DIFFERENTIAL SOIL IMPEDANCE OBSTACLE DETECTION

REVISED 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 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.

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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. 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

A new prototype (Figure 3) was built to address some issues noted in the previous quarter. Recall that the previous sense elements were screws made of zinc plated stainless steel. Since these screws were different material than the carbon steel of the sensor blade tip, an electrochemical potential was generated that affected the readings. The new prototype uses carbon steel set screws.

Figure 3. New Prototype

Other improvements to the new prototype make the unit easier to disassemble for testing, while also making it a bit more robust for the tests being done (both in electrolyte solution, and moving in a soil). The last prototype had the pipe portions connected via unthreaded couplings that were sealed with a waterproof adhesive sealant. Although it was waterproof, to make

changes to the internal connections in the pod, the sealant had to be cut and the pieces pried apart. The current prototype uses threaded portions of PVC that are sealed with Teflon pipe thread tape making it easier to disassemble the pod for changes.

The last prototype had one long mini-coax cable going from the protoboard to a crimp ring connector that was attached to the sense element via nuts. With enough twisting and vibration, the cable could eventually come loose from the crimp connector. The new prototype has a small piece of mini-coax cable soldered directly to a carbon steel tab that is threaded directly to the setscrew. A mini-coax connector connects that piece to the long cable going to the protoboard. Another coax connector is used to connect to the protoboard housing making the connection a little more solid as well.

It should be noted that the setscrews do currently protrude from the surface of the pod. This is to allow addition of different shapes of steel shim stock to do tests on whether a larger sense element enhances the signal pickup. Even though the setscrews are larger than the previous stainless steel screws, there is a concern that there is not enough surface area in contact with the surrounding ground. For initial testing purposes, the shim stock will be screwed down to the setscrew. Such a setup would not be robust enough for field tests, as noted in previous prototypes. When the correct size of sense element is found (including the ratio of distance between the tool blade and drill stem), a new prototype will be made in-house with the GTI CNC machine. This will take place in the next quarter.

Recall from the last quarter that the AD630 was having problems rejecting the DC drift. The initial proposed solution was an additional amplifier stage with a gain of 10 between the AD621 and the AD630. Capacitively coupling the stage to the AD621 should help reject the DC component. It would also allow a gain of 10 at the AD621 stage to optimize the component's gain bandwidth characteristics.

An LF412 was chosen for the middle amplifier stage. The LF412 is a low drift, high-speed op amp. In addition to capacitively coupling to the AD621 stage, a filter was added across the 412 to help reject additional high frequency noise. Because the target signal frequency is 166kHz, successive high and low pass filters were used across the LF412 to accept frequencies in the range of 50 kHz-284 kHz.

Figure 4. New Schematic with LF412

In addition to adding the intermediate LF412 amplifier stage, another thought was to test the circuit at lower frequencies. The AD630, when used as a lock-in amplifier, has a 350 kHz full-power bandwidth. Since the AD630 switches at a ± 2 gain, using our current 166kHz signal approaches the limits of its operating range. Some tests were done changing the frequencies of the excitation signal. Results are outlined in the next section.

A significant accomplishment in this quarter was the completion of the larger indoor soil test bed towards the middle/end of the quarter (Figure 5). The new test bed is approximately 10' x 20' x 6' deep and consisted of a loam-type soil. The previous material in the test bed was clay that gets really hard when it gets dry, making it difficult to dig out the material. The loam soil has fairly good moisture content and is much easier to dig out even when left alone for a significant time. Next to the loam test bed is another 10' x 20' test bed of clay (the original material) used for another experiment. Between this clay test bed, the concrete from the remaining floor and the outer walls of the building itself, we will also be able to determine if we can see these boundaries by the sensor in addition to obstacles placed in the path of the sensor.

Figure 5. Indoor soil test bed

Some preliminary tests were done with the new prototype in the soil test bed towards the end of the quarter. There is an existing 4" pipe (seen in the figure above) in the soil approximately 3 feet below the surface that extends the width of both test beds. The tests were only done with the setscrews alone as the sense elements. So far results look promising compared to the smaller electrolyte tub. Data is included in the "Results and Discussion" section. In the next quarter tests will be done with larger sense elements.

