Review

Condition assessment of the buried utility service infrastructure


A R T I C L E   I N F O

Article history:
Received 4 August 2011
Received in revised form 18 October 2011
Accepted 31 October 2011
Available online 29 November 2011

Keywords:
Condition assessment
Infrastructure

A B S T R A C T

An extensive array of utility networks are buried underneath the ground surface and provide essential services for society’s daily life in terms of water, natural gas, electricity, telecommunications, sewerage, etc. All utilities have a limited service life and it is crucial to assess their condition throughout their life cycles to avoid potential catastrophic failure due to their deterioration. This paper reviews current state-of-the-art technologies for condition assessment of underground utilities (especially water and sewage pipelines) and their advantages and technical challenges for different application areas. Recommendations on how to address these challenges are made and it is highlighted that the system of combined sensor technologies being developed by the Mapping the Underworld (MTU) project may provide a valuable addition to the street works engineer’s armoury in determining the condition of the buried infrastructure. Moreover the ground in which the utility services infrastructure is buried supports the pipes and cables and prevents their permanent or transient displacement under static and dynamic loads, or lateral stress relief associated with adjacent trenching. The ability of the MTU sensing technologies to determine also the condition of the ground is thus equally relevant and is discussed.

Crown Copyright © 2011 Published by Elsevier Ltd. All rights reserved.

Contents

1. Introduction ...................................................................................................... 332
2. Condition assessment of buried utilities ............................................................... 333
3. Visual techniques ............................................................................................... 333
  3.1. Closed-circuit television (CCTV) .................................................................. 333
  3.2. Sewer scanner and evaluation technology (SSET) .............................................. 333
4. Electromagnetic and radio frequency techniques ................................................... 334
  4.1. Magnetic Flux Leakage (MFL) .................................................................... 334
  4.2. Eddy current technique ................................................................................ 334
  4.3. Hydroscope technology .............................................................................. 334
  4.4. Rapid magnetic permeability scan (RMPS) ................................................... 334
  4.5. Low frequency electromagnetic field (LFEM) ................................................. 335
  4.6. Passive magnetic fields (PMFs) .................................................................... 335
  4.7. Ground Penetrating Radar (GPR) ................................................................. 336
1. Introduction

The network of underground utilities that serves our towns and cities is one of the most complex networks in the world, and yet one that is invisible from the ground surface and thus one that goes unnoticed unless it fails in some manner. Thus the task of locating this buried infrastructure in the absence of comprehensive and accurate maps, and moreover determining the condition of this buried infrastructure, is highly problematic. The complexity of the underground utilities networks derives from the many types of utility services being supplied and the materials of the pipelines and conduits through which they are delivered, their interconnectness, their different ages and their different sensitivities to disturbance. The different utility service lines include water pipes, gas pipes and electricity cables; sewers and storm water drainage (which are sometimes combined, 04-CTS-6URA, 2010); telecommunications cables (fiber optic cables being particularly vulnerable to damage and expensive to repair); and street lighting and traffic lighting cables (McMahon et al., 2005). It is widely appreciated that the type and quality of materials have varied through the decades, and occasionally centuries, over which these pipelines and cables have been installed, even in the case of the same utility; for example cast iron from different ages is very different in chemical make-up and physical consistency (e.g., density, air voids, impurities as inclusions), due to its manufacturing processes, while the jointing techniques since their review was started in 2002. The limitations of current assessment methods relating to condition assessment are also discussed. This paper reviews the state-of-the-art technologies for condition assessment of underground utilities (especially water and sewage pipelines). It seeks to update the review done by Costello et al. (2007) and to address the development of the different techniques since their review was started in 2002. The limitations of current condition assessment techniques will be compared and discussed. A companion paper (Rogers et al., 2012) covers the parallel issues of technologies for condition assessment of roads and railway foundations, as exemplars of the surface infrastructures that typically overlie the buried utility services infrastructure, the symbiotic relationship between the infrastructures, the common influencing feature of the ground on which or in which it sits and the need for assessment of the condition of the ground alongside any assessment of the infrastructures. Current asset management methods relating to condition assessment are also discussed. Ultimately it would be highly desirable not only to be able to assess the condition of buried utilities and surface infrastructures using the most advanced geophysical and other sensing technologies, but also to interpret the results from a geotechnical point of view, i.e., to assess the influence of the ground on the utility and surface infrastructures. This would form a vital element in moving towards a far more sustainable approach to street works.
2. Condition assessment of buried utilities

The condition assessment of underground utilities cannot be a more important topic for civil engineers and the society that they serve, since quite apart from the essential services they provide to support civilized life, certain catastrophic accidents result directly from gas pipe leaks or broken water mains. It is contended by the authors that if the condition of the buried infrastructure is routinely assessed and monitored, proactive warning of impending failure might be achieved and thus the probability of the serious consequences of accidents caused by deterioration of the utility network can be effectively reduced.

Traditionally, sewer surveys were carried out by sending out inspectors to ‘see and touch’ the defects inside those man-entry pipes along the network. However, this method, although highly effective at revealing the internal condition and providing certain clues about the external condition, suffers from inefficiency in terms of manpower, and it is obviously impractical for the majority of pipes and cables that make up the network. Moreover, modern legislation restricted this approach of direct inspection by operators for health and safety reasons (Hodgkinson, 2000). Remote (i.e. non-manual) techniques were developed to overcome this concern and greatly increase the inspection efficiency, and will form the primary subject of this paper.

3. Visual techniques

3.1. Closed-circuit television (CCTV)

Current alternatives to direct man-entry and visual observation include the collection and inspection of CCTV images, or the use of Light Line surveys. However, these methods are slow, largely subjective and may require a sewer length to be drained or pre-cleaned before inspection, and thus they are expensive. Consequently, no more than 2% of the main sewer network in the UK had been surveyed by 2004, and at least 20% of those observations obtained by CCTV were thought to be inaccurate (OFWAT, 2004).

