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3D Mapping of Underground Utility Networks Using Ultra Wideband Multi-Antenna Array Step Frequency Radar

Mohamed Jaufer Rakeeb

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3D mapping of underground utility networks using ultra wideband multi-antenna array step frequency radar

Mohamed Jaufer, Rakeeb
Mél : rakeeb.jaufer@cerema.fr

Abstract: This thesis work aims at development of an Ultra Wide Band (UWB) multi antenna array Step Frequency Radar (SFR) system and necessary signal processing steps required for detection, localisation and classification of underground utility networks. The system shall equip linear antenna array to cover the entire width of the road or the survey channel at optimal high speed suitable for highway and local urban roads. Moreover, it shall be capable of producing multiple parallel B-scans (radar image representation). The thesis was inspired as the solution to recently introduced government regulations in maintaining the geomatics database about the underground utility networks and positioning standards as a damage prevention measures during excavations. For example, class A, precision of three-dimensional position of sensitive buried networks is 11.25 cm as bound in NF-S70-003-2 standard in France. On the other hand, the solution must be very robust in highly dynamic, complex, unpredictable, dispersive subsoil environment which is suggested by the nature of this application. We have split the vast objective into two different sub tasks such as SFR system prototyping with data acquisition software development; and signal processing techniques for automatic pipe detection, depth and diameter estimation provided that the localisation accuracy meets the expectation of Class A precision. Hence, the prospective signal processing methods are highly oriented on Machine learning and computer vision based AI algorithms combined with other physical signal processing techniques.

Keywords: *Utility mapping, Step frequency radar, GPR, Machine learning, Deep learning, Signal processing.*
Collaborations : Cerema, Logiroad, Université Gustave Eiffel (formerly, IFSTTAR).

1 Context

Utility surveying generally refers to the locating, positioning and identification of buried pipes, cables and ducts irrespective of their sizes, depths and material types. The need for precise utility mapping aroused as a consequence of catastrophic damages incurred on the existing utility network while attempting excavations around existing facilities. In these scenarios, the excavation damages costs massive amount of time and resources for the corrective maintenance [1]. In addition to that, the inaccuracy of the underground utility network asset details resulted in serious accidents roughly at scale of 50,000 to 100,000 per year including 4500 gas leaks in France alone causing several damages and put human life at risk. Hence, fatal accidents in 2007 and 2008 in France led to the amendment of the labor regulations in the vicinity of pipelines since 1 July 2012, including legislation, four decrees and a standard (NF S 70-003 - Part 1 to Part 3). The standard defines the accuracy of the location of a pipeline, from class A when the 3D positioning uncertainty is less than 40 cm, which suggests depth uncertainty of 11.25 cm. On the other hand, database of geographical information systems applied to networks have become the main focus of local authorities, which demands heavy investments in geomatics science.

As damage prevention measure in accordance with regulations, utility network detection and mapping have become in practice worldwide. Traditional destructive testing methods are usually expensive and time consuming and they cause damage to the tested structures. Some Non-Destructive Techniques (NDT) such as acoustic, electromagnetic or RFID technologies are used to find underground pipes. However, existing NDT-based mapping methodologies are not very economical and precise to meet the expectations, as several methods are limited to metallic pipes. Ground-Penetrating Radar (GPR) is a relatively new NDT technology based on electromagnetic pulse which is applied in various civil engineering applications. It does not directly provide a 3D position but a 2D subsurface mapped image (described as B-scan) that requires interpretation by an expert. These B-scans can reveal soil conditions and buried utility pipes down to depths up to 2 m. The hyperbola signature on the B-scan is the ultimate local feature to investigate the presence of pipes in the target medium. Thus, any GPR based signal processing methods have been focused on identifying and quantifying such hyperbolic features on the radiogram (B-scan). The attraction of GPR technology over lead other NDT methods by its ability to detect metallic and non metallic pipes. Nevertheless, the lack of 3 dimensional mapping provision of conventional impulse GPR, the slow acquisition speed and its limitation of bandwidth are the constraints for utility mapping application. This nature of application requires high speed and high resolution sensors to adopt to different non predictable environment

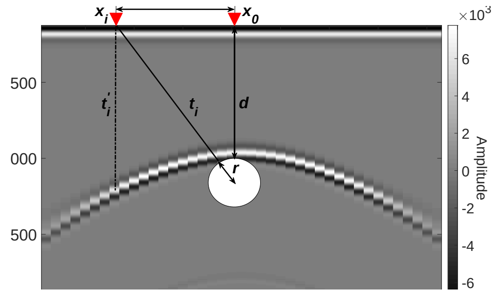

Figure 1: Example of a GPR signal image (B-scan) with a ground truth geometry of a buried cylindrical pipe at d: depth, r: radius, x_i: horizontal positions of zero-offset ground coupled GPR, t_i: travel time of the pulse.

