DIFFERENTIAL SOIL IMPEDANCE OBSTACLE DETECTION

QUARTERLY TECHNICAL REPORT

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ABSTRACT

This project develops a new and unique obstacle detection sensor for horizontal directional drilling (HDD) equipment. The development of this new technology will greatly improve the reliability and safety of natural gas HDD construction practices. This sensor utilizes a differential soil impedance measurement technique that will be sensitive to the presence of plastic and ceramic, as well as metallic obstacles.

The use of HDD equipment has risen significantly in the gas industry because HDD provides a much more cost-effective and less disruptive method for gas pipe installation than older, trenching methods. However, there have been isolated strikes of underground utilities by HDD equipment, which may have been avoided if methods were available to detect other underground obstacles when using HDD systems. GTI advisors from the gas industry have ranked the value of solving the obstacle detection problem as the most important research and development project for GTI to pursue using Federal Energy Regulatory Commission (FERC) funds available through its industry partner, GRI.

GTI proposes to develop a prototype down-hole sensor system that is simple and compact. The sensor utilizes an impedance measurement technique that is sensitive to the presence of metallic or non-metallic objects in the proximity of the HDD head. The system will use a thin film sensor conformal with the drill head. The impedance of the soil will be measured with a low frequency signal injected through the drill head itself. A pair of bridge type impedance sensors, mounted orthogonal to one another, is capacitively coupled to the soil. Inclusions in the soil will cause changes to the sensor balance distinguishable from homogeneous soil.

The sensor will provide range and direction data for obstacles near the HDD head. The goal is to provide a simple, robust system that provides the information required to avoid obstacles. This must be done within the size and ruggedness constraints of the HDD equipment. Imaging obstacles is not within the scope of this work, as it would require a more elaborate sensor than is practical within the HDD head.

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EXECUTIVE SUMMARY

The North American gas industry is increasing its usage of guided directional drilling for the installation of gas services and mains. This increased usage is limited by an increased awareness of the hazards associated with drill head collision with buried utility lines such as gas, electric power, water, telephone and sewer. Users of guided drilling equipment, the customers they serve, and the owners of buried utility lines would all benefit from the development of sensing technology that could help avoid unintentional contact with buried obstacles.

GTI has kept abreast of recent developments in proximity sensing and ranging. Electronic methods for sensing and ranging non-metallic objects are finding their way into commercial products such as stud locators, level sensors, and moisture detectors. Military technologies for the detection of plastic landmines have likewise progressed and are finding their way into civilian markets. Much of this technology is readily available for license from national laboratories.

The obstacle detection system being developed in this project utilizes a capacitive array sensing technique. This technique can resolve small changes in the impedance of the surrounding environment caused by objects of varying dielectric properties. Plastic pipe and ceramic conduits represent discontinuities in the soil that should be easily discernable. The sensor would simply be an array of conductors conformal with the drill head.

Simple signal processing and multiplexing would be used to determine the direction and range of an obstacle. The goal is to detect and avoid the obstacle, not to image it, eliminating the need for high frequency time-of-flight signal processing. The normal rotation of the drill head will be utilized to scan the vicinity of the head for obstacles. The array could also be used to passively sense the 60 Hz signatures radiated from buried power lines.

INTRODUCTION

This project will focus on the development of technology to improve the reliability and safety of gas distribution systems and construction methods. The objective is to further develop an obstacle detection system for directional drilling rigs by testing a sensor concept in a variety of simulated field conditions

GTI has been involved in developing new technologies for guided directional drilling since 1984. GTI supported the conception and commercialization of new products that made horizontal directional drilling (HDD) an increasingly growing practice in the gas distribution industry. In the 1980s, several manufacturers developed new hardware and methods for guided horizontal drilling for service installation applications: gas line services, electrical and cable installations, water and sewer lines, and telephone systems. Consequently, today there are many manufacturers and users of horizontal directional drilling equipment worldwide. In North America, GTI-patented technology is present on about 70% of all newly manufactured HDD equipment (Figure 1).

Figure 1. Typical HDD Rig for Gas Applications

With the success in reducing installation costs and the subsequent increased use of HDD, crowded utility easements have become more common and the potential for underground contact with other utilities or obstacles has risen dramatically. Over the past few years, there have been a few extreme incidents of damage resulting from drill collisions with buried facilities.

In addition to dramatic incidents, there are thousands of other utility strikes on gas, electric, telecommunications, water, and sewer lines that occur on a yearly basis. Taken together, these examples illustrate the problems for guided drilling equipment and the need for obstacle detection. For the gas industry, one of the most serious situations occur when a guided drilling head or back reamer penetrates a residential sewer line, and a plastic gas pipe is then inadvertently installed through the sewer line. Later, when the sewer becomes clogged, a sewer-cleaning device can cut through the live gas line, releasing natural gas into the sewer and potentially releasing a flammable gas mixture in adjacent buildings (Figure 2). Several gas companies have experienced this type of incident.