Using CCTV to inspect the interior of pipes was introduced in 1960s. The system consists of a television camera mounted on a tractor (as shown in Fig. 1) and remotely controlled by an operator. In subsequent decades, the CCTV inspection technique has been widely used throughout the world. The obvious advantage of this method is that it provides direct illuminated images of the defects of the pipe’s interior wall, which can be examined in detail by zooming the camera or viewing from different angles by controlling the tractor. The natural limitation of this technique is that the images of the interior wall can only be obtained above the water surface in the case of sewer and water pipes. Since the CCTV tractor travels along the pipeline, unsteady camera movement and lack of geometric references are considered to be further limitations of the technique (Kirkham et al., 2000). Moreover the CCTV images can only provide a view of the internal condition of the pipe wall; it is generally not possible to determine the depth of a crack or perforation, only a hint at the seriousness. A CCTV camera therefore typically provides no reliable indication as to whether the crack runs through the pipe wall and is therefore a possible route for the ingress of groundwater or the escape of sewage. The analysis of CCTV images will also not provide information as to whether a void has formed outside the pipe. Voidage in the ground surrounding a pipe is important as it can progressively increase in size until the surrounding ground becomes unstable and collapses, causing the potential for dislocation of the pipe and significant structural damage. It is therefore highly desirable to detect voids before failure occurs so that appropriate remedial action may be taken.

Recent research has focused on how to improve the quality of the inspection images, how to improve the interpretation of poor-quality images, and how to improve the automation of the inspection. For example, Sarshar et al. (2009) proposed a software system to semi-automatically extract historical condition data information from sewer inspection CCTV files, while Cherqui et al. (2008) proposed an algorithm which calibrates dysfunction indicators based on the results of visual inspections. Yang et al. (2011) proposed the use of a CCTV image quality index, considering both the luminance distortion and the contrast distortion, to improve the inspection confidence when compared to reference images. Although the quality of the inspection images is being improved steadily thanks to the fast evolution of CCTV camera technologies, the images captured still cannot provide satisfactory confidence of identifying the defects of pipes, especially under harsh conditions, and more work is needed for a higher level of automated detection.

More recently, a guidance report by the US Environmental Protection Agency (EPA) identified and evaluated innovative CCTV and related technologies currently used by more advanced wastewater utilities to conduct condition assessment programs (US-EPA, 2010). It also summarized the technology applications and lessons learned from various utility case studies to illustrate specific concepts accordingly.

3.2. Sewer scanner and evaluation technology (SSET)

In late 1990s, optical scanner and gyroscope techniques were introduced to facilitate pipe interior inspection. Unlike CCTV inspection, the SSET device does not need to stop at the suspicious defect locations, since the interpretation of defects or cracks can be carried out after the device has finished inspecting the whole length of pipe. This conceptually increases the inspection efficiency; however it requires a higher level of expert assessment since, when the survey is finished and the assessment has started, there is no chance to re-evaluate the suspicious defects locally. The other limitation of this technique is that it also requires manual interpretation of the images. Research has been undertaken to automate the assessment process in order to increase efficiency and interpretation accuracy (Chae and Abraham, 2001) and SSET has also been combined with other inspection technologies, such as Ground Penetrating Radar (GPR) as shown in Fig. 2 (Koo and Ariaratnam, 2006). In the deployment of SSET in the practical pipeline inspection, commercial systems such as PANORAMO system by RapidView IBAK and SOLO system by RedZone have been deployed in pipeline inspection with high image resolution, inspection speed and efficiency.

![Fig. 1. CCTV pipeline inspection equipment (from Koo and Ariaratnam (2006)). Reproduced with permission of Elsevier.](image-url)
4. Electromagnetic and radio frequency techniques

4.1. Magnetic Flux Leakage (MFL)

The MFL technique is widely acknowledged and used for metallic pipeline inspections. A pipeline inspection gauge (pig) is normally inserted into the system and travels along the pipeline, and is used to detect and characterize the metal loss defects such as corrosion and cracks on the interior wall of the pipeline (Mukhopadhyay and Srivastava, 2000; Saha et al., 2010). MFL technology is claimed to have good detection capabilities even for small pitting anomalies, attributed to the fact that the MFL pattern registered by the inspection tool is larger than the anomaly itself. MFL technology is therefore potentially suitable for detecting very small pitting defects; even under extremely poor conditions, a magnetic response is still obtained. The working mechanism is briefly reviewed by (Costello et al., 2007), while the technique has been reviewed in detail by Carvalho et al. (2006), Sophian et al. (2006), Jonidecha and Prateepasen (2009), and Khodayari-Rostamabad et al. (2009). There are various deployment of MFL technique in the inspection of metallic pipelines, for instance, EM-TEK (http://www.emtek.us/) combines Extra High Resolution (XHR) MFL with other sensors such as near-field sensors, 6-axis strap down inertial sensor and high-resolution geometry sensors to provide a comprehensive inspection of internal, external defects and geometric anomalies.

4.2. Eddy current technique

Eddy current testing tends to be used for smaller diameter metallic pipes, e.g., down to 100 mm diameter pipes. In eddy current testing, a time varying magnetic field is induced in the pipe by using a magnetic coil with alternating current. This magnetic field causes an electric current to be generated, which in turn produces small magnetic fields around, conducting materials. The smaller magnetic fields generally oppose the original field, which changes the impedance of the magnetic coil. Thus, by measuring the change in impedance of the magnetic coil as it traverses the pipe, different characteristics can be identified (Atherton, 1995).

Smith et al. (2001) reported on the use of the eddy current technique in gas pipelines. They described a miniaturized version of the standard tool, which is reversible, as it is non-contacting, thereby allowing the deployment and recovery through one major entry point on a pipeline. The problem with eddy current testing is the dimension of the skin depth that is examined, which is dependent on the induced frequency (e.g. for steel pipes at 50 Hz the skin depth is about 3 mm). To overcome this problem, the Remote Field Eddy Current method was developed. The current can travel along the outside of the pipe and be detected by far field coils, which are separated by approximately twice the pipe diameter from the excitation coils. This method relies on the fact that the remote field signal is larger than the direct eddy current signal measured by the detector coils. Remote field inspection is a through wall, electromagnetic, non-destructive evaluation method. It uses a circular emitter coil, placed inside the pipe so that the axes of the pipe and coil are parallel. A pickup sensor, also inside the pipe, is located more than 2.5 pipe diameters away from the emitter (Makar and Chagnon, 1999).

