DIFFERENTIAL SOIL IMPEDANCE OBSTACLE DETECTION

QUARTERLY TECHNICAL REPORT

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ABSTRACT

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

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

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

Even though results have been better in the large soil test bed compared to the smaller test box and electrolyte tanks previously used, it is still proving very difficult to establish a balanced condition across the symmetric axis with no obstacles present. Most of the work in this quarter was done to determine if the balance issues are being caused by the sensor configuration or something within the circuit. A review of the sensor geometry and nomenclature is given in the following section, "Sensor Configuration".

Some slight changes were made to the sensor configuration to try to improve the sensitivity and balancing of the pod. Steel shim stock pieces (Figure 4) were attached to the setscrews acting as the sense elements. This was done to determine if increasing the surface area of the sense elements has any effect on the sensor's sensitivity. There was concern that the setscrews alone would not have sufficient contact with the soil and could be the cause of some of the weak results seen.

Resistors (1 MΩ) were added between each of the sense elements and the drill pipe (circuit ground). This should provide a better path to ground for the sense elements to keep the pickup circuit a bit more stabilized, especially in cases where stray noise is picked up by the sense elements. For soil tests this quarter, the resistors were attached externally. For a field suitable device, these would have to be attached internally.

Shielding was added along the threaded rod portion extending through the entire pod between the tool blade tip and the end of the pod. With the threaded rod exposed inside the sensor tube, there was a concern that some of the signal might be "bleeding" to the sense elements rather than through the soil. For the shielding, the threaded rod was covered with a layer of electrical tape, a layer of metallic tape, and a second layer of electrical tape. The metallic layer is connected to the drill pipe/circuit ground. This effectively creates a coaxial signal feed for the tool tip where the threaded rod is the signal conductor and the metallic wrap is the shield.

Some changes were made to circuit. An additional stage was added between the sense element and the AD621 stage. Instead of having the sense elements feed directly into the AD621 with the shield of the cable connected to circuit ground, the shields of the coax cables now go through a buffering amp, with the outputs connected to the AD621. The result is intended to null out the capacitances of input cable shields, thus minimizing any capacitance mismatch between inputs. In a field-ready prototype this most likely wouldn't be a factor since there would be very little cabling between the sense elements and the circuits. But in a situation we have now where this is a long length of cable connecting the sense elements to the circuitry, it serves as an extra safeguard.

Tests in this quarter were performed exclusively in the pit lab. The high and low-pass filters across the AD412 still exist to help with noise rejection. In the last quarter, the filtering was set to reject noise lower than 50kHz and higher than 284 kHz since the initial target frequency was set at 166 kHz. Some tests were also performed at 50 kHz to determine if lowering the frequency helped improved results. It was decided to test even lower frequencies, so in this quarter tests were also performed at 900Hz. To accommodate the lower frequency, the filter circuit was adjusted to accept a low frequency of 500 Hz. The new circuit with the above changes is shown in Figure 3.

