INNOVATIVE TECHNOLOGY DEVELOPMENT FOR SAFE EXCAVATION

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ABSTRACT: Serious injuries and costly damages caused by excavators hitting underground utilities are constantly in the headlines of the news media. The accidents sometimes result in the death of one or more persons. Thus, excavation represents a dangerous operation that has to be executed with care. The Construction Automation and Robotics Laboratory at North Carolina State University has been searching for a technology to help avoid these types of accidents. A prototype of the active metal detection and tracking system has been developed using a nontraditional approach. The system generates and transmits its own magnetic impact and detects the coupling effect with any buried utility line in its detection range. It is installed directly on the excavating equipment and integrated with its operation. Experiments have been carried out with this system and the results are promising. The work deliberated in this paper presents an ongoing effort to develop an effective and reliable system that can be attached to any type of construction and utility digging equipment for underground utility line detection.

INTRODUCTION

The hazardous nature of excavation in construction is well documented. The Occupational Safety and Health Administration estimated that the fatality rate was at 50.8 deaths per 100,000 workers per year from 1984 to 1988. The National Institute of Occupational Safety and Health estimated that at least 172 persons were killed as a result of all excavation-related accidents (''Occupational'' 1989). Further, airports are sometimes closed because of cut communication cables on the ground. For a similar reason, the space shuttle has been forced to delay landing, and businesses such as banks, investment companies, and travel agencies have been forced to close for weeks because of excavation mishaps that damaged vital communication cables.

Accurate location of pipes and cables without resort to trial pits is a problem experienced by utility and highway authorities worldwide. A variety of gadgets now being used with varying degrees of success rely on transmitters plugged into the buried service, magnetic field detectors, and ground probing radar (Winney 1986). The most common of these search techniques is the magnetometer, which measures the disturbance of the earth's magnetic field caused by ferrous objects buried in the ground. Such instruments sold as service locators are similar to metal detectors used by treasure seekers and make an audible beep signal. Interpretation of the signal depends on the skill of the operator. It is hard to assess from the strength and quality of the sound whether the instrument has found a small object near the surface or a large one deep down. In an interesting development, researchers from the Defense Research Establishment Suffield have developed a vehicle-towed detector system capable of locating and marking buried metallic objects close to the surface (Das et al. 1990). This system, which utilizes two adjacent electromagnetic induction sensors, was mainly designed for locating underground ordinance.

At the Construction Automation and Robotics Laboratory, a new approach has been developed that integrates microprocessing technology, ''mechatronics,'' and traditional construction equipment in an innovative way. Its objective is to provide the operator with a sophisticated tool that is attached to the machine and easily embedded in its control. This paper presents this technology that is capable of locating underground utilities and any other ferrous or nonferrous objects in order to avoid costly damages and accidents. First, a short summary of the passive metal detection approach commonly used for locating underground utilities will be given. Then a prototype design of the Active Metal Detection and Tracking System (AMDTS) is presented, followed by a presentation of the first test results acquired during laboratory experiments. Finally, data from the initial field testing of this system is discussed.

TRADITIONAL PASSIVE METAL DETECTION

Magnetic detection is considered as an effective procedure for finding the position of buried ferrous or nonferrous utility lines. Conventional underground line detection and location requires two equipment units: (1) a transmitter; and (2) a receiver. A buried line is located and traced by applying a distinctive transmitter signal to it and then tracing it with the receiver from the surface. There are usually two ways of applying the transmitter signal, known as conductive and inductive tracing, respectively. In conductive tracing, the transmitter is physically attached to the pipe and ground with a clamp. Once it is hooked up, a magnetic field, which is generated along the line, can be detected with a receiver from the ground surface. Fig. 1 illustrates a situation where the conductive tracing is performed. The operator is holding a handheld signal receiver to trace the underground pipeline. Colored marks are put on the ground to indicate the detected position and orientation of the pipe.

