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 will 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 fourth quarter was to address the problems with sensitivity when the sensor is placed in soil. The breadboard sensor was fabricated during the first quarter. During the second quarter it was tested in soil boxes of various sizes both with and without obstacles. However, the sensitivity of the device was much lower than expected. Some modifications to the structure of the sensor were made in the third quarter, but similar sensitivity issues still remained. Changes to the drive and conditioning circuitry were made in the fourth quarter with promising results. These changes greatly enhanced the sensitivity of the device. 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 spaced electrodes. Each diametrically opposed pair of electrodes being the differential 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 exploitation of the tool tip and its asymmetry to prevent a blind spot dead ahead of the sensor is a unique feature of this technology. With other sensor technologies, such as GPR, the metallic mass of the tool tip is a substantial obstacle to forward sensing.

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. An insulating layer prevents direct contact with the soil. 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.

Fig 5. Sensor Breadboard Disassembled

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 6. Equivalent Circuit of One 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

In the third quarter, there were continued problems detecting obstacles in the soil or air unless they were placed almost directly on top of one of the sensors in. Passive drive shielding was applied by adding several buffer layers of metallic tape alternated with insulation between the drive layer and the tool blade. This arrangement, shown in Figure 7, should reduce the parasitic impedance load on the signal source by a factor of three. This along with increasing the size of the sense elements did help with the noise floor and balance of the sensor, but did not help with the sensitivity of the device in soil.

In the beginning of the fourth quarter, actively driven shielding was investigated. Instead of having two passive layers between the drive layer and the tool blade, the first passive layer underneath the drive layer was fed with the same signal as the drive layer using a dual output function generator. Two outputs are required so that the drive layer and the active shield layer beneath it receive the signal from separate low impedance sources. This driven shield should remove any parasitic loading effects of the tool body on the sense elements and enhance the directivity of the sensor. The effect of having two adjacent layers driven with the same signal is that the capacitance between these layers is nulled out. So long as the adjacent layers are driven with separate amplifiers, they cause no loading upon one another. Any loading caused by the central body of the drill is solely on the, inner, shielding layer. The entire signal applied to the, outer, sensor drive layer is directed outward into the soil. This technique is furthered described in the patents of Vranish and McConnell referenced by this report.

There still remained a passive layer between the driven layer and the tool body. Furthermore, each successive layer proceeding outward was slightly smaller in length to allow some guarding between each of the layers. Innermost, the first passive layer covers almost the entire length of the drive tube, followed by a layer of electrical tape, followed by the driven shielded layer about a $\frac{1}{4}$ " shorter on each end, another layer of electrical tape, and the primary sensor drive layer another $\frac{1}{4}$ " shorter on each end. Unfortunately the driven shielding did not achieve the desired result of improving the sensitivity.

Extensive discussions were held with the principal investigator of the capacitive tomography project. Although the geometries being dealt with are different, the overall theories of balancing, driving, and shielding the sense elements are similar. There was a concern that the differential pre-amp being used was not the most optimal for the application. It is necessary that all extraneous loads on the sensing elements be minimized in order to maintain sensitivity. The input impedance of the differential amp was thought to be unduly loading the sensor.

**Electrodes Separated by Insulation
Separation Exaggerated for Clarity**

Figure 7. Detail of Sense Electrodes with Drive and Shielding Layers

Instead of replacing the differential pre-amp entirely, high input impedance buffering amplifiers were added to each sensor leg ahead of the differential stage. These amplifiers minimize the loading effects on the sensor elements. Also, it was realized that power to the components was given via a single-ended 9V supply when the components actually have a larger +/- voltage supply range. The components are now being powered by +/-12 V that improves the operating range of the circuit.

The drive and sense configuration were changed to the configuration shown in Figure 8. Instead of having the excitation signal go directly to the drive layer with the ground to the tool blade, a coupling transformer was placed between the source and the drive/sense portion. In the new configuration, the excitation signal is placed across the primary of the transformer. One end of the secondary is connected to each bridge of sensing elements via tuning capacitors (the tuning capacitors help to fine tune the balance). The other end of the secondary is connected to

the tool blade. The center tap of the secondary is connected to the drive layer. The transformer has made the bridge circuit easier to balance and much more sensitive. At least some of this must be due to the improved impedance matching between the signal source and the bridge. This would help to maximize the amount of signal power driven into the soil.

