service design for water

RAS enabled full autonomy will bring the opportunity for disruptive business models that swap ownership for on demand services. At customer and on demand delivery over the final mile will alter the pattern of logistics delivery.

New business models and services will disrupt current practices allowing services to be quickly customised after initial process by including variation in the processes design flow. This will result from automation and up-skilling of complex tasks, the maximisation of capital investment through reconfiguration and integrated, cooperative human/robotic working. Common standards will enable RAS to become a contracted out service provision. This will reduce the capital cost of automation, reducing stock holding, and lower the cost of service. It offers the opportunity of variable contract lot size, shorter time to services provision, improved service conformity, reduced lead-times and greater service flexibility including backup redundancy. This will concentrate expertise, rapidly increases UK capability, and optimises capital investment.

As utility pipes become a readily accessible RAS highway there will be opportunities for utilising them for alternative business routes such as communications or transport.

Manufacturing currently signposts one of the greatest success stories of RAS to date. The water industry can learn from this success when considering its capital investment and engineering schemes. By integrating service sub-processes into the design path it will reduce time to service delivery. Integrating safety into design will improve verifiability and infrastructure resilience. RAS allows service variability to be built into the design process and enables service offerings to be adapted to different customer needs more easily. Integrating assembly processes into the design path will reduce time to build [1]. Allowing technical variability to be built into the design and process will enable designs to be adapted to different construction methods more easily. Design tools are critical to RAS implantation and competitiveness.

5. New generation of RAS and its potential for water

The fundamental change that marks out the new generation of RAS technology is its ability to enable humans to directly and physically interact with robots, using all sensory cues including emotional which enables true co-working (see Box 6).

In all areas of application this close coupling between robot and human is a key part of the RAS opportunity and provides for future opportunities in water through human and robot co-working [1]. How a robot is controlled by the user will depend on the application but water does present opportunities. This coworking maybe through voice or physical interaction or in the future through translation of emotional signals such as facial expression or even brainwaves (see Box 4 and Box 6). In remote handling or evaluation where moment

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Box 6

Back Office Co-worker Robots

Robots will work autonomously reporting, collaborating and multitasking. They could become the hidden and backroom face of an organisation, co-working in call centres, control centres and providing technical advice to remote workers.

There a range of technologies deployed for this task - Robots, digital assistants, virtual agents, bots, chatbots, even metabots.

They all play a role in customer service although they have different capabilities and, to some extent, serve different markets and customer needs. It's fair to say robots have carved out a great opportunity for contact centres to reduce live assistance of inbound volumes, leading to huge savings in time and support costs. As the next step in the evolution of self-service, robots are becoming an important part of today's multichannel contact centre environment which could in the future focus on the control centre environment.

to moment interaction is essential there will be an immediate mapping of human motion to robot motion. In the water context this might be exploited through AR or VR in remote working or in hazardous or constrained environments. To this interaction RAS will add safety, dexterity, scaling and an overlay of information such as engineering diagrams, best practice, maintenance history or pipe layout to help the user make decisions. In other applications robots will learn by copying human actions such as valve positioning, jetting or cleaning operations, or will take high level commands about what to do while filling in the operational details. Where teams of robots are carrying out a task the human user may only need to issue high level mission instructions such as which section of pipe to locate to and wait for the next moment that needs a decision, such as "repair damage".

Autonomy is a sliding scale, applications will employ as much or as little as they need [1]. Interaction between humans and robots will become increasingly physical. Training a robot will involve showing it what to do, physically guiding it and demonstrating while it watches, e.g. procedures for complex maintenance or cleaning tasks in water pipes. Robots will be able to feedback the shape and texture of the object it is holding to a user as physical sensations. Robots will use our body pose and facial expressions to interpret our intentions and decode our instructions. In the context of water this might be limited to customer engagement activity.

Through machine learning and AI instructing a robot to carry out a new task will no longer need an expert [1]. Future applications of RAS will enable us to extend reach into distant, remote or hazardous locations; support cognition, through training or machine learning; reinforce safety in hazardous, unfamiliar, difficult or remote environments (eg. constrained pipes, sewers or chlorine dosing); enable physical interaction and manipulating at a distance (e.g. remote working or jetting or cleaning)), through video imaging, augmented or virtual reality (e.g. remotely engaging with a treatment works dashboard); commanding a multifunctional and complex team interacting with "big data" and other external RAS platforms (e.g. find and fix swarming robots); interpret and predict intent through training or historic precedent (e.g. site security) or by decoding social cues (e.g. customer contentment).

