



## Engineering Innovation

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# Pipebots for Rising Mains – Phase 1

## Research & Feasibility Study – OFWAT Catalyst Project

### Overview Report FINAL

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## Executive Summary

The Pipebots for Rising Mains Research & Feasibility Study has been the first Ofwat Innovation fund project undertaken and completed by the partners, namely Thames Water Utilities Ltd, Wessex Water Services Ltd, Dwr Cymru Cyfyngedig (Welsh Water), The University of Sheffield and Synthotech Ltd. The project has been successful and has delivered the required outputs to the agreed programme.

The application for funding was based on the aim of developing a rising main inspection tool by harnessing the expertise of academia and industry beyond the water sector. The scope of the project was ambitious within an original 10 month plan, to design, build and test a robotic platform to house novel sensor inspection systems. During the project, field visits and desktop studies have been undertaken to support the mechanical and electrical design work packages.

A target of 300mm diameter metallic pipe was chosen for the initial project focus. Metallic pipe in all forms constitutes the largest proportion of the asset base and operational failures due to material deterioration. Existing access points into mains are extremely limited. Any live inspection systems are likely to require engineering works to drill and fit a tee onto the main, with an isolation valve for working under pressure.

The use of fluid-borne triaxial accelerometers and low frequency acoustics as a pipeline condition assessment tool has been investigated and the results from the tests are encouraging. The trials have shown that variance in pipe wall thickness can be determined, and defects successfully identified with sensors mounted on a robot system. The original project objective to fulfil proof of concept for the technology has been achieved and the Technology Readiness Level (TRL) has increased from 1 to 3\*. Further work is needed on the interpretation and calibration of data, the mounting of the accelerometers and the influence of the robot body on the results. These factors combine with the next challenge of operating in a live rising main, with high pressure, fast moving rag laden flow.

The physics behind the use of accelerometers to assess pipe condition is complex and a high level of technical expertise has been demonstrated by the suppliers. Excellent working relationships have been maintained with all the partners throughout the project which has been successfully delivered.

There is a continuing industry need for tools to undertake internal inspections of live rising mains. Further research and development of the Pipebots for Rising Mains work should continue to target TRL 6\* with an Ofwat Innovation Fund application for Phase 2. If successful, the development can continue to build on the work to date and ultimately provide the industry with a viable rising main inspection tool. Such a tool would enable operators to assess the condition of mains, identify defects and plan rehabilitation works. This capability would reduce the risk of failure leading to pollution, reduce the risk of flooding to customers and reduce the inconvenience and expense of emergency repair works.

\*TRL 1 = Basic principles, TRL 3 = Proof of Concept, TRL 6 = demonstration in live environment

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## 1. Introduction

### 1.1 Ofwat Innovation Fund

The Ofwat Innovation Fund was launched in 2020 to support innovative initiatives to deliver benefits for customers, society and the environment. The Water Breakthrough Challenge, Round 2 was launched as part of the Fund in October 2021, which invited applications for projects under the Catalyst and Transform Stream. Entries to the Catalyst Stream closed in December 2021, with the winners being announced in March 2022.

Thames Water Utilities Ltd submitted the Pipebots for Rising Mains Research & Feasibility Study entry during Round 2 of the Challenge. The proposed project was in partnership with Wessex Water Services Ltd, Dwr Cymru Cyfyngedig (Welsh Water), The University of Sheffield and Synthotech Ltd. The entry was adapted from an earlier unsuccessful application to the Fund during Round 1 by Wessex Water Services Ltd. A funding request of £230.9k was submitted with £112.3k being contributed in kind by the partners resulting in a total project value of £343.3k. The project was to be led by Thames Water and delivered over a 10 month period. Notification of the successful bid was received by Thames Water in March 2022 and the project commenced from April 2022. The original Water Breakthrough Challenge submission document is included in **Appendix 1**.

### 1.2 Pipebots

Pipebots is an umbrella term, being both the name of an academic research partnership developing robots for the inspection of buried pipe infrastructure and a generic name for a wide range of robots used for pipe inspection purposes ([www.pipebots.ac.uk](http://www.pipebots.ac.uk)). The Pipebots partnership comprises: The University of Sheffield, University of Birmingham, University of Bristol and University of Leeds. Each University has specialist areas of expertise and they have been working closely with industry to develop inspection tools as part of an Engineering and Physical Sciences Research Council (EPSRC) project. The Pipebots for Rising Mains project aimed to build on expertise developed by The University of Sheffield during their Pipebots work, to instigate the use of acoustics as an inspection tool for live rising mains.

### 1.3 Partners

One of the benefits of the Ofwat Innovation fund is to encourage the transfer of technology from other industries into the water sector, particularly from the petrochemical industry which uses a wide range of pipe inspection techniques. Synthotech Ltd have extensive experience in pipeline inspection for the gas industry and are widely recognised for their innovation skills, products and systems development. Synthotech Ltd were therefore an ideal partner for the Pipebots for Rising Mains project, bringing engineering, site and systems capabilities to enable lab-based technologies developed by The University of Sheffield, to be adapted into practical tools for use in the water industry.

