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Title: *Mapping, Assessing and Monitoring Urban Underground Infrastructure for* Proceedings of the **11th International Workshop on Structural Health Monitoring 2017**

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ABSTRACT

This paper presents results from a series of measurements aimed at mapping, assessing and monitoring underground infrastructure, i.e. the water, sewer, gas, electricity, telecommunications and other supply lines that are vital to modern society. Most of this infrastructure is buried out of sight, in uncertain and highly congested locations and in an aging condition. Mapping, assessing and monitoring this infrastructure can lead to significant improvements in management, repair and growth practices. The sensors include multi-band and multi-static ground penetrating radar (GPR), and underground flow and condition sensing of water systems, including acoustic leak detection, linked by wireless and high-speed fiber-optic networks. Ground penetrating radar is one method available for locating underground utilities, but becomes challenging in urban environments due to the congestion of piping and difficulties with GPS-denied position registration. Ongoing efforts to overcome these challenges with advanced GPR techniques and the integration into a mapping database are presented, including results from field tests with pre and post construction ground truth evaluations. Data telemetry from buried infrastructure for IOT-type monitoring is hampered by the high-attenuation rate for wireless electromagnetic transmission. Results from experiments aimed at low-speed magnetic signaling with potential for high penetration through soils are presented.

INTRODUCTION

Buried urban infrastructure supports utilities, such as water, sewer, storm water, gas, electric, etc., along with transportation, i.e. subways. This infrastructure comprises vital components of modern society. Much of this infrastructure is in aging, in uncertain condition and uncertain locations. The American Society of Civil Engineers gives the drinking water and waste water infrastructure in USA grades of D [1]. As examples, Figure 1.a. shows an age distribution for drinking water pipes for a city in the northeastern U.S., and Figure 1.b. shows an old cast iron drinking water pipe with typical tuberculation on the inside walls.

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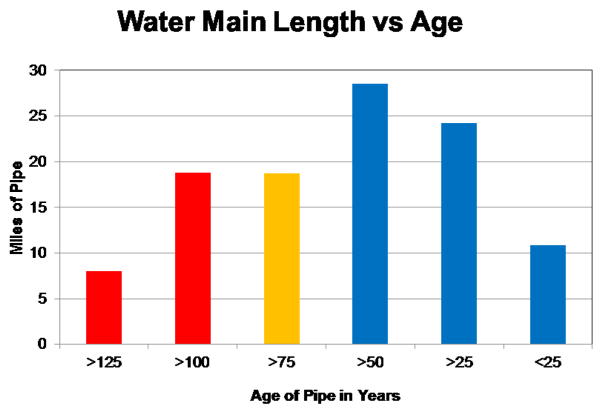
a.



b.

Figure 1. a. Age distribution of drinking water pipes in Burlington, VT., b. Aged drinking water pipe with tuberculation.

SMART CITIES APPROACH TO INFORMATION MANAGEMENT

Smart cities technologies aim at using modern network and sensor based methods to help better manage operations. Underground infrastructure management is a prime candidate for these techniques because much of the uncertainty of condition, location and prognosis for the infrastructure centers on the nature of being buried underground some time ago with many critical items out-of-sight, unrecorded and forgotten. Filling in the information voids can lead to more effective management of limited resources for the upkeep and growth of underground infrastructure, as well as cyberphysical control techniques. The proposed approach is to begin with a smart database map and sensor network for infrastructure buried in cities that is scalable in both technical and geographic scope. Some of the key ingredients are:

1. *Urban underground 3-D utility mapping and sensor network database* – This contains both 3-D mapping and condition assessment of underground infrastructure. The mapping should be compatible with industry-standard databases, i.e. BIM and GIS.
2. *Mapping with high-speed tomographic ground penetrating radar (GPR)* – GPR, while non-trivial to use, can provide images of underground infrastructure. An agile tomographic system that can move with traffic is needed.
3. *Underground sensor system* – Pipes and other buried structures should be monitored to determine condition and operational behavior. Technical challenges include energy supply and the high attenuation of wireless signals by most soils.
4. *Automated analytics* – GPR and sensor network data streams are multichannel, complicated and voluminous. Automated approaches for data analytics and visualization are needed, possibly with augmented reality techniques.
5. *Field test ground truthing* – It is imperative to verify the accuracy of sensory information, usually by observing conditions before and after excavations.

The successful implementation of these technologies will involve a long term effort, with expected information storage lifetimes running into decades, or even centuries with technical improvements on multiple fronts. Figure 2. shows an overall roadmap. The remainder of this paper describes some recent improvements towards this end.

