DIFFERENTIAL SOIL IMPEDANCE OBSTACLE DETECTION

QUARTERLY TECHNICAL REPORT

(July 1 through September 30, 2003)

Principal Investigator: Maximillian J. Kieba

Project Manager: Christopher J. Ziolkowski

847-768-0549, chris.ziolkowski@gastechnology.org

Report Issue Date: October 2003

DOE Contract #: DE-FC26-02NT41318

Submitted by

Gas Technology Institute
1700 South Mount Prospect Road
Des Plaines, Illinois 60018

GTI Project Number: 61152

Submitted to

NETL AAD Document Control Bldg. 921
U.S. Department of Energy
National Energy Technology Laboratory
P.O. Box 10940
Pittsburgh, PA 15236-0940

DOE Project Officer
Richard Baker

DISCLAIMER

“This report was prepared as an account of work sponsored by an agency of the United States Government and the Gas Technology Institute (GTI). Neither the United States Government, nor GTI, nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, GTI, or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.”

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 simple sensor incorporated into 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 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.

TABLE OF CONTENTS

	<u>Page</u>
DISCLAIMER	2
ABSTRACT	3
EXECUTIVE SUMMARY	6
INTRODUCTION	7
EXPERIMENTAL	9
RESULTS AND DISCUSSION	18
CONCLUSIONS	27
WORK PERFORMED IN SIXTH QUARTER	28
WORK PLAN FOR NEXT QUARTER	29
REFERENCES	30
LIST OF ACRONYMS AND ABBREVIATIONS	31
APPENDIX A – DETAILED WORK PLAN	A-1

LIST(S) OF GRAPHICAL MATERIALS

	<u>Page</u>
Figure 1. Typical HDD Rig for Gas Applications	7
Figure 2. Damage to Lead Sewer Pipe from HDD Tool	8
Figure 3. A Typical HDD Drill Head	10
Figure 4. Capacitive Sensor Breadboard with Electrodes in place	11
Figure 5. Sensor Breadboard Disassembled	12
Figure 6. Equivalent Circuit of Differential Electrode Pair	13
Figure 7 Anticipated current flow of capacitive configuration	14
Figure 8. Block diagram of new sensor configuration	15
Figure 9. New Prototype	16
Figure 10. Setup for Initial Test	19
Figure 11. Schematic of Drive and Amplifier Circuitry for Capacitive Setup	20
Figure 12. Schematic of new configuration	21
Figure 13. Example of AD630 output waveforms	24
Figure 14. Indoor Soil Box used for Experiments	26
Table 1. Results of Initial test	19
Table 2. Soil box tests with new configuration	23
Table 3. Obstacle tests outside	25

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. GTI also maintains a dialogue with the natural gas industry through various advisory groups. This feedback has provided a set of criteria for an obstacle detection system. These define the constraints on the cost and complexity of any system to be deployed in an underground construction environment.

The obstacle detection system being developed in this project utilizes an impedance sensing technique. This technique can resolve small changes in the impedance of the surrounding environment caused by objects of varying resistive and 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 electrodes around the drill head; no additional sensors are required above ground. The body of the drill itself is used to launch the sensing signal into the soil, eliminating any blind spot ahead of the drill. The sensing signal is in the frequency range below 500kHz, avoiding the attenuation issues associated with Ground Penetrating Radar operating in the range above 100MHz.

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 beginning of the quarter was devoted to addressing issues related to the continued sensitivity problems when the device is placed in the soil. As was detailed in the earlier reports, the sensitivity of the device has been lower than expected. The physics of the sensor configuration were revisited in light of how the sensor will operate in a horizontal directional drilling job with several hundred feet of steel drill pipe present. There was concern that even if the sensitivity issues are resolved, problems will arise when the drill pipe is added.

The method originally proposed injected the signal between the drill tip and a capacitive element behind the sense elements. The coupling at the drill tip was resistive and the coupling at the sense elements was capacitive. This embodiment was overly sensitive to the geometry of the sense electrodes and capacitive drive element. The impedance of the various capacitive elements was measured with respect to the surrounding soil, and found to be quite high. This high impedance limits the amount of sensing current that can be injected into the soil, which in turn limits the sensitivity that can be achieved.