## 1.4 Project Management

Winning an Ofwat Innovation Fund bid was new to all the project partners, so the processes and agreements necessary to undertake the work needed to be established. Initially, Thames Water were required to sign a Winners Agreement with Ofwat (via Nesta). This outlined the process for the funds to be paid (by Ofwat) to Thames Water and the obligations for Thames Water to manage the project, payments and reporting. This agreement was signed in May 2022.

Following the Winners Agreement, a Collaboration Agreement was needed between all the partners. This detailed the contributions and deliverables from the suppliers in terms of outputs and the contribution of the water companies in terms of resources. This was a complex legal document and required detailed discussions with legal teams from all parties. After significant work by all the partners, the Collaboration Agreement was signed in late December 2022.

Lastly, individual Delivery Agreements were required between the suppliers, namely The University of Sheffield, Synthotech Ltd and Thames Water. This agreement defined contractual delivery commitments and legal responsibilities. Again, following lengthy legal discussions, the Delivery Agreements were signed in late January 2023.

Without experience of previous projects, the extent of the legal process was not anticipated by the partners during the application process. As such, the initial 10 month delivery programme became impossible to achieve, as Purchase Orders for the work could not be raised until all the agreements had been signed (preventing the purchase of hardware etc. by the suppliers). Thames Water therefore requested a 5 month project extension from Ofwat, from May 2023 to October 2023 which was granted in December 2022.

The project timeline was ambitious, even with the 5 month extension. The scope to undertake field tests, the design and build of a robotic transport system, sensor development, rig tests and data interpretation were challenging. The project was defined as a Research & Feasibility Study with the aim of demonstrating proof of concept from a low technology readiness level (TRL).

To manage the project, a Steering Group was established and chaired by Thames Water. Representatives from all the partners attended the meetings which were held on a monthly basis. The Steering Group reviewed outputs and approved payments in line with the agreed schedules. In parallel with this, a Technical Working Group was also formed, chaired by Thames Water to lead on the technical aspects of the project. These meetings were held fortnightly.

## 1.5 Rising Mains – The Challenge

Rising mains are pressurised pipelines that convey flow from pumping stations, where sewage is pumped from a low level to a higher level for gravity discharge or treatment. A rising main burst can lead to severe environmental impact, as pressurised sewage flow from a large-scale burst or leak is likely to result in pollution via uncontrolled sewage discharge. The pipeline materials vary, but they are predominantly cast or ductile iron and typically range from around 100mm to 1000mm diameter. Managing sewer flows in the event of a burst can have a widespread impact on customers. If a pumping station and rising main need to be isolated to undertake a repair, upstream flows need to be managed. This is normally achieved using road tanker lorries which is an expensive and disruptive short-term solution. There is generally no redundancy, such as twin mains for diversion of flows. The temporary reduced capacity at the pumping station during a repair can lead to increased risk of flooding for customers upstream. The challenges of dealing with flows for emergency pipe repairs equally apply to temporary shutdowns for pipe condition inspections. As such, routine internal condition surveys are rarely undertaken.

The development and availability of 'in-pipe', live inspection tools are desperately needed for rising mains, an asset which is unique to the water sector. Such tools would enable operators to assess the condition of mains, identify defects and plan rehabilitation works. This capability would reduce the risk of failure leading to pollution, reduce the risk of flooding to customers and reduce the inconvenience and expense of emergency repair works.

## 2. Project Scope & Deliverables

The project scope and deliverables included in the original submission were refined during the compilation of the schedules for the Collaboration and Delivery agreements. The project was split into two work packages, namely:

Phase 1 – External inspection and Sensor Optimisation

- 1a Field work
- 1b Lab work
- 1c Desktop study

Phase 2 – Proof of concept

- 2a Sensor insertion (access system)
- 2b Robot platform
- 2c Sensor package
- 2d Field tests
- Reporting

Deliverables in terms of report outputs for the phases were defined for Synthotech and The University of Sheffield. These were detailed in Schedule 1 of the Collaboration Agreement and Schedule 3 of the Delivery Agreements. A staged payment schedule was linked to the deliverables from the supplier. The deliverable components are detailed in tables 1 & 2 below

Table 1. Synthotech outputs

D1	Site Findings Report (access locations)	Measurements taken during site visits (by The University of Sheffield) Access location review & observations to inform specification and concepts.
D2	Sensing requirements capture	Review of pipeline materials, environment and sensing requirements to benchmark.
D3	Specification	Specification and key design parameters for Proof of Concept, commercial solutions and operational needs.
D4	Lab tests report	Test reports on Proof of Concept
D5	Test rig trial reports	Test reports on Proof of Concept
D6	FMEA	Documented process for value capture from pipeline inspection
D7	End to end process	Documented process for value capture from pipeline inspection
D8	Project close out report	Close out report

Table 2. The University of Sheffield outputs

U1	Computational Model	Documenting field, lab and simulations – including potential of sensors, sensitivity, frequency & range can operate and deployment needs.
U2	Lab Report	Documenting field, lab and simulations – including potential of sensors, sensitivity, frequency & range can operate and deployment needs.
U3	Delivery of final report	Sections / appendices as agreed with Steering Group – updated simulations of how will work on robot and experience from lab/field conditions.

