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Pipebots

Intelligent Buried Pipe Infrastructure: Present and Future

This position paper has been produced by the Pipebots Academic Team.

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The University Of Sheffield. University of BRISTOL UNIVERSITY OF LEEDS UNIVERSITY OF BIRMINGHAM

Intelligent Buried Pipe Infrastructure: Present and Future

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Abstract:

The Pipebots Programme Grant (www.pipebots.ac.uk) vision is for an intelligent, robust and resilient buried pipe network leading to significant reductions in infrastructure and service failures and the disruption these causes. Its mission is to create a new, pervasive and autonomous robotics platform that will radically improve the water industry's ability to generate a real-time condition and performance map of buried pipe networks; and, use this new knowledge to transform the way utilities manage and maintain buried pipe networks in the future. Delivering the vision will require excellent science from the project team in the fields of sensors, robotic systems, autonomous control, navigation, communication and power. It will also require an awareness of, and a willingness to make allowances for, the existing operational and regulatory structure of the UK water industry. To meet the aspirations of the project, the robotic platform will need to be both systemically desirable and culturally feasible. In other words, the platform will need to deliver its benefits in the context of the existing system, which makes a good understanding of that system a vital foundation to the success of the project.

This position paper provides background information that will help to steer the Pipebots Programme Grant. It covers asset management in the UK water industry, the state-of-the-art of pipe inspection and repair technologies, and research that is needed to support their future developments. The purpose of this paper is three-fold. Firstly, it is written to help the Pipebots team to understand well the state-of-the-art technologies which currently exist to inspect, rehabilitate and to manage the buried water pipe infrastructure. In this respect, the paper is structured to review the science and technology advances related to the seven research themes within the Pipebots Programme Grant. Some of previous research and technologies will be used as the basis for the development of new science as proposed by the Pipebots team. Secondly, this paper is written to benefit a larger research community who work in the areas of buried pipe inspection, robotics and asset management relevant within a liveable city context. Thirdly, this paper lists key challenges which the research community is facing and explains roles of the seven themes in developing better pipe inspection technologies and asset management strategies.

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1 Introduction

The replacement value of UK buried water and wastewater pipes, a network with a length of approximately 1M km, is between £300B and £600B (Long, May 2018). Similar figures can be assigned to the gas supply pipe network and network of pipes supporting telecommunication cables. None of these pipes are smart and their inspection is slow and labour intensive, analysis is subjective, and their deployment disrupts traffic (Metje et al., 2015, Rogers et al., 2012a). The lack of knowledge about the condition of buried pipes results in sporadic, unforeseen failures (Metje et al., 2007). Locating and repairing these faults causes huge disruption to road traffic, pedestrians and local businesses (Makana et al., 2018).

As a result, 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 (McMahon et al., 2005). Anecdotal evidence suggests up to 1/3 of these 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 buried pipe infrastructure ages. 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 (Caffoor, 2019). Our comprehensive international journal review (Mills et al., 2017) of robots for pipeline inspection reveals robots that 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. Pipebots will focus on much smaller robots with a size that is an order of magnitude less than the pipe diameter. These robots will be minimally invasive to the flow, pervasive and able to operate in swarms in all areas of pipe networks autonomously.

Pipebots proposes to develop 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 Pipebots project 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 on both a national and international level. Figure 1 illustrates the challenges, research methodologies and themes which need addressing to develop autonomous pervasive in-pipe sensing with multiple cooperating small robots to cover the complicated network of buried pipes. We have assembled the key ingredients for successful implementation: (i) clear and achievable philosophy for technology transformation; (ii) leading expertise in the relevant areas of science and technology; and (iii) appetite from the industry worldwide to radically transform their efficiency in pipe inspection, condition assessment and asset management.

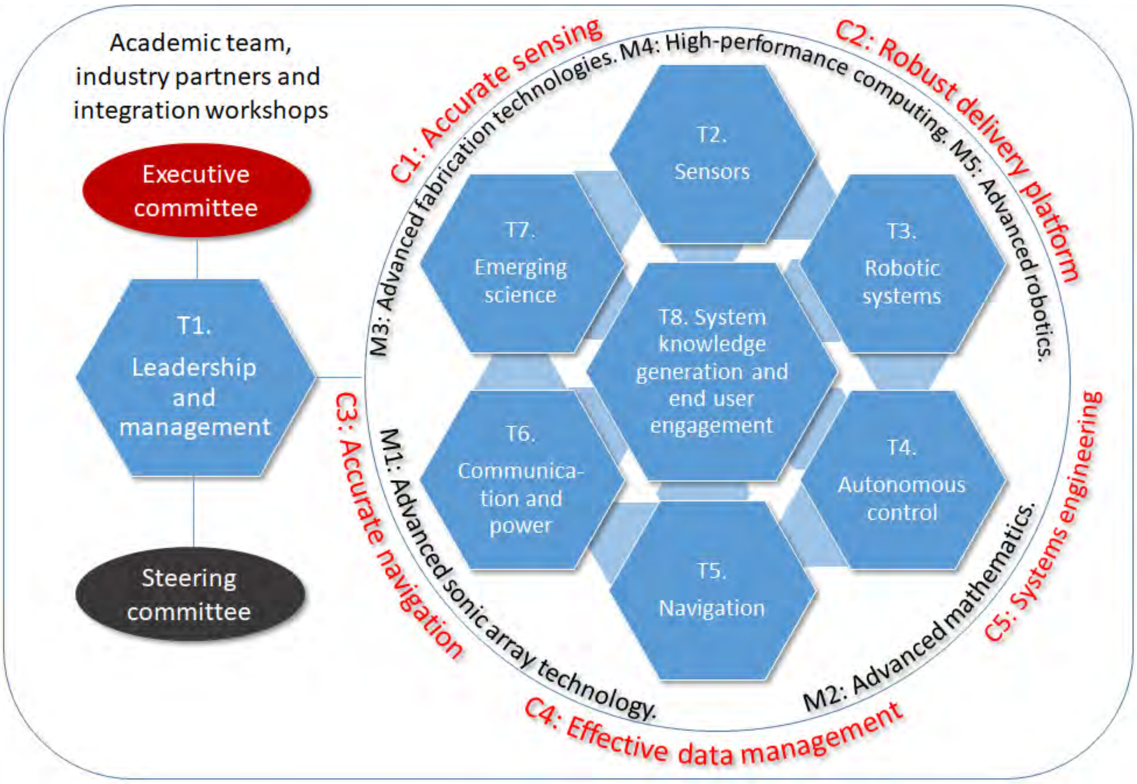

Figure 1: Pipebots programme grant structure, high-level challenges (Cx), methodologies (Mx) and links.

The remainder of the paper will review state-of-the-art research and technologies on which this vision is based. This new pervasive and autonomous robotics platform will: (i) radically improve our capability to generate real-time condition and performance map of buried pipe networks; and (ii) use this new knowledge to transform the way utilities manage and maintain buried pipe networks. This platform is much more than just a new tool for autonomous inspection and rehabilitation of buried pipes. It is a new philosophy for the future management of complex infrastructure and hidden assets which are poorly accessible to humans. Pipebots solutions will empower industry with: (i) the ability to collect accurate data about their assets pervasively and in real time, reducing time to locate and repair any critical events; (ii) new knowledge about their asset conditions and deterioration rates; and (iii) a step change reduction in the associated operation and management costs and asset failure rates.

This paper illustrates that the current state-of-the art approaches for non-destructive pipe inspection are either Pigs (Coramik and Ege, 2017, Kishawy and Gabbar, 2010, Mills et al., 2017) or externally applied guided wave systems (Howard and Cegla, 2017). The externally applied systems can be ruled out as they require sections of the pipe to be exposed, making them disruptive and costly. Pigs are snake-like or tractor sensors systems that are deployed periodically to test specific sections of pipe. They are time-consuming and hence costly to deploy, require a shutdown of the region tested, need large entry and exit points and are not able to cope with changes in pipe size or cross-section. For these reasons, they have only been used in applications where these requirements can be met, e.g. inspections of certain sections in petrochemical plants and inspection of major oil and gas pipelines (Coramik and Ege, 2017, Kishawy and Gabbar, 2010). However, these requirements preclude their use for applications, such as water or gas pipes, that Pipebots addresses. Thus, whilst we seek to capitalise on the knowledge generated in the development of existing pipe inspections, Pipebots will require the development of new science and inspection approaches compatible with deployment on small pervasive robotic platforms which are autonomous (Caffoor, 2019).

Pipebots aims to utilise a range of technologies and to develop non-destructive testing (NDT) and flow monitoring solutions from inside the pipe. Acoustic (including ultrasonic) waves is a most attractive inspection technology to develop for this purpose. The reasoning here is that: (a) water pipes are often non-conducting, ruling out electromagnetic NDE techniques; (b) defects could occur at any location within the pipe wall ruling out reliance on near surface techniques such as simple optical inspection; (c) acoustic waves are very sensitive to changes in the pipe wall condition and in the fluid flow. Acoustic inspection and monitoring is one of the common technologies (alongside electromagnetics) currently used in pigs (Vanaei et al., 2017). In this respect, acoustic waves are an excellent candidate for the new inspection technology platform that Pipebots seeks to develop. These waves propagate within the pipe walls, surrounding soil and in the fluid as either bulk, guided or surface waves and can be generated by a single transducer of various sizes as well as by multi-element arrays - each of these inspection strategies will be evaluated as a pervasive robot sensor solution within Pipebots.

A key requirement is to demonstrate sensitivity and ability of a robot swarm to adapt to all defect types, changes in the flow conditions, pipe diameters and wall materials. Wall cracking and blockages are the most common defect types in the pipe. Cracks are only visible from certain specific illumination angles - as the illumination angle changes from the optimal, so the probability of detection decreases (Humeida et al., 2014, Malkin, Sep, 2016). Blockages can develop very rapidly and require continuous monitoring (Bin Ali et al., 2011). Pipebots will seek to understand these relationships and use data fusion methods to produce probabilistic estimates of inspection quality as a function of operational conditions in the pipe. For example, as regions of the pipe are inspected from different locations at different angles in the presence of flow, this information will be used to update the detection probabilities. We will also exploit acoustic bulk and guided waves at a range of frequencies. These two wave types offer distinctly different detection performance, so this multi-mode data can be interrogated to extract additional information or fused to increase the probability of detection.

The Pipebots will develop adaptive and cooperative robot swarms (see Figure 2) suitable for deployment in dry, pressurised and partially filled pipes over a prolonged period of time. These dense swarms of robots will interrogate autonomously the pipes from the inside to continuously monitor for the onset of defects, navigate to and zoom in on sub-millimetre scale regions to examine them in detail. These inspection robots will communicate information and to help guide any rehabilitation works to repair the infrastructure at an early sign of deterioration, i.e. when the cost of repair is low and the disruption to the services is minimal. These robots will be much smaller than the diameter of the pipe so that they will not present a danger of blocking the pipe if damaged or when run out of power. By being abundant, they will introduce resilience through a high level of redundancy in the inspection system, i.e. inspection can continue even after the loss of a proportion of the robots in the swarm. By using sonic waves and other types of sensing these robots can monitor any changes in the condition of the pipe walls, joints, valves and lateral connections. An attractive feature to explore is that a robot swarm will mimic nature, i.e. the individual robots are small and relatively unsophisticated, but the swarm is highly smart, capable and precise.

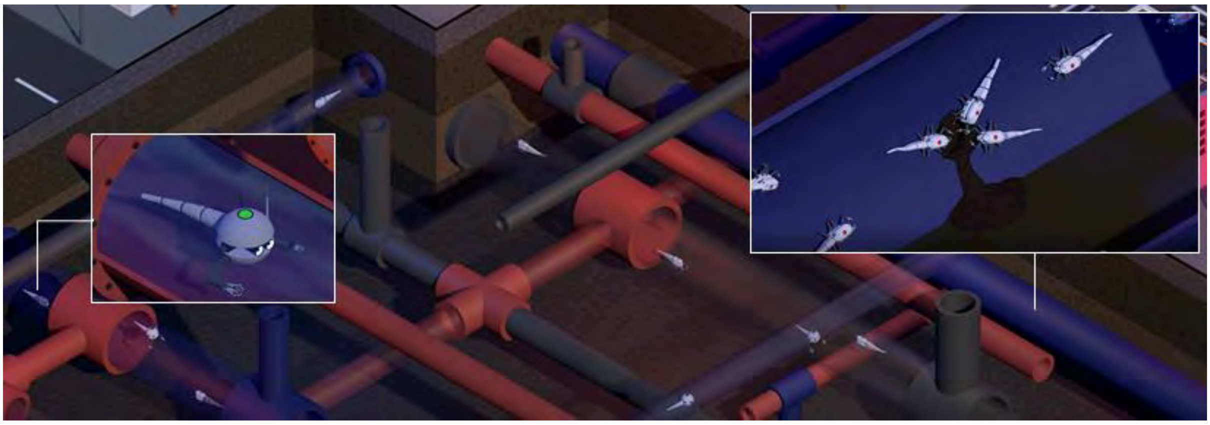

Figure 2: A swarm of autonomous sensors for pervasive pipe inspection.

The proposed technology platform will be developed through a series of design iterations involving rigorous analysis, validation and feedback and guidance from stakeholders. Within each of these iterations there will be a number of important steps that will be sequentially addressed. The *first step* is to form the new design specifications for the robots. These must be able to cope with the uncertainties in the buried pipe infrastructure whilst aligning with end user requirements in terms of hardware, software and communication protocols. The *second step* (see Figure 1) is to integrate hardware designs, models and simulations developed for sensors (T2), robots (T3), autonomous control (T4), navigation (T5), communication and energy harvesting (T6) and emerging science (T7) to ensure that the developed robotic sensing technology platform is optimised to account for any conflicting requirements emerging from the technical themes. The *third step* is to build new robots and measure their performance both in the laboratory and in the field (T8). These design iterations and this rigours approach to testing and evaluation will provide the basis to convince the end users that this technology platform actually works, it is robust and flexible enough to survive the aggressive environment and return useful data which can be turned into actionable information for water companies. The success of these iterations depends on good knowledge of the state-of-the-art research and technologies related to pipe inspection, robotics and asset management of buried infrastructure.

2 Review of sensing technologies (T2)

The underground water and wastewater/sewerage pipe networks are challenging environments for sensing. The requirements of such devices range from measurement of internal geometry and operational parameters, such as flow, to blockages, leaks and the structural integrity of the pipe itself. The pipes are made from a disparate selection of materials including, various polymers (e.g. high-density polyethylene (HDPE)), cast iron, ceramic, concrete and masonry. It is immediately apparent from these lists of requirements and materials that no single sensor technology is capable of this diverse range of measurements. The topology of this system is complex. It is full of connections, inspection chambers, hydrants, valves and pumps. A key challenge that Theme 2 faces is the diversity of the buried pipe system which topography and conditions are highly unknown.

The most common sensors in use today are CCTV, ultrasonics (acoustic waves above 20 kHz), passive and active acoustics (audible acoustic waves below 20 kHz), but other technologies such as laser profiling, Eddy Current Testing (CET) and Magnetic Flux Leakage (MFL) are also common. This means that the pipe inspection engineer has a large toolbox of sensors and methods at their disposal to cover this wide range of needs (Barbian et al., 2011, Hunaidi et al., 2004, Liu and Kleiner, 2013, Rizzo, 2010b, Wang et al., 2010).

Most sensors are still deployed and operated manually. For example, leak detection in water pipes is regularly performed by teams of inspectors who visit suspect regions and make manual measurements with listening sticks or attach acoustic detectors to hydrants. Similarly, manual deployment of CCTV equipment to visually inspect the internal sewer pipe condition is common. CCTV is seldom used for the inspection of clean water pipes. The need for human inspectors means that such measurements are expensive and time consuming. Typically, inspections are performed in response to a reported incident, such as a flooding or blockage, meaning that only a tiny fraction of the network is covered. Leaking clean water pipes are usually excavated and replaced. A consequence of this responsive approach is the that the opportunity for condition-based maintenance is missed.