There was another issue related to the presence of the drill pipe behind both the drill tip and the circumferential sensing elements. Specifically, the predominant signal currents may no longer travel from the drill tip to the sensing elements, but instead travel from the drill pipe to the sense elements. This would occur because it is impossible to electrically isolate the drill tip from the rest of the drill string in such a small enclosure. The current would be injected into the soil by both the drill tip and the length of drill pipe aft of the sensing region. The current return path is through the capacitive region where the sense elements are located. This would reduce the sensitivity of the device to obstacles in the vicinity of the drill tip, seriously degrading the usefulness of the device.

An alternative method of injecting the signal current into the surrounding soil is now being tested. In the alternative method, the sensing signal is now injected from the drill tip to the drill pipe. The sense electrodes are located in an insulating ring between the tip and the pipe rather than being directly in the signal current path. This configuration is based on electrical resistance tomography. Rather than being adversely affected by the addition of the drill pipe, this approach uses the addition of the drill pipe as an advantage. The sense electrodes detect the potentials in the soil generated by the passage of the signal current. These concepts will be illustrated in the body of the report.

Sensor Configuration

Certain aspects of the sensor design remain consistent regardless of the method used to inject the signal into the soil. The basic shape and construction of the drill head dictate constraints to the design. In all cases the drill blade, or tip is used to inject an electrical signal into the soil ahead of the drill. This strategy was adopted to eliminate any blind spot dead ahead. In all cases the rotation of the drill head is used to scan the surrounding volume for obstacles. Some discussion of the original, capacitive, sensor concept is provided to illustrate both the common issues and the reasons for changing the approach.

The initial proposed configuration for a capacitive tomography sensor consisted 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 original 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. Capacitive Sensor Breadboard with Electrodes in place

Figure 5 shows the capacitive 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. The return path for the sensing current is capacitive, passing through both the sensing electrodes and a “drive” electrode located behind them. The anticipated current paths are shown in Figure 7.

The circuitry to support this low number of channels and modest frequency requirements will be straightforward and inexpensive. Since the sensing signal is injected by direct contact the device can operate at multiple frequencies. This is in contrast to GPR, where each frequency of operation requires a tuned antenna. This broadband sensitivity also allows the sense elements to detect 60 Hz or other active signatures that may radiate from buried infrastructure.

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. The drive electrode consists of a lexan tube that is covered with aluminum tape and wiring brought out. The copper strips in the foreground are the sense electrodes, mounted on a larger 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 in resistive contact 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.

Figure 7. Anticipated current flow of capacitive configuration

Figure 7 shows the anticipated current flow of the capacitive configuration as described in the original proposal. Keep in mind there is a layer of air and a sleeve of lexan between the sense elements and the soil. The pod with capacitive sense elements is about 18" in length. If you then add several hundred feet of metal pipe behind the pod, the current flow will likely be from the drill pipe as well as the tip.

With the new proposed sensor configuration based on electrical resistive tomography, the signal current is intentionally injected at the tool blade and collected by the drill pipe. Instead of having the sense elements separated from the soil with a section of air and the lexan sleeve to

create a capacitor with the soil, the sense elements now protrude through the lexan sleeve to make resistive contact with the soil. These contacts are depicted as the rounded protrusions on the sides of the drill body in Figure 8. They are located on an insulating sleeve that separates the drill tip from the drill pipe.

Figure 8. Block diagram of new sensor configuration

The prototype resistive contact elements are 4 screws placed equidistant around the circumference of the lexan. These contacts will probably be made flush with the drill body as prototyping progresses. The concern is that any projection will be subject to wear in the normal environment of a horizontal directional drill. The actual area and construction of the contact points will require additional investigation. The contacts must also be sensitive to 60Hz currents and other known infrastructure signatures.