Figure 2. Damage to Lead Sewer Pipe from HDD Tool

EXPERIMENTAL

No experimental work has yet been performed on this project. There are results in related areas however, that demonstrate the feasibility of impedance techniques for detecting objects embedded in soil.

Sensor Configuration

The proposed sensor consists of a series of electrodes distributed circumferentially about the drill head just aft of the blade. Figure 3 shows the typical structure geometry for a directional drill head. The blade itself is used to inject the signal into the soil ahead of the drill. The anticipated embodiment is four equally space electrodes. Each diametrically opposed pair of electrodes being the sense elements of one sensing bridge.

Figure 3. A Typical HDD Drill Head

Figure 4 shows schematically the arrangement of the sense electrodes and the anticipated signal current flows about the drill head. The opposed pairs of electrodes will provide two orthogonal axes over which the soil impedance can be measured. The angle of drill blade will cause an asymmetry in the distribution of signal current. This asymmetry will be exploited to prevent a “blind spot” immediately in front of the drill. In a soil without inclusions (homogeneous) the sense bridge across the symmetric axis of the drill will be balanced to within some reasonable error band. An inclusion dead ahead of the drill would perturb the symmetric bridge very little. The signal currents around such an inclusion would be symmetric about the drill axis.

The sensing bridge across the asymmetric drill axis is anticipated to be unbalanced in homogeneous soils. In this case an inclusion dead ahead of the drill will cause some alteration of the sensing bridge balance point. The anticipated effect is that conductive inclusions will pull this bridge closer to balance by shortening the current path, insulating (plastic, ceramic) inclusions will push the bridge further from balance by lengthening the current paths.