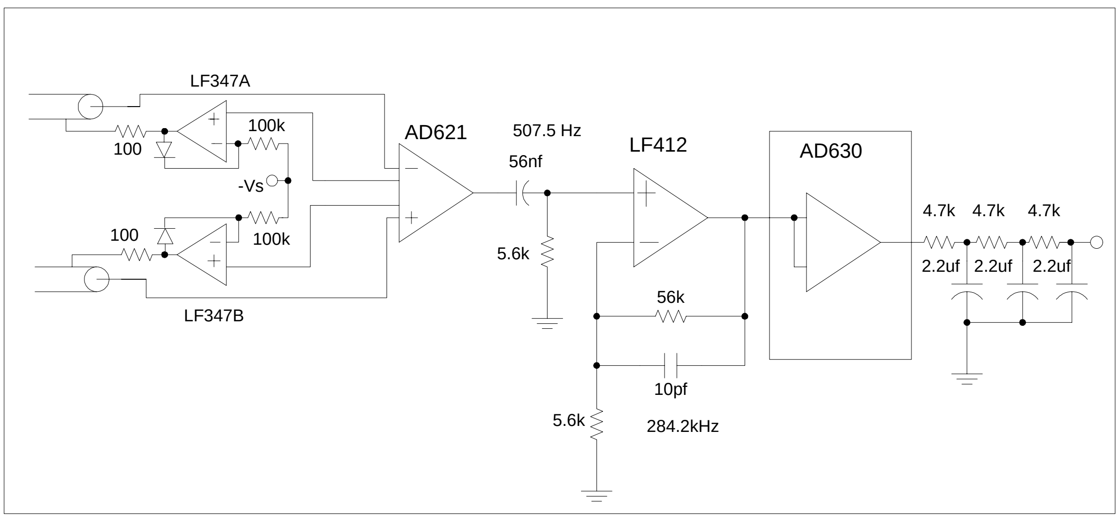

Figure 3. Circuit with Differential Shield Driver and Change to Filter Values

To further troubleshoot the balance issues, the frequency was swept through the entire range of the filter circuit and a little beyond. In the large soil test bed with no obstacles, the signal is expected to be the most balanced at very high frequencies (in the MHz range) since the “viewing area” is smaller. As the frequency is decreased, the viewing area should increase until the signal is eventually unbalanced by the detection of the concrete sidewalls of the lab.

In addition to viewing the signals on the oscilloscope, direct resistance measurements were taken both with the pod out of the soil and in the soil to determine if the physical configuration had an effect on the balance issues. Results will be detailed in the next section.

As a final attempt to create a balance state, four large plastic sheets (4’x 4’x 1/4”) were placed in the soil (Figure 4a) to establish a boundary obstacle of uniform size and properties equidistant around the pod. This is different from the electrolyte and sand tests in the smaller soil box in previous quarters because that box had an odd shape to it. Not to mention outside of the small soil box there was air, whereas outside this boundary condition you have the same soil material. Measurements were taken both with the soil in its existing state (dry on top, and gradually wetter at deeper depths) as well as with the soil more equally saturated throughout.

Figure 4a Prototype with large plastic sheets

Figure 4b. Close-up of prototype with steel shim 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 5. A Typical HDD Drill Head

Figure 6 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.

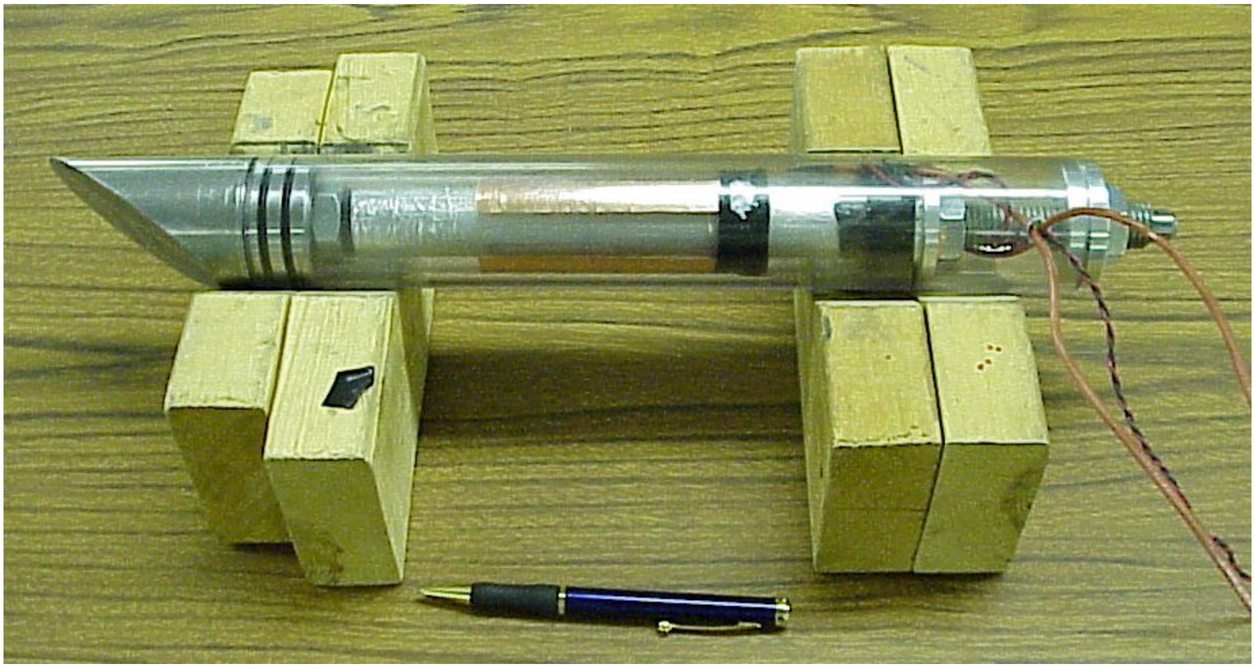

Fig 6. Capacitive Sensor Breadboard with Electrodes in place

Figure 7 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 8.

