Rapid Response Non-Destructive Inspection Robot for Condition Assessment of Critical Water Mains

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Abstract

This paper presents a robotic system that is able to rapidly assess the wall thickness of a cement lined cast iron (CI) water main pipe during the short time interval between a pipe failure and its repair. Wall thickness measurement through a cement lining of unknown depth is achieved using a sensor based on the pulsed eddy current (PEC) technique. Sensor geometry is selected such that remaining wall thickness' up to 20mm can be reliably measured. A six arm mechanism incorporating inbuilt compliance allows contact between the sensors and cement lining to be maintained even when the cement lining thickness is non-uniform; which is typically the case with in-situ lined pipes. A cart capable of navigating debris and steps transports the sensing mechanism through the pipe and also ensures it is positioned concentrically within a range of pipe sizes. Descriptions of the sensing strategy, sensor mechanism, driving cart and the robot control system are presented together with results from actual in-field pipe deployments to demonstrate effectiveness of the developed system.

1 INTRODUCTION

About 70% of the worldwide asset base of urban water utilities consists of buried pipes. [Nicholas and Moore, 2009] In Sydney, pressure mains, typically 375-750mm in diameter, constitute a large portion of these assets and have been in service for over a century. As pipes deteriorate with age, pipe failures will continue to occur resulting in disruption to water supply as well as damage to properties in the vicinity of the failures, leading to implications for the sustainability and effectiveness of water and services. In Australia, it is estimated that the costs of urgently needed asset replacement over the next five years are around AU$5 billion. Maintenance costs over the same period are estimated at some AU$2.5 billion. In the USA, the USEPA estimates that the US public water sector will require US$476.2 billion of capital investment over the next 20 years to sustain essential service levels, of which US$312.6 billion in replacing and refurbishing aging or deteriorating pipelines. US studies also indicate that the average cost per failure for large diameter pipes exceeds US$500,000. [Gaewski and Blaha, 2007]

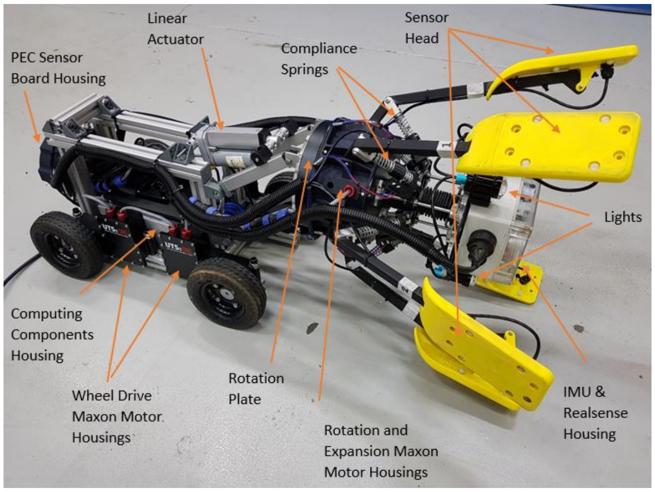


Figure 1: R2T2 with on-board components labelled.

In response to these cost drivers, and to meet demands for reliable water supply for its customers, Sydney Water has engaged University of Technology Sydney (UTS) to develop a Rapid Response Thickness Tool (R2T2) to be deployed at a point of pipe failure. One of the key aspects of this tool is the ability to utilise the short period of time between a break occurring and the repair taking place. Within the available shut-down period, this robotic tool is to be able to travel inside the pipe, either side of the break, and provide information as to whether large corrosion patches that have the potential to initiate a break in the near future are present. Therefore, the information gathered makes it possible to take necessary action to prevent repeated failures in the same geographic location and save costs by identifying and replacing only the vulnerable sections of the pipe line.

