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Combined application of Pipe Penetrating Radar and LIDAR for large diameter pipe inspection

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ABSTRACT: Pipe Penetrating Radar (PPR) is the underground in-pipe application of ground penetrating radar (GPR), a non-destructive testing method that can detect defects and cavities within and outside mainline diameter (>18 in./450mm) non-metallic (reinforced concrete, vitrified clay, PVC, HDPE, etc.) underground pipes.

Light Detection and Ranging (LIDAR) has become an accepted method for providing detailed information from the inner pipe-wall. Concrete corrosion, deteriorations, and ovality are easily detectable by this tool. However, this visual technology produces information from the inner pipe-wall only. The structural problems outside the pipe-wall remain hidden from this method.

Pipe deteriorations are more reliably detectable by the combined application of PPR and LIDAR. Pipe-wall thickness is directly detectable with the radar method, while corrosion and loss of pipe material can be measured with LIDAR. Fast and accurate results are obtained about the state of pipe-wall deterioration by the combined application of both methods. The cost efficiency of later repair processes can be highly increased by multi-sensor pipe inspection. Recent case studies will illustrate successful deployments.

PPR and LIDAR are physically different methods, so the results complement or validate each other, thereby providing asset managers with more complete information for maintenance and rehabilitation decision making.

1. INTRODUCTION

Underground pipe infrastructure including tunnels and culverts is deteriorating at an alarming rate (ASCE, 2009). The majority of the current underground pipe infrastructure was built over 50 years ago and is close to the end of its design life. In order to establish the extent of rehabilitation or the timing of replacement an internal inspection method is necessary. Although CCTV is an effective tool for identifying visible defects on the internal wall of pipelines it cannot see behind the pipe's inner surface. In order to overcome this limitation and provide utility owners and decision makers with a quantitative and predictive inspection and asset management tool, pipe penetrating radar (PPR) the in-pipe application of ground penetrating radar (GPR) has been developed. This technology allows the implementation of proactive preventative maintenance procedures for non-ferrous wastewater and water underground infrastructure. The combined application of PPR, CCTV and laser (LIDAR) provides the most complete and state of the art inspection technology to enable proactive asset management and allow utility owners to plan and schedule the inspection and rehabilitation of critical utilities prior to the occurrence of emergency scenarios (Koo and Ariaratnam, 2006).

This paper reviews recent advancements in PPR. New developments in hardware and software are illustrated through a recent case study.

2. PIPE PENETRATING RADAR FUNDAMENTALS

Pipe Penetrating Radar (PPR) is the underground in-pipe application of ground penetrating radar. The PPR pulse travels through a pipe material as a function of its dielectric properties which are in turn a function of the materials' chemical and physical composition. Some of this pulse will also be reflected and refracted by any sharp change in material properties, such as at the interface between pipe material and air or water. The greater the difference in the material properties, then the greater is the amount of energy reflected back. These reflected waves are detected by a receiving antenna and recorded as a single trace (A-scan). This process is repeated continuously as the antenna is moved along a survey line to build up an entire profile (B-scan) along the survey line (Figure 1).

