Journal of Applied Geophysics 92 (2013) 8–19

Contents lists available at SciVerse ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

3D mapping of buried underworld infrastructure using dynamic Bayesian network based multi-sensory image data fusion

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ARTICLE INFO

Article history:
Received 11 January 2013
Accepted 11 February 2013
Available online 27 February 2013

Keywords:
Vibro-acoustic
Pipe excitation
Ground excitation
Image data fusion
Ground Penetrating Radar
Dynamic Bayesian network

ABSTRACT

The successful operation of buried infrastructure within urban environments is fundamental to the conservation of modern living standards. In this paper a novel multi-sensor image fusion framework has been proposed and investigated using dynamic Bayesian network for automatic detection of buried underworld infrastructure. Experimental multi-sensors images were acquired for a known buried plastic water pipe using Vibro-acoustic sensor based location methods and Ground Penetrating Radar imaging system. Computationally intelligent conventional image processing techniques were used to process three types of sensory images. Independently extracted depth and location information from different images regarding the target pipe were fused together using dynamic Bayesian network to predict the maximum probable location and depth of the pipe. The outcome from this study was very encouraging as it was able to detect the target pipe with high accuracy compared with the currently existing pipe survey map. The approach was also applied successfully to produce a best probable 3D buried asset map.

1. Introduction

The preservation of buried infrastructure within the urban landscape is of fundamental importance if modern living is to be maintained. Failure to maintain the buried infrastructure can rapidly result in the breakdown of utility service provision; yet traditional open-cut methods used to repair and replace the buried utilities are inherently disruptive to society's functions and damaging to the carriageway (beneath which the utilities are commonly buried), and potentially the buried infrastructure itself. A recent UK study estimated that street works cost the UK £7bn in lost revenues annually; comprising £5.5bn in social costs and £1.5bn in direct damages (Royal et al., 2011). Open-cut practices deployed within the carriageway constitute a significant proportion of this work, and hence cost (Muggleton et al., 2011). Trenchless technology could be used in place of open-cut methods when installing or repairing the buried infrastructure, although concerns over the risk of damaging existing adjacent utilities have limited the uptake of these techniques (particularly those that excavate, displace, or otherwise disturb the ground). These risks partially stem from the inability to precisely locate all buried utilities below the carriageway without some form of proving excavation. The Mapping the Underworld (MTU) initiative is an umbrella for several EPSRC-funded projects that collectively aim to research and develop the tools necessary to locate, position, and electronically record the buried utilities, in the context of UK practices. One of the MTU research projects focuses on developing a prototype multisensory platform that can be used to improve the probability of complete detection of all buried utilities below the carriageway (Muggleton et al., 2012a, 2012b). This platform will employ four geophysical location technologies previously identified in a feasibility study as being potentially complementary and which, when intelligently combined, should improve the probability of utility detection. Vibro-acoustics is one of the four technologies to be incorporated into the platform (Hao et al., 2008).

The outcomes from a prior feasibility study identified that Vibro-acoustics offers the opportunity (Beck et al., 2007) to locate buried infrastructure, in particular plastic pipes. Two basic deployment strategies were identified: direct excitation of the utility (via an access point, such as a manhole) and excitation of the ground (Metje et al., 2007). A modified system would also have significant potential for use in-pipe, although this is not being researched at this stage (Royal et al., 2010).

To meet the aim of the MTU project, that is, to demonstrate the ability to detect all utilities buried below the carriageway, a comprehensive programme of proving trials is being undertaken to assess the capability of the prototype device (Muggleton and Brennan, 2006). However, as the sensing technologies and their deployment strategies are being developed, it is important that initial phases of testing

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http://dx.doi.org/10.1016/j.jappgeo.2013.02.005

on sites containing simple utility layouts, with known positions, are carried out (Muggleton and Brennan, 2008).

The first phase of testing occurred at a site located near Blithfield reservoir in Staffordshire, UK (Muggleton et al., 2002). The test site was specifically created to permit the investigation of leakage detection in water distribution pipes using acoustic technologies, and as such comprises a buried water pipe (over 100 m long) with several access points spaced along the pipe allowing for the simulation of leaks via a shaker or standpipe. The site also contains a buried electricity cable, thus allowing for the testing of all sensor types being developed for the project (Muggleton et al., 2004).

The development of the Vibro-acoustic location methods has reached the stage where initial testing was undertaken and the findings provide important leads for those seeking to optimize individual sensor technologies or seeking to combine sensors to improve detection rates. The results from the two types of Vibro-acoustic image data namely, direct excitation of the utility (via an access point, such as a manhole) and excitation of the ground have been analysed and proved to be very encouraging.

