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Pipebots

Report on Water Industry Challenges Workshop

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Executive Summary

This report provides an overview of the Pipebots Water Industry Challenges Workshop held on 12th July 2019. The aims of this workshop were to (i) identify the key buried infrastructure inspection challenges that the UK water industry faces and (ii) to disseminate information to build understanding of the scientific and technical challenges for Pipebots. The workshop comprised three sessions: firstly to identify and rank the inspection challenges; secondly three short presentations on the current technical capabilities and challenges for robotic pipe inspection systems; and finally to draft plans to deliver practical implementation of autonomous robotic inspection systems to deliver the highly ranked challenges from the first session.

The first session led to the identification of six key challenges for Pipebots: Asset Mapping; Cost – Benefit; No Disruption; Leakage; Impact on the Environment; and Condition Monitoring. For each of the challenges delegates examined the impacts upon the public, the water utilities and the environment, then considered how these would vary in three future time horizons and under different socio-economic scenarios. It was seen that different challenges do have different impacts, e.g. disruption will directly impact on the public, whereas condition of the network mainly impacts on the water company until it causes disruption. Delegates did not identify significant differences in the impacts with time horizon, except where climate change is a factor. However, the different socio-economic scenarios were perceived to impact on the importance of the challenge.

The short presentations on robotic systems and sensing technologies provided the background for the final session where delegates were asked to identify delivery routes and timescales for the six key challenges. For each of the challenges, ideas of timescales were developed, some such as asset mapping were expected to be feasible at a small scale by 2025, with full implementation of swarms by 2030. Other challenges, such as leakage were expected to need a more stepped implementation from deploying existing sensors on robots in the shorter term to developing new sensing technologies that could identify precursors to leaks in the medium term and incorporating more complex hydraulic measurements in the longer term.

The information collected during the workshop will be used to develop the initial challenge specifications for the “Pipebots” project.

1 Introduction

The aims of this workshop were to (i) identify the key inspection challenges that the UK water industry face regarding the provision and operation of buried piped networks in the short and medium term and (ii) to disseminate information to the UK water industry to build understanding on the scientific and technical challenges faced with the development and delivery of autonomous robotic inspection systems.

The information on the water industry inspection challenges and the scientific and technological development challenges will be collated to develop the initial challenge specifications for the "Pipebots" project.

The workshop contained three sessions: first a session to identify and rank the inspection challenges the water industry faces in managing their large buried pipe networks; secondly, three short presentations on the current technical capabilities and challenges for robotics and robotic pipe inspection systems; and finally a workshop session to develop the highly ranked water industry challenges from the first session and combine these with knowledge on current capabilities and technological challenges to develop draft plans to deliver practical implementation of autonomous robotic inspection systems.

In the first session workshop delegates worked in groups to identify and discuss the known and expected challenges faced by the water utilities in the management of buried pipe networks and which could be aided by the robotic and sensing technologies that could be developed during and after the Pipebots project (2019-2024). The analysis of the challenges were framed into three time epochs: the next AMP[1] period, 2020-25; the following two AMPs, 2025-2035; and then further into the future 2035-2050. The challenges were also framed by a number of socio-economic scenarios that included a combination of influencing pressures and drivers, such as climate change, environmental regulations, technology acceptance, economic factors and organisation of the UK water sector. The final task of this session was to rank the key challenges for different scenarios and epochs. These were tested on their impact and their robustness across different scenarios.

The final session developed the six most highly ranked water industry challenges and combined these with the current technological capabilities and challenges in robotic inspection and sensing to develop first versions of delivery plans. These plans aimed to identify realistic timelines for the development of the required technologies, together with important milestones and link these with the potential investment and regulatory conditions. Milestones covered different aspects from the development of a technology, to demonstrations at different scales and preparing the water industry and regulators for use of such radically new technologies.

[1] AMP = Asset Management Plan, the water industry in England and Wales has a price review every five years which links into the company business plans. AMP periods tend to have different focuses for performance improvement by the water companies.

2 Identifying Key challenges

In the first session, groups contained delegates from the water industry and other industries that managed buried pipe networks and researchers from the “Pipebots” project with expertise in several of the technologies associated with robotic sensing.

The first task was to identify the expected challenges that pipe networks would experience until 2050. Delegates were given time to individually brainstorm the expected challenges to ensure that no valid challenge was omitted. The proposed challenges were then grouped, and subjected to more in-depth examination. The delegate groups were asked to examine the potential challenges in terms of their potential impact on the: (i) public; (ii) water utility; and (iii) environment (in the widest sense). Each identified challenge was examined and a description of its impacts was made.