The tool is targeted at the backbone of the water distribution network in Sydney which consists of 350mm-750mm diameter cast iron pipes. These pipes have an approximately 10mm thick cement lining to prevent internal corrosion. In some pipes, the cement lining has been applied in-situ, which has resulted in lining thickness varying between 2-25mm at a given location. Sensors based on remote field eddy current (RFEC) and the PEC techniques can sense a cast iron pipe wall through the cement lining and generate an estimate of wall thickness ([Huang and Wu, 2015]). Russell NDE Systems Inc. (www.russelltech.com) uses RFEC technology in their See Snake internal tool. However, this tool is designed for assessing the condition of long lengths of pipes and requires a significant lead time for deployment due to requirements associated with insertion. Two commercial tools based on PEC technology capable of measurement through cement linings, Lyft from Eddyfi and BEM from the Rock Solid Group are relatively slow taking a few seconds to take one wall thickness estimate, making these impractical in the present application, given the need for maximising the length of the pipe inspected. During this project, a low noise signal acquisition system was designed, making it possible to get an estimate of the average wall thickness under an elliptical sensor with a cross section area of 50 mm^2 in 150msec. A sensor head, that can carry six such sensors and has adequate compliance to maintain contact between these sensors and the inner wall of the pipe in the presence of lips, tapers and non-uniform cement lining was designed, built and tested.

An extensive search was conducted to explore commercial solutions available for positioning the sensors inside a pipe. All commercial systems available are targeted at visual inspection where positioning a sensor unit in contact with the wall is not required. Furthermore, these are all closed systems where it is not easily possible to integrate additional sensing units, electronics and computing. Therefore, a four wheel drive cart that can traverse the pipe carrying the sensor head was also designed, built and tested.

The paper is organised as follows. Section 2 discusses the core requirements and how the core system components operate. Section 3 details how the main sensing module functions, in both mechanical and electrical aspects. Section 4 discusses the cart design, detailing how the locomotion of the system works. Section 5 demonstrates how the control and thickness map components are achieved. Section 6 shows an evaluation of the system being deployed to field. And finally Section 7 discusses the on-going work on the project.

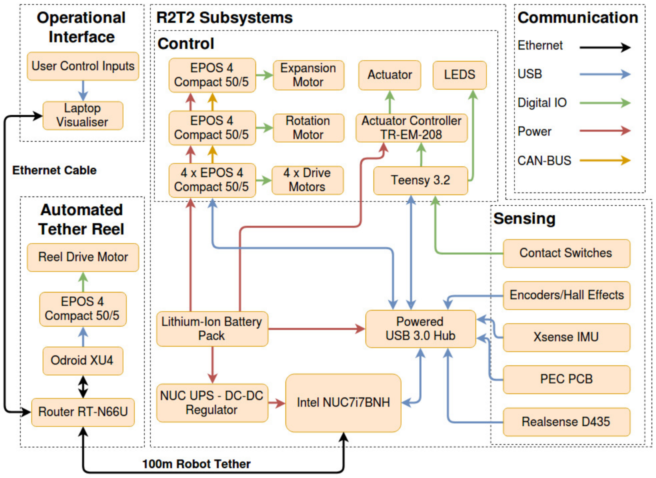


Figure 2: R2T2 System Diagram

2 Robot Architecture

2.1 System Requirements

The core requirements for the robot were derived based on discussions with the Sydney Water assets management team. It was decided that the tool should have a range of 100m and should be able to operate in pipes ranging from 350mm up to 750mm in diameter. Although the pipe is dewatered after the break, it is possible to have water pooling and debris, through which the robot should be able to navigate. While the pipe is predominantly circular, there may be significant deviations due to uneven cement lining. The tool is not expected to traverse past major junctions, however, it should be able to deal with up to 75mm step changes in pipe diameter that may exist due to previous repair work on the pipe line. Due to the limited time window available during mains breaks, the system should also be able to scan at a minimum rate of 10m/h with full surface coverage.

2.2 System Overview

The system is composed of three primary modules, the robot which is inserted into the pipeline, the automated tether reel and hand-held user interface. Each system runs individual computers running Robot Operating System (ROS), all linked through Local Area Network (LAN) communication. The main tether provides a 100 MBit/s LAN connection so the user can receive data and send commands to R2T2 in real-time. Figure 2 shows the core components of each subsystem and how they link together, and Figure 1 shows the robot with labelled components.