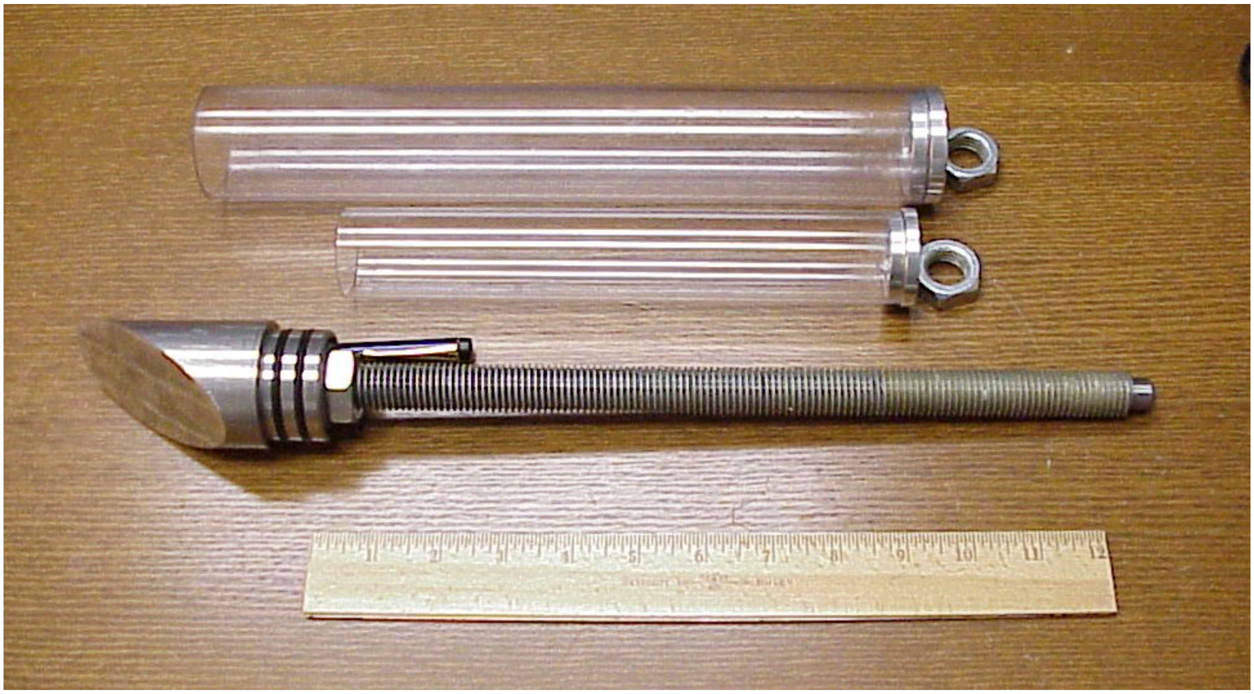

Fig 7. Sensor Breadboard Disassembled

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 9.

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.

