Intelligent Utility Locating Tool for Excavators

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Abstract: Currently, backhoe excavator operators have to depend on color-coded markings applied by utility locators to expect the location of utilities buried in the ground. As accidents prove time and time again, this method is unreliable. While more efforts should be spent on subsurface engineering and as-built documentation, excavators should have their own tools to "see" cables, wires, and pipes while working underground. This paper presents the result of work aimed at supplying backhoe operators with a device capable of scanning the ground for metallic objects. The "fishfinder" type tool is thought to be the last "barricade" against horrific accidents caused by the damage of buried utilities. The writers not only present the results of extensive tests in the laboratory and the field but also highlight that the outdated contractual principles used by the government, utility companies, and insurers establishes insurmountable barriers for transferring this novel technology into the industry. The relevance of the presented work is in the experimental data that has been collected and analyzed both in the laboratory and in the field.

DOI: 10.1061/(ASCE)0733-9364(2006)132:9(919)

CE Database subject headings: Subsurface environment; Utilities; Excavation; Safety; Laboratory tests.

Introduction and Background

In his report to the Federal Laboratory Consortium, R. Sterling addressed the inherent problems related to the subsurface "world" of cities, towns, and even rural areas in the United States. He summarized succinctly what is known by everybody familiar with the construction industry dedicated to building and maintaining the lifelines of our 21st century society when he wrote: "Overhead utility lines are becoming a thing of the past, except in rural areas. The urban underground has become a spider's web of utility lines, including phones, electricity, gas, cable TV, fiber optics, traffic signals, street lighting circuits, drainage and flood control facilities, water mains, and wastewater pipes. In some locations, major oil and gas pipelines, national defense communication lines, mass transit, rail and road tunnels also compete for space underground" (Sterling 2000). The U.S. Congress had become aware of the risks associated with damaging buried utilities even before the installation of the Homeland Security office, when it stated in the Transportation Equity Act for the 21st Century, TEA 21, Title VII, Subtitle C, Section 87301, that: "unintentional damage to underground facilities during excavation is a significant cause of disruptions in telecommunications, water supply, electric power, and other vital public services, such as hospital and air traffic control operations, and is a leading cause of natural gas and hazardous liquid pipeline accidents." In almost any state of the United States, a contractor is required by law to call the One-Call center at least 48 h before the digging begins. Connecticut was one of the first states to pass a "Call Before You Dig Law" in 1978, which had the effect that accidental cuts of utility lines declined by 60% while the length of new underground utilities being buried increased. One-Call centers are set up so that anyone who will be digging or excavating using mechanized equipment—commercial contractors, road maintenance crews, telephone pole installers, fence builders, landscape companies, or home owners (to name just a few)—can make one telephone call to give notice of their plans to dig in a specific area.

Subsequently, the One-Call center immediately inform all utility companies that have assets in the digging area, giving them enough time to go and mark the presumed location of their buried utilities. Lately, directional drilling crews have become very important customers of One-Call centers as well. In an effort to standardize the quality of data, ASCE has developed a National Consensus Standard titled ASCE C-I 38-02 (ASCE 2002), "Standard Guidelines for the Collection and Depiction of Existing Subsurface Utility Data." The intent of this standard is to present a system of classifying the quality of existing subsurface utility data as a basis for establishing working strategies according to assessed risks. Despite all these efforts, accidents do occur and the direct/indirect costs, in addition to loss of lives and serious injuries, are staggering (Bernold 2003).

Difficult Hazard to Control

The *San Francisco Chronicle* reported in an article on November 10, 2004 that: "A fireball several stories high roared out of the ground near downtown Walnut Creek on Tuesday, killing two construction workers, injuring six, and leaving two workers missing after a crew accidentally cut an underground jet fuel line" (May et al. 2004). In order to protect the gas line, its owner had implemented strict rules about damage prevention. As this case highlights, however, present methods and tools are still insufficient to prevent disasters of this kind. Despite the successful implementation of the One-Call systems in most of the U.S.

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Note. Discussion open until February 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on April 8, 2005; approved on December 8, 2005. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 132, No. 9, September 1, 2006. ©ASCE, ISSN 0733-9364/2006/9-919–927/$25.00.

states, the accidents caused by damaging underground utilities result in a wide variety of impacts reaching from clogged residential sewer lines to gas explosions, cut phones, and high speed cables. Magazines such as *Underground Focus* have shown that utility records often contain inaccurate utility positions and/or depths. Some live services do not even show up on utility plans. This puts a high responsibility on the locators to accurately determine the on-site location, nature, and depth of utilities. In an effort to support utility locators, in particular the excavator operator, researchers at the North Carolina State University's Construction Automation and Robotics Laboratory (CARL) have been working on a multisensory locating concept. This paper will discuss the system design followed by laboratory and field experiments.