Underlying the RAS opportunities are advances in key technologies that enable a higher level of capability. Not least is the challenge of mapping a complex, sometimes arbitrary, unconstrained and pressurised water network. As each technology achieves a step in capability new markets will be opened. In turn the market will pull technical development and direct attention to reducing technical deficits in order to enable new markets and business models to succeed [1]. Each RAS process as detailed in the above paragraphs and in Figure 2 above, depends on specific sets of underlying technologies and these are detailed below [1]:

- **Cross-cutting technology**
  Technical developments that cut across sectors. For example new technologies for grasping and manipulation in manufacturing can be applied in water.
- **Cognitive technologies**
  Cognitive technologies provide the context, interpretation, recognition, learning and reasoning required to make autonomy smart and effective in given application such as navigating a new complex pipe network.
- **Mechatronics**
  Mechatronics is the core of every robot mechanism. driven by actuators and sensors informing controllers of state generating responses to stimuli that control motion, grasping, and interaction. This enables RAS to physically interact with the environment and users.

The particular challenges in water include miniaturisation, communication and motion below ground in pressurised water pipes and power and materials of construction limitations.

- **Systems Engineering**
  RAS systems in water integrate a wide range of technologies from mechanics to complex software in the cloud to mapping, communication technologies, power and robot recovery procedures. Robotics is often seen as the ultimate systems engineering challenge. Integrated design systems, safety led processes, and certification all needs support from well designed systems engineering tools that manage complexity, engage users and customers and speed time to market.

These in turn rely on underlying areas of technology such as sensors, communications, energy storage, materials, software engineering, "big data handling", machine learning and electronics.

It requires technologies capable of effective robot deployment and recovery, navigating and mapping in unstructured and often unmapped environments such as pipes, in order to contextualise the features of its environment and its artefacts, the condition of such and its rehabilitation needs. Within these environments it needs to be capable of detecting objects and obstacles and contraventions to the norm, and interpret the local environment and integrated safety into its decision making or its motion control through dynamic motion planning. High level communications, map generation and adaptive planning through optimisation of space and time usage, analysing motion, analysing power usage will be essential components to enable adaptive strategies in unstructured pipe networks. Monitoring specific characteristics, chemistry, sound, colour, texture, organisms and materials and communicating this raw data and the interpretation of state or condition, interrogating information and "big data" in the cloud to make decisions will be essential to machine learning and adding to knowledge. Picking up, examining rotating, sorting and placing objects precisely and safely without knowing how to handle them in advance will be essential for the "fix" strategy in pipes. As will object recognition, 3D sensing, grasp planning, actuation, force sensing, proprioception, scene analysis, and the utilisation of affordances [1]. Intuiting human intention from social cues, motion and facial expressions and using multiple inputs such as touch, sound, vision and gestures will enable the modelling of human motion to secure safe operation in above ground situations. This in turn will rely on interfaces that manage complexity, task based commands and interactive mission planning [1]. As RAS proceeds into hitherto uncharted environments, materials of construction capable of and permitted for deployment in drinking water and explosive environments such as sewers will become more important, as will the need to expedite the manufacture of specialised RAS components for water such as miniaturised non-toxic power sources. The opportunity to use find and fix solutions in pipes will also drive new challenges in material science for the reduction of crack propagation and preventative maintenance in pipes.

6. Enablers for RAS in water

If the opportunity for RAS in the Water Industry is to be met then a number of enablers need to be in place including;

- opening the regulatory environment and establishing standards and certification processes,
- investment in academic research, technology and its delivery to market,
- lowering the barriers to market entry for SMEs, including the provision of safe demonstrator facilities,
- building a matching skills base that is focused on STEM and RAS,
- stimulating public and private collaboration,
- synchronising research, innovation and investment with market opportunity and needs.

Robotics and autonomous systems do not work in isolation. They require regulation, standards, inter-institutional cooperation, research, responsible innovation, investment, testing facilities, access to big data, demonstrators, skills development, co-worker and customer acceptance and ethical evaluation. All of these non-technical aspects of RAS are essential enablers and as equally important as technical progress; indeed in some areas they are a prerequisite for market development and business investment. Developing these underpinning enablers will be an essential part of growing UK RAS capability in water and in general.