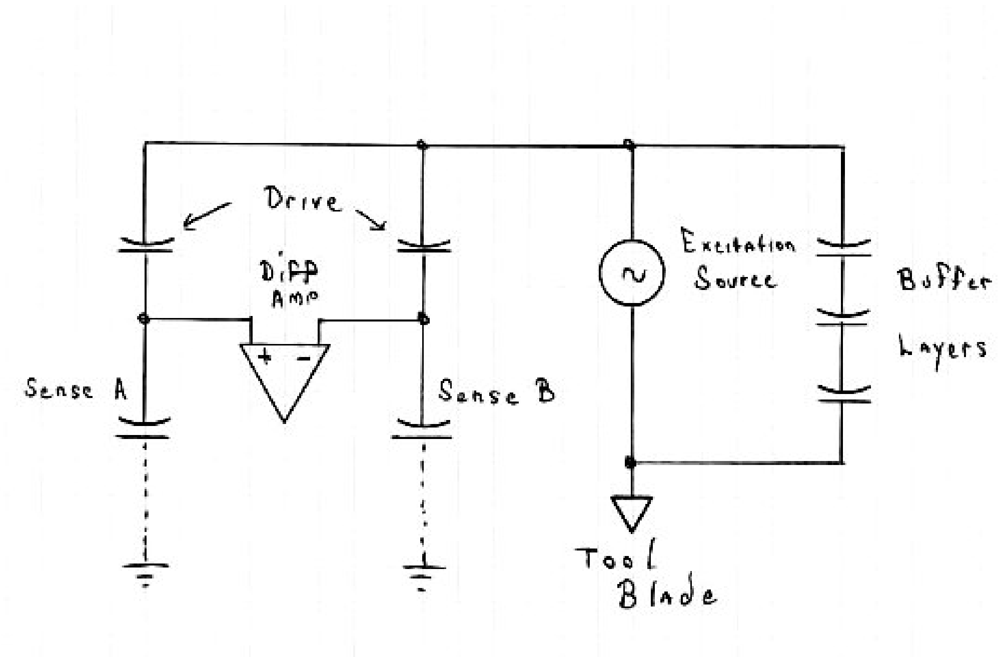

Fig 8. Equivalent Circuit of Capacitive Differential Electrode Pair

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.

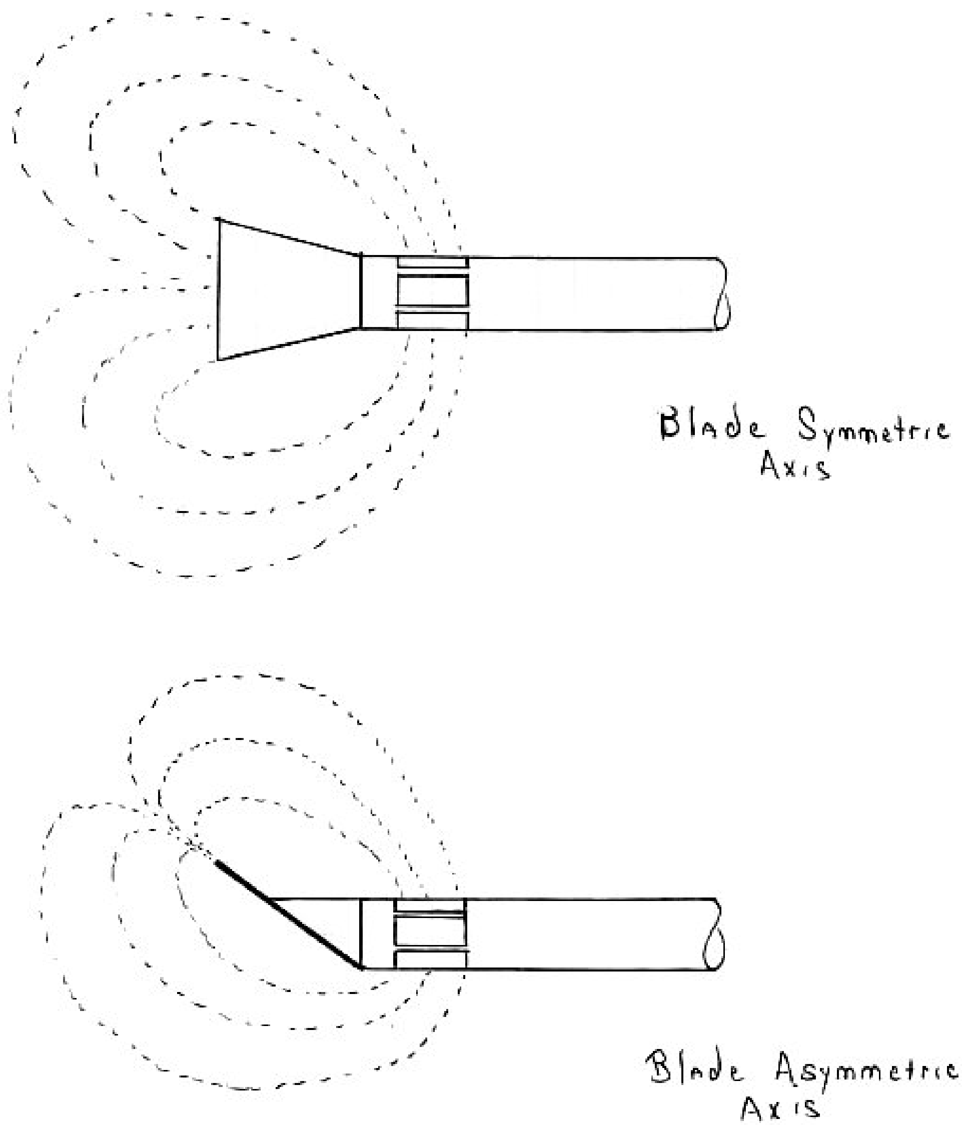

Figure 9. Anticipated current flow of capacitive configuration

Figure 9 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 10. They are located on an insulating sleeve that separates the drill tip from the drill pipe.

