COMPREHENSIVE COLLISION AVOIDANCE SYSTEM FOR BURIED UTILITIES

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ABSTRACT

Society is often guilty of taking our buried utilities for granted. However, just like every other type of infrastructure, their neglect can have catastrophic effects. Therefore urgent attention is needed in order to facilitate and improve upon the current buried utilities maintenance techniques. The underground world is sometimes denser than the above-ground world. A classic example of this is Hong Kong where there are around 37 km of underground utilities under each kilometer of road. This figure is 8 times of that in the United States (Hong Kong Institute of Utility Specialists 2006). Unlike other types of infrastructure, buried utilities are difficult to locate and often even the act of accurately locating the utility poses a significant problem. Several accidents are caused due to mislocated or unmarked utilities. A system that helps in accurately locating as well as assisting in routine maintenance tasks of buried utilities is a top priority. This paper presents ongoing research at the University of Michigan that is investigating the use of high-accuracy Real Time Kinematic Global Positioning System (RTK-GPS), combined with Geospatial Databases of subsurface utilities to design a new visual excavator-utility collision avoidance technology. 3D models of buried utilities in the vicinity of an operating excavator are created from available geospatial data. These models and their corresponding attribute information are then superimposed (i.e. projected) over the excavator's work space using geo-referenced Augmented Reality (AR) technology to provide the operator and the on-site spotter with visual information on the location and type of utilities that exist in the vicinity of the excavator's digging implement. Additionally, the paper also introduces future goals of having a sensor augmented GIS system that would help warn database managers as soon as anomalies are detected. It is our belief that the combination of these systems would help in tackling the current difficulties experienced by maintenance personnel and contractors alike.

KEYWORDS

Buried Utilities, Augmented Reality, Collision Avoidance, Geophysical Technologies.

INTRODUCTION

As our cities have grown larger and denser, so has the underground infrastructure web. This underground infrastructure is a primary reason why today's mega cities can function smoothly. However with aging buried infrastructure, pipe bursts, costly repairs and exposure of citizens to risks of asbestos poisoning have become more common place (Belson and DePalma 2007). For example, Hong Kong's fresh water and salt water supplies are provided through a network of 7,200 km of water mains, most of which are underground. Approximately 45 per cent of the water mains were laid 30 years ago and are now approaching the end of their service life, becoming increasingly difficult and costly to maintain. Their repair is a massive project that will take place between 2000 and 2020 at a cost of $US1.3 billion (Trenchless Australasia 2005). Furthermore, our complete dependence on the smooth functioning of the underground buried utility systems such as Water, Gas, Sewage and Electricity becomes even more evident when a failure of any such system causes innumerous delays and inconveniences. Thus it is obvious that the area of buried infrastructure is in need of urgent attention.

The leading cause of accidents in both transmission and distribution systems is damage by digging near existing pipelines or conduits. Frequently, this damage results from someone excavating without asking or without waiting for the standard 48-hours that gas companies take to mark the location of its lines (American Gas Association 2010). The US Department of Transportation's Office of Pipeline Safety (PHMSA) combines third party damage, operator damage and outside force damage. This combination yielded nearly a 40% cause of all accidents being excavation related (American Gas Association 2010) leading to job sites such as the one seen in Figure 1 below.

The situation in a place such as Hong Kong is several times more complex. The dense and crowded environment of Hong Kong's streets is mirrored underground, where road openings invariably reveal a crowded spaghetti-like complex of utility services. It is common to find utilities running alongside each other with little or no clearance between them. This means that there is intense competition for space between the utility services, all of which are planning to upgrade or expand their underground services in the coming years (Vickbridge 2007).

Figure 1 The site of an excavator hitting a utility line

This fact tells us that operators and excavation contractors need some tools that will assist them to carry out their excavation in a safer manner, eliminating all the uncertainty attached with the current process. This paper describes our ongoing research towards addressing this critical issue and also introduces new technological solutions to aid in this effort.