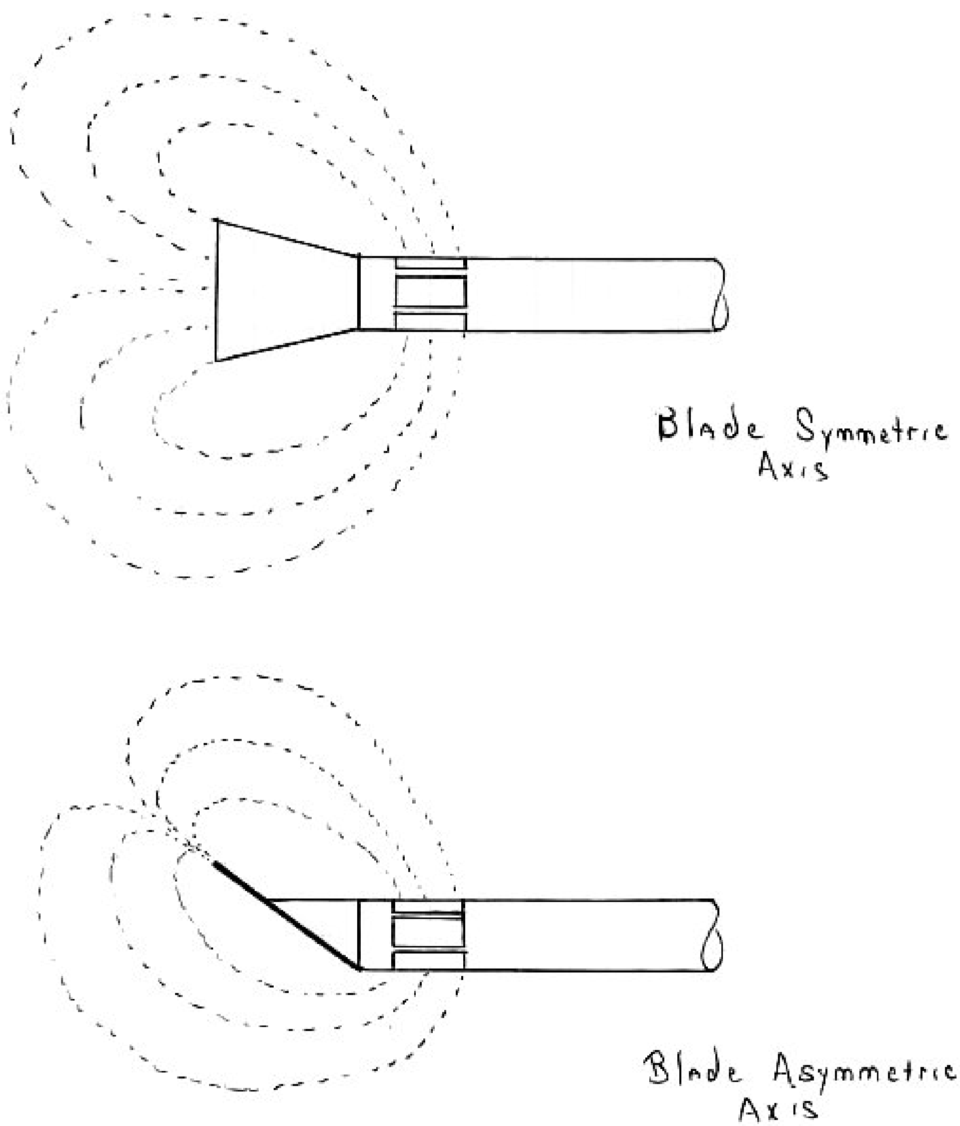

Figure 4. Anticipated Arrangement of Sense Electrodes

This arrangement of two orthogonal bridge sensors yields two channels of obstacle detection data. The symmetric channel will be most sensitive to objects that are off center with respect to the drill path. The asymmetric channel will be most sensitive to objects directly in the drill path. The data fusion of these two channels can be used to sense extended objects such as pipes in the drill path. In order to use the normal drill rotation to scan the vicinity of the drill head a third channel of orientation data is necessary. A tilt sensor will be required on the drill head to provide the instantaneous angle between sensing electrodes and the “down” direction.

The sensing plates will be capacitively coupled to the soil: covered by an insulating layer. The sensing current injected through the drill blade will be an AC signal in the range below 500kHz. It is anticipated that the circuitry to support this low number of channels and modest frequency requirements will be straightforward and inexpensive.

RESULTS AND DISCUSSION

The use of impedance techniques to sense buried objects is the subject of another NETL-GRI collaborative project: "Capacitive Tomography for the Detection of Buried Plastic Pipe." The intent of the CT project is to provide a coarse image of buried objects using a sensor panel laid on the surface of the ground. The intent of "Obstacle Detection" is to detect and range soil inclusions in the immediate vicinity of the drill head.

The experimental results from the CT project have been very encouraging. Buried plastic pipe can be detected through 3 feet of soil using an AC excited capacitive bridge sensor. No problems are anticipated in using a similar technique to find obstacles in the immediate vicinity of the drill head. Also, the obstacle detection sensor requires only two sensors since the drill rotation can be used to scan the vicinity. The CT imaging sensor requires electronic multiplexing to scan the many sense electrodes required to build up an image.

CONCLUSIONS

- Based on the current state of the art, the use of impedance techniques to sense obstacles in front of a moving drill head is a new and unique application.
- Data from a related project confirms that an AC excited bridge sensor can readily sense plastic inclusions in soil.
- The sensing and data acquisition requirements for the impedance techniques are modest and there is a reasonable expectation that the electronics package can be mounted on the drill head.

Work Performed in the First Quarter

Task 1: Research Management Plan

The draft "Research Management Plan" was written and submitted. An assessment of the state of the art in Obstacle Detection as relates to horizontal drilling and subsurface detection was prepared and submitted. These documents are included as appendices to this report.

Task 2: Evaluate Sensor Concept

Sub task 2.1, "Evaluate Impedance Bridge Based Sensors" is in progress. A body of technique relating to impedance tomography in general has been identified. No other sub tasks have yet been started.

Task 3: Demonstrate Obstacle Detection in Ground

This task has not yet started. No work was performed on this task during the first quarter.

Technical Problems Encountered

No technical problems that will impact the ability to perform the project or project schedule have been encountered.

Project Management Problems Encountered

No project management problems were encountered this quarter.

Action Requested of Doe NETL Project Manager

There are no action items requested of the DOE COR.

WORK PLAN

Work Planned For The Second Quarter

The following items are planned for the next quarter:

- Find data on "tilt" sensors that can determine the orientation of the drill head.
- Construct a breadboard of an instrumented drill head suitable for testing in soil boxes.
- Prototype support electronics for the breadboard drill head.
- Perform balance tests of the simple breadboard in air and various soils.
- Present a project update on Obstacle Detection at the NETL "Natural Gas Infrastructure Reliability Industry Forum" in September.

REFERENCES

In a patent entitled “ Driven Shielding Capacitive Proximity Sensor”, patent number 5,166,679, dated November 24, 1992, inventors John M. Vranish and Robert L. McConnell have presented an invention for a capacitive proximity sensor that will detect the intrusion of a foreign object into the working space of an electrically grounded robotic arm. The capacitive proximity-sensing element is backed by a reflector that is driven by an electrical signal of the same amplitude and phase as that signal which is detected by the sensor. It is claimed that by driving the reflector plate with the same signal that is on the sense element significant increases in the sensor's range and sensitivity are accomplished.

In a patent entitled “Steering Capaciflector Sensor”, patent number 5,363,051, dated November 8, 1994, inventors Del T. Jenstrom and Robert L. McConnell, present an invention that will allow for the steering of the electric field lines produced by a capacitive type proximity sensor. The inventors assert the claim that by steering or focusing the electric field will allow an increased ability to discriminate and determine the range of an object in the area of observation over that of previous capacitive sensors. Differential voltages applied to shielding plates spatially arranged around the sensor plate accomplish steering of the electric field lines.

