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ACCIDENT PREVENTION THROUGH EQUIPMENT-MOUNTED BURIED UTILITY DETECTION

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ABSTRACT

The demand for new buried utilities is growing with new construction, re-construction, and the growth of the subsurface infrastructure worldwide. As a result, contractors are busy digging and drilling into the ground in order to bury new pipes. Because the machinery for placing the new utilities underground, such as backhoe excavators, trenchers, augers, drills, and plows, cannot sense when they are getting close to already buried objects, utilities are easily damaged, possibly leading to electrocutions or gas explosions. Despite great efforts in locating existing utilities before a contractor is allowed to dig, accidents of all kinds occur in great numbers.

This paper will discuss a multi-sensor approach to detecting and locating various kinds of utilities using a combination of electromagnetic induction (EMI) and ground penetrating radar (GPR). While the EMI detects metallic material, the GPR is capable of finding concrete ducts and pipes made of non-ferrous material. The two sensory systems have been integrated into a mobile unit and a system that mounts directly onto a digging machine. This paper will describe the integrated system, describe the sensors, and show how the system was used to successfully support an excavating contractor working on a chilled water distribution system on a university campus.

KEYWORDS

Accident prevention, buried utility detection, electromagnetic pulse induction, ground penetrating radar, machine mounted sensor,

INTRODUCTION AND BACKGROUND

The congressional Transportation Equity Act for the 21st Century, TEA 21, Title VII, Subtitle C, SEC. 87301, states 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." One does not have to look far to discover that these findings of Congresses are well documented. Underground Focus Magazine (1999) publishes an Accident File in every issue. For example, it stated that from December 8th until December 11th 1998, seven major accidents occurred. On the 9th a fiber optic cable was cut by

an excavation contractor that supported the 911 service for five counties in Jacksonville, Texas. The most tragic accident, however, occurred on Dec. 11 when "a crew using an 'anchor cranker' to install a guy wire anchor for a telecommunications pole augured unto a gas main." In this accident, four people were killed, and 14 were injured when the gas exploded in St. Cloud, MN.

Such excavation accidents can occur as a result of mis-located or unlocated underground utility lines. Underground trenches are often crowded with utilities that are buried at various depths and following various courses or traverses. Most importantly, there generally are no accurate as-builts for buried utilities.

As stated by the document from Congress, these accidents cause problems for more than just the contractor and the owner of the utility; they are a great cost to society as a whole. Everyday citizens, who are unrelated to the project, are inconvenienced and possibly injured or killed by the disasters.

State-of-Practice in Accident Prevention

There are many different parties that are actively and passively involved in the excavation and trenching process. Active participants include 1) owners of a new facility, 2) designers, 3) planners, 4) contractors, 5) utilities, 6) locators, 7) construction workers, and 8) equipment operators. In most states of the U.S. a contractor is required by law to call a "One-Call Center" 48 or more hours before digging can begin. 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. The centers serve as a clearinghouse for excavation activities that are planned close to pipelines and other underground utilities. "Our purpose is to prevent damage to underground facilities. To promote safety, we provide an efficient, cost effective communications network among designers, excavators, and facility owners." http://www.pipeline101.com/PipelinesYou/onecall.html Every reader will most probably have seen one or two of the logos, displayed in Figure 1, that promote the use of the One-Call system at no cost. 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 48 and sometimes up to 72 hours prior to the beginning of any excavation activities. Lately, directional drilling crews have become very important customers of One-Call centers as well.

Figure 1: *Promoting Safety in Excavation, Digging, and Drilling*

From the One-Call website it is evident that many believe that one does not have to call if one can see the markers of a buried utility (e.g., phone). "Right-of-way markers along a pipeline

route or at a grade crossing only show the approximate location of a pipeline because the right-of-way they are marking is much wider than the pipeline. Thus, the markers are not always located precisely over a line. (Nor do the markers indicate the depth of the line.). Also, a pipeline may curve or make an angle underground as it runs between markers in order to avoid some natural or manmade feature such as a historical site or another underground facility such as a television cable."