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 6 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 6. A Typical HDD Drill Head

Figure 7 shows the arrangement of the sense electrodes on the original capacitive 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 7. Capacitive Sensor Breadboard with Electrodes in place

Figure 8 shows the disassembled capacitive prototype prior to applying the electrodes. The sensing electrodes are capacitively coupled to the soil in this earlier version of the sensor. The outermost lexan tube prevents the sense electrodes 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 electrodes. This innermost is the electrode labeled “drive” in Figure 9.

Fig 8. Sensor Breadboard Disassembled

Figure 9 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 10.

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 9. Equivalent Circuit of Capacitive Differential Electrode Pair

In relation to the equivalent circuit of Figure 9, 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 7. 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 an intermediate 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 10. Anticipated current flow of capacitive configuration

Figure 10 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 sensor configuration based on resistive rather than capacitive 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 11. They are located on an insulating sleeve that separates the drill tip from the drill pipe.

Figure 11. Block diagram of new sensor configuration, asymmetric axis

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 11 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. Notice in Figure 11 that the one equipotential line does not pass directly through the sense contacts at the same point. Along the asymmetric axis, the upper current path is slightly shorter. As a result, the equipotential is slightly askew. This is why when comparing values for the two axes, the values for the asymmetric axis should be slightly unbalanced when compared to the symmetric axis in a homogenous soil. For comparison, view how the symmetric axis would most likely look in Figure 12.

Figure 12. Equipotential lines for symmetric axis

When an object is placed near the sensor, the potential distribution will be affected, changing the amplitude of the filtered signal. Figure 11 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 potential distribution, therefore changing the differential voltage. Figure 13 shows the distribution when an obstacle is introduced. Take note of the equipotential line going through the sense elements. When an obstacle is introduced, the currently path on that side now becomes longer and slightly distorted. This affects the equipotential line, causing an imbalance to be detected by the signal conditioning electronics.

Figure 13. Equipotential lines of symmetric axis with obstacle introduced

The second version of the prototype is shown in Figure 14. 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. When in-ground tests take place, a more rugged prototype will be made.

Figure 14a and 14b. Second Prototype

The source excitation signal is applied between the steel pipe and the tool blade tip. The tool tip is connected to the threaded rod, creating a coaxial feed 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 sensor pod is now 41.5" in total length.

The most recent (third) version of the prototype was shown in Figure 3. The major changes include:

- Replacing the two sections of threaded rod between tip and end cap with one uniform piece
- Replacing the zinc plated stainless steel screws with carbon steel set screws. The setscrews currently protrude from the pod, but this is only to allow addition of different size sense elements for testing purposes.
- Making the cabling more robust inside the pod itself by using a combination of threaded metal tabs and mini-coax connectors. The coax connectors are also used to connect to the housing of the protoboard for a better common ground
- Replacing the clear lexan portion with PVC. In addition, threaded connections are used instead of using adhesive to connect the unthreaded portions. PVC is not as durable as lexan, but using threaded PVC is easier to assemble and disassemble the pod.

After more tests with the latest prototype using different sized sense elements, GTI's in-house CNC operators will make a new prototype. The new prototype will make the entire unit more robust.

RESULTS AND DISCUSSION

During the previous quarter a series of impedance measurements were made between various elements of the sensors. These measurements were performed with a HP analyzer. It was noted that the impedance between the four screws used as circumferential sensors and the tool tip were not symmetrical. That is, reversing the probes of the impedance analyzer between the tip and the screws gave different results. This was ascribed to electrochemical potentials created in the surrounding media by the dissimilar metals of the tip and screws. Initially the screws were zinc plated stainless and the tip, carbon steel. Replacing the zinc plated stainless steel screws with carbon steel setscrews reduced the discrepancy in impedance readings when the polarity of the probes was switched.

For comparison, readings between the tool blade tip and stainless steel screw sense element 1 showed $4.50\text{M}\Omega$ and $-2.90\text{M}\Omega$ depending on the polarity. With the new configuration of carbon steel set screw, the same measurement showed $1.74\text{M}\Omega$ and $-1.29\text{M}\Omega$. For sense element 2, readings between the tip and stainless steel screw showed $6.94\text{M}\Omega$ and $-2.9\text{M}\Omega$. With the carbon steel set screw, the readings were $1.86\text{M}\Omega$ and $-1.36\text{M}\Omega$. Readings weren't taken of sense elements 3 and 4 with the old configuration, but one would very likely see the same large discrepancy. With the new setup, measurements for sense element 3 showed $1.95\text{M}\Omega$ and $-1.41\text{M}\Omega$. Measurements for sense element 4 were $1.94\text{M}\Omega$ and $-1.326\text{M}\Omega$.