The delegates were then asked to consider the size of the impacts under four different socio-economic scenarios at three different time scales: (i) 2020-2025 (next AMP); (ii) 2025-2035 (next two AMPs); and (iii) 2035-2050 (far future). The four socio-economic scenarios (see Appendix 1) described potential futures that the water industry may face in terms of pressures (demand/climate), regulation and economic and technical capacity. Each of these factors would influence the size of the impact of each of the identified challenges. The groups then assessed the importance of the impacts for each scenario under the 3 time epochs and then ranked the challenges in terms of their overall impact.

The six challenges identified as being most significant are detailed in the following sub-sections. Some of these challenges are more relevant to either water distribution systems, or to drainage systems, while others are relevant to both types of system.

2.1 Asset Mapping

2.1.1 Challenge overview

Buried pipe networks are likely to exist into the foreseeable future (up to 2050 and beyond). While the water industry manages the largest buried pipe networks in the UK, other organisations, such as Network Rail and the Highways Agency, also manage significant buried pipe drainage networks. It was identified that mapping and identifying assets was a major challenge as many networks are old and the data concerning location, size, material, etc. is often uncertain, inaccurate or missing. Specifically, one group noted that asset data typically has a 40% error rate, while another group suggested that 46% of buried pipe networks are unmapped. Damage to buried assets by other utilities was also cited as a problem.

Lack of data on the location and characteristics of an asset creates many issues, for example inaccurate locations result in ‘dry holes’ being dug where holes are dug to repair and asset and no asset is found, costing money and causing unnecessary disruption to traffic. Not knowing the size and material of an asset means that future planning is hampered because the capacity of the asset is unknown, as is its likely condition. Furthermore poor asset data leads to poor hydraulic models which are difficult to calibrate, high quality asset data would allow models to become a “digital twin” of the network.

2.1.2 Challenge impacts

The direct impact of high quality asset mapping is low for the public, and environment, but very high for the water utility. Indirect impacts for the public are higher, for example in terms of traffic disruption. Similarly the indirect impact on the environment is higher, because it is important to the location and dimensions of assets in order to manage effectively the impact of any buried pipe network on the environment.

2.1.3 Variations in future scenarios

Pressure on assets will increase under scenarios involving high climate change due to decreasing rainfall volumes and increasing high intensity rainfall events. Asset pressure will also increase in scenarios exhibiting strong population increases. Where there is more pressure on assets, better knowledge of those assets is more important for effective management. This is especially true if low GDP growth leads to less investment in the water, sanitation and drainage sector, so investment needs to be targeted. However if the lower investment arrives before asset knowledge has reached a good level it is likely that available funds will only be directed towards reactive maintenance, rather than asset mapping. Some scenarios have weak governance or declining regulation, which would impact on the priorities of water utilities, where this is combined with strong investment in water then asset mapping would continue, however with declining investment the water utility would likely focus on the parts of the business which generate income, which would most likely be the distribution network, especially in high climate change scenarios.

This challenge was ranked high or moderately high in all scenarios.

2.2 Cost – Benefit

2.2.1 Challenge overview

Cost control is an important issue for water utilities and other industries managing buried piped networks. Compared to other sectors using pipes to transport fluids and gases, water is of low value. The regulation of the water industry in particular drives the need to manage networks at the "lowest" cost whilst providing "acceptable" levels of service and environmental impact. The question was raised as to how robotic technologies could be used in this environment, given that historically such technologies have been very expensive. There will be a need to show that the results obtained from the use of robotics is very cost-efficient.

It was noted that the monetary value of benefits can be direct, or may be indirect through regulatory incentives and penalties. For example the direct benefit of preventing property flooding has a tangible value that can be estimated based on historic flooding incidents. However, reducing the number of flooding incidents can also have a significant impact on regulatory drivers, which link to future regulatory determinations. Conversely, under current economic conditions the tangible value of water lost through leakage is low (especially compared to the cost of locating and repairing leaks), but the cost (and hence benefit of reducing leakage) can be artificially imposed on the water industry through regulation. Using robotics to better understand the performance of networks would allow for better prioritisation. Regulation driven benefits are particularly subject to change with time – e.g. in recent years fines for sewer network derived pollution events have increased by around 2 orders of magnitude.