4.3. Hydroscope technology

The Hydroscope technology is based upon the Remote Field Eddy Current (RFEC) technique briefly described above, which enables non-destructive evaluation of buried cast or ductile iron and steel pipes. This technique assesses the condition of water pipelines by sensing the changes in an electromagnetic signal as it passes through the pipe wall, the signal being induced into the pipe by an exciter mounted in the Hydroscope tool, which is inserted into the pipe through a hydrant. The signal, as modified by the pipe, is detected by sensors positioned in the tool (Fig. 3), which essentially consists of a train of sealed modules containing processing and transmission electronics. It is designed to traverse bends and tees and is usually propelled through the pipe by water flow. The tool records a data set every 1.5 mm of travel, the data being transferred by a wire line cable to a service vehicle, and thus claims to examine 100% of the pipe wall with a survey rate of up to 1000 m per day. The manufacturers claim that the Hydroscope tool is able to detect general wall loss, pitting and graphite corrosion, is equally sensitive to internal and external wall loss, can be deployed in either wet or dry pipes, and can test through lining and scale, so extensive prior cleaning of the pipe is not necessary. However, it was reported that pits of less than 3000 mm² in size cannot be detected (Makar and Chagnon, 1999).

4.4. Rapid magnetic permeability scan (RMPS)

As described by Roubal (1999), the RMPS technique applies a magnetic field from strong permanent magnets into a metallic pipe wall. The high magnetic permeability of the material defines and channels the magnetic field flux while the flux density is a function of the cross-section of the metallic pipe. The state of the pipe thus can be qualitatively monitored by the changes in the magnetic field.

![Fig. 3. The Hydroscope tool (reproduced with permission of Russell Technologies and Hydroscope Canada Inc., www.hydroscope.com).](image-url)
consists of a trolley that supports the system controller and power supply, along with a distance measuring device and notebook PC, which is attached to up to seven capacitive electrodes, and a final transmitting electrode, each with their electronics. The CORIM system, which has continuous data collection capability, can be useful in applications for the measurement of earth resistivity in cases where other geophysical techniques may not be appropriate, such as in areas underlain by soils having a high clay content. The CORIM system can be expected to make measurements with a 3–4 m depth limit, with a resolution of approximately 0.3 m.

The CRI system was based upon research reported by Kuras (2002). This was then further developed and tested by the British Geological Survey. The fundamental underpinning theory behind this system is documented by Kuras et al. (2006) and subsequent field-trial results are presented by Kuras et al. (2007), showing that towed-array CRI is capable for environments where the conventional methodology would be impractical, and a tomographic 3D imaging is possible using datasets acquired with moving arrays. The system, depicted in Fig. 5, consists of non-contacting capacitive electrodes that permit continuous towed data acquisition on highly resistive engineered surfaces in the built environment (e.g., on roads and other paved surfaces) where invasive DC coupling is difficult and undesirable. A real-time kinematic global positioning system provides accurate navigation and location recovery.

Both the CORIM and CRI systems offer the advantage of being able to conduct sub-surface surveys in conditions that are normally challenging for Ground Penetrating Radars, such as a ground with a high electrical conductivity. By using non-invasive capacitive electrodes, both systems allow surveys to be conducted over engineered surfaces commonly found in urban environments. Although both systems are limited in that they both operate on a single, non-variable frequency, this has little impact on their effectiveness in the intended target application of sub-surface resistivity profiling. However, for the specific application of leak detection from water pipelines, and the detection of anomalies arising from the symptomatic manifestations of pipe degradation, a fixed array arrangement and a fixed frequency regime may not be optimal.

More recent research has concentrated on active surveys by injecting signals, and passive detection of self-potential as well as electro-kinetic potentials. An active detection approach is similar to the CORIM and CRI systems in that a signal is injected into the ground and anomalies associated with the disrupted flow of this signal are detected. The current research introduces two novel aspects: the implementation of a multi-frequency strategy, and the exploitation of the heading of the signal flow (Foo et al., 2010). A multi-frequency strategy enables multiple signals to be excited in the ground simultaneously, while this frequency can be varied as required. This is useful for adapting the frequency of the signal to reduce the effect of interference both from the environment as well as from other sensors that might be present on a multi-sensor device. Unique transmission pulses, such as linear-frequency modulated sweeps, can be used for evaluating noise-levels before specific transmission frequencies are selected (Foo et al., 2010). Furthermore, a multi-frequency transmission can be used with a heading sensor to provide signal excitation with unique vectorial properties, such that each frequency represents a signal flow in a unique direction. This enables the characterization of detected anomalies in terms of heading and directions.

4.5. Low frequency electromagnetic field (LFEM)

Low-frequency electromagnetic field surveys rely on the detection of electrical signals in the frequency range of 0.5–50 kHz. This technique is also referred to as a low frequency electric field survey (Tabbagh et al., 1993; Tabbagh and Panissod, 2000), as the relatively low signal frequency often provides for a quasi-static approximation of the field. The LFEM acts as a means for observing beneath the ground, while the parameter that is usually calculated for the interpretation of anomalies is the apparent resistivity encountered by the low-frequency electrical signals (Timofeev, 1974).

The measurement of sub-surface apparent resistivity using a low-frequency electrical signal is well known and established. However, the approach of measuring non-invasively (i.e. without electrode insertion) is relatively new. There are currently two main providers of this solution, the continuous resistivity imaging (CORIM) system supplied by the AEGIS Instruments Ltd., and the capacitive resistivity imaging (CRI) system developed by the British Geological Survey (BGS). The CORIM System, as depicted in Fig. 4, consists of a trolley that supports the system controller and power strength. For instance, a sharp bending of the flux lines indicates a sharp, high-amplitude anomaly, which may refer to a crack in the pipe wall perpendicular to the field direction. A gradual thinning of the pipe wall, on the other hand, shows up as a symmetrical, gradual change in the field strength (Roubal, 1999). The RMPS has been demonstrated to be useful for the condition assessment of relatively bigger metallic pipes, i.e., 100 mm and greater in diameter.

![Fig. 4. The CORIM system (reproduced with permission of Terraplus Inc., http://www.terraplus.ca).](image)

![Fig. 5. The BGS CRI system (reproduced with permission of BGS).](image)
part of the deployment of a multi-sensor device (Muggleton and Brennan, 2008), the acoustic excitation would induce vibrations in the utilities and adjacent soil. Such vibro-displacement will also generate detectable electro-kinetic potentials caused by the presence of electrolyte, both in the pipes and within adjacent soil.