## 2.1 Reporting

The outputs from Synthotech Ltd and The University of Sheffield were submitted to the Steering Group as standalone documents. This Overview Report serves as a summary of the various aspects of the project and references the outputs as appendices. This Overview Report can be published with or without the appendices as required.

## 3. Project Outputs & Results

### 3.1 Site Investigations & Scoping

Phase 1 of the project initially focused on field work and data gathering. The aim of this work was to enable The University of Sheffield to mount accelerometers on live rising mains, to record the movements and vibrations during pumping cycles. This was the first step towards assessing the feasibility of using accelerometers as a condition assessment tool. Three sites were made available for inspection, a Welsh Water site at Bretton and two Wessex Water sites at Christchurch and Weymouth. The Bretton site provided three excavated external access points onto a live 300mm diameter cast iron pipe which was soon to be replaced. The Christchurch site provided external access to a live 400mm diameter ductile iron pipe via a flow meter chamber. The Weymouth site provided external access to a live 800mm and 1100mm diameter cast iron pipe via a valve chamber which required confined space entry. A summary of the findings completed by The University of Sheffield is included in: **U2 – Field & Lab Testing Report, Appendix 2.**

Following the initial site visits, The University of Sheffield pursued lab and computer modelling work to further explore the concept of using accelerometers for condition assessment. A 1.5m length of 300mm diameter ductile pipe with invert corrosion holes was provided to The University of Sheffield by Thames Water for lab testing purposes. A summary of the findings completed by The University of Sheffield is included in: **U1 – Computational Modelling, Appendix 3.**

The physics behind the use of fluid-borne accelerometers to determine pipe condition is based on the measurement of microscopic movements of the fluid in the vicinity of the pipe wall. The pipe material minutely flexes during internal pressure changes due to pumping transients or induced sound pressure waves. This creates a complex scattering pattern of acoustic velocity near an area of wall damage. The 'vibro-acoustics' technique seeks to measure the differing movements in the pipe wall, depending on the thickness and structural integrity due to corrosion or other defects.

While The University of Sheffield were undertaking their measurements at the Christchurch site, a team from Synthotech Ltd also visited the site and surrounding area to assess the general layout of pumping stations and potential rising main access options. A summary of the findings completed by Synthotech Ltd from this element of the project is included in: **D1 Site Findings Report, Appendix 4.**

Statistical data on rising main assets including diameter, lengths, age, materials and burst history was provided by the partner water companies to Synthotech Ltd. Using this data, the initial scope for an inspection tool for the project was developed. A target of 300mm diameter metallic pipe was subsequently chosen as the initial project focus. Metallic pipe in all forms constitutes the largest proportion of the asset base and operational failures due to material deterioration. The vibro-acoustic technique may not be limited to the survey of metallic pipe. It offers potential to

survey a variety of other materials, although this has not been investigated during the scope of this project.

### 3.2 Sensor Options & Specification

While defining the scope for the inspection tool, alternative sensor systems were considered for potential use. The vibro-acoustics technique was being pursued for development, but conventional condition assessment technologies could be operated in parallel to provide supporting data. Synthotech Ltd therefore undertook a review of existing technologies, namely ultrasonic and electromagnetic systems and outlined the advantages and disadvantages of each. Synthotech Ltd produced an output from this stage of the project, which is included in: **D2 Sensing Requirements Capture, Appendix 5.**

As the target pipe size and material detail evolved, the specification for the robot platform and testing environment developed. In conjunction with The University of Sheffield, Synthotech Ltd had undertaken outline conceptual designs for the proof of concept robot platform and accelerometer mountings. A specification was refined to test and assess the various elements of the system, such as the sensor performance and robot platform operability. An additional requirement of the vibro-acoustics sensing technique is a sound pressure generator. An 'in pipe' speaker system had been proposed, laboratory tested by The University of Sheffield and included in the specification for field development and trials. The specification is included in: **D3 Specification, Appendix 6.**

It was agreed that future live installation techniques would be considered in terms of a desktop review, but not fully fabricated and tested. Access into rising mains is generally extremely limited and there are few suitable access points. Any live inspection systems are likely to require engineering works to drill and fit a tee onto the main, with an isolation valve for working under pressure. The internal diameter of a drilled tee onto a host pipe for access purposes could vary depending on the material and condition of the main. Although noted for future development, elements relating to insertion were not fully explored for proof of concept testing.

### 3.3 Lab Tests & Mechanical Development

Phase 2 of the project commenced in January 2023 with the detailed design of the robot platform, data interface, sensor package and sound generator. Close working arrangements were maintained between The University of Sheffield and Synthotech Ltd to optimise the layout and mounting of the accelerometers. A halo ring at the back of the robot crawler evolved as the preferred layout, with six accelerometers mounted around the circumference. Pictures of the robot crawler are shown in figures 1. & 2. Below.

