Engineering and
Physical Sciences
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Pipebots

Challenges and Plans for each Pipebots Theme

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Introduction

Pipebots is an EPSRC funded research project which is developing autonomous swarm robots to inspect sewers and water pipes. Water utilities operate large, complex pipe networks with often limited information on system connectivity and asset condition. Currently many utilities manage their pipe networks using two data sources: historical records of pipe location, age and material; and contemporary inspections. Action is typically only taken once failure occurs and performance is compromised. Such asset failure is undesirable because it can cause service disruption or economic loss to the customer, pollution, damage to other infrastructure such as roads and added congestion when unplanned roadworks are required to repair or replace the asset.

Currently, there is no inspection system which measures pipe condition accurately in real time and at a high enough spatial granularity to identify and measure pipe defects. In-pipe inspection systems worldwide use manually operated, tethered platforms that move through pipes carrying sensors. A comprehensive review of pipeline inspection technologies revealed that the robots currently available are mainly laboratory prototypes designed for large diameter pipes, are human controlled, heavy (tens or hundreds of kg) and are devices suitable for a single short duration intervention.

A report from the Twenty65 project[1] on robotic autonomous systems (RAS) for the Water Industry[2] identified key opportunities as "mapping, condition assessment and rehabilitation within underground pipe assets".

Pipebots aims to revolutionise buried pipe inspection with the development of autonomous micro-robots designed to work in complex pipe networks. New algorithms to process the autonomously collected data for pipe condition assessment will be developed. The outputs from these algorithms could be directly mapped to the hydrodynamic performance of single pipes or fed into a deterioration model that can predict the useful remaining service life of a pipe. The Pipebots project has six technical themes: Theme 2 is Sensors; Theme 3 is Robotic Systems; Theme 4 is Autonomous Control; Theme 5 is Navigation; Theme 6 is Communications and Power; Theme 7 is The Emerging Science of Pervasive Sensing; and Theme 8 is System Knowledge Generation and End User Engagement. Figure 1 graphically illustrates this structure and details the high level challenges and methodologies that will be used.

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[1] https://www.twenty65.ac.uk/