Innovation funding and business investment will be essential if RAS for water infrastructure in the UK is to grow. This investment must align with UK government business strategy, be cross cutting and joined up across the innovation pathways in the UK. Emerging technology breakthroughs in fields such as AI, robotics, and the Internet of Things are significant in their own right. However, it is the convergence of these Industrial Digital Technologies (IDTs) that really turbo-charges their impact [16]. This includes building a national digital ecosystem that will be significantly more visible and effective and that will accelerate the innovation and diffusion of industrial digital technologies. This also includes developing a national adoption programme focused on increasing the capacity of existing growth hubs and providing more targeted support. It includes upskilling of a million industrial workers to enable digital technologies to be adopted and exploited through a single Industrial Digitalisation Skills Strategy [16]. It requires the refocusing of the existing innovation landscape by developing a number of Digital Innovation Hubs, large-scale demonstrators, and digital research centres focused on developing new technologies as part of a new national innovation programme. It requires leadership through the establishment of a national body, comprising industry, government, academia, further education, and leading research and innovation organisations, which would be responsible for developing the UK as a leader in industrial digitalisation technologies and skills, with a mandate to develop the UK's own domestic and global brand and unlock the potential of IDTs [16]. Digital technologies are transforming industry. In a 2017 report, the World Economic Forum identified a $100 trillion opportunity for both industry and society through the adoption of these technologies [16]. The positive impact on the UK through faster innovation and adoption of IDTs could be as much as £455 billion for UK manufacturing over the next decade, increasing manufacturing sector growth between 1.5 and 3 percent per annum, creating a conservative estimated net gain of 175,000 jobs throughout the economy and reducing CO2 emissions by 4.5 percent [16]. Robotics and Automation, Virtual reality and augmented reality and the Industrial Internet of Things were three of the areas in which it was recommended that the government should create digital research centres in the "Made Smarter" review in 2017 [16].

In this respect the following initiatives contribute to this challenge. The EPSRC TWENTY65 Grand Challenges project (EP/N010124/1) and the recently announced EPSRC Programme Grant on Pervasive Sensing for Buried Pipes (EP/S016813/1) both featuring a major theme of robotics for buried infrastructure represent a good start. SMEs are also critical to the process of innovation in all sectors, identifying them, engaging them early in the innovation process and supporting them to enter this market must be high on the innovation agenda and the TWENTY65 Thought Leadership Club initiative is contributing to this engagement. Supporting the validation of first use of RAS technology for buried pipes, developing live demonstrators in real application scenarios, production and deployment of robots pervasively are seen as being critical to uptake. However, the needs of the water industry are specific and if SME's are going to invest in the R&D to take this technology to the market they would need some assurances the water industry market size, scope and needs. It is therefore incumbent on the water industry to help define and develop the market through R&D investment, definition of technical specification and standards and help with the certification and approval processes. Without such support it is likely that development of RAS will be constrained to small, low risk niche applications providing incremental benefits.

In general there is a poor level of adoption of IDT's in the UK. The UK is behind other advanced nations in overall productivity (output per worker), which is in part due to lower levels of adoption of digital and automation technology [16]. This is particularly acute among SMEs. One of the identified causes is an ineffective and confused landscape of business support, with no clear route to access help and ambiguity about what 'good' looks like. SMEs, in particular, perceive significant barriers to adoption, such as risks around cybersecurity, and a lack of common standards allowing different technologies to connect. Unlike other developed nations, the UK's tax system is not targeted enough to incentivise the opportunity [16]. The growth of robotics in the UK may be solely limited by the availability of skilled engineers and technicians. There is a general technical skill shortage in the UK in engineering, RAS disciplines and in general. Businesses are hindered by a fragmented skills system and a lack of systematic engagement between education and industry [16].