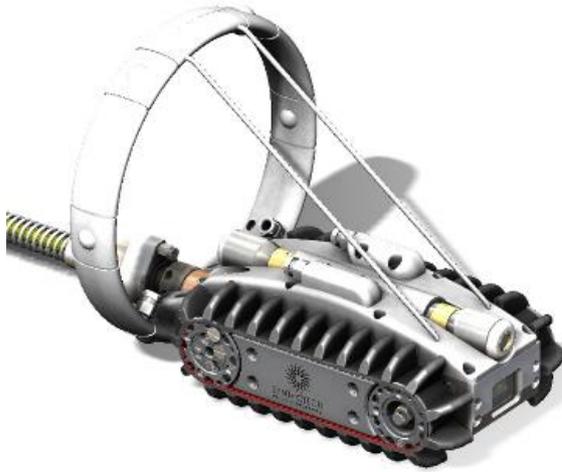


Figure 1. Design image of robot crawler, forward and rear facing cameras mounted on the body



Figure 2. Completed build with accelerometers mounted on the halo to the rear

Steady progress on the build of the robot system was maintained by Synthotech Ltd during the early months of 2023. The accelerometers procured for the robot by Synthotech Ltd were tested within the rig at The University of Sheffield. Discussions continued regarding the mountings, the mechanical isolation and housings for the accelerometers. Details of the lab testing by Synthotech Ltd for the robot, data acquisition systems and accelerometer sensors is included in: **D4 Lab Tests Report, Appendix 7.**

In parallel with the build of the robot, options for the rig testing were considered. Original plans for testing in an abandoned main at Wessex Water were changed, as the site was no longer available and quantifying the test results would not be possible. Rising mains are a challenging, hostile environment, particularly for potential live surveys. Corrosive sewage containing rag, silt and solids is intermittently pumped at velocities up to 2.4m/s, with surge pressures potentially over 10bar. It was accepted that it would not be feasible to replicate this scenario in a rig and not needed for initial proof of concept testing.

A bespoke rig at the Synthotech Ltd test site at Ripon was therefore proposed that could be operated under pressure with flow velocity, but use clean water as opposed to sewage. The rig would be buried in a trench with sand and gravel backfill to replicate site conditions. A variety of machined defects were discussed and agreed by the partners to simulate defects in the field. During subsequent testing, the exact position and extent of a simulated defect would be known, which could be precisely referenced with data from the sensors.

A rig comprising 4 x 2m sections of new 300mm diameter ductile iron pipe, 2 x equal tees and 2 x 1m upstand pipe was agreed. The pipework was procured by Thames Water and delivered to the Ripon test site in April 2023. Blank flanges, valves and a clean water circulation system were supplied and installed by Synthotech Ltd. Sketches of the test rig are shown in figures 3. & 4. Below.

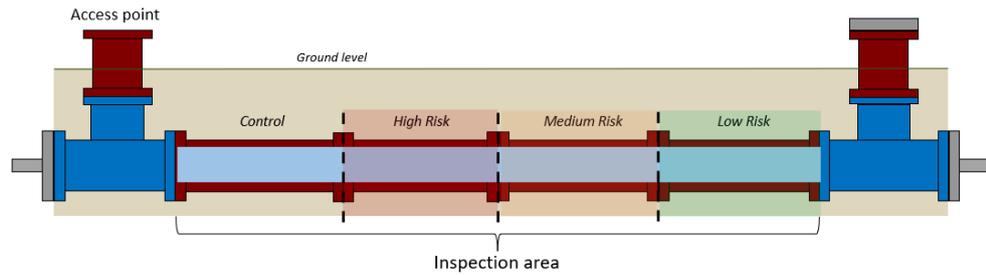


Figure 3. Test rig pipework

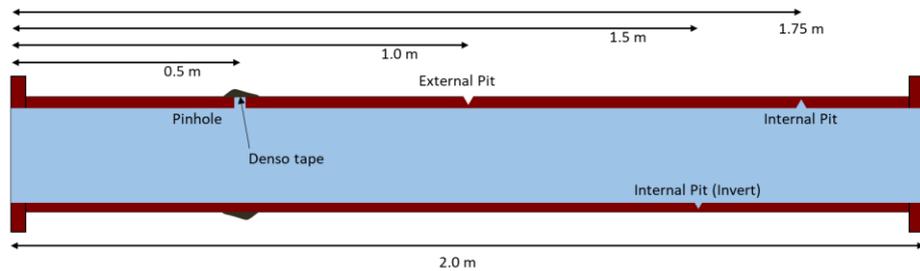


Figure 4. Pipe section with machined defects

### 3.4 Rig Testing

The following rig test details and summary (shown in *italics*) have been imported directly from the Synthotech Ltd outputs: *D8 Closure Report, Appendix 8* and *D5 Test Rig Trial Report, Appendix 9*.