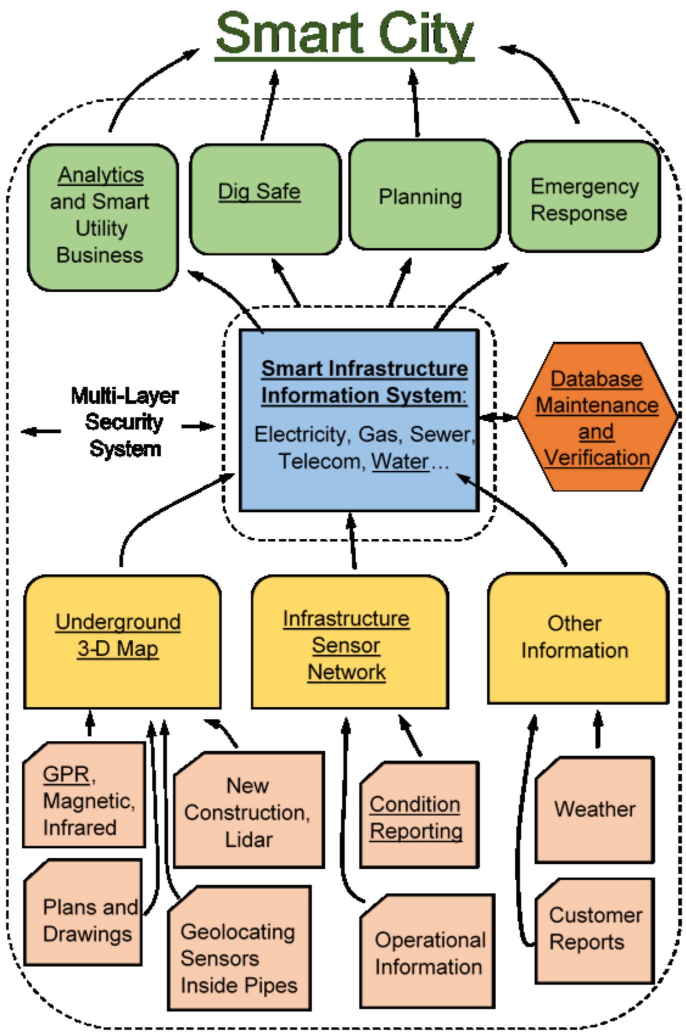


Figure 2. Long term vision of smart cities underground infrastructure mapping, monitoring and management system. Underlined items are those planned for inclusion in this project.

GROUND PENETRATING RADAR

Acoustic, electric, electromagnetic and magnetic approaches are the primary methods of noninvasively determining underground features and conditions. The long wavelengths associated with typical acoustic, electric and magnetic methods allow for sensing of conditions, but make it difficult for imaging. Electromagnetic methods allow for the use of high-frequencies and short wavelengths that enable tomographic imaging methods. Ground penetrating radar (GPR) is the most common of the electromagnetic methods.

GPR operates by launching high-frequency electromagnetic field disturbances into the ground and measuring the reflected waves and disturbances. GPR technology is somewhat mature, but more development is needed to overcome the technical challenges associated with sensing the underground infrastructure in an urban environment. These challenges include: 1. Need for rapid broad coverage of streets – Most GPRs collect data at travel speeds that are much slower than urban traffic (when it is moving). Ground-coupled sensing, places the antennas placed closely to the ground surface for improved penetration, which imposes mechanical constraints on sensing speed. Regulations covering radiated electromagnetic emissions limit the strength and repetition rate of the launched field disturbances [2]. 2. Key features often buried at depths of 2 m or more – A common solution is to operate at lower frequencies to enhance penetration. This comes at the expense of reduced spatial resolution and the need for additional signal processing to compensate; 3. Clays and wet soils prevent deep penetration with electromagnetic waves – The geological conditions may be sufficiently challenging to preclude GPR testing and require other methods, such as magnetic or acoustic. The appearance of localized wet and/or dry soils can correspond to water and/or gas leaks; 4. Variable dielectric properties produce lensing and scattering effects – Multi-channel signal processing methods have some potential for overcoming dielectric gradient scattering; and 5. Cluttering underground pipes and layers cause multipath effects – The congestion of underground urban infrastructure can pose severe data processing challenges.