Figure 8 shows the two elements measuring across the asymmetric axis of the tool blade. There are another two screws used to measure across the symmetric axis. The signal current passing from the drill tip to the drill pipe generates voltage potentials along its path. The contacts directly sense these potentials. The signal is detected by taking the voltage difference between opposed pairs of these contact points. The signal is then amplified and filtered to get a signal that can be measured.

In a perfectly homogenous soil, the amplitude of the signal after the filtering will have a reasonably steady value. When an object is placed near the pod, the equipotential surfaces will be affected, changing the amplitude of the filtered signal. Figure 8 shows the distribution of potentials across the asymmetric axis of the drill. It is anticipated that there should be a small differential voltage across the drill body in this plane, caused by the asymmetry. Similarly, the drill has a symmetric axis if rotated 90 degrees. Contacts on opposite sides of this symmetric axis should see very little differential voltage in homogenous soil. Any inclusions in the soil change the symmetry of the system, therefore changing the differential voltage.

Figure 9a and 9b. New Prototype

The new prototype is shown in Figure 9. The tool blade tip and the length of the first section of lexan remain the same. The screws that act as the sensing elements can be seen protruding from the lexan just before the first section of PVC pipe. The section of PVC connects the lexan portion to the steel pipe portion representing the drill pipe. Another PVC section

connects the end of the steel pipe to another portion of lexan to provide an exit point for the cabling. Finally, the metal end cap of the sensor attaches to the end of the small portion of lexan, keeping the metal cap, threaded rod, and drill tip electrically isolated from the drill pipe. The PVC coupling pieces needed to be added because the lexan pipe does not have the same ID and wall thickness as standard PVC or steel pipe. Since the original prototype was made to the dimensions of the lexan, both lexan and PVC had to be used with the new configuration. When in-ground tests take place, a more rugged prototype will be made.

The source excitation signal is applied across the steel pipe and the tool blade tip/threaded rod, thus creating a coaxial effect for the excitation signal. Because of this, there is no need for the added buffering layers of the drive tube used with the capacitive configuration. The threaded rod connects the tool blade tip to the end cap. The black miniature coaxial cable is the cabling for the sensing elements. The entire pod is now 41.5" in total length. An exploded view of the new sensor can be found in Figure 12 with a schematic of the support circuitry.

RESULTS AND DISCUSSION

Miniature coax is used for the cabling from the sensing elements to the AD621 with the shield connected to the circuit ground. Each pair of coax cable is twisted from the pickup points to the protoboard. There is one twisted pair of coax for the symmetric axis points, and another pair for the asymmetric points. With the capacitive setup, disturbing the cabling between the pod and protoboard had a significant effect on the signal levels. This effect was caused by the capacitance of the cable being in parallel with the capacitance of the sense element. Flexing the cable varied its capacitance and acted as a source of noise in this application. A similar effect was seen when standard twisted pair wire was used with the new configuration. Using coaxial cable for the sensing elements with the resistive tomography setup has significantly eliminated this effect.

The first tests of the new setup had the pickup points going directly into an AD621 instrumentation amplifier. The pod was placed vertically in the soil box with the asymmetric axis parallel with the length of the soil box and the symmetric axis parallel with the width of the soil box. The pod was placed far enough into the soil so that the bottom of the steel pipe section was about four inches below the surface of the soil, thus providing coupling for the excitation signal via the soil. True RMS digital multimeters were used to measure the voltage differences between each of the sense elements on the two axes. One multimeter was placed across the elements on the asymmetric axis; another was placed across the elements of the symmetric axis. At first, very little change could be noticed when an object was placed near one of the elements of the asymmetric axis. A slight change was noticed on the symmetric axis even when the asymmetric axis was the intended axis of measurement. The results are shown below. Measurements for “1 / 2” represent the measurements across the asymmetric axis. Measurements for “3 / 4” represent the measurements across the symmetric axis.