State-of-the-Art in "Seeing" through the Earth

The Commission on Geosciences, Environment, and Resources (CGER) of the National Academy of Sciences wrote (CGER 2000): "Much of the site characterization conducted today uses techniques that are more than 20 years old. . . . Noninvasive site characterization would probably be used more frequently and efficiently if much of the data acquisition, data processing, and decision making could be automated. . . . By producing a better result, more rapidly, and at lower cost, robotics and decision support system could be the key to more—and more effective—use of noninvasive site characterization methods. Automation of site characterization allows measurements and preliminary interpretation to be made in real time." The noninvasive or invasive effort to detect and locate buried objects before excavation should address five basic questions: What are the objects' (1) position in the x-y plane; (2) position on the z-axis; (3) size and shape; (4) orientation; and (5) material composition (i.e., metal, plastic, concrete)? Utility contractors are further interested to know if the utility is alive or dead (e.g., power cable). "Active noninvasive searches involve the emittance of some energy into the soil, which in turn causes the buried objects to respond in a way that can be measured. Passive searches, however, depend on identifying the changes between the natural environment and objects that have been buried, referred to as anomalies. The following briefly reviews the most common geophysical noninvasive methods used today:

1. Metal detectors, generally used by "treasure hunters." A transmitter coil generates an electromagnetic (EM) field around itself, causing a metal object positioned within its field of influence to induce an eddy-current that can be sensed by a receiver coil.
2. The induced polarization (IP) instrument detects the speed with which the eddy-current decays change with the size, distance, and type of ferrous material of a buried object.
3. Geomagnetic survey uses instruments called magnetometers to measure anomalies in the earth's magnetic field due to the presence of ferrous material in the ground surface.
4. Geoelectrical resistivity is used to characterize vertical and lateral changes in subsurface electrical properties.
5. Ground penetrating radar (GPR) emits short electromagnetic (EM) pulses and senses reflections caused by abrupt changes of the dielectric constants in the ground.
6. Seismic surveys use acoustic energy that is sent into the subsurface via explosive charges, hammers, or vibrating elements.
7. A gravity meter senses the acceleration variations in the earth's gravitational field at a given location. These variations indicate lateral changes in the density of the subsurface in the vicinity of the measuring point.
8. Radio-frequency locators use radio signals at differing frequencies that are broadcasted into a continuous piece of metal such as metal pipes, copper wires, or steel cables.

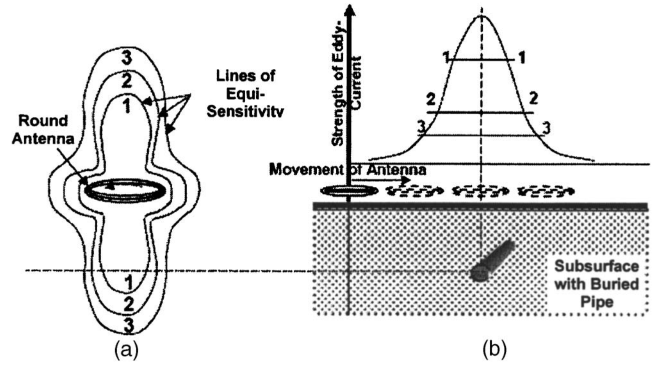

Fig. 1. Schematic of EMPI scanner: (a) sensitivity of circular antenna/receiver; (b) EMPI output during scan across buried pipe

Multisensory Approach

Each of the preceding eight geophysical method has its advantages and its limitations. Taking a multisensory approach to underground sensing promises to generate more reliable and accurate results by decreasing the degree of ambiguity and increasing the probability with an integrated interpretation. "Data integration should consider all of the data, not just geophysical data, acquired during a site characterization. Multiple sources of data provide the ability to check the quality of individual data sets against each other. . . . Each observation contains an associated error, and each data set is the result of a statistical distribution in space and/or time." (CGER 2000) One opportunity of applying a multisensory approach is the integration of a geophysical with spatial data. By collecting both data sets simultaneously, it would be possible to calculate marginal changes based on spatial positions as well as absolute/relative maximum values. Furthermore, unique characteristics of specific sensing devices may present additional opportunities that can be exploited for the purpose of locating buried utilities.

EM technology is one sensing that has shown great promise in locating metallic objects very reliably. Fig. 1 presents a simplified view of the two key principles that can be integrated to increase its effectiveness. In effect, the depicted concept combines the EM and the IP sensing methods, which will from now on be referred to as electromagnetic pulse-induction (EMPI). The round antenna serves as transmitter as well as receiver. It first transmits, at the speed of light, an electric pulse into the environment. After a short delay, the antenna senses the induced eddy-currents created by any kind of magnetic target within the field of influence. As indicated in Fig. 1(a), the sensitivity of the receiver is not uniform, thus creating three-dimensional surfaces of equisensitivity. In the case of an air-cored round antenna, the sensitivity is highest along the central axis perpendicular to the antenna. If a buried pipe is outside the sensitivity area, as depicted in Fig. 1(b), the receiver senses no eddy-current. Moving the antenna over the center of the pipe causes it to slice through the sensitivity spheres, similar to a knife cutting through an onion. Fig. 2 reveals that the EMPI read-