2.2.2 Challenge impacts

Cost-Benefit is likely to have a high impact on the public, the water utility and the environment. For the public it directly impacts bills, as well as levels of service. For the water utility it impacts profitability and also determinations from the regulator. For the environment it is important to have a balanced approach in order to maximise benefit within a known resource envelope.

2.2.3 Variations in future scenarios

Cost-Benefit will be important, to some degree, in all future scenarios, but the balance will vary depending on the particular pressures of different scenarios. For example where investment in water and sanitation is increasing this could mean cost is relatively less important, so allowing uniform coverage and global impact from robotic technologies, whereas decreasing investment would mean prioritisation is much more important. Changes in governance structures would also impact on this as decreasing regulations may result in fewer drivers for the water utility to keep bills low.

2.3 No Disruption

2.3.1 Challenge overview

Disruption covers two potentially linked, areas for water companies. Firstly disruption to supply of the service – be that water supply or sewerage; and secondly disruption to other non-water utility activities (e.g. transport) caused by failures or maintenance to the piped network. For other owners of piped drainage networks (e.g. Network Rail or the Highways Agency), the service being supplied is usually transport.

Water companies serve many millions of customers, a key challenge is to deliver reliable services with no or little disruption. The challenge is the same for those managing drainage for transport infrastructure, especially Network Rail where service disruption has a high economic and reputational cost. Flooding from drainage networks, especially internal sewer flooding of properties causes significant customer disruption and is likely to increase with high climate change and population growth. Flooding is mainly caused by in-pipe blockages and pipe collapses of pipes and other system failures (e.g. pumps).

System knowledge gained from robotic inspection would allow a better understanding of network condition and performance, while causing little or no disruption. This would allow maintenance to be better planned and also potentially increase the take up of trenchless technologies which further reduce disruption.

2.3.2 Challenge impacts

The impacts of disruption are very significant to the public, whether that be in terms of continuous supply, or travel disruption. The water utility impacts will also be relatively high as supply disruption would have impacts on determinations from the economic regulator resulting from increased negative customer contacts. Environmental impact would generally be moderate and mainly related to reduced carbon if disruption due to digging holes and repairs is reduced, unless the disruption is to a wastewater service and resulted in flooding or pollution incidents.

2.3.3 Variations in future scenarios

This challenge was seen as particularly important in scenarios that had strong regulation and high economic growth.

2.4 Leakage

2.4.1 Challenge overview

Leakage from piped water distribution networks is a key (and enduring) challenge. Leakage from drainage networks is a different issue, usually only occurring when the pipes are surcharged, and there is the potential to result in environmental pollution, especially of ground water. Leakage reduction from water distribution networks would be driven by water resource considerations, but actions to reduce leakage must not cause loss of service or other types of disruption. A key challenge for leakage is to detect and locate the leak with reasonable precision (1 m was suggested) and to do this in a timely manner. Leakage also has potential links to hygiene – pressure transients could draw in contaminated water through leaks. Infiltration to and exfiltration from wastewater networks are linked to leakage, as it can significantly increase the volumes of water that need to be transported and treated. This problem may become bigger under scenarios with low investment where assets are likely to deteriorate and climate change may also impact this issue.

2.4.2 Challenge impacts

In general the direct impact of leakage on the public is low, although indirect impacts such as disruption for the repair, potential for the water to freeze on roads, or potential for contaminant ingress could be more significant. The impact on the water company is higher, partially due to losing a saleable commodity, but also related to regulatory drivers. The impact on the environment is mainly low as the water is clean and leaks are usually relatively slow, however bigger leaks, or leaks from wastewater networks could have a significant impact on the environment.

2.4.3 Variations in future scenarios

High climate change and high population growth would be key drivers exacerbating water scarcity and hence the importance of controlling leakage. Scenarios with increasing investment in water and sanitation mean that more money is available to comprehensively tackle leakage, whereas those with lower investment would need lower cost, more targeted, solutions to minimise leakage, probably on a more reactive basis. Governance and equity would also be important factors, with weak governance and declining equity, solutions may not be applied uniformly across the networks.

Leakage was ranked most highly in scenarios with high climate change, but it was seen that in scenarios with more funding available there is more expectation to repair leaks quickly, whereas in scenarios with lower economic growth there is a higher expectation for low cost solutions. In scenarios with lower climate change leakage was considered moderately important.