Problems with Locating Buried Utilities

In the U.S. in 1989, the approximate mileage of major elements of the existing U.S. underground utility network was as follows (Kramer, et al., 1992):

- Electricity - 370,000 miles of underground distribution cables
- Natural gas - 900,000 miles of distribution mains and 600,000 miles of distribution services
- Sewers - 600,000 miles of collector sewers with 600,000 lateral connections
- Telephone - 260,000 miles of direct buried cables and 300,000 miles of cable in conduit
- Water - 450,000 miles of distribution pipe

In addition, in 1994 the Electric Power Research Institute (EPRI) estimated that 7,000 to 8,000 miles of electric transmission lines in the U.S. were located underground. These totals do not include the construction of new national fiber optic networks. However, by 1999 Qwest, Inc. alone had laid 880,000 miles of fiber optic cables across the US.

According to a report by Sterling (2000) http://www.nal.usda.gov/ttic/utilfnl.htm#ref, current technologies used to locate the different utilities have a variety of weaknesses. For example, they can not:

- locate all types of utilities (e.g. plastic).
- be used in all types of soils (e.g., wet clay)
- penetrate to required depths (e.g. 6 feet)
- resolve smaller utilities at the required depths.

In addition, the locating process is not trivial and has to expect many inconsistencies such as induced signals that "jump" from one utility to another one close by, loops, or "detours" around a tree root that has long since disintegrated. Figure 2 presents a summary of the present shortcomings.

a) Plastic Gas-Line 3 feet from Yellow Mark

b) Accident Despite Intensive Locating

Figure 2: *Ineffective Locating Tools and Lacking Failsafe Methods*

Figure 2 a) portrays the outcome of a hand-dig to find a buried plastic gas line which had been located and marked in yellow by a locating company in Charlotte, NC. The pipe was eventually found 3 feet from where it had been marked. The photograph in Figure 2 b) was downloaded from www.enr.construction.com which reported a pipeline blast on Nov. 9, 2004 in Walnut Creek, California: "Three workers have been confirmed dead and two were missing and presumed dead after a pipeline ruptured and exploded during construction of a water pipeline." The new water line ran parallel to a jet fuel and gas pipeline. In this incident, "Two died in the explosion and a third worker succumbed a day later to third-degree burns. Four others are still in the hospital with moderate to severe burns. Due to safety concerns about residual gas vapors, rescue teams have been thwarted in their attempt to locate the missing workers who could be trapped inside a 15-ft-dia water pipeline." In order to protect the gas line, its owner had implemented strict rules about damage prevention. As mentioned above, there are still conditions that can exist that cannot be anticipated.

Despite the successful implementation of the One-Call systems throughout most of the U.S, the accidents caused by damaging underground utilities result in wide variety of impacts ranging from clogged residential sewer lines, cut phone lines, and severed high speed cables to fatal gas explosions. The list of impacted parties that incur death and damage comprises not only the laborers, contractors, utility and property owners, or people at the accidents, but also the customers of disrupted utilities (e.g., private homes, governmental agencies, service companies, schools, hospitals, industrial firms, transportation systems, freight trains and trucking companies,

retailers, and the utilities themselves. Overall, the damages of such accidents are staggering, necessitating the development of more sophisticated prevention approaches.

SEEING THROUGH THE SOIL

Utilities that are buried in the ground represent an anomaly which should stick out like "a soar thumb" and thus easily recognizable. In reality, however, the underground in areas that has been inhabited by burrowing animals and different plants and trees is itself full of anomalies making it hard to pinpoint specific items such as a cable or pipe. One exception are metallic cables and pipes which can be detected because of their magnetic field. Another anomaly that could be used for detection are the empty tube-like spaces that are being created by non-metallic pipes such as plastic, concrete, or terracotta. The following section will briefly review the scientific principles of both systems of detection before demonstrating how two key detection technologies have been fused together.

Searching with Electromagnetic Induction

According to the laws of physics, whenever a conductor moves through a magnetic field, the conductor will experience an electric force. If the conductor is part of a closed circuit, a measurable current will flow. On the other hand, a coil may be used with metal items to induce a magnetic field, which than can be detected by an antenna. If one uses a receiver coil one is able to "listen" to the reflected signal which indicates its presence. This can be done by either continuous wave EMI (Electromagnetic Induction) or a Pulse EMI.

EMI sensors have been used since the 1950's for quality control on manufacturing production lines to safeguard against contamination. In more recent times, they have been used as a tool for mining, non-destructive testing, security, archaeology geology and other related fields. Metal detectors using electro-magnetic induction, especially pulse induction are not new in the field of buried utility detection. With two antennae, or one moving antenna in many positions, it is also possible to determine the depth of the buried pipe. This technology has also been used to discover unexploded ordinance (Lorenc and Bernold, 1997).