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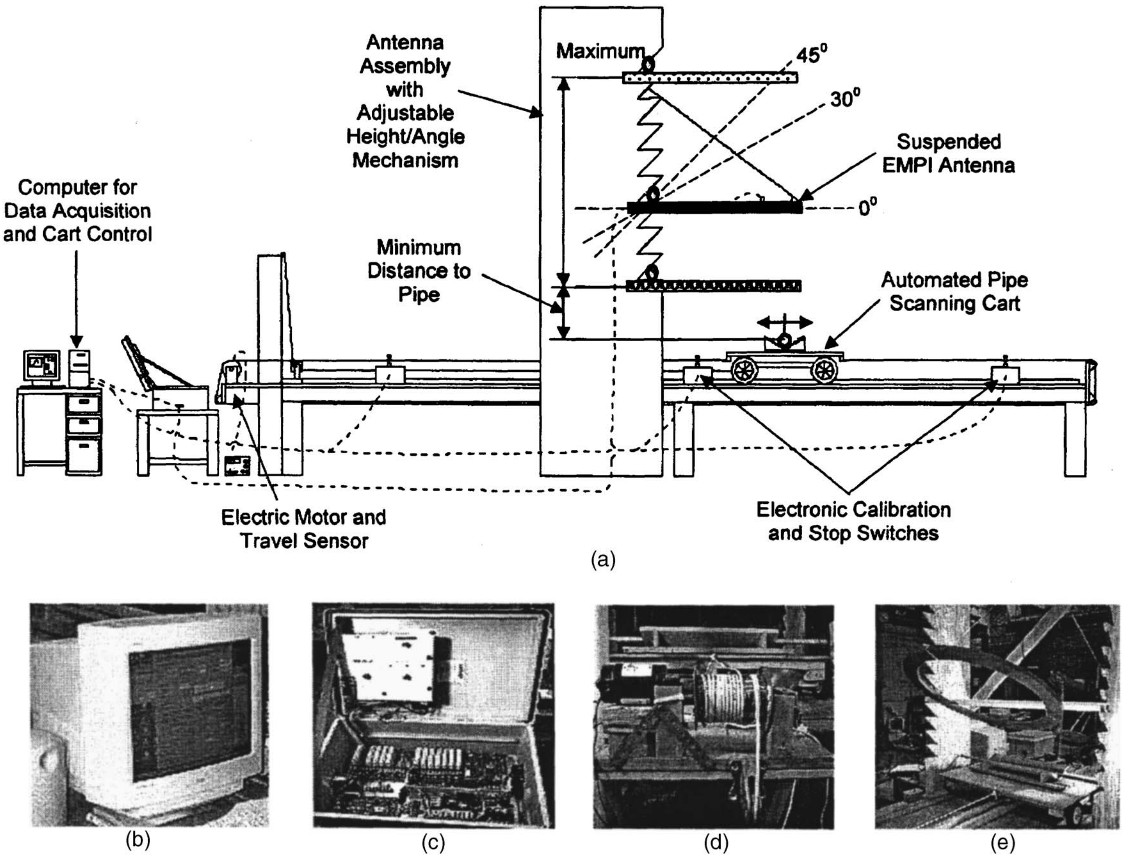

Fig. 2. Automated test facility for EMPI scanning: (a) schematic view of test facility; (b) GUI in V-Basic; (c) communication and EMPI hardware; (d) motor and winch; and (e) cart passing antenna

ing increases and decreases as the pipe "cuts" through the sensitivity contours of the antenna. The resulting inverted U-shaped curve provides the opportunity to define peak levels as well as ratios (e.g., slope) which may offer quantitative values that could be made use of in predicting desirable features of a buried object. Furthermore, changing the angle of the antenna, which will change the contours of the sensitivity curves, may allow the use of triangulation to find the center of the pipe. The next section talks about the experiments that were conducted to better understand the relationships between antenna shape, distance to target, and angle of the antenna.

Experimental Investigation of the EMPI

Quantifying the effects of different conditions of a buried utility on the EMPI readings required a experimental approach. The goal was to collect and analyze EMPI readings for various pipe diameters, metals, distances, and orientations. For this purpose, a facility was built that guaranteed consistent results from repeated experiments.

Automated Facility

The specific purposes of the established facility, schematically depicted in Fig. 2, were threefold: (1) provide consistency and reliability for the many experimental runs; (2) automate as much as possible the tedious data collection process; and (3) allow easy changes in test setups. The resulting facility consisted of: (1) antenna positioning assembly; (2) a cable-controlled cart and track to automatically transport different types and sizes of pipes; and (3) a data acquisition system (Fig. 2). Changing the distance between the antenna and pipe was made possible by a wooden frame while the antenna angles could be set via a rope and pulley system. Pipe orientation was easily changed by rotating the V-shaped pipe holder mounted on the cart. The automation of a run was accomplished by installing a computer controlled geared motor and winch operating a continuous cable. By connecting the cable on the opposite ends of the cart, the winch and cable were able to pull the cart back and forth between the two stop-switches. Shown in Figs. 2(b and c) are the Visual Basic graphical user interface (GUI) and an Opto22 communication board with the EMPI processor mounted into a mobile box. Fig. 2(d) presents the electric motor, the winch with continuous cable, and the encoder measuring of the cable movement between the switches, including one in the middle of the run. Finally, Fig. 2(e) illustrates the situation when the cart with pipe is traveling past the antenna suspended in air.

Pipe Testing Matrix

As mentioned previously, a contractor ready to dig would like to get a variety of data points about a buried object. For this investigation on metallic pipes, it was decided to focus on following four characteristics of a metallic pipe: (1) type of metal; (2) pipe diameter; (3) depth of burial; and (4) direction of the center axis. For the purpose of establishing a sequence of experiments necessary to establish correlations between the various variables and the EMPI readings, a matrix of pipe materials and sizes was established and is presented in Table 1. For each sample, a 91.4 cm

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Table 1. Matrix of Tested Pipe Samples

Material	Pipe Size 12.7 mm (0.5 in.)	25.4 mm (1.0 in.)	38.1 mm (1.5 in.)	50.8 mm (2.0 in.)	63.5 mm (2.5 in.)	76.2 mm (3.0 in.)	101.6 mm (4.0 in.)
Steel	√	√	√	√		√	√
Cast iron	√	√	√	√	√		
Galvanized iron			√	√		√	√

Note: Pipe size=internal diameter of pipes, in inches. Pipe thickness −7.62 mm(0.3 in.).