2.5 Impact on the Environment

2.5.1 Challenge overview

All piped networks can have an impact on the environment, but this is highest from wastewater networks which contain pollutants. The type of environmental impact depends on the event and location. Wastewater networks most commonly cause pollution when they are overloaded and spill, although extreme overloading can also result in flooding and potentially erosion. Pollution from clean water is limited as the chemicals are relatively benign, however leakage and bursts can result in flooding, while leakage will also impact on water scarcity, potentially resulting in over-abstraction from the natural environment.

2.5.2 Challenge impacts

The impact on the public of environmental impact is on average moderate, but very variable, depending on how members of the public view and use the natural environment. The impact on the water company depends on the regulatory regime, recently these impacts, in terms of fines have been increasing by up to 2 orders of magnitude. There may also be an impact of environmental pollution in terms of increased costs to treat raw water for potable water supply.

2.5.3 Variations in future scenarios

High climate change and high population growth would put more stress on existing assets and therefore on the environment, especially from wastewater collection networks, but also increasing demand for water. Increasing investment in water and sanitation would allow damage to the environment from buried piped water networks to be minimised and previous damage to be reversed, whereas decreasing investment would be likely to make minimising environmental impacts increasingly difficult. Governance and equity are important differences between the scenarios for environmental impact, deregulation may remove drivers for protecting the environment, prioritising profit to the water utility, whereas declining equity may focus environmental mitigation in certain locations to the cost of other locations. Certain scenarios may also allow more radical changes to water systems, for example complete recycling of wastewater – including nutrients, etc., rather than sending screenings/sludge to landfill.

2.6 Condition Monitoring

2.6.1 Challenge overview

Future large scale investment in current pipe networks is unlikely for almost all scenarios. Accurate and timely data on the condition of existing assets will be important to maintain or improve service performance and extend the life of assets at an affordable cost.

Condition monitoring needs to be able to identify characteristics within pipes that lead to reduced performance or failure. In drinking water distribution networks this may include corrosion of pipe materials, failing joints, changes in profile indicating high stress, build-up of sediments and biofilms which may affect water quality as well as cracks or holes in the pipe. In drainage networks, there are some commonalities with water distribution systems, such as failing joints, changes in profile, sediment build up, cracks and holes, but also other factors such as root intrusion and other partial or complete blockages due to build-up of grease, wipes and also foreign objects such as traffic cones or tree debris.

2.6.2 Challenge impacts

The direct impact on the public is generally low because the assets are out of sight and hence out of mind, it is only when the condition becomes critical and causes some form of disruption that the public are impacted, often significantly. For the water utility the impact of knowing the condition of assets is high because it allows for better planning and better use of available funds, showing better management of networks will also be favourable for regulator determinations. Impact on the environment is similar to the public impact, it is only when condition results in failures that impact occurs and even then the severe impact is only usually from wastewater networks.

2.6.3 Variations in future scenarios

Condition monitoring is important in all future scenarios, because even with increasing investment in water and sanitation, it is still not feasible to replace significant amounts of the buried piped networks. Understanding the condition of these aging networks is therefore key to enhanced management. There would be differences in how new technologies might be applied in future scenarios. For example in scenarios with high economic growth and stable or increasing investment in water and sanitation, the cost and number of robots could be higher, giving better and more frequent data to build deterioration models. In scenarios with lower economic investment there is less capacity to be proactive, but there would still be an economic driver for condition assessment, although the robots may need to be cheaper and used less frequently, searching for imminent failures alone.

2.7 Other challenges

Alongside the major challenges described above a number of less significant challenges were identified. These are summarised below.

Health and Safety regulations affect the cost and viability of many maintenance activities within buried water and drainage pipe networks, increasingly strict regulation on access could make the cost and complexity of maintenance activities much higher, which would make the relative costs of using autonomous robots lower and therefore their deployment more attractive.

Rapid repair and trenchless technologies are closely linked to the selected 'No disruption' challenge, but also offer specific opportunities to change the way buried pipe networks are managed. A "zero carbon" UK is a significant challenge for the water sector which is still very energy intensive. Trenchless technologies for repair may help contribute to emission reduction by reducing repair related disruption and also the embedded carbon in repair materials.

Development of new instrumentation and making effective use of data provide challenges to water companies. While water companies already handle technical data, systems for effective processing and analysis of very large datasets are lacking. Consideration of how to best use data from new pervasive inspection systems is needed before and during the technology development phase for the robotic inspection systems to ensure data and its analysis are managed optimally.