[2] http://pipebots.ac.uk/wp-content/uploads/2019/03/robotics-report-web-4.pdf

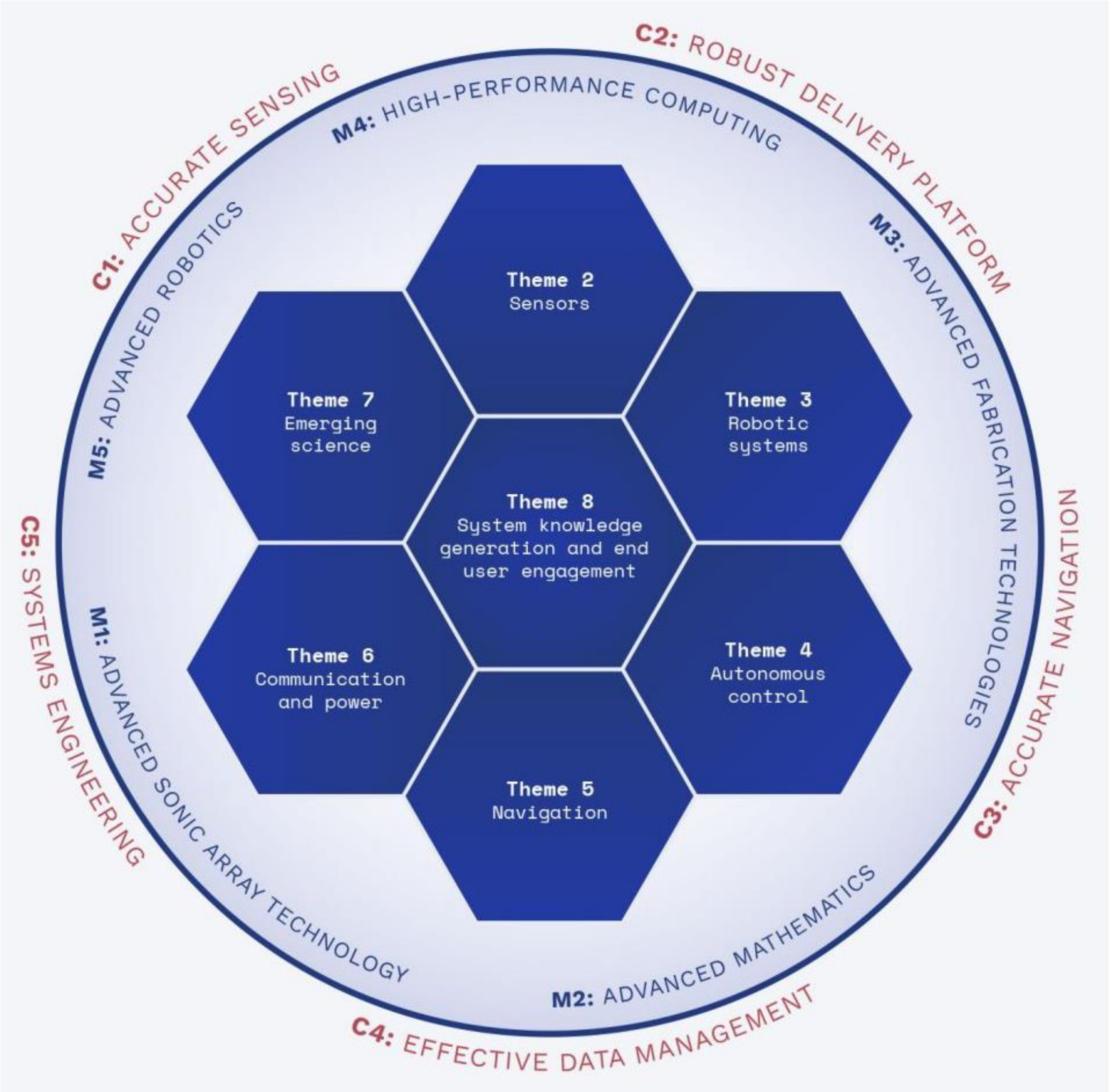

Figure 1: Project structure showing high level challenges (C) and methodologies (M).

Theme 2: Sensors and non-destructive testing

This theme focusses on the sensing technologies needed to better assess pipe condition. The team, based in Bristol and Sheffield, has a large amount of experience in using ultrasonic sensors in the non-destructive testing (NDT) arena and complimentary experience in acoustic sensing for condition and flow monitoring. The science of Theme 2 is very mature, with many industry applications, however to achieve the specific aims of Pipebots development is needed for sensors to work in the in-pipe environments found in the water industry. There have been applications to inspect pipelines in the oil and gas industry using bulk wave sensors attached to tethered Pigs which are expensive and would not be relevant to the water industry (on cost grounds) or to the pervasive inspection concept in this project. Another technique is the guided wave, which is especially used to inspect pipe wall thicknesses, however the current technology needs to be applied externally to pipes so is not feasible in buried pipe networks.

Ultrasonic sensors are typically used in contact with the material being tested, the technology is most suitable for relatively dense and homogenous materials, so is appropriate for steel and plastic pipes, but materials with a more complex structure (e.g. cast iron, clay and concrete) are significantly more challenging to assess. Currently, these sensors often operate at high voltages , so new developments will necessarily focus on low voltage and low power sensing. Usually a single unit will generate and receive the ultrasonic signal, but as the robots are in a swarm, it may be possible to use a different robot(s) for the wave generation and the sensing. Furthermore there is the possibility for some robots to be designed to look at specific in-pipe features.

The research team aims to first obtain new pipes to test sensor response. Later, defects in these pipes will be engineered then defective “used” pipes will be tested. This will inform the choice and operation of the sensors to be developed. They will work alongside other themes to understand how best to move the sensors through the system (T3), be able to accurately locate the sensor (T5) and optimise the coverage of the sensing (T3, T4) and to understand what types of defect to focus on (T8).

There is the potential that data from sensors could be used to help with the localisation of the robot within a pipe, but network location may need to use other data. Conversely, other sensors such as a camera might be used to target where pipe condition data needs to be obtained. Each pulse from a single sensor will characterise a relatively small part of the pipe, so it will be important to understand the coverage and spatial resolution requirements to accurately understand the pipe condition and how swarms might interact to ensure adequate coverage. Furthermore it is important to understand how to process and save this data so that as well as identifying and measuring defects, subsequent robotic surveys can allow the change in pipe condition to be accurately assessed.