(example: highway, urban, rural roads and pavements) and different ground conditions (example: soil, concrete, asphalt etc). Moreover, commercial GPRs are highly expensive.

To overcome the technical limitation of conventional time-domain impulse GPR, Step Frequency Radar (SFR) can be used. Developed by researchers and commercial manufacturers for ultra wide band scientific measurements, SFR is a type of GPR that operates in the frequency-domain. It is highly attractive by its dynamic control of the impulse bandwidth (frequency points) and relatively higher acquisition speed. However, in the domain of utility survey application, existing commercial SFR acquisition systems are highly expensive and do not provide any detection and inversion features (such as automatic pipe detection or parameters estimation features). Limited amount of studies have been already performed by researchers to develop varieties of signal processing techniques for automatic detection, depth and diameter estimation of utility pipes. However, neither of them demonstrate its robustness nor are they validated on unpredictable dynamic ground conditions and/or on large spatial field stacked data. Consequently, this thesis has been focused firstly on developing a sophisticated solution to counter the above outlined problems. Whereas the research includes development of a novel ultra wide band step frequency radar system with appropriate ultra wide band multi antenna array and necessary hardware and software components. In parallel, several scientific studies are performed to develop necessary signal processing techniques for the automatic pipe detection, depth and diameters inversions. The scope is therefore subdivided into two different domains such as SFR systems engineering and signal processing to simplify the thesis structure.

2 Thesis objectives

This thesis work aims at construction of a Ultra Wide Band (UWB) multi antenna array based Step Frequency Radar (SFR) and develop necessary signal processing steps required for detection, localisation and classification of underground utility networks. The system equips a linear antenna array to cover the entire width of the road or the survey channel at optimal high speed suitable for highway and local urban roads. Moreover, it shall be capable of producing multiple parallel B-scans. In the mean time, the solution must be very robust in highly dynamic, complex, unpredictable, dispersive subsoil environment which is suggested by the nature of this application. We have split the vast objective into two different sub tasks such as SFR hardware prototyping and data acquisition software development; and signal processing techniques for automatic pipe detection, depth and diameter estimation provided that the positioning inversion accuracy meets the expectation of Class A precision. Hence, for the prototyping, we have carefully studied the selection of most suitable signal generators, antenna and other components, in terms of ultra wide bandwidth, dynamic range, maximum output power and measurement speed.

It is confirmed that the 'hyperbolic' signature on the GPR image representation (B-scan) is the ultimate feature confirms presence of a pipe [2]. Thus, the signal processing techniques deal with A-scans and B-scans as shown in Fig. 1. According to various bibliographic studies suggest that Utility network detection, positioning and classification requires series of signal processing steps such as A-scan and B-scan formation, Geo-correction, data preprocessing like time zero offset, gain, background removal, clutter and noise removals, frequency filters, automatic hyperbola detection, depth and diameter parameter estimation.

On the other hand, ray-based method and machine learning algorithms such as SVM (Support Vector Machines), ANN (Artificial Neural Network) and CNN (Convolutional Neural Network) have been identified as potential methodologies for the hyperbola detection and parameters estimation respectively. Several studies have been already initiated by researchers with this approaches. Hence, Ray-based method, Multi-class SVM, Support Vector Regression (SVR), ANN and CNN are proposed in this thesis for the estimation of depth, radius and velocity. Due to lack of labeled experimental data at this stage of research, the open source GPR modeling software namely gprMax [3] was used to simulate and build approximately 2500 B-scans with single metallic pipe varying depth, radius of the pipe and, velocity and conductivity of the propagation medium. As input signal features for SVM, SVR and ANN, the hyperbolas were initially extracted from all B-scans *w.r.t.*, the travel time and then the features were extracted from these hyperbolas. In the meantime, CNN approach uses the raw B-scan signal images. Likewise, for automatic pipe detection from the signal images, deep learning algorithms such as Faster-RCNN and Yolo-3 has been studied combined with necessary signal processing techniques. The models have been subsequently numerically validated at this stage. Finally, experimental validation is scheduled in very near future.

3 Implementation

3.1 Step frequency radar development

Step Frequency Radar (SFR) is a type of Ground Penetrating Radar (GPR). In fact, an impulse GPR generates direct time domain signals (A-scan), and several A-scans are then stacked together to form a 2D signal image namely B-scan. In contrast, SFR transmits and receives narrow discrete pulses in the frequency domain. This is followed by inverse Fourier transform to build the time signals (A-scans or B-scans). Due to the dynamic frequency configuration and better acquisition speed performance, SFR technique has been adopted in this thesis.