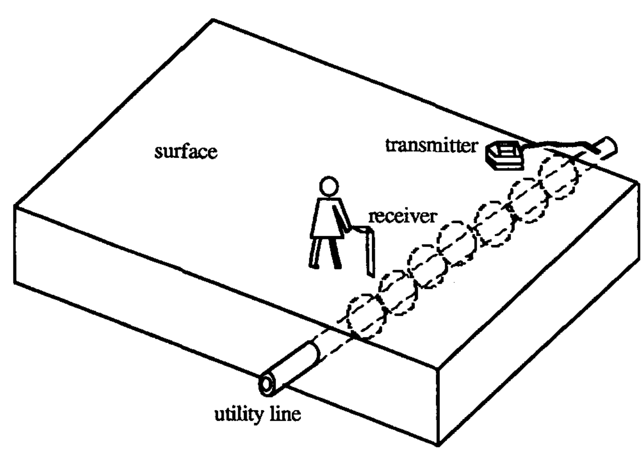

FIG. 1. Conductive Tracing of Underground Line

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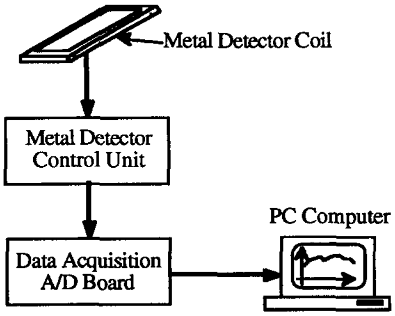

FIG. 2. Computer-Integrated Metal Detection System

In inductive tracing, the transmitter does not have to be physically connected to an underground line. It is placed closely to the buried pipe or cable but without a direct contact. The transmitter is capable of inducing a signal into the pipe or cable, which serves as a carrier. The receiver senses the pipe or cable by picking up the induced signal.

Based on the "passive state" of the receiver, both conductive and inductive tracing are considered passive detection methods. In both cases, the operator has to know beforehand an approximate location of the underground utility line. It is apparent that this requirement limits the applicability of the technology in situations where the knowledge about the existence of underground utilities in the area to be investigated is incomplete.

There is ample evidence that the traditional locating from the surface does not guarantee accident-free digging and trenching. Markings that indicate a buried line get lost, are covered up, run over, or can be overlooked by a busy machine operator. The result is not always as drastic as the recent accident in Allentown, Pa., where a backhoe broke a gas line and caused an explosion, killing one person and injuring 70 others ("Gas" 1994). While surface locating is certainly the most practical and economical way to plan a digging operation, a second tier of damage prevention is needed, preferably a tool that can be used by the machine operator during the digging operation. The following section presents the basic concept of such a machine mountable technology.

COMPUTER-INTEGRATED ACTIVE METAL DETECTION

Despite the availability of marks indicating the approximate location of underground utilities, the machine operators of trenchers and backhoe excavators operate the equipment "blind." An electronic device that provides a real-time warning of the utility lines immediately ahead of the digging tool could be an effective mechanism for the generation of such an "early warning" system.

Differing from the previously discussed traditional metal detection techniques, the selected sensing device is considered an active search system. It consists of (1) a metal detector search coil; (2) a signal processing (control) unit; and (3) a PC computer equipped with an analog-to-digital (A/D) converter interface. Fig. 2 presents the relationship among these three core components of the system.

In contrast to the traditional metal location technologies, active metal detectors generate their own magnetic field through the transmitter module and search coil. Its impact on any metal object in its detection range is coupled and then picked up by the receiver module of the detector. The signals from the search coil are processed by the control unit. It also supplies the necessary DC power. As shown in Fig. 2, a data acquisition board is connected to an analog output port of the control unit via a simple cable. It performs an A/D conversion at a high sampling rate. A QUICK-BASIC program imports the data from the control unit. Thus, the computer is able to receive real-time data about the magnetic changes in its vicinity, graph it on the screen, sound a signal, and store it in a file for analysis. The programming capability of the microprocessor provides an excellent platform for the future development of algorithms that engage in real-time pattern recognition, helping to infer from the data stream detailed information about the depth, location, orientation, and even the size of the metal object.

After the development and testing of the computer-integrated metal detection system, laboratory experiments were performed to prove that it is possible to detect metal using a detector mounted on an excavator stick made of steel. The next chapter discusses the laboratory findings.