Figure 10. Setup for Initial Tests

Placement of Obstacle	1 / 2 reading (VAC)	3 / 4 reading (VAC)	1 / 2 change	3 / 4 change
No Obstacle	0.158 V	0.092 V	None	None
PVC close to 1	0.159 V	0.074	Little	Lower
PVC added to 2	0.159 V	0.086 V	None	Higher
Both out (void of air in soil)	0.158 V	0.086 V	Little	None
Fill voids	0.158 V	0.086 V	None	None
PVC close to 3	0.160 V	0.098 V	Higher	Higher
Add PVC close to 4	0.159 V	0.095 V	Little	Lower
Take both out (void)	0.159 V	0.068 V	None	Lower
Put both back in	0.159 V	0.068 V	None	None
Fill voids	0.159 V	0.064 V	None	Lower

Table 1. Results of Initial test

There are a few issues with the results. First, very little change is noticed in the readings between the sensing elements of the asymmetric axis, especially when an object is placed near one of the elements. Even when the asymmetric axes is the intended axis of measurement, more change is noticed across the symmetric elements. Second, the signal level returns to its original state very slowly when the obstacle is taken out and the void filled with soil. The compaction of the soil is altered when the obstacle is introduced and removed, making it very difficult to return to exactly the same state. However, in most cases above, there was virtually no change in the levels when the voids were filled.

It was decided that some of these effects might be due to noise. To improve sensitivity an AD630 stage was added after the instrumentation amp stage. Not only is the physical configuration different from its predecessor, but the conditioning electronics are different as well. For comparison, the amplifier circuitry of the capacitive configuration is shown in Figure 11.

Figure 11. Schematic of Drive and Amplifier Circuitry for Capacitive Setup

The new setup, shown in Figure 12, takes out the external transformer and the first buffering amplifier stage for each sensing element. It also eliminates the tuning capacitors used for balancing the bridge. Instead, the output of each pair of sense elements (i.e. the screws) is fed directly into an AD621 differential amp stage with a fixed gain of 10 or 100. The output the differential amp stage is then fed into an AD630.

The AD630 is a synchronous demodulator, or “lock-in” amplifier. It allows a signal of a known frequency to be separated from a large level of background noise. In this case, the frequency of interest is that of the signal injected into the soil. It is “known” in that an uncorrupted version of the signal is directly available from the drive oscillator. The gain of the AD630 toggles between +2 and -2 causing constructive interference at the toggling frequency. The interference is destructive at all other frequencies, providing an extremely narrowband filter around the signal. The AD630 output is then low pass filtered to complete the extraction of the signal.

Figure 12. Schematic of new configuration

With the capacitive setup, balancing the bridge with the tuning capacitors would achieve maximum sensitivity. With the current setup maximum sensitivity is achieved with the demodulating capabilities of the AD630. This removes DC drift effects often associated with impedance bridges and other AC sources such as 60 Hz. The two parameters that most impact the performance of the demodulator are the signal phase at which the toggling takes place and the low pass filtering at the output. The sensitivity of the demodulator also facilitates separating the obstacle detection data from other signals of interest such as radiation from power lines and tracer wires.

All of the components are powered by $\pm 12\text{V}$. Initially the voltage reference pin of the AD621 was tied directly to ground, i.e. the halfway point between $V+$ and $V-$. However, the output of the 621 had a very high DC bias. Connecting the reference pin to a potentiometer as shown in Figure 12 allowed the bias level of the 621 output to be adjusted properly.

Initially the excitation signal went directly into the comparator. This resulted in the square wave output of the comparator to be out of phase with the AD621 signal. Ideally the square wave should be at 50% duty cycle and the switching points of the square wave should intersect the sine wave at its crossing points. Connecting one input of the comparator to the excitation signal through a phase shifting network allows the phase of the square wave to be adjusted for maximum sensitivity.