(3 ft) long section was prepared and tested under a set of predefined distances, orientations, and antenna angles. For example, the distance between antenna and pipe was varied from 20.32 cm (8 in.) to a maximum height of 101.6 cm (40 in.) Antenna angles tested were 0, 30, and 45°, respectively. Furthermore, the effect of pipe orientation was assessed by placing the pipes at 0 (perpendicular to the motion of the cart) and at 45°, respectively.

Data Analysis

This section discusses the results of the many tests that were conducted by correlating the EMPI readings to selected variables.

Material and Distance

Fig. 3 compares the plotted test results for white and galvanized steel pipes with distances between the antenna and the pipes between 13.46 cm (16 in.) and 91.4 cm (36 in.). As expected, every pass of the cart produced an almost perfectly symmetrical curve. On the other hand, changing distance and pipe material resulted in significant changes in the EMPI readings. As is shown, the maximum distance between the antenna and pipe element was limited to 0.91 m (3 ft), a distance that still created distinct EMPI readings. On the other hand, pipes closer than approximately 0.41 m (16 in.) caused the system to saturate, a fact that is acceptable, because the goal is to detect pipes as far away as possible. Also apparent is the fact that white steel creates a much higher response than galvanized steel and cast iron as well, but this is not shown in the graph. The galvanization process showed a diminishing effect the greater the distance, starting with a value of 390 at the distance of 0.51 m (20 in.), 28% of the reading for white steel, changing to 195 at a distance of 0.61 m (24 in.), also 28% of the reading for steel. This phenomenon seems to indicate that there exists some consistency in the way the EMPI reacts to changing parameters. It is interesting to notice that the 5.1 cm (4 in.) increases in distance between antenna and pipe, starting at 0.51 m (20 in.), lead to a reduction in EMPI reading of 700, a difference that is being divided in approximately half with increasing incremental distance. This potential trend will be more closely investigated hereafter.

Compounding Effect of Diameter and Distance

Fig. 4 highlights the results of testing steel pipe sizes according to the matrix presented in Table 1. Comparing the EMPI readings for the 5.1 cm (2 in.) pipe with pipes of different diameters, consistent features emerge. For example, between EMPI 600 and 1,420 a linear relationship between changes in distances and EMPI outputs exists. Particularly for pipes smaller than 5.1 cm (2 in.), a consistent slope of 81 EMPI/cm (205 EMPI/in.) emerges. Above EMPI 1,400 the readings seem to be influenced by the saturation point at approximately 1,800, thus making the reading less consistent. Overall, it is apparent that distance affects the EMPI readings after an initial threshold level of 50 has been reached. The ability to match standardized S-curves seems to offer a first opportunity to predict the size of a pipe. However, it is also clear that pipe diameter and distance to the antenna lead to compounding effects on the EMPI readings. In order to correctly predict one value, it is critical to know the other. The next section investigates the problem of separating the effects of diameter and distance on the EMPI.

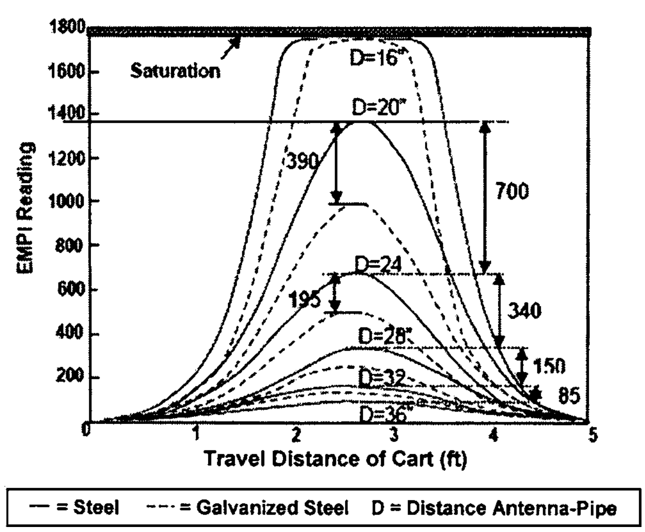

Fig. 3. EMPI scans of 2 inch (5.1 cm) diameter pipes

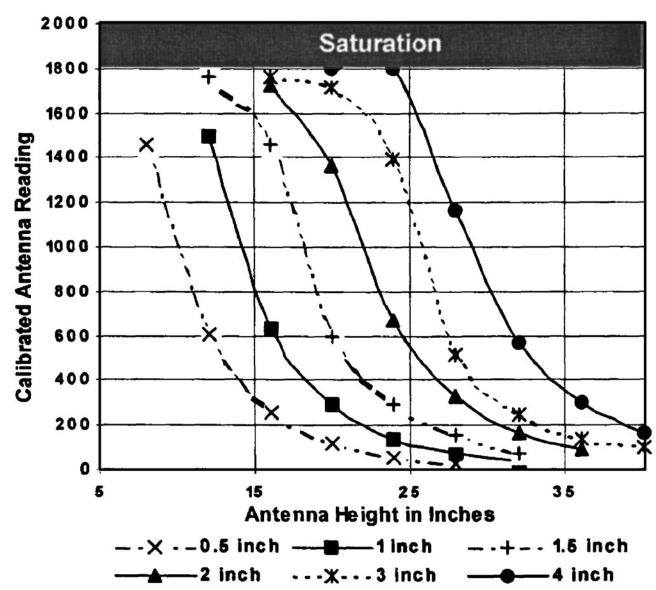

Fig. 4. Effect of diameter and distance on EMPI output

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Table 2. EMPI Sensitivity Changes as Function of Size and Distance