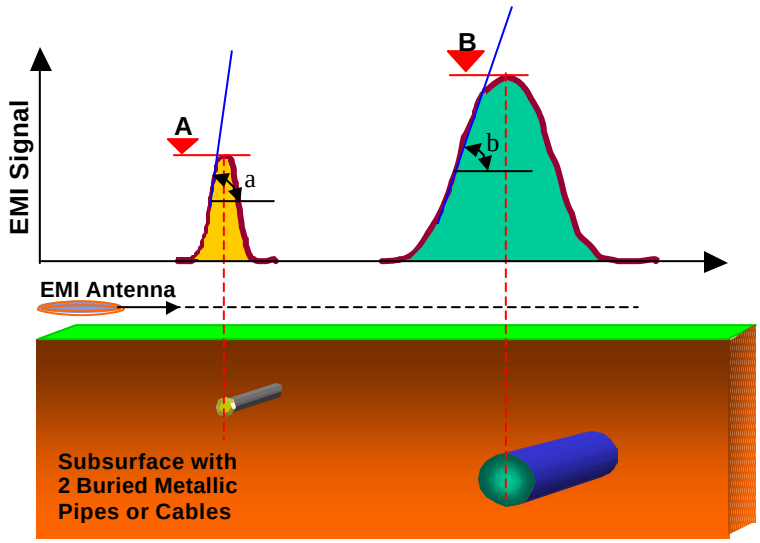


Figure 3: *Features of Metallic Pipes/Cables on EMI*

The EMI creates a signal output that represents the strength of a measured magnetic field which varies as a function of size and distance. Small pipes that are nearby create a field that is smaller and more concentrated than a large pipe that is farther away. However, by measuring the slope angle of the hyperbola that is being created by moving the EMI antenna over the pipe or cable, one is able to distinguish size. Here β is smaller than α which relates to the diameters which is inverse. On the other hand, the peak of the hyperbola alone, labeled A and B, may mislead the inexperienced locator in that the larger signal belongs to a pipe that is buried deeper. Only when the slope angle is combined with the peak measurement is one able to predict both size and depth of the metallic object.

Searching with Reflected Radio Waves

A technology which is being used to detect plastic landmines Gader (et al., 2001) and archeological objects underground is called Ground Penetrating Radar (GPR) a device that uses a radio wave source to transmit a pulse of electromagnetic energy into a nonmagnetic body. The wave propagates, interfaces with materials of different dielectric properties or of differing conductivities, and is then received by the receiver. These interfaces that the wave has might affect its amplitude and phase, which effectively constitutes a signal that describes the nature of the ground below. The data consists of a) changes in reflection strength, b) changes in arrival time of specific reflections, c) source wavelet distortion, and d) signal attenuation.

The GPR record consists of a continuous graphic display of reflected energy over a set time interval. The set time interval is the two-way travel time, measured in nanoseconds. The depth of the material the wave penetrates can be determined if the velocity of the electromagnetic energy through the material is known. An ideal wave would just be an impulse shot vertically downwards from the center of the GPR. However in practice, the wave can be imagined as a cone with its tip at the center of the GPR and a circular radius. Consequently the value at each pixel of the created GPR image is a result of a convolution carried around the spread of the cone. This results in a hyperbola being created for objects that are able to reflect the waves due to large differences in dielectric properties. Figure 4 demonstrates the basic concept of a GPR unit that is moved over the ground from left to right. As indicated, a sender emits waves in the form of a cone into the ground. The reflections created from changing densities inside the soil or from a buried rock are being plotted on a time-based graphical chart. As indicated, small pipes or cable made of hard material (e.g., metal) develop a typical hyperbola when buried in sand. Even a trench that was once dug up shows a typical feature. Echoes created by waves that return to the pipe a second time can also be identified.

As mentioned earlier, the velocity of pulsed waves are controlled by the materials that they have to penetrate, their density, and the water content. While dry sand represents the best condition, wet clay does not allow any wave to reflect on objects. Nevertheless, since GPR works in non-saturated material it represents a viable tool to detect buried objects but might need sophisticated software tools to account for the difficulties to “see” anything using the graphical output. The

next section discusses how the two technologies, EMI and GPR, have been integrated with each other as well as with the equipment that is the immediate cause of many accidents, the backhoe excavator.

