DIFFERENTIAL SOIL IMPEDANCE OBSTACLE DETECTION

REVISED QUARTERLY TECHNICAL REPORT

(Oct 1 through December 31, 2003)

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Report Issue Date: February 2004

DOE Contract #: DE-FC26-02NT41318

Submitted by

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GTI Project Number: 15328 (formerly 61152)

Submitted to

NETL AAD Document Control Bldg. 921
U.S. Department of Energy
National Energy Technology Laboratory
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ABSTRACT

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

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

GTI proposes to develop a prototype down-hole sensor system that is simple and compact. The sensor utilizes an impedance measurement technique that is sensitive to the presence of metallic or non-metallic objects in the proximity of the HDD head. The system will use a 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

The current prototype being used is still the configuration based on electrical resistance tomography. The “work to be performed” listed in the last quarterly report included fixing the distortion seen in the signal at the output of the AD630. Recall that the AD630 acts as a lock-in amplifier for the circuit. The main cause of the distortion was thought to be the AD621 differential amplifier output and the comparator reference in the AD630 not being properly in phase with one another. It also occurred when the DC drift of the 621 output signal was too great. There were also concerns that the close proximity of the walls of the soil box were affecting the readings.

It was decided to perform tests in an electrolyte solution. This would allow a uniform setup for each test to determine if the phase and drift problems after cycling power still exist. It also enables repeatable tests where compaction of soil is no longer an issue. Finally, it helps test the waterproofing of the pod. The electrolyte solution was made in the current soil box using a 1 mass percent of each of Sodium Chloride, Sodium Sulfate, and Sodium Carbonate. Details are specified in the “Results and Discussion Section”.

An RC network was added in the last quarter to the comparator reference of the AD630 to help with the phase adjustment. A potentiometer network was added to the reference pin of the 621 to manually trim the DC drift when doing tests in the soil box. The drift was assumed to be caused by the boundary effects of the relatively small test box. These changes did temporarily solve the problems, but phase and DC drift often needed readjusting each time the power to the circuit was cycled, whether turned on after sitting overnight or when cycled quickly.

To help with troubleshooting, a resistor network simulating the sensor interaction with the soil was created (Figure 3). With a more controlled simulation of the sensor setup, it is easier to determine if the problems in the sensitivity are indeed caused by the test conditions or if there is a problem somewhere else in the circuit. Each side of the resistor network represents one of the sense elements and its resistive contact with the soil. An adjustment of the potentiometer on the right hand side of the bridge circuit represents a change in the signal. More specifically, an obstacle placed in the path between the tip and the drill pipe will change the resistance of this path.

Figure 3. Schematic of resistor representation of sensor

A dual output function generator was used to provide one output for the excitation signal and another output for the reference signal into the AD630. This generator enables the user to set the phase reference more accurately than could be done with the RC network. The next iteration of the sensor simulator added a second function generator to introduce a controlled noise signal into the circuit. This allows simulation and testing of how susceptible the amplifier circuit is to noise.

The final bullet listed in the work to be completed mentioned that future work would be done in a larger soil box. A larger box was not obtained for this quarter, but a proposal is being made to obtain an indoor test bed so tests can be performed through the winter months. The test bed will be around 10'x10' to 20'x10' and located indoors.

Tests in both the electrolyte solution and with the sensor simulator revealed additional sensitivity issues. One of the issues is very likely caused by the generation of a potential between the carbon steel of the sensor blade tip and the zinc plated stainless steel of the sense element screws. This and other issues are explained further in the Results and Discussion section.

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 4 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. The soil provides the variable resistance legs of the bridge that are seen in the simulated soil-sensor system of Figure 3.

Figure 4. A Typical HDD Drill Head

Figure 5 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 5. Capacitive Sensor Breadboard with Electrodes in place

Figure 6 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 7.

Fig 6. 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 8.

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 7. Equivalent Circuit of One Differential Electrode Pair

In relation to the equivalent circuit of Figure 7, 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 5. 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 8. Anticipated current flow of capacitive configuration

Figure 8 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 9. They are located on an insulating sleeve that separates the drill tip from the drill pipe.