LABORATORY EXPERIMENTS

After the initial prototype system was built, laboratory tests were conducted by mounting the metal detector search coil onto a computer controlled hydraulic backhoe excavator available in the laboratory (Huang and Bernold 1992). Fig. 3 presents the initial setup used to test the effectiveness of the metal detector. This metal detector coil is connected with a PC laptop computer through an A/D convertor. Therefore, when the coil is rotated to scan the field, a real-time reading of the output signal can be obtained. Several steel pipes were buried for the tests in the soil box.

As shown, the active search coil assembly is installed on the underside of the excavator stick. The metal detector is a 70 cm (2 ft 4 in.) long by 70 cm wide squared coil, mounted on a plastic frame that can be rotated away from the stick

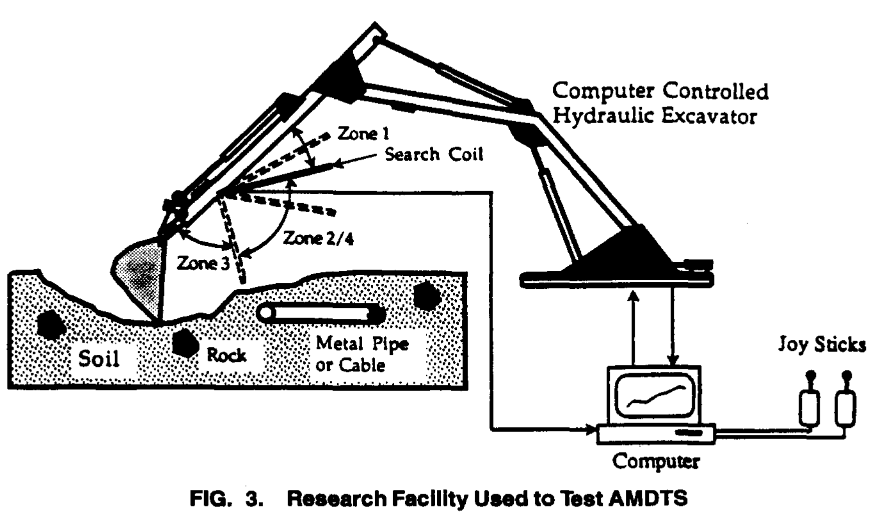

FIG. 3. Research Facility Used to Test AMDTS

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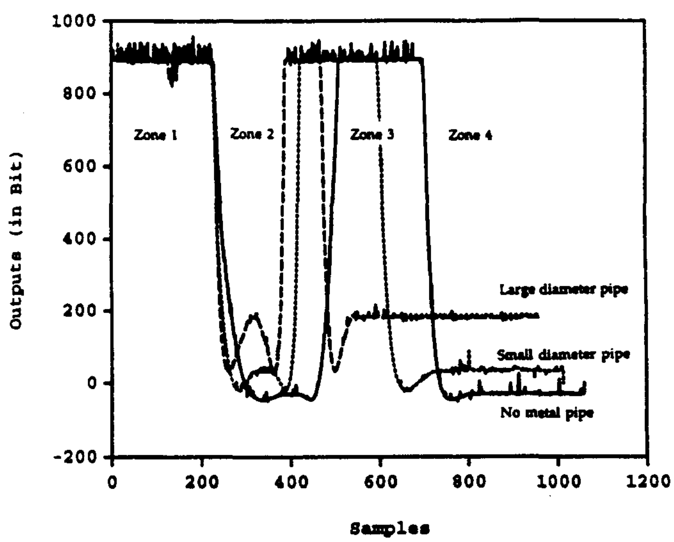

FIG. 4. Sensing Patterns of Actuated Metal Detector

when detection is needed. As soon as a metal object emerges within the detection range, the coil's magnetism couples with that object. As a result, the output signal from the coil increases proportionally to the size, distance, and orientation of that object. The metal detector is also able to screen out the effect of the metallic backhoe stick and bucket. Before the detection begins, the output from the search coil can be initialized as if there were no metal objects in the field of range. During the detection process, any increase in the magnitude of output signal indicates an additional metal object nearby. Different from a passive metal detection system, this method does not require any additional hardware. The installation of a hinge allows active and fast scanning of the soil ahead of the bucket. For the initial test, the coil assembly was manually operated. The collected data, plotted in Fig. 4, showed some very important patterns.

