APPLICATION OF ULTRA-WIDE BAND (UWB) RADAR IN DETECTING UNEXPECTED UTILITY LINES IN OPEN CUT OPERATIONS

*J. Zou
Design and Construction, Drainage Services, the City of Edmonton
14323 115 Avenue
Edmonton, Alberta
Canada T5M 3B8
*(*Corresponding author: junhao.zou@edmonton.ca)*

M. Lu, R. Karumudi, A. Tan and X. Shen
University of Alberta
Edmonton, Alberta
Canada T6G 2W2

APPLICATION OF ULTRA-WIDE BAND (UWB) RADAR IN DETECTING UNEXPECTED UTILITY LINES IN OPEN CUT OPERATIONS

ABSTRACT

Open-cut method is most widely used for shallow utility lines installation. In urban areas, unexpected utility lines buried underground potentially turn open-cut construction into a highly risky operation, increasing the construction cost while presenting additional safety hazards. Examples include: breaking existing water main leads to flooding the downtown area; hitting an unexpected gas line causes an explosion. To prevent those accidents, the current practice is to stake out the underground utility lines before the open-cut construction based on the as-built information collected from various utility companies and government agencies. However, the as-built information is not always complete and accurate. To verify the locations of some important utility lines and protect them against damages caused by open-cut construction, new techniques and technologies are used but have their limitations in revealing underground utility lines, such as hydro vacuum method and ground penetration radars (GPR). The emerging technology of ultra-wide band (UWB) radar holds the potential to provide a cost-effective, non-destructive detection method. In this paper, a critical review of current practices and established methodologies is given. The functionality and working mechanism of UWB radar technologies are described. Application potential in open-cut construction is demonstrated by conducting lab experiments. Testing set-ups for detecting unexpected utility lines in soil along with preliminary results are presented. The effects of soil moisture content on the detection range are discussed. Research findings are summarized and constraints are discussed in conclusions.

KEYWORDS

Construction management, Radar, Utility lines

INTRODUCTION

As the urbanization process accelerates in many municipalities in both developed and developing countries, more utility lines will be constructed in order to meet the demand from the growing urban population. Based on data collected in US, utility installation increase roughly 3% per year and there were over 183 million feet of buried utilities, valued at over USD $7 billion in 2003 (Jeong and Abraham, 2004). Open cut is the most efficient construction method in terms of cost and time to install shallow utilities lines, including water lines, cables, telephone lines, gas pipes and sanitary services pipes. Most of those pipes are buried up to 3 meters below the ground level. Although open-cut method has been applied for hundreds of years, damages to unexpected existing underground utility lines are not unusual. In the US in 1993, there are 104,000 utility line incidents resulting in costs exceeding USD $83 million. A single incident can be costly, especially when all consequential costs are taken into account (Table 1), not to mention any casualties as a result of breaking an unexpected gas line. Another investigation carried out by Drainage Services, City of Edmonton, Canada (City of Edmonton, 2011) shows that there were totally 136 utility line damage incidents caused by drainage pipes installation using open-cut method from 2008 to early 2011.

Table 1 - Breakdown of costs incurred during a single 1996 natural gas line rupture near a major shopping mall, caused by a backhoe puncturing a buried pipe (adapted from Bernold, 2003)

Cost Items	Estimated Amounts ($)
Fire Department	7,477
Police Department	3,759
Dept. of public works and utilities	4,532
Rescue Team	1,025
Repair by gas company	20,000*
Estimated loss of sales for 6 h evacuation	262,810
Estimated loss of wages to hourly employees	13,370
Total economic impact	**312,973**

*Note: This estimate does not include the actual cost of the lost natural gas.

To avoid damaging existing subsurface utility lines, "one-call" program has been implemented through the North America to coordinate various utility companies in providing safe underground utility locations. However, the staking of "one-call" is not completely reliable (Osman and El-Diraby, 2007) due to the incompleteness and inaccuracy of as-built information of underground utility lines. As a result, the staking of utility pipes, especially gas pipes and water mains needs to be confirmed by hydro-vac technology: a suction excavator or vacuum excavator loosens the earth by a water jet and removes earth surround the pipe slowly without damaging the underground pipes. However, hydro-vac also relies on the accuracy of staking. If the staking is not at the right place, the suction excavator is not able to expose the pipe. In short, chances of finding unexpected utility lines by using hydro-vac would be slim. And hitting unexpected utility pipes also constitute claims on increased costs and time extensions. As a result, how to identify unexpected underground pipe lines is vital to mitigate schedule and safety risks and reduce costs on open-cut projects.