#### *Simulated Testing at Ripon*

*The initial objective of the simulated testing was to validate the suitability of the crawler and halo's design for vertical insertion into the test pipe. This assessment included a dry run to evaluate the insertion process from a vertical, open riser, followed by a wet deployment into the test rig using the same approach. On each occasion, the deployment and retrieval of the robot were executed successfully, and the overall functionality remained intact throughout the entire process. A schematic of the test rig, robot insertion and speaker is shown in figure 5. Deployment of the robot into the launch pipe and the control system is shown in figure 6.*

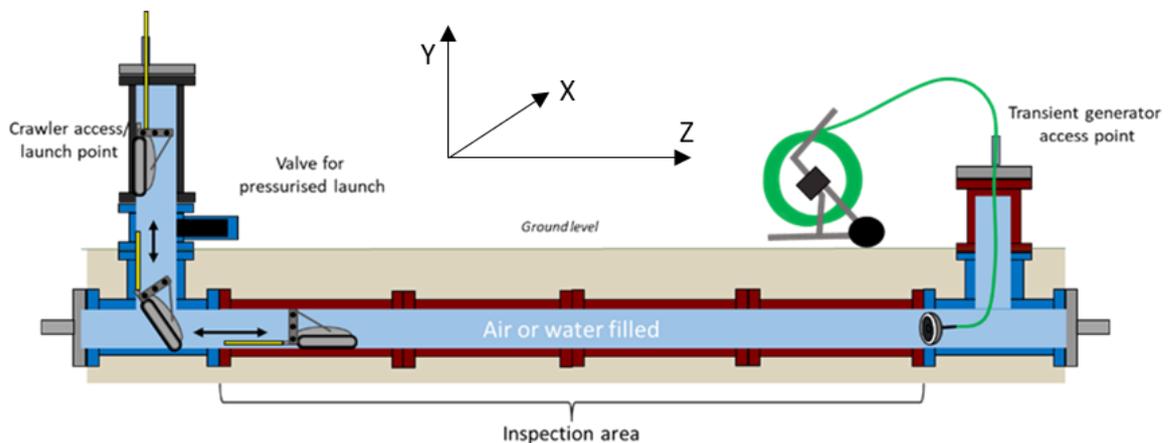
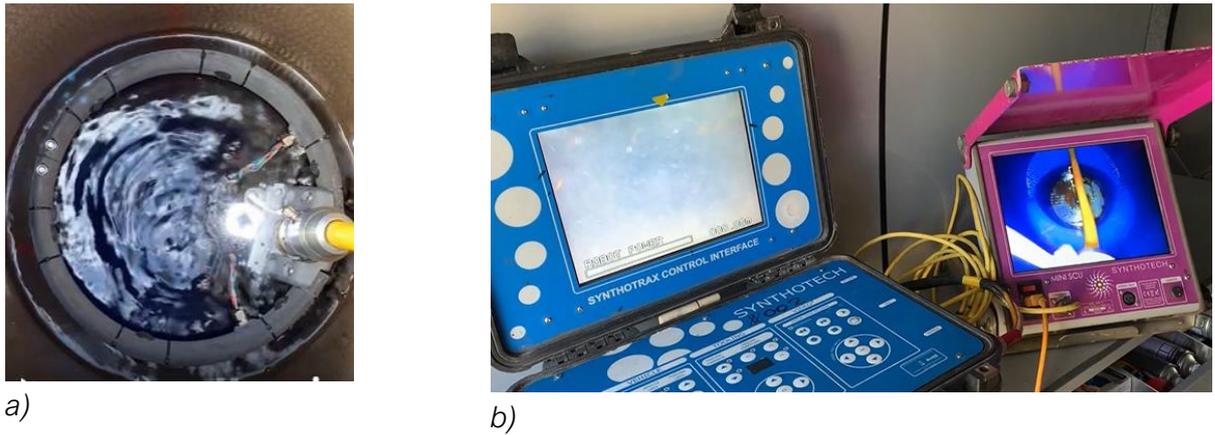


Figure 5. Schematic of the test rig, test configurations and sensor orientation



a) crawler in wet riser, b) control and display unit showing crawler visuals from within pipe.

Scans were captured within the test rig under static conditions, with the robot at rest, to evaluate both data quality and the consistency of repeated measurements. The variance among these repeated measurements was minimal, signifying that a single scan would be adequate for data collection during subsequent testing and operational procedures. Consequently, a complete circumferential scan would take approximately 36 seconds using the current data acquisition method within the proof of concept. It's worth noting that this duration could be reduced to 6 seconds if data were simultaneously collected from all accelerometers which can be completed within the next stage. Examples of repeat scans from the rig tests are shown in figure 7. and accelerometer mounting positions shown in figure 8.

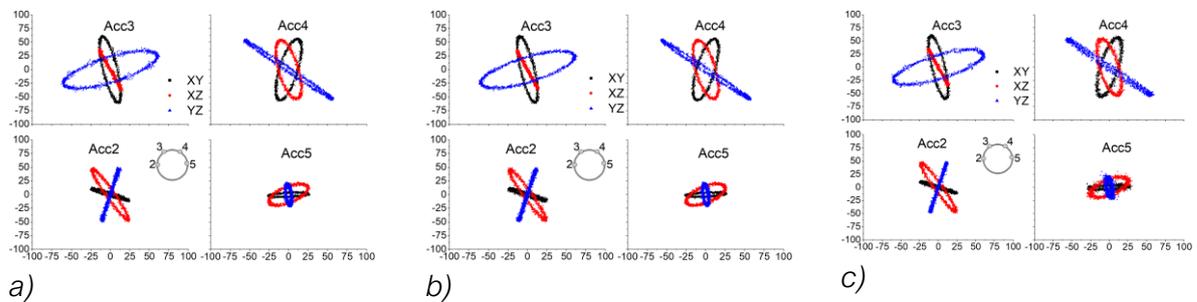


Figure 7. Example of repeat scans with triaxial accelerometers within the test rig.