Theme 3: Robotic Systems

This theme will develop the physical aspects of integrated robots for inspection and surveying of buried pipes. The first challenge is develop robots to gain traction and move within pipes and to physically take sensor payloads to all areas of the pipe network. We define this ability as robot dexterity. For larger robots, dexterity could be achieved through high degrees of freedom and flexibility. Small robots could simply move around many large obstructions but are required to reliably stick to pipe walls and face new challenges, for example climbing internal geometries such as manhole walls.

The second challenge is the robot miniaturisation. Some pipe systems and elements, such as clean water pipes, are significantly smaller than conventional distribution pipes (e.g. gas). Therefore we require radically smaller robotic solutions. So we aim for robots at 1 cm^3 size.

The third challenge is environmental resistance of robots working in a corrosive pipe environment over a long period of time under high pressure, flow velocities and range of temperatures, while eliminating the risk of causing an explosion in potentially combustible atmospheres (such as in some sewers). Aligned with this is the challenge of creating robots that do not pollute the pipes in which they operate. The team assembled is uniquely placed to address these challenges, with clear vision for the future of infrastructure robotics, relevant expertise in robotics, advanced manufacturing and robot locomotion mechanisms.

The field of in-pipe robotics covers a vast and varied range of approaches. The in pipe features a robot can overcome will depend on the locomotion mechanism and the way traction is obtained within the pipe.

Figure 2: Locomotion techniques within pipes

A wide variety of locomotion mechanisms (Figure 2) can be used in-pipe. We completed a comprehensive review of in-pipe robotic systems. Wall press robots, such as MOGRER, and YonSei Robot tend to be larger and heavier to be able to reach both sides of the pipe. They are designed to allow for operation in a range of pipes, but this is severely limited. Robots with the ability to stick on or swim in pipes have the ability to operate in a wide range of pipe diameters. However swimming robots rely on pipes filled with mostly stationary fluid. In all pipe applications gaining traction (grip) to push the robot forward is critically important. Traction methods include; *Gravity:* reliance on gravity alone restricts vehicles to only horizontal and slightly inclined pipes. Such robots would be similar to traditional exploration robots, being wheel or track based; *Wall-Pressing:* using the reaction force from the enclosed walls, usually in combination with diametric adaption mechanisms; *Wall adhesion:* utilising some form of adhesion to produce a reaction force. In ferrous pipes magnetism is a viable option, whereas in non-ferrous pipes small robots could in principle use bio-inspired adhesion methods based on those employed by insects or geckos.

The majority of innovative robot fabrication research currently focusses on nano and micro structures with limited application outside Micro-Electro-Mechanical Systems (MEMS) integrated systems. Research has demonstrated that the creation of small scale robotics using conventional manufacturing approaches is possible. New approaches include pop-up robots that 'self-assemble' when laser cut from sheets. Fabrication approaches must consider the fact that combustible gases can build up in pipes, and it is critical that robots do not cause explosions. Larger robots have been designed to operate in explosive environments, but extending this feature to small robots poses a substantial challenge.

Theme 4: Autonomous Control

One of the major challenges of the project is the design and implementation of control algorithms that enable full autonomy in all functions related to locomotion, navigation and inspection of the pipe infrastructure networks. Bringing robots out of the lab and into our buried infrastructure presents great opportunities as well enormous challenges for control, and all the more so for buried pipes. In particular, fully autonomous operation will require our robots to prioritise tasks and make choices in the presence of uncertainties and limited data in order to function effectively within buried pipes. Responding to variable environments and hardware system requirements will likely require the robots to constantly adapt their actions based on context and need.

Control solutions for such complex behaviours are unheard of in engineered systems but ubiquitous in nature. All animals navigate their dynamic environments to seek food and favourable conditions and to avoid predation and other dangers. In contrast, successful biologically inspired solutions to engineering problems have largely been limited to system components (vision systems, bioinspired materials such as artificial skin and artificial muscle) or computer software such as artificial neural networks or biologically inspired optimization algorithms. The Theme 4 group at Leeds proposes to tackle the challenge of pervasive robotics by combining traditional approaches from control engineering with novel solutions informed by naturally occurring computational systems. We have extensive experience in translating design principles from animal behaviour to hardware, including active and embodied sensing systems and sensory-motor control systems for robust and adaptive behavioural strategies. Our recent work in the Self Repairing Cities project[3] demonstrates an effective biologically inspired control system for fully autonomous crack inspection robots. While many principles of that research and development work are likely to transfer over to pipe robotic navigation and inspection, other aspects of our Pipebots solutions are likely to be entirely novel.