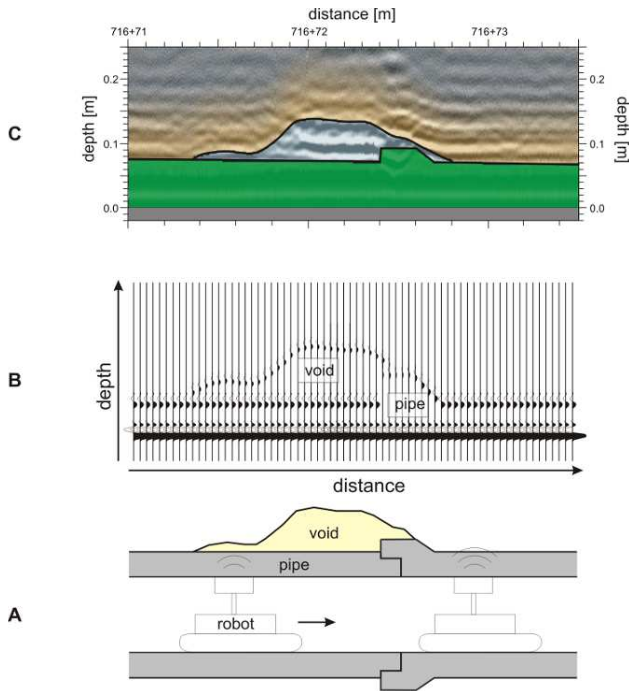


Figure 1. PPR Principle: A: robot mounted antennas continually emitting and recording pulsed PPR signals, B: signals are recorded as a series of A scans making up the corresponding radar "wiggle" trace (B scan), C: interpretation is superimposed on the processed radar plot.

Signal penetration depth is dependent on the dielectric properties of the pipe and the host material, and on the antenna frequency. The penetration depth of high frequency antennas (2.6 GHz – 500 MHz) which are the most suitable for pipe investigations is on the order of 60 cm to 3 m (2 ft to 9 ft) beyond the pipe wall. Resolution is primarily determined by the wavelength, but is also affected by other factors such as polarisation, dielectric contrast, signal attenuation, background noise, target geometry and target surface texture, all of which influence the reflected wave. As a general rule the thinnest layer that can be resolved is ¼ of the wavelength used. For a 2.6 GHz pulse travelling through a concrete pipe, this equates to approximately 9 to 15mm thickness. Once a layer is resolved, its thickness can be measured to a precision dependant on the time base sample rate and on the signal jitter of the GPR system used. For a depth range of 200mm (8 in.) this can be as small as 4 mm (1/8 in.) (Donazzolo and Yelf, 2009).

Since the primary factor determining signal penetration is the conductivity of the soil, it is important to point out that PPR works where traditional "above ground" GPR does not. If for example, a pipe is buried in conductive soils (more than 58% of USA and Canada) at 1.8 m (6 ft) deep or deeper, the signal from "above ground" GPR most likely will not penetrate the soil for more than 0.6 m (2 ft). In-pipe GPR signals, however, will penetrate non-ferrous pipe walls, the pipe bedding and even the conductive soil to some degree mapping air or water filled voids on the way from within the pipe. In most cases, native soil conditions in specific geographic locations have little bearing on detection of voids outside pipelines because bedding and backfill tend to be coarse grained with favorable dielectrical properties.