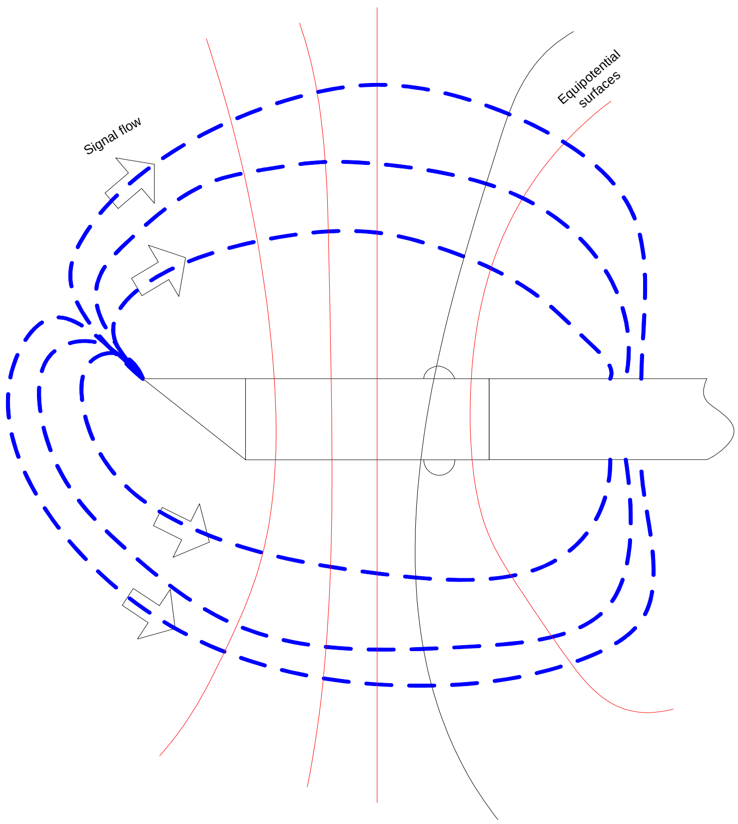

Figure 10. Block diagram of new sensor configuration, asymmetric axis

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 10 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 10 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 11.

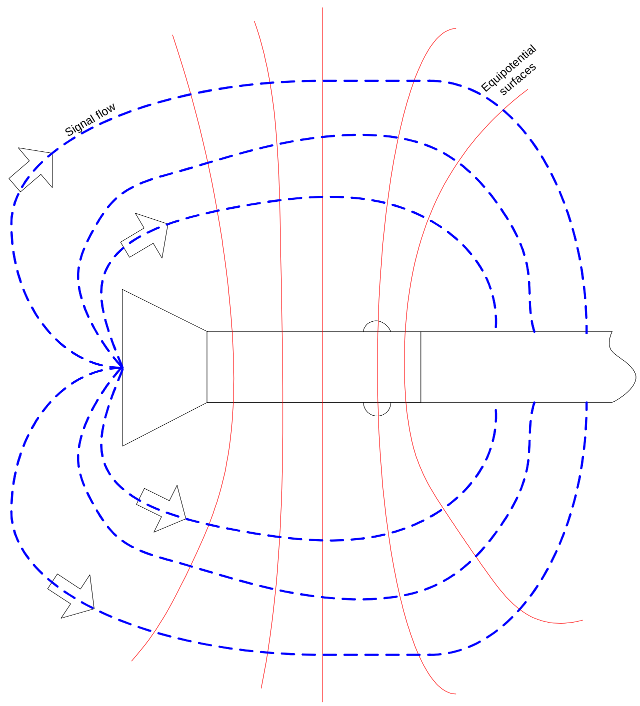

Figure 11. Equipotential lines for symmetric axis

When an object is placed near the sensor, the potential distribution will be affected, changing the amplitude of the filtered signal. Figure 10 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 12 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 current 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.