We will follow both bottom-up and top-down approaches: on the one hand, beginning with low level sensory-motor control in individual robots, and incrementally adding functionalities, and on the other hand, beginning with large scale requirements and swarm architectures to inform low-level design of our control strategies. We will initially implement conventional, reactive and hybrid locomotion control algorithms for appropriately selected robotic platform classes. We envision prototyping in a physics based simulation environment, before testing in hardware. The solutions will depend on the motor requirements, be they crawling on pipe surface, swimming, climbing or hovering in proximity to a pipe defect for inspection purposes, and rapid escape modes. One key challenge will be dealing with changing flow conditions in pipes. A second challenge will be recovery from failure. We will then incorporate control algorithms for additional motor tasks, e.g. turning, docking, instrument placement and rapid escape.

Beyond motor control for locomotion, we will develop, implement and test control algorithms for autonomous exploration and inspection of the pipe networks. To deploy robots effectively in pipe networks, the algorithms will use sensory and internal state information to choose a motor strategy (roam, inspect, avoid, escape, communicate, dock, etc.). Affordance (value based) neural architectures are ideally suited for such processes. For example, the frequency of defects detected can modulate a high level strategy to continue inspecting a specific pipe or move on. While reactive control is well suited to such adaptive control tasks, conventional sequential planning algorithms will

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[3] http://selfrepairingcities.com/

override motor programmes in certain scenarios (e.g. rapid hazard detection may require a robot to back up to a mapped docking location). As part of the long term vision of a smart pipe network, robots will label locations within the pipe network, thereby contribution to the mapping effort, providing time stamped local navigational information to the SLAM algorithms (Theme 5) and aiding other robots in their navigational tasks. These novel control algorithms will be tested on real robots in real pipe networks using the UKCRIC[4] facilities at Sheffield and Birmingham.

Finally, we will develop, implement and test swarm control algorithms for deployment in real pipe networks: In close collaboration with Theme 5, we will focus on collaborative tasks. Different pipe networks can support different densities of robots. Within pipe and robot constraints, we will consider different distributions of robot agents that permit different levels of cooperation (e.g. individuals, pairs and variable size groups). Such groups may reduce the space coverage rate of the network, but facilitate higher fidelity collaborative inspection and maintenance tasks. In the first instance, we envision swarm control algorithms that rely either on indirect cooperation through complementary actions by different agents, or direct cooperation, by binding/unbinding of modular robots. One possible application of the latter will be cooperative climbing swarms for manholes, hydrants or robot rescue after a failure event. Each co-operative control algorithm will be evaluated through experiments in silico and on real robot platforms in real pipe networks.

The work in this theme will be guided by user needs and integration requirements across the different themes of the project. We will utilise robots developed in Theme 3 as a starting point, including the processing and battery power of the electronic systems and firmware. Sensors from Theme 2 will be instrumental for different aspects of control of locomotion, inspection, instrument placement and physical collaboration between pairs or small groups of robots. Our navigation and motor control algorithms will also be constrained by the infrastructure needs of underground communications specified in Theme 6. Effective navigation and inspection algorithms will allow the robots to provide key localisation and mapping information necessary for mapping of the buried infrastructure and its condition. We will therefore also work closely with Theme 5 (focusing on SLAM, mapping and navigation) to develop and test techniques to manage uncertainty. The evaluation of our proposed solutions will link directly to technology validation, evaluation and demonstration to end users.