4.6. Passive magnetic fields (PMFs)

Unlike the eddy current technique, PMF uses the flow of current within an underground AC power cable to monitor the associated oscillating magnetic field. PMF sensors are designed to find the location of underground power cables based on the principle proposed by Michael et al. (1998), who used an array of passive search coils arranged in a 3D configuration for magnetic field detection. They equally have the potential to detect anomalies in an AC current field in the case of a deteriorated or faulty power cable.

Cable fault locators are common tools for detecting the break of cables. For example, commercial cable fault locators (e.g., www.3m.com) identify and measure points of cable damage where there is metallic contact to earth via a conductor or cable shield.

4.7. Ground Penetrating Radar (GPR)

The first use of GPR for buried objects detection appeared in a German patent by Leimbach and Löwy in 1911 (Daniels, 2004). Since the 1970s, intensive research on GPR technologies has been carried out for a wide variety of applications, such as environmental and agricultural monitoring (Hubbard et al., 2005) and glaciological monitoring (Hamran and Langley, 2004). In the area of sub-surface engineering, GPR is widely used for buried utility detection (Graumueck et al., 2005), and also condition assessment of infrastructure (Chen and Wimsatt, 2010; Evans et al., 2008).

In the area of utility service deterioration monitoring, GPR has been used effectively to detect abnormally wet areas within the ground, such as from leaking water pipes, as well as leaking oil from high voltage cables. Applying the inverse of this logic, GPR could equally be used to detect abnormally dry areas, which might result for example from a failing electricity cable that is producing heat and drying out the surrounding soil.

4.7.1. Traditional GPR

GPR technologies can be categorized into three main types:

- **Time domain**: Impulse GPR.
- **Frequency domain**: Frequency modulated continuous waveform (FMCW), stepped frequency continuous waveform (SFCW) and noise modulated continuous waveform (NMCW) GPR.
- **Spatial domain**: Single frequency GPR.

The impulse GPR technique is well established commercially and GPR systems utilizing the impulse technique are most commonly available. FMCW and SFCW GPR technologies are comparatively new and under intensive research both in the academic and industrial domains. As a result, there are few commercial products available in the market. The single frequency GPR has only recently been shown to be viable, while the developments in NMCW GPR are just gathering pace (Daniels, 2004). A detailed review of impulse GPR, FMCW GPR and SFCW GPR is given by Metje et al. (2007).

4.7.2. In-pipe GPR

Unlike the traditional GPR system configured in ‘look-down’ mode, a novel in-pipe GPR system was proposed to work in ‘look-out’ and ‘look-through’ mode (Foillard et al., 1995; Pennock et al., 2006; Pennock and Redfern, 2007). In the ‘look-out’ mode, both the transmitter and receiver are mounted on a pig inside a pipe, while in ‘look-through’ mode, the transmitter is mounted on a pig inside the pipe and the receiver is on the surface, or indeed vice versa. The advantage of these configurations is that the path loss due to the attenuation of soils is reduced compared to the traditional GPR systems, particularly for the ‘look-through’ mode where one-way travel of the signal occurs, while for the ‘look-out’ mode a localized inspection around a particular pipeline can be realized, (see Fig. 6).

Shellshear (2000) reported that collapses of sewers are usually triggered by conditions external to sewers. Both traditional GPR and in-pipe GPR can be used for the detection of significant ground voidage and pipeline collapse, which is commonly associated with sewers and drainage culverts. It is also reported that GPR systems can be used for leak detection (Hunaidi and Giamou, 1998; Hyun et al., 2007), while various signal processing methods have been developed to aid leakage detection (Tang et al., 2009; Crocco et al., 2009). As part of the MTU project, the GPR and soil properties researchers are exploring propagation mechanisms in clay soils where iron pipe corrosion products can ‘hide’ cast iron pipes from GPR. This occurs because corrosion products in the soil increase radio frequency (RF) signal attenuation and reduce reflection (Pennock et al., 2010).

4.8. Time domain ultra wideband (UWB)

Time domain UWB technique shows its advantage in the condition monitoring of pipelines for a broader working frequency range and a better resolution (Sachs et al., 2008). Recently, Bonitz et al. (2008) reported a sewer crawler mounted with a UWB radar based on the M-sequence radar principles (Sachs, 2003) while Jaganathan et al. (2006, 2010) proposed to employ the time domain UWB technique for condition assessment of buried non-ferrous pipelines. It employs an ultra-short pulse to detect the voids occurring in the soil envelop surrounding the pipe, and the numerical and experimental data demonstrated the ability of the system to clearly distinguish a relatively small void in the soil envelop. It is believed that the time domain UWB technique has the potential to provide accurate condition assessment of predominantly non-ferrous buried pipes including the presence, location, orientation and dimensions of soil voids; detection of external corrosion; and measurement of wall thickness of buried pipes (Jaganathan et al., 2010).

5. Acoustic and vibration techniques

5.1. Sonar

Acoustic techniques have been adopted in condition assessment of utilities since they provide the possibility to measure the corrosion loss and volume of debris inside a pipeline. The sonic characterization technique is a particularly active research area. In sonar surveys, the time of the sound from the point of excitation, through transmission and reflection to the point that it is finally received is measured; the distance from the source to the target can be determined by the speed of the sound in the travelling medium. Such information is used to construct a sonar image from which the condition of the pipe interior can be assessed. As discussed by Eiswirth et al. (2000), the images above and below the water surface have to be constructed and assessed separately since the speed of sound in air and water is different.

An adaptation of the sonar survey has been suggested by Eguchi et al. (1997) for the inspection of tele-communication conduits to determine fitness for purpose. Defects preventing cable installation in tele-communication conduits are generally caused by outside factors such as earthquakes, ground subsidence or road excavation,
by deterioration such as rust or corrosion, or by deformation of flexible conduits in inadequately constructed surrounds. Established methods such as CCTV and mandrel passing tests require large amounts of time and labor, whereas a newly proposed method, developed by NTT Access Networks Laboratories in Japan and available in prototype form only, involves inserting a sensor probe into the conduit duct from a manhole access point which then emits an acoustic wave along the conduit and receives the reflected waves. An arithmetic and control unit controls the system and calculates the algorithms for estimating cross-sectional changes in the conduit. It is expected that the system will be used as an efficient and economical first pass with targeted CCTV inspections carried out on those areas where defects are highlighted.