Innovations in GPR can resolve some of these issues: 1. Phased array multichannel source methods with polarization control – These methods can electronically steer GPR source signals in a manner that is similar to traditional airborne phased array radar systems, but must account for the near-field geometries of GPR systems and the distortions of dielectric changes from air to soil, and gradients within soils [3]. Polarization control helps with locating elongated structures, such as pipes; 2. Full waveform multi-static data acquisition methods – The high-speed fluctuations of GPR signals renders them difficult to sample with ordinary analog-to-digital converters. Sub-sampling and frequency-domain methods are workarounds, but slow the overall sampling time and increased unwanted radiated emissions. It is possible to increase the sampling speed with high-performance full-waveform digitization techniques [4]; 3. Software Defined Radar (SDR) – SDR systems use digital control of send and receive hardware to provide facile flexibility of operational modes, some of which may be configured to advantage for challenging GPR situations; and 4. Position registration – Determining the position, orientation and polarity of GPR systems relative to the underground is essential for the use of synthetic aperture and related tomographic methods, especially for systems that must maneuver in traffic. GPS systems are inadequate to provide the proper resolution and difficult to use in urban canyons. Alternative registration systems are needed.

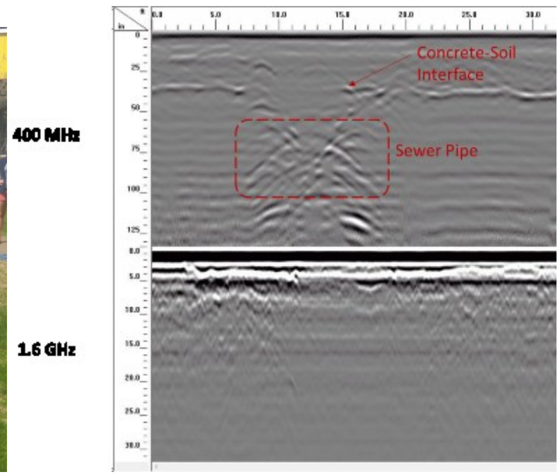
GPR Field Tests

Recent experiences with the measurements of underground infrastructure have laid out some of the possibilities and issues associated with the use of conventional GPR and the path forward for more advanced systems. The centerpiece of these measurements was a customized tri-band GPR system. This was an impulse radar system that operated with three channels and associated antennas as independent bi-static radars with center frequencies 1. 400 MHz, 2. 1.6 GHz and 3. 2.3 GHz. In general the experience has been that the 400 MHz band was the most effective for detecting subsurface pipes and feature due to the combination of resolution and depth of penetration, whereas the 1.6 GHz band was good for detection of pavement layers down to about 0.35 m and the 2.3 GHz system was well-suited for measuring to depths of 0.1 m, especially in reinforced concrete.

An example is the detection and location of a water drainage pipe under a bike path at the University of Vermont. The pavement above the pipe is mildly distressed due to soil subsidence. The pipe location and drains, along with an associated GPR scan appears in Figure 3. The GPR B-scans indicate that the 400 MHz band is better for identifying features at the depth of the pipe, whereas the 1.6 GHz band shows more detail near to the pavement. An examination of the soil layers indicated that the pipe was installed by a cut and cover process, which led to the subsequent subsidence.

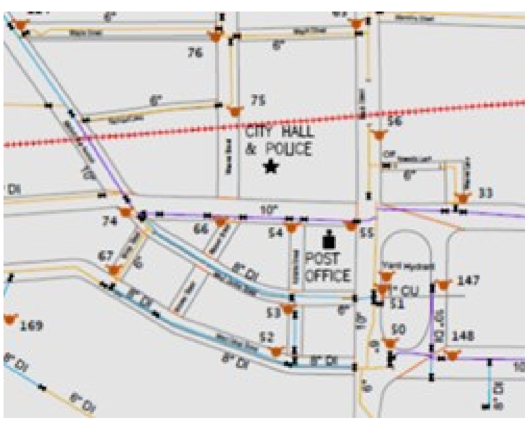
GPR also has the ability to detect subsurface dielectric anomalies corresponding to water leaks. Figure 4. shows a site in Winooski VT suspected of harboring a leak in the fresh water supply.

a. Bike path and drainage pipe direction.



b. B-scans at 400 MHz and 1.6 GHz with the GPR traversing the pipe.

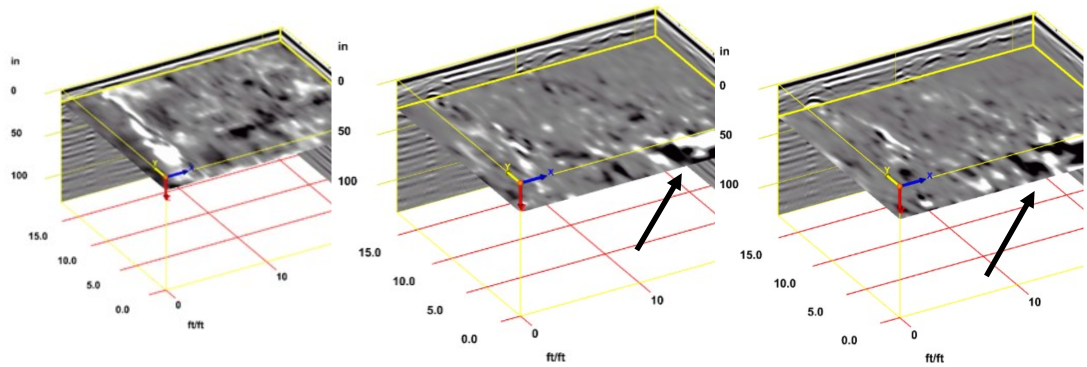
Figure 3. GPR scan of drainage pipe under bike path. The 400 MHz scan shows pipe and soil disturbance due to cut and cover installation.



a. Map of Winooski, VT with Railroad Ln.

b. Dual-band GPR system on Railroad Ln.