PROBLEM DESCRIPTION

Current safety steps and methods

Utility companies (e.g. electrical, gas, etc.) are striving hard to reduce the number of accidents caused due to excavation related incidents. The Natural Gas Industry spends nearly $6 billion per year to keep up its excellent safety record (American Gas Association 2005).

Among the various efforts, the 'one-call' systems are arguably the efforts that have yielded maximum benefit in terms of incidents avoided. Under the one-call system anyone looking to carry out excavation of any type is required to call the local one-call program. The one-call agency in turn gets the location of utility lines in the concerned area by contacting utility companies in the area. A field agent is then sent to the field to mark out the approximate location of underground utilities using flags, stakes or spray paint. These color coded markings give a good indication to the operator of potential utility lines. In recent years however, the system has been further improved upon by allowing users to call a single '811' number that connects them to their respective local agency. In the US state of Michigan, MISS DIG SYSTEMS is the One-Call Utility Notification Organization. The turnaround time is about 48-72 hours from when a request is made till the markings are made. (Call811 2010) and may vary from state to state. The American Gas Association (AGA) estimates that nearly $58 million per year is saved through reduced damage to the environment, public safety and property loss as a result of the one-call system. However, the current one-call system suffers from a few limitations: firstly, the location of a buried utility is marked approximately on the surface within a 3 feet wide band rather than its exact location. Secondly, MISS DIG system (and most one-call systems) does not provide any information regarding depth of a buried utility (MISS DIG Systems Inc. 2009).

Other than the one-call system, efforts are targeted towards identifying corrosion before it leads to a pipe rupture. Miniature robots called pigs are used that travel through the pipes and check for areas of corrosion particularly in the petroleum industry (GE Energy 2010). Use of tracer wires and higher strength transmitters for plastic pipes that are otherwise difficult to detect is also an important step in using better quality materials (Finnsson 2006). Gas agencies frequently perform visual inspections of areas and check for patches of dried vegetation which is a clear sign of there being a gas leak (American Gas Association 2005).

Current Locating Techniques

Geophysical technologies are those technologies that assist in investigating the earth's sub-surface. While tremendous development has taken place in the field of locating technologies over the past decade, no one method has emerged as being complete and without flaws. The following is a brief description of the most commonly used methods in locating underground utilities.

Ground Penetrating Radar (GPR): Ground Penetrating Radar (also known as Ground Probing Radar) is a technique that uses short duration, high frequency electromagnetic wave pulses. These pulses are transmitted from an antenna into the ground. Materials such as rocks, water, or pipes buried below the surface reflect the waves which are returned as an echo. While GPR is widely used with good results, when used with conductive soils (clays, saturated soils, etc.) and in congested environments (presence of rocks etc.), it gives below par results (Read and Vickridge 1997)

Electromagnetic Techniques: Electromagnetic methods detect the field generated by the buried network and not the buried pipe itself. Electromagnetic techniques can be Active or Passive. Active systems depend on current being applied to the pipe and detecting the field thus generated. While in passive systems, the location is based on receiving natural signals transmitted from the underground assets themselves as would be the case of an electric conduit that has current flowing through it naturally. Electromagnetic methods are low cost, simple and quick but cannot locate non-metallic pipes except if tracer wires or Sondes are used (Read and Vickridge 1997).

Magnetometer Technique: This method works on the fact that the earth's magnetic field varies over a particular distance which is caused by underground features such as metallic pipes, large voids and ore bodies. The setup uses two coils to evaluate the difference in intensity and/or direction of the vertical component of magnetic flux which maybe caused by a ferromagnetic object. The advantage of this method is that it is relatively cheap. However, presence of buildings, cables, fences, etc affects the output considerably and thus this method cannot be relied upon entirely (Read and Vickridge 1997).

Resistivity Methods: The setup for this method uses 4 electrode probes placed in a line in the ground and a current passed through the outer pair. The inner pair measures the potential drop between them, giving an estimate of ground resistivity. However this method is quite slow. The electrodes need to be coupled very well with the ground making surveying beneath roads for buried assets difficult (Read and Vickridge 1997).

