DIFFERENTIAL SOIL IMPEDANCE OBSTACLE DETECTION

QUARTERLY TECHNICAL REPORT

(October 1 through December 31, 2002)

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Report Issue Date: January 30, 2003

DOE Contract #: DE-FC26-02NT41318

Submitted by

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GTI Project Number: 61152

Submitted to

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National Energy Technology Laboratory
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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

The experimental work performed during the second quarter was to continue tests to determine the sensitivity of the breadboard sensor in soils. The breadboard sensor was fabricated during the previous quarter. During the second quarter it was tested in soil boxes of various sizes both with and without obstacles. Some modifications to the structure of the sensor were made. The following is a brief review of the sensor design and principles.

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 the arrangement of the sense electrodes on the prototype. The opposed pairs of electrodes 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. The leading edge, or tip, of the prototype is simply an angled cylinder. A blade could also be bolted on to the elliptical face of the tip to simulate varieties of drill heads used in the field.

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.

Fig 4. Sensor Breadboard with Electrodes in place

Figure 5 shows the prototype disassembled and without electrodes applied. The sensing plates are capacitively coupled to the soil: covered by an insulating layer. The outermost lexan tube provides this function: it prevents the sense plates from shorting directly to the soil and generally protects the internal electronics. The inner lexan tube carries the sense electrodes on its outer surface, in proximity with but not touching the soil. A third tube slides directly over the threaded rod, within the one carrying the sense electrode. This innermost carries the drive electrode.

Figure 6 shows the equivalent circuit of one pair of the sense electrodes, the sense amplifier, and the drive circuitry. The sensing current injected through the tool tip is 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.

Fig 5. Sensor Breadboard Disassembled

Fig 6. Equivalent Circuit of Differential Electrode Pair

In relation to the equivalent circuit of Figure 6, the drill tip corresponds the “tool blade”. The drill tip is one terminal of the signal generator providing the bridge excitation signal. The intimate contact between the drill tip and the soil ensures a reasonable amount of excitation current is injected into the soil. The “drive” electrode is the silver cylinder at the center of the other lexan tubes in Figure 4. This electrode consists of a lexan tube that fits directly over the threaded rod without any appreciable play. It is then covered with aluminum tape and wiring brought out. The copper strips in the foreground are the sense electrodes, mounted on their own lexan tube between the drive electrode and the outside world.

There are four sense electrodes equally spaced about the circumference. Diametrically opposite pairs are wired together to form the impedance bridge. This arrangement forms a three-layer capacitor where the third plate is the soil outside of the largest lexan tube. The soil is electrically continuous with the tool tip as noted above. With reference to the equivalent circuit, this three-layer capacitor is identical to two capacitors in series, which make up each leg of the bridge circuit.

RESULTS AND DISCUSSION

The second quarterly report stated that the device could sense nearby objects in the air. To cause a change in the differential signal amplitude, the object has to be placed almost directly on top of one of the sensing plates. If the object is placed further away, specifically some point in front of the head, no change is noticed. These results are reasonable for experiments performed in air.

It was anticipated that sensitivity would increase in soil, but the results were not as expected. There is a noticeable change in the bridge balance when one sense plate is in the open air (and the other three plates submerged in the soil) versus when all four are in the soil. There is virtually no change in differential amplitude when an object is placed in the soil. As with the air tests, the object has to be placed directly next to one of the sense plates for any change to be measured.

The first soil tests were conducted in sand in a relatively small soil box measuring 12”wide by 12”high by 18”long. The device itself is about 17.5” in length so it was difficult to accurately test for objects ahead of the device. A much larger soil box measuring 50”L x 29”W x 25”H was obtained, but the results didn’t improve.