Power comes from a lightweight lithium-ion battery pack (sealed in a water-proof housing) which is rated to 11.6Ah and allows the robot to operate for 3-4 hours in the typical use-case, with a quick-swap attachment so operators can easily change the battery as required. Provisions are also in place to run power down the tether if required. The robot travels through the pipe using four direct drive motors sealed in water-tight enclosures. Each of the motors are equipped with high resolution encoders, which in combination with the encoders on the tether reel provide an effective solution for robot localisation. All of the motor controllers in the system are daisy chained and connected via a can-bus providing a simple interface method from the computer with real-time performance.

The robot also includes an Intel Realsense D435 and four Lumen LED lights housed at the front. These components allow the user to get an idea of conditions inside the pipe, thus facilitating safe operation. The Realsense provides an infrared (IR) image, an RGB image and a depth image all available for viewing/recording purposes. Currently the depth image is utilised to estimate the sensor modules centre offset in the pipe and allow the system to make changes to ensure concentricity - see Section 5.1 for details. In the future the depth image may be further used to generate a 3D model of the internal pipe surface to help assess cement lining conditions.

The intended operating procedure for this robot is to drive the system the required distance into the pipe, expand the PEC sensors until they contact the wall, activate the PEC continuous scanning mode and then drive the robot back towards the entrance at a fixed speed, taking thickness readings every 150msec from all 6 sensors. These readings are recorded and a thickness map is produced as the robot moves. Once the desired region is scanned, the sensors are retracted, the sensor module is rotated, and the process is repeated until the entire circumference of the pipe is scanned. As each traverse produces six thickness maps each 50mm wide, the number of traverses required to achieve complete coverage depends on the pipe diameter. Longitudinal resolution is dependant on robot movement speed which is adjusted to suit the time available and the level of detail required.

3 Sensor Module

3.1 PEC Sensing

As discussed in the introduction, it was decided to utilise PEC technology as the core R2T2 sensing modality. The PEC sensors themselves consist of two copper wound coils, concentrically aligned, one acting as exciter while the other acts as a detector. A voltage pulse passed through the exciter coil induces eddy currents in the material under inspection. The detector coil captures the decay of the magnetic field generated by these eddy currents. The signal induced in the detector coil is in the order of 200μV, and is amplified using an instrumentation amplifier with a 2000V/V gain to get to a measurable range. Figure 3 shows the decay curves obtained when plates with different thicknesses are placed under the sensor unit. The detected signal can be processed to generate an estimate of the average thickness of the material under the sensor unit. Based on previous work on PEC sensors [Ulapane et al., 2017], oval shaped coils were designed, 3D printed, wound and tested with a custom acquisition PCB designed specifically for six channel operation allowing measurement of six positions on the pipe simultaneously at a frequency of 6.67Hz.

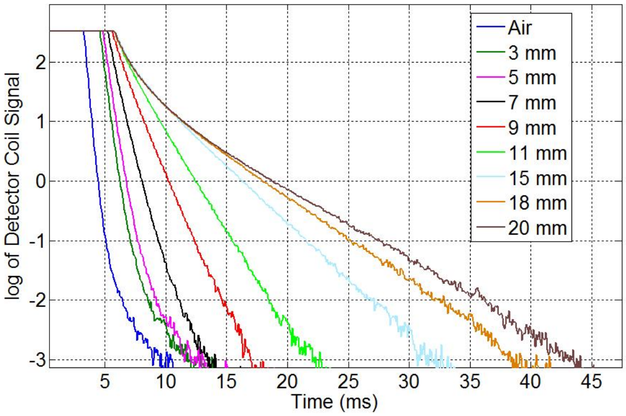
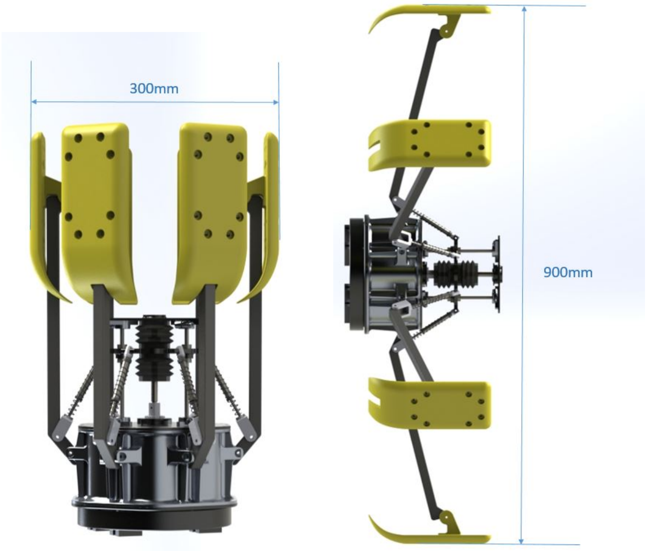