Figure 8. Schematic of Drive and Amplifier Circuitry for One Axis

The new sensor configuration has greatly improved the sensitivity of the device both in air and in soil. Whereas previously a difference could not be detected unless the object was

directly on top of one of the sense elements, with the new configuration a difference can be noticed in air when the object is waved several inches away from the device. When the device is placed in the large soil box in Figure 7, sensitivity is even better. A difference in the sensing signals is noticed when other objects are placed in the soil. A difference is also noticed when one touches a hand to the outside of the soil box or even when a person walks by the soil box.

There is still work to be done to fine-tune the circuit. There is a negative DC drift in the RMS levels of the signals even when the bridges are balanced, causing the signal to be clipped. At the end of the fourth quarter, some changes were made with the various RC values to try to fix the drift, but that had a negative effect on the sensitivity of the device. Another confusing phenomenon is when one of the bridges is unbalanced, the signal eventually returns to the balanced state even if the object is not removed.

Work needs to be done to better isolate the bridges from one another. At this time there is a distinct interaction, or cross talk, between the two bridges. This was most noticed in the test where a hand is placed on or near the outside of the soil box. Both the asymmetric and symmetric axis bridges appear to change equally regardless of which axis the object is closer to. Part of this may be that since the soil box surrounds the device on all sides, the device sees a hand on the outside of the box as only a change in the properties of the entire box rather than a different object near a certain bridge. On the upside, when the device is placed straight down into the soil with the asymmetric axis aligned along the length of the box, it is more unbalanced than the symmetric axis, which is expected.

The shields of each of the individually shielded twisted pairs in the cabling are not currently connected to anything. This can also be affecting the isolation problems between the bridges: simply touching the cable can change the signals. Various connections of the shields were tested previously, but nothing created a very desirable result. This was before the shielding of the secondary legs were connected to the center tap and circuit ground, so the shielding of the individual wires will be revisited. Also, eventually all of the conditioning components, specifically the first pre-amp stage, will be housed within the device avoiding the effects of the long cable.

The addition of the coupling transformer implements a different type of the driven shielding from that tested at the beginning of the quarter. However, as already stated, the new use of the coupling transformer does create drive shielding another way. The setup will still be investigated to improve the shielding even more. Also, the size of the coupling transformer needs to be examined. It is a wound ferrite rod in a shielded plastic box with coax cables connecting the various legs to the circuit, external to the device. Eventually this will all have to

be placed in the tool blade housing, which already has limited space. Some work is being done in the capacitive tomography project where an identical transformer was used. In that project initial tests are being performed with a high voltage RF amplifier circuit to replace the coupling transformer. So far results have been good.

Figure 9. Soil Box used for Experiments

CONCLUSIONS

- Driven shielding via another layer on the drive tube alone did not help the sensitivity of the device.
- Sensitivity was significantly improved by incorporating a coupling transformer with the drive and sense circuit.
- There is an undesirable negative DC bias on the sense electrodes when the bridges are balanced that needs to be addressed.
- Further isolation of the bridges from one another needs to be addressed.

Work Performed in the Fourth Quarter

Task 1: Research Management Plan

The third 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. Incorporation of a coupling transformer has finally yielded greater sensitivity, but more testing needs to be done to improve the isolation of the bridges from one another and even out the balance of the DC level when bridges are balanced.

No other sub tasks have yet been started, meaning the project is behind schedule compared to the original work plan. However, with the break through of the improvements of sensitivity, attempts will be made to get the project back on schedule.

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 fourth quarter.

Technical Problems Encountered

The desired sensitivity is finally starting to be obtained, but there are still undesirable DC bias levels when the bridges are balanced and the bridges are not isolated well enough from each other. Also, the current setup of the drive circuitry yielding the desired sensitivity is too large to fit into the device. Some effort has to be made as to how it can be modified to have the same sensitivity but fit into the drill head. The initial testing in another project to replace the coupling transformer with a high voltage RF amplifier circuit looks promising.

Project Management Problems Encountered

No project management problems were encountered this quarter.

Action Requested of Doe NETL Project Manager

Please consider extending the project by six months to allow additional outdoor testing of the apparatus.

WORK PLAN

Work Planned For The Next Quarter

The isolation of the bridges from one another will be examined by trying to connect the drive tube and tool blade in another way so as to keep the sensitivity gained by the transformer, but eliminate the use of the tuning capacitors. The circuit will be examined and modified to eliminate the DC drift that exists. Once the isolation of the bridges and DC drift can be improved, test in different soil materials will take place.

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.