Large robotic platforms known as pipeline inspection gauges (PIGs) are also widely used primarily by the petro-chemical industry (Quarini and Shire, 2007). These snake-like devices fit into the pipe and are powered by the internal pressure. PIGs can carry a range of sensors to provide something approaching 100% inspection. However, they require the pipe to be in relatively good condition, of constant diameter, free of internal complexity and sharp bends. They are also expensive to operate and present access challenges at insertion and extraction. For these reasons, PIGs are only able to inspect a relatively small proportion of the pipe network. More recently robotic platforms such as *SmartBall* and *Sahara* (WRc Infrastructure) have emerged which enable the inspection of a wider range of clean water pipe geometries and because of their smaller size, reduce the access requirements relative to PIGs. These devices and their technological successors are starting to open the possibility of condition-based maintenance.

In the following sections we review the sensor technologies for water mains and wastewater/sewerage pipe networks. The wide-ranging inspection requirements and materials effects are recurrent themes. We show that all the inspection methods for buried pipes require human intervention. As a result, they are relatively slow, not sufficiently pervasive and subjective.

2.1 Acoustic methods

Multiple acoustic techniques have been developed over the years for applications in water industry that include detection of leaks (Brennan et al., 2008), blockages (Duan et al., 2015) and sediment depositions in pipe networks (Horoshenkov, 2012) as well as mapping the location of underground pipes (Muggleton et al., 2011). These methods rely on sound waves which frequency is less than 20 kHz, i.e. audible frequency range.

Acoustic sensing techniques are non-invasive and allow inaccessible pipe sections to be inspected with minimal disturbance. Active sensing requires presence of a sound source and a receiver to measure the acoustic response. Passive sensing is used for leakage detection when noise generated by high-pressure fluid escaping from a perforated pipe is measured directly by a hydrophone or accelerometer (Gao et al., 2004). This section reviews acoustic sensing techniques for condition assessment of water pipelines using accelerometers (acceleration) and hydrophones (acoustic pressure).

2.1.1 Accelerometer detection

Acoustic correlators attached to a hydrant have been used for more than three decades to detect and locate leaks from water pipes with commercial products (e.g. *LeakFinderRT*) and lab prototypes (Almeida et al., 2014, Fuchs and Riehle, 1991). The location of water leaks was estimated from the peak in the cross-correlation function between the leakage signals measured by accelerometers at two different positions in the water pipe (Gao et al., 2004). The cross-correlation based techniques have less than 10 cm leak location error (Liu and Kleiner, 2013) in metal pipes. In plastic pipes, rapid attenuation of acoustic waves associated with relatively large loss factor in pipe walls makes the problem of water leak detection more challenging especially for high frequency signal (Hunaidi, 2012, Liu and Kleiner, 2013). Almeida et al. (2014) reports the use of low frequency range from acoustic spectrum generated by leak (below 100 Hz) and the location error using acoustic correlators is less than 1m for plastic pipe.

Accelerometers can also be used in impact echo testing for non-destructive evaluation. It is conducted by hitting the test surface at a given location with a small instrumented impulse hammer or impactor and recording the reflected wave with a displacement or accelerometer sensor adjacent to the impact location. Impact echo can be used to detect cracks and fractures in concrete, masonry materials, stone, plastic and some ceramics (Carino, 2001) and the underground cavities formed by leakage of pipelines (Kang et al., 2017). The accuracy is less than 2% at high resolution and the typical thickness of the structure for the impact echo testing ranges from 66 mm to 1.8 m (Liu and Kleiner, 2013).

Another method of using accelerometer for damage detection and assessment in pipeline system is based on pipe-flow interaction. It is observed that a sharp change in fluid pressure is always accompanied by a sharp change of vibration on the pipe wall at the corresponding locations along the pipe length (Shinozuka et al., 2010a, Shinozuka et al., 2010b). Therefore, water pressure-monitoring can be transformed into acceleration-monitoring of the pipe surface with less cost using Micro-Electro-Mechanical Systems (MEMS) or other acceleration sensors (Shinozuka et al., 2010a, Shinozuka et al., 2010b). However, these methods have difficulty in distinguishing pressure changes from a leak and those due to other transient sources (such as loops, valves and bends) (Yazdekhasti et al., 2017).

There also exist some early stage studies the results of which have not been applied to real pipe networks. According to these studies damage of water pipeline can be detected using accelerometers measuring the change of vibration response characteristics of the pipeline structure, its natural frequencies (Murigendrappa et al., 2004a, Murigendrappa et al., 2004b) and mode shapes (Chen and Büyüköztürk, 2017). However, this approach requires accurate information of the pipeline system and the changes due to defect can be swamped by the uncertainties in the boundary conditions. Furthermore, vibration response characteristics of a pipeline are global features that may be similar for several defect types, positions and severities, making it challenging to determine a unique defect signature (Farrar and Worden, 2006, Yazdekhasti et al., 2017). For blockage detection, Lile et al. (2012b) and Lile et al. (2012a) used accelerometer to measure the vibration signal on a circular carbon-steel/plastic pipe for blockage levels identification. However, the accuracy of the detection depends on the closeness of the blockage to the sensing position (Datta and Sarkar, 2016, Lile et al., 2012b).

2.1.2 Hydrophone/microphone detection

A hydrophone is an acoustic transducer capable of measuring sound pressure underwater, which can be used for listening surveys in the water pipelines. For example, a commercial product (e.g. *Sahara* (WRc Infrastructure) see **Error! Reference source not found.** (left)) is a tethered hydrophone which t ravels with the flow inside in-service water mains to detect leak noise and to locate the leak (Hoes et al., 2009, Liu and Kleiner, 2013). A locator beacon can then be tracked above ground, enabling leaks to be marked for excavation and subsequent repair (Clarke, 2000). Buried unknown leaks as small as 0.005 gal/min can be identified, and a typical location accuracy can be within 0.5 m (1.5 feet) (Pure Technologies Ltd, 2019). This device is ideal for deployment on a small robot to measure sound in the vicinity of a leak.

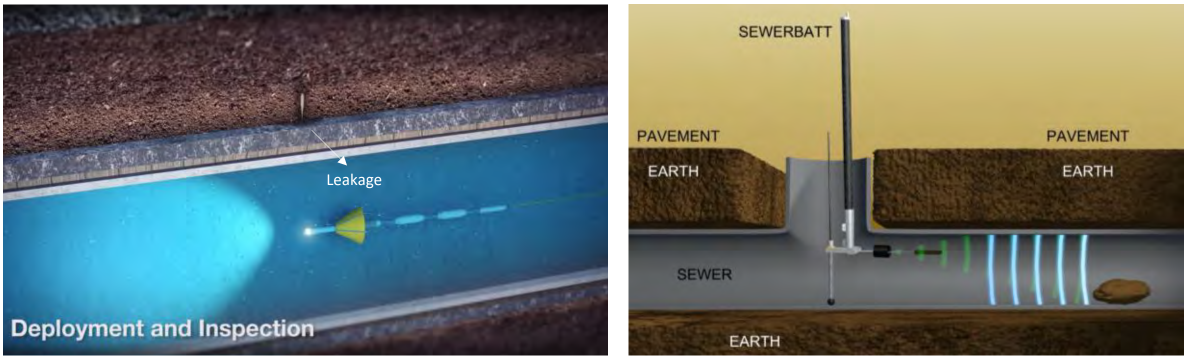

Figure 3: A typical inspection system: (left) in clean water pipe using hydrophone and CCTV (provided by Pure Technologies Ltd (2019)); (right) in sewer pipe using a speaker and microphone array (Bin Ali et al., 2011).

Hydrophones have also been used as sonar systems for inspection in the pipe when CCTV cameras fail in pipes carrying murky fluids (e.g. Model 1512 Pipe Profiling Sonar and VS 200 Sonar). Sonars measure the time of flight taken for the sound wave to travel to the target and back to the receiver. These devices provide a 2D dimensional data on the pipe geometry, submerged debris in the pipe, grease accumulation, blockages, pipe deformation etc. (Ogai and Bhattacharya, 2018a). Commercial sonar profiling system usually use a narrow-band ultrasonic wave for inspection, e.g. Model 1512 Pipe Profiling Sonar uses 2 MHz acoustic wave to give 8 mm resolution at 2 m distance. Using acoustic correlator technique similar to that developed for accelerometers, hydrophone measurements can be used to estimate the location of leakage. Compared with accelerometer, pressure responses measurement by sonar are known to be effective for low signal-to-noise ratio (SNR) situation particularly for plastic pipes (Almeida et al., 2014, Gao et al., 2005). A sharper peak of correlation coefficient can be achieved if hydrophones are used in combination with accelerometers (Gao et al., 2005). Almeida et al. (2014) also concluded that for large distance between sensors and high attenuation factors (i.e. plastic pipe) hydrophones offer the most accurate results (with <0.5 m error) compared to other sensors (i.e. accelerometers and geophones have <1m error).

Sewers are partially filled pipes which enable inspection with microphones. (Bin Ali et al., 2011) developed technique for rapid inspection of sewers for blockages and defects, using acoustic intensity, similar to sonar, but with a speaker and microphone array that is lowered into a manhole (see Figure 3 (right)). This technology uses the principle of sound reflectometry, which is similar to that adopted by bats in wild. The signal emitted from the speaker is a sinusoidal chirp sound that covers the frequency ranges from 10Hz to 20000Hz. Once the reflected signal is recorded, signal analysis is performed to determine the pipe condition and to locate defect within 10-20 cm resolution and 90% classification success (www.acousticsensing.co.uk).

2.1.3 Data-driven methods based on acoustics

Data-driven techniques are used to identify the leakage of the pipe from vibration or acoustic wave measurement. These techniques require no specific knowledge about the system and formulate the challenge as a classification problem (Chan et al., 2018, Wu and Liu, 2017). The approach is divided into two stages: (i) generating a classifier from a set of measured vibration/acoustic data; and (ii) applying the classifier to predict the category (i.e. whether the leakage exists or not). Many classifiers have been investigated based on measured acceleration signal, (e.g. standard deviation by Martini et al. (2014), Martini et al. (2015), and leak detection index based on the cross-spectrum density by Yazdekhasti et al. (2018), Yazdekhasti et al. (2017)), and acoustic wave (e.g. Singular Spectrum Analysis (SSA) by Cody et al. (2018), and acoustic energy by Feng et al. (2019)). Classification using machine learning methods are also applied, such as support vector machine (Cody et al., 2018), k-nearest neighbours (Feng et al., 2019), Artificial Neural Networks (Nasir et al., 2014). The main disadvantage of data-driven method is the requirement of a large amount of data to develop a stable classification or predictive model (Chan et al., 2018, Wu and Liu, 2017). Data uncertainty, particularly non-stationary signal in recorded data and outliers will propagate to the predicted value (Hutton et al., 2012, Wu and Liu, 2017) and affect the accuracy of detection. The fidelity of these methods can be improved if longer-term, better quality data obtained through pervasive deployment of robots in pipes become available for better machine learning and condition classification.

2.1.4 Fibre optic detection

A fibre optic sensor, is usually installed as a distributed or point sensor. It has been used extensively to assess the condition of pipelines due to its geometric flexibility, high sensitivity, wide dynamic range and safety applications (Huang et al., 2007, Hutton et al., 2012). Another benefit of using fibre optics for leakage detection in pipelines is its ability to detect small leaks (Tanimola and Hill, 2009). Fibre optic sensors are usually fixed on the surface of pipes to detect temperature, vibration and acoustic pressure induced optical phase signal of the optical fibre (Huang et al., 2007, Tanimola and Hill, 2009).

For fibre optic acoustic sensing, the leakage position can be identified from the frequency spectrum (Huang et al., 2007, Kurmer et al., 1992). Due to its wide applicability, fibre optic sensors are used for the detection of leakage in oil gas and water pipelines (Bhuiyan et al., 2016, Guo et al., 2019, Stajanca et al., 2018). The sensing element can pinpoint the leakage location with <1m error and it is durable of over 30 years with minimum maintenance costs. However, this technique has certain limitations since soundproof material has to be added to minimize the sensing of background noise for sufficient signal to noise ratio (Datta and Sarkar, 2016). Furthermore, the fibre optic systems are expensive to develop and install. Usually these are installed while the pipe is being constructed and it may be problematic when a section of the pipe is damaged and required to be replaced. Fibre optic sensing method is highly sensitive in detecting the leakage noise and has low rate of false alarm and detection promptness compared with other methods; however, it is expensive in operation (Adegboye et al. (2019)).

2.2 Ultrasonic methods

2.2.1 Inspection with bulk waves

Bulk wave ultrasonic inspection for structures such as plates and pipes has traditionally been performed using single or multiple transducers (Karautramer and Krautkramer, 1983, McIntire, 1991). A typical configuration involves a single transducer (pulse-echo) or a pair of transducers (pitch-catch). The ultrasonic bulk waves can be generated by methods such as piezoelectric ceramics or polymers, that require contact or a liquid or solid couplant or by non-contact methods such as lasers or electromagnetic acoustic transducers (EMATs) for conducting materials (Liu and Kleiner, 2013). The bulk waves travel through the solid material as either longitudinal or shear modes and where there is a discontinuity such as a defect or backwall, a portion of the wave energy is reflected towards the transducer. The angle of the incident transducer and the angle of the receiving transducer (if present) are selected to optimally detect the feature of interest. For example, vertical cracks from the back wall of a plate/pipe can often be detected using a single transducer set at an angle to receive the large reflection from the crack corner and possibly the smaller signal from the crack tip. The proportion of the incident energy reflected from a defect depends on its size and type, e.g. a large air-filled crack results in a complete reflection, whereas a water-filled crack results in a partial reflection making it harder to detect (Boström and Wickham, 1991, Davis, 1989, Ricci et al., 2012, Silva et al., 2012, Zahran et al., 2002). As the wave-packet propagates through the material the energy available for defect detection reduces due to a combination of spreading, absorption/damping and scattering from the microstructure. The reflected signals are then analysed to detect and locate defects as well as measuring the material thickness (Davis, 1989, Matz et al., 2006, Mažeika et al., 2007, McNab and Young, 1989, Nandi et al., 1997). Table 1 compares the bulk wave speed and attenuation in typical pipe materials used in drinking water and sewerage pipes. All the materials used present challenges in terms of their ultrasonic inspectability, with inhomogeneous materials such as concrete and brick presenting particular difficulties due to their very high attenuation.

Table 1: Sound velocity and attenuation in typical water and sewerage pipe materials (Egerton et al., 2017b, Engineeringtoolbox, 2019, GE Infrastructure, 2004, Kamigaki, 1957b, Schickert, 2002b, Zhang, 2013b). Low attenuation means less than 1dB/cm, medium is between 1-15dB/cm and high is more than 15 dB/cm at frequency 5 MHz.

Material	Cast iron	Plastic (PVC)	Plastic (PE)	Concrete	Asbestos cement	Brick
Attenuation	Low	Medium	Medium	High	High	High
Longitudinal velocity (m/s)	4550	2400	1950	3700	2200	4200
Shear velocity (m/s)	2500	1060	540	3200	-	3600

There are 3 types of bulk wave ultrasonic scans and displays commonly used in plate/pipe inspections:

- A-scan, or time domain plot: provides 1D information on reflections along the direction of the ultrasonic beam. For example, Inductosense technology (Inductosense, 2019) uses A-scan for inspection of structures including pipes from their external surfaces.
- B-scan: provides a 2D cross-sectional view by combining A-scans from multiple transducer positions (or multiple transducers). One axis of the cross-section is in the thickness direction, the other is typically axial or circumferential. Mentor UT Flaw Detector (Baker Hughes, 2019) is a commercial system using a phased array and is commonly used for B-scan of pipelines from the external surface.

- C-scan: provides a 2D map from the plate/pipe surface by extracting specific features from A-scans. In case of a pipe, the transducer is moved in both axial and circumferential directions. Tablet UT (Tablet UT™, 2019) is an example of a system that can produce A-, B- and C-scan images of pipes, again, from the exterior.