As shown in Fig. 4, the signals picked up from the search coil during a fast forward and a slow backward scan through zones 1, 2, 3, and 4 clearly indicate the existence of a steel pipe. The coil was rotated through zones 1, 2, 3, and 4 sequentially. Zone 2 and zone 4 share the same region (see Fig. 3). Zone 1 and zone 3 are very close to the steel arm, and hence the outputs are almost saturated. The coil performs the most effective detection only in zone 2 during the forward sweep and in zone 4 during the backward sweep. While time duration in zone 2 is very short, the coil is held in zone 4 so that a steady reading can be achieved for illustration purpose. In fact, the intensity of the signal relates to the size of the pipes placed 60 cm (2 ft) away from the stick of the backhoe boom. The small steel pipe is of 6 cm (2.5 in.) in diameter and 61 cm (2 ft) long. The large steel pipe is of 12 cm (4.5 in.) in diameter and 73 cm (2 ft 5 in.) long. Compared with the case when no pipe is buried, a small pipe yields a much smaller signal magnitude than the bigger pipe. Here, the signals, measured in bits, increase with the size of the pipe, the recognizable pattern the research team was anticipating.

FIELD TESTING

After the successful laboratory test, two field versions of the AMDTS were designed. Supported by the city of Raleigh's Department of Public Utilities, the research team was able to conduct several field tests with a backhoe excavator and a Ditch Witch trencher. The following discussion describes those field tests and an analysis of the collected data.

The excavator version required two additional components: (1) a mechanical attachment that allowed automatic rotational actuation of the coil; and (2) a hydraulic rugged and self-contained actuator with position feedback. Fig. 5 presents an initial design of the backhoe-mounted AMDTS.

As shown, the computer integrated metal detection system developed for the laboratory experiments was slightly adapted. A small laptop computer is now used because the microprocessor has to fit into the excavator cabin so that the human operator can carry out the metal detection function from his/her seat. The function is initiated by pushing a button. Also, an A/D converter for the control of the hydraulic cylinder was added and the wall outlet was replaced with a DC/AC inverter that draws its power from the backhoe battery. The next two sections briefly discuss the two added system components.

Mechanical Subsystem

A JCB model 1550B backhoe excavator was used to act as a test bed for the different field experiments. Convenient con-