		Distance between antenna and pipe							
	Threshold	40–36 in. (101–91 cm)	36–32 in. (91–81 cm)	32–28 in. (81–71 cm)	28–24 in. (71–61 cm)	24–20 in. (61–51 cm)	20–16 in. (51–41 cm)	16–12 in. (41–31 cm)	12–8 in. (31–20 cm)
Pipe size	[in. (cm)]	[EMPI/in. (EMPI/cm)]	[EMPI/in. (EMPI/cm)]	[EMPI/in. (EMPI/cm)]	[EMPI/in. (EMPI/cm)]	[EMPI/in. (EMPI/cm)]	[EMPI/in. (EMPI/cm)]	[EMPI/in. (EMPI/cm)]	[EMPI/in. (EMPI/cm)]
3 in. (7.6 cm)	40 (102)	16 (6.1)	**22 (8.7)**	77 (30)	197 (78)				
2 in. (5.1 cm)	36 (91)	16 (6.1)	26 (10)	**32 (13)**	84 (33)	223 (88)		Saturation	
1.5 in. (3.8 cm)	32 (81)		19 (7.5)	19 (7.5)	**34 (13)**	76 (30)	216 (85)		
1 in. (2.5 cm)	28 (71)	Below threshold		10 (4)	17 (7)	**38 (15)**	85 (33)	214 (84)	
0.5 in. (1.3 cm)	24 (61)				7 (3)	15 (6)	**34 (13)**	88 (35)	212 (83)

EMPI's Sensitivity to Distance

The plots in Figs. 3 and 4 suggest that changes in EMPI reading might follow a predictable pattern based on pipe size and distance. In other words, pipes with different diameters may show the same slope when the distance results in the same average EMPI reading. Table 2 compares the slopes of EMPI increases/decreases for various steel pipe diameters and settings. The first column lists the five pipe sizes that were analyzed, while the second column indicates the threshold distance at which the EMPI reading passes above 50. Two distinct areas do not provide any readings, because they are either below the threshold value or above the saturation point. The values in bold text highlight a pattern of common EMPI reading. It is interesting to notice that, despite the fact that the EMPI output is caused by eddy-currents induced by a magnetic pulse into pipes that are of different size and stock, a distinct pattern of gradients can be observed. However, the pattern seems to disappear for the 7.6 cm (3 in.) pipes, which might be a sign that the larger the surface area of the induced field, the less sensitive the system is to changes in distance.

The presented analysis of some data clearly indicates that the EMPI output, when correlated with distance, material, and object size, reveals consistent patterns that in fact can be used to predict the value of different descriptors. Moreover, inherent features can be utilized to test the probability of a right prediction. For example, the size of a pipe can be predicted using the point where the system is saturated as well as the slopes between sectors. Based on these assertions, which are also supported by the large amount of data that could not be presented here, the research team embarked on developing an automated scanning system that could be used by a backhoe operator in real-time as a means to "seeing metallic utilities in the ground."

Automation of Subsurface Sensing

Utility locators utilize detection tools that are either hand-held or mounted on a cart (e.g., ground penetrating radar) and apply color markings on the surface that indicate the location of one. The operator of the digging equipment has only the markings and obvious "hints" such as water hydrants or gas meters available as guides. In order to take advantage of the EMPI concept during excavation, a device that controls the antenna needs to be mounted directly on the backhoe arm to allow scanning of the ground in advance of a "scoop" even deep down inside a trench.

Autonomous Operation

As discussed by Huang et al. (1996), mounting an electromagnetic detection system on a large piece of metal causes the system to saturate. This problem can be overcome by creating a sufficient space between the antenna and the metal so that its influence on the EMPI is small. Moreover, the antenna needs to be protected for it to "survive" the rugged motion of the boom during operation. Fig. 5 presents the key components of a design, capable of

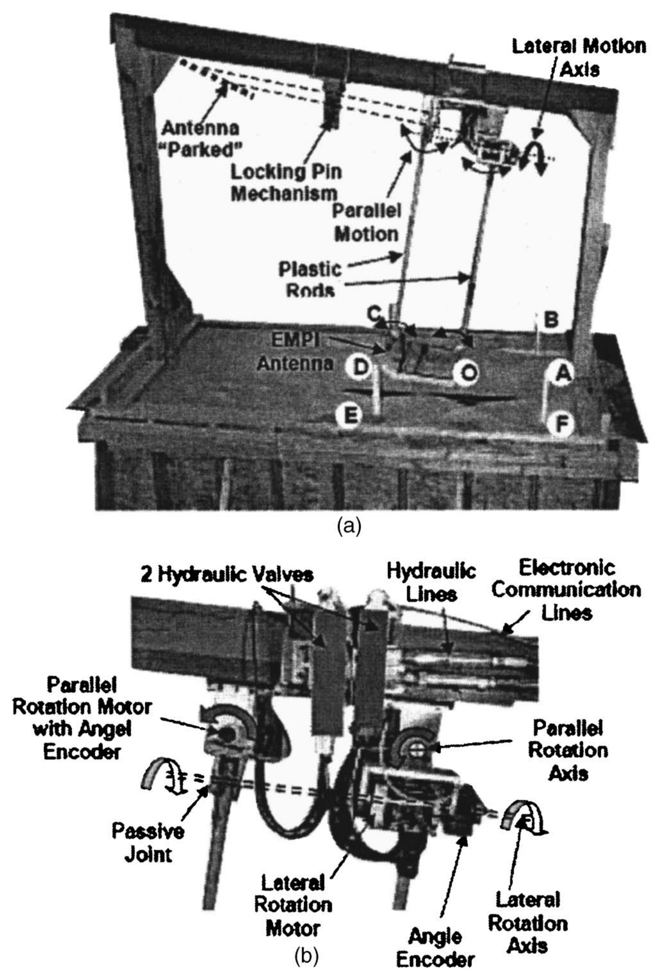

Fig. 5. Components of remotely controlled EMPI scanner: (a) parallel spherical antenna actuator during experiment; (b) two motors with encoders mounted on attachment plate