People and skills were also seen as a challenge for the future, new technologies and changing regulations mean changes to the skill sets required for water company staff and contractors. The skill levels needed would be dependent on the ease of use and levels of autonomy of new robotic technologies.

3 Delivery of Robotic technologies to meet the challenges

A short presentation was given to the delegates on the current level of development of robotic inspection systems and sensing technologies. This was supplemented by a short report that had been distributed to the delegates before the meeting.

Using the highly ranked six key challenges, the workshop delegates then attempted to identify potential delivery routes from the current state to a state in which autonomous robotic sensing technologies could be implemented to meet the six highly ranked challenges. Each group discussed two of the challenges and proposed a series of activities that need to be undertaken taken to deliver an effective robotic based solution to mitigate the impacts identified in any particular challenge. The groups identified tasks, timescales and responsibilities, based on available resources and the ability of the water industry to adopt new robotic based technologies. The timescales used in this session were the same as in the earlier challenge identification session: (i) 2020-2025; (ii) 2025-2035; and (iii) 2035-2050.

3.1 Asset Mapping

This challenge has two key parts, firstly mapping the location of the pipes and other features and secondly identifying pipes and other features. Both types of networks are generally buried, so any robot inside the pipes will not be able to access a GPS signal which would be the obvious solution to determine location. Instead it is necessary to use the motion of the robot, potentially alongside other information, such as from an on board camera and prior knowledge of the pipe network to incrementally build up an accurate map of the network, which can be used in the future.

Assessing the asset characteristics might use some of the same sensing data as mapping, but requires different processing and most likely additional sensors to collect different data. The systems would not only need to determine pipe size and material, but also discriminate key geometrical features such as manholes and hydrants. Technical challenges are thought to be different between water distribution networks and drainage networks, the latter having different cross-section shapes for larger pipes, while distribution pipes are usually circular regardless of diameter. The type and spacing of joints is likely to be useful in confirming distances where networks are made from discrete lengths of pipe, as is the case for clay and most concrete sewer pipes.

Mapping, unlike condition assessment, should only need to be done once, assuming practices are put in place to ensure proper records are kept for new and rehabilitated pipes, and that a single pass is adequate to give the required accuracy.

A consensus on timescales was generally achieved. One group proposed a 2020 target which was to establish current maps and ideal test areas. By 2025 it was suggested that a robotic CCTV solution for small area, collecting data remotely, travelling hundreds of metres could be achieved. The second group was slightly more ambitious, suggesting that by 2025 robots would be competing with manual CCTV crews and surveying a 2 km reach from a single manhole. Both groups considered robot swarms could be achieved by 2030.

3.2 Cost – Benefit

Cost-benefit is a challenge for both the water industry in general and something that robotic technologies must achieve by providing greater benefit than cost. Cost-benefit is not a specific task for robots, but one to be achieved through the design and implementation of the robots. A specific benefit suggested would be the reduction in vehicle miles for operational inspection and maintenance activities, thus reducing costs and carbon. It was highlighted that key costs are in employing people, health and safety risks and disruption to streets. Appropriate robotic technologies could reduce costs in all three areas. It was also noted that costs and benefits shift with pipe size, i.e. risk, probability and consequence scales with pipe diameter.

Through lowering the overall cost of inspections, robots could allow the frequency and coverage of pipe inspection to increase significantly. Targeting of resources, including robots, to failing assets is seen as key to maximising cost-benefit. For example, anecdotal evidence presented suggested that 50-75% of blockage occurs in 100-150 mm diameter sewers. These small diameter pipes are rarely inspected, so lower cost robotic technology could lead to widespread inspection and so reduce the significant costs associated with in-pipe blockages. Pervasive information from robotic inspections could have knock on operational effects, e.g. cleaner pipes may not need additional monitoring.

It was suggested that in the short term (not specified) that robots could locate and classify known problems, so would be working locally. The costs of infrastructure for powering robots may mean that robots remaining almost permanently in the network is only possible in the long term.

Long term delivery could be truly disruptive, overall system costs be reduced significantly, not only water company costs, but also costs to the environment and the public. For proactive vs reactive maintenance considerations it is important that clear evidence is available.

One group suggested a 5 year timescale for limited robotic technologies to be deployed at small scale. This group also took the view that major benefits in cost and consequence are in pipes of 300 mm diameter and upwards and that early robotic applications should focus on these pipes.