Measurements were first made in the soil box with only the asymmetric axis connected (1 and 2 as shown in figure 11). The excitation signal was set at 166 kHz with amplitude of 1.0V pk-pk. Measurements were taken at the output of the 621, at the output of the 630 and at the output after the filter. The results are shown below. Both the peak-to-peak and rms levels of the 621 outputs were measured. Only the peak-to-peak values of the 630 outputs were measured since the signal should have a minimum point of zero volts with a series of rectified peaks as shown in figure 13. Three obstacles are used for measurement: a small piece of pvc (1.5" OD, 13.5" long, filled with air), large pvc (2.5" OD, 19" long, filled with sand), and a metal rod (0.75" OD, 24" long). The negative signs after the rms values indicate that they are biased negative.

Obstacle placement	621 pp	621 rms	630pp	Filter out
None (*)	1.78 V	615 mVrms (-)	2.48 Vpp	903 mV
Small pvc close to 2	1.88 V	678 mV (-)	3.28 V	980mV
Take piece out, fill void	Negligible change	Negligible change	Negligible change	Negligible change
Small pvc close to 1 (**)	1.92 V	787 mV (-)	4.24 V	1.02 V
Take piece out, fill void	1.88 V	Negligible change	Negligible change	Negligible change
Metal rod near 1	1.90 V	771 mV (-)	Negligible change	1.0 V
Big pvc near 1 (***)	1.56 V	882 mV (-)	4.56 V	940 mV
Fill void, pvc by 2	1.04 V	581 mV (-)	3.44 V	660mV
Metal rod between pvc and 2 (****)	340 mVpp	2.20 V (-)	9.20 V (clipped)	120 mV
Take rod out, adjust pot for 621 out visually rms = 0	400 mV	1.16V	---	221mV
Metal rod back in (*****)	1.18V	821mV	Not clipped	560mV

Table 2. Soil box tests with new configuration

The 630 output results are a bit misleading since the signal did not maintain a uniformly rectified “positive hump” shape throughout the tests (the first signal below in Figure 14). With some tests the odd humps were larger; in other tests, the even humps were larger. In addition, the bottoms of the peaks were only sharp at the beginning of the tests when the 621 output was set close to a zero bias. Otherwise, the transitions between humps were distorted or the bottom peaks dipped below the zero point. Although not to scale, Figure 14 shows examples of the

relative change in waveforms seen at the output of the AD630. The test to which each waveform belongs is noted in the table and Figure 14. The results of the filtered output in the table are not entirely accurate either since the waveforms being filtered are distorted themselves.

Figure 13. Example of AD630 output waveforms

Even if the waveforms are distorted, a relative change in the signal amplitudes can still be seen when various obstacles are placed in the soil. This is better sensitivity than was ever seen with the capacitive configuration. The distortion appears to be caused by the AD621 and AD630 comparator signals getting slightly out of phase with different tests. More work on the filtering in the circuit should yield cleaner signals.

It was also thought that the soil box still might not be large enough to represent a homogenous state without obstacles. Similar to the capacitive setup, when the pod is placed in the soil, the tip is only a few inches from the bottom of the tub. In addition to sensing obstacles placed in the soil, the pod may also be in part sensing the walls of the tub. This may also be the reason why attaching the Vref pin of the AD621 to ground does not result in a signal biased at or near zero.

The final test at the end of the quarter was to take the pod outside and repeat the measurements in a large sand pit. Whereas the soil box is 49" long by 29" wide by 21" deep, the pit is 10 ft wide by 10 ft long by 4-5 feet deep.

With the pod in the soil and Vref connected to ground, the 621 output signal still had a DC bias, but not as bad as was seen in the lab. The output of the 621 was 520mVpp, 830mVRMS (+), the 630 output was 3.76-4.0Vpp, and the output of the filter was 208mV. The

results are shown in the table along with the waveform of the 630 output (arrow denotes the zero point). The +/- symbols after the RMS values denote the polarity above or below the zero point.