Figure 9. 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 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. Notice in Figure 9 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 10.

Figure 10. 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 9 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 11 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 11. Equipotential lines of symmetric axis with obstacle introduced

The new prototype is shown in Figure 12. 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 12a and 12b. New Prototype

The source excitation signal is applied across 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. An exploded view of the new sensor can be found in Figure 15 with a schematic of the support circuitry.

RESULTS AND DISCUSSION

As noted in the introduction, experiments are currently being performed in an electrolyte solution rather than sand. There were a number of repeatability issues associated with the sand filled 100-gallon trough. The moisture content and compaction of the sand were very difficult to control. Obstacles placed in the sand and then removed caused changes in compaction that were not completely reversible. The density and conductivity of an electrolyte is much easier to normalize for a series of experiments.

The 1 mass percent of sodium chloride, sodium carbonate, and sodium sulfate (on anhydrous basis) to tap water is a fairly standard mixture for electrolyte solutions according to a staff scientist. Some tests increase the mass percents to as much as 5% and include distilled water. The 100-gallon trough used for experiments was filled with 85 gallons of tap water; this is enough to leave room at the top of the tub, but also enough to cover a significant portion of the steel pipe portion of the sensor. To get a 1 mass percent, 3390g of each of the salts were added. This yielded just slightly over 1%.

There have been some issues with sensor sensitivity in the electrolyte solution. It was thought that having a more uniform medium with much lower impedance might solve the problems noticed in sand. However, there may be the case that the sensitivity of the sensor in the solution is so high that the problems from the boundary effects of the tub are that much worse.

Tests were first performed with plain water in the tub. The circuit was still using the resistor network and potentiometer to adjust the phase of the lock in amplifier. With the comparator square wave and reference signal in phase with one another, there was much better range of sensitivity with the water compared to the sand. Objects could create a change around 6" away from the sensor versus the sand where the object had to be right against the sensor. But although change in the signal of the AD630 output could be noticed further away, the signal itself was distorted. Specifically, the signal had peaks on both the positive and negative DC side of ground. The signal should only have a rectified signal fully on the positive side. Having a signal span both sides of ground results in the filtered output of the AD630 output being adversely affected. The worst case occurs where the peak amplitude is equally the same on both the positive and negative; this results in a filter output of 0V, even if the peak-peak amplitude of the AD630 output signal is much greater. Figures 13 and 14 better illustrate the problem.

Another problem noticed in the solution, both with water alone and electrolyte, is the constant DC drift of the AD621 differential amplifier. The lock-in amplifier of the AD630 should be able to remove this, but the effect can be seen in the filtered output of the AD630.

There was a thought that the DC drift was a result of the tub of solution not having a proper common ground with the circuit board. A galvaline magnesium anode was connected to house ground and placed in the solution. This did succeed at protecting the pipe a bit from rust, but did not prevent the DC drift.

To help test the sensitivity problems further, it was decided to try placing the sensor at an angle into the solution. As the sensor is rotated, there should be a change noticed in the AD630 filtered output. For instance, if measuring across the asymmetric axis and the top element (sense element 1) is pointing toward the top of the tank, you might notice, say, a mean value of +1V out of the filtered output. If the sensor is rotated 180 degrees such that sense element 1 is now pointing towards the bottom of the tank, the mean value of the filtered output should read -1V.

The mean value did not change equal in absolute value, opposite in sign, as expected while the pod was rotated. For one, it was difficult to maintain equal excitation signal strengths as the pod was rotated. The amount of steel pipe in the solution has an effect on the strength of excitation signal and thus the signal seen at the sense element. The greatest change is noticed when comparing the steel pipe fully out of the solution versus in the solution about six inches. If looked at closely, there is a significant enough change noticed if the pod is moved even slightly out of the solution to have an effect on the results. Not to mention the still-present DC drift problem helps to confuse the issue even further.