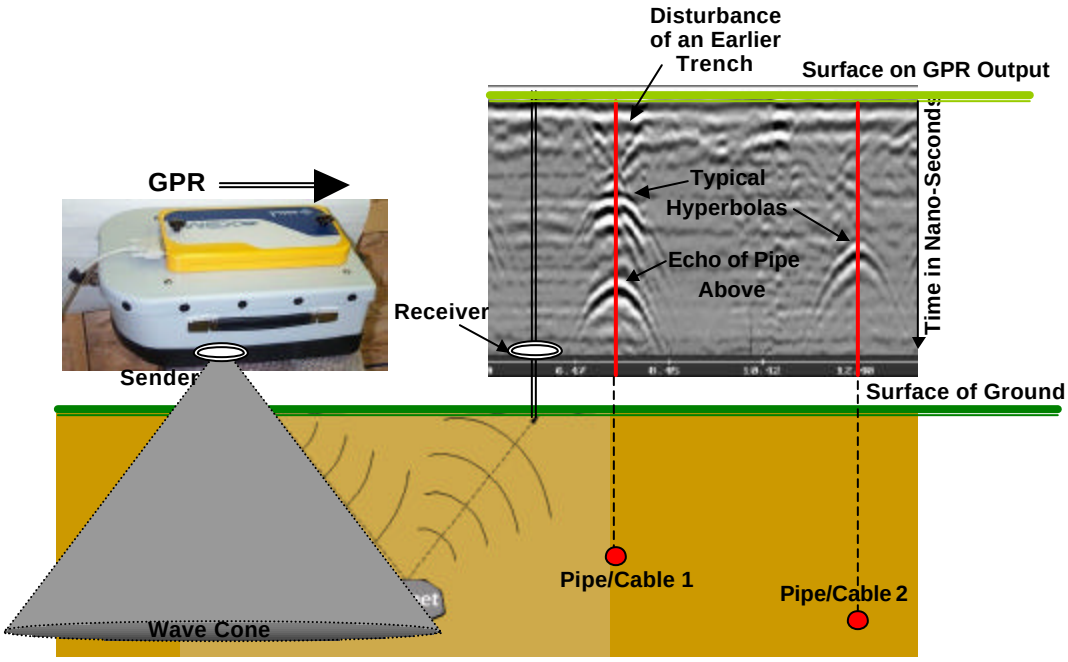


Figure 4: *GPR's Time-Based Graphical Outputs of Pipes Buried in Sand*

INTEGRATION OF SENSORS, PEOPLE, AND MACHINES

The previous section demonstrated that one sensor is not able to detect all the possible buried objects while able to distinguish between "trash" and vital utilities. In addition, an attempt was made to show how the sensory outputs are not always easy to understand. For that reason it is important to create a real-time, accurate, and, more importantly, reliable "fish-finder" type utility detection system with minimal false warning. Combining the two different sensors into one system was deemed to be one way of improving the underground detection capabilities. For example, the GPR module is able to detect plastic, but is unable to distinguish between a metallic and a plastic pipe. Similarly, the EMI, by itself is not capable of providing any information about non-metallic objects. These limitations of the individual sensors can be overcome by a fusion of the sensory data.

Figure 5 shows a schematic process of the fusing of GPR and EMI after the ground has been scanned. Data are fed to two parallel processors which check the two streams for features that are recognizable in order to establish a list of possible problems. These two lists, including probabilities, are fed to a third processor in order to develop a final prediction about the location and type of utilities. The last step consists of establishing a 3-D or drawing of the prediction.

The key to the success of this process is the accurate interpretation of the sensor data using all the capabilities provided by modern computer power. The question is: What do the data indicate about the conditions?