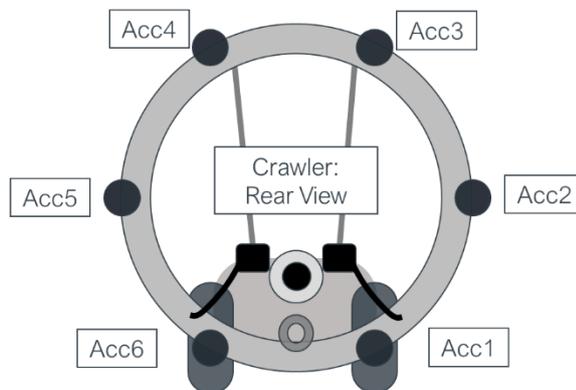


Figure 8. Accelerometer mounting positions

Joints were scanned to understand changes in the amplitude and position data compared to that of the pipe barrel. The crawler was aligned before a joint and moved forward, taking scans at different positions to track accelerometer data changes across the joint. These results are shown in Figure 9.

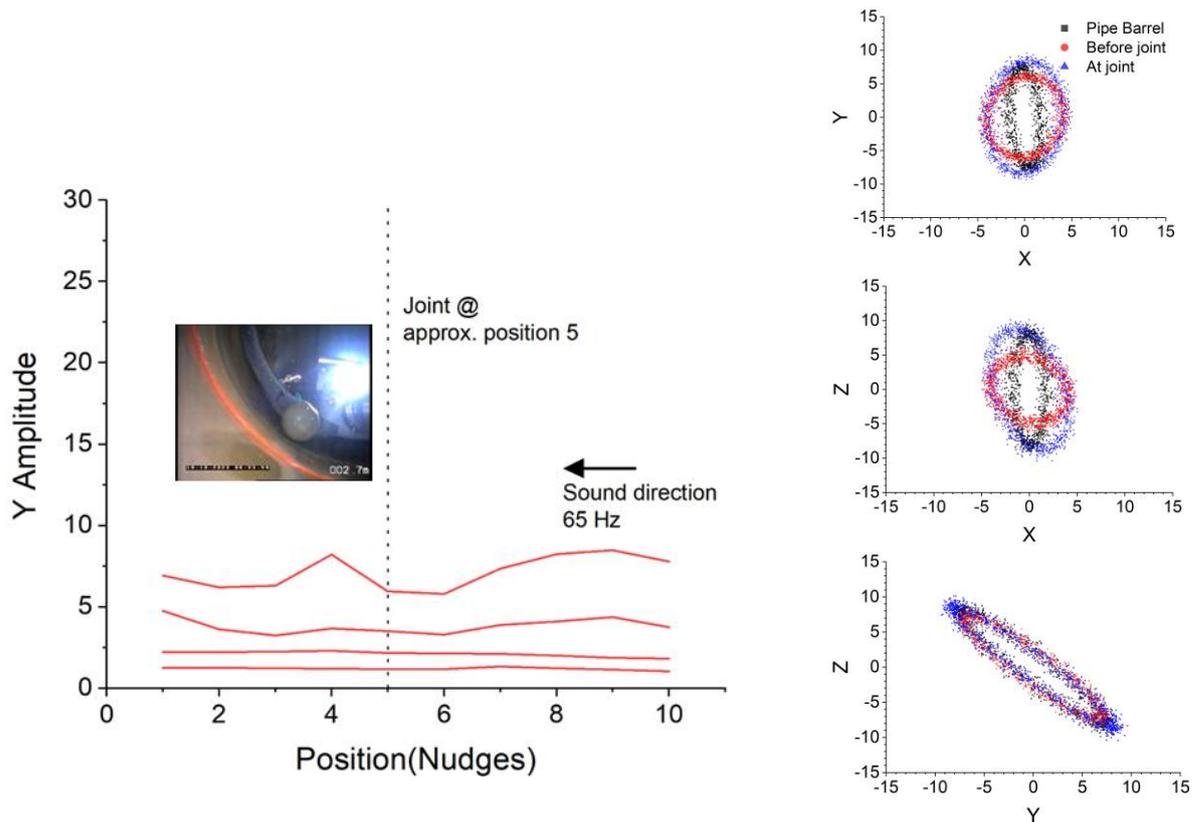


Figure 9. Joint detection with accelerometer data, showing changes in the amplitude of the three acceleration components (XYZ) in the pipe barrel (black), pipe section before the joint (red), and the joint itself (blue).

To test the system’s ability to detect significant pipe structure changes, defects were created in the test rig. A 1” hole was machined, threaded, and partially sealed to simulate internal material loss. The data was captured in the same way as a joint. Figure 10. Demonstrates that this approach is capable of sensing the defect, as shown by the increased amplitude in Y around the defect, and also the angle change in the position data when compared to the pipe barrel. Further work to pinpoint the future orientation of sensors will ensure these changes in the position data are more obvious.