Another issue is the solution has a loading effect on the excitation signal. Although the low impedance of the solution may help from a sensitivity standpoint, it does attenuate the signal, by as much as a 10:1 ratio when comparing the signal out of the solution versus in the solution. For instance, if measuring the peak-peak value of the signal with the pod in air, the excitation value is 1V_{pp}. When placed in the solution, this can drop to around 100mV. The signal strength can easily be increased after the pod is in the solution, but it's difficult to constantly monitor this and notice whether the change in signal strength at the sense element is caused by the boundary effect of the water surface or the attenuation effect of the solution.

With further problems in the solution, it was decided to construct a simulation of the sensor using resistors as shown in Figure 3 above. The thought was to provide a more controlled sense set-up, to make sure the signal conditioning circuitry was working properly. It would also be easier to change certain elements to closely match the impedances seen in the actual sensor pod and to separate sensor impedance issues from amplifier issues.

As shown in figure 3, a ratio of 100:1 (resistors in the legs to the value of the potentiometer) yielded a better overall signal seen out of the AD621 when a gain of 10 was used

at the AD621 stage. The signal was distorted more when a ratio of 10:1 was used, but a greater change could be seen as the potentiometer was adjusted. The signal was cleaned up when the AD621 gain was changed to 100, but then the 100:1 ratio setup resulted in a saturated signal.

At first one dual output function generator was used to provide the excitation signal at one output and the reference signal from the second output. A second generator/third output was added to induce noise into the circuit to check the ability to reject noise. At first the lower signal seen by the 10:1 ratio was a result of too high of a buffering resistor ($1\text{M}\Omega$) used between the two different function generators. Adding a series resistor with a larger value means less signal voltage across the simulated bridge. The resistor was then dropped to 100K. This did result in a stronger signal with the 10:1 setup, but there was still a distortion seen with only a gain of 10.

Figure 13 shows a screen capture of the oscilloscope measuring different points along the circuit. The top two signals show the excitation signal (sine wave), and comparator reference signal (square wave), both in phase with one another. The middle waveform (3) is the output of the AD630. Ideally this should be a positive rectified signal as shown. The bottom waveform (1) shows the filter output from the AD630 output signal 3. Compare this figure to Figure 14.

Figure 13. Waveforms of acceptable output signals

Figure 14 shows the waveforms when a 10:1 ratio is used. Notice not only that the signal is very weak, but also the output of the AD630 has peaks on both sides of ground, resulting in a filtered output around 0V. As mentioned, the weak signal could be fixed with a gain of 100, but then the 100:1 ratio setup results in a distorted signal. The gain-bandwidth product of the AD621 causes the distortion. The higher gain decreases the bandwidth available for the signal. Stated another way, at higher gains the amplifier has difficulty “keeping up” with fast signals.

Figure 14. Outputs with 10:1 ratio

The circuit did do a fair job at rejecting noise below 131 kHz and above 1.28MHz. When the frequency was between these values, the noise affected the signal. It was worse at 488kHz, which is the third harmonic of the excitation. The lock-in will be less effective at rejecting noise at the excitation frequency and its odd harmonics. These values were taken with the 100:1 ratio in legs and a 1M buffer resistor. When the buffer resistor was changed to 100K, the affected range was 4kHz-1.28MHz, still rejecting 60Hz. When the ratio was dropped to 10:1 (still with a 100K buffer resistor), noise affected a much greater spectrum, including 60Hz. It wasn't as jittered at 3.26MHz, but there was a negative drop in the mean level of the 621 output signal.

Because of the noticeable effects of just changing the resistors in the legs of the simulation circuit, the impedance of the electrolyte solution was closely measured to verify the

values in the circuit were correct. When the probes of the digital multimeter were placed directly in the solution, impedances between 50-100K were measured.

However, when measuring from the sensor tip (where the excitation signal is injected into the “soil”) to the sense elements, not only were much greater values measured but also the values changed when the polarities of the probes were switched. The readings were taken at the end of the cabling where it is attached to the protoboard. In one orientation, the values measured +4.5M Ω . When the polarity was switched, the readings measured -2.9M Ω .