Ground Penetrating Radar (GPR) reckoned by many to be the mainstay of the shallow geophysical techniques used to detect buried utilities. Image data from the traditional surface-mounted GPR sensor were analysed in this study along with the Vibro-acoustic image data. Commercially available dual frequency pulse-system GPR (250 MHz and 700 MHz) was used for this study for multi-sensor image data fusion to detect the water distribution pipe as a common target (Fig. 1).

2. Science challenge

The MTU multisensory device project focuses not only on the development of the multisensory platform, but also intelligent combination of the sensors' outputs with information on the properties of the ground, via the development of a Knowledgebase System, as well as utility companies' record data. It is widely reported that the deployment of a single geophysical sensing technology, or a sequential use of sensor technologies, is unlikely to locate all underground utilities.

The development of image processing algorithms for the Hybrid Vibro-Acoustic and Ground Penetrating Radar systems was the main focus of this study to make the whole image inspection process automatic. This will replace the manual inspection process and eliminate the possibility of human assumptions.

This study also focused on an intelligent image data fusion framework using dynamic Bayesian network to combine these different types of images to produce 3D buried infrastructure map of the unknown underworld objects.

3. Vibro-acoustic location methods

Detection via pipe excitation arose from previous work on leak noise propagation and detection, indicating that when a leak is present, a significant amount of energy can propagate from the pipe to the surrounding medium at low frequencies (Muggleton and Brennan, 2004). The technique is depicted in simplified form in Fig. 2(a) and (b), with excitation of either the fluid directly or of the pipe structure (Popat et al., 2002).

Measurements on a dedicated experimental pipe rig demonstrated that the pipe excitation method could be successful in locating the run of a pipe when the pipe was excited vertically at the surface with an inertial shaker (Muggleton et al., 2012a, 2012b).

Frequency response measurements relating vibrational velocity on the ground to the input excitation were acquired. Contour plots of spatially unwrapped phase revealed the location of the pipe to within 0.1 m–0.2 m. Magnitude contour plots revealed the excitation point and also the location of the pipe end.

The ground excitation method exploits shear waves, which are generated at the ground surface. The resulting ground surface vibrations are measured, using geophones, along a line traversing the anticipated run of the pipe. Cross-correlation functions between the measured ground velocities and a reference measurement adjacent to the excitation are used to generate a cross-sectional image of the ground using a stacking method (Muggleton et al., 2012a, 2012b).

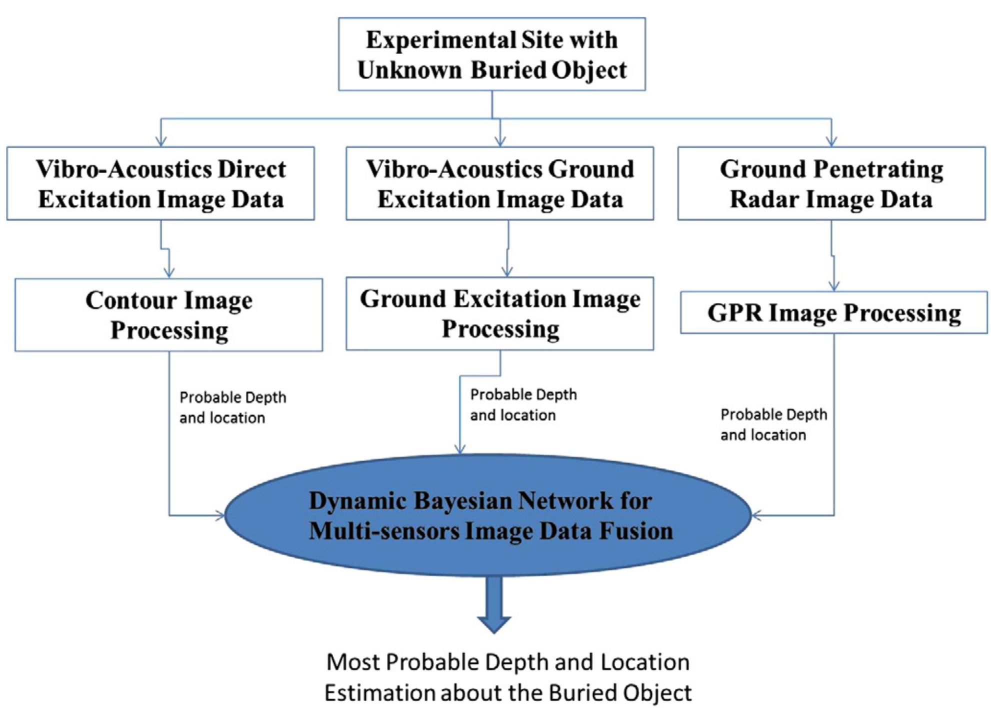

Fig. 1. Graphical abstract to demonstrate the work flow of the paper.