In a patent entitled “Buried Pipe Locator Utilizing A Change In Ground Capacitance”, patent number 5,617,031 dated April 1, 1997 inventor John E. B. Tuttle has invented a portable buried pipe detection device that utilizes changes in the electrical properties of the soils surrounding underground pipes. The detection method consists of the injection of a low frequency sinusoidal wave into the ground via an array of injector/sensor plates. Subsequent modification of the injected signal by variations in ground impedance brought about by the existence of buried piping structures will result. The modified signals will be detected by the spatially separated sensor elements located on the device. The injector/sensor elements are constructed in such a manner as to comprise a capacitive bridge circuit when viewed in conjunction with the ground. As the detection array is moved along the ground any occurrence of underground piping structures will imbalance the capacitive bridge and give rise to a detectable electrical signal.

LIST OF ACRONYMS AND ABBREVIATIONS

CT - Capacitive Tomography

COR – Contracting Officer's Technical Representative

DOE - Department of Energy

FERC – Federal Energy Regulatory Commission

GPR – Ground Penetrating Radar

GRI – Gas Research Institute

GTI - Gas Technology Institute

IGT – Institute of Gas Technology

IRNG –Infrastructure Reliability of Natural Gas

APPENDIX A

Differential Soil Impedance Obstacle Detection

Detailed Work Plan

A. OBJECTIVES

The objective of this project is to design, fabricate, and test a prototype sensor system for detecting obstacles in front of or around the head of a horizontal directional drilling (HDD) rig. The sensor system shall be sensitive to metallic, plastic, or ceramic obstacles embedded in the soil. The detection live power lines with the same sensor will also be investigated.

B. SCOPE OF WORK

In order to reach the goal of designing, fabricating, and testing, a viable prototype of an obstacle detection system for guided directional drilling, GTI shall perform the following tasks.

1. Program Management

2. Evaluate Sensor Concepts

3. Demonstrate Obstacle Detection in Ground

The completion of these Tasks in an orderly fashion will result in the fabrication and testing of a sensor that can be mounted on the drilling head of a horizontal directional drill. The sensor will be tested with a mixture of target obstacles in soil. This testing will be performed using a sensor probe driven vertically into the soil rather than horizontally bored in the interest of saving time and costs.

C. DELIVERABLES AND SCHEDULE

1.0 Program Management

1a Detailed Work Plan – 6/02

1b State of the Art Assessment – 7/02

1c Quarterly Technical and Financial Reports - 8/02, 11/02, 2/03, 5/03

1d Final Technical Report – 8/03, 10/03

1e Topical Reports and presentations as required

2.0 Evaluate Sensor Concepts

2a Evaluation of Impedance Bridge Sensors –11/02

2b Evaluation of Soil Properties – 2/03

2c Detailed Plan for In Ground Tests – 4/03

3.0 Demonstrate Obstacle Detection in Ground

3a Test Passive Sensing of Live Power Mains – 5/03

3b Test Active Sensing of Obstacles – 6/03

3c Demonstrate Sensor with Multiple Obstacles – 7/03

D. TASK WORK DETAILS

1.0 Program Management

This task will subsume all the necessary reporting, meeting, presentation, and demonstration requirements for DOE. The FERC provided cofunding will cover any additional program management requirements incurred by the gas industry sponsors.

1.1 Research Management Plan

GTI shall develop a work breakdown structure and supporting narrative that concisely addresses the overall project as set forth in the agreement. GTI shall provide a concise summary of the technical objectives and technical approach for each Task and, where appropriate, for each subtask. GTI shall provide detailed schedules and planned expenditures for each Task including any necessary charts or tables, and all major milestones and decision points. This statement of project objectives shall form the basis for the deliverable Research Management Plan

1.2 Technology Assessment

GTI shall prepare and submit a report describing the current state-of-the-art of the technology being developed. The report should describe existing technologies and positive and negative aspects of using this technology. The report shall not exceed five typewritten pages in length. The report is not to contain any proprietary or confidential data as the report will be posted on the NETL website for public viewing. The report is to be submitted within 60 days of award. The DOE Contracting Officer's Technical Representative (COR) shall have 20 calendar days from receipt of report to review and provide comments to the contractor. Within 15 calendar days after receipt of DOE's comments, the contractor shall submit a final Report to the DOE COR for review and approval.

2. 0 Evaluate Sensor Concept

In this task GTI will do a more detailed evaluation of specific technologies relating to obstacle detection. Some of these technologies may be identified in the state of the art evaluation. Bench experiments will be carried out in this task preparatory to performing tests in soil.