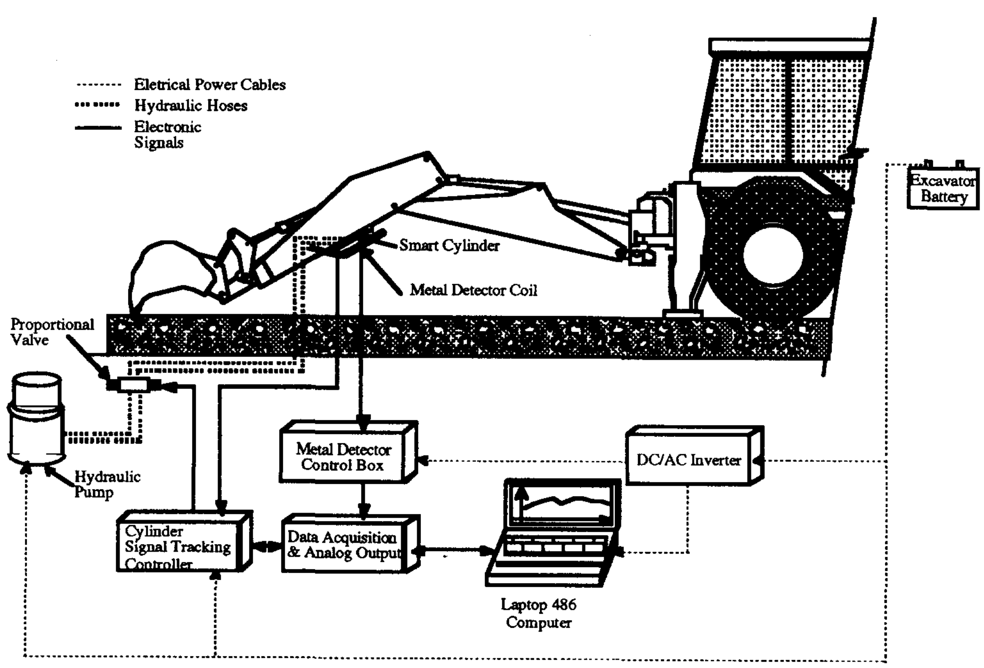

FIG. 5. AMDTS Mounted on Backhoe Excavator

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nections were designed and mounted onto the stick of the excavator to allow easy installation and removal of the metal detection system. Attention was given to the fact that the attachment was relatively safe from being damaged in the process of excavation. The main mechanical element consists of a mounting bracket that allows a rotational actuation of the search coil while keeping it close to the stick when not in use. Besides three small welded-on plates, no modification of any part of the excavator was necessary. The backhoe excavator provided the power for the AMDTS. A Ditch Witch trencher, provided by the same public utility department, was also used for metal detection experiments. Here the installation of the AMDTS was much simpler. Detailed information about this concept is presented in the latter part of this paper.

Hydraulic Subsystem

As discussed earlier, the metal detector search coil needs to be actuated. To satisfy this requirement, a hydraulic ''smart'' cylinder was selected as the main actuator. It is a standard

FIG. 6. Preparation of Backhoe for Field Testing

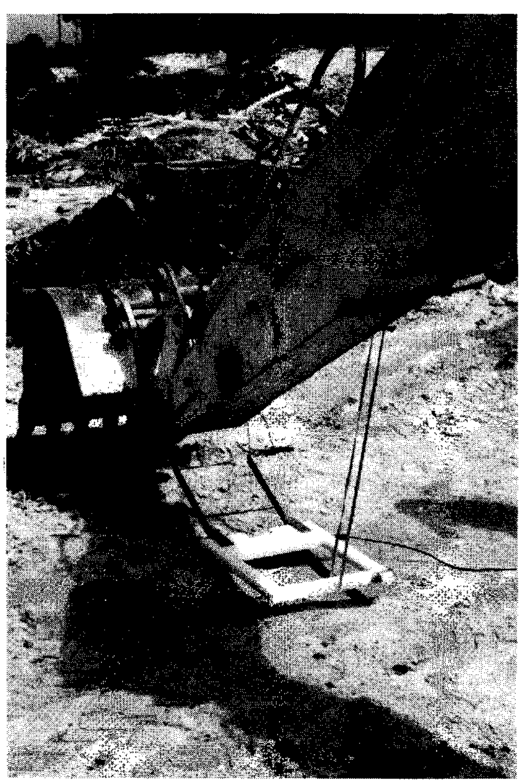

FIG. 7. System Setup for Horizontal Predig Ground Scanning

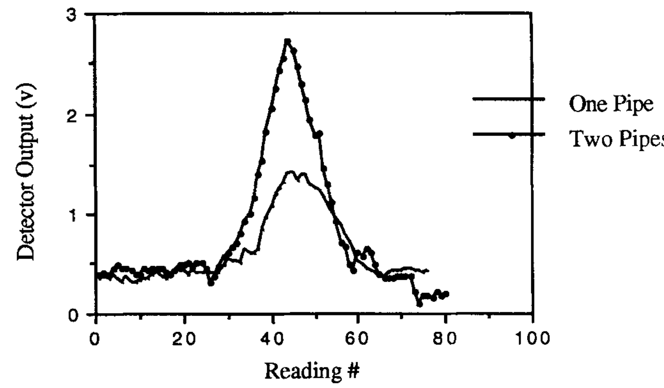

FIG. 8. Data from Horizontal Predig Scans with Buried Metal Pipe(s)

40.64-cm (16-in.) stroke hydraulic cylinder with a linear resistance transducer (LRT) installed inside. The LRT is a simple resistive element that measures the position of the rod and ''feeds it back'' in the form of an analog signal. The ''smart'' cylinder is part of a closed-loop tracking system composed of a controller, a hydraulic pump, and a proportional hydraulic valve. This characteristic provides a real-time position feedback enabling a controller to accurately move the cylinder to the desired position.