Figure 3: PEC Signals on Different Thickness Plates

Although PEC sensors are able to generate thickness measurements even when there is an air gap between the sensor module and the metal pipe, the sensor accuracy deteriorates with increasing lift-off [Ulapane et al., 2017]. The PEC sensors in R2T2 provide reliable readings up to 20mm lift off, where accuracy begins to diminish. It is therefore important to position the sensor so that it is always in close contact with the cement lining, even when lining thickness is uneven. It is also desirable for the sensors to be able to operate in all pipe diameters to avoid the need for multiple sensor modules. To meet these requirements, an expansion mechanism was designed capable of operating in pipe diameters from 350-750mm whilst also providing independent compliance for each of the sensor units.

3.2 Mechanical Design

Figure 4 shows the final design and expandable range of the mechanism. An 8mm diameter ball screw with a 2mm lead driven by a high torque brushless electric commutation (EC) motor moves the central plate along the linear rails, which in turn forces the arms to pivot about their hinge point on the housing. As shown the fully compressed to fully expanded ratio effectively covers the required range with a single drive motor. The spring loaded pistons that connect the central plate to the housing provide approximately 50mm of compliance, necessary for pits in cement lining, debris, and to correct



(a) Closed (b) Expanded

Figure 4: Sensor Module Expansion Ratio

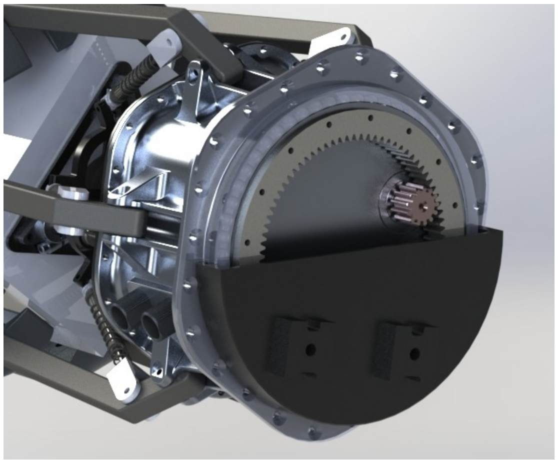
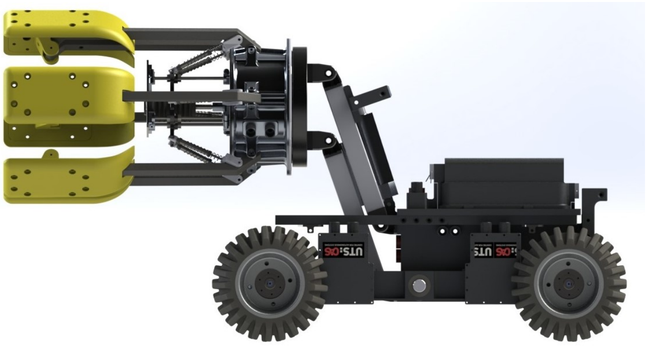


Figure 5: Section View Rotation Component



(a) Raised Position - for larger pipes

(b) Lowered Position - for smaller pipes

Figure 6: Sensor Module Lifting Mechanism

for the sensor module being off-centre.

The module also has a second brushless EC motor driving a custom slewing bearing/internal gear arrangement to allow the entire sensor module to rotate about the pipe axis, shown in Figure 5. With six sensors spaced at 60 degree increments, 60 degrees of rotation allows complete 360 degree coverage of the pipe. The last required control mechanism is a linear actuator connecting the sensor module to the cart body through a parallelogram link. The parallel links between the sensor module and the cart ensures the sensor module is always parallel to the axis of the pipe. Figure 6 shows the raised and lowered position of the sensor module, and the actuator itself can stop in any position between to suit different diameter pipes.