5.2. Vibro-acoustics

Vibro-acoustics is being researched as part of the MTU project with the aim of delivering a vibro-acoustic system for stand-alone use and as part of the multi-sensor device, and a comparative performance assessment between the outputs and usefulness of geophones and scanning laser technology to detect the acoustic responses at the ground surface. In parallel with this research, Gao et al. (2005), addressing the problem of detecting leaks in water distribution pipelines, investigated the behavior of the cross-correlation coefficient for leak signals measured using pressure, velocity and acceleration sensors. A general review of this technology for leak detection is given by Brennan et al. (2006).

5.3. Impact echo/spectral analysis of surface waves

This technique has been widely applied for the assessment of damaged prestressed concrete pipes according to Makar and Chagnon (1999), while one employment example of this technology is Coreview technology by Fibrwrap (http://www.fibrwrapconstruction.com). It consists of a source of controlled impacts, such as falling weight or a large pneumatic hammer, and one or more geophones mounted against the wall of the pipeline. When the pipe wall is struck by an external force (e.g., from a hammer), low frequency surface waves are generated, transmitted, and detected by those geophones. Since these waves have different frequencies, travelling speeds and penetrating depths, one can correlate such information to the various conditions of the pipe as well as the soil surrounding the pipe (Makar and Chagnon, 1999).

5.4. Correlator and listening stick for leaks

Commercial leak detection equipment based on the detection of leak noise is widely available. Leak noise correlators listen for leak noise either side of a suspected leak using sensors on the pipe and then calculate time delay differences based on estimates of wave-speed in the pipe. Fig. 7 shows a typical correlator arrangement. Wave-speeds in metal pipes are easy to predict, but this is not so for plastic pipes. Research is currently being undertaken to model wave behavior in pipes to enable better predictions and real-time measurements of wave-speed (Gao et al., 2005, 2009; Ahadi and Bakhtiar, 2010).

5.5. Other acoustic techniques

More recently, a fast and efficient alternative method with the potential to analyse objectively the condition of a sewer pipe wall has been proposed (Tolstoy et al., 2009). The method is based on measuring the direct and reflected instantaneous acoustic intensity of normal modes excited by a sound source in a sewer pipe containing obstructions or structural defects. The speed of the measurements and the ability to measure pipe sections from a manhole, rather than moving an instrument through the pipe, means that this method has the potential to be at least two orders of magnitude less costly than traditional CCTV methods. It is now capable of identifying obstructions and pipe surface defects by comparing the measured acoustic intensity with a repository of benchmark signature data covering a number of common obstacles/defects. However, due to the physical limitations of the acoustic sound wave (acoustic permeability of air $\gg$ acoustic permeability of the wall) it is unable to penetrate beyond the inner surface of a sewer pipe. This prevents the acoustic sensor reliably detecting voids behind the pipe surface, and the depth and characteristics of any full pipe wall penetration crack.

Ultrasonic guided waves have been used extensively for pipe corrosion assessment (Demma et al., 2004; Belanger and Cawley, 2008; Sposito et al., 2010; Tse and Wang, 2009), and this remains another active area of research as well as industrial development.

Acoustic Pulse Reflectometry (APR) is based on the measurement of one-dimensional acoustic waves propagating in pipes, any change in the pipe's cross-sectional area creating a reflection which is recorded and analysed in order to detect defects. The principle is based on the fact that an acoustic pulse injected into a semi-infinite straight-walled tube will propagate down the tube without generating any reflections. This pulse can be measured...
by mounting a small microphone with its front surface flush with the internal tube wall, through a hole in this wall. The microphone will measure the pulse once only, as it passes over the microphone diaphragm. If, however, the pulse encounters a discontinuity in cross-section, a reflection is created. The amplitude and form of the reflection is determined by the characteristics of the discontinuity: a constriction will create a positive reflection, whereas dilation (increase in cross-section) will create a negative reflection. Neither of these discontinuities will change the shape of the pulse in their vicinity, but the reflection measured by the microphone will be an attenuated and smeared replica of the impinging pulse, due to propagation losses. A hole in the tube wall, on the other hand, will create a reflection having a more complicated shape, affected by the size of the hole and the radiation of acoustic energy to the space outside the tube (http://www.acousticeye.com/en-us/technology/overview.asp). APR is mostly used for the detection of blockages within a pipe and leaks. Recently reports indicate that even when using relatively crude equipment, the technique can be successfully applied to detect defects in single pipelines and pipeline networks with large diameters and lengths exceeding 5 km (Papadopoulou et al., 2008). For further information on this technique see Sharp and Campbell (1997).

SmartBall is a commercial leak detection technology from Pure Technologies (www.puretechnologiesltd.com). SmartBall’s acoustic sensor passes through the entire length of pipe being surveyed. The sensor, typically less than one-third the diameter of the pipe-line, can discern the acoustic activity associated with leaks, while the data are recorded and post-processed to report the presence and location of leaks. It calculates the locations of leaks by detecting acoustic pulses emitted by the ball at receivers attached to pipe appurtenances. The locations of the leaks relative to the receiver positions are determined by analyzing arrival times of the pulses. Additional instrumentation in the SmartBall is used to calculate flow rates along the pipeline and to identify valves, pipe joints and other features of the line. The advantage is that it can be inserted and retrieved from a pipeline under normal operation, and it is claimed that the ball can travel with the water flow for up to 15 h, collecting information about leaks over many kilometers of pipeline with a single deployment.

6. RFID/sensor techniques

RFID techniques help to locate the position of underground utilities by detecting pre-defined radio frequency resonances. Discrete low frequency (kHz range) RFID markers, which typically come in the form of small plastic items, such as 100 mm diameter plastic balls, are placed in a trench at the time of excavation near to specific points. They can be programmed with limited information and ‘read’ later using a special locator. The locator excites the RFID tag to respond with the defined frequency. The locator then identifies the frequency and reports the appropriate asset (e.g., Electronic Marking System (EMS) from www.3m.com).

One of the main advantages of these RFID marker solutions is due to the lower frequency they operate at, meaning they can be detected in wet conditions where GPR would struggle to achieve sufficient signal penetration. Recent work by Hao et al. (2008) has concentrated on developing a multi-frequency passive tagging system which enhances the detection of the location of underground utilities. A similar idea has been patented for monitoring the condition of utilities by applying multi-frequency passive RFID tags which are sensitive to change in a pipeline’s condition, e.g., due to leaks and degradation (Burd et al., 2009).