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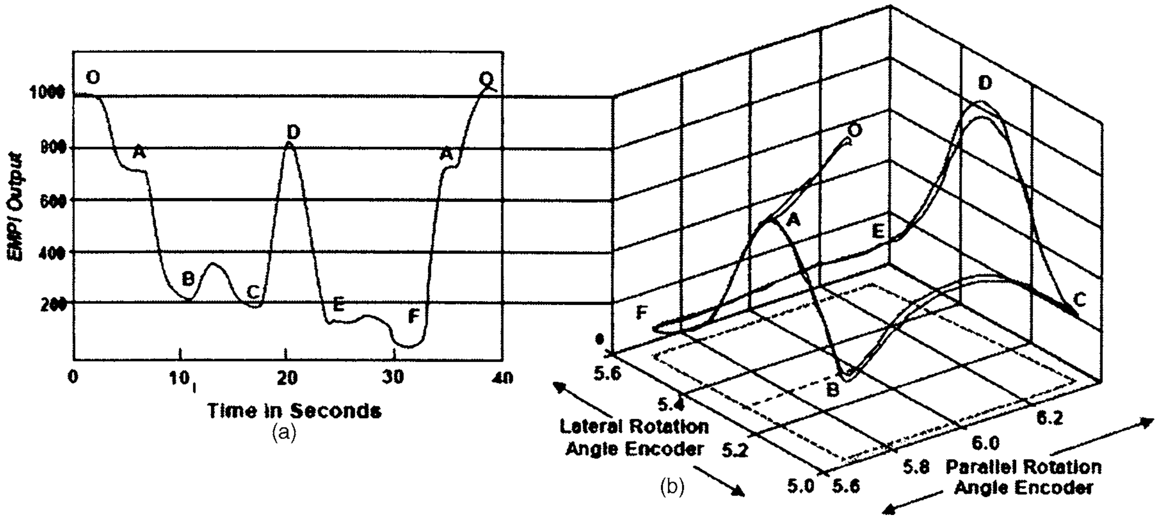

Fig. 6. EMPI readings during scanning: (a) time-based plotting of EMPI data; (b) spatial plotting of EMPI data

meeting the stated requirements, that was built and pretested in the laboratory. Two hydraulic motors activate two long plastic rods connected to the EMPI antenna at the other end. As depicted in Fig. 5(b), the two motors, each equipped with an electronic angle encoder, are arranged perpendicular to each other, creating lateral and parallel rotation axis. Electrohydraulic valves actuate the motors, which are jointly able to move the antenna to any point within a spherical plane defined by the maximum motion angles of the motors and the length of the plastic rods. When in the parked position, the antenna rods are being held and locked securely to the underside of the backhoe stick. The electronic interface to a digital controller, a laptop computer, was "threaded" to enable the independent control of the two hydraulic valves/motors while reading the two angle encoders relaying the angle of the motors and the output readings from the EMPI.

The setup in Fig. 5(a) was built to conduct laboratory experiments to prove technical feasibility and to test automatic scanning and search routines. As shown, the setup consists of a beam, representing a backhoe arm, and a sand box, over which the scanning mechanism is being suspended.

Scanning Routine to Define Pipe Direction

In a second step, a control program was created to actuate the EMPI antenna in a predefined scanning motion over the surface of the sand while collecting sensory data. Fig. 6 depicts test results for a steel pipe of internal diameter 38.1 cm (1.5 in.) buried in the sand directly underneath the beam [see Fig. 5(a)]. The reader should be aware that the square antenna used for this experiment is different from the round antenna utilized earlier. The alphanumeric labels used to denote specific spots on the two plots in Fig. 6 correlate to the labels shown in Fig. 5(a). The start and end of the antenna scan is the location marked as O. Other intermittent points along the path of the antenna in the square routine mode have been marked A through F. The time-based plot of the EMPI readings shown in Fig. 6(a) is the result of the antenna moving away, closer, or crossing the centerline of the buried pipe. For example, progressing from location O to A results in the EMPI signal getting weaker, because the rotational motion of the plastic rods increases the distance between the antenna and the pipe. Based on the experiences from the experiments conducted earlier, this performance was expected. The weakening of the EMPI reading between positions A and B reflects a further increase in distance when the antenna advances along a circular path brought about by the lateral rotation motor. While motion generally increases or decreases the EMPI readings, stoppages create horizontal plateaus. This phenomenon is eliminated when the data is plotted against the two angle encoders as shown in Fig. 6(b). A visual comparison of the two plots illustrates instantly the benefits of the spatially integrated representation of the data. In particular, the human eye recognizes immediately how the peaks, A and D, belong to two symmetrical U-shaped curves resulting from the lateral paths C–E and F–B. Lining up the two peaks, one is able to easily predict the centerline of the buried pipe as parallel to the boom. The slight increase of the reading between B and C is again the result of the nonplanar motion of the antenna along its path. However, between E and F no such increase is observable, due to the fact that the limits of the lateral motor are not exactly symmetrical.