Acoustic Detection Systems: Although acoustic detection methods are primarily used for locating leaks in water mains, they can also be employed for detecting and mapping water distribution pipe networks. However the system requires easy access to the pipelines like a hydrant or a water meter. Passing traffic can also lead to sources of errors. Thus it is limited to small and shallow networks. No depth value can be obtained as well (Read and Vickridge 1997).

Infrared Thermography: This method is based on measuring very slight variations in temperature, and producing a thermographic image, where objects are represented by their thermal rather than their optical values. An infra-red scanner head and detector are used to capture the thermal data. The equipment is relatively expensive. Ground moisture content drastically affects the readings and depth values cannot be measured. Thus it needs a supplementary system to measure depth values (Read and Vickridge 1997).

Vacuum Extraction: Another method often used is Vacuum Extraction (Vacuum Excavation) or Potholing. This method offers the option of safely and economically excavating in areas inaccessible to conventional digging equipment. The air excavation method however cannot be used on hard surfaces like pavements and has a higher initial cost. The water vacuum excavation systems can cut pipes or electrical conduits due to the force of the water (Read and Vickridge 1997).

Each of the described techniques is effective in certain scenarios and less effective in others. However given the wide range of variables that one has to deal with in underground utility location, no single technology emerges as being comprehensive in locating underground utilities of all types in a range of soil conditions. Thus it is generally accepted in the industry that a multi-sensory approach that would utilize a combination of such technologies is likely to give more accurate results.

Inaccurate as-built drawings

Discrepancies between as-built drawings and actual location of utility lines and incomplete as-built drawings are the single largest cause for utility line hits (Hammond and Weintraut 2001). This issue leads to negating the positive effect of the One-Call System. Most utility owners including our collaborator DTE Energy, Detroit, Michigan concede that often times the as-built drawings show a completely different picture from what actually exists beneath (DTE Energy 2009, Personal Communication). Part of the problem lies in the method of laying utility lines. In extremely crowded urban environments, contractors are left with no choice but to shift utility alignments by a few inches to a few feet to account for existing utility lines occupying the same space. As-Built drawings thus do not actually represent the reality of what lies beneath (Hill 2006). Since existing As-Built data solely does not accurately serve the purpose of underground utility locations, an alternate method of location, based on a combination of recorded as-built data, and active real-time sensing is proposed in the following section. The accuracy of the as-built drawings is typically better for newer installations than for maps that are decades old. Thus data stored in a GIS (Geographic Information System) Database for newer installations can be relied upon with a great deal of confidence (DTE Energy 2009, Personal Communication). Our research aims to take advantage of the existing methods while complimenting it with additional technologies that together seek to tackle this uniquely complex problem of buried utility collision.

IMPORTANCE OF THE RESEARCH

The annual cost of accidents due to utility line hits during excavation is estimated at well over a billion US dollars. The number hits are so frequent that it virtually corresponds to one hit every 60 seconds (Spurgin et al. 2009). Incidents such as the death of 4 persons (Pipeline Accident Report 1998) due to a gas main explosion in St. Cloud, Minnesota in 1998 and the loss of power to Newark International Airport due to damage to the electrical line supplying power to the airport (Minneapolis Star Tribune 1995) have brought the attention of the government and public alike.

Federal Interest in Utility Locating Technologies

A Federal Study on Utility Locating Technologies suggested that that multi-sensor technology (GPR, Acoustic plus Electromagnetic) and multi-frequency approaches offer the greatest potential for stand-alone utility location in the future (Sterling 2000). The use of this multi-sensor technology together with a 3D model view of the buried infrastructure is one of the responses to the Statement of Need. The view would be of such quality so as to allow identification of material of pipe and other essential details. Section 15 of the Pipeline Safety Improvement Act of 2002 discusses the National Pipeline Mapping System which requires operators of pipeline facilities to provide to the Secretary of Transportation geospatial data appropriate for use in the National Mapping System, the name and address of the person with primary operational control, and a means for a member of the public to contact the operator for additional information about the facilities. There is a requirement to update the information as necessary. Such information can then be used by a system to create 3D models of the buried pipes and be projected onto the real world view. Thus there is all-round effort, guided by a federal agenda, to convert buried utility data into a format that is interoperable, accessible, and always current.