One technique, the ground penetrating radar (GPR) was developed for revealing subsurface conditions thanks to its cost efficiency. The fact that radio signals can penetrate solid objects like glacier was found in 1929. But until late 1950s, no research had been carried out to use radio signals to detect subsurface objects. Since 1970s, GPR has caught more and more attention and has found diverse applications. Nowadays, conventional GPR operates in the microwave band and on a frequency normally less than 2 GHz. The principle of its operation is straightforward: when radio waves emanating from GPR encounter the boundary of two types of materials with different dielectric constants, a return signal reflects. The receiving antenna detects the return signal and determines the distance the radio wave travels. The advantages of GPR include: (1) it is a non-destructive method to detect underground objects; (2) The detection range of conventional GPR can reach up to 30 meters when GPR is used in dry materials. The limitations are: (1) it cannot perform well in high-conductivity materials, like wet soils; (2) interpreting the radargrams needs special training; and (3) considerable knowledge is necessary to design and conduct GPR surveys.

There have been many applications of conventional GPR in published research of geophysics. GPR was applied for detecting soil moisture levels in real ground conditions; the effects of soil electrical conductivity and soil roughness on the detection results were analyzed (Minet et al., 2011). The effects of soil properties on the performance of GPR were specifically evaluated (Takahashi et al., 2011). GPR was also used to detect geotechnical properties like liquid limit, dry density and percentage linear shrinkage of materials (Thomas et al., 2010). For preventing the rockburst, GPR was used to evaluate performances of different types of support in preventing the development of fracture inside crisp rock (Zhang et al., 2010). In addition, GPR has also been applied in materials research. One research effort applied GPR to discover the rebar in concrete (Soldovieri et al., 2011). Another used GPR to detect the corrosion of the steel bars in concrete and the water content in materials, such as concrete during different stages of hydration and brick wall buried in different depths (Lai et al., 2011). GRP was utilized to detect shallow structures. To improve the signal/noise (S/N) ratio, multiresolution wavelet analysis (MWA) was used for GPR noise suppression. Image processing methods were used to make the MWA process more effective by using a sub-image filtering technique (Jeng et al., 2011).

Because hitting existing underground utility lines is a major safety concern in pipeline installation, GPR was also applied in research to locate underground pipe lines, assisted by differential GPS positioning, robotic total-station positioning, and software systems for data acquisition, processing and interpretation, resulting in the creation of an accurate 3D model of underground structure and utility lines (Young et al., 2009). GPR was used to detect unexpected utility lines and infer utility pipe materials by the velocity of the radio signal when it travels through the pipes (Lester and Bernold, 2007).

Although GPR has been applied in research and application, existing GPR has yet been able to detect all underground pipe lines, identify the pipe materials and locate the pipe lines. It cannot disclose accurate information of underground utility lines. The problem can be attributed to the fact that "GPR operates in the microwave band of 300 MHz to 3 GHz which is lower than ultra-wide band (UWB) spectrum of 3.1 GHz to 10.6 GHz" (Lee and Singh, 2007). In contrast, UWB radar has the potential to provide more accurate data than existing GPR techniques. UWB is a technology for wireless communication operating on a radio wave of wide bandwidth. UWB is studied as the new generation of short-range wireless data transmission systems with high data rates. Due to its penetration capacity, it can also be used as part of real time locating system. Using pulse-based UWB radars and imaging systems can achieve precision locating and tracking. In comparison with conventional GPR, UWB radar's detection range reduces while its precision increases.

UWB is a fast developing non-destructive detection method and has been applied in many medical applications. For example, UWB was applied to detect the location of tumors in breasts for early detection of breast cancers as tumor and surrounding normal breast tissues have relatively different dielectric constants and the change of properties can be recognized by UWB antennas (Xiao et al., 2007). Another example is to use UWB to detect the characteristics of human arm muscles (Eldosoky et al., 2009).