4 Locomotion

The uneven nature of the interior surfaces found within mains water pipes makes it necessary for each drive wheel to be individually driven to maintain adequate torque in scenarios where multiple wheels have lost contact with the surface. Early investigations showed frequent occurrences where two wheels would lift off the driving surface, leaving only two diagonal wheels making contact. This not only occurred when driving over large bumps and holes but was also the case for seemingly minute variations in the cross sectional profile of pipes. As mentioned previously in many circumstances the inner cement lining of a pipe is non-uniform and can vary in thickness; not only along the axial direction of the pipe but also around the circumference of a given cross section.

The drive system has been designed to navigate over obstacles up to a height of 75mm, which corresponds to a 150mm diameter variation between adjacent pipes which is not unheard of. To achieve this, solid rubber wheels with a ribbed tread grip provide a protruding feature that can grab onto the edge of a step and allow to robot to climb over. The geometry of these ribs allow the wheel to apply a direct downwards force onto the edge of a step without relying on friction between the two materials. A basic suspension system has also been integrated into the design so the motor housings can pivot and move up and down relative to the main body. The motor housings are fixed to a plate that can pivot about its centre, with spring loaded pistons providing the returning force at each end. These are passive and ensure all four wheels are always in contact with the interior surface of the pipe, giving way to a more adaptable and robust system.

5 Software

The software running this system consists of many nodes that can pass data back and forth, utilising ROS as the core communication module. Since ROS is an open source framework commonly used in the robotics community, this section looks mainly at the major contributions that have been developed specifically for this robot, those relating to robot control, PEC interpretation and generating the thickness maps.

5.1 Controlling Motion

All six motors in the Maxon daisy chain have high resolution incremental encoders and hall effect sensors attached. These sensors are sampled by the motor controllers at a high frequency (2.5 KHz) allowing for tightly regulated control schemes at hardware level. The sensor data is also published into ROS at a fixed 50Hz providing effective position, velocity and torque feedback for high level control. This allows the robot to utilise several different control paradigms for effectively controlling motion.

The main drive motors use velocity controllers, ensuring each of the wheels (and therefore the robot) maintain the set-point velocity, regardless of the required torque. The published position/velocity feedback is also used as odometry, when combined with encoder readings from the tether reel to provide a useful position reference. This provides an outer position control loop for sending the robot to particular locations in the pipes and the tight velocity control means more accurate thickness maps.

Rotation of the sensor module is achieved using a velocity controller at hardware level and a position controller for high level control. This scheme was chosen to overcome the backlash in the rotation joint, which caused major drift in position estimates when using encoders. Instead, an inertial measurement unit (IMU) is utilised to provide the feedback for the angular position control. This has the advantage of maintaining accurate rotation speed even with variable load and gives the capability to set a goal position for the module, also ensuring the angular position stays fixed relative to the pipe in the case that the robot rolls. This is important for ensuring sensors are scanning the correct circumferential position.

Expanding the sensor module and maintaining adequate surface contact requires a two part control scheme. Position control is utilised to expand the sensors out until contact with the pipe wall is made (based on diameter being scanned), then a torque feedback controller is activated. The torque controller effectively ”pre-loads” each of the sensor arms to ensure that surface contact is maintained over bumps and pits.