Ultrasonic bulk waves have been extensively used for condition assessment of pipelines especially in the oil and gas industries to detect and characterise corrosions (Lei et al., 2009), cracks (Baby et al., 2003) and residual stresses (Javadi et al., 2013); Tanala et al. (1995) in pipes, particularly in welded joints. In addition, research has also explored their use for assessing the condition of water and sewerage pipelines. Various commercial systems are available in the form of pipeline inspection gauges (PIGs) (shown in Figure 4), typically based on angle beam B-scan and C-scans. For example, the UltraScan CD inspection tool (GE Oil & Gas, 2019) uses a number of 45° shear wave transmitters and receivers arranged around the interior of the pipe circumference to detect cracks that are parallel to the axis of the pipe (Rizzo, 2010) (see Figure 5). This is an area of active research. Zhu et al. (2015) developed and tested ultrasonic bulk waves for the condition assessment of buried plastic pipes in water distribution systems to assess void formation and critical loss of support in HDPE and PVC materials. They used a water coupled transducer with centre frequency of 10 MHz and detected machined grooves/slots (1 to 2 mm) in PVC plates (6 mm thickness). They also reported successful detection of major cracks in PVC and voids in both PVC and HDPE.

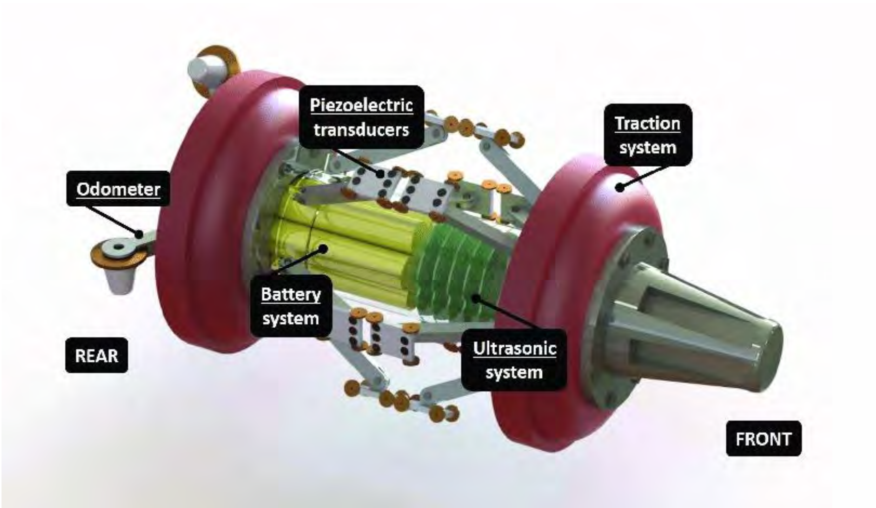

Figure 4: A schematic of an ultrasonic PIG (Rodríguez-Olivares et al., 2018). Multiple transducers are arranged circumferentially to inspect the pipe wall as the PIG is moved through the pipe.

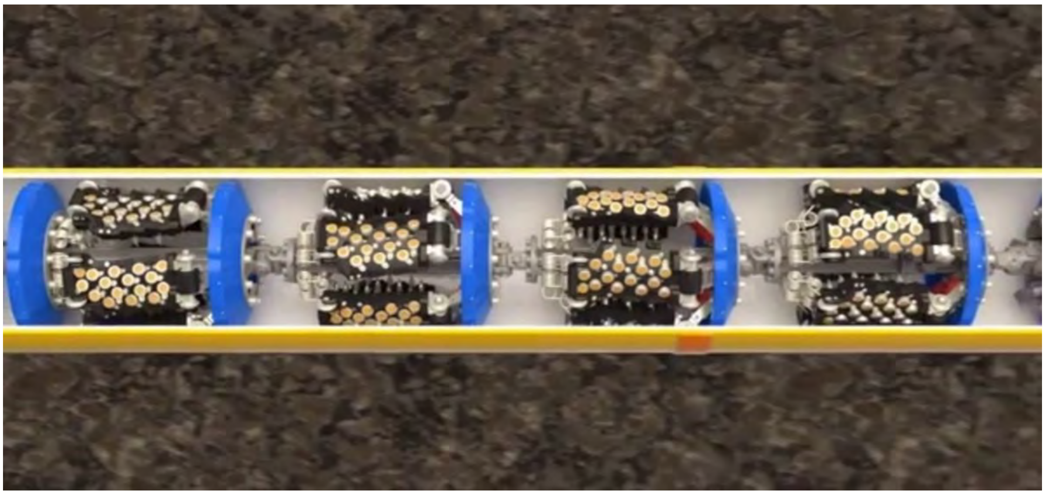

Figure 5: Schematic of the Ultrascan CD tool being used as a PIG in a pipe (Arkin, 1998).

Hong et al. (2017) used nonlinear modulation between a low frequency pump wave (6-16 kHz) and a high frequency probe wave (155-165 kHz) to successfully detect various defects (lengths 0-35 mm and depths of 0-2.5 mm) in PVC pipes (53 mm diameter and 3 mm thickness). Nonlinear techniques such as this have yet to find commercial application.

Skjelvareid et al. (2013) studied ultrasonic inspection in a cast iron pipe, which was originally part of a water pipeline in Skien. They proposed synthetic aperture focusing to extend the focal range of transducers and used a pulse-echo setup with a transducer of 2.25 MHz centre frequency. They inspected 4 small drilled holes as point scatterers and showed their focusing technique extends the focal range and increases resolution of scatterers outside the transducer's original focal zone.

Many buried pipelines are made of precast concrete (PCCP) that has a large bulk wave attenuation due to its heterogeneous nature (Iyer et al., 2012). Hence, getting the ultrasound energy into and back from the defect regions is challenging. As a result of higher attenuation in concrete, the area inspected by conventional ultrasonics or guided waves is smaller compared to metal pipes and the ultrasonic frequencies used must be lower, typically in the range of 50 to 200 kHz (Schickert, 2002). In 2012, Iyer et al. (2012) evaluated the ultrasonic inspection and imaging systems for concrete pipes. They measured the through thickness resonances, which was 31.25 kHz in 60 mm thick concrete, and used this to determine the thickness. They also carried out an experiment on concrete slabs (60 mm depth) containing a hairline crack (~75 mm), crack (~75 mm), fracture (~75 mm) and a hole (~10 mm diameter) using a 250 kHz transducer and identified all 4 types of defects with C-scan imaging.

2.2.2 Inspection with phased arrays

Ultrasonic phased arrays are arrangements of individually connected transducers (or elements). Generally, the arrangement of the elements within the array are classified as 1D, 2D or annular (Drinkwater and Wilcox, 2006). The most common type of array in industry is a 1D linear array in which the array images a cross section of the pipe through the thickness direction. This type of array allows beam steering and focusing within a 2D inspection plane. 2D or mosaic arrays allow beam steering and focusing within a 3D inspection volume and annular arrays provide variable focal depths.

Figure 6: Commercial array imaging system in which an externally mounted 1D array is swept through a range of angles to inspect a weld (Olympus Industrial Resources, 2019).

Hagglund et al. (2012) have taken advantage of 32-element ultrasonic phased arrays of 2 MHz and 4 MHz central frequency with pulse-echo configuration for inspection of polyethylene (PE) butt fusion joints. They used pipe sizes of 220 mm to 450 mm outer diameter and reported successful detection of flat bottom holes of depth 40 mm and diameters of 1.5–8 mm. Also in 2018, Rachev et al. (2018) investigated the in-service inspection of large diameter pipes using PIG-mounted phased arrays and immersion scans from inside of oil pipes with a focus on detection and sizing the depth of axial surface breaking cracks. They studied the performance of plane wave imaging (PWI) (Le Jeune et al., 2016) and total focusing method (TFM) (Holmes et al., 2005) characterising cracks of 1–8 mm length in a 42” (~1.07 m) outer diameter and 10 mm thickness pipe. The use of ultrasonic imaging methods is highly attractive to estimate the severity of a leak through a crack or faulty pipe joint. This information is impossible to get with other acoustic inspection methods, but it is important for the utility company to prioritise their maintenance and rehabilitation work to reduce associated disruption.

2.2.3 Guided wave inspection

Guided waves are usually ultrasonic waves that travel in bounded structures, and of relevance here are waves guided by plates and pipes. Typically, a pipe acts as a waveguide trapping the propagating wave energy and allow wave energy to travel long distances, i.e., several meters, but potentially kilometres if the conditions are right. In the typical experimental arrangement for guided wave pipe inspection, several transducers (Alleyne et al., 2009, Mudeg, 2001) are clamped in a circumferential ring on the external surface of the pipe to offer 100% screening for loss of the pipe wall material, i.e. corrosion or erosion. In order to achieve long range guided wave testing (i.e. many tens of metres) operating frequencies below 100 kHz are common. Lowe and Cawley (Cawley, 2007, Lowe and Cawley, 2006) also described shorter range (typically less than 5 m) system using frequencies in the range 0.5-1 MHz. An infinite number of different wave modes can exist in any given pipe and this means that coherent signals from the high-order modes can be a problem unless the excitation system is designed to excite a single mode at a suitable frequency. For example, in commercial systems a relatively low-order (i.e. low-frequency) guided wave with a simple mode shape (torsional or longitudinal) (Alleyne and Cawley, 1996b, Alleyne et al., 2009b, Long et al., 2003a, Niu et al., 2019a) is used as it leads to reduced measurement complexity and the longest propagation distances. Currently, the available commercial use the piezoelectric (PZT) array technology (Eddyfi, 2019, G. Ultrasonics, 2019) and have been developed to test all standard diameter pipe sizes (e.g. 38.1 mm to 1.98 m (Eddyfi, 2019)). The sensitivity of most application is in the region of 5% (Mudge and Speck, 2004, Sonomatic, 2019) metal loss of the pipe wall cross-section on oil and gas pipelines.

Ultrasonic guided wave technologies as applied to buried water pipe and wastewater pipe non-destructive evaluation (NDE) haven been reviewed in (Ghavamian et al., 2018, Liu and Kleiner, 2013, Rizzo, 2010b). As well as the pipe material itself, the media both inside and outside the pipe has a dramatic effect on the guided wave propagation (Aristegui et al., 2001, Berliner and Solecki, 1996, Plona et al., 1992). Rose et al. (1994) showed both experimentally and theoretically that in the case of wave propagation in a 5 mm outer radius steel tube, external water loading leads to increase mode attenuation. Lafleur and Shields (1995) have studied the propagation of low-frequency axisymmetric wave modes in liquid-filled tubes. The experimental system consisted of water in a 313 cm long, 5.08 cm inner diameter, 1.27 cm wall thickness aluminium tube. A signal pulse at the centre frequency of 17 kHz was excited using a PZT transducer and this led to excellent experiment-theory agreement in terms of the phase velocity as a function of frequency (i.e. the dispersion curves) and this showed the effects such ad liquid loaded could be accurately modelled. Aristegui et al. (2001) addressed leakage by both longitudinal and shear waves can occur which leads to very high attenuation rates when the pipe is embedded in a solid media. The experiment was carried out using a copper pipe having inner radius 6.8 mm and wall thickness 0.7 mm. Measurements in pulse-echo mode using a 250 kHz longitudinal transducer was applied to excite longitudinal wave modes propagating on between 0.8 and 2 m long pipes were achieved at experiments. Plona et al. (1992) described a set of axisymmetric modes that are characteristic of the “fluid” cylinder inside the steel and a set of modes characteristic of the pipe-like structure (e.g. cylindrical shell) plus fluid outside the steel. The attenuation and dispersion curves were verified successfully using a PZT ring source (50-240 kHz) as transmitter and a movable ring receiver on a steel cylindrical shell with an outer radius of 9.53 mm and an inner radius of 7.94 mm. The case of external ground loading (Leinov et al., 2016) has been shown to reduce the amplitude of the guided waves and hence limit the inspection range. Alleyne et al. (2001) showed a field test using at 21 kHz, in which corrosion on a 254 mm outer diameter steel pipe passing through an earth wall was found. The test operating range was 50 m (25 m in each direction) and the sensitivity of the inspection system is reduced (compared to the over ground case) to about 10-15% cross-sectional loss because of the higher attenuation through the buried section. Demma et al. (2005) reported a 203.2 mm outer diameter buried steel pipe under guided wave testing and suggested that the range of the inspection sometimes can be reduced to about 5 m on either side of the system due to limiting factors, such as the conditions of pipe, coating and soil. Lebsack (2007) also showed wave propagation through a 27-40 m buried pipe with 91 m above ground. The high attenuation of guided waves in buried pipes depended on the variable conditions of the pipe, coating, soil moisture content and soil type. Long et al. (2003a), Long et al. (2001) studied the attenuation of the fundamental non-torsional modes that propagate down buried iron water pipes. Whilst attenuation is not limiting in metal tubes/pipes, it is high in the other common materials, e.g. HDPE (Chan and Cawley, 1996b, Chan and Cawley, 1998b, Egerton et al., 2017b), and concrete (Finno and Chao, 2005, Philippidis and Aggelis, 2005). Chan and Cawley (1998) have studied the influence of material attenuation on the guided wave dispersion behaviour in HDPE water plates. They chose a frequency range of 0.1-0.3 MHz in the guided wave experiments following bulk wave experiments at 2 MHz. A pitch-catch guided wave inspection was carried out on a 12.7-mm-thick HDPE plate at 137 kHz. Na et al. (2003) used cylindrical guided Lamb waves to inspect the concrete–steel interface. In their experiments, the transducer–receiver arrangement on the concrete surface to excite guided waves at 50 kHz was used for detecting interface delamination in 76.2 mm or 127 mm thick concrete. Exciting and detecting guided waves from inside the pipe using multiple robots with sensors is an unexplored area of research which can provide significant improvements in terms of the detection range and spatial resolution.

At sufficiently high frequencies (i.e. short wavelengths) surface waves can exist on the internal pipe walls (often called a Rayleigh wave, or leaky Rayleigh wave, depending on the energy leakage into the surroundings). Yew et al. (1984) demonstrated the use of Rayleigh waves for the detection of a surface-breaking crack (0.6 mm thickness slot) on an aluminium plate. Zerwer et al. (2005) and Song et al. (2003) examined the use of Rayleigh waves for the detection and sizing of surface-breaking cracks in concrete beams. The results show that by combining information from Rayleigh wave dispersion and energy dissipation, it is possible to determine the location of surface-breaking cracks. However, the sensor coupling conditions on rough concrete surfaces limit the test accuracy and application of this technique.

The air-coupled ultrasound was used by Kee and Zhu (2010), Yazdekhasti et al. (2018) as a solution to the sensor coupling problem. Musolino et al. (2007) investigated Rayleigh waves to detect the presence of voids in masonry using one transmitter that generated a transversal (shear) waves in the frequency range 4-128 kHz and multiple receivers. They showed that this configuration allowed wave propagation up to 4 or 5 meters. The region under test can potentially be enlarged by using an array of transducers (Concu et al., 2009, Jacqus et al., 2012, Musolino et al., 2008).

2.3 Eddy current testing of conducting pipes

Eddy current testing (ECT) is a method that uses electromagnetic induction to measure wall thickness and detect any discontinuities in pipes made of a conductive material such as steel and cast iron. In this method, an eddy current is generated by a transmitter coil and its strength is then measured at a distance by a receiver coil. The received magnetic field is related to the wall thickness and any discontinuities in the pipe wall cause a change in signal magnitude and phase (Liu and Kleiner, 2013). ECT has been used for pipe condition assessment and detecting defects such as metal loss (Angani et al., 2011b, Angani et al., 2010b, Mao and Lei, 2016b, Rifai et al., 2017, Ulapane et al., 2017, Ulapane and Nguyen, 2019).