2.1 Evaluate impedance bridge based sensors

GTI shall survey existing methods of remote obstacle detection with a focus on those methods employing impedance bridge based sensors. Capacitively coupled impedance bridges have been evaluated for the location of sub-surface plastic objects such as plastic pipes and landmines. There is also a large body of work dealing with capacitive sensors for soil moisture measurement.

Simple experiments shall also be carried out in this task. A small-scale model consisting of a steel rod with an angled tip and an electrode array shall be constructed. This shall be tested in an electrolyte tank with submerged samples of various obstacle materials. Custom electronics are not necessary for these experiments. They shall be carried out using laboratory instrumentation.

2.2 Evaluate Soil Properties

Given the critical interaction between the soil and the sensing method, current data on soil properties shall be examined. The conductivity and dielectric properties of typical obstacles shall also be examined at this time. Soil survey data shall be obtained to estimate the distribution of soil types over North America. Part of this sub-task is to identify any “problem” soil types and extents. Any deficiencies in soil dielectric and conductivity data shall be identified at this time. Using the previously constructed probe and laboratory instruments, tests shall be carried out on single obstacles in representative soils.

2.3 Design of Task 3 Demonstration

Once the sensor and soil data are available, design of experiments shall be carried out. Tests for the detection of electric power mains in both the energized and off states by passive methods shall be designed. Tests for detecting and ranging inclusions in the soil by change of impedance shall be designed. Examples of obstacles with impedance lower than the soil are cast iron or metal pipes and metallic debris. Examples of obstacles with impedance higher than the soil are plastic pipes, clay tiles, and masonry rubble.

3.0 Demonstrate Obstacle Detection in Ground

Using the results of Task 2, GTI will demonstrate the detection of obstacles using differential impedance measurements in soil.

3.1 Passive Sensing Tests

In passive sensing tests the sensor probe will be used to detect the electromagnetic radiation signature emitting by live power lines. The probe will not emit signals in the frequency range characteristic of power lines. Electric mains may be buried directly in soil or buried in metal, concrete, or plastic conduits in the soil. Electric mains may be carrying three-phase or single-phase power at various voltage and current levels. These power lines shall have known voltages, currents, and phasing. In order to test the passive EM sensing mode of the array in soil, the test probe array shall be inserted vertically into the ground in the proximity of AC mains. Current and voltage monitors on the power mains will provide reference data for the evaluations of the array's sensitivity to this category of sources

3.2 Active Sensing Tests

In active sensing tests the sensor probe will be injecting an electrical signal of known characteristics into the soil. GTI shall develop a simplified field test site. Input shall be solicited from industry advisors during the construction of this facility to insure that relevant features are not overlooked. The number of representative soil types shall be determined. Appropriate numbers and sizes of obstacles shall be buried. Test sites that provide interference between obstacle types shall be included.

3.3 Perform Obstacle Detection Tests

After the simplified field environment has been completed, tests to determine the range, accuracy, and resolution of the sensor array shall be carried out. The effects of soil type, obstacle type, and obstacle size on array performance shall be observed. These experiments shall be performed with vertically driven probe arrays in the interests of keeping costs within bounds. These probes shall be driven incrementally closer to buried obstacles while simultaneously rotating the probe. A simple user interface and display shall be constructed to facilitate these tests.

APPENDIX B

STATE OF THE ART FOR DIFFERENTIAL SOIL IMPEDANCE OBSTACLE DETECTION

Prepared
By

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Electrical Engineer
Electronic & Telecomm Research

1.0 INTRODUCTION

This document serves as a state of the art for technologies in the field of differential impedance obstacle detection. Specifically, the obstacles in question are those encountered during a horizontal directional drilling operation; most importantly other previously installed service lines that are metallic, ceramic or plastic in composition. There have been no technologies found that use differential impedance to detect obstacles in the ground. A patent research was performed, and no technologies relating to Differential Impedance Obstacle Detection could be found. There are, however, other technologies that detect obstacles by different means.

2.0 OLDER OBSTACLE DETECTION TECHNOLOGIES

The most comprehensive document discovered on obstacle detection is a PRCI (Pipeline Research Council International, Inc.) document entitled "Obstacle Detection to Facilitate Horizontal Direction Drilling" written by Dr. David H Cowling and Dr. David T Iseley. However, as the report was written in 1994 it is somewhat outdated. Attempts have been made but have proven unsuccessful to contact Dr. Cowling and Dr. Iseley for further information. According to the Trenchless Technology Center, more updated work was not performed in this exact field, but a related activity was performed on a state of the art for utility location. The utility location research is described later in this report.

2.1 GPR

Ground Penetrating Radar (GPR) is the most common technology, described in the report above and through other research, which is used to detect plastic pipe and other obstacles underground. Different set-ups exist for GPR, but the frequency used is typically in the range of 10-1000 MHz.