Global effort in utility repair and rehabilitation

With rapid increase in urban population and requirements to increase city sizes both horizontally and vertically, a corresponding increase in utility service lines is to be expected. An example of this is the $1.4 billion project undertaken by Hong Kong’s Water Supplies Department (WSD) to repair and upgrade nearly 3000 km of water pipelines with project completion scheduled for 2015 (Vickbridge 2007).

Shortcomings in current locating aids

As described earlier, current locating aids such as geophysical technologies are somewhat specific and no single technology can be applied to a large sample space. Furthermore, with the one-call system, once the top layer of pavement or soil is removed by the backhoe or shovel, and if the trench depth is more than mere hand digging depth, the markings are no longer present to aid the excavator operator. With rapid improvement in surveying technology and use of laser scanners to take location measurements, field readings can be relied upon much more than in the past. This leads to as-built drawings in the form of GIS databases that are not just graphical representations of what really exists but ‘smart’ data that can be processed and used in making location judgments. Our approach takes these limitations and advancements into account which is introduced in concept below and described in further detail in the following sections.

Collision Avoidance

Given the above challenges and critical nature of the problem at hand; it is felt that a collision avoidance system to aid the backhoe operators and excavation contractors is urgently needed. Such a system would provide feedback to the equipment operator is real-time and aid his/her decision making process. Collision avoidance systems have been seen in operation in some form or another in industries such as aviation and automobiles (Connolly 2007). Given their success in these fields, we believe a successful implementation is possible in the construction industry as well. This is particularly so in the area of excavations in congested urban environments. The following sections describe in detail the components of such a Collision Avoidance System and the challenges that are faced in implementing it. Given the current state of underground infrastructure in many of today's megacities, a comprehensive repair and rehabilitation program would be needed sooner rather than later. This situation provides excellent motivation to develop a system that would allow excavations to be carried out in the safest manner possible.

TECHNICAL APPROACH

The proposed collision avoidance system is envisaged as being able to be installed within the cab of a backhoe and also provide visual aid to the equipment operator. This represents a micro-level collision avoidance support. However such a system can easily be scaled up to provide a macro level collision avoidance framework. Details on these systems are described in the following sections along with the technologies used to implement and operate such a system. The main technological components are 1) GIS Data, 2) High precision Global Positioning System (GPS), 3) Telemetry and 4) Construction equipment installed with sensors.

Geographic Information System (GIS) Data

Utility companies are modernizing the way their asset data is stored. In the past the as-built drawings were in paper format and accessing such data meant searching through bundles of maps which led to a waste of time and money. Later these maps were digitized but were still 'non-smart' digital versions of the paper maps. In order to make full use of existing data, it would need to be stored in a format that can be manipulated by users and processed to obtain information at the click of a few buttons. We learnt from Detroit Edison Energy (DTE) that most utility providers have been undertaking massive efforts to convert all their existing data into easy to access GIS data which is typically stored in a Geodatabase (DTE Energy 2009, Personal Communication). In case of new pipe installations, use of laser scanners gives data with a much higher level of accuracy. This data is directly stored in a GIS database. Similarly for repair and rehabilitation exercises, the excavations carried out can be used to check the data stored and create a more up-to-date version of the dataset. GIS data allows us to easily extract data and create 3D models of pipes and appurtenances. These models can be used to provide visual cues to the backhoe operator through the use of Augmented Reality (AR) Visualization which is described in the following section. They can also be used to run collision detection algorithms and check for proximity between the backhoe digging implement and the pipes. Without GIS data it is a very tedious process that can lead to a lot of errors creeping into the system to arrive from simple CAD drawings to 'smart' GIS data. We have classified existing datasets of utility companies into 4 cases which can be seen in the Figure 2 below:

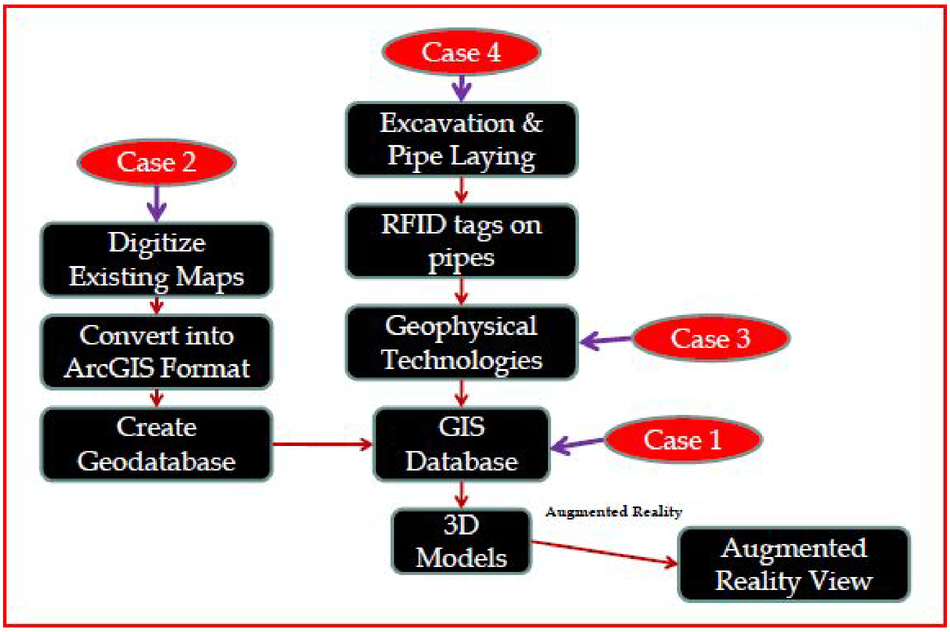

Figure 2 Buried infrastructure data classification cases 1- 4.

Case 1 is the best case scenario where utility owners have all their assets stored in a GIS database. Case 2 refers to those owners who have the asset information stored in the form of maps and drawings either in paper or digital form but not in the form of an intelligent database. These maps then need to be converted into GIS format from which a database can be built. When utility owners already have pipes buried underground but are unsure about their exact location or are carrying out repairs and rehabilitation, it is classified as Case 3 in our classification. This case will require the use of Geophysical Technologies to get the exact location of the underground utilities. After the location is obtained, a database would be constructed using the geophysical test results. These steps would then bring the data up to the level of Case 1. Case 4 refers to the case when new pipes need to be laid and thus along with documenting the location of pipelines, the use of new technologies such as Radio Frequency Identification (RFID) tags and sensors mounted on pipes is also envisaged. Thus Case 4 is the all encompassing case. The eventual goal for any case is to produce 3D representations of the underground pipes and project them in Augmented Reality.

Augmented Reality (AR)

The 3D models created can be used in collision detection algorithms and warn the backhoe operator of an impending collision. They can also be used to provide visual cues to the operator through a visualization technology known as Augmented Reality (AR). Augmented Reality as its name suggests is a combination of Reality and Virtual Reality. Virtual objects, in this case 3D models of pipes are superimposed on the real world scene to generate a view such as the one in Figure 3 below. The system uses real-world information such as position of the backhoe through high precision GPS and a constant video feed of the real world.

The GIS data is converted into Keyhole Markup Language (KML). In the KML schema, geographical coordinates, geometric characteristics and other attribute information of the pipelines are represented. At the same time, the real world data contains the real time tracking data and video stream of the real excavation scene. The tracking data supplies the AR system with position and orientation of the backhoe, which is used for establishing the camera reference coordinate system with the origin at the video camera. The CAD models of pipelines, which are originally represented under the geographical coordinate system, can thus be aligned with the new camera reference system, calibrated and superimposed on the video sequence representing the real world.