2.4 CCTV & Laser profiling inspection

An overwhelming number of buried sewer pipes are surveyed with the CCTV method of inspection (EN 752, 2008, Pace, 1994) as illustrated in Figure 7 (left). Clean water pipes are rarely inspected with the CCTV because of difficulties with access to the pressurised clean water pipe network and dangers of water discolouration. Therefore, the most common method of inspection of clean water pipes is with acoustic leak detectors (see section 2.1). The results of CCTV inspection of sewer pipes are used as the basis for rehabilitation planning (Yang and Su, 2006). This method of inspection does represent a considerable challenge since the collection of suitable quantities of CCTV data on sewer pipe condition is a time consuming and an expensive process. Improvements to CCTV detection techniques are ongoing and recent development for inspection include the so called "scan" technologies (e.g. *DigiSewer*® or *Panoramo*®). The scan technology enables digital images of the entire sewer wall to be recorded (Chae et al., 2008). The pictures are then processed offline by the operator or engineer in the office. Depending on the software and type of CCTV measurements 2- or 3-D imaging and analysis is possible with this technology. Development of digital image processing for automatic recognition of defects (such as cracks and joint offset) is a topic of ongoing research worldwide (e.g. Li et al. (2019a)). Additionally, related techniques such as laser profiling methods (e.g. South East Services (2019)) for cross-section analyses (see Figure 7 (right)), or ground penetrating radar (Deserno et al., 2019) for background information have also been developed.

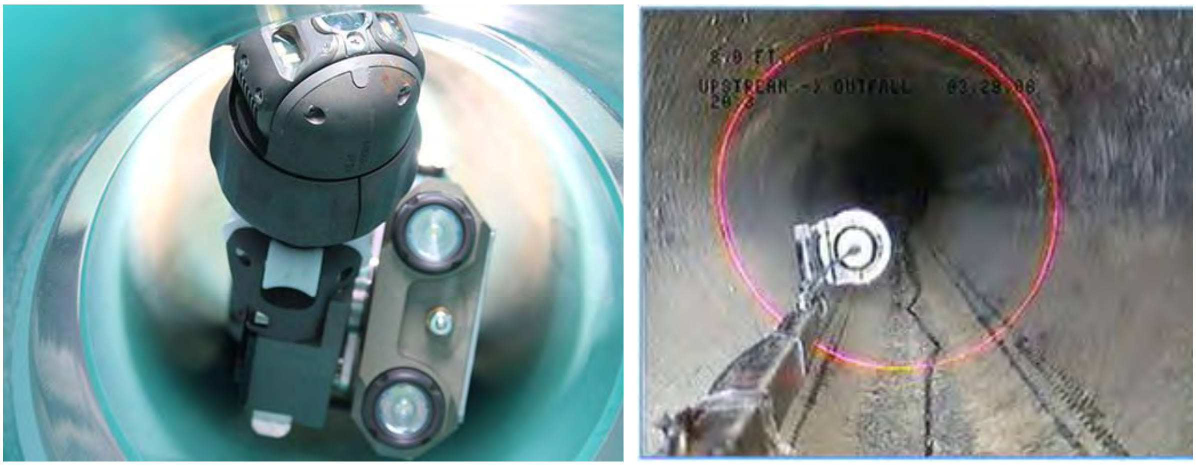

Figure 7: **Left** - A typical CCTV pipe inspection system (Rausch, USA). **Right** –in-pipe CCTV and laser profiler (South East Services, USA).

A further alternative to the CCTV and laser profiler methods are optical zoom cameras technology (e.g. MesSen Nord). This technology has been adapted to inspect the condition of live sewers or drainage pipes from a single point at a manhole as illustrated in Figure 8. These cameras have proved their practical application as a screening tool without man entering the pipes, although the resolution can be restricted by the inspection distance (e.g. Rinner et al. (2008)). According to Rinner et al. (2008) and Plihal et al. (2016), these cameras can inspect the sewer pipes 3 to 4 times faster than conventional CCTV inspection (2 to 3 km of sewer can be inspected per day using these cameras, whereas conventional CCTV inspection is limited to approximately 700 m of sewer per day).

Deploying CCTV on autonomous robots is an obvious development of the traditional CCTV method. CCTV data can be also be used for robot navigation (see Section 5) and mapping. This platform can benefit from automatic pipe condition detection (e.g. Li et al. (2019a)) to become fully autonomous.

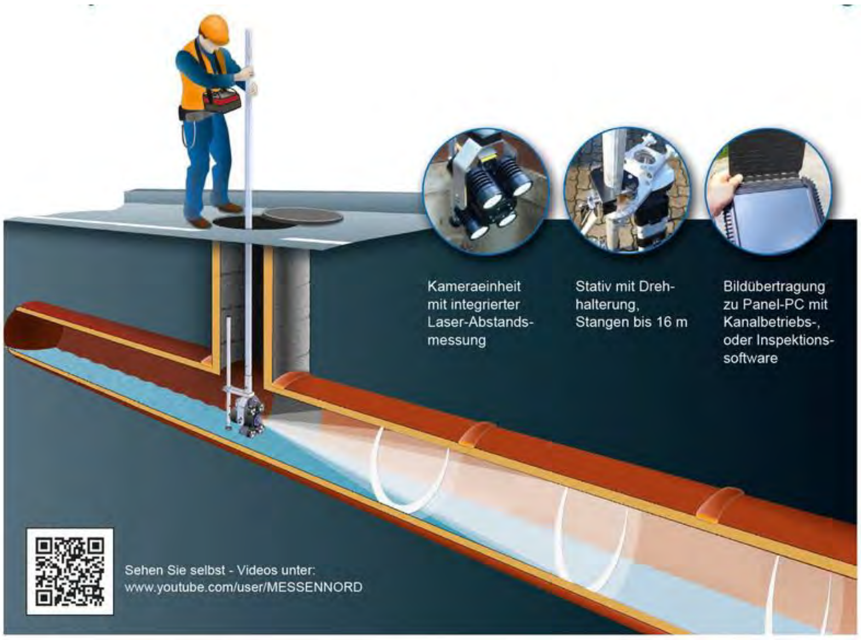

Figure 8: Inspection of buried pipes with a zoom camera (MesSen Nord, Germany).

2.5 Temperature measurements

The first application of distributed fibre-optic cable sensing in sewers was work in Delft in the mid 2000's studying the use of distributed temperature sensing to measure the wastewater temperature to identify illicit lateral connections (Hoes et al., 2009). This was the first time that distributed fibre sensing has been applied to sewer networks. Fibre-optic distributed temperature sensing is a monitoring technique developed in the early 1980s (Dakin et al., 1985), it was developed for testing telecommunication fibre-optic cables. For temperature measurement in a sewer, a fibre optic cable is normally surrounded by a gel in a stronger outer protective sheath to avoid direct stress on the cable, the sheath is dragged between two manholes and left in the sewer invert for a number of days and then retrieved. To obtain a temperature measurement with distance, a pulse of laser light is transmitted down the fibre optic cable causing Rayleigh, Raman and/or Brillouin scattering. Each type of scattering has an effect on wavelength and intensity of the scattered light. The Rayleigh and Raman components of the backscattered light are used in combination to estimate temperature. The Rayleigh backscatter is unshifted from the incident wavelength. Knowing the speed of light, the Rayleigh backscatter provides information on the location of the scattered light. By discriminating between these scattered components, it is possible to estimate temperature at a known location along the fibre. This measurement needs an empirical calibration for individual cables, most commercial systems can attain n accuracy of +/-0.1C. The spatial resolution depends on the temporal resolution of the signal interrogator and for most commercial systems this is of the order of several metres. Tyler et al. (2009) reported short-term drift of around 0.1°C and 0.3°C, no long-term drift measurements were reported, so care should be used when using measurements were reported, so care should be used when using distributed fibre-optic cable sensing (DFOS) for long term measurements.

DFOS has been used to look for large temperature gradients, especially along a fibre. They have been used in stormwater sewers to locate illicit connections during periods of dry weather flow. A study by Schilperoort et al. (2013) demonstrated that it was possible to locate the position of warmer illicit wastewater connections in stormwater sewer that were dry and submerged (due to system end condition). The temporal pattern observed at the illicit connection locations were different, but the locations were identifiable. Similar studies by Schilperoort (2011) were conducted in combined sewers with a dry weather wastewater profile and depending on the temperature and spatial resolution it was possible to identify the location of household connections.

In summary, the use of DFOS in sewer has shown that it can identify legal and illegal connections, though the task becomes more difficult in combined sewers. The level of temperature and spatial resolution currently possible with DFOS means that it would be a challenging task to identify smaller infiltration discharges. This has been confirmed by the more recent work by Panasiuk et al. (2019) in a foul sewer in Sweden when inflows and possible infiltration were only identified during the colder winter months when the temperature difference between groundwater/run off flows and foul sewage was high.

2.6 Summary

The on-line document (Summary of sensing technologies) presents a summary of the sensing technologies reviewed in this section. This document matches the physical method against the pipe material for which this method can be successfully applied.

All the existing pipe inspection methods require human intervention, are not fully autonomous and can return information on relatively small proportion of the buried pipe network and for a particular time frame. Clean water pipes are regularly inspected for leaks from above ground, because it is difficult to access pressurised clean water pipes and because of potential issues related to water discolouration by the inspection tool. Sewer pipes are usually inspected with CCTV equipment which is traversed through the pipe by the operator. This process is relatively slow, intermittent and analysis of images is subjective. Acoustic methods for the inspection of sewer pipes exist, but also require human intervention and manhole access.

There are a number of advanced acoustic and non-acoustic methods which are attractive to adapt to work on autonomous robots. It seems feasible to develop acoustic and CCTV equipment to be carried by robots in the pipe over a prolonged period of time to take measurement at a large number of positions. This will enable the operator to develop a much better understanding of how pipe conditions change over time and when this change becomes critical to require intervention.

3 Review of robotics technologies (T3)

This section is focused on robot locomotion, robot resilience, including power, and robot miniaturisation. A key requirement for a robot in a pipe is to carry a payload of sensors for in-pipe inspection. In order to traverse the pipe network in a controlled manner, the proposed robot will need both a method of gaining friction against the wall (**traction**), and a method of movement (**locomotion**). One key challenge which Theme 3 faces is the ability of the robot to move through the network of buried pipes which made of a plurality of materials and which conditions are highly unknown. Another key challenge is to develop robots which are small enough to fit into a majority of buried pipe without getting stuck blocking the pipe and effecting the flow.

3.1 Traction

Figure **Error! Reference source not found.**9 presents the seven possible traction methods that could b e used in pipe environments. Traction depends heavily on the normal force the robot can apply to the surface.

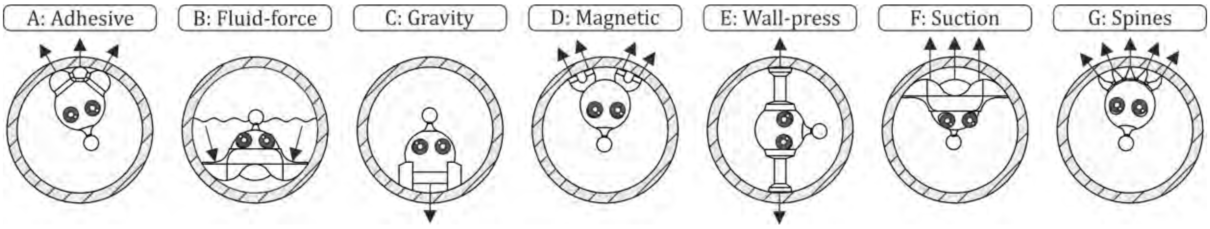

Figure 9: Seven fundamental methods that could be used by the in-pipe robots to gain traction (1.A) to (1 .G).

Adhesives (Figure 9.A) have been used by biological species and mechanical devices to successfully climb walls. Adhesives can be wet (Koh et al., 2019, Osswald and Iida, 2013) and dry that mimic gecko feet and exploit Van-Der-Waals force (Liu and Seo, 2018). Adhesives have the advantage of having low energy costs, but struggle on dirty surfaces. Wet adhesives provide large traction forces (Tavakoli and Viegas, 2015) but limited operational time as the robot must be resupplied with the glue. Reversible adhesives are a promising development, but face limitations including environmental issues, power and manufacturing (Croll et al., 2019). Fluid dynamic forces (Figure 9.B) can be manipulated to create downforce in a similar way that an F1 car does, mainly in clean water pipes. This has been accomplished in "Towfish" robots which utilise hydrodynamics while being towed through water to generate downforces using actuated fins (Khan et al., 2008). Gravity reliant robots (Figure 9.C) use only their own weight to produce enough tractive force to move. These conventional systems must be denser than the surrounding fluid, cannot climb walls and can only traverse relatively shallow inclines. Magnetic (Figure 9.D) robots work in ferrous pipelines but struggle with ferrous debris that can clog locomotion mechanisms and reduce magnetic force, and hence traction (Khirade et al., 2014). Electro-permanent magnets can be used to control and switch magnetic states on or off without requiring the constant power drain of electro-magnets. Wall-pressing (Figure 9.E) is the traditional in-pipe climbing method (Chattopadhyay et al., 2018) and allows in-pipe robots to take full advantage of the unique environment to move through vertical sections (Mills et al., 2017)**.** With these typically full-bore systems, T-Sections become challenging, as wall contact is often lost when turning a corner. Suction (Figure 9.F) has been used for wall climbing, but cracks and porous surfaces can cause issues. With a strong enough vacuum, this has proven successful on bricks and concrete. As weight is a significant limitation, these robots often use tethers. A supply of compressed air can be used to generate a vacuum through the Venturi Principle or a pump (Silva and Machado, 2010). Passive suction cups have been shown to work effectively on smooth surfaces (Ge et al., 2016). Spines (Figure 9.G) can enhance traction on many surfaces and arrays of miniature hooks enable climbing on sufficiently rough surfaces. Large robots have used this method to scale climbing walls (Nagaoka et al., 2018), and smaller robots have climbed vertical brick surfaces (Spenko et al., 2008) but inverted climbing has not been shown. Compliance where the spines are attached is important as it allows them to interlock with surface features (Xu et al., 2018).

3.2 Locomotion

Figure 10 summarises 12 fundamental locomotion methods that could be used in pipe environments (A-L) together with a variety of traction methods.

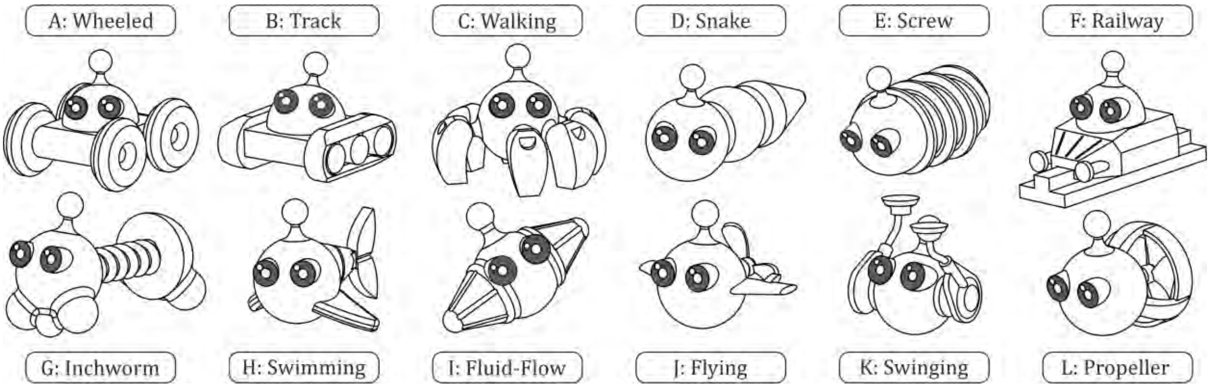

Figure 10: Twelve fundamental methods of producing movement in a pipe environment (2.A - 2.L).