In civil engineering, so far the UWB applications are mainly for resource localization, for example, using UWB to locate a vehicle in indoor and outdoor environments (Fernandez-Madrigal et al., 2007; Maalek and Sadeghpour, 2013), using UWB to identify potential collisions between labour and equipment (Teizer and Castro-Lacouture, 2007), performance evaluation of UWB localization (Saidi et al., 2011; Cheng et al., 2011; Shahi et al., 2012). Another research attempt was to use UWB tags to track assets on a construction site: tags sending off UWB waves were attached to objects; sensors at fixed locations were used to accept signals from the tags and determine accurate locations of objects (Cho et al., 2010). Another research effort compared the accuracy of UWB, WLAN and indoor GPS for localization (Khoury and Kamat, 2009).

It is appealing for construction engineers to apply UWB radars for detecting unfavourable ground conditions during construction so as to prevent unexpected accidents. Researchers in Europe are working on similar applications with GPR using UWB radio waves. Those UWB radars are mainly used to detect objects within a depth of 0.3 meters (Yarovoy et al., 2007; Zhuge et al., 2007). China is another country focusing on the development of UWB radars (Fang 2007). In another recent research, 3D information of buried objects was acquired based on the density of reflected UWB radio signals at various depths. Material types of objects were inferred by the estimated dielectric constants and the thicknesses of the various underground materials were estimated (Zou et al., 2012). The proposed research of UWB radar application uses similar methods to identify unexpected utility lines in open-cut construction applications. The objective of the research is to detect various types of pipes using specially designed UWB radar resulting from latest research in electrical engineering and to analyze the impact of varied soil moisture contents on the penetration depth of UWB radio signals.

METHODS

Imaging of Buried Pipes

This research was carried out to identify underground pipes in a storage yard. The power of the radar was increased to 4mW in this experiment. Using a set of movable transmitting and receiving antennas as in Figure 1, multiple measurements were performed on the surface of ground. To construct the 3D model, a grid was prepared to cover the measured area. The UWB radar measured the scattered signals in every intersection of grid one by one and recorded reflected signals from clay and objects. Then it used a post-processing program to generate 2D sections at certain depths and create a 3D plot of signal intensity based on the reflected signals received in different locations. With this method, the 3D information of buried objects can be obtained.

This experiment was set up to probe the 3D information of an empty PVC pipe, a PVC pipe with water and a 10mm thick steel plate (mimicking metal pipe.) See Figure 2 for the detailed dimensions of the objects. Those three objects were buried in depths of about 30cm and 50cm (the distance between the surface of backfill material and the bottom of the objects) as in Figure 3. The backfilling material is composed by sand, pebble and gravel with a moisture content of 5%. Figure 4 to Figure 7 show the measured contour section scans at various depths. The blue area in the figures is the area with low density of reflected radio signals and the red area in the figures is the area with high density of reflected radio signals. Compared with the PVC pipe with water, the empty PVC pipe is more difficult to be detected since

PVC material reflects less strength of radio wave than water and metals. That is why the empty PVC pipe is not able to be detected at the buried depth of 50cm. To increase the radar power can solve this problem. Using the similar method demonstrated in previous experiments, the object materials can be identified and what kind of utility pipe can be inferred.