As they stand now, the carbon steel setscrews protrude from the body of the pod. This is to allow the testing of the different sized sense elements. There is a concern that even if the carbon steel material is an improvement from an impedance perspective, there may not be quite enough surface area to get the signal pickup desired. Even if the carbon steel screws are slightly larger than the previous stainless versions, they are still very small compared to the size of the tool blade tip. Aside from the size and distance relative to that of the tip and the drill stem, there is also the concern the small sense element will not get enough contact with the surrounding soil, especially in a live HDD application.

Steel shim stock pieces of different thicknesses were purchased to fabricate sense elements of varying sizes. These will be applied next quarter. They can be drilled and secured about the circumference of the prototype using the setscrews. Once an optimum size is found, a new prototype will be made which will permanently incorporate the new size of sense elements to make the entire pod more robust.

The new signal conditioning circuit is shown below. The addition of the intermediate LF412 stage appears to be an improvement. With tests in the electrolyte tank, there is still a

Figure 16. Tests in electrolyte tank

The first set of graphs below show the waveforms for a 166kHz excitation, 1V pk-pk signal. The purplish waveform at the top is the sensed signal as it goes into the AD630. The square waveform is the comparator signal for the AD630. The yellow signal is the waveform after it comes out of the AD630, and finally the blue waveform is the filtered output.

(a)

sense 1 up... 031604

(b)

sense2 up 03/16/04

(c)

sense 1 back up 03/16/04

Figures 17a,b,c. Screen captures for 166kHz, 1V pk-pk excitation

166kHz at 1V pk-pk	0 deg	180 deg	360 deg
Pre-amp out pk-pk	120mV	144mV	144mV
AD630 out mean	55.5mV	41.0mV	70.6mV
Filter out mean	61.1mV	45.2mV	75.1mV
Figure	17a	17b	17c

Table 1: Data from Figure 17 (Electrolyte Tank, 166kHz, 1V pk-pk Excitation)

The peaks where the zero crossings intersect the edges of the comparator square wave signal are very noticeable, very much like shown in the figure from the previous quarter. However, in this case the DC drift isn't nearly as bad. The lowpass filter after the AD630 can remove these momentary peaks but could not remove the DC drifts seen last quarter. The two signals with the “sense 1 up” are fairly close to one another whereas previously the signal drifted.

The next test was to keep the 166 kHz excitation frequency, but increase the excitation amplitude to 9Vpp. The screen captures and data are shown below.

Figures 18(a,b,c) – Screen Captures for 166kHz, 9V pk-pk

166kHz at 9V pk-pk	0 deg	180 deg	360 deg
Pre-amp out pk-pk	580mV	500mV	560mV
AD630 out mean	307mV	78.8mV	299mV
Filter out mean	295mV	76.5mV	283mV
Figure	18a	18b	18c

Table 2: Data from Figure 18 (Electrolyte Tank, 166kHz, 9V pk-pk Excitation)

The 3rd test was keeping the excitation amplitude at 9Vpp, but lowering the excitation frequency to 50kHz. In this test, we rotated the pod 90 degrees each time, so we also got values for when the sense elements were parallel to the water surface.

Figures 19 (a, b, c, d) – Screen captures for 50kHz, 9V pk-pk

50kHz at 9V pk-pk	0 deg	90 deg	180 deg	270 deg
Pre-amp out pk-pk	560mV	320mV	440mV	340mV
AD630 out mean	304mV	-13.7mV	-177mV	159mV
Filter out mean	299mV	-10.9mV	-168mV	159mV
Figure	19a	19b	19c	19d

Table 3: Data from Figure 19 (Electrolyte Tank, 50kHz, 9V pk-pk Excitation)

A screen capture of sense 1 back up was not taken, but the values were close to the original. The signals for 50kHz and 9V pk-pk look a little more like you'd expect: the AD630 signal especially shows a positive signal when the sense 1 element is up, and almost equally negative value when down, and somewhere in between (ideally half way) when it's rotated 90 degrees.