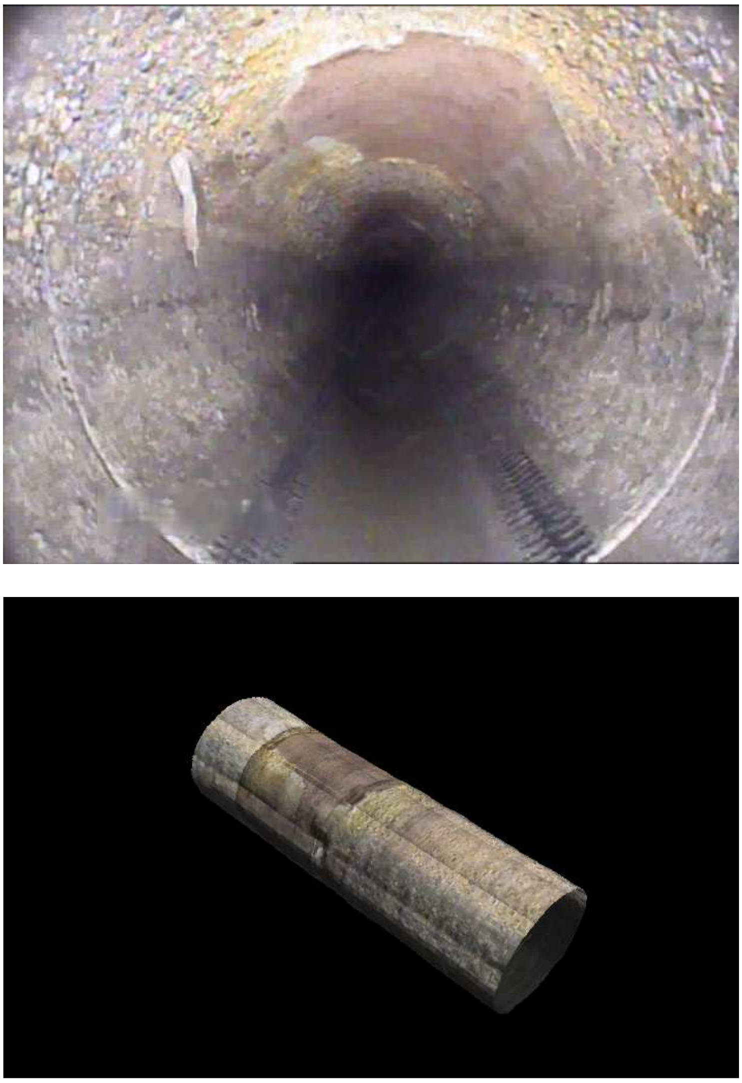
3. DEVELOPMENT OF MULTI-SENSOR INSPECTION ROBOT INCLUDING PPR

Several case studies have demonstrated that manned entry PPR inspections provide otherwise unobtainable information on the condition of the pipes (Parkinson and Ékes, 2008). Since manned entry is often not feasible or possible the combination and integration of two or more inspection technologies onto a robotic platform including critical sensors (e.g., CCTV, sonar, and laser scanners) has been attempted and some of these multi-sensor inspection robots have been commercialized in various forms in Europe, North America, Japan, and Australia (USEPA, 2010).

Figure 2. Fourth generation multi-sensor inspection robot equipped with pan, tilt, zoom CCTV, LIDAR, and pipe penetrating radar.

The first commercially available PPR system was developed and commercialized as a multi-sensor inspection (MSI) robot that uses visual and quantitative technologies (CCTV, LIDAR, and GPR) by SewerVUE Technology Corp. This fourth generation PPR pipe inspection system is mounted on a rubber tracked robot and equipped with two high-frequency GPR antennae (Figure 2). The system can be adjusted between 18- and 36-inch (450 to 900 mm) diameter pipe, while the GPR antennae can be rotated between the nine and three o'clock positions. Radar data collection is obtained via two independent channels in both in and out directions, providing a continuous reading on pipe wall thickness, rebar cover, and locating voids outside the pipe. CCTV data is recorded simultaneously and is used for correlation with GPR data collection. The robot is also outfitted with LIDAR capabilities to map quantitative measurements of inside pipe walls (Figure 3). This technology employs rotating laser to collect inside pipe geometric data which is then used to determine pipe wall variances from a manufactured pipe specification. LIDAR data is correlated with an onboard inertial navigation system (INS) that can accurately map the x, y, and z coordinates of the pipe without the need for external references.

The unit is equipped with three cameras (front, antenna, and back). Maximum tether length is 6,000 feet. Optional condition assessment technologies that can be added as additional payload include continuous H_2S Gas Monitoring and other atmospheric condition recording equipment. The unit provides quantifiable results such as pipe wall thickness and rebar cover for buried infrastructure structural condition assessments.



A

B

C

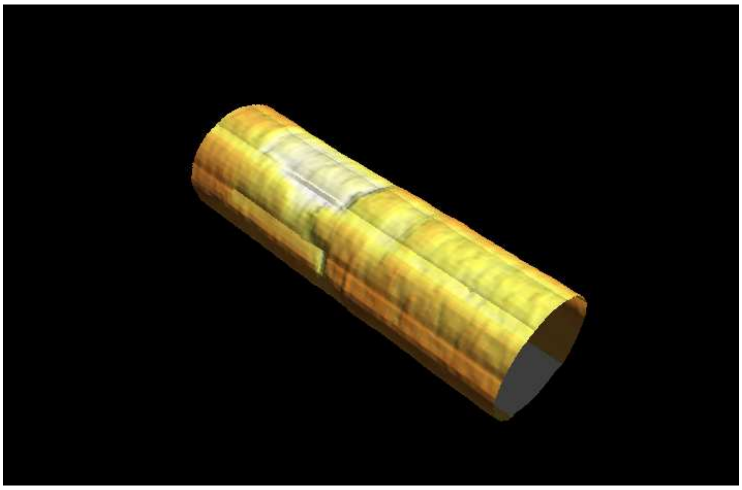


Figure 3. Different visualizations of a 30 inch reinforced concrete pipe segment generated from CCTV and laser data. A: CCTV frame capture. B: Shaded 3D view of inner pipe-wall texturized with CCTV result. C: Shaded 3D view of inner pipe-wall showing pipe-wall loss.