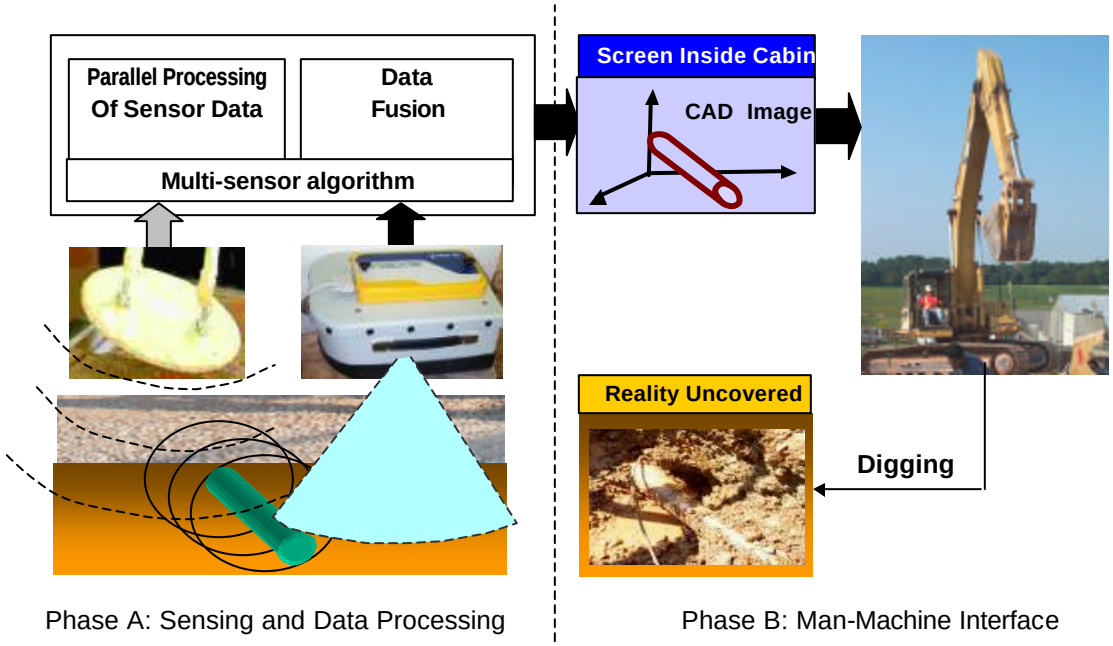


Figure 5: *Sensor Fusion to Locate and Inform the Backhoe Operator Real-Time*

Besides having the sensors integrated with each other, it is critical to link the sensors and sensory feedback with the operator who, at the present, has only color markers on the ground as a guide. By providing the operator a tool to independently scan the ground immediately before the bucket bites into the soil, even inside a deep trench, real-time data would be generated about the situation just ahead of the next dig. By mounting the sensor on the equipment itself, the weaknesses of present technologies in sensing range/depth could be overcome. The final part of the paper will describe how this concept was implemented and tested in the field.

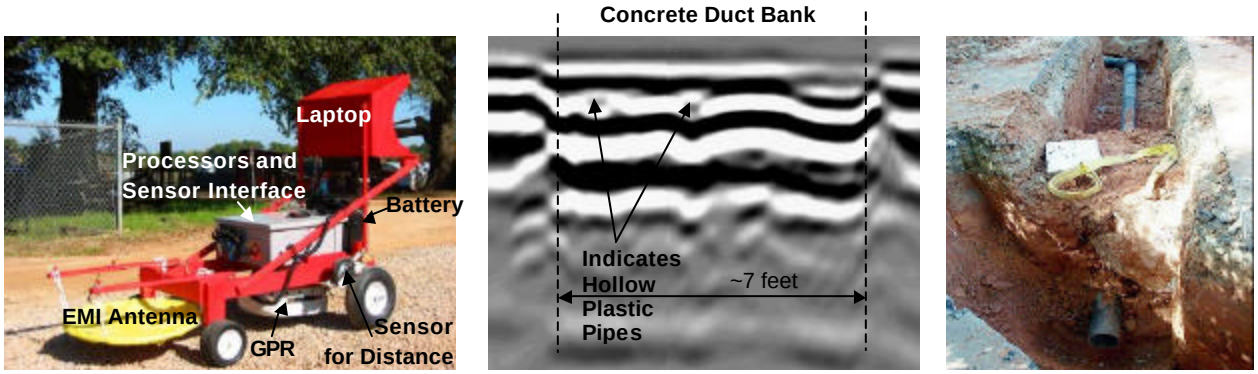
FIELD TESTING A BURIED UTILITY DETECTION SYSTEM

Pre-Dig Subsurface Scanning

After intensive testing in the laboratory, the Buried Utility Detection System (BUDS) was tested in the field in the form of a mobile platform (Mo-BUDS). Figure 6 exhibits the developed hardware with an example output and the actual situation.