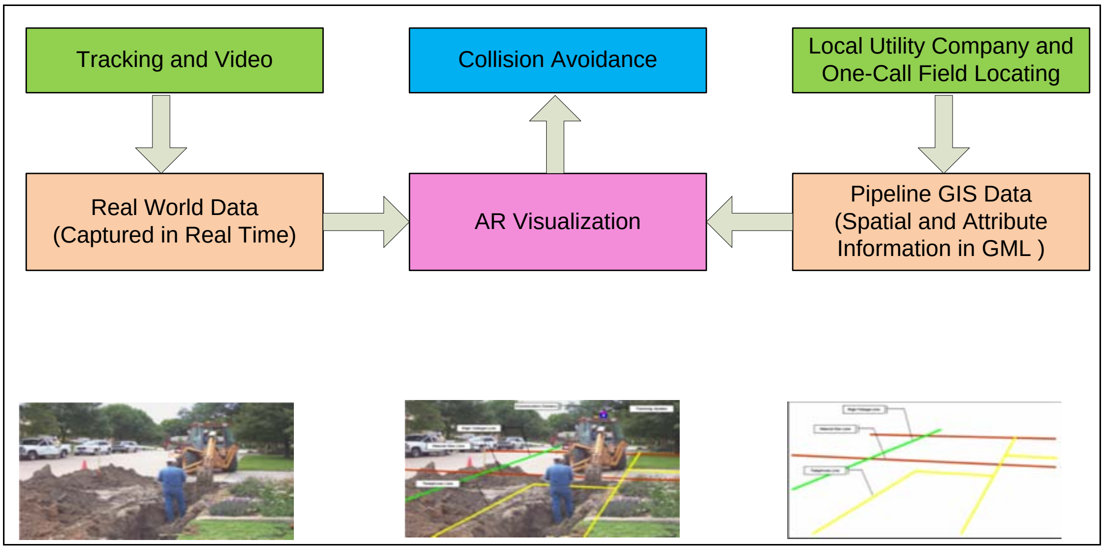

Figure 3 Data Flow for Collision Avoidance System Using Augmented Reality

The end result of the AR system is to give the backhoe operator a view such as the one seen in Figure 4 below which is a thematic representation of the visual cues a backhoe operator can obtain as a result of the system.