Locating a Pipe

Fig. 6(b) highlights the fact that the track scan supplies data useful for calculating the direction and center location of a buried pipe. A search-subroutine can now be employed to find two peaks along its path that define two points that can be connected to establish the direction of the pipe. Next, a final subroutine is launched to define the center and the perpendicular angle as the input for sending the antenna on a final path to define size and depth using lookup tables that are based on passing over the pipe perpendicularly.

Development of Remote Control

When installed on an excavator, the Equipment Mounted-Buried Utility Detection System (EMBUDS) had to (1) enable the operator to initiate the scanning process; and (2) provide information about what it found. The first step in controlling the device remotely was made possible by electronic communication, either wireless or cable-based. In this phase of system development, cables were used and installed along the boom connecting the OPTO22 communication and the EMPI processor, residing in the operator cabin with the motors, encoders, and antenna. In addi-

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tion, DC power and hydraulic oil can be provided by the backhoe itself. Buttons on the joystick or within easy reach of the operator offer several scanning options. For example, a quick-scan commands the antenna to follow a fast and simple path from the parking position to the farthest point and back. Should the system detect the presence of a metal object, a more thorough track-scan is available. The objective of this scan is to define the direction, depth, and size of the buried pipe using the knowledge and search procedures that have been discussed in the previous sections. A very interesting and important problem that was still left to be solved was how to communicate the result of the track-scan to the operator inside the cabin.

Intelligent User Interface

Communicating the predicted direction, depth, and size of a located pipe is in fact a problem of how to present the output of the computer to humans. However, most research discussed in the literature focuses on maximizing the entering of data into the computer. The first basic question that arises is: "How do we inform the operator where a pipe is?" Display screens, commonly employed for such communications, face serious risks in a hostile environment that includes dust, heat, and dynamic shocks. Another option for creating a visual interface are head-mounted displays, but these are not only expensive but also at risk in an excavator cabin. One promising concept for "working with" a computer in construction is the use of sound (Bernold 1993). "Speech can be used to replace a textual display . . . Audio output has a short duration and must be understood when it is spoken, or it must be repeated," writes L. Bass (2001). However, one drawback could be excessive engine noise and the need to put the output into words. The common saying "a picture is worth a thousand words" is certainly true when one has to describe the exact location and direction of a pipe buried in the ground to somebody else. In order to avoid these many risks, a new approach to communication had to be sought.

Studying human-computer interactions is the interest of researchers focusing on intelligent user interfaces (IUIs). One such researcher is Maybury (2001), who summarized the goal of such efforts: "IUIs specifically aim to enhance the flexibility, usability, and power of human-computer interaction for all users. In doing so, they exploit knowledge of users, tasks, tools, and content, as well as devices for supporting interaction within differing contexts of use." A distinctively fresh look at how humans may interact with computers has its foundation in the activity theory. Bannon and Kaptelinin (2001) write: "The mechanisms underlying this integration (human-computer) can be understood from the point of view of activity theory as the formation of a functional organ. This means that computer applications are the extensions of some natural (precomputer) human abilities. . . . The problem here is not simply that features of the interface are inscrutable, but more fundamentally, the whole nature of the activity may have changed as a result of the technological possibilities."

While EM BUDS does not change the way excavation takes place, it does replace and drastically improve a laborer who scans the ground from inside the trench. Because Occupational Safely and Health Administration (OSHA) rules prohibits entering the trench without protection, utility locating is generally done visually by helpers who stand on the side of the trench looking for signs of a buried utility being unearthed. In that sense, the precomputer human activity that is replaced and enhanced is: (1) the "visual hunt" for a metallic pipe during excavation; (2) warning of the operator when "something" has been detected; and (3) communicating its location, including the depth, of the something. Observing phase (3) on a trenching job, one notes that the prevalent method of communication are hand-signals that "tell" the operator to stop, point to the location where something was detected, and indicate the approximate depth, type, and size of the pipe. While the stop signal and depth and size information can be easily substituted with simple electronic devices, such as a red lamp or a digital numbers display, pointing with the arm has a 3D component that cannot be easily transferred into a graphical mode that is easily understood by the operator. Thus, it was hypothesized that the best way to substitute the arm pointing by a helper was to turn the 2D antenna assembly, shown in Fig. 5(a), into a "pointer." As discussed in the previous section, the autonomous scanning program is able to define the direction and the midpoint of the detected pipe based on the angles provided by the two encoders mounted on the motors. Using a path-planning subroutine, the computer is thus able to delineate motions for the two motors that would let the antenna not only point at the midpoint but also indicate its direction. Finally, having the capability to control each motor separately while receiving feedback from the two encoders, EM BUDS is enabled to execute the desired path.

Field Testing EM BUDS

In October 2003, EM BUDS was ready to be field-tested on an available JCB backhoe-loader. Fig. 7 shows several photos from the tests that were conducted in a fill area of a construction site. In particular, Fig. 7(c) shows how EM BUDS was mounted to the backhoe arm, using a clamp assembly consisting of four threaded rods and two plates. Hydraulic power was provided by a mobile pump. In the experiments, for each test a 1.27 cm (0.5 in.) pipe section was buried in the clay type soil found most often in the Piedmont area of North Carolina. While the EMPI is not impacted by the presence of soil, one end of the pipe was left visible for the purpose of visually documenting the performance of the system. Fig. 7(a) illustrates how the antenna followed the rectangle path marked as *a* through *e*. After reading the previous section, it is apparent that this very path had previously been developed and tested in lab experiments. Therefore, the same subroutines for analyzing the scan data could be used. In particular, the program was able to detect the peaks created by the EMPI output and calculate the midpoint and orientation of the pipe. Figs. 7(b and c) document the final highlights of the project. Pipe 1, buried slightly off-center of the axis of a new trench, was detected and pointed to by the antenna. Pipe 2 was oriented almost perpendicular to the trench. As illustrated in Fig. 7(c), EM-BUDS not only detected the presence of the pipe but aimed correctly at the midpoint of the pipe within the space of the trench.