One version of GPR uses two separate antennas laid on the ground. The transmitter sends a short pulse of 1-2 nanoseconds and the receiver picks up the returned echo. Like most GPR, this setup has very good resolution assuming the soil conditions are optimal, but when soil is wet the conditions can be lossy enough to make it unusable. The solution in lossy conditions is to lower the centering frequency of the GPR, but this often requires increasing the size of the antenna and also affects the resolution.

Another setup is called borehole-to-borehole GPR, originally used in the 1970s to detect tunnels underground. With this formation two vertical holes are dug a maximum of 50 meters apart. The transmitter antenna is lowered down one hole and the receiver antenna lowered down the other. The information on a subsurface structure or obstacle between the boreholes is determined from the time delay and signal strength of the arriving signal at the receiving antenna.

In this format the transmission is one-way, so it is not required to retrace its path as in surface GPR. The loss of data between boreholes is measured as an inverse of the distance to the second power as compared to inverse of the difference to the fourth power when using surface GPR. The spacing between the boreholes can be a maximum of 50 meters, but the boreholes are most often 20 feet apart. Boosting power can increase the range, but since battery packs are most often used and depending on the diameter of the borehole this may not be possible. As with other GPR, one can lower the frequency to increase range, but this affects the resolution.

2.2 AC RESISTIVITY

Borehole AC resistivity is a method by which transmitter electrodes are driven by a known current. The transfer resistance is the ratio of the voltage between one pair of adjacent electrodes to the current driving them. The receiving antenna senses the phase shift and attenuation of the signal as it passed through an object between the transmitter and receiver. Currents that flow around objects of low conductivity also aid in signal pickup.

There are two basic types of systems for AC Resistivity: borehole-to-borehole and surface-to-borehole. In borehole-to-borehole, several adjacent electrodes are placed vertically in a borehole. As already described, a known current is applied to each adjacent pair of electrodes and the resulting resistance calculated. An equal amount of electrodes are placed in another borehole for the receiving end. For an electric dipole set-up, the electrodes are placed in contact with the formation. In a magnetic dipole configuration, vertical-axis coils replace the electrodes and the transmitted current detected by induction.

In a surface-to-borehole system where only one borehole is available, a transmitter loop is placed on the surface a receiver probe is placed in a borehole either inside the loop or offset from it. A stronger current can be applied since the transmitter loop is on the surface, but the system is not as sensitive as the borehole-to-borehole measurements.

The AC resistivity systems are sometimes used in place radar to overcome the "expanding energy bubble" effect. With radar, energy radiates from the antenna in a bubble pattern. As the bubble expands, the energy drops off as the square of the radius of the bubble. In the cases where the radar transmitter and receiver occupy the same antenna housing, any reflection from an object will likewise cause the energy to drop off. A large transmitted signal tends to overwhelm the receiver with reflections from small local targets.

Since the AC resistivity methods use a transmitter and receiver far removed from each other, and since transmission is one way, the effects of radar are not an issue. The information of the obstacle is not contained in the time or frequency content of the signal, but instead is contained in the spatial relation of the signals as the transmitter and receiver are moved in their respective holes. Depending on the number of electrodes on the transmitter and receiver, the desired resolution can be achieved.

The downside of using AC resistivity is that interpretation of the data requires knowledge of the likely structure and electromagnetic properties of possible materials/objects in the transmission path. The models used lead to the use of tomography to help from a 3-D image of the object. Without a model of the composition of expected obstacles, the received data is of little use.

2.3 SEISMIC SYSTEMS

Obstacles can also be detected using seismic systems. In these systems, mechanical acoustic waves generated from a source are reflected and refracted by underground structures. Receivers, or geophones, pick up the returned waves and the information is processed.

With land surface seismic systems the transmitting transducers produce signals in the range of a few hundred Hz to the medium kHz range. The lowest frequencies are typically created by explosive charges or by mechanical shakers and electro-mechanical devices. Higher frequencies are produced by impact devices and mechanically resonant structures designed to impart energy on the earth's surface. The receiving geophones are ground mounted near/about the transducer. Sometimes they are mounted just below the surface to cut down on surface noises and interference.

Borehole seismic systems are similar to the land surface system, but the use of boreholes enables the transmitter and receiver to be placed closer to the source. Sources in borehole work are most often in the form of explosive charges. If compression waves are desired, the borehole is filled with water and devices used to create signals in the higher portion of the spectral range.

2.3 MAGNETIC SYSTEMS

Geophysical surveys are often performed using magnetic methods. These systems most often consist of three components: a plate, magnetic sensor or sensors, and a recording system. Different types of magnetometers exist. A flux-gate magnetometer is sensitive to both DC and AC fields with frequencies up to a fraction of some rod-saturating frequency. Proton-procession magnetometers are the most common for all types of surveys. They measure an absolute value of the earth's magnetic field and don't require precise orientation. Unlike the fluxgate types which furnish continuous measurements, the proton-procession type produce discrete measurements at 1-second intervals.