3.3 No Disruption

Robotic technologies have the potential to significantly reduce the potential disruption caused to services through a number of means, which are linked to other challenges. More accurate location and asset data will allow any interventions to be much more accurately targeted. Improved knowledge on asset condition could allow pro-active maintenance, which is properly planned to minimise disruption both to network performance and road transport. This could result in meeting the water sector’s 2050 aspirations such as “no blockages” and “no leaks”. Better knowledge of buried assets also opens up more opportunities for better deployment of existing and new trenchless technologies for the repair and rehabilitation of pipes.

In the 2020-25 timescale it was thought that robotic systems could be involved in responding more effectively to customer reported failures. It was not thought that data collected by robotic systems would be of a quality or quantity to deliver pro-active actions to prevent disruption.

In the period from 2025-2035, continuous monitoring and understanding of network condition and performance would allow a progressive move to proactive strategies. This is where the “Pipebots” outputs could have large impact. There is a need to better understand precursors to failures, e.g. the initial build of FOG, or pipe geometry changes for leakage. A key is getting early information, and better knowledge of failure paths. Historical statistical information on specific failure "hot spots" is currently available and there is a need to make use of this information to develop effective pervasive robotic inspection strategies.

3.4 Leakage

It was noted that there are current, state of the art, in-pipe technologies that "can detect leaks under ideal conditions". Examples of these are Lighthouse, Smartball and Sahara, all of which use flow in the pipe for propulsion, the first two are un-tethered. Leak noise correlators have now also been developed. In the short term (2020-2025) robots could be used to deploy these technologies.

The project should consider a number of alternative methods for leak detection, including acoustic, pressure fluctuation, particle tracking and optical / infrared techniques. Links to sensing water quality and discolouration should also be considered. Collecting more data on leaks will allow improved predictive failure models to better predict future leakage risks. While initial work should focus on methods to detect active leaks, future sensors development (2025-2035) should aim to detect the pre-cursors to leaks.

One of the groups advised that robot friendly infrastructure should be developed now where current infrastructure is replaced. Linked to this concept was a suggestion for "Pipebots" to work with the industry to 'merge robots with smart pipes'. The group suggested that "Pipebots" should also be looking at the need for robot hubs and investigating the resource required to upgrade existing systems. In terms of timeline, short term access was the issue, in the medium term inspection and then in the longer term (2030-2050) hydraulic measurement capabilities were suggested.

The other group suggested that initially a portable robotic inspection platform designed for leaks and failing pipes was desirable. The case for early consideration of smart infrastructure for robots, e.g. charging hubs, was made and a comment that Scottish Water, for example, are including smart elements when they undertake a major scheme. A virtual reality video, aimed at government to get policy support for the deployment of autonomous robotic inspection to address this challenge was suggested.

3.5 Impact on the Environment

Environmental impacts come in many forms, and as with the Cost-benefit and No disruption challenges, this challenge is not focussed on a specific task that a robot could achieve, rather an impact that robots doing specific tasks could affect. Furthermore, robots could have an indirect impact on the environment through reducing vehicle miles, reducing traffic disruption and ensuring the network is better maintained, hence requiring less energy (i.e. pumping).

Flooding was considered to be the biggest impact. CSO spills would seem important to consider here as well. Identification of blockage and sewer collapses were considered to be important requirements to reduce such environmental impact, the method suggested was visual inspection.

It was considered that robot swarms would be needed to tackle blockage problems, but the time horizon for this would be around 2050. Swarms which frequently monitor pipes (especially small pipes) could spot developing blockages. A rapidly developing blockage would need to be identified in a timescale of hours for effective response.

Long term goals identified in this challenge were: robots to measure surface roughness; to collaborate with RTC systems; self-powering robots reducing vehicle numbers; and sacrificial robots that will fix leakage by physically blocking leaks 'Brinker bots'.

3.6 Condition Monitoring

Existing infrastructure is likely to be in use for many years, but it is ageing and deteriorating at unknown rates, which leads to unforeseen performance issues, such as leakage and intermittent discharges. Improving knowledge on current pipe condition and how it changes with time should allow better deterioration models to be developed, leading to a fuller understanding of risks and better operation to enhance reliability. Better understanding of asset condition could significantly reduce negative public perceptions by proactively targeting interventions and avoiding emergencies.