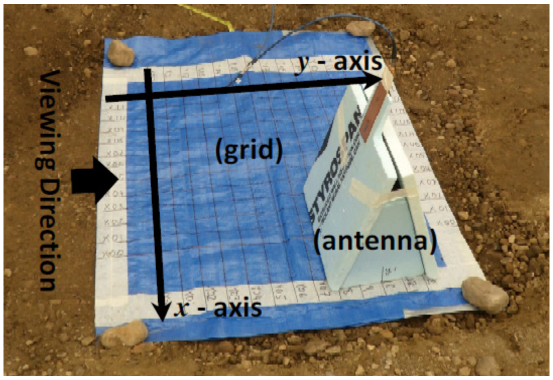

Figure 1 - The measurement grid and antenna

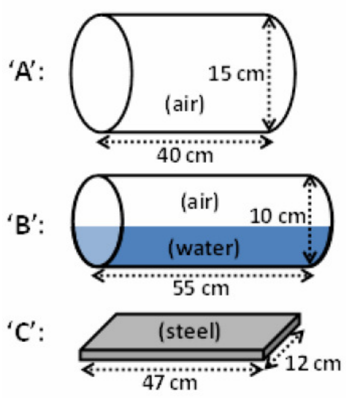

Figure 2 - The dimensions of object A, B and C

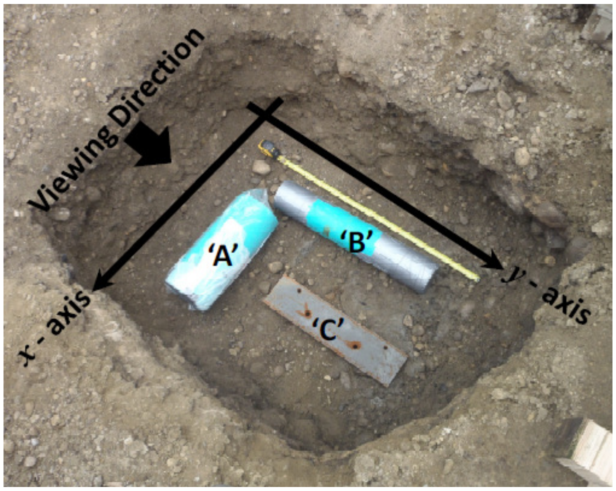

Figure 3 - The buried objects

Case 1 (buried depth = 30cm)

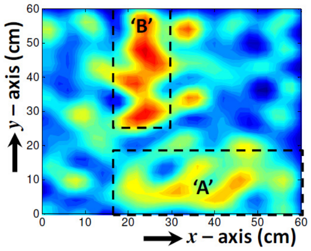

Figure 4 - Image of buried object A and B at a depth of 23cm

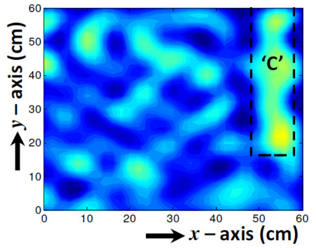

Figure 5 - Image of buried object C at a depth of 29cm

Case 2 (buried depth = 50cm)

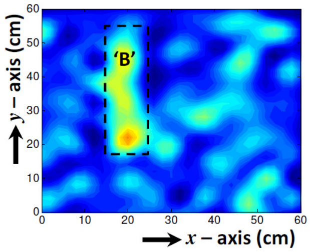

Figure 6 - Image of buried object A and B at a depth of 43cm

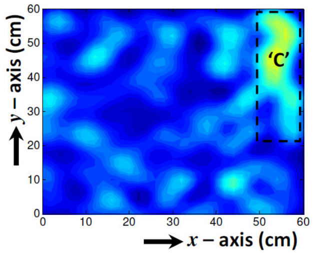

Figure 7 - Image of buried object C at a depth of 50cm

Impact of Moisture Contents

As it is mentioned in this paper before, dielectric constant (relative permittivity) controls the loss of strength of the radio wave passing through a specific material. And it is affected by humidity of the material. To understand how the dielectric constant of materials changes when the moisture content varies is very important to determine the detection range of the proposed UWB radar. As a result, another experiment the research team completed recently is to measure dielectric constants of sand with moisture contents ranging from 0 to 13.3%. The setup of the experiment is shown in Figure 8. Table 2 summarizes dielectric constants of sand decrease when the moisture contents increase. This is because that the dielectric constants of the media depend on the components of the media. Water's dielectric constant is much higher than dry sand's. So the more water in sand, the greater dielectric constant the sample has. Table 2 also lists the detection ranges under a specific power which can detect the objects buried one meter in dry sand by theoretical calculation. From Table 2, the detection range deteriorated quickly in wet sand.