The PipeNet project attempted to detect leaks in water pipelines (Stoianov et al., 2007). It is an active system, which is based on the Intel Mote Sensor Node and which uses Bluetooth to communicate between various sensors. The disadvantage of active systems is obvious in that they are merely dependent on the lifetime of the battery, thus most of the effort has been put on how to reduce the power consumption (Stoianov et al., 2007; Kim et al., 2007). A similar system, so-called Smart Pipes is reported by Metje et al. (2011). It is a universal system that uses off-the-shelf sensors and communication elements incorporated into a Smart Pipe. The sensed information is transmitted to a Smart Server from which the data can be transmitted a longer distance along the pipe or through the ground. An alternative approach is to use a Smart Pig, which consists of sensors, electronics and communication components, to collect, store and transmit sensed data when it travels along the pipe (Metje et al., 2011).

7. Other techniques

7.1. Infrared thermography

Based on energy transfer theory, i.e., energy flows from warmer to cooler areas, infrared thermography has the potential to be used for both the location and condition assessment of underground utilities. This is because different underground materials (e.g., various types of soils, utility service pipeline materials, and their contents) respond differently to the flow of energy (Weil, 1990), thus can be used to locate underground objects such as pipelines, boulders and voids (Choi et al., 2008; Bagavathiappan et al., 2008).

7.2. Continuous wave Doppler sensing technique

An innovative sensor technique has been developed to detect water leaks in supply pipes, especially in cases where the existing methods do not offer a reliable solution, such as in plastic pipelines or for minor leaks. The system uses a continuous wave (CW) Doppler sensing unit operating at 2.45 GHz, consisting of a low power transmitter, a homodyne receiver and a digital signal processing unit. The principle of operation relies upon the detection of the Doppler frequency shift of reflected electromagnetic waves from slightly moving water that leaks out of a pipe (Bimpas et al., 2010).

The results of the CW Doppler system are claimed to be promising, notably the ability to detect and locate accurately the exact leakage point, no matter the environmental conditions (e.g., weather), the soil condition and the pipeline material; the proponents note that plastic (polyvinylchloride (PVC), high density polyethylene (HDPE)) pipelines provide a particular challenge for water leak detection using acoustic methods. Thus, it is argued that this system might be expected to work synergistically with other commercial water leak detection equipment to provide an integrated system for locating and detecting water leaks no matter what is the pipeline material or the extent of the leakage. However, there is a need for an improved digital signal processing algorithm for data acquisition, since it usually takes more than 3 min to detect water leakage using the current algorithm, and this is the subject of current research, development and proof testing.

7.3. Laser surveys

Reviewed by various researchers, such as Vickridge and Leontidis (1997) and Hodgkinson (2000), the laser survey technique employs a continuously generated laser beam projected around the pipe interior, thus highlighting and profiling the shape at any point along the area being surveyed. Due to the possible diffraction of the laser beam under water, laser surveys can only be used reliably above the water surface when surveying inside water pipes and sewers. More recently, the development of 3D laser scanning and modeling makes it possible to provide a 3D profile of the pipe, while 2D plans,
elevations or cross sections can be established by extracting vector distances.

7.4. Combined techniques

7.4.1. Broadband electromagnetics/wave impedance probe (WIP)

The broadband EM technique is a hybrid of Ground Penetrating Radar and electromagnetic techniques, and detects differences in the electromagnetic impedance of the material being tested. It can be implemented as a Non-Destructive Testing (NDT) tool, depending on the size of the sensor selected, and strength of output signals. The system was initially designed as a geophysical technique and is especially suited to shallow surveys at the 0.5–10.0 m scale. Received signals usually require post-survey processing; however major anomalies can be identified on site. The broadband EM results are highly sensitive to changes in bulk physical properties caused by voiding or saturation of soils. The system is useful for all except ferrous pipes, and has now been developed for in-pipe operation and is capable of surveying in excess of 300 m of active sewer or storm water networks. Units have been developed for surveys of pipes ranging from 200 mm to 5 m in diameter (Roubal, 1999; http://www.rocksolidgroup.com.au).

7.4.2. Pipe inspection real-time assessment technique (PIRAT)

Multi-sensor pipe inspection systems such as PIRAT (Kirkham et al., 2000) have been developed to detect automatically the type, location and size of damage in a sewerage system. This modular system normally consists of digital multi-frequency profiling sonar, a rotating mounted laser scanner, a gas monitor, a flow monitor, a digital CCTV and an enhanced digital virtual 360° CCTV device with high resolution, and a position sensor, all of which are mounted on robotic tractors controlled either via wired cables or wirelessly.

7.4.3. Other combined techniques

Another innovative inspection platform, called the Autonomous Inspection Mobile Platform (AIMP), integrates a panospheric camera and a laser scanner for inspection of small diameter pipes ranging from 150 to 450 mm and acquires data independent of human operators (Kuntze and Haffner, 1998). More recently, a comprehensive automated defect detection methodology for sewer inspection and condition assessment was proposed (Guo et al., 2009; see Fig. 8).