The duct bank detected during an experiment to detect buried obstacles before the installation of a new water-pipe was not expected since the plans indicated the it followed the side of the road. Figure 6 clearly displayed a feature that could only be exhibited by a buried 6 foot slab approximately 1 foot bellow the surface of the road. Both, the GPR and the EMI were in

agreement that there were no metal pipes or cables inside the concrete, just conduits possibly filled with fiber optic cables. Although the contractor was warned about the existence of the duct bank he proceeded as if nothing was there expecting to install an 90 degree elbow exactly where the GPR indicated the existence of the concrete bank. To the contractor's own surprise, the interpretation of the GPR was almost correct in that the concrete duct bank was only 4 feet wide. After the water pipe was re-routed the contractor was able to pass the cast iron pipe underneath the shallow bank and turn right after it was passed, as shown inn Figure 6 c). What is not shown is the fact that to the left of the picture, the bank made a 30 degree turn which had as its consequence that Mo-BUDS crossed it in an angle, thus turning a 4 foot wide bank into a 7 foot slab.

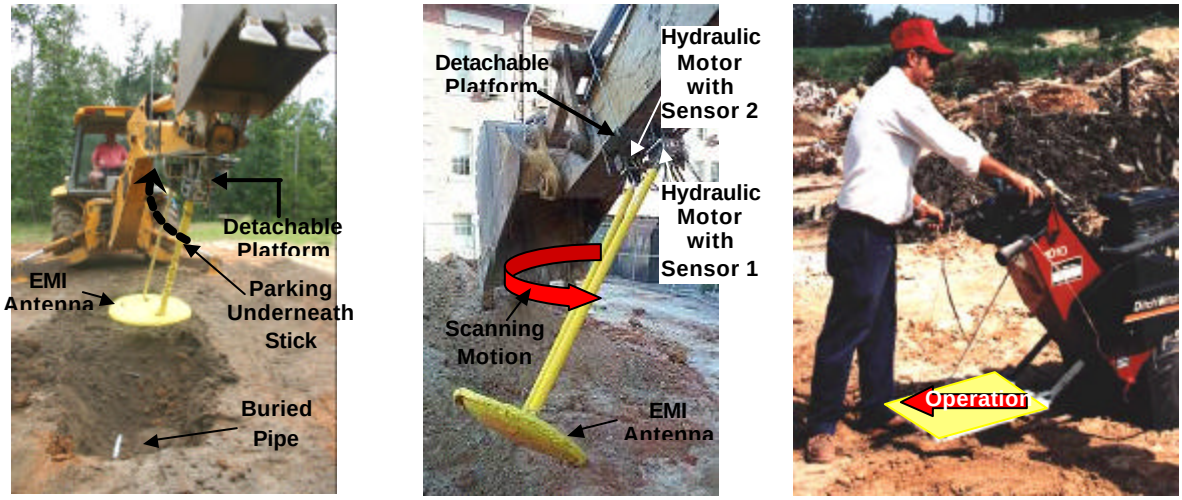


a) Mo-BUDS During Field Tests b) GPR Showing a Concrete Duct Bank c) Pipe Under Duct Bank

Figure 6: *Mo-BUDS Prototype With a Find*

Real-Time Scanning with Equipment Mounted Device

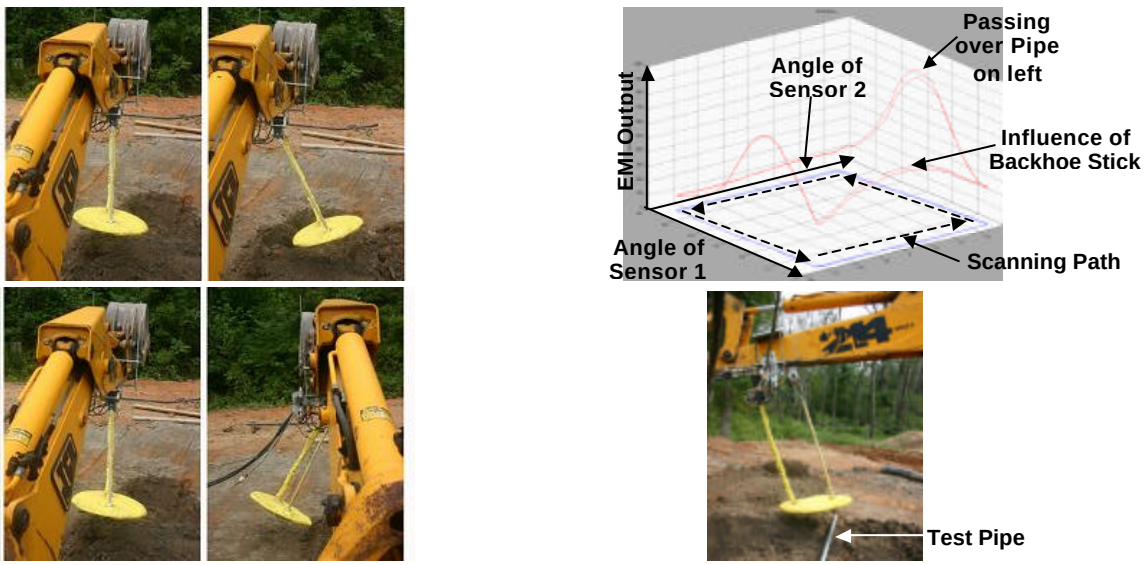
Integrating the sensors with the equipment and providing the mechanism for an operator to initiate a scanning of the subsurface required the development of attachable hardware. Figure 7 highlights three different types of equipment for which utility detection concepts were designed: a) backhoe-loader, b) backhoe excavator, and c) trencher.