Figure 7. Soil Box used for Second Quarter Experiments

The first drive cylinder tested had no buffering layers other than the lexan between it and the shaft of the tool blade. Referring to Figure 6, this situation is equivalent to the “buffer layers” being replaced with a single large capacitor. This capacitance would be much larger than

that of the sensing elements and would represent low impedance across the signal generator. The speculation is that this parasitic impedance is absorbing the majority of the excitation current. This would lead to less excitation current being injected into the soil where it is desired. Even with very sensitive differential amplifiers, a reasonable amount of current must be present in the soil for the bridge circuit to operate properly.

A new drive cylinder was reconstructed with two layers of aluminum tape between the drive layer and the tool shaft. These layers are concentric with the driven layer but electrically insulated from it. They reside interior to the driven layer, between it and the tool shaft. These “dead” layers change the single capacitor formed by the drive tube and the tool shaft into three series capacitors. This raises the parasitic impedance across the signal source by a factor of three. The anticipated result is that the current lost in the parasitic impedance will be reduced to one third of the previous value.

Further, a new lexan tube for the four sensing elements was constructed with the elements as large as possible. This will increase the capacitance of the bridge elements with respect to the parasitic capacitance, allowing greater coupling to the soil current that is present. The first sensing elements were $\frac{1}{2}$ ” wide by 4” long with $\frac{11}{16}$ ” spacing in between each. The new elements are 1” wide by 9” long with $\frac{3}{16}$ ” spacing in between. In addition, the cabling between the device and the protoboard containing the pre-amp circuitry was replaced with cable containing individually shielded wire. This was done to insure the proper isolation of the two orthogonal bridge circuits from one another.

These efforts did improve the noise floor and balance of the sensor. However, they did not noticeably improve the sensitivity to objects embedded in the soil.

CONCLUSIONS

- The breadboard sensor did not have the anticipated sensitivity to nearby objects embedded in soils.
- The construction of the breadboard sensor is such that drive and sense electrode arrangements can be readily modified.
- The probable cause of the insensitivity is the excitation current being absorbed by internal impedances of the sensor, before the current can be successfully injected into the soil.
- Raising these internal impedances by the use of passive shielding was not effective.
- Active, or driven shielding needs to be investigated.

Work Performed in the Third Quarter

Task 1: Research Management Plan

The second quarterly report was prepared and submitted.

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. A breadboard of the sensor systems has been constructed and testing started. Testing in soil boxes has not yet yielded the desired sensitivity. Active shielding techniques that can improve this sensitivity have been identified. These will be investigated in the coming quarter.

No other sub tasks have yet been started.

Task 3: Demonstrate Obstacle Detection in Ground

This task is not scheduled to start for some time. No work was performed on this task during the third quarter.

Technical Problems Encountered

The sensitivity of the breadboard sensor to objects embedded in the soil was much lower than anticipated. The proposed reason for this is losses in parasitic impedances within the sensor. It is anticipated that active shielding techniques can remedy this.

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 Third Quarter

In the beginning of the next quarter, the problem of sensitivity in the soil will be explored further. Preliminary measurements with standard capacitance meters showed that the bridges appear to be balanced, but the device will be measured using a more accurate impedance analyzer. Tuning capacitors will be added to the sensing elements to improve the balance of the bridge.

Active shielding of the drive element from the tool stem will be tested. This method could greatly reduce parasitic impedance losses within the sensor. Reducing these losses will increase the amount of excitation current injected into the soil. This should cause a corresponding increase in the sensitivity. There is an existing body of work in this area to draw upon. Specifically, the patent listed in Reference 1 teaches a method of shielding capacitive sensors from an underlying metal substrate.

The first differential pre-amp stage will be examined. Initial searches found some low noise precision amplifiers that may be better suited for the application. The input characteristics of the current amplifiers being used may have an undesirable loading effect on the sensing elements.

Discussions took place with principal investigator of the capacitive tomography project concerning ways in which the balancing of the bridges can be improved. In addition to the tuning capacitors mentioned above, theories are being formulated on ways that the excitation circuit between the drive and ground can be modified.

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.