2.4 MICROGRAVITY SYSTEMS

Finally, the report describes micro-gravity methods that involve relative measurements of acceleration of gravity on the surface with high accuracy and precision. The gravitational field of the earth's surface varies because of location, elevation and time, and in this case variations caused by subsurface geology. By calculating the values with those expected for that particular area, data can be formulated as to the composition of the subsurface features. The difficulties with this system is there can often be several structures that can contain the same gravitational characteristics. Because of this, micro-gravity should only be used as a complement to other methods.

2.5 POTENTIAL FOR FUTURE WORK (AS OF 1994)

As of the writing in the report in 1994, the most probable methods from those described to be used for further research included sonar, seismic, borehole to borehole activities, and GPR. GPR for instance will be more usable if the signal to noise ratio of the received signal, especially in lossy conditions, can be improved. Land-based seismic systems are limited by the amount of resolution that can be achieved at very low depths. Using sheer waves rather than compression waves in the future will help solve the problems somewhat. Seismic systems alone cannot be a complete solution, but can be a good complement for GPR. GPR does not work well in wet clays, but seismic systems do. On the other hand, whereas seismic systems do not work well in air-filled voids, GPR systems do.

Low frequency EM/AC resistivity methods benefit by deeper penetration, but suffer in poorer resolution. The resolution can be improved to some degree by the placement and amount of electrodes used in borehole-to-borehole systems, but only to a certain degree. The resolution will be further helped by better computer methods, but at most, the authors felt it could only be used effectively when combined with other methods.

3.0 UTILITY LOCATION RESEARCH

Since the report in 1994, there was no more current report published by the Trenchless Technology Center on the state of the art of obstacle detection to facilitate HDD. There was, however, research and a report published in September 1999 entitled "Statement of Need: Utility Locating Technologies". The research was performed by the Trenchless Technology Center and the Technology Transfer Information Center of the National Agricultural Library, Agricultural Research Service, U.S. Department of Agriculture with sponsorship by the Federal Laboratories Consortium.

The report described a few common "destructive" methods, such as soil borings, test pits, etc., of determining the utilities already in the area, but this of course involves some form of excavation. Most of the non-destructive/geophysical methods outlined are those already described in the report of 1994: seismic waves, GPR, magnetic fields, electrical fields and variations in gravitational fields. It also describes a couple other technologies including temperature fields, nuclear methods, and gas detection.

Temperature field methods measure the amount that certain objects in the ground disturb normal ground temperature fields, either because of the function of the object (i.e. a steam pipe) or due to the thermal characteristics of the object compared to the surrounding area. Sometimes even solar radiation is enough to provide a difference between the effects on normal soil versus soil containing an object.

As the name implies, nuclear methods introduce a certain amount of radiation into the ground and measure the response using detectors. Gamma and neutron rays are most common, as well as naturally occurring radiation such as cosmic radiation.

Gas detection methods are used to detect objects that outgas during their lifetime. If the diffused gas is in detectable concentrations, the approximate location of the object can be determined.

3.1 SOLICITATION OF CURRENT RESEARCH IN DEVELOPMENT

The report does not go into depth as to specific technologies that used one or all of the methods described. There was a follow-up report written in February 2000 after the Statement of Need report was sent to federal labs, universities, and private industries to solicit help in defining current technologies in the field. Thirty responses were received as a result, out of which thirteen were included in the report. Since the information on the report only depends on the willingness of companies to provide information about the technologies, it is not an exhaustive list of all technologies that exist.

Below is a list of technologies identified in the report along with their limitations (these are specifically taken out of the report):

1. **Bakhtar Associates.** The features of the technology include GPR, step frequency approach, low power (average power of less than a watt), image processing and tomography. It was developed for detection of unexploded ordnance. The most innovative aspect of the hardware and software developments is its use of relatively narrow frequency bands of [GPR] pulses to perform a step-frequency based interrogation of the subsurface. This provides a much better signal-to-noise ratio than conventional methods. It is still subject somewhat to the limitations of GPR.

2. **Ball Subterranean Subsystems.** The features for the technology include GPR broadband antennas, and downhole use for HDD applications. The technology was researched in cooperation with three partners in South Africa to develop "see ahead" downhole systems. The innovation makes use of polarimetry to improve data interpretation and low-power compact systems for use downhole in HDD. The questions include on whether it is limited by the normal constraints of GPR and what the "see ahead" range is. Out of all the technologies listed in the report, this was the one most related to the obstacle detection project as it focuses on a downhole

system. However, the company is no longer involved in this research. The contact person stated the company decided it was no longer in its core business area.