a) Backhoe-loader b) Backhoe Excavator Scanning c) Trencher Scans Ahead

Figure 7: *Attachment Based Hardware to Locate Utilities During Excavation*

As revealed by the pictures, the equipment mounted BUDS (Em-BUDS), in the case of backhoes, is actuated via two hydraulic motors providing 2 degrees of freedom for scanning. In the case of the trencher, the present design is fixed and centered in the path of the trencher chain that follows the sensor. Two parallel rods are used to move the antenna away from the metal of the backhoe stick, while, in the "parking position", they are folded up safely underneath the stick secured by a locking guard mechanism. As indicated in Figure 7 a) and b), the developed control algorithm actuates the round EMI antenna, pinned to the end of the rod, to follow a scanning pattern. This is enabled by the two hydraulic motors and angle sensors which allow the system to move along a desired path, collecting data about its position, indicated by the two angle sensors, while reading the output of the EMI in real-time. Figure 8 demonstrates the outcome of such a scanning process.



a) Scanning Routine Following a Square b) Data Collection, Analysis, and Pointing at Pipe Location

Figure 8: *EMI Scanning Algorithm to Pin-point Buried Pipes and Cables*

Figure 8 b) presents the data collected during a test run of Em-BUDS using the EMI. The measurements of the two angle encoders are plotted in the x-y plane while the EMI output is shown on the z-axis. For a pipe positioned perpendicular to the backhoe stick the Em-BUDS creates the 3-D curve colored in red. It is apparent that the two hydraulic motors are actuated in sequence, thus creating a closed rectangle. While passing over the test pipe (which was unearthed for the picture) the EMI output increases and decreases gradually, creating a hyperbola. Even the influence of the metallic backhoe itself is visible since at one end the antenna is getting closer to the stick than on the other. Finally, the algorithm is quickly calculating the closest distance to the pipe and actuates the two motors so that the rods/antenna point to it. This tells the operator not only that there is a buried pipe but also indicates its

approximate location. From the graphical output of the sensors in Figure 8 b) one can see that the available data could be easily used to show also the direction and even the depth of the pipe.

SUMMARY AND CONCLUSION

Damage to buried utilities cost many lives per year and many more are injured. This paper presented information on the One-Call system, the main approach to prevent such accidents, before focusing on a novel technology to detect buried utilities. Taking advantage of fusing two sensor capabilities, the Pulse EMI and the GPR, mounted to the digging equipment, the technological intervention is able to provide the equipment operator a "fish-finder" type warning system. The premise of fusing the two sensory data streams is to maximize reliability/accuracy while minimizing false positives. Two prototype systems have been built for field testing the concepts under real conditions. A mobile unit was used extensively to scan the ground ahead of a pipe-installation job on the North Carolina State University (NCSU) campus and to verify its results with the actual conditions. The second prototype was mounted on three different types of excavating equipment and was extensively tested on a backhoe-loader. As the results of the test demonstrate, the computer controlled scanning mechanism, termed Em-BUDS, was able to provide valuable information to an operator in a simple form. It is hoped that the staggering number of accidents caused by damaging buried utilities will encourage the industry, especially utility owners, to seek and support additional solutions to prevention.

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