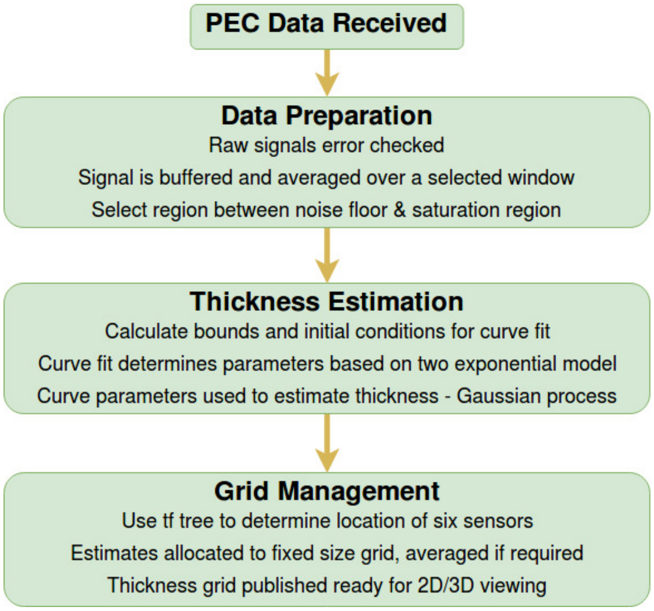


Figure 7: PEC Signal Interpretation Algorithm

For the sensors to function effectively, the axis of the sensor module must be closely aligned with that of the pipe. A Realsense D435 mounted to the front of the robot produces a depth image which a cylinder is fit to using RANSAC [Fischler and Bolles, 1981]. This provides an estimate of the diameter of the pipe as well as the offset between the sensor module and the centre of the pipe, which is used to position the sensor module.

5.2 PEC Interpretation

PEC signals can be used to obtain the thickness of the pipe wall under each of the sensors using techniques discussed in [Ulapane et al., 2017] and [Valls Miro et al., 2017]. As discussed in Section 3.1, the decay rate of the signal acquired can be used to estimate the thickness of the material.

Figure 7 shows the strategy used for interpretation. Signals acquired from PEC sensors are first smoothed and averaged to reduce noise. An exponential fit is used to obtain the decay rate of the signal from which the thickness is estimated. A Gaussian Process (GP) is utilised to accurately model this relationship using measurements obtained from calibration plates with known thicknesses. Python SciPy library has been utilised for the real-time implementation of the complete thickness estimation algorithm. An example data set used for calibration is shown in Figure 8.

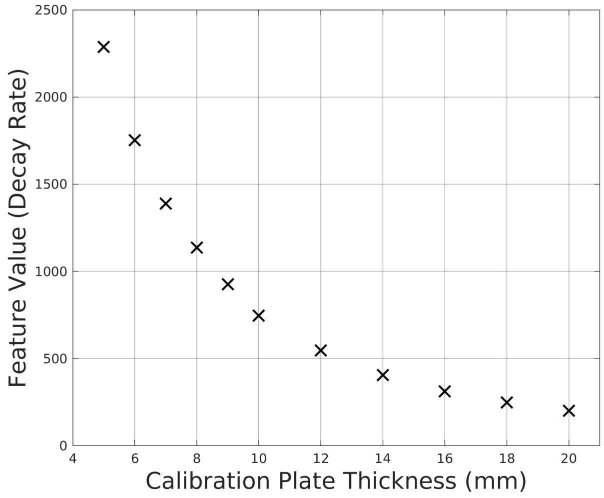


Figure 8: Calibration Plate Thickness Captured by the Decay Rate Feature.

Table 1: Metrics of R2T2 vs GT Scan

T2P2 Metrics	GT Scan	R2T2 Scan
Maximum Thickness	19.97 mm	19.34 mm
Minimum Thickness	4.32 mm	6.7 mm
Mean Thickness	15.25 mm	14.45 mm