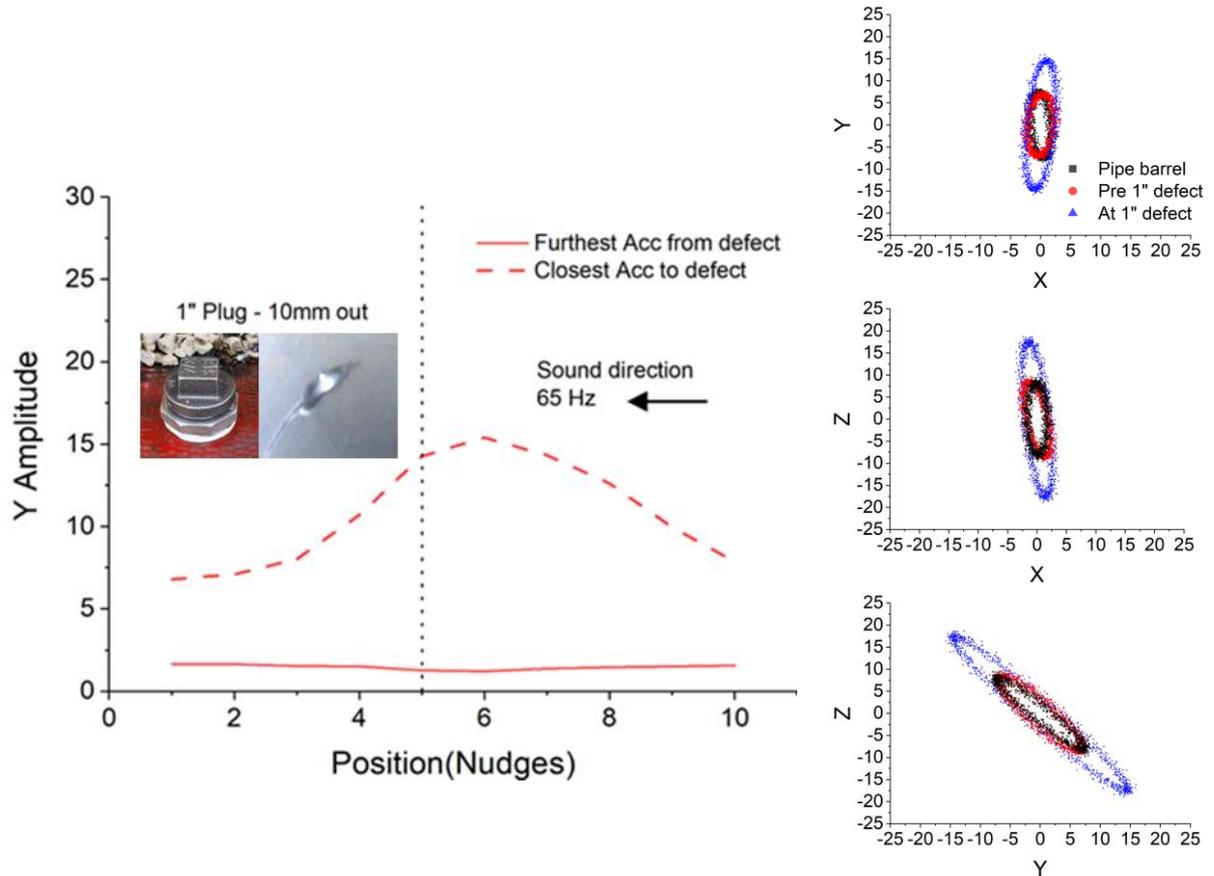


Figure 10. Defect detection with triaxial accelerometer data, showing amplitude changes over the robot's position and comparing XYZ position data of the pipe barrel (black), pipe section before the defect (red), and the defect itself (blue).

The comparison between a joint sweep and a defect sweep has revealed significant distinctions in feature characteristics, particularly in the XY and XZ dimensions. Notably, joints exhibit a tendency to become more circular with minor amplitude changes, whereas the 1" defect displays subtle angle adjustments and increased Y-axis amplitude. While further testing and in-depth data analysis are required to validate these observations across a broader range of internal pipe features, this provides a foundation to develop a portfolio of feature characteristics that can be used by operators on site.

A further technical summary of the accelerometer sensor testing, results and theory behind the concept is included in the final report from The University of Sheffield, namely: **U3 Final Report, Appendix 10.**

### 3.5 End to End Process

The final element of the testing programme was to assess the launch and recovery procedure for the inspection system. As outlined in section 3.2, the diameter of drilled tees onto host mains for access purposes was not fully explored. For the proof of concept tests, the access tees into the rig were equivalent to the main pipe diameter, namely 300mm. A launch tube was fabricated and pressure tested for insertion simulations. The outline for a potential future survey process is

included in: **D7** End to End Process, **Appendix 11**. A failure mode and effect analysis (FMEA) was also undertaken by Synthotech to capture potential failure scenarios and risks, primarily for the testing process. This output is included in: **D6** FMEA, **Appendix 12**.