More work will be done in the next quarter to do more tests with lower frequencies. Higher frequencies couldn't be fairly tested due to the values for the high/low pass filters across the LF412. However, these values will be tested as well.

At the very end of the quarter, the pod was placed in the soil in the pit lab using the existing pipe as the obstacle. Graph captures like above could not be obtained in time for the end of the quarter, but values were still taken. The sense pod was placed vertically in the soil, with the steel pipe interface going 1 foot below the surface of the soil. The pod was about 3 feet away from the pipe. Excitation was 166 kHz, 9V pk-pk. The setup for the test is shown in Figure 20 with data in Table 4.

Figure 20. Setup for pit lab tests

	AD630 in	AD630out	Filter out
0 degrees (A)	6.0Vpp, 430 mV mean	7.60Vpp, 2.70Vmean	2.40V mean
90 degrees (B)	5.80Vpp/346mV mean	8.60Vpp/1.51V mean	1.32V mean
180 degrees (C)	5.60Vpp/368mV mean	8.80Vpp/984mV	794mVmean
270 degrees (D)	5.60Vpp/346mV	8.60Vpp/1.72Vmean	1.54V mean
360 degrees (E)	6.0Vpp/338mV mean	8.40Vpp/1.95Vmean	1.75V mean

Table 4. Data for Pit Lab tests

As with previous soil tests, the compaction of the soil has an effect on the readings. With the sense 1 element facing the pipe, when the soil is compacted, the values jump up. As previously stated, one cannot expect a perfectly repeatable test for this reason. However, increasing the size of the sense elements should help with the coupling to the soil to minimize this effect. Also, in the soil the peaks at the zero crossing weren't nearly as noticeable as with the electrolyte tank tests, this even being with the frequency back to 166kHz. Notice also the amplitude of the signals in the soil compared to those in the electrolyte tank. They are much higher. As previously reported, the very low impedance of the electrolyte solution had a bit of a damping effect on the excitation signal.

Overall, results are starting to look much more promising. The DC drift isn't as much an issue with the addition of the LF412 as an intermediate stage and with the bandpass filtering added. The addition of the carbon steel set screws is a good change. The results are looking much better in the soil.

CONCLUSIONS

- Replacing the stainless steel set screws with carbon steel set screws lowered the impedance discrepancies in the electrolyte solution. The discrepancies were most likely a result of the electrochemical potential between the dissimilar materials of the screws and the tool tip.
- Adding the intermediate LF412 stage with bandpass filtering has significantly helped the DC drift problems previously seen. The signals are much more stable.
- The indoor soil test bed was completed. Although only one test was performed at the very end of the quarter, the signals are looking much better compared to those in the electrolyte tank. These items are really work planned for next quarter, not conclusions.
- The improvement of the observed signal in the larger soil test area indicates that the sensitivity of the device has been improved. Many of the problems of the last quarter may have been caused by the boundary conditions of working in the small tank.

Work Performed in the Eighth Quarter

Task 1: Research Management Plan

The seventh quarterly report was prepared and submitted.

Task 2: Evaluate Sensor Concept

Sub task 2.1, “Evaluate Impedance Bridge Based Sensors” is in progress. Tests were performed in an electrolyte solution to avoid the repeatability issues with soil tests. Further issues were discovered, but the reasons for these issues are being identified and resolved. .

Task 3: Demonstrate Obstacle Detection in Ground

A small amount of indoor testing was performed at the end of last quarter. The construction of a larger indoor test bed was completed.

Technical Problems Encountered

The DC drift problem has been resolved, but it is still unknown how much this has improved the range. With the new changes described, this will be tested in the next quarter.

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 September 30th of 2004. No other action is requested at this time.

WORK PLAN

Work Planned For The Next Quarter

Tests in the larger indoor soil box will continue in the next quarter. The size of the sense elements will be examined to determine if larger elements will help with range of detection and coupling of the soil.

A new prototype will be made using GTI's in-house CNC machine. The new prototype will be more robust. Initially the new prototype will have the same dimensions as the current prototype. However, thought has to be made to begin placing all the electronics within the pod.

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.