Summary and Conclusion

Excavators all over the globe are forced to cope with accidents due to buried utilities that are being damaged. One-Call Centers established in almost every state in the United States have reduced the incidents per mile (km) of new facilities, but the increase in the amount has kept the total number high. The work presented in this paper intends to create one more layer of accident prevention by providing the excavator operator an intelligent tool to "see pipes through the earth." This novel approach to

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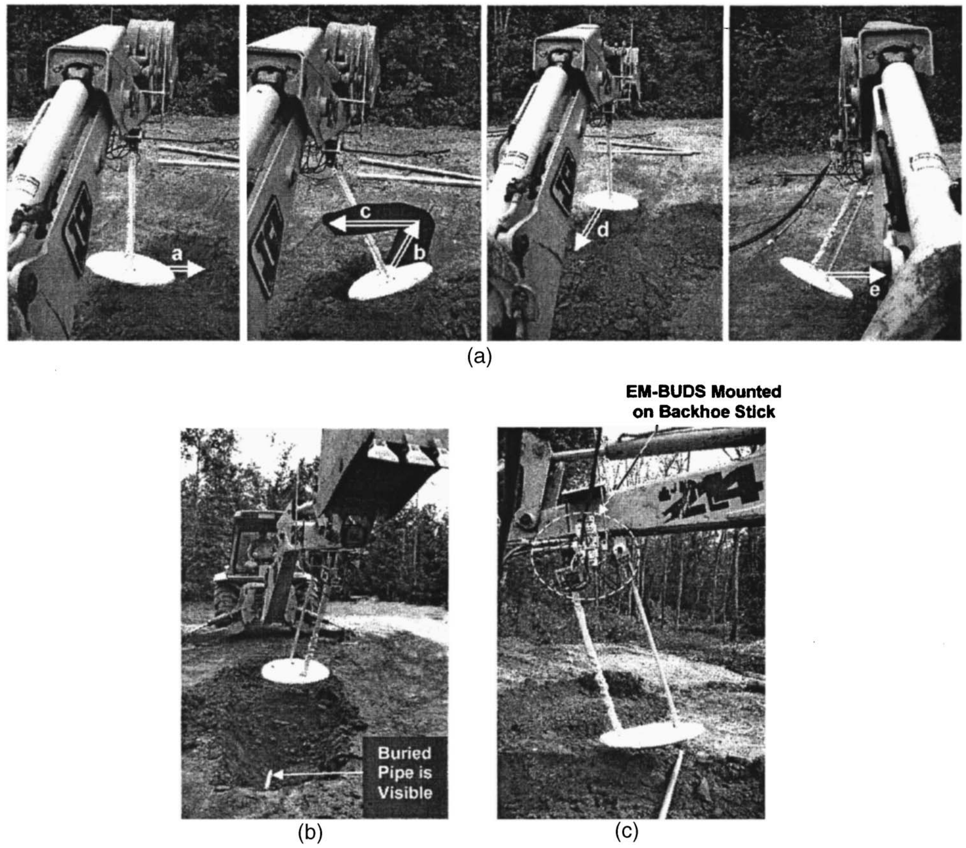

Fig. 7. EM BUDS during field test: (a) track scanning of subsurface; (b) pointing at midpoint of Pipe 1; and (c) pointing at midpoint of Pipe 2

locating metallic utilities without prior knowledge of their existence represents a "fish-finder" type technology capable of discerning the direction, depth, size, and center point of elongated metallic objects. While the present sensor is limited to finding metallic objects, most utilities in the ground today are made of copper cables of pipes made of steel or cast iron, or have guide wires attached. Most importantly, the computer controlled actuator can be easily expanded to carry other sensing devices such as AC current detectors or ground penetrating radar (GPR).

Applying activity theory in devising a study operator-computer interface, a novel method for displaying the outcome of a scan was developed. Rather than providing the operator numbers on a small screen, the motors and rods of the scanner serve as a output device capable of pointing to the closest center-point of a pipe/cable that crosses the area of the trench. Developing and using a site-worthy EM-BUDS will require up-front investments from both fabricators and contractors. In addition to purchasing cost, an excavator will incur a reduced productivity due to the time needed to scan the ground. As long as the lowest bid will become the winning bid, EM-BUDS will never find its way into the field, a situation that will only change if utility companies and insurers switch from saving money to paying for preventive measures such as EM-BUDS. But there is always that "head-turning" accident that causes us to pause and realign our outdated guiding principles.

Acknowledgments

Funding for this work has been provided by the Public Health Service–National Institutes of Health (NIH) under Contract Nos. 5 R01 CCR413051-02 and 1R01 0H04201-01. Its content is solely the responsibility of the writers and does not necessarily represent the official views of NIH. The writers also acknowledge the contributions made by the many members of the BUDS team working at the CARL laboratory, especially Matt Baldwin, an undergraduate student in Electrical Engineering, who would not stop until the devices worked. Finally, the support of Steve Baldwin Construction Inc. was essential in conducting the final tests with actual equipment.

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