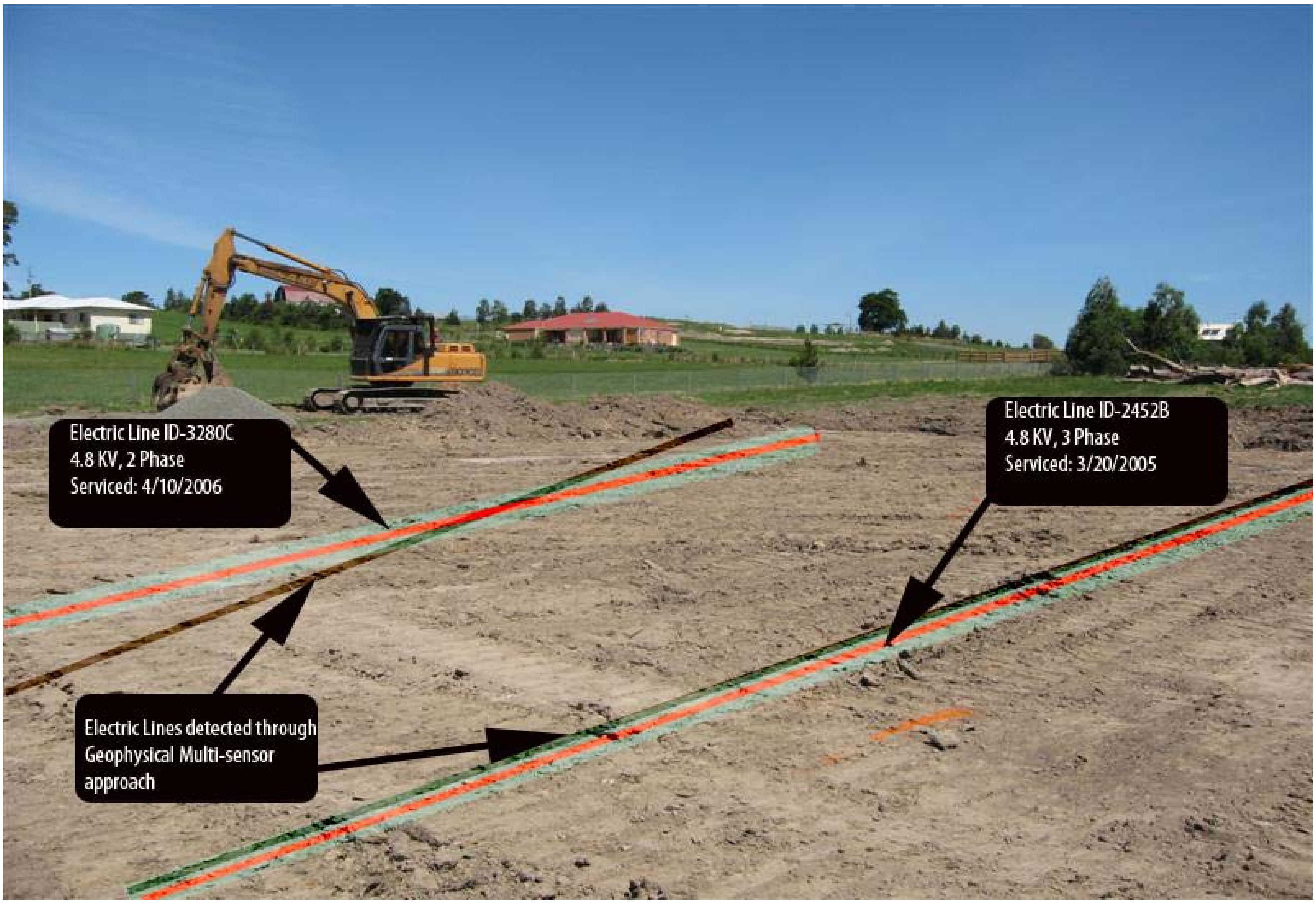

Figure 4 Third person view of AR visualization

High precision Global Positioning System (GPS)

The success of a collision avoidance system depends largely on how effectively equipment can be tracked on site. Figure 4 above shows the backhoe carrying a Real-time Kinematic (RTK) GPS that transmits geographic coordinates with an accuracy of inches (Trimble AgGPS RTK 900 Brochure). Using the latitude-longitude-altitude data of the backhoe and the location of the 3D models created from GIS databases, proximity queries can be performed to check for imminent collision. Hence, having extremely accurate GPS signal for the equipment out on the field is very important.

Telemetry

Another very important component of the framework is telemetry. For a collision avoidance system to be useful to the operator, it must send and receive data in real-time. Any slower and the system would not be able to warn the operator of an impending strike in time. To achieve such real time data transfer, the system would depend upon a system similar to that seen in modern motor racing (Ford and Milnes 2001). Thus, high precision GPS units installed on backhoes coupled with wireless telemetry would be combined to produce the desired results. Data from GPS would be transferred to the system, which in turn would use data from 3D models of the buried pipes and carry out proximity queries. The operator would be provided with an easy to read display informing him/her of the current distance between the digging implement and the bucket as seen in Figure 5 below. In order to make the system capable of making predictions prior to events, a stochastic ability would be built into it. This is further described in the future work section.

Construction equipment installed with sensors

Many equipment manufacturers produce construction equipment that comes with on-board instrumentation that can give accurate positioning of the backhoe and its digging implement (Trimble Grade Control Systems 2010). For older equipment which did not come with on-board instrumentation, a number of OEMs of such tracking sensors can retrofit these pieces of equipment with similar sensors (Voyatzis 2002). Using this sensor based tracking system, the proximity of the digging implement to the pipes at any point can be computed and displayed to the backhoe operator. Over time, if the digging implement comes within the safety tolerance zone, an alarm can be sounded within the cab of the backhoe and the operator would know immediately that he/she is on the verge of striking a buried utility and can pull back and avert the danger. A schematic view of how such a system would work is shown in Figure 5 below. Initially the bucket is far away enough from the underlying pipe (red) for the system to output a "Not in range" message. As the operator keeps excavating, the bucket gets closer to the underlying pipe. A snapshot of the output when the pipe is 5 feet from the pipe is shown in the second figure. In the final figure, the bucket is presumably just 1 foot from the pipe and a warning is sounded in the cab to warn the operator so he/she can pull the bucket back immediately.