In the robotic system which consists of different traditional sensors (e.g., CCTV, sonar, laser), a multiphase scenario was proposed to handle the different inputs from sensors. In the first phase, the inspection robot will move at its normal speed, and it will detect whether a potential defect exists or not in the pipe under inspection. If a potential defect is identified, the robot will be instructed to stop and record higher quality visual data and then it will be determined from this newly-collected information whether it is a real defect or a false alarm. This first phase is called ‘defect detection’. If a ‘defect’ is identified as a false alarm, the robot will keep moving. Otherwise, the robot will stop, call for further sensing, and perform an in-depth examination. This is the second phase and is called ‘defect interrogation’. In the third phase, called ‘defect classification’, the defect detected will be classified automatically, either during the inspection process or off-line after the inspection process, using a variety of defect classification techniques. In the defect interrogation and classification phases, multiple sensors might be used to capture different aspects of the pipe condition. It is noted that the method for object detection and recognition is still an active research area in the fields of image or video processing and computer vision. Further
Table 1
Advantages, disadvantages and potential of the current techniques for condition assessment of utilities especially water and sewage pipelines.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Main advantages</th>
<th>Main disadvantage (technical challenges) and potential solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Visual techniques</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visual inspection</td>
<td>Most accurate for areas which can be seen</td>
<td>Most of the utilities do not allow human access; slow; subjective and good training required; only to be carried out in big and accessible pipe/ sewer/ tunnel; cannot see inside defects</td>
</tr>
<tr>
<td>CCTV</td>
<td>Real time assessment</td>
<td>Subjective; relatively inaccurate; can be slow; image must be above the water surface; lack of geometric references, unsteady camera movement and generally poor quality images; limited information since relying on images of pipe interiors</td>
</tr>
<tr>
<td>Sewer scanner evaluation technology (SSET)</td>
<td>Increased survey speed since it uses post processing method</td>
<td>Post processing, rely on obtained images only, which means no chance to re-evaluate the suspicious defects locally; subjective Automation assessment can improve efficiency; assessment algorithm can improve accuracy; accuracy can be improved by a combination with other sensing techniques, such as GPR and CCTV</td>
</tr>
<tr>
<td><strong>EM and RF techniques</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic Flux Leakage (MFL)</td>
<td>Good for cast iron and steel pipes; can detect small defects</td>
<td>Access to pipe required; cleaning of pipe interior required; close contact with the pipe is hard to maintain and can damage the lining of the pipe; struggles to detect short and shallow defects</td>
</tr>
<tr>
<td>Eddy current technique</td>
<td>Good for small metallic pipes</td>
<td>Access to pipe required; inspection depth is restricted by the skin depth  This can be overcome by Remote Field Eddy Current (RFEC) method which works in far fields Access to pipe required</td>
</tr>
<tr>
<td>Hydroscope technology (RFEC)</td>
<td>Good for big metallic pipes; can detect areas of corrosion pitting, as well as through holes</td>
<td>Not suitable where a thick pipe coating or lining is present</td>
</tr>
<tr>
<td>Rapid magnetic permeability scan (RMPS)</td>
<td>Available in both surface and in-pipe systems; quick and easy to operate; real time assessment</td>
<td>Cannot work well on less conductive ground; both active and passive detection are possible; in-pipe sensor system is possible</td>
</tr>
<tr>
<td><strong>Acoustic techniques</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sonar</td>
<td>Can measure pipe wall deflection, corrosion loss and volume of debris in invert</td>
<td>Can be operated in air or water, but not both simultaneously  Geophones need to be half-buried thus may not work for hard ground surfaces; bends in the pipework can pose problems for signal propagation; big attenuation in certain types of soil</td>
</tr>
<tr>
<td>Vibro-acoustics</td>
<td>Good for all types of pipes and cables</td>
<td></td>
</tr>
<tr>
<td>Ultrasonic guided waves</td>
<td>Good for corrosion detection; quick inspection</td>
<td></td>
</tr>
<tr>
<td>Acoustic Pulse Reflectometry (APR)</td>
<td>Useful for the detection of blockages within a pipe and leaks</td>
<td>Access to pipe required  Access to pipe required</td>
</tr>
<tr>
<td><strong>Rapid magnetic permeability scan</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radial flux leakage (LFEM)</td>
<td>Good for detection of live power cables; a passive system</td>
<td>Requirements are for skilled operators; signal maybe fully attenuated in certain types of soils; efficiency can be improved by modulation schemes</td>
</tr>
<tr>
<td><strong>Magnetic field techniques</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traditional GPR</td>
<td>Real time assessment; can determine ground condition; trenchless inspection, thus no need to dig</td>
<td>Requires a skilled operator; signal maybe fully attenuated in certain types of soils; efficiency can be improved by modulation schemes</td>
</tr>
<tr>
<td>In-pipe GPR</td>
<td>Real time assessment; signal attenuation is greatly reduced</td>
<td>Requires a skilled operator; access to pipe required; efficiency can be improved by modulation schemes</td>
</tr>
<tr>
<td><strong>Time domain UWB</strong></td>
<td>Broad working frequency range; better resolution; near real-time signal processing and visualization</td>
<td>Only works for non-conductive pipes; (semi) hollow pipe required</td>
</tr>
<tr>
<td><strong>Continuous wave Doppler sensing technique</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sonar</strong></td>
<td>Can measure pipe wall deflection, corrosion loss and volume of debris in invert</td>
<td>Can be operated in air or water, but not both simultaneously  Geophones need to be half-buried thus may not work for hard ground surfaces; bends in the pipework can pose problems for signal propagation; big attenuation in certain types of soil</td>
</tr>
<tr>
<td><strong>Laser surveys</strong></td>
<td>Can determine internal profile of the pipe along its length</td>
<td>Can only be used above water surface in sewer and water pipes</td>
</tr>
<tr>
<td><strong>Impact echo/spectral analysis of surface waves</strong></td>
<td>Overall condition of pipe can be assessed; works for pre-stressed concrete pipes; objective</td>
<td>Access to pipe required; geophones need to be mounted onto pipeline</td>
</tr>
<tr>
<td><strong>Wave impedance probe (WIP)</strong></td>
<td>Real time assessment; good for all pipes except ferrous pipes; can be used to assess conduit surrounds and pipe condition depending on the sensor and output strength selected; available in both ‘surface’ and ‘in-pipe’ systems Can see whole pipe interior; increased survey speed since it uses post processing method; objective</td>
<td>Received signals usually require post processing but major anomalies can be identified on-site Sonar scanner has low survey speed and low resolution (can use laser scanner in preferred situations); sonar surveys only detect gross defects; laser scanner do not work well for certain types of pipe wall (e.g., brick sewers); automated analysis of images possible Expensive; fibers are easy to break and difficult to repair</td>
</tr>
<tr>
<td><strong>Pipe inspection real-time assessment technique (PIRAT)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Acoustic Fiber Optics (AFO)</strong></td>
<td>Suitable for long term monitoring; one sensor and data acquisition system can be used to monitor up to 12.4 miles of pipe</td>
<td>Access to pipe required; hydrophone on umbilical cable inside pipe needs to be traced on surface of the ground in order to pinpoint leaks</td>
</tr>
<tr>
<td>Sahara system</td>
<td>Real-time system</td>
<td></td>
</tr>
</tbody>
</table>
research is needed to adapt and improve the existing techniques in image reasoning and computer vision for application to sewer pipeline infrastructure systems.

In addition, a combination of Magnetic Flux Leakage and ultrasonic testing has been proposed by Beuker et al. (2009). In such combination, general wall thinning and largely corroded areas are accurately and reliably scanned with the ultrasonic unit, while very detailed information about pitting corrosion is obtained from the MFL measurement. Blind spots of echo loss, occasionally observed in the ultrasonic data, are compensated by the more robust measurement from the MFL sensors. This is due to the fact that a magnetic pattern is typically larger in dimension than the anomaly that caused it, which greatly improves the probability of detection.