Further, literature suggests that the data acquisition speed performance of a SFR depends on number of sweep frequency, Inter-frequency Bandwidth (IFBW) and horizontal distance between two adjacent A-scans (*i.e.*, horizontal resolution). Then, the depth penetration ability is influenced by the transmit power and gain of the antenna. Hence, we have studied all possible factors, appropriate type of signal generators and antenna characteristics which would highly fulfill the technical aspects of the application. In this context, we have initially developed a two antenna SFR prototype operating between 400 MHz - 3.5 GHz, with a high directive Vivaldi antenna as shown in the Fig. 2.a. Moreover, a distance encoder was integrated to the prototype in order to trigger the control system in equal horizontal distance. Apart from that, a real time data acquisition and visualisation software development with multi processing computational capability which has been developed in python platform. Finally, the system was validated on a geo-site located the Nantes site of the Gustave Eiffel university. The prototype could attain the acquisition speed around 5 Km/h at horizontal resolution of 5 cm between two measurement positions. The B-scan of the experiment is presented in the Fig. 2.b and observed hyperbolas indicate the presence of buried pipes.

[a]

[b]

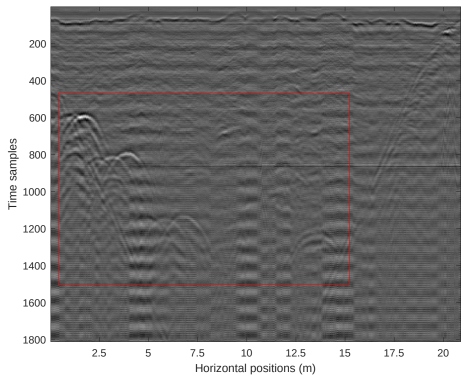

Figure 2: a) Two antenna array step frequency radar prototype, frequency band: 400 MHz - 3.5 GHz; b) B-scan produced by prototype. Hyperbola indicates presence of buried pipes

3.2 Parameter estimation (depth and radius)

The inversion of geometric parameters, such as depth and radius of embedded cylindrical pipes, as well as the dielectric parameters of its surrounding material is of great importance for precise 3D mapping of underground utility networks. In this aspect, innovative signal processing techniques associated with GPR are capable of performing such physical and geometric characterization tasks. Hence, Machine learning methods (SVM, SVR, ANN and CNN) and physical ray-based methods are all researched and proposed in this thesis with their individual advantages and limitations. All methods were studied to correlate information about the radius and depth of embedded pipes with the velocity of stratified media in various configurations. The approach is based on the hyperbola trace emerging in a set of B-scans, given that the shape of the hyperbola varies greatly with pipe depth and radius as well as with velocity of the medium. According to the ray-based method, an inversion of the wave velocity and pipe radius is performed by applying an appropriate nonlinear least mean squares inversion technique. The features selection within machine learning models is also implemented on the information chosen from observed hyperbola travel times. Simulated data are obtained by means of the Finite-Difference Time-Domain (FDTD) method with the 2D numerical tool GprMax. The study is carried out on mono-static, ground-coupled GPR datasets. Finally, a parametric comparison is performed on the aforementioned techniques in terms of relative error estimation with respect to design parameters. Overall, its found that the depth information can be retrieved at precision > 97% using above mentioned machine learning and deep learning approaches that satisfies Class A precision of the government regulation.

3.3 Pipe detection

Literature specifies several works already carried out on the automatic detection of hyperbola (as a signature of pipe) on GPR B-scans. However, most of these works focus on the use of supervised machine learning algorithms for automatic detection of pipes. [1] has recently built a pipe detection model based on hyperbola dictionary developed through three parametric features of hyperbola with the learning algorithm of SVM. His method achieved around 95% accuracy on limited experimental data with several assumptions. In this context, our research proposes the models based on Faster-RCNN and YOLO-3 based deep convolutional neural networks (DCNN) for the auto detection of pipes from GPR signal images. The models have been numerically validated, and the experimental validation shall be first performed on SFR data obtained from commercial SFR, in near future. At this stage of the research, numerical validation indicates detection accuracy > 99%.

4 Conclusion

The aim of this paper about development of technology necessary for mapping of underground utility networks using step frequency radar; and relevant signal processing method for detection, localisation and estimation of geometric parameters based on physical and artificial intelligence methods. At this stage, proposed sensor and methods provide promising results and require further work to accomplish a fully operational solution.

5 Accomplishments

- Published a conference paper entitled “Ray-based method vs. SVM for the inversion of embedded cylindrical pipe’s parameters from GPR data: Numerical comparative study “ in 18th International Conference on Ground Penetrating Radar, Golden, Colorado, 14–19 June 2020. https://doi.org/10.1190/gpr2020-093.1
- Submitted a journal article entitled “Ray-based method vs. SVM for the inversion of embedded cylindrical pipe’s parameters from GPR data: numerical comparative study” to Journal of NDT& E International
- Submitted a conference paper entitled “Deep learning for the parameter estimation of buried cylindrical pipes” in Near Surface Geoscience Conference & Exhibition 2021, Bordeaux,France
- Submitted a conference paper entitled “Deep convolutional neural network for estimation of depth and radius from GPR raw signals” in Near Surface Geoscience Conference & Exhibition 2021, Bordeaux,France

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