Wheeled (Figure 10.A) and Track (Figure 10.B) based movement are standard locomotion methods that could be applied in pipes, but are unlikely to be optimal (they would struggle with ledges and steep inclines, and the solids in sewer systems would likely cause issues). Walking (Figure 10.C) systems generally have many joints and degrees of freedom which brings many advantages but makes them complex to control. These systems would need to be simplified to work at the intended scale (Lu et al., 2015). Snake (Figure 10.D) systems similarly come with mechanical and control complexity due to the number of joints. Both walking and snake robots could achieve wall-press traction by pressing their limbs or bodies against the pipe walls (Yabe et al., 2012). Screw (Figure 10.E) systems tend to be full-bore devices as the thread requires constant contact either with a wall or a liquid medium, which means that wall-press traction is usually used (Ren et al., 2019). Railway (Figure 10.F) systems would create their own tracks as they move, such as dragline locomotion inspired by spiders (Wang et al., 2014). Inchworm (Figure 10.G) robots lock one body section in place before moving the next section forward. This alternating lock and release cycle require a strong traction method like wall-press, adhesion, magnetism or suction. Swimming (Figure 10.H) robots use bio-inspired movement through the actuation of body parts to generate propulsion in a fluid. This has been accomplished in micro-robots using shape memory alloys (Wang et al., 2008). Fluid-Flow (Figure 10.I) in the pipe can be used to propel a passive or semi-passive device. Conventional Pipeline Inspection Gauges (PIG's) are typically uncontrollable full-bore devices (Hu and Appleton, 2005), although free flowing devices also exist (Caffoor, 2019). Flying (Figure 10.J) locomotion can be used to navigate large open spaces efficiently and collision-resistant examples have been created for space restricted applications such as pipelines (Briod et al., 2014). Swinging (Figure 10.K) robots could exploit arboreal locomotion styles as used by primates in nature. This concept would need heavily simplifying compared to current methods (Tavakoli and Viegas, 2015). Propeller (Figure 10.L) based robots are a conventional approach at large scale, but micro-scale versions have been created using piezoelectric actuators (Wang et al., 2019).

3.3 Long-term considerations

The vision of this project, of robots `living' long-term in pipe systems, requires a high degree of environmental resistance to withstand the harsh in-pipe environment as well as methods to achieve power autonomy. The robots will sometimes be subjected to low temperatures (e.g. in sewer pipes in winter) and may require additional insulation, potentially increasing their volume (Caffoor, 2019). The continual flow of water also means that the robots must be resilient to wear and corrosion caused. In sewer pipes, consideration must also be given to the potential for a build-up of combustible gasses as organic matter decomposes. The risk of explosion can be mitigated through `ATEX' rated `explosion proof' robots, but this has typically been achieved at a significantly larger scale (Taurob, 2019). The robots may be able to refuel themselves from the environment, much like living creatures (Guo et al., 2015). As robots are miniaturised, the amount of power that can be stored on-board is severely limited and this will affect many of the design constraints for sub-systems including sensors, actuators and traction methods (Breguet et al., 2006). In general, robots are often equipped with tethers, removing the need for on board batteries and aiding miniaturisation and communication. But the in-pipe environment, long-term deployment and use of multiple robots largely precludes tether usage due to friction, entanglement and flow impediment. Battery technology has improved in recent years and Lithium Polymer (Li-Po) is the current standard for high energy density storage. A single cell provides 3.7V which is ideal for powering many low voltage components, but these batteries have a limited number of charge-discharge cycles (Agarwal et al., 2010). This severely limits their long-term usefulness, especially if the robot is designed to be recharged regularly using energy harvesting or docking. Super capacitors, on the other hand, can be recharged up to one million times, but their voltage levels drop rapidly meaning they can only supply the required power for a short time each cycle. Innovative mechanisms which minimise the number of actuators will greatly reduce the power requirements of the robot. For example, dynamic climbing motions (Degani et al., 2007, Liu and Seo, 2018) and steerable walking (Zarrouk and Fearing, 2014) have been demonstrated using only one actuator.

3.4 Robot miniaturisation

Many of the smallest robots (down to approx. 1cm diameter and 2cm length) are developed within the medical industry as pill style packages that are externally magnetically driven (Sliker et al., 2015). These robots generally contain no batteries or motors and hence can reach a centimetre scale with relative ease. External field actuation would be impossible to implement in the Pipebots project, but the use of Soft Robotic components is a potentially appealing for robotic platforms to be used in constrained environments (Verma et al., 2018). This can be achieved by moulding, as well as lithography (Martinez et al., 2014), and 3D printing (Bartlett et al., 2015), but challenges exist around power and actuation. Additive manufacturing can be used to create relatively small features while electroforming of electrodeposition can be used to create micro scale actuators (Chatzipirpiridis et al., 2018). This is a rapidly developing technology, with an ever-wider range of materials and greater level of detail (20 µm). Micro-injection moulding also allows for a range of materials, with minimum features below 5µm (Attia and Alcock, 2011, Yuen and Altintas, 2016). Subtractive manufacturing can also be utilised. CNC machining has the potential to reach accuracies in the region of 0.2µm (Yuen and Altintas, 2016). Chemical Etching can be used to produce high detail 3D components by selectively applying an etchant to the intended material (Li, 2012). Electronics such as micro-controllers are too large for end product applications (40mm x 20mm). It is possible to use these boards to develop fully functioning prototypes first and then to develop our own, customised micro-boards based on the components used.

3.5 Summary

In conclusion, we have discussed a range of methods for enabling robots to travel through in-pipe environments. Through this, it has been identified that deploying robots of sufficiently small scales is a significant and interesting challenge which will likely require innovative hybrid approaches. Notably, much inspiration has been taken from climbing robots, rather than typical pipe robots. This is due to the desire to operate in live networks, without restricting the flow, which requires robots that are small relative to the pipe diameter. Such robots would have to move along a single surface of the pipe. This project will investigate methods to achieve the required miniaturisation while balancing other competing demands, to create a robotic platform that can operate in real world conditions.

4 Control (T4)

Bringing robots out of the lab and into the real world presents great opportunities as well as enormous challenges for individual and collective control, and all the more so if such robots are to be deployed autonomously in our buried pipe infrastructure. Miniaturisation of hardware and cost constraints (especially for swarm deployment at scale) may impose limitations on motor power and computational power when taking into consideration that to fully inspect a given section of pipe it is necessary to achieve complete coverage (so called 100% volumetric inspection) at some predefined spatial resolution. These constraints, combined with the challenges posed by the complex in-pipe terrain, limited knowledge of the environment and limited sensing capabilities will require innovative approaches to control. Rapid advances in real time computation, adaptive and real time control, including compliant and soft body control open up exciting opportunities for making this vision a reality over the coming years.

A robot system that works in buried pipe conditions must be able to perform multiple different tasks. Here, we focus on challenges relating to autonomous deployment for purposes of navigation, mapping and inspection. In the longer term one may consider additional infrastructure engineering tasks, e.g. those relating to infrastructure maintenance and repair.

4.1 Challenges and state of the art

Coverage of a large scale, currently unmapped network of pipes bring considerable challenges to swarm control and requirements for coordination to ensure that all parts of the pipe system are inspected and maintained regularly. To address these needs, robots must be able to reach different locations in the pipe system. They may need to migrate over considerable distances within the pipe or pipe network, to change direction, to move between pipes, etc. Network coverage may also require a regulation of swarm densities in different areas. Different control strategies will depend on the infrastructure (e.g. solutions for high pressure flows will likely differ from solutions for large, empty pipe networks). In addition, different control algorithms may be adopted depending on the conditions within the pipe, on progress with the task at hand and on communication with the swarm.
Detailed pipe inspection may require robots to repeatedly scan certain surfaces, interact with the pipe surface and exploit different sensing strategies, possibly with the help of manipulators and appendages carrying sensors. Such tasks may require the direct cooperation of two or more robots.

Deploying, maintaining, and repairing the robots within the swarm represents new challenges for the swarm system. Specific challenges include: (i) how to maintain the energy levels of the swarm (Arvin et al., 2018); (ii) how to detect robots that have failed and how to fix them. Is it better to take them above ground for replacement or repair, or would it feasible (and advantageous) to fix them underground using other robots (Neubert and Lipson, 2016)? Or shall we give up on fixing robots, and instead make them sacrificial in terms of cost and material? Even so, safe and regular disposal of faulty robots would be a challenge for the swarm. Implementing swarm control systems for long-term autonomous deployment would require investigating answers to these questions.

In the context of long-term deployment, without central control of every robot at every instant, each individual robot, and the collection of robots as a whole, must actively perform self-maintenance. This includes avoiding and reacting to dangerous events (such as high flow and collisions with high velocity rigid objects), docking on various structures to stay at safe positions, and monitoring and maintaining energy by switching to sleep mode whenever possible. Different control challenges, and likely robot cooperation tasks, will be faced for failure recovery or recovery from constrained locations (e.g., after a collapse of a pipe section).

Given these challenges, the control problem of such a robot system can be addressed at three different levels: (i) swarm level, including distributed decision making and robot-robot cooperation; (ii) individual behaviour level, including the integration of sensory and communication signals for real time decision making and planning; and (iii) individual motor skill level, for such tasks as locomotion, orientation and manipulation, docking and perching.

4.2 Swarm coordination

Swarm control algorithms may either rely on indirect cooperation (through complementary actions by different agents), or direct cooperation (through direct communication or physical cooperation, e.g. binding/unbinding of modular robots). One example of the latter may be the development of cooperative climbing swarms for manholes, hydrants or robot rescue after a failure event such as cracking detected in the pipe.

There is a rich literature in swarm robotics (Correll and Rus, 2013, Şahin, 2004) including coverage (Rutishauser et al., 2009), cooperative obstacle avoidance (Trianni et al., 2006), foraging (Hoff et al., 2010), and other behaviours. Still, no real swarm system has yet been shown to successfully perform these operations in as challenging an environment as pipe networks.

Collaboration and coordination between smaller numbers of robots have also been studied from a more traditional planning and control point of view, for collaborative tracking (Jung and Sukhatme, 2006), pushing (Mataric et al., 1995), assembly (Dogar et al., 2015) and others. Depending on the size of the robot group, and the scale of the task, a robot system may need to switch between distributed swarm approaches and traditional planning approaches.

4.2.1 Behaviour-level control

Control strategies of individual robots will likely to use sensory and internal state information to choose a motor “behaviour” (roam, inspect, avoid, escape, communicate, dock, etc.) (Lones et al., 2017). In a swarm context, different robots may need to be developed with different skills and hence different strategies and decision-making protocols. Each behavioural strategy can be reactive (Arkin, 1998), based on principles such as subsumption (Brooks, 1991), or based on environmental affordances (Fallon et al., 2015). Autonomous control of multiple behaviours may require hybrid solutions adopting lessons from all of the above. Achieving long-term tasks will further require planning over multiple time scales, as in recent task-and-motion planning approaches (Wolfe et al., 2010).

4.2.2 Motor control

Finally, the pipe robot system will require each individual robot to display a variety of low-level motor skills. The particular skill set can change depending on the particular pipe network, its size, and its internal conditions. Locomotion solutions are varied, and few are suitable for all scenarios. For example, wheel-based control is robust and efficient and has been used for prototype pipe inspection robots (Scholl et al., 1999), but such control is generally limited to relatively smooth terrains (Siegwart et al., 2011). Adhesion-based locomotion (Menon et al., 2004) may be suitable for some pipe surfaces, e.g., metal pipes (Mills et al., 2018). Other strategies include rolling, swimming (Colgate and Lynch, 2004) and stepping (Neubauer, 1994), and even modular robots (Brunete et al., 2005, Brunete et al., 2017). Inspection, fault detection and communication may exploit sensors and communication devices mounted on the main body, hence requiring the robot to orient appropriately as well as sensors mounted on manipulators or other appendages. The latter would require solutions for controlling the robot or robot appendages for scanning and instrument/sensor positioning (Nelson 1994). Control algorithms exploiting physics, such as pushing (Lynch and Mason, 1996) are useful for robot rescue, robot cooperation and other physical tasks such as clearing blockages and may be extended and generalised. State-of-the-art approaches to implementing such motor skills range from bioinspired motor control (Boyle et al., 2012b, Boyle et al., 2012a), model-based optimal-control (Todorov, 2004) and learning, particularly reinforcement learning based control (Riedmiller et al., 2009).

4.3 Summary

In summary, buried pipes present exciting challenges for individual and swarm control of robots to achieve high level of autonomy. Here, we have separated our discussion of motor primitives, behavioural strategies and swarm control. In fact, the context of real-world tasks in tightly constrained environments calls for integrative, system approaches, not only of control, but also unifying control and robot design. Such approaches, though still in their infancy (e.g., Cheney et al. (2015)), may one day pave the way for truly flexible, robust and multitasking control.

5 Mapping and robot navigation in buried pipes (T5)

Pervasive sensing in buried pipes will require the robot sensing devices to navigate cooperatively across the whole pipe network and is a challenging problem because it is a GPS-denied environment. Cooperative navigation will require detailed mapping of the pipe network and robot localisation, to ensure global and timely coverage of the network. Robot localisation within the map will also be critical to pinpointing the location of asset damage and deterioration for precise interventions by utility companies.

We divide the problem of robot mapping and localisation into three key challenges here. The *first challenge* is to generate accurate 3D maps of pipe networks using sensor measurements in relatively feature sparse environments. The s*econd challenge* is to incorporate prior knowledge (e.g. from geographical information systems (GIS)) to enhance map initialisation. The *third challenge* is to combine mapping and localisation information from multiple (swarm) robots to produce a real-time fused pipe network map and condition localisation information.

5.1 Robot mapping and localisation in pipes

Robot mapping and localisation methods are usually based on simultaneous localisation and mapping (SLAM), where raw sensor data is processed in a front-end for feature extraction and data association, and robot location and map estimates are produced by a back-end algorithm, as shown in Figure 11 (Cadena et al., 2016, Durrant-Whyte and Bailey, 2006). The typical SLAM problem is formulated by combining the robot pose (robot location and orientation in 2D/3D space), with the location of map features into a single state vector. This vector is associated with the robot position and it is estimated for each time step. Estimation algorithms are usually either filter-based (online), e.g. using the extended Kalman filter (EKF) (Gamini Dissanayake et al., 2001) or Rao-Blackwellised particle filter (RBPF) (Montemerlo et al., 2002), or smoothing/optimisation-based (offline), e.g. GraphSLAM (Dellaert and Kaess, 2006, Kümmerle et al., 2011).

Key to many SLAM algorithms is the extraction of appropriate features (landmarks) from the environment to generate the map and localise against. Features in the pipe environment might consist of T-junctions, elbows, valves, pipe-joints, customer connections, fire hydrant connections and manholes. These features are typical for clean and wastewater pipes, intermittent and relatively sparse compared to domains where SLAM is often successfully applied, e.g. in driverless cars.

Another important feature of SLAM is loop closing, which means recognising places when the robot returns to a previously visited location, allowing drift errors to be corrected. Loop closing is likely to be more challenging in pipes because they are highly homogeneous with little variation in visual/surface features. The lack of distinguishable features means that the robot might fail to recognise that it has returned to a previously visited location preventing successful loop closures.

SLAM algorithms usually rely on reducing uncertainty in the map and robot localisation by taking successive measurements of the same (static) map features from different locations. However, the robot movement in pipes is restricted to predominantly 1D movements along the pipe, whilst the pipe network itself exists in a 3D space. This restricted movement means that the same map features cannot be observed from many perspectives to help reduce map and localisation uncertainty. Therefore, SLAM in pipe networks presents significantly different challenges compared to other applications due to the sparsity of features, similarity of surface features and restricted movement.