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[4] https://www.ukcric.com/

Theme 5: Navigation

The role of theme 5 in Pipebots is to provide technology to allow robots to map the pipe network and also to identify their current location. This will enable the robots to successfully navigate the network and to record the location of any defects within the network, as well as allowing existing GIS mapping, and potentially asset data, to be updated and enhanced. The key challenges of localisation and mapping in pipe networks are the relative lack of features and the ability to move in only two directions (forwards and backwards) along any single pipe. Vision based sensors will be investigated first as these are platform agnostic, allowing this element of research to commence while other details of the autonomous robots are developed. The data from the cameras will be used in conjunction with odometry data from the platform. In the second phase of the development IMUs (Inertial Measurement Units) will be used, these incorporate accelerometers, gyroscopes and sometimes magnetometers. Data from IMUs can be used to determine accurately the movement of the robot. Significant research is however required to better understand how to minimise errors which build up as the robot travels further through a network. Simultaneous Localisation and Mapping (SLAM) algorithms will need to be created based on the available data, as with other themes the data and hence algorithms are likely to be different between distribution and drainage networks. It will also be necessary to combine the data from multiple robots in the swarm, where these travel the same pipes the data can be merged to potentially significantly reduce overall error. As most pipe networks have some degree of existing mapping, this prior knowledge can be incorporated into the SLAM algorithms to enhance the initial mapping. Key features in any network, such as hydrants in distribution and manholes in drainage are likely to be important node points which can act as fixed points to further reduce errors in the mapping.

Theme 6: Communications and Power

To fully realise the vision of autonomous robotic system for in-pipe inspection it is necessary to be able to draw on the important capabilities of tether-less communications, localisation, wireless power charging and energy harvesting. For communications between robots and from the robot(s) to an external communication network, the environment is exceptionally harsh and the wide range of potential environmental conditions: diverse pipe materials, pipe diameters, contents and water levels, make reliable communications difficult to achieve. In empty metal pipes, radio waves can propagate with sufficiently low loss providing the "waveguide" nature of the pipe is considered.

However, depending on factors such as frequency and pipe diameter, the electromagnetic permeability of steel/cast iron pipes can lead to very high propagation loss, furthermore only the very lowest RF frequencies can propagate in water, limiting data rate dramatically. Instead, it has been shown that infrared and visible light can be used in water and high data rates achieved, potentially over distances of up to 10s of metres. In other cases, the contents of the pipe will be so turbid that only acoustic waves can propagate. Acoustic transmission is possible over long distances but the data rates are only sufficient for remote control and the relaying of basic information.

Because of this, there is no single communications approach that can be employed and an approach is needed where the robot can switch between electromagnetic, sonic or optical/infrared subsystems as necessary. We will pursue an approach using relaying and modular transceiver architectures, leading ultimately to a cognitive system that can perform channel sounding from acoustic, through RF to infrared and visible light as needed in order to optimise the communication performance. Transmission from above ground down to the robot in a pipe is only possible at very low frequency but co-operation between robots in-pipe and above ground will be highly advantageous for mapping and reporting purposes.

Due to the hard-to-access nature of pipes it is difficult to install communication infrastructure. Consequently, we believe that the in-pipe communication system should rely upon two distinct types of robot nodes, i.e. (i) sensor nodes (SNs) and (ii) aggregator anchor nodes (ANs). The ANs are like miniature base-stations, providing the backbone connectivity, with some serving as gateways to an over ground network at certain key places, especially manholes or hydrants (see Figure 3) and some being above ground, following the robots inside pipes. Notice that ANs are robotic nodes whose sole target is to facilitate communication by shortening the range for individual communication links.

Many well-known techniques from established RF communications, such as MIMO, cooperative relaying and diversity will need to be adopted and adapted for this environment. Leeds has the extensive experience in hardware and signal processing that is needed to address this major challenge, and will work in close cooperation with Sheffield and Bristol teams..