3. **Environmental Investigations Corporation/CTC/NASA.** The features for the technology include acoustic resonant approach, use of ambient vibrations, and use of frequency domain. The "Resonant Acoustical Profiling (RAP) System" uses signals collected by piezoelectric sensors in contact with the ground surface. These signals are amplified and digitized and then converted from the time domain to the frequency domain using a version of the Fourier Transform. Positional and dimensional information is then extracted using special algorithms. The innovation claims the ability to extract information from ambient ground vibrations and the frequency domain approach. The questions remain as to specifics of how the use of ambient vibration levels provides information. Also, the new approach at the time had little documented effectiveness.

4. **Geophysical Survey Systems, Inc. (GSSI).** The features include GPR, multi-frequency antennas, and GPR positioning. The pulse GPR systems are tailored to specific applications. There is a wide range of antennas and interpretation software available. The innovation claims real-time, onsite interpretation of utility position. The general limitations of GPR apply.

5. **Geo Radar, Inc.** The system uses stepped-FM GPR that emits a continuous wave at a number of frequencies rather than a narrow pulse. This allows better signal interpretation and resolution of closely spaced objects. Stepped-FM GPR is less subject to interference caused by nearby metal objects and radio transmitters than pulse GPR. Work has also been carried out at Lockheed Martin Corporation on 3-D imaging of utilities using proprietary algorithms, synthetic aperture processing, and a two-directional linear filter. The questions are whether it is has the limitations of GPR and what is the required grid frequency for 3-D imaging.

6. **Johns Hopkins University, Applied Physics Laboratory.** The technologies include an Electrical conductivity object locator (ECOL), magnetometers for corrosion sensing, xylophone magnetometer for detection of small magnetic objects, and TerraHertz imaging system. Determination of anomalies in electrical conductivity, sensing of impressed currents in a pipeline, or tracer wire, and multifrequency approaches were also being pursued.

7. **NSA Engineering, Inc.** The technology developed is seismic reflection tomography for use in imaging ahead in tunnels. The method uses seismic signal generated by normal mining and tunneling equipment together with an array of piezoelectric cells and accelerometers positioned within the tunnel and back from the face. It produces a three dimensional image of the rock mass ahead of the tunnel face. Innovations found in the system include the use of vibration generated

during a normal tunnel cycle, receiver array design, and signal processing. There is a question of the diameter of the tunnel/drill hole required to resolve ground conditions ahead of the bore.

8. **Penn State University/Cold Regions Research and Engineering Laboratory (CRREL).** The research looks at the process determining the position of shallow buried pipes in complex configurations using GPR. Both forward modeling (generating synthetic GPR data for comparison with field data) and migration analysis using a 3-D Kirchhoff integral method are pursued. The technology still suffered from the normal limitations of GPR.

9. **SC&A, Inc.** The features of the technology include magnetometer and electromagnetic induction, multi-sensor arrays, and coupling to GPR. The techniques were developed for detecting unexploded ordnance. There are questions on the relative effectiveness of the technology when compared to other systems.

10. **Sequel Research Corporation/Ventus, Inc.** The features of the technology include advanced impulse electromagnetic radar (AIR) to control frequency, pulse duration and power to enhance penetration of the signals. It claims enhanced penetration when compared to normal GPR. Although no scientific reports were provided to document the phenomenon.

11. **Computing Devices Canada.** The system makes use of Electrical impedance tomography (EIT). EIT uses low-level electrical currents to probe a conductive medium and produce and image of its conductivity distribution. An array of electrodes (currently 1 square meter with 64 electrodes) is placed on the ground surface to provide an image. The presence of a metal or plastic object disturbs the conductivity distribution in the soil. The image reconstruction algorithm uses the difference between the measured potentials and the ones predicted from a model to solve for conductivity perturbations in the medium. The calculations are done with a linearized version of Laplace's equation, which allows fast reconstruction of the conductivity distributions. The technology is not expected to work through asphalt or concrete.

12. **Sensors and Software.** The technology uses selectable frequency GPR, signal processing, and user oriented display software. The antenna frequencies range from 12.5 to 1200 MHz. It claims increased signal-to-noise performance, but it still somewhat affected by the general limitations of GPR.

13. **IDS (Italy).** This company claimed a technology of highly integrated GPR using multiple antenna arrays and multiple frequencies. Like the others technologies, it has limitations associated with GPR.

4.0 GTI TECHNOLOGIES

GTI is currently involved with three obstacle detection technologies. One of the technologies being performed use the drill head itself to inject the acoustic waves into the soil. The system uses an acoustic sensor array placed on the surface that determines the obstacles in proximity of the underground drill bit.

The second obstacle detection technology is based on electromagnetic technology. The system has been designed with a walkover type receiver, similar to those used with pipe locator systems. The system has detected energized direct- and alternating-current power cables, ferrous pipes and structures; fiber-optic cables and plastic pipes installed with tracer wires and non-metallic pipes with inserted RF transmitters in the laboratory environment.

GTI is planning to initiate a third project on obstacle detection system based on the GPR that is incorporated in the drill rig itself.

5.0 BIBLIOGRAPHY

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