Condition monitoring can rely on information such as fluid parameters, pipe size, contemporary condition, pipe materials and construction methods. This range of parameters means there are many data sources to build an understanding of the condition of a pipe and ultimately possible failure modes. Pipe conditions which affect performance may not indicate imminent collapse, for example pipe roughness affects flow capacity; issues with joints lead to leaks or water ingress, and also increase blockage risk. Only gross physical deformations may indicate potential structural failure. Currently condition monitoring in drainage networks is primarily by CCTV, traditionally image analysis has been a human task, but recent research has developed techniques for automated analysis which could be of benefit to "Pipebots". In the short term it was considered that additional data sources e.g. satellite monitoring; soil data; tree cover (which impacts soil moisture) should be considered to examine the potential for correlations with existing data sources.

In the short term the groups specified asset type and material characterisation as the key inspection tasks, followed in the medium term by the development of sensors for coarse condition assessment, such as leakage detection. In the longer term a move to finer condition assessment would support the development of reliable deterioration models. It was considered that in the longer term fully autonomous robotic swarms would have the capability to sense key defect characteristics and map this to location and then auto generate repair/replacement requests. Pipe condition sensing technologies would be based on material. It was noted that inspection techniques for some materials are already well advanced in other fields, however materials with coarser or less homogenous structures (e.g. cast iron and concrete) still present a significant technical challenge.

3.7 Other technical constraints to adoption of robotic platforms

In water distribution networks, the motive forces need to move robots should be deployed in such a way to limit the removal of biofilms and corrosion deposits which could cause discoloration issues. However, removing some of these materials could be beneficial in maintaining the pipe, as long as levels are low enough not to cause water quality and discoloration issues.

The concept of robots working from hub(s) through which data is relayed to the surface was common across challenges and network types. These hubs may also allow charging. Powering the robots is common constraint across all challenges. Ideas were expressed to minimise energy use and also to examine the feasibility of harnessing energy from the water, or even using bio-processes?

Looking at short term development, it was suggested that the robots could initially be tethered and increase intelligence and autonomy with experience. They could operate in larger diameter pipes initially and then move into smaller diameter pipes as confidence in their autonomous capability grows.

4 Conclusions

Mixed teams of academic researchers and experienced end users, mainly from the UK water sector were asked to identify the major challenges that the UK's buried pipe networks face in the short, medium and long term. The teams identified a long list of challenges and then assessed the impact of these challenges on the (i) water utility, (ii) the environment and the (iii) public. The level of impact and its change under four climate and socio-economic scenarios, and for three different time frames (2020-2025, 2025-2035 and 2035-2050) was assessed by the workshop participants and this information was used to identify the six major challenges that the UK water sector's buried pipe networks face and need to be addressed for effective, long term management of such networks.

The six major challenges that were identified were:

1. Asset Mapping
2. Cost-Benefit
3. No Disruption
4. Leakage
5. Environmental Impact
6. Condition Monitoring

The teams then were given information on the current technical maturity and future potential capabilities of autonomous robotic inspection systems. Using information on the key challenges and considering the potential development of the capabilities of robotic inspection technologies the teams were asked to propose potential timelines for activities to achieve the deployment of robotic inspection systems to address the six major identified challenges.

For the Asset Mapping challenge, consensus on timescales was achieved. It was suggested that by 2020 demonstrator test areas could be identified so that by 2025 a robotic solution could be demonstrated for small areas, collecting data remotely and travelling up to 2 kilometres could be achieved. It was thought that robotic swarms focused on asset mapping could be achieved by 2030.

For the cost-benefit challenge, it was suggested that in the short term that robots could locate and classify known problems in a small area. Long term delivery could be truly disruptive, overall system costs be reduced significantly, not only water company costs, but also costs to the environment and the public. Given the delivery costs of a hub infrastructure for powering robots so that they can operate permanently in pipe networks, pervasive permanent robotic inspection is only possible in the long term. Strong clear evidence is needed for water utilities to move from reactive to pro-active asset maintenance. The size and cost of robots was discussed, less complex (single task) robots would be lower cost. In the medium term there is likely to be a market for a range of robots to achieve task of different complexity and each of which has an associated cost (and benefit). It is likely that the market needs to be built slowly and that water utilities will start with less complex single task and lower cost technological options.