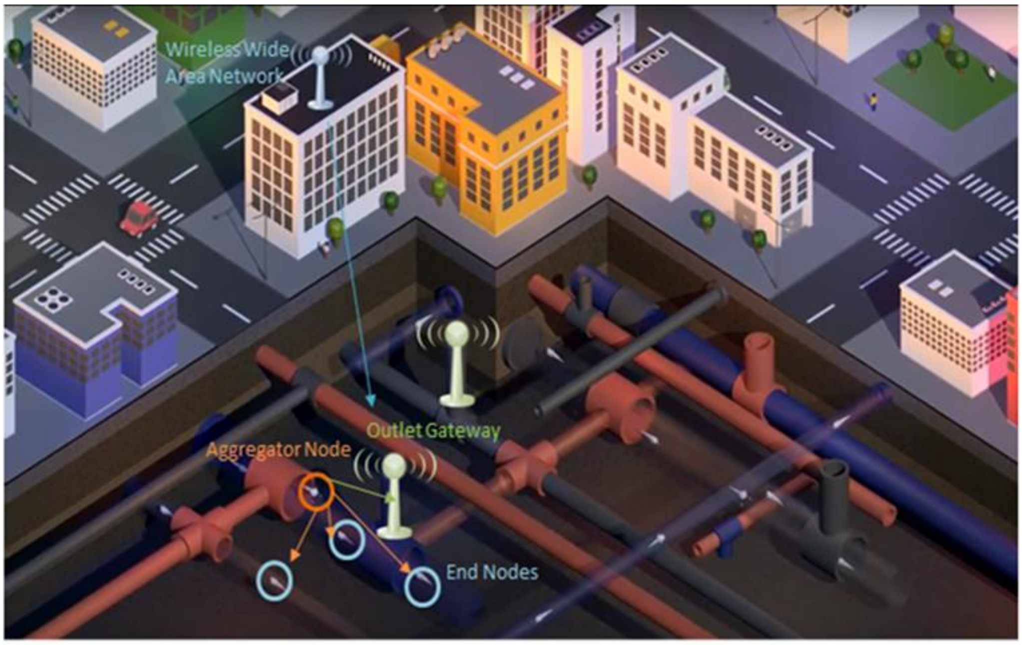

Figure 3: Conceptual In-Pipe Communications Network

The communication subsystems will be integrated with other modules such as the autonomy, sensing and navigation. There is an optimum balance to be found at the system level: at one end of the “spectrum”, the solution could be a sophisticated robot with extensive on-board AI, which downloads all its data in bursts when it can access the network. At the other extreme, extensive use of communications can allow a swarm of less intelligent robots to work collaboratively on inspection. This means there is overlap between the work on communications and the work on bio-inspired solutions and AI in Theme 4.

The optimum energy harvesting technique will depend very strongly on the local environment and a wide range of techniques such as inductively-coupled and RF power transfer, turbines and piezo-electric energy harvesting will be investigated. Two relevant opportunities for achieving reliable in-pipe power are harvesting energy from water flow or using charging stations at manholes and hydrants. Other sources such as heat and vibration are only suitable for low power sensor nodes. To quantify and optimise the power that can be generated, the various integrated energy harvesting techniques will be explored using lab-based in-pipe testing. MEMS and micromachined-based components, such as piezoelectric materials and MEMS resonators, can be integrated on the in-pipe robot due to their miniaturisation and high energy harvesting efficiency. Conformal MEMS components will be also investigated as an alternative novel energy harvesting technique.

Theme 7 – Transformation of the Buried Infrastructure Landscape

We are proposing a potentially radical transformation of the management of the water supply, wastewater and drainage systems. In order to understand how to bring about the transformation and the impacts that it will have comprehensive system maps demonstrating how the piped systems interact with all other urban systems are needed. 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– can appreciate the value and nature of the intended transformation. The availability of RAS derived data offers the potential for a radical shift from reactive repair and maintenance to proactive maintenance, refurbishment and upgrading. This will enable a move from emergency construction operations based on trench excavation to trenchless operations, which minimises or avoids 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). 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.

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. These frameworks will 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 are needed to deliver resilience.

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 and the multi-dimensional value frameworks. Alongside the compelling case for doing things differently must lie the enabler of change 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.

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. This will allow us to identify barriers to deployment and to engineer mitigation strategies.

The final point to make here is that the advances in science and engineering that are needed to underpin our vision are likely to be of value to those addressing other challenges of analysing the condition of inaccessible ageing or deteriorating infrastructure, or materials more generally. We will also therefore explore how our novel technological developments might be translated to other applications.

Theme 8: System Knowledge Generation and End User Engagement

Theme 8 has three distinct elements, firstly defining the requirements for robotic pipeline inspection in the water sector and translating these into detailed challenge specifications. These challenge specifications will be developed into a delivery plan through discussion with each of the other technical themes and external users in order to guide and prioritise the development work. This element of Theme 8 requires a strong and ongoing connection with the water industry, not only including the water utilities, but also the consultants and contractors who work alongside them.