4. PPR DATA DISPLAY AND INTERPRETATION

The objective of PPR data presentation is to provide a display of the processed data that closely approximates an image of the pipe and its bedding material with anomalies that are associated with the objects of interest in their proper spatial positions. The five types of data display were reviewed by Ékes et al. (2011).

The integrated pipe penetrating radar data display (IPPRDD) developed by SewerVUE is the most comprehensive. In the reporting function of IPPRDD PPR results are displayed with the interpretation superimposed on the actual depth profiles versus distance (Figure 4). The top three lines show the individual PPR profiles with the corresponding clock position and antenna frequency denoted with an icon to the left of the corresponding profile (Figure 4). The scales are in feet (horizontal) and inches (vertical). The location of the scan lines are marked on the foldout view of the pipe at the bottom of each pipe segment with the corresponding clock positions on the vertical axis. Anomalies and other notable features are color coded.

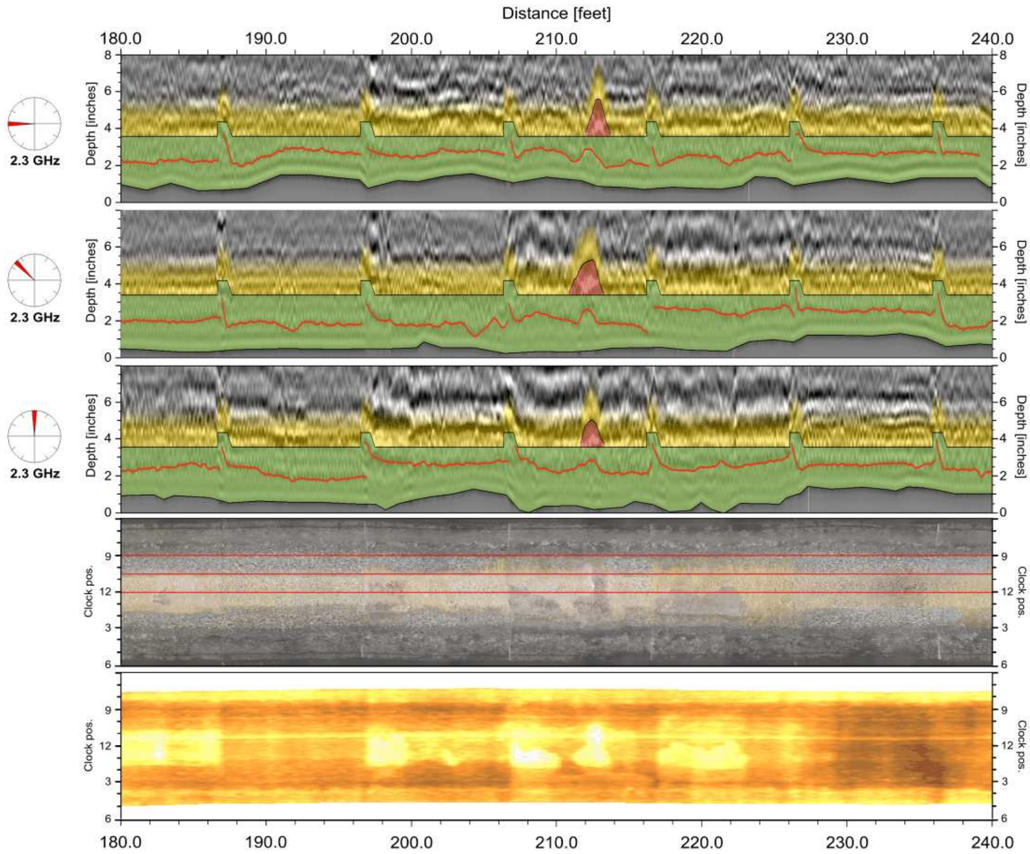


Figure 4. PP RADIAN views of a 30 inch (750mm) reinforced concrete sewer pipe: longitudinal cross sections at multiple clock positions with corresponding CCTV and LIDAR foldout view.