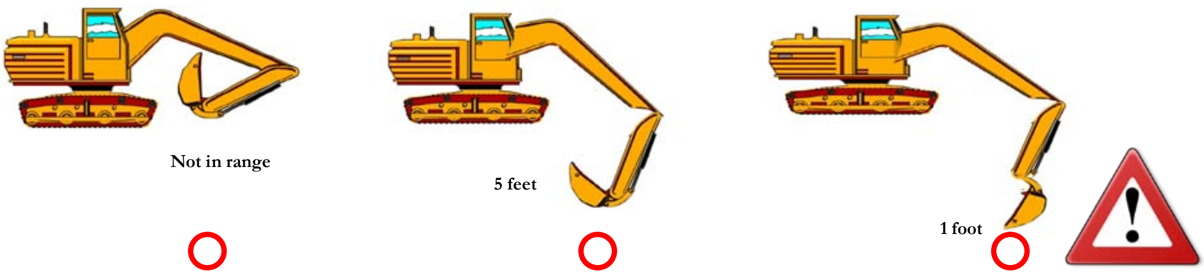

Figure 5 In-cab collision avoidance output for operator

Macro approach and Micro approach

A jobsite can consist of single backhoe performing an excavation at an intersection or a large excavation pit attended to by a number of backhoes. The first case is what we describe as requiring a micro approach. A collision avoidance system installed within the cab of the backhoe is sufficient to monitor the backhoe progress and warn the operator as and when needed. With the second case however, it might be prudent to have a jobsite wide system that can track all the equipment and personnel on site. A jobsite administrator can use the output from such a system to identify potential collision incidents. Often time such incidents might not be seen by operators due to the large blind spots on backhoes and trucks. Such a macro-level system will provide operators with a 'virtual' second pair of eyes.

CONCLUSIONS AND FUTURE RESEARCH

Considering all the factors discussed thus far, the incorporation of a combination of technologies such as Augmented Reality Visualization, Collision Avoidance Detection and Multi-Sensor Geophysical Techniques is thought to be the best approach in tackling a multi-faceted problem such as this. However, the lack of extensive use of such technologies in the field of excavation has its own set of limitations that need to be dealt with in due course of time. The following section talks about the limitations in the abovementioned approach as well as the plan for current and future work.

Limitations

As accurate as GPS might be, until the next few years in which civilians are allowed the use of higher accuracy grade GPS or GPS III (Engst 2009), the effect of high-rise buildings on GPS signal and multi-path phenomena (Mehaffey 2010) limit its accuracy from making it a fool-proof system.

While newer datasets are very accurate and can be relied upon while producing 3D models and use in collision avoidance detection, the use of older datasets cannot be avoided entirely and dependence on such potentially inaccurate data might lead to less than optimum results. With this in mind, it is our aim to use a Multi-Sensor Geophysical Technology approach to check the validity of older datasets. A multi-sensor verification approach would also lend more confidence to results obtained from the collision avoidance system.

Ongoing and Future Work

An operator performing a typical excavation operation in the field would need to be warned with a sufficient time gap for him/her to stop the current cycle. With this in mind, our group is working on incorporating a stochastic approach in the collision avoidance algorithm. This feature would allow the system to predict in advance where the bucket is heading to and give the operator a longer warning time than if it computed all the data without a pre-empting warning.

The system is envisaged in such a way that it can use 3D models produced from GIS databases or take advantage of radio signals from transponders or RFID tags installed on brand new pipe installations. Such adaptability makes us believe that a system such as this would be able to handle future advancements in technology for the near future at least. (Tucker et al. 2004)

Our immediate goal is to carry out laboratory tests as a proof of concept of the micro-level system and thereafter perform a field test to understand the real-world implementation issues of such a system.

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