Backhoe-Mounted Metal Detector Tests

The experiments were carried out in a landfill managed by the city of Raleigh. The backhoe, as the ''host'' for the AMDTS, was brought to the site and equipped with all the necessary attachments. The connection plates had been previously welded on. Fig. 6 shows the preparation of the backhoe and AMDTS in the field.

Excavation accidents involving cutting utility lines often happen during the backhoe's first dig. Therefore, a predig detection of any metal object is considered important. Predig detection focuses on scanning the ground, which basically repeats the traditional locating operation from the surface, but without a tracer signal. For the predig experiment, a 6.03 cm (2-3/8 in.) diameter metal pipe was first buried approximately 33 cm (12 in.) below the surface. Fig. 7 shows the assembly for a predig detection test. Because the rotation-based actuator of the coil assembly discussed in the previous sections, does not allow a horizontal positioning of the coil close to the ground, a simple cable suspension system was used to position the coil. For this test, the backhoe operator rotated only the boom of the backhoe, which ensured that the detector coil was kept parallel to the surface of the ground while scanning the area beneath.

Fig. 8 depicts the collected data during the above predig scanning. The vertical axis represents the metal detector output in volts, which is proportional to the size of the metal in combination with its distance from the coil. The horizontal axis corresponds to the sample number associated with the sequence of digitized analog signals acquired from the control box during the scanning process. The sample number is related to the positions of the boom in polar coordinates (angle).

As shown in Fig. 8, the two curves, representing two pipe sizes, reach their peak at sample 40. The maximum output value of 1.4 V resulted from a 6.03 cm metal pipe buried at approximately 33 cm depth. To test the influence of pipe size, a second test was conducted with two pipes, 6.03 cm diameter each, buried 33 cm deep. As indicated by the second curve, metal influence reaches the peak at the same place with a value of 2.8 V. This value is double that of a single pipe. Thus, the doubling of the sensor output amplitude is clearly related to adding a second pipe. The sensor outputs from the predig

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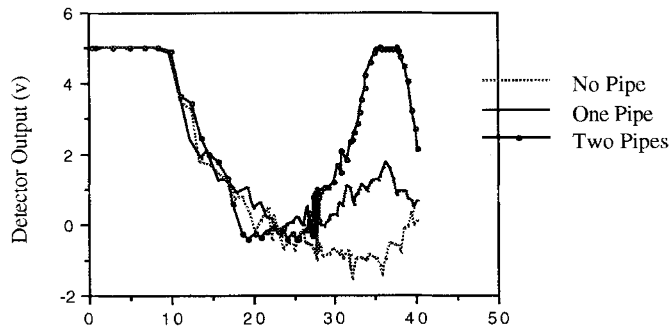

FIG. 9. Data from Rotational Scans

FIG. 10. Trencher-Mounted Metal Detector Setup

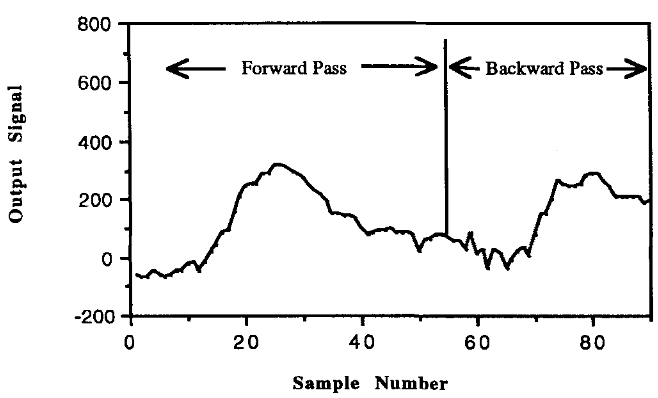

FIG. 11. Data from Forward and Backward Passes with Trencher

scanning tests showed again distinct patterns that may be used not only to detect metal, but also to distinguish between large and small metal pipes at different depths.