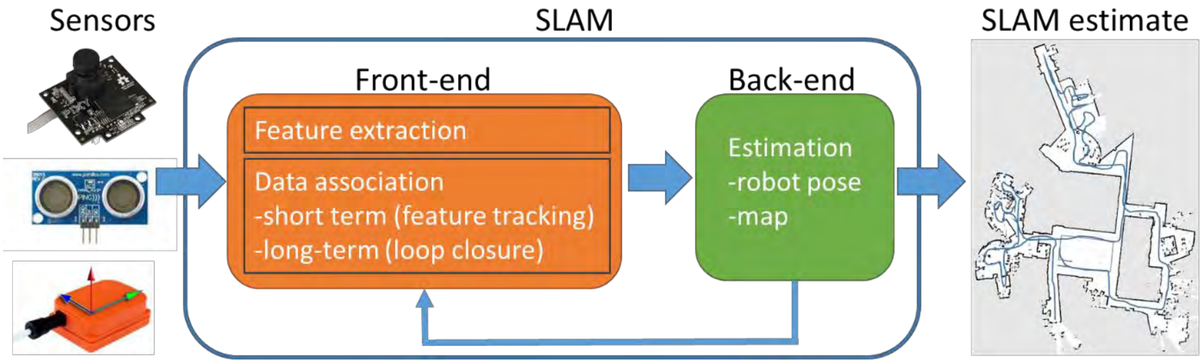

Figure 11: Typical SLAM system. The sensors transmit raw data to a 'front-end', which processes the raw data, extracts features and performs data association. The front-end transmits the processed data to the 'back-end', which estimates the robot pose (robot location and orientation) and the map. The back-end typically uses a standard method such as an extended Kalman filter, particle filter or optimisation method to perform the estimation. The back-end can provide feedback to the front-end for loop closure detection. (Modified from Cadena et al. (2016))

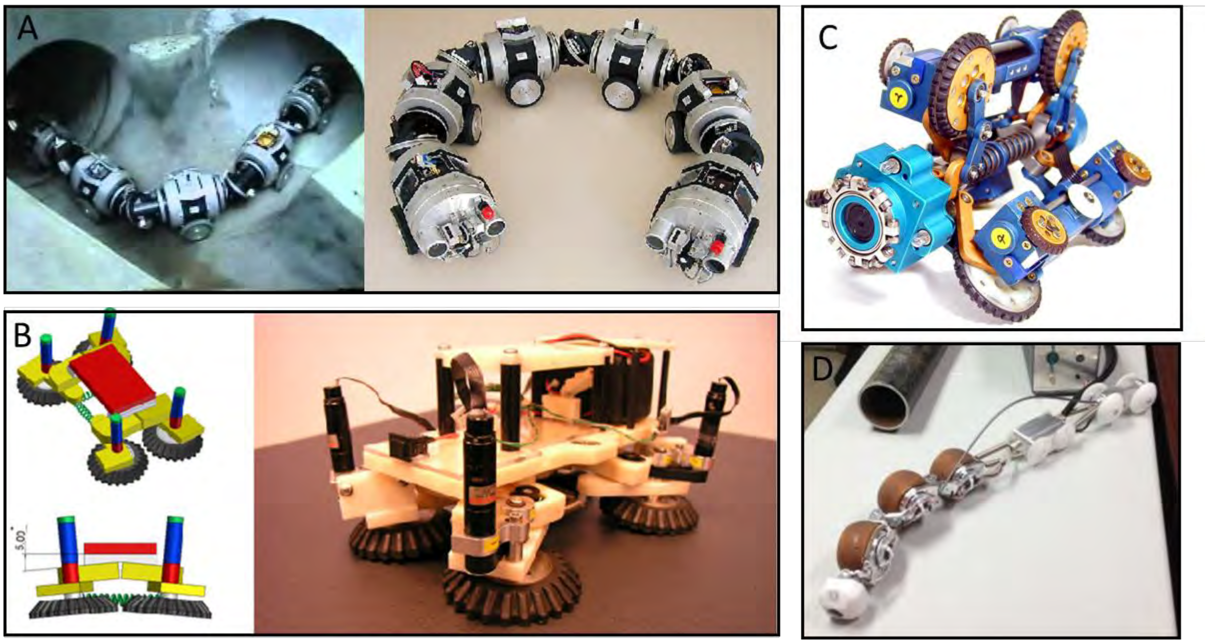

Figure 12: A selection of pipe inspection robots that all include cameras for visual inspection. These cameras could also serve the purpose of acquiring data for visual SLAM and visual odometry algorithms. A: MAKRO. B: KANTARO. C: MRINSPECT. D: PipeTron-VII.

5.2 Sensor choice for in-pipe mapping and localisation

Sensors are a key choice to make in SLAM. The back-end algorithms tend to be common and interchangeable across domains, but the sensors can be selected to suit the environment.

Cameras are very often included on pipe inspection robots so that damage can be detected by visual inspection, such as in MAKRO (Rome et al., 1999), KANTARO (Nassiraei et al., 2006), MRINSPECT (Roh et al., 2008) and PipeTron (Debenest et al., 2015), see Figure 12. Therefore, cameras and visual information about the surroundings are a natural choice to pursue for navigation. Camera-based methods are well developed in SLAM, including monocular (single camera) (Engel et al., 2014, Mur-Artal et al., 2015) and stereo algorithms (Engel et al., 2015, Mur-Artal and Tardos, 2017). Monocular SLAM algorithms have the disadvantage that additional sensors need to be used to resolve scale ambiguity and scale drift, but these are simpler to implement than stereo solutions. Cameras are also often fused with inertial measurement units (IMUs) to resolve scale ambiguity and also to improve the visual SLAM solution (Mur-Artal and Tardós, 2017).

Visual odometry algorithms (Engel et al., 2018, Scaramuzza and Fraundorfer, 2011), where the robot pose *only* (i.e. the robot location and orientation) is estimated from image frames, are also of relevance in pipes because reconstruction of the robot path from the pose generates the pipe network map as a by-product. However, visual odometry algorithms do not perform loop closure in contrast to SLAM algorithms, so drift in pose estimates tends to go uncorrected.

Visual SLAM/odometry methods have been developed for water and sewerage pipes (Kim et al., 2015, Krys and Najjaran, 2007, Lim et al., 2008, Najjaran and Krys, 2010), as well as gas pipes (Hansen et al., 2011, Hansen et al., 2015). Early work by Krys and Najjaran (2007) used vision to estimate distance travelled along the pipe only, via an image mosaicking algorithm and a laser range finder for depth perception. The latter work by Kim et al. (2015) in water pipes and (Hansen et al., 2011), Hansen et al. (2015) in gas pipes used more sophisticated visual SLAM/odometry algorithms to estimate the entire robot pose from sequential image frames. Kim et al. (2015) proposed the use of attaching a paintball gun to the robot to create artificial visual landmarks by firing paintballs at the pipe wall to overcome the lack of visual features. The latter work by Hansen et al. (2015) using monocular visual odometry removed the need for stereo cameras as used in Hansen et al. (2011), by using geometric constraints and structured lighting to successfully overcome problems of scale drift and ambiguity in the pipe environment.

Cameras can also be used to drive appearance-based SLAM methods (Cummins and Newman, 2008, Lowry et al., 2015) and to recognise landmark features in pipes such as T-junctions, elbows etc. (as listed above) (Choi et al., 2017, Lee et al., 2013, Lee et al., 2009, Thielemann et al., 2008). These features can also be recognised using laser scanners (Ahrary et al., Kim et al., 2018, Lee et al., 2010, Lee et al., 2014). In sewer pipes, visual odometry has been combined with manhole recognition to correct drift, which is an appealing approach (Alejo et al., 2017). Also, landmark recognition can be used to construct a topological representation of the pipe network map to enable the application of topological SLAM (Boal et al., 2014, Choset and Nagatani, 2001). This links naturally to topological path planning methods for exploring pipes, which are very efficient (Hertzberg and Kirchner, 1996).

Cameras do have certain disadvantages for use in pipes: (i) the environment might lack visual features; (ii) vision-processing is usually computationally intensive so can require sophisticated and large computational hardware (which can be power intensive); (iii) the camera lens might become dirty and occluded by objects, particularly in sewerage pipes; and (iv) the pipe environment is dark, so a light source is required (which consumes battery power).

A number of related methods have emerged recently that seek to overcome the potential limitations of vision, by using ultrasonic (Ma et al., 2015), acoustic (Ma et al., 2017c, Ma et al., 2017b), (Bando et al., 2016) and radio frequency (RF) (Seco et al., 2016) sensing. These methods have the similarity that they all use an emitter-receiver approach to create a 1D map along the pipe that is continuous in nature, and hence more feature-rich than intermittent visual landmarks. The methods by (Ma et al., 2017c, Ma et al., 2017b, Ma et al., 2015) have the advantage that the emitter-receiver are carried on-board the robot, in contrast, the other acoustic (Bando et al., 2016) and RF (Seco et al., 2016) localisation methods require the emitter to be placed in a fixed location, with the receiver on-board the robot.

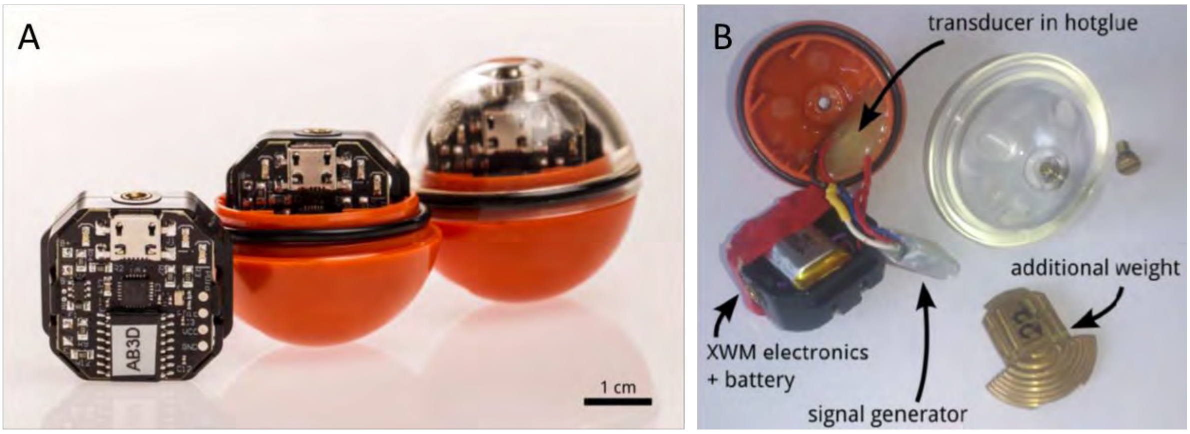

Figure 13: Figure 13 Sensor motes for passive pipeline inspection and exploration (diameter 39 mm). A: Early model incorporating an IMU and data storage flash card. B: Later model that includes an ultrasonic transducer. (From Duisterwinkel et al. (2018))

The most simple methods of in-pipe localisation for robots have been based on dead-reckoning techniques, usually combining an IMU for heading estimation with some form of odometry to measure distance travelled, usually from a tether system (Al-Masri et al., 2018, Murtra and Mirats Tur, 2013, Siqueira et al., 2016). Drift is the key problem with dead-reckoning, and so dead-reckoning has also been combined with drift correction using detected landmark locations (Chowdhury and Abdel-Hafez, 2016, Sahli and El-Sheimy, 2016). Sensor motes have also been proposed that could use an IMU for localisation, although this has yet to be demonstrated as fully effective (Duisterwinkel et al., 2018), see Figure 13. The idea of the sensor mote with IMU is to sense movement dynamics and correlate that to sections of pipe, and also use the magnetometer to sense changes in (metal) pipe material that can then be correlated to a location. Distance travelled was estimated using average flow speed. So, the sensor mote can combine dead reckoning with the potential for landmark recognition using the IMU. This is a promising avenue of study but will require some investigation to fully evaluate the feasibility.

The key advantages of these simple dead-reckoning methods, over more sophisticated sensors such as cameras, is that they are likely to be more easily miniaturised, be cheaper, consume less power and be more robust. In the context of small diameter water pipe environments, dirty sewer pipes and low overheads in the water utilities industry preventing uptake of expensive and complex technology, these benefits could prove decisive.

5.3 Incorporating prior map knowledge

SLAM methods are often developed with the assumption that there is zero prior knowledge of the environment. However, this is far from the case for pipes. Prior information of pipe networks maps can come from a variety of sources. Utility companies usually have basic geographical information systems (GIS) maps of their pipe networks, including pipe locations and access points such as manholes and fire hydrants. However, notional locations of pipes and access points in GIS maps might differ significantly from what is actually present on the ground. Therefore, the use of prior knowledge needs careful consideration and management for inclusion in SLAM.

In Georgiou, Anderson and Dodd (Georgiou et al., 2017) a framework was developed for using Bayesian priors for SLAM in buildings. The results demonstrated the benefit of using meaningful prior knowledge but in a highly specific scenario. There is an opportunity to generalise the results from (Georgiou et al., 2017) to form a generic framework for prior knowledge in SLAM that can subsequently be adapted to pipe networks. A key element here will be extracting information from GIS and customer databases in a manner suitable for Bayesian priors.

5.4 Multi-robot mapping and localisation

The final element of the theme considered here is combining SLAM from multiple robots and developing corresponding navigation strategies that ensure full coverage of the pipe network. Multi-robot SLAM in pipes raises a number of problems beyond single robot SLAM, regarding both the data and mapping-localisation algorithms, which are described below.

Key questions on data include (Saeedi et al., 2015): (i) What type of data will be shared (raw or processed data)? How will data be shared (issues of limited coverage and bandwidth)? (ii) Where and how will data be processed (centralised, decentralised, or distributed)? Real pipe networks present a reasonable ground for these questions such as potentially limited communication range, bandwidth, memory and processing power for small robots in pipes. There is the possibility of using a larger, computationally powerful robot to perform centralised processing in supervision of many smaller drones.

The algorithms for multi-robot SLAM tend to be extensions of single robot algorithms, such as those based on the EKF (Zhou and Roumeliotis, 2006), the extended information filter (EIF) (Nettleton et al., 2000, Thrun and Liu, 2005), the RBPF (Howard, 2006) and GraphSLAM (Cunningham et al., 2012, Kim et al., 2010). A key part of multi-robot SLAM is merging maps from all robots to construct a single, global map of the environment. To merge maps, generally either the initial poses of the robots must be known, or the robots must rendezvous to ascertain each other's pose, or the maps must overlap (Saeedi et al., 2015). For the pipe environment, this mean obtaining the initial pose by taking GPS readings of the robots before they enter the pipe network, or exploiting prior knowledge of the location of the pipe access points. Robots will probably need to rendezvous in pipes to communicate and share map data, which would also serve to provide line-of-sight pose estimation.

Finally, it is worth noting that if features with known locations in the above-ground world coordinate frame are used in SLAM, e.g. manholes as in (Alejo et al., 2017) or fire hydrants, then the mapping can be directly performed by each robot in the world coordinate frame, which should greatly simplify the map merging process. In conclusion, this project will investigate a number of promising avenues in multi-robot SLAM to provide novel solutions for pervasive sensing throughout pipe networks.

5.5 Summary

We have outlined a number of different sensor-types that might feasibly be used for SLAM in pipes, which broadly classify into: (i) Visual SLAM/odometry for full robot pose estimation. (ii) Appearance-based mapping and landmark recognition using vision and laser scanners. (iii) Emitter-receiver methods (acoustic, ultrasonic, RF) for 1-D spatial localisation along the pipe. (iv) Simple dead reckoning methods using inertial sensors with odometry, that can also include augmentation for drift correction using known landmarks. We have noted that water and sewerage pipes will have some prior map information available that should be incorporated into the SLAM system, but that this information might be unreliable on occasion, and so uncertainty needs appropriate handling. Finally, the SLAM methods will be implemented by a swarm of robots operating collaboratively, which will require design of multi-robot SLAM algorithms. This will require careful consideration of data processing, storage and communication given the likely limitations of the robots.

6 Communication (T6)

The Pipebots would require the ability to wirelessly communicate with one another, as well as with the outside world, if they are to realise the vision of an autonomous, cooperative swarm that continuously monitors, reports on, and repairs both drainage and distribution pipes (Metje et al., 2011). This capability is seen as enabling and underpinning for system aspects such as distributed swarm control (Theme 4), and mapping and navigation (Theme 5), where individual robots would need to exchange information quickly in order to maintain pipe network coverage. At the same time, the timely transmission of the data collected by the sensing system (Theme 2) back to above-ground control centres would be required to meet the challenges of reducing disruption and a shift from reactive to proactive buried pipe infrastructure management.

There are two main system-level challenges identified so far, that will shape the research direction in this Theme. Like the other systems, the communications one will operate in a resource-constrained environment, with an emphasis on miniaturisation and low energy consumption. This gives rise to the first challenge, which is the trade-off between data transmission bandwidth and Size, Weight, and Power (SWaP) requirements. The other challenge is ensuring network connectivity coverage and managing the communications traffic from the different data sources, i.e. sensing, telemetry, localisation and mapping, and swarm control; which will have different priorities.

6.1 Modes of Communication

Drainage and distribution networks present a complex environment for the propagation of wireless signals, due to the wide range of pipe materials, shapes, and sizes used. In addition, the contents and respective fill levels of these also differ between the two networks, as well as varying with time of day. To address this variety and to find optimum communication solutions for the different environments three modalities are considered – radiofrequency (RF) wireless signals, sound and ultrasound, and visible light communication.