Details of the End to End Process are included below, imported directly from the D7 report: (shown in italics)

*To facilitate the deployment of the system into a live rising main, an end-to-end process was devised on how the current system could be deployed on a network rising main. Based on existing live access deployment of CCTV robotic inspection systems, the process involves isolating the crawler within a launch vessel that directly connects to a valve, see figure 11.*



Figure 11. Insertion trialling at the StaRs site, Ripon

*The operator would control the crawler from a position near the access point, whilst managing the crawler's tether which would pass through a glanding system – a methodology that allows a tether to pass in and out of a pressurised pipe without leakage of the fluid from within the pipe. The tether is directly connected to the crawler, situated in the launch vessel. To purge the launch vessel before launch, chlorinated water is pumped in to remove the air. Any submerged system checks can then take place, in addition to leak tests of the vessel and connections prior to opening the gate valve for access to the live rising main.*

*To open the valve, the launch vessel must reach operational pressures. Higher pressures might require a bypass or bleed valve. Once the valve is open, the system enters the pipe and begins taking measurements. In the proof-of-concept phase, the development of the data acquisition has been the focus rather than the speed of inspection, with measurements taken incrementally. In the future with improved data capture and post-processing, data will be collected faster while the robot continually drives forward.*

*To retrieve the robot from the pipe, the robot is driven back to the launch point and pulled up into the launch vessel. Upon re-entry into the launch vessel, the valve is closed to isolate the rising main. Pressure in the launch vessel is relieved, and foul water is purged with chlorinated water. The system is left to sit for disinfection, and then air is pumped in to remove the water. Any launch*

*tube pressure is again released. The launch tube can then be unbolted from the valve, equipment removed from the network and broken down for further cleaning and disinfection on-site. To manage foul water, it's advisable to employ a hazardous waste tank for collecting wastewater from purging and cleaning. A suitable portable bowser would enhance site manoeuvrability. Disposal should align with water company practices and regulations, possibly reintroducing the wastewater into the rising main system through disposal in a wet well or other accessible foul water drains.*

This concludes the development and testing work undertaken by Synthotech Ltd and The University of Sheffield for the Pipebots for Rising Mains – Research & Feasibility Study.

## 4. Conclusions

The scope of this project was ambitious from the outset. The original 10 month programme required the partners to undertake field tests, design and build a robotic transport system, develop, test and interpret new sensor systems and complete rig tests. Even with the 5 month extension (due to delays with the legal agreements) the timeline was extremely challenging. All the partners, particularly the suppliers, Synthotech Ltd and The University of Sheffield have completed the work with significant outputs in terms of hardware built and testing for the proof of concept feasibility. Excellent working relationships have been maintained with all the partners throughout the project.

The use of fluid-borne triaxial accelerometers as a pipeline condition assessment tool has been investigated and the results from the tests are encouraging. The trials have shown that variance in pipe wall thickness can be determined and defects successfully identified with sensors mounted on a robot system. In this respect, the proof of concept has been achieved and the TRL has increased from 1 to 3. Further work is needed on the interpretation and calibration of data, the mounting of the accelerometers (in terms of orientation), the viability of the halo and the influence of the robot body on the results. These factors combine with the next challenge of operating in a live rising main with high pressure, fast moving, rag laden flow. Initial work focused on 300mm diameter, metallic pipe, but varying size pipe and materials will need to be considered for future development. The tracked crawler system was chosen to overcome potential silt deposits within the pipe. Existing access points into mains are extremely limited and bespoke fittings and chambers are likely to be required as part of a future end to end survey process.

There is a continuing industry need for tools to undertake internal inspections of live rising mains. Further research and development of the Pipebots for Rising Mains work should continue with an Ofwat Innovation Fund application for Phase 2. If successful, the development can continue, to build on the work to date and ultimately provide the industry with a viable rising main inspection tool. Such a tool would enable operators to assess the condition of mains, identify defects and plan rehabilitation works. This capability would reduce the risk of failure leading to pollution, reduce the risk of flooding to customers and reduce the inconvenience and expense of emergency repair works.

## 5. Recommendations

- The development of Pipebots for Rising Mains should continue with an application to the Ofwat Innovation Fund for a Phase 2 project. This will enable the system to be tested in live rising mains and to optimise the robot design to cope with rag and silt laden flow. This will progress the Technology Readiness Level from 3 to 6.
- The results from the project should be published and communicated to the water sector and wider industry through UKWIR, other national research communities and specialist interest groups. Wider awareness of the need for inspection tools, the challenges to overcome and the work completed to date can hopefully kickstart further development in this field.

## **Appendix 1. Water Breakthrough Challenge Submission**

## **Appendix 2. U2 – Field & Lab Testing Report**

## **Appendix 3. U1 – Computational Modelling**

## **Appendix 4. D1- Site Findings Report (Draft)**

## **Appendix 5. D2 - Sensing Requirements Capture**

## **Appendix 6. D3 - Specification**

## **Appendix 7. D4 - Lab Tests Report**

## **Appendix 8. D8 - Closure Report**

## **Appendix 9. D5 - Test Rig Trial Report**

## **Appendix 10. U3 - Final Report**

## **Appendix 11. D7 - End to End Process**

## Appendix 12. D6 - FMEA