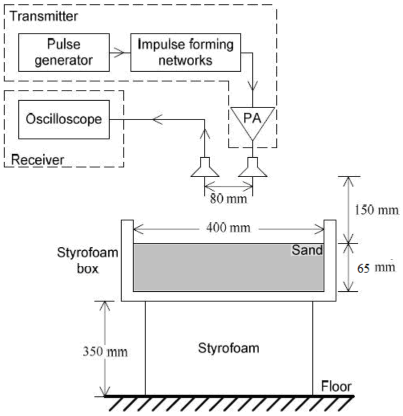

Figure 8 - Experimental set-up of lab testing to measure the dielectric properties of sand with various moisture contents

Table 2 - Dielectric constant of sand with various moisture contents and the depths of penetration

Sample No.	Moisture Content (%)	Estimated Thickness (cm)	Estimated Dielectric Constant	Estimated Detection Range	Comments on Experiment Data
0	0.00	6.27	2.32	1 m	Ok
1	2.70	6.60	3.20	31 cm	Ok
2	4.90	6.20	4.77	18 cm	Ok
3	9.20	8.10	3.90		This sample was deemed to be inaccurate during the measurements
4	10.40	6.05	5.83	12 cm	Ok
5	13.30	7.10	7.46	12 cm	Ok

CONCLUSIONS

From the existing research, UWB radar has demonstrated its capability to detect buried PVC pipes with or without water and metal objects in realistic site conditions. Once this technology becomes cost-effective and commercially available in the near future, the engineer can request a scan along the alignment of open-cut trench using the UWB radar so that a 3D model of existing underground utility lines can be created. The engineer can avoid a design option which collides with the existing underground utility lines, while the contractor can minimize the risks of damaging the unexpected underground utility lines during the excavation. Compared with traditional GPR, UWB radar has the following technical advantages in detecting underground utility lines.

1. UWB is capable of identifying different materials based on dielectric properties of various pipe materials.
2. UWB's system configuration is much simpler than the giant antenna array of traditional GPR and has a good mobility.

3. Since UWB has a shorter wave length than conventional GPR radio wave, UWB's sensing accuracy is much higher than GPR.

Although the UWB radar has the above technical advantages, it has its own limitations. First, the loss of UWB radar signals is higher compared with conventional GPR especially when it passes through wet materials. Second, application frequencies of UWB are very close to electromagnetic waves of microwave ovens and wireless communication devices, potentially causing signal interferences. Finally, there are still arguments on the safety hazards caused by UWB radiation if its power is significantly boosted. In the short future, we will limit the power of the UWB radar below 1W which is equivalent to the electromagnetic radiation released from a cell phone and still deemed safe.

REFERENCES

Bernold, L.E. (2003). Economic model to optimize underground utility protection. *Journal of Construction Engineering and Management, November/December 2003*: 645-652.

Cheng, T., Venugopal, M., Teizer, J., & Vela, P. A. (2011). Performance evaluation of ultra wideband technology for construction resource location tracking in harsh environments. *Automation in Construction, 20(8)*, 1173-1184.

Cho, Y., Youn, J. and Martinez, D. (2010). Error modeling for an untethered ultra-wideband system for construction indoor asset tracking. *Automation in Construction, 19 (2010)*, 43–54.

City of Edmonton (2011). Open cut procedures and processes: A review of open cut construction near utilities, April 7, 2011.

Eldosoky, M. A.A. (2009). The applications of the ultra wide band radar in detecting the characteristics of the human arm muscles. *Proceedings of 26th National Radio Science Conference, New Cairo, Egypt*.

Fang, G. (2007). The research activities of ultrawide-band (UWB) radar in China. *Proceedings of IEEE International Ultra-Wideband, 2007, ICUWB 2007*, Singapore.

Fernandez-Madrigal, J.A., Cruz-Martin, E., Gonzalez, J., Galindo, C. and Blanco, J.L. (2007). Application of UWB and GPS technologies for vehicle localization in combined indoor-outdoor environments. *Proceedings of IEEE International on Signal Processing and Its Applications, ISSPA 2007*, Sharjah, United Arab Emirates.

Jeong, H.S. and Abraham, D.M. (2004). A decision tool for the selection of imaging technologies to detect underground infrastructure. *Tunnelling and Underground Space Technology, 19*: 175-191.

Jeng, Y., Lin, C., Li, Y., Chen, C. and Yu, H. (2011). Application of sub-image multiresolution analysis of Ground-penetrating radar data in a study of shallow structures. *Journal of Applied Geophysics, 73(2011)*, 251-260.

Khoury, H. and Kamat, V. (2009). Evaluation of position tracking technologies for user localization in indoor construction environments. *Automation in Construction, 18 (2009)*, 444–457.