Once the technologies have been developed, Theme 8 will work alongside the other themes to test and improve each technology and the technologies when combined onto a robotic platform under full scale laboratory conditions. Once the performance of the robotic sensors has been confirmed in the laboratory, testing will move onto representative controlled field conditions. This will allow the developed robotic based technologies to be evaluated under realistic conditions so that the sensing, navigation and communication capabilities can all be clearly demonstrated.

A third element of Theme 8 is to work alongside the other themes and the water industry to ensure that the data obtained from the pervasive robotic sensing can be transformed into actionable knowledge. Technologies like data analytics, AI, cloud computing, augmented intelligence and blockchain provide new capabilities to analyse, automate, correct in real time, predict and minimise risks from large and detailed datasets.

The extra (in both time and space) and much better quality data collected by RAS provides new opportunities for developing new ways of linking single defects to the condition of single assets and opportunities to develop reliable deterioration models for single defect types so as to predict the future service life of individual assets. The potential amount and current nature of the RAS collected data also offers opportunities to link with other data sources to better predict asset performance and identify potential failure before it occurs. Figure 4 provides a vision of an integrated future for the water sector using these data sources.

At the rate at which our ability to analyse data are growing in society in general, it is reasonable to expect that most UK water companies will be using data analytics in the next five years. It is foreseen that robotic inspection / data collection will add increasing amounts of data and so significantly increase the impact of data analytics efforts.

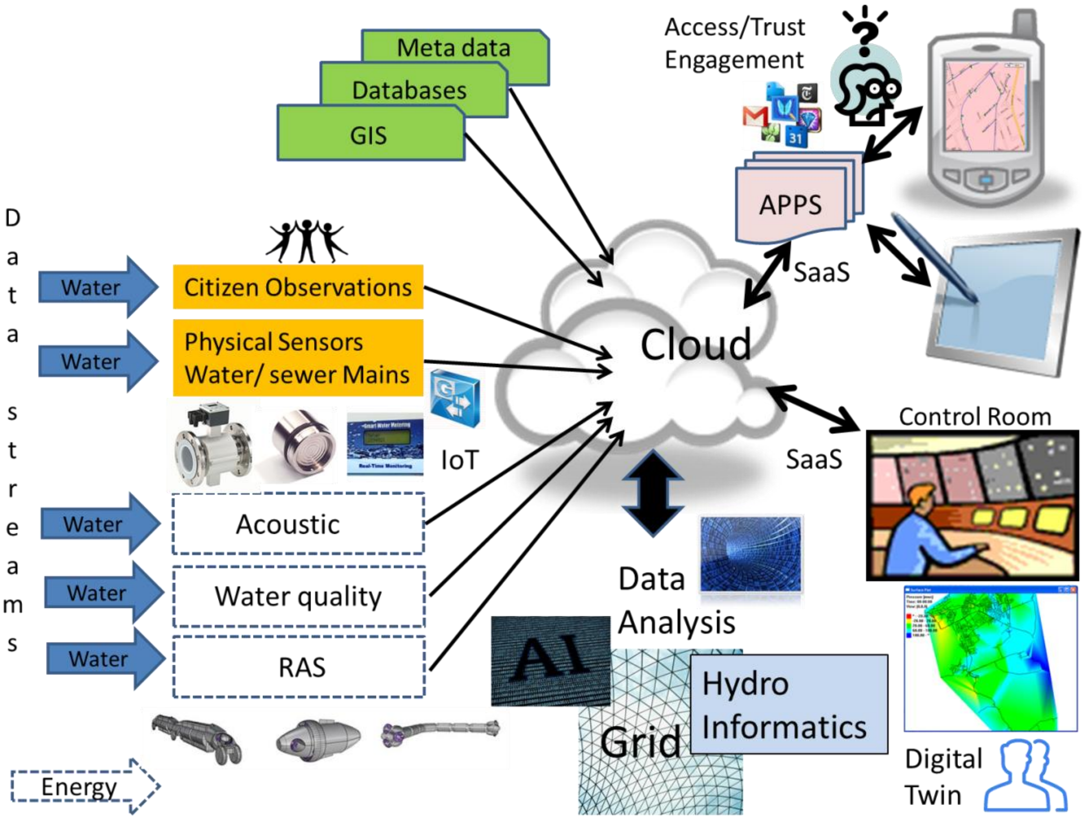

Figure 4: Vision of an integrated future

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