LIDAR

LIDAR (Light Detection and Ranging) is an optical remote sensing technology that measures properties of scattered light to find range and/or other information of a distant target. The prevalent method to determine distance to an object or surface is to use laser pulses. Like the similar radar technology, which uses radio waves, the range to an object is determined by measuring the time delay between transmission of a pulse and detection of the reflected signal.

The SewerVUE Surveyor's LIDAR data is correlated with an onboard inertial navigation system (INS) that uses a computer, motion sensors (accelerometers), and rotation sensors (gyroscopes) to continuously calculate via dead reckoning the position, orientation, and velocity (direction and speed of movement) of the robot without the need for external references. This technology is commonly used on vehicles such as submarines and guided missiles and is specially adapted for the use of multi-sensor inspection robots for underground infrastructure surveys where LIDAR is utilized and location and time measurement data is necessary.

A section of the processed LIDAR data is shown in Figure 4 together with the foldout CCTV view and corresponding PPR profiles. Figure 3 illustrates a reconstructed 3D image of a 24" RC pipe section showing internal pipe wall corrosion.

5. KING COUNTY, WASHINGTON CASE STUDY

The 62nd Avenue interceptor is a 30 in. diameter reinforced concrete sanitary sewer pipe in Seattle, King County, WA. The objective of the survey was to demonstrate the capabilities of the SewerVUE Surveyor multi sensor inspection robot equipped with PPR, LIDAR, gyroscope, and CCTV. All four sensors were collecting data simultaneously.

This project's PPR survey was completed using 1.6 and 2.3 GHz frequency antennas. 2D line data was collected on the springline and along the obvert of the pipe. The PPR lines were located along the 9:00, 10:30, 12:00, 1:30, and 3:00 o'clock positions inside the pipe.

The PPR data were of excellent quality. PPR results are displayed with the interpretation superimposed on the actual depth profiles (Figure 4). Anomalies and other notable features are color coded. Pipe wall thickness is marked by a continuous black line; reinforcement is marked by red dots which are then connected by a red line.

The PPR data shows variations in pipe wall thickness, as well as location, depth, and spacing of rebar. Vertical exaggeration is used to better illustrate variations in pipe wall thickness measurements. The PPR data has been corrected to an assumed continuous outside pipe wall dimension as these manufacturing tolerances are generally tighter to ensure proper seating in gasketed pipe joints in order to reflect changes in inner pipe wall diameter.

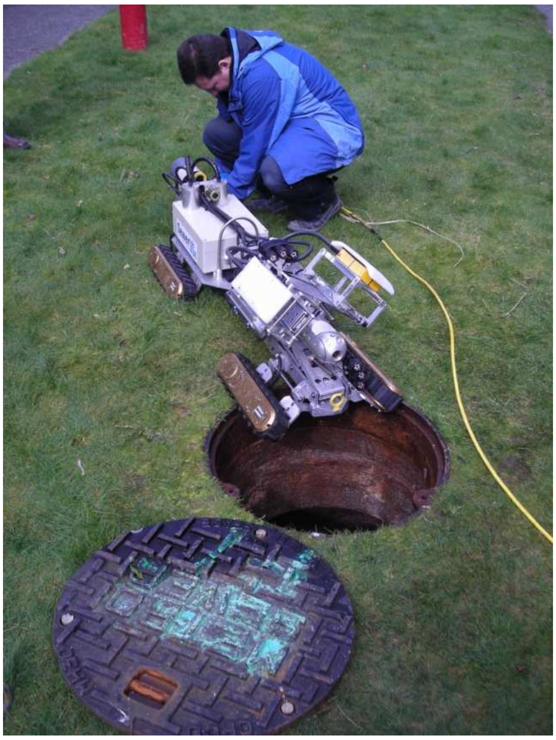


Figure 5. Technician connecting the tether to the SewerVUE Surveyor robot before insertion at the 62nd Avenue interceptor in King Co., WA.