It was realized that the screws used for the sense elements were zinc plated stainless steel while the tip was still carbon steel. Having different materials creates a potential in the electrolyte solution that explains the change in sign along with change in value of the impedance measurement. The electrochemical potential between the dissimilar metals in the electrolyte introduces an additional dc voltage into the measurement. Since a standard ohmmeter uses a dc voltage to perform the measurement, there is interference.

As a further test, the ohmmeter was used to measure the impedance of the solution again, but via a carbon steel screw and stainless steel screw of equal size. With the stainless steel screw on the (+) probe and the carbon steel screw on the (-) probe, the value measured -3.27M Ω . When the polarity was switched (stainless steel (-), carbon steel (+)), the value measured +8M Ω . To double check, switching them back gave -3.3M Ω . With the ohmmeter probes directly in the solution, the measurement was on the order of 160K Ω .

This electrochemical potential most likely is not the cause of all of the sensitivity questions, but having an additional potential created between the tip and sense element certainly doesn't help. At the end of this quarter, carbon steel set screws were ordered to replace the stainless screws currently used as sense contacts. These not only replace the material, but will also help to begin addressing the concern of the ruggedness of the device when the sense screw is protruding from the surface. A new prototype will be built with these screws in the next quarter.

If problems still occur, the same configuration will be used with copper strips as the sense elements. This may create additional problems similar to what was seen with the capacitive set-up, but there is an additional concern that having very small sense elements will result in a poor pickup during an HDD application. Having a larger sense element will help insure at least part of the element will have sufficient enough contact with the soil.

In addition to the copper strips, a resistor will be added between the sense element and the drill pipe. This will give the signal a better path to ground in hopes of fixing the DC drift problem.

There is yet another thought that part of the problem might be caused by the sense elements being too close to drill stem when compared to the distance to the tip. Right now the lexan portion is approximately 10.5" in length. The sense screws are 1.5" away from the drill stem and 9" away from the tip. An additional prototype design having the sense element more equidistant between the two ends will be tested.

Since the current lock-in amplifier is having problems rejecting the DC drift problems, another lock-in amplifier circuit will be examined. The most probable direction here would be to add a gain of 10 stage between the AD621 and the AD630. This stage could be capacitively coupled to the AD621 to eliminate feed through of the dc component. The additional gain would allow the AD621 to be operated at a gain of 10, where its gain bandwidth is optimum.

Figure 15. Schematic of new configuration

CONCLUSIONS

- Tests in electrolyte solution and with a more controlled set-up exposed additional sensitivity issues, one of which is the potential created from the different materials of metal used for the tool blade tip and sense elements
- A new prototype will be built using the same material for the sense elements, drill tip, and drill shaft to eliminate electrochemical potentials
- The placement and size of the sense elements in relation to the tool blade tip and the drill pipe will be examined using the new prototype
- A new lock-in amplifier circuit will be tested; the current one is not properly handling large DC drifts in the AD 621 output signal
- Construction of a larger indoor test bed will continue to be pursued

Work Performed in the Seventh 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 becoming more and more logical.

Task 3: Demonstrate Obstacle Detection in Ground

A small amount of outdoor testing was performed at the end of last quarter. The construction of a larger indoor test bed is still being pursued.

Technical Problems Encountered

There are continued sensitivity issues, but this time in the electrolyte solution. The material used for the sense elements and the size and location of the sense elements in relation to the tool blade tip are the likely cause. There is still a large DC drift that makes it difficult to take steady reading with varying obstacles. If improving the current lock-in amplifier isn't successful, a new lock-in amplifier circuit will have to be used.

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 will continue in the electrolyte solution, but using a better material for the sense elements that will match the material used in the tool blade tip. Various prototypes will be tested using the new sense element material and also to test how the placement and size of the sense elements affect the results.

Resistors between the sense elements and the drill shaft will be added to give a better path to ground.

The lock-in amplifier circuit will have to be examined more closely to determine if a new setup is needed. Even with a controlled resistor representation of the sensor DC drift problems and distortion of the signal were noticed. The most probable change will be an additional gain stage of 10. This stage will have a gain of 10 within the band near 166kHz but will block dc components from the AD621. The gain stage can also incorporate filtering above 300kHz to eliminate any higher harmonics of the excitation signal.

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.