Figure 4. GPR Scan for water leak on Railroad Ln in Winooski, VT.



a. Depth Slice 1 – 15.3 inch.

b. Depth Slice 2 – 29.2 inch.

c. Depth Slice 3 – 33.2 inch.

Figure 5. C-scan horizontal slices from GPR scan of Railroad Ln showing a dielectric anomaly with location corresponding to the site of a probable water leak, indicated by arrows.

LoRa and Magnetic Signaling Methods for Wireless Point Sensing

The placement of an array of sensors at fixed locations is another mode of sensing the condition and operational behavior of underground infrastructure. Flow, temperature, moisture, and acoustic leak sensors are among the possibilities. Transmitting data to and from the sensors can benefit from wireless connections, especially for sensors buried underground.

The LoRa wireless networking system is well-suited for the transmission of data at low rates (10 bps or slower) over relatively long distances (1 km or more). It uses software-defined spread spectrum protocols for transmission [5]. In the U.S. the frequency band is 902-928 MHz. This network protocol favors some of the slower data rate and low-power sensing requirements for underground infrastructure. Figure 6. shows LoRa transceiver and sensor modules undergoing benchtop testing. The near term goal is to install these sensors as flow monitors in storm water sewers.

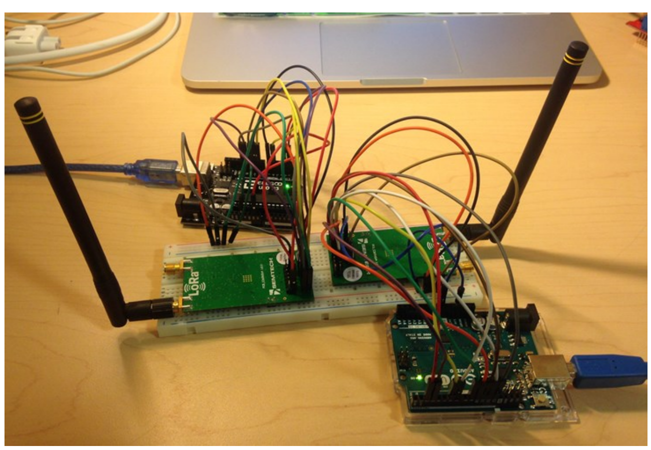
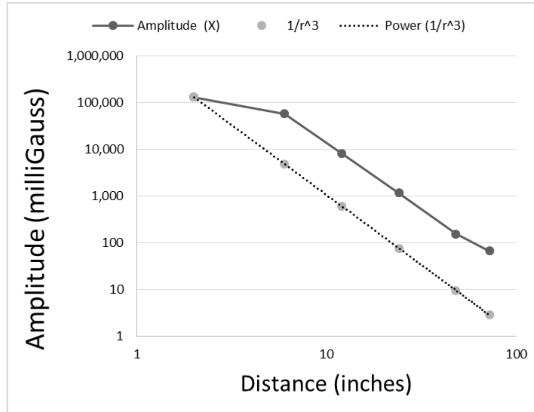


Figure 6. LoRa transceivers and sensor modules undergoing benchtop testing.

a. Rotating magnet transmitter in water tight box with rocks.



b. Field strength amplitude from rotating magnet versus distance and $1/r^3$ theoretical value.

Figure 7. Rotating magnet transmitter and field strength.

The high attenuation rate of wireless signals as they pass through earth and water makes them impractical for many underground sensor signaling applications. Magnetic field signaling at less than 3 kHz is a viable alternative for applications that can tolerate low data rates. The magnetic fields propagate in a quasi-static near field manner that drops off at a $1/r^3$ rate [6]. The recent appearance of relatively low-cost compact magnetometers (some down to 1 nT) combined with the mechanical movement of rare earth permanent magnets opens up the possibility of practical magneto-mechanical signaling methods. Towards this end, a series of proof-of-concept experiments has been undertaken to establish viability. Figure 7. contains a rotating magnet signal transmitter placed in a box with rocks for ballast in underwater testing, along with some typical field strength measurements in air.

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