6.1.1 RF/Wireless

This mode of communication are well-suited for empty or partially-filled metal pipes, which would act as low-loss waveguides (Doychinov et al., 2017). The propagation in air-filled waveguides is well-understood for the case of smooth inner walls (Marcuvitz, 1986), however further measurements are necessary to quantify the effect of sediment and biofilm build-up in pipes that have been in active use. Due to the high loss and absorption in water this modality is not suitable for communication between Pipebots deployed in distribution pipe networks.

Even though there is a lower limit on the RF frequencies that can be used in a metal pipe due its waveguide nature, examples exist of developing custom hardware to upconvert traditional communication signals (Nguyen et al., 2018). In this case the Pipebots can take full advantage of the high data rates offered by mature technologies such as Wi-Fi.

Buried ceramic and other non-metal pipes on the other hand present a high-loss propagation environment to RF signals, limiting the communications range and bandwidth. A potential advantage would be the ability to transmit through the pipe and the soil to an above-ground receiver, something studied and demonstrated in (Van Hieu et al., 2011), (Wu et al., 2014) and (Mekid et al., 2017). These utilise sub-GHz frequencies, which are shown to penetrate soil, ceramic, plastic, and even some water, much better than the 2.45 GHz and 5 GHz used by standards like Wi-Fi and Bluetooth. The downside is that the achievable data-rate is much lower, maximum demonstrated being 38.4 kbps.

Previous studies have also explored RF wireless links to inspection robots inside empty pipes at these more traditional Industrial, Scientific, and Medical (ISM) frequencies, e.g. (You et al., 2008) and the case studies in (Ogai and Bhattacharya, 2018b). Even though establishing a stable communication link has been successful in these works, there are some significant limitations. First of all, the robot platforms are physically large to the point of occupying most of the pipe cross-section. Next, only Line-of-Sight links were demonstrated without investigating potential scattering and diffraction at pipe junctions. Finally, these have all been carried out in a laboratory setting which presents a different propagation environment to that of pipes buried underground.

6.1.2 Visible Light

Visible Light Communication (VLC) is a topic that has gathered significant research (Matheus et al., 2019b) and standardisation (IEEE, 2018) interest due to its potential applications in indoor high-speed communication using commercial LED lightbulbs (Karunatilaka et al., 2015). The existence and availability of Free and Open Source (FOS) prototyping and development platforms (Klaver and Zuniga, 2015, Matheus et al., 2019a, Wu et al., 2017a) has enabled research into systems utilising novel modulation schemes (Haigh et al., 2015b), advanced transceivers (Haigh et al., 2015a), and using multiple wavelengths, or colours (Matheus et al., 2019a).

The feasibility of using VLC for underwater wireless communication has also been studied both theoretically and experimentally (Saxena and Bhatnagar, 2019, Sticklus et al., 2019), with multi-Gbps channel capacity reported at distances of up to eight metres (Li et al., 2018a, Lu et al., 2016). Research focus has been predominantly on VLC in harbour, coastal, and open ocean settings (Sticklus et al., 2019), with the effects of various parameters such as water turbidity and air bubbles (Oubei et al., 2017), water contents (Smart, 2005) and presence of small organisms (Kaushal and Kaddoum, 2016) on the absorption, attenuation, and scattering of light extensively studied and quantified. Finally, rigorous channel modelling formulas and design guidelines have been published (Giles and Bankman, 2005, Liu et al., 2019, Saxena and Bhatnagar, 2019).

Despite these promising results, a VLC system integrated with a robotic platform is yet to be demonstrated within a buried pipe environment. Furthermore, due to its highly directional and Line-of-Sight nature, it would only be suitable for short range links within the same length of pipe. The required alignment between two Pipebots to achieve the high data rates mentioned previously could be quite demanding on the robotic platform, especially in distribution networks with high water flow.

6.1.3 Sound and Ultrasound

The final modality considered for the communication system of Pipebots is acoustic and ultrasonic communication. Compared to the RF and VLC ones, this is not as mature in terms of miniaturised hardware availability and standardisation (Potter et al., 2014). However, it will be invaluable in enabling long-rage communication capability for the Pipebots, particularly in distribution networks consisting of fully water-filled pipes.

Much of the research in recent years has been focused on the fundamental and theoretical modelling of pipes as acoustic waveguides, with detailed findings published on propagation modes, effect of pipe material and thickness, noise, and acoustic properties of surrounding soil (Dubey et al., 2019, Li et al., 2017, Li et al., 2018b, Li et al., 2019b). The findings from these illustrate a complex environment, suffering from multi-mode propagation and dispersion.

In addition to the above-mentioned studies, using ultrasound to communicate through the air has also been experimentally demonstrated with additional research exploring the propagation characteristics and multipath environment (Ens and Reindl, 2015, Jiang and Wright, 2016, Mazurek, 2018).

However, ultrasonic communication using low-cost and low-power commercial hardware has only been demonstrated to achieve data rates of no more than a few kbps (Chakraborty et al., 2015, Getreuer et al., 2018, Santagati and Melodia, 2017).

Similarly, to the previously discussed RF and VLC, ultrasound communication has also not been demonstrated fully-integrated with a robotic platform in a buried pipe scenario. Even though some of the studies reported here have conducted field trials and measurements, they have done so using stand-alone laboratory equipment.

6.2 Network Aspects

In order to ensure network connectivity and coverage for the Pipebots swarm, a system model and higher-level communication protocols will have to be developed and optimised for energy consumption and computational power, among other constraints. This will also require close collaboration with Themes 4 and 5 to avoid competing requirements and demands on the individual Pipebots. Network resilience and fault-tolerance will also be an integral part of these. Such protocols will be built on top of existing lower-level ones, such as IEEE 802.15.4 in the case of RF communications, or IEEE 802.15.7 in the case of VLC. The JANUS protocol which was introduced in Section
6.1.3 Sound and Ultrasound will form the basis in case of acoustic and ultrasound communications.

Use of existing communications infrastructure such as smart metres will also be explored, as well as utilising fire hydrants and other access points for the placement of fixed Aggregator Nodes (ANs). These ANs can be used to recharge individual Pipebots, download and store larger volumes of data, and provide access to existing telecommunication infrastructure.

6.3 Summary

From a communications point of view, the buried pipe infrastructure for drainage and distribution networks presents a complex and varied environment. It will be particularly challenging to implement solutions that offer good quality of service in all scenarios, while minimising energy and computational power needs. A multi-modal solution, where one communication modality is used for long-range, low data-rate in conjunction with a short-range, high data-rate is one potential option.

Extensive measurement and experimental campaigns will be undertaken to rigorously and accurately model the communication channels under different, real-world conditions. Close collaboration with other Themes will ensure that the communication system seamlessly integrates with the rest of the future Pipebots platform and delivers the necessary connectivity to make the vision of the project a reality.

7 Road to implementation (T7)

For pervasive sensing to flourish and integrate with emerging technologies, a number of things have to happen. Firstly, a unique research capacity grounded in trans-disciplinary team working must be created. Secondly, the dynamically evolving infrastructure and urban systems with which pervasive sensing interacts must be mapped and understood. Thirdly, technologies emerging from other spheres must be explored and trialled; and, finally, alignment with the political, economic and social environment that would enable pervasive sensing to integrate seamlessly into practice must be ensured.

7.1 Trans-disciplinary working

The project has already assembled a team of researchers and industrial and other stakeholders representing the principal scientific and practice domains involved in pervasive sensing. However, while this is vitally important, and the stakeholder community will grow as the research matures, this multi-disciplinary collaboration needs training and support to move the whole research team (the academics and their project partners) towards transdisciplinary working (Leach and Rogers, 2019). This is a manner of working that enables any member of the team to be sufficiently informed of the complete scope of the programme and its progress to challenge, and help to shape, any other aspect of the programme. Without this, there is a risk that research will remain silo-based and the project will fail to deliver on one of its founding aims: namely, whole system improvement for the water industry, as the initial target, and the pipeline industry more generally.

The UK water industry is a complex environment and within that, Pipebots is seeking to address a multi-faceted problem. Moreover, each water company has its own challenges and priorities, and operates in its own unique context (geographically and otherwise), while the pipeline industry more generally provides numerous different contexts in which Pipebots research findings will be implemented. To tackle such a multi-faceted problem effectively while remaining nimble enough to apply the research to this broad range of contexts, the project needs to be clear about what it is focusing on as its starting point. Researchers and project partners need to agree the following: the principal scenarios that the research will focus on; how Pipebots will integrate its work with water company operational requirements and commitments while remaining cognisant of the operational requirements of the pipeline industry more generally; and, the outline operational concepts that will be employed in implementation of the research findings.

Synthesis of this general approach with water industry specificity will be a fine balance and requires a two-way process between Pipebots and the water companies, noting that some aspects of the research might be prioritised to meet immediate needs of the water companies, where feasible and beneficial to the research programme, or to take advantage of emerging opportunities for testing technology in the field. This approach offers the chance to deliver early impact and to 'advance by learning' (see below), and helps avoid the risks inherent in conducting field trials towards the end of the project.

The first stage of this process – identifying the principal scenarios on which to focus – was aided by the Water Industry Challenge Workshop held in Sheffield in July 2019 (Pipebots, 2019). This helped to highlight the principal challenges that the water companies face, although they lacked context in terms of pipe type, age, diameter, etc. It has been suggested by the academic team that large diameter, high-pressure water mains might be an important initial scenario to focus on for political (i.e. leakage is a major national concern) and technical reasons, and this scenario needs to be enriched through further dialogue with the water companies.

However, coming to a point of initial focus requires a broader set of processes that firstly require the aspirations of all those affected by the proposed radical intervention of introducing robotic swarms to assess pipeline condition to be captured. The Aspirational Futures tool developed for city and infrastructure interventions (Rogers and Hunt, 2019) will be applied to achieve this. Equally important is a deep understanding of the problems that this radical intervention would address, and similarly an urban diagnostics tool (Leach et al., 2019a) will be employed to structure this analysis. This in turn requires a comprehensive understanding of the contexts in which the interventions are to be made, and how they derived. The preliminary work with our project partners in co-creating the Pipebots grant application and the Water Industry Challenge Workshop provides a strong steer, yet additional work on governance – formal (legislation, regulations, codes and standards) and informal (societal attitudes, practice norms, political direction) – is needed to enrich the picture (Honeybone et al., 2018, Leach et al., 2019b, Rogers, 2018).

Within the context of the scenarios mentioned above, agreeing the operational concept(s) for pervasive sensing will be crucial to shaping the research and Pipebots transdisciplinary working. Operational concepts paint an early, overall picture of a system's real-world operations from the stakeholders' points-of-view (Pyster et al., 2012). In the case of Pipebots, the concept(s) will describe the project team's best guess about how the research findings will be employed to asset manage buried pipe networks; they do not describe the research process itself. As an example, an operational concept for pervasive sensing in the water industry might describe things such as how robots will be launched and recovered; what level of human control there will be while the robots are in the pipe; how failed units will be dealt with; what sort of intra-robot communication there will be; etc. It is the vision of how the robots will be used that will help to identify knowledge gaps and shape Pipebots' research. Pipebots is in the process of defining a generic operational concept for application to any pipeline system, alongside specific operational concepts for application in water and wastewater systems, with both matched to the collective aspirations and to address the problems revealed by the analytical processes described above.

7.2 System mapping

Pipebots' research is taking place in the context of existing systems, and as such, the research team does not have a blank sheet of paper to work with. Therefore, research impact will depend on Pipebots contributing to the transformation of the existing pipeline systems and their operation and maintenance regimes. The initial focus will be on the water-network asset-management system, with the aim of seeking to transform it in a way that is systemically desirable and culturally feasible. This is a complex problem with no right answer, and as such it requires the research team to advance by learning (Arnold and Wade, 2015, Bouch and Rogers, 2017, Meadows, 2008). More specifically, Checkland and Scholes (1999) developed a soft system methodology as an iterative learning process to help businesses with this sort of problem. Figure 4 shows a simplified version of the principles behind this soft system methodology.

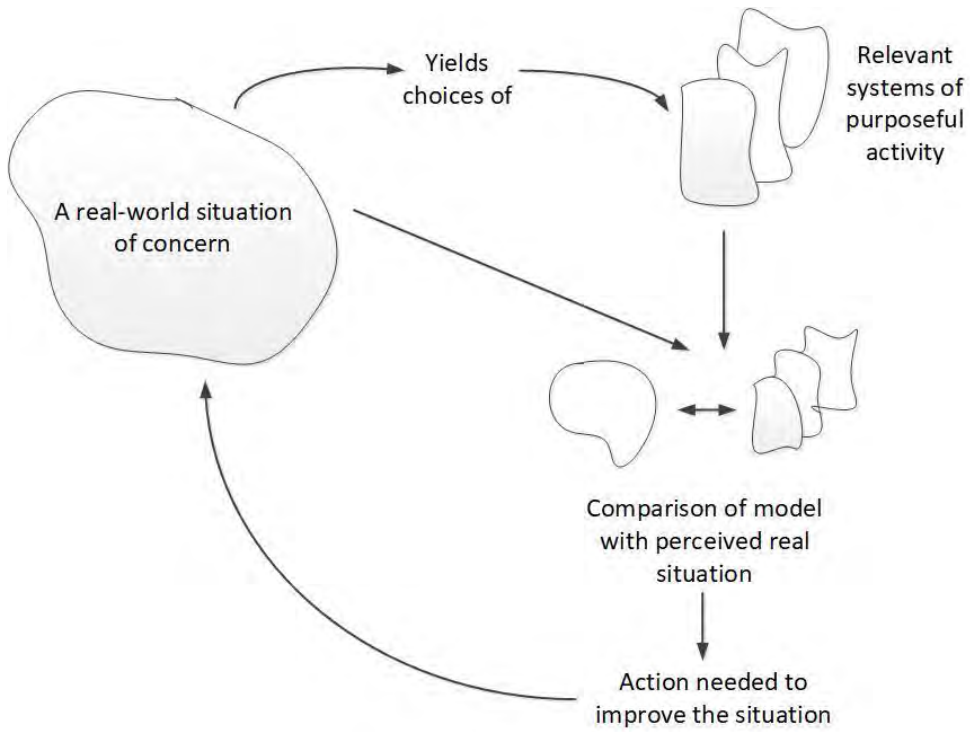

Figure 14: Simplified version of soft system methodology (after Checkland and Scholes, 1999).

The process starts in the top left of the diagram with work to understand the existing system. Moving clockwise, the next step is to formulate some systems of purposeful activity: in other words, changes to the existing system designed to improve it. These are then tested against the existing system to establish whether they are systemically desirable and culturally feasible: that is, if they are applied to the existing system will they result in the anticipated improvement? Implementation of the changes then creates a new 'real-world' situation with scope for further changes, hence providing the opportunity for iteration that addressing complex problems requires.

Building on Checkland's work, research carried out as part of the recent EPSRC-funded iBUILD project developed an objective and repeatable methodology for the mapping of existing, real-world situations (Bouch et al., 2018) which can create: (i) a map of the system's physical components; (ii) a map of generic value-generating opportunities; (iii) a map of enablers and constraints relating to the system; and; (iv) a holistic, historic narrative for the system that provides an essential foundation for its future development. These maps will be brought together to assist the Pipebots team in proposing systems of purposeful activity for change.

7.3 Facilitating the transformational change

It is not sufficient to prove the efficacy of the scientific and engineering innovations and how they fit with current systems. If the innovations and their operational protocols, which are encapsulated in a proposed engineering intervention in pipeline industry systems, are to be adopted in practice, a comprehensive articulation of the benefits of doing so needs to be undertaken, the case for change – a balance of all the positive and negative consequences of introducing the radical change – needs to be made and a suite of alternative business models formulated that balance different combinations of benefits against the investment required (Rogers, 2018). This requires the impacts on the existing system of interest (initially the water asset management system) and all other systems with which it is interdependent to be identified, and once again system mapping is required (Bouch and Rogers, 2017). It is essential that this impact takes into consideration future contextual change, and a futures analysis will therefore be undertaken (Rogers et al., 2012b).