While this can be solved with immigration there is a pressing need to rebalance STEM uptake in line with a rebalanced economy. It is also recognised that any changes to the free movement of global skills may impact on the availability of RAS skills in the short to medium term. Hence the provision of Doctoral Training Centres focussed on the RAS environment and specifically on application areas such as utilities, pipelines or water will greatly assist in meeting the medium term skills needs. Investment in Universities must be backed up across all levels in the education system from primary schools to in-work training schemes and apprenticeships. Robots will create jobs in the medium term but will also cause displacement. Skills investment must therefore also recognise the need for retraining, particularly in co-working with RAS. Standardisation of protocols will enable transferable skills across RAS application sectors. If the UK is to make the next step deploying robotic co-workers and hybrid RAS applications then boosting skills will be an essential driver of uptake and thus improved competitiveness [1].

Trust in robots and autonomous systems will enable the market to grow. Regulation and customer awareness and engagement provides the basis of that trust. The lack of regulation standards and certification is recognised as a significant barrier to growth. In many sectors the opening up of test and demonstrator spaces is essential for product development and first use validation. Never more so than water when public health is a key business driver. Regulation that specifically includes autonomous systems is essential. The vivid nightmare of robots running amok which is painted in fiction is only a programme error or poor regulation away and must be taken seriously. User and customer trust, engagement and acceptance is key to success and this trust can be built through a legal framework for autonomy and the underpinning insurance framework. Greater customer expectations in water, the current cost of service delivery and the need to find alternatives business models to current service delivery are in themselves RAS enablers.

Ethical and responsible innovation are important prerequisites of a successful service built on RAS, particularly to a water utility whose raison d'etre is public health. Water utilities report additional constraints to the evaluation and implementation of RAS. They report on: entrenched views within the organisation; the need for cultural change; the lack of resources to appraise and implement radical innovation; different levels of ambition and investment across the sector; long development and implementation timeframes (equating to two AMP cycles) which makes the cost benefits case complex and difficult to justify; as being factors discouraging the adoption of RAS.

Over half of the world's people will live in urban areas by 2025. In developed countries the population in urban areas will reach 80%. The constraints and opportunities that urbanisation brings with decaying underground infrastructure, traffic management and city systems integration issues is also seen as a significant enabler of RAS for buried pipe infrastructure.

7. Conclusions

This paper has provided a personal and largely optimistic perspective on the use of, and transition to, RAS applications in the water sector. Such change will require significant investment, levels of stakeholder, disciplinary and professional collaboration supported by innovative business models, transformative technologies and, perhaps most importantly, new ways of valuing RAS solutions. Industrial digitalisation is a massive opportunity for UK industry and the wider economy. The technologies that underpin it are also highly disruptive, requiring business to be innovative, agile and adaptable. Industry and government need to work in partnership to provide the infrastructure and ecosystems that can enable manufacturing businesses and their supply chains to maximise these opportunities and be competitive. The water sector as a whole has the vision and ambition to address the challenge. However, realising this possible future with the unique pressures on the sector, as outlined in this paper, will require a sector push that is somewhat removed from its historic approach to innovation. What is required is: deep cultural change in organisations' governance, regulation and certification; development of new skills and co-working approaches; open standards; open access to big data; and changes in customary practices, behaviours, expectations, processes and relationships. The real challenge is to achieve such change while maintaining public trust and confidence in the sector, and to find ways of realising a RAS future that is promoted and sustained by complementary social attitudes and conduct including within the water sector workforce. The RAS priority is clearly for mapping and condition/performance assessment in underground infrastructure, transitioning to a full "find and fix" solution in the future which integrates with other city transport and utility systems. This future will enable significant opportunity for disruptive services and new business models.

In developing a business case for RAS the costs of sensors, digital visibility, communications and technology are relatively easy to project but the benefits gained by such transformational change are not. Forecasting this type of impact and the way markets will change is challenging, but by pro-actively engaging stakeholders through direct measures, including academia and other technical experts, market specialists and end users, it is possible to exploit this transformation potential. The rapid evolution of such technology also makes the timing of business investment an uncertain prospect. The needs of the water industry are specific and it is therefore incumbent on it to help define and develop the market through, R&D investment, technical specification and standards, help with the certification and approval processes and provide SME's assurances on the market size, scope and needs. Without such support it is likely that SME development of RAS will be constrained to small, low risk niche applications providing incremental benefits only. The current approach of the industry to high risk R&D is to be a "fast follower". Given this and without a change in approach it is almost inevitable that transformation and the resulting benefits will be incremental and based on clear unambiguous winners.

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