Obstacle	621pp (V)	621rms (V)	630pp (V)	630rms (V)	Filter out	630 Waveform
None, Vref grounded	520mV	830mV	3.76-4.0V	416Vrms	208mV
None, Vref to pot	436mV	156mV	1.12V	416mV	245mV
Metal near 1	540 mV	162mV(-)	2.0 V	280mV	240mV
Give some time to settle	520mV	317mV(+)	1.76V	1.02V	224mV	same
Rod out, compact soil	540mV	248mV(-)	2.48V	318mV	264mV
Large pvc	640 mV	1.10V (-)	6.32V	2.67V	272mV
After 15 mins settle	680mV	887mV(+)	3.76V	1.37V	232mV	Same
Take out, fill void, compact soil	680mV	622mV(+)	1.92V	792mV	232mV
After 15 mins	680mV	643mV(+)	2.64V	935mV	232mV	Same

Table 3. Obstacle tests outside

For the most part, the AD630 output signals did not get as distorted as the tests in the lab. However, the amplitude of the filtered output didn't change all that much even when there were significant changes in either the 621 output or the 630 output. This will have to be examined more closely in the next quarter.

Figure 14. Indoor Soil Box used for Experiments

CONCLUSIONS

- Changing the sensor configuration to one based on electrical resistance tomography has greatly increased the sensitivity of the sensor in soil.
- The increased sensitivity reduces the usefulness of the small indoor soil box because of boundary effects. Better results were obtained in an outdoor soil pit.
- Using coaxial cabling for the sense elements (pickup screws) has eliminated the previous negative effects on the signal when grabbing the cable.
- There is still an issue with the signal levels returning to values seen before obstacles were placed in the soil. This is mainly due to compaction changes in the soil not being entirely reversible. In actual operation, the drill would move with respect to stationary obstacles rather than vice versa, so this issue only complicates experimental setup.
- Work needs to be done to fix the distortion problem in the waveform of the AD630 outputs. Modifying the phase reference signal to the AD630 and improving the output filtering can accomplish this.

Work Performed in the Sixth Quarter

Task 1: Research Management Plan

The sixth quarterly report was prepared and submitted.

Task 2: Evaluate Sensor Concept

Sub task 2.1, “Evaluate Impedance Bridge Based Sensors” is in progress. The prototype was modified to make use of resistive contacts with the soil to form the impedance measurement bridge. A different method of injecting the bridge excitation signal into the soil was tested. These two changes increased the sensitivity of the device to obstacles in soil. Many of the “false positive” sensitivity issues present with the capacitive coupling method were eliminated.

Task 3: Demonstrate Obstacle Detection in Ground

A small amount of outdoor testing was performed at the end of this quarter.

Technical Problems Encountered

Changing the sensor configuration to one based on electrical resistance tomography has greatly increased the sensitivity of the device in soil. However, there is still room for improvement in the signal conditioning circuitry. The soil box currently being used for experiments may still be too small for tests due to the large size of the new prototype. There is a concern that the shape and size of the soil box may be affecting the signal pickup. Tests can be done in the outside pit for a while longer, but when the weather gets significantly colder, a new test setup will have to be created.

Project Management Problems Encountered

No project management problems were encountered this quarter.

Action Requested of Doe NETL Project Manager

A no cost time extension was formally requested from DOE National Energy Technology Lab and granted through February of 2004. Please consider a further extension to allow a longer period of outdoor testing. This would not involve any additional funding.

WORK PLAN

Work Planned For The Next Quarter

Work will be done to fix the distortion seen by the output waveform of the AD630. There is a strong signal when the phase reference is adjusted before tests, but the signal gets distorted more and more throughout tests. It won't be possible to adjust the voltage reference before each reading in the field. Some form of automatic adjustment of the phase reference combined with digital filtering of the output should improve this.

To help with troubling shooting, only one axis of the sensor was measured with the new configuration. Now that positive sensitivity results are being seen with the new configuration, the sense elements for the other axis will be incorporated.

Future experiments will be conducted in a larger indoor soil box that is part of the GTI facility or outdoors as weather permits.

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.

The website entitled “Underground Radio by Le Magicien” was used to help design and explain the new sensor configuration. The website is located at http://www.geocities.com/lemagicien_2000/elecpage/ugr/undr.html.

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.