Figure 9: Grit Blasted Ground Truth Pipe

6 System Verification and Field Trials

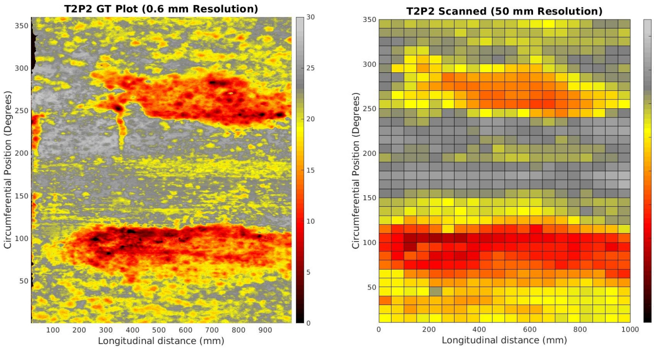
6.1 Validating PEC Sensors

In order to effectively evaluate the performance of the robot it was deployed and tested in a 3.8m pipe segment that had been exhumed, grit blasted, then laser scanned to provide effective ground truth (GT) data (process described in [Skinner et al., 2014]). The pipe shown in Figure 9 is the target pipe, labelled as T2P2, which has significant corrosion levels and had failed in an existing pipeline prior to be exhumed. The reference markers used when generating the GT are also visible. The GT and scanned data results are shown in Table 1 and the produced thickness maps are shown in Figure 10b. Note, in order to calculate mean thickness the GT scan results have been capped in the 4-20 mm region for the max/min/mean calculations, as this is the rated penetration region for the PEC sensors on-board the robot. This sensor limitation is not a concern as any regions greater than 20mm are not of significant interest, and by limiting higher end thickness sensitivity the sensors have higher accuracy in lower thickness regions.

6.2 Field Deployment

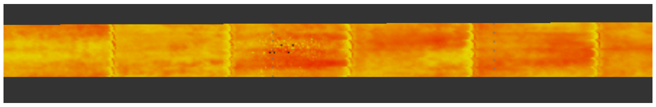
R2T2 has also been operated and tested in a decommissioned pipeline located in Sydney, which has nominal internal diameter of 580mm, nominal thickness of 27mm and cement lined in-situ. Access to a 1km section of this pipe was provided by Sydney Water. This pipe has been used extensively for previous projects, and therefore has available comparison data. To deploy the robot, a pipe section was removed and a safe pit was erected around the entry point. The first two deployments to this site gave practical validation to the mechanical and electrical aspects of the system, where the robot was able to sustain prolonged operation and scanning small isolated regions.

The most recent deployment produced a thickness map of a 20m section live at the test site. This took 1.5 hours scanning, which is within the specification requirements for scan speed. This was useful as it demonstrated the additional timing constraints related to running the system and recording the data which were not accounted for when calculating the length of pipe that can be scanned in the available time frame. In Figure 10c the vertical lines represent the joints between each pipe section, which appear as a low thickness reading followed by a high thickness reading due to their physical arrangement. This demonstrates the thickness readings around the joints are less reliable for corrosion inspection, however presents a useful opportunity for odometry correction. Similar to the validation plots, the red sections indicate higher corrosion levels (less remaining metal) and the yellow represents closer to nominal thickness. From these data graphs Sydney Water has a process of determining maintenance decisions based on probabilistic modelling as described in [Ji et al., 2017].



(a) Ground Truth Scan.

(b) R2T2 Scan.



(c) Testbed 20 m Live Generated Scan.

Figure 10: Validation and field deployment. Comparison of Ground Truth vs R2T2 Scan (top). Testbed 20 m live generated scan (bottom).

7 Conclusion and Future Work

This paper presents a robotics system designed to measure remaining wall thickness of CI pipes that can be deployed during the repair of a mains break. The sensing has been validated with extensive testing on a decommissioned pipe. Mechanical and electrical systems have also been thoroughly evaluated for robustness. Figure 11 shows the final design of the robot, with the last mechanical changes soon to be integrated. Further work on corrosion models to enhance the accuracy and resolution of the thickness measurements are in progress. Deployments using the robot in the Sydney Water network during live break scenarios are also being planned.

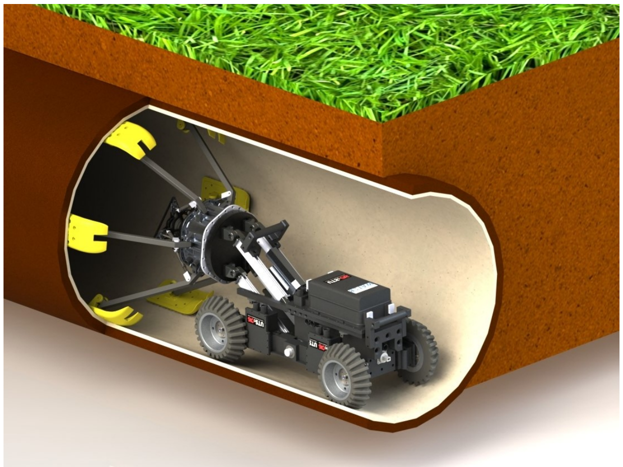


Figure 11: R2T2 Final Design Rendering

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