Acoustic monitoring of a pre-stressed concrete cylinder pipe (PCCP) has mostly relied on the application of hydrophones or piezoelectric sensors to continuously monitor the acoustic activity in a pipeline to identify the acoustic event associated with a breaking pre-stressing wire (Al-Wardany, 2008). Hydrophones and piezoelectric sensors have certain limitations that sometimes make it difficult to implement practical monitoring solutions. Recently, Higgins and Paulson (2006) reported that a significant advance was made in Acoustic Fiber Optics (AFOs). It applies acoustic monitoring technology for pipelines through the application of fiber optic sensors and optical data acquisition systems. The system consists of fiber optic sensors running through the pipe and on end is attached to an optical data acquisition with a laser that projects a beam of light through the fiber. Acoustic waves in the water column impart pressure waves on the fiber, which in turn, imparts stress waves on the fiber. When the beam of light encounters a changing stress field in the fiber the light is dynamically reflected. This dynamic reflection of light is returned to and analyzed by the data acquisition system to acoustically monitor the pipeline. Since the data acquisition system is using the entire length of fiber as a channel to transmit light, the entire length of fiber is being used as an acoustic sensor. A detailed description of the application of the fiber optic monitoring system on a 48 in pipeline where it was run in parallel with an acoustic monitoring system relying on standard hydrophone technology is given by Higgins and Paulson (2006). A commercial product using this technology can be found at www.puretechnologiesltd.com.

7.5. Sahara project

As shown in Fig. 9, Sahara pipeline inspections of water distribution pipelines are conducted while the main remains in service by inserting a sensor into any tap that is 50 mm or larger. A small parachute uses the flow of water to draw the sensor through the pipeline. The sensor is tethered to the surface, allowing for real-time results and maximization of sensitivity, while the position of leaks and other pipeline features are claimed to be located to within 500 mm (Clarke, 2000).

7.6. Integrated pipes

The multi-layer pipe is a new trend of pipe design. For instance, Egeplast (www.egeplast.de) produces ‘leak control pipes’ containing a thin electrical conductive layer inside of the pipe wall, which is made from aluminum and permits continuous leak monitoring as illustrated in Fig. 10. Similarly, as shown in Fig. 10, Egeplast SLM DCT pipes have thin conductive spirals embedded in the pipe wall. When currents are applied at one end of the pipe, the transmitted and reflected current can be monitored and the location of a broken point can be identified.

8. Multi utility tunnel (MUT)

A multi-utility tunnel (MUT) is ‘any system of underground structure containing one or more utility services which permits the placement, renewal, maintenance, repair or revision of the service without the necessity of making excavation; this implies that the structure is traversable by people and, in some cases, traversable by some sort of vehicle as well (APWA, 1997). According to Jefferson et al. (2006), there are no global standards for MUTs, thus a variety of alternatives exist and are in operation worldwide. They vary in size, shape, material, placement and location. Short-term cost is generally the issue for wide adoption of this method, while long-term costs should be much lower, which is particularly important in terms of sustainable infrastructure development. Research has been undertaken with the emphasis on sustainability of infrastructure development, for example see Hunt and Rogers (2005), which is adopting MUT, bespoke utility corridors or utili-dors (Rogers and Hunt, 2006). Indeed, Laistner (1997) showed that the long-term costs for MUT schemes were considerably lower than implementing trenching methods in Germany, while recent efforts have been put on the strategic planning needs for MUT in order to achieve sustainability development, see Hunt et al. (2006, 2009).

9. Discussion

Various techniques that might be capable of assessing or monitoring the condition of underground utilities are summarized in Table 1, where the advantages of the techniques are listed, while the technical challenges and potential solutions are also pointed out. It is evident that the advantages of one technique may well correspond to the disadvantages of another technique, and this is because the technique was developed for different practical scenarios such as for different types of pipe materials, different utility types, different soil conditions, and different ground surfaces. The collection of these techniques gives us the freedom to choose, however in some situations one technique cannot provide satisfactory inspection results and other techniques have to be incorporated in the inspection. Instinctively, the combined techniques can solve this problem to some extent, although it is impossible to produce
all of the combinations of the techniques listed in Table 1 that might suit particular specifications of conditions met in practice. Moreover, although the multi-sensor approach provides the most promising way forward, it is also important to note that an engineer has to decide for the specific practical situation being encountered whether to use a combined system or a series of single sensing techniques in sequence, since there is a wide variety of factors within the utility networks and the environment they are buried in that might favor one approach over another, and even the ground surfacing might influence the decision. One approach being considered is whether the technologies being developed for the Mapping the Underworld project (see Royal et al., 2011) might be of value in determining not only the location, but the condition of the buried utility service pipelines and cables beneath the streets. It is both evident and encouraging, therefore, that much effort has been, and is continuing to be, devoted to this subject area and the outcome is likely to be a more sustainable approach to street works in the future.

10. Conclusion

This paper has outlined and critically reviewed the various techniques that are used, and in some cases proposed, for the condition assessment of buried utility services. The wide variety of approaches is encouraging, and combinations can be chosen to suit particular site requirements and conditions. The commercial combination of certain complementary technologies is helpful, although in some instances it might be better to choose single technologies and use them in sequence. The point is made herein, and in a companion paper, that the buried utility infrastructure is to some degree controlled by the ground in which it is buried, and it is the condition of the ground as well as the condition of the infrastructure itself that needs to be taken into account. This is not only important in terms of the condition of the buried asset, as part of any assessment procedure, but is vital to inform engineers of the likely consequences of undertaking construction or maintenance operations for the asset in question or adjacent buried infrastructure. The concept of an integrated database containing ground properties (i.e. ground type and geotechnical/geophysical properties, and by extension ground condition) alongside utility infrastructure properties/current condition and surface infrastructure properties/current condition, has been proposed in the companion paper. The technologies reported and discussed herein provide one essential feature of being able to realize such a goal.

Acknowledgements

The authors wish to thank the UK Engineering and Physical Sciences Research Council (EPSRC) for funding the research that underpinned this paper via EPSRC Grants EP/F065965, EP/F06585X, EP/F065906, EP/F065973, EP/F06599X and EP/F007426. The authors are also grateful for the support from many industrial partners of the projects.

References