Lai, W.L., Kind, T. and Wiggenhauser, H. (2011). Using ground penetrating radar and time–frequency analysis to characterize construction materials. *NDT&E International, 44* (2011), 111–120.

Lee, J., and Singh S. (2007). Using UWB radios as sensors for disaster recovery. *Proceedings of IEEE International Ultra-Wideband, 2007, ICUWB 2007*, Singapore.

Lester, J., & Bernold, L. (2007). Innovative process to characterize buried utilities using Ground Penetrating Radar. *Automation in Construction, 16 (2007)*, 546-555.

Maalek, R., & Sadeghpour, F. (2013). Accuracy assessment of Ultra-Wide Band technology in tracking static resources in indoor construction scenarios. *Automation in Construction, 30*, 170-183.

Minet, J., Wahyundi, A., Bogaert, P., Vanclooster, M. and Lambot, S. (2011). Mapping shallow soil moisture profiles at the field scale using full-waveform inversion of ground penetrating radar data. *Geoderma, 161* (2011), 225–237.

Osman, H. and El-Diraby, T. (2007). Implementation of subsurface utility engineering in Ontario: cases and a cost model. *Canadian Journal of Civil Engineering, 34*: 1529-1541.

Saidi, K. S., Teizer, J., Franaszek, M., & Lytle, A. M. (2011). Static and dynamic performance evaluation of a commercially-available ultra wideband tracking system. *Automation in Construction, 20(5),* 519-530.

Shahi, A., Aryan, A., West, J. S., Haas, C. T., & Haas, R. C. (2012). Deterioration of UWB positioning during construction. *Automation in Construction, 24*, 72-80.

Soldovieri, F., Solimene, R., Monte, L. Bavusi, M. and Loperte, A. (2011). Sparse reconstruction from GPR data with applications to rebar detection. *IEEE Transactions on instrumentation and measurement, vol. 60, no. 3*, March, 2011.

Takahashi, K., Preetz, H. and Igel, J. (2011). Soil properties and performance of landmine detection by metal detector and ground-penetrating radar — Soil characterization and its verification by a field test. *Journal of Applied Geophysics*, 2011.

Teizer, Jochen, and Daniel Castro-Lacouture. Combined ultra-wideband positioning and range imaging sensing for productivity and safety monitoring in building construction. *Proceedings of the 2007 ASCE International Workshop on Computing in Civil Engineering. 2007.*

Thomas, A.M., Chapman, D.N., Rogers, C.D.F. and Metje, N. (2010). Electromagnetic properties of the ground: Part II – The properties of two selected fine-grained soils. *Tunnelling and Underground Space Technology, 25 (2010)*, 723–730.

Xiao, X., Kubota, S. and Kikkawa, T. (2007). A Method for Quasi 3- dimensional Imaging for Early Breast Cancer Detection by UWB. *Proceedings of IEEE International Ultra-Wideband, 2007, ICUWB 2007, Singapore*.

Yarovoy, A., Meincke, P., Dauvignac J., Craddock, I., Sarri A. and Huang, Y. (2007). Development of antennas for subsurface radars within ACE. *Proceedings of IEEE International Ultra-Wideband, 2007, ICUWB 2007, Singapore.*

Young, G., Wallbom, M., DiBenedetto S., Romero F. and Sjostrom K. (2009). Advances in underground imaging. *International No-Dig Show 2009, Totonto, Canada.*

Zhang, L., Sun, H., Li, S., Qiu, D. and Zhang D. (2010). Application of Ground Penetrating Radar to rock failure analysis in high risk tunnels. *Applied Mechanics and Materials Vols. 34-35 (2010)* pp 1661-1665.

Zhuge, X., Savelyev, T.G., Yarovoy, A.G. and Ligthart L.P. (2007). Subsurface imaging with UWB linear array: evaluation of antenna step and array aperture. *Proceedings of IEEE International Ultra-Wideband, 2007, ICUWB 2007, Singapore.*

Zou, J., Lu, M., Karumudi, R. and Shen, X. (2012). Application Potential of Ultra-Wide Band Radar for Detecting Bried Obstructions in Construction. *Proceedings of Construction Research Congress 2012: Construction Challenges in a Flat World. 2012*.