For the no disruption challenge, effective delivery of autonomous robotic inspection could result in the UK water sector meeting its ambitious 2050 “no blockages” and “no leaks” aspirations. In the short term robotic systems could be involved in responding more effectively to customer reported failures. Historical asset information on specific failures should be used to develop effective pervasive robotic inspection strategies ahead of technological development. By the 2025-2035 period pervasive monitoring of network condition and performance would allow for a progressive move to proactive strategies. Such pervasive data would identify precursors to failure and so deliver opportunities for proactive responses. Better knowledge of the assets also opens up more opportunities for better deployment of existing and new trenchless technologies for the repair and rehabilitation of pipes.

For the leakage challenge, it was noted that there are in-pipe technologies that “can detect leaks under ideal conditions”, it was suggested that in the short term robots could deploy these technologies. In the medium term there is a clear need to develop sensing technologies that can not only identify leaks but also detect the pre-cursors to leaks. It was realised that access to pressurised networks was a key constraint for the deployment of robotic systems, it was suggested that robot friendly infrastructure should be developed now and deployed when current infrastructure is replaced. In terms of an overall timeline, short term access was the issue, in the medium term enhanced sensing capabilities and then in the longer term (2030-2050) more complex hydraulic measurement capabilities were suggested.

For the impact on the environment challenge, flooding was the biggest impact issue. Rapid identification of blockage and sewer collapses were considered essential to reduce such impact. Given the intermittent and pervasive nature of in-pipe blockages, it was considered that robot swarms would be needed. Swarms which frequently monitor pipes (especially small pipes) could spot developing blockages. However the time horizon for such capability would be 2030-50.

For the condition monitoring challenge, it was considered that in the short term the key tasks were asset type identification and material characterisation. In the medium term sensors would need to be developed for coarse condition assessment, such as leakage detection. In the longer term a move to towards higher resolution condition assessment would be required to support the development of reliable deterioration models. In the longer term fully autonomous robotic swarms would have the capability to sense key defect characteristics and map these to location and then auto generate repair/replacement requests.

Appendix 1: Scenarios Used

Scenario	Characteristics of Scenario	Criteria	2020-2025	2025-2035	2035-2050
A	High Socio-economic capacity High climate change	%GDP growth per year	2.5	3.5	3.5
		Investment in water and sanitation (%GDP)	8	8	10
		Primary energy consumption change per year from today (%)	-	+1.7	+2.0
		Population change from today	-	+2M	+5M
		Social Values, attitudes and capacity	Nationalist, individualistic, high capacity	Nationalist/Internationalist /entrepreneurial, high capacity	Internationalist, libertarian, high capacity
		Governance Structures	Declining Regulations	Deregulating and consultative	Weak, Dispersed and consultative
		Equity	Apparently promoted	Strongly declining	Strongly declining
B	Low Socio-economic capacity High climate change	%GDP growth per year	0.5	2	1.5
		Investment in water and sanitation (%GDP)	8	4	3
		Primary energy consumption per year change from today (%)	-	+1.0	+1.0
		Population change from today	-	+1M	+0.5M
		Social Values, attitudes and capacity	Nationalist/strongly regulated, low capacity	Nationalist/communitarian, growing capacity	Nationalist/communitarian, growing capacity
		Governance structures	Declining Regulations	weak, national, closed	weak, national, closed
		Equity	Apparently promoted	Declining	Declining

Scenario	Characteristics of Scenario	Criteria	2020-2025	2025-2035	2035-2050
C	High Socio-economic capacity Low climate change	%GDP growth per year	2.5	2.8	3.5
		Investment in water and sanitation (%GDP)	8	8	8
		Primary energy consumption per year change from today (%)	-	+0.1	+0.1
		Population change from today	-	+1.5M	+1M
		Social Values, attitudes and capacity	Nationalist and individualist, strong capacity	Internationalist/ entrepreneurial, strong capacity	Internationalist/ entrepreneurial, strong capacity
		Governance Structures	Declining regulations	strong, coordinated, consultative	strong, coordinated, consultative
		Equity	Apparently promoted	Improving	Improving
D	Low Socio-economic capacity Low climate change	%GDP growth per year	0.5	1.25	0.5
		Investment in water and sanitation (%GDP)	8	4	2
		Primary energy consumption per year change from today (%)	-	-1.0	-2.0
		Population change from today	-	0	-0.5M
		Social Values, attitudes and capacity	Nationalist/individualist, low capacity	Localist, cooperative, growing capacity	Localist, cooperative, growing capacity
		Governance Structures	Declining regulations	Strong, local participative	Strong, local participative
		Equity	Apparently promoted	Strongly Improving	Strongly Improving