Metal detection during digging was the second configuration that was tested. In this scenario, the operator initiates a rotational motion of the coil before the bucket cuts through the soil. Fig. 9 displays the data collected during three scanning actions. In this figure, the vertical axis represents the amplitude of the output signal in volts, while the horizontal axis indicates the hydraulic cylinder's stroke length in centimeters. This length is measured by how much the cylinder rod extends from its initial position. Three curves represent the output signals of tests with (1) no buried pipe; (2) one 6.03 cm diameter metal pipe buried 30 cm deep; and (3) two 6.03 cm metal pipes buried 30 cm deep. Since the scanning movement starts with the metal detection coil very close to the backhoe stick, a saturated output signal caused by the metallic stick itself is expected. The influence of the stick results in the initial horizontal line between cylinder position 0 and 12.7 cm. for all three curves shown in Fig. 9. After this range, the effect of the stick is drastically reduced and the metal detector becomes sensitive to pick up any additional metal influences. This phenomenon was already observed during the laboratory tests discussed earlier in this paper.

The peak influence of the pipes can be noticed at a cylinder extension of 36 cm. At this point, an output of 1.8 V is measured. As Fig. 9 indicates, when no pipe was buried, an output of approximate zero was measured. With two identical 6.03 cm diameter metal pipes buried 30 cm deep, a peek with a saturated output of 5 V resulted. Again, doubling the size of the metal showed a drastic change in the output signals.

Trencher-Mounted Metal Detector Tests

For the laying of television cables and household utilities, trenchers are the preferred digging machines. While basically applying the same concept as in the excavator-mounted approach, the trencher-mounted metal detection does not require an actuation of the coil. Fig. 10 depicts the installation of the trencher-mounted metal detection in the field, where detection is performed while the operator is running the trencher. Fig. 11 illustrates the data collected during a trenching operation. Again, one 6.03 cm diameter metal pipe was buried about 50 cm below the surface. Subsequently, the trencher was maneuvered twice over the location of the buried pipe, first in a forward and then in a backward motion.

It can be concluded from Fig. 11 that the presence of the metal pipes affects the output of the signal since there are two distinct peaks in the output signal when the trencher drove across the pipes on a forward and backward pass. An increase of the output signal when passing over the pipe indicates the detection of the metal. In general, data from this experiment showed the same patterns as the data collected during the experiments with the two excavator setups.

CONCLUSIONS AND FUTURE WORK

The initial experiments demonstrated that active metal detection can be successfully implemented and interfaced with a microprocessor. An innovative machine mounted system, AMDTS, was prototyped and tested in the laboratory and the field. The experimental results suggest that such a system might constitute an effective technology for the detection of buried metallic objects during the excavation process itself. However, further research is necessary to evaluate its reliability and to test its capability of distinguishing between different cables and pipes placed at different distances and orientations. Future work plans include the testing of a manipulation system that enables the coil to scan closer to the ground. This mechanism not only provides more flexibility related to different scan distances, but it will also hopefully increase its detection depth.

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TECHNICAL NOTES

Technical notes provide a way of publishing: (1) Original, practical information; (2) preliminary or partial results of research; (3) concisely presented research results; and (4) innovative techniques to accomplish design objectives. Technical notes should not exceed 3,500 words or word-equivalents in length. An abstract of 150–175 words, which will be published if length permits, and nine or so key words should be submitted with the technical note. Abstracts for technical notes are included in *Transactions, ASCE Publications Information*, and Civil Engineering Database. Discussions may be written on Notes.

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1. The length of titles must not exceed 70 characters and spaces.
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3. Approximate the length by counting the number of words on a typical manuscript page and multiplying that by the number of total pages (except for tables and figures). Add word-equivalents for figures and tables by estimating the portion of the journal page each will occupy when reduced, usually 75% to 50%, to fit on a 140 mm × 245 mm journal page. (A journal page is approximately 1,040 words; e.g., a figure reduced to one-half a journal page would be 520 word-equivalents.) When reduced, the figure must be legible and its type no smaller than 6 point (2.12 mm). The overlength aspect of papers that are positively reviewed must be put through a special approval process prior to publication; however, valuable overlength contributions are not intended to be discouraged by this procedure.
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12. If experimental data and/or relations fitted to measurements are presented, the uncertainty of the results must be stated. The uncertainty must include both systematic (bias) errors and imprecisions.