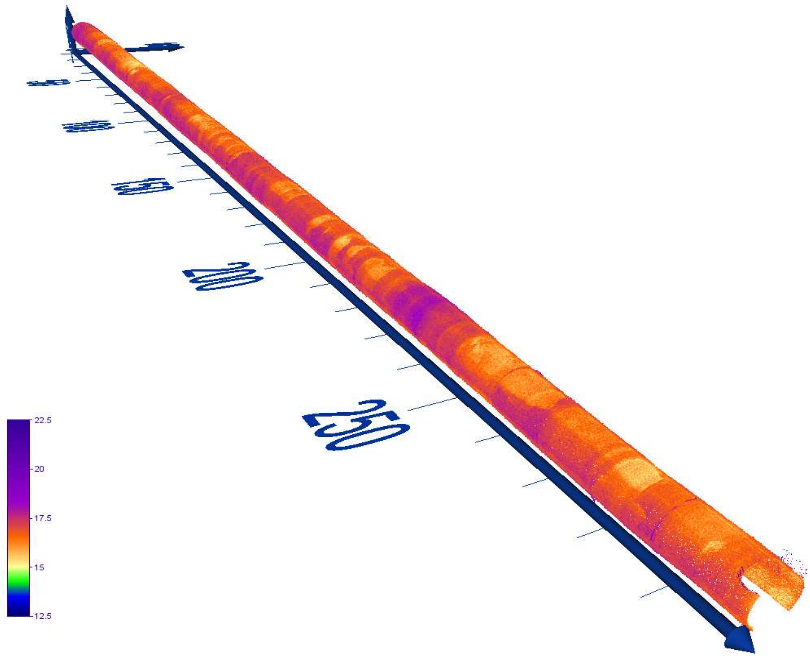


Figure 6. 3D view of processed LIDAR data showing variation in inner pipe wall diameter. Accurate pipe alignment has been calculated from gyroscope data. View is from South to North, manhole opening is shown at closest end.

The processed PPR data indicated four locations along the pipe where anomalies have been detected which may require further investigations. Exact locations and the nature of these anomalies have been reported to the client.

The multisensory SewerVUE Surveyor inspection tool demonstrated that PPR and LIDAR data can successfully measure inner pipe wall diameter, rebar depth and spacing, as well as void type anomalies outside the pipe. LIDAR data supported and complemented the PPR data interpretation.

6. CONCLUSIONS AND CURRENT RESEARCH

PPR has demonstrated early successes as a standalone pipe inspection system operated both in manned entry and remote robotic mode. Current research is underway to investigate the feasibility of in-pipe use of UWB antennas which circumvent the need for having the antennas placed in contact with the pipe wall (Jaganathan et al., 2006).

The next step in the continuing development of hardware system is to combine the output not only from CCTV with PPR but incorporate LIDAR and 3D LIDAR and accurate x, y, and z positioning, and optionally sonar data into a comprehensive reporting package. The hardware is already in the market (Figure 2) the processing and visualization software has been developed and passed the pilot phase. Commercial rollout has begun in February 2011.

Condition assessments using multiple surveys over time can yield extremely important trending data that can assist in determination of an assets remaining safe service life, advancement of voids, and quality control for manufactured pipe by assessing surveyed wall deterioration (USEPA, 2010). Pre and post construction installation as well as establishment of an installed asset’s baseline measurements can also be determined, as can be warranty inspections for pipe rehabilitation technologies. One of the most promising new condition assessment technologies is pipe penetrating radar (PPR), the in pipe application of GPR (Najafi, 2010). Recent hardware and software developments of this emerging technology are presented in this paper and its capabilities are demonstrated through examples from recent case studies.

PPR can provide a better understanding of expected life cycle and deterioration rates for the proper use asset management systems. PPR can also fill some key gaps as an improved nondestructive inspection and condition assessment tool, enabling assessment of thickness and material properties for pipe liners and identification of annular gaps between the liner and the host pipe.

7. REFERENCES

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