The outcomes of these analyses will then feed into the development of the case for change (Leach et al., 2019b) – why the introduction of pervasive sensing using robot swarms should be introduced. They will likewise underpin the formation of the alternative business models that would enable this change to implemented in practice (Bouch and Rogers, 2017, Bryson et al., 2018, Rogers, 2018). Once the systems of governance have been identified, analysed and recommendations for their change proposed to enable the radical change towards pervasive sensing to be accommodated in practice (Rogers, 2018), the final process is to prepare the way for implementation in terms of political, social, environmental and economic acceptance. The business models will deal will most of these concerns, yet there needs to be political will behind the change. This requires an enhanced focus on governance.

7.4 Emerging technologies

Pipebots is aiming to do original research to bring about a transformation of pipeline industry asset management, and a transformation of water industry pipeline asset management from reactive to proactive. However, it is also keen to leverage technologies emerging from industries other than water. The search for such technology will be assisted greatly by the development of scenarios and operational concepts as mentioned earlier. These will help to shape and focus the research effort, generating in the process a range of specific research challenges. Being clear about the challenges will in turn help to focus the search for technologies that could be incorporated into the work of Pipebots.

The advances in science and engineering that are needed to underpin Pipebots vision are likely to be of value to those addressing other challenges of analysing the condition of inaccessible ageing or deteriorating infrastructure across the whole of the UK and globally, or materials more generally. We will therefore explore how our novel technological developments might be translated to other applications, in the same way that we will explore how developments elsewhere might help us. This reinforces our principle of working under the umbrella of UKCRIC – the UK Collaboratorium for Research on Infrastructure and Cities – where collaboration across sectors, governance silos and disciplines will lead to better outcomes.

7.5 Summary

Trans-disciplinary working is a critical component in the successful implementation of Pipebots. The Programme Grant has already assembled the necessary team of researchers plus industrial and other stakeholders, representing the principal scientific and practice domains involved in pervasive sensing. Throughout the course of this Grant Theme 7 will continue to direct the provision of training and support to ensure the whole team takes a trans-disciplinary approach. System mapping will support the team's research, technology transfer work and decisions on which systems to map and to what level of detail will be guided by the 'advancing by learning' approach embodied in Checkland's soft systems methodology (Checkland and Scholes (1999). Advancing by learning will also provide the foundation necessary to facilitate the transformational change that Pipebots seeks to achieve, by checking that proposed changes are systemically desirable and culturally feasible. Finally, Theme 7 will be on the lookout for asset management technologies emerging in other sectors, with a view to investigating how they might contribute to Pipebots' aims.

8 System knowledge (T8)

Having demonstrated the challenges with respect to robot design, communication, propulsion and sensing, it is also vital to better understand the requirements by industry and where their biggest problems occur, i.e. in gravity wastewater or potable pressurised water networks. Therefore, Theme 8 brings together the academic and industry community to develop the specifications, technology requirements that will provide the basis upon which the proposed Pipebots, i.e. design of robotic pipe inspections systems will take place, given a clear understanding of the environments in which the robots will work. This knowledge needs to include the pipe materials, sizes, joints, as well as ancillary structures such as hydrants, manholes, pumps, valves, etc. Furthermore, the researchers need to know how the networks deteriorate, how to avoid the robots causing issues in the network - e.g. mobilising silts and biofilms which would discolour the water.

Buried pipes deteriorate in different ways, which are a function of the material, the joints, the surrounding soil and the characteristics of the water flowing in the pipes. For example, a key factor in the deterioration of ferrous metal pipes will be rusting, which will reduce the strength of the pipe, internal rusting will also decrease the cross-sectional area, thus decreasing flow capacity and increasing pressures (Cole and Marney, 2012). All pipe networks will include some form of joint between discrete lengths of pipe and between the pipe and other assets, such as valves as well as ancillary structures such as hydrants, manholes, pumps, valves, etc. (Caffoor, 2019). These joints are often a key point of weakness as the materials age and also as ground conditions change the joints will be subjected to increasing stresses which may lead to failure, leading to leakage from the pipe, or ingress of groundwater, depending on the relative pressures (Davies et al., 2001). Some indication of network performance can be gained from flow data (and in distribution networks, pressure data). However, this data tends to be spatially sparse, and for sewerage networks is usually only collected as part of occasional short term flow surveys, so the data cannot be used to accurately locate network problems (Hao et al., 2012).

Prior to deploying any new device for assessing pipe condition into a live network it will need to be developed and tested in a controlled environment in unpressurised and pressurised water pipes. The Theme 8 team have a significant role to play here by supporting the testing of the sensing technologies, validation and demonstration of the pervasive autonomous sensing technology platform developed in Themes 2–7 to ensure that it is appropriate and properly integrated (with Theme 3) in laboratory conditions (e.g. at the UKCRIC National Distributed Water Infrastructure Facility at Sheffield) and then at carefully selected offline full scale pilot sites which have been made available to the are available at project through several industry industrial partners, (e.g. Thames and Scottish Water) to develop an experiment to demonstrate robots operating in clean water pipes which are not connected to customers.

While such robotic technologies can provide data describing individual pipe defects, this information needs to be aggregated into actionable knowledge which allows the water utilities to make informed decisions to manage their piped networks. For an extensive sewer pipe network, the Sewerage Rehabilitation Manual (WRc, 2011) gives guidance to transform results from a sewer condition survey into an internal condition grading, which is based on the most severe defect in the sewer length. This grading however only considers the sewer's potential for collapse, rather than any other serviceability issues, which require additional data (ISO, 2019). Developing methods to transform the data from pervasive sensing into actionable knowledge is the third key element of the work to be carried out in Theme 8, as well as making use of the data from a single point in time, the data can be used to better understand the deterioration of networks and to develop better deterioration models which can predict the structural and operation performance of the pipes (Berardi et al., 2008). In the case of clean water pipe network utilities set company targets to reduce leakage. These targets are relative high (e.g. 15% reduction for Wessex Water) and can only be met through better knowledge of the real-time system condition and performance.

8.1 The role of new autonomous robotics for pipe inspection within a smart city

What we are proposing represents a radical transformation of the water supply and wastewater removal systems that serve society - and ultimately perhaps a transformation of how we maintain all buried pipelines - and this transformation inevitably impacts on the systems with which they interact. In order to understand both how to bring about the transformation and the impacts that it will have, both positive and negative, we need to create comprehensive system maps demonstrating how the pipeline system of interest interacts with all other urban systems – the dependencies and interdependencies between them. Understanding and making explicit the landscape in which we are operating, and which we propose to change, is therefore the first task.

Acknowledging that we are not the only actors looking to improve the way we operate and maintain our buried infrastructure systems; we will seek to develop and trial our novel technological approaches alongside developments elsewhere. These developments include the move towards comprehensively sensed and monitored infrastructure and urban systems, and thus we will be adding to the 'big data' and AI-enabled landscape that is developing all the time. In short, what we are proposing is a radical shift from reactive repair and maintenance to proactive maintenance, refurbishment and upgrading, which in turn will enable a move from emergency construction operations based on trench excavation to trenchless operations, with all the benefits that these bring in the form of minimising or avoiding damage and disruption to interdependent infrastructures and society.

The wider perspective of the Pipebots research is that we urgently need to make our infrastructure and urban systems more sustainable, resilient, liveable and 'smart' (noting that 'smart' is only 'truly smart' if it enhances sustainability, resilience and liveability) (Rogers, 2018). This is for many reasons, yet the most compelling are economic limitations – we cannot afford to deal with our infrastructure systems in the way we have done in the past – and planetary limitations – both on resources and in terms of limiting the damage that we are causing to the natural environment that supports us (associated with, for example, the contemporary issues of air quality and climate change).

This requires us to create bespoke sustainability assessment frameworks for pervasive sensing, providing a comprehensive picture of how our new system would impact on the many indicators of sustainability as well as what this picture would be without our new developments. This will, at a glance, provide the starting narrative for how we create a case for change. However, this exercise inevitably points to what pervasive sensing using swarms of miniature robots might achieve if it were introduced tomorrow, yet sustainability and resilience is focussed on the far future. We will therefore undertake futures analyses of each of the existing systems with which our work is associated to understand where the vulnerabilities lie and where interventions (i.e. changes to these systems) are needed to deliver resilience. This in turn will allow us, in collaboration with our industry and other stakeholder supporters, to develop a suite of "*what if?*" future scenarios. This will be done in 'safe spaces' via workshops to explore the potential for radical / fundamental changes to buried infrastructure systems. The exercise will demonstrate where the vulnerabilities lie in our proposed implementation plan, but also where additional opportunities lie. In essence, it will enable us to future proof our engineering designs and implementation strategies.

Using the system maps, we will then be able to undertake deep analyses of the each of the systems to determine where the opportunities lie to make the system truly smart (i.e. be able to deliver multiple benefits to the economy, society and the environment). This provides the foundation on which to establish a common vision for pervasive sensing, which will be captured as an accessible narrative so that all stakeholders – industrial service providers, local authorities, citizens and those who govern them, academics and others – can appreciate the value and nature of the intended transformation. Such a narrative will help to establish the Pipebots team at the core of a world-leading research capability in Autonomous Sensing for Buried Infrastructure in the UK.

Building on this foundational work, we will then be in a position to create the business case for change in pipeline asset management practices, drawing from the technological evidence base created by the research and the multi-dimensional value framework that will be progressively developed as the programme advances. Alongside the compelling case for doing things differently in practice must lie the enabler of change – that is, the suite of alternative business models that would allow an investment to realise the multiple benefits identified. The primary task here is to translate the generic value frameworks into context-specific business models for pipeline maintenance, repair, upgrade and renewal, recognising that any intervention will take place in a specific context – geographical, political, economic, social, environmental, etc.

However even if one or more of these business models prove(s) to be compelling, there might still be barriers that could prevent implementation of the intervention. We therefore need to analyse all of the systems of governance that operate in the specific context in which the intervention is to be applied. These governance systems include all formal forms of governance, such as those that limit certain actions – legislation, regulation, codes & standards – and those that incentivise or disincentivise actions, such as taxation. They also include all the informal forms of governance, such as individual and societal attitudes and behaviours, societal norms, ethical issues, and operational & practice norms. Of interest, of course, are the specific systems of governance relating to pervasive sensing using swarms of miniature robots in water and sewer pipes, but these inevitably extend to those of the service provision associated with the pipelines in question. This will allow us to identify barriers to deployment and to engineer mitigation strategies, such as recommending alteration to the systems of governance.

8.2 Wider role of new science to the UK and its relevance to the UK's Industrial Strategy.

Pipebots addresses directly three societal challenges: (i) utility service provision with minimal societal disruption; (ii) resource efficiency; and (iii) infrastructure resilience. Safe and secure water and energy supply is fundamental to society, but is faced with global challenges from climate change, water stress, carbon targets, demographic change, urbanisation and cost constraints. It is erroneously inferred that the UK's buried sewer and clean water asset lives are 800+ and 120+ years, respectively(Liu and Kleiner, 2013) . Maintaining these ageing assets will become increasingly problematic and we note that failures continue to escalate despite recent high levels of spending, e.g. the £22 billion of private investment in water infrastructure in 2010-15 – water services will remain threatened without a new, and radical, solution. OFWAT has indicated that across 2020-25 utilities will need to deliver greater resilience combined with customer price reductions (OFWAT, 2017).

The strategic importance of this research is also evidenced by a 3-4 fold increase in the number of UK's publications on pipe inspection with waves since 2000, while the UK lies only behind the USA and China in the number of publications related to sonic pipe inspection (Liu and Kleiner, 2013). This research contributes strongly to the UK's economic success in sustaining its position as a global leader in next generation infrastructure engineering science. Pipebots is aligned with: (i) the EPSRC Connected and Resilient Nation prosperity outcomes in terms of a new intelligent technologies (C4) and well-connected and properly maintained network of pipes which are resilient to change and abuse (R2, R5); (ii) Productive Nation prosperity outcomes in terms of developing new sensing products and technologies and IP which will be manufactured and marketed by UK businesses (P1); and (iii) with the Healthy Nation prosperity outcome in terms of providing a well-maintained network of pipes which supply clean water to all in a safe and uninterrupted manner to prevent disease and its spread (H2). Pipebots also aligns with the EPSRC strategic objective to grow the research portfolio in robotics and autonomous systems and to capitalise on the recent £128M investment in UKCRIC testing facilities for infrastructure research.

8.3 Summary

Water companies in the UK currently have limited amount of data to understand the performance of their networks. Existing methods of sensing either only give time series data for a limited number of locations, or very infrequent spatial surveys of key parts of the network. Pipebots is therefore aiming to fill the data gap in order to manage water distribution and drainage networks more efficiently. There is a need to work with the water industry to understand their needs in order to develop suitable technologies. Ensuring that the needs of the water industry are met is the only first step to ensuring the technologies are accepted. The project will also need to demonstrate the technologies, initially outside of the networks in laboratory and then at designated testing sites, before prototypes would be allowed in live networks. Once in the networks, pervasive sensing technologies will produce new types of data and larger volumes of data, which will require methodologies to transform the data in order to better manage the networks. The new data streams will allow new models to predict deterioration based on the new data streams to be produced, further enhancing the ability of to manage the buried pipe networks proactively.

9 Conclusions and action plan

The length of the buried pipe networks in the UK and in the rest of the developed world is immense. A large part of this infrastructure is aged and require serious interventions to keep it operational. Currently, a majority of these interventions are administered through road excavation. The quality of rehabilitation work, time required and the amount of associated disruption depend heavily on the ability to identify clean water pipes which are likely to leak or wastewater pipes which are likely to develop blockage or structural damage. Timely identification of these issues presents a problem for the current methods of pipe inspection. All the existing inspection pipe methods are not pervasive enough, sensitive enough and accurate enough to identify the failing pipes before they can be rehabilitated with minimum disruption. A big obstacle here is that majority of the current inspection methods for buried pipes are slow and all require human intervention, e.g. they are not autonomous. This problem is global.

Therefore, there is an opportunity for the UK to develop radically new pipe inspection technology to market worldwide with a massive economic return. A radical transformation here is that the inspection should be delivered from within the pipe by using robots which are autonomous. These robots can carry a payload of sonic, optical and thermal sensors to inspect the pipe network over an extended period of time to detect the onset of damage and report it before it becomes a major service disruption.

The time for this step change in pipe inspection methods is right. A great amount of knowledge has been developed through systematic research on traditional pipe condition monitoring methods which can be achieved through sonic, optical and thermal sensing. Recent advances in miniature electronics and embedded systems paves the way for the development of robust sensor packaging which can be fit in a small robot to operate autonomously. Modern methods of subtractive manufacturing and 3D printing has the potential to reach accuracies in building robotics components at the micron scale. The development in biologically inspired control solution paves the way for much greater swarm of robot's autonomy and coordination in buried pipe network than have ever been attempted. There are a plurality of traction and locomotion solutions for small robots which can be adopted and developed for robot operation in clean and wastewater pipes. The motion of these robots can be informed through novel methods of localisation and mapping which can be informed through the incorporation of basic prior map knowledge, onboard sensors and advanced sensor fusion algorithms.

Finally, there has been a massive amount of research on new communication methods which be developed to deliver data from robots operating in a buried pipe network to the above ground operators who manage this kind of assets. Combined with modern AI and machine learning these data can be processed rapidly contributing to the transformation of the pipe operation and maintenance regimes and generating actionable knowledge about the way these assets evolve over time as a part of a liveable urban system.

There are number of research and technical challenges to make this technology transition a reality. The Pipebots Programme Grant has been formulated and its research programme has been adapted to address these challenges systematically. This position paper will help to steer the Pipebots. The Action Plan is being developed based on the plans proposed by the 7 Research Themes (see here). The plan will reflect the Challenge Specification and Roadmap documents which have been developed through the Sprint 1 (4/5 June 2019) and Industry Challenges Workshop (12 July 2019). The Action Plan will be finalised at the next Academic Team meeting in London on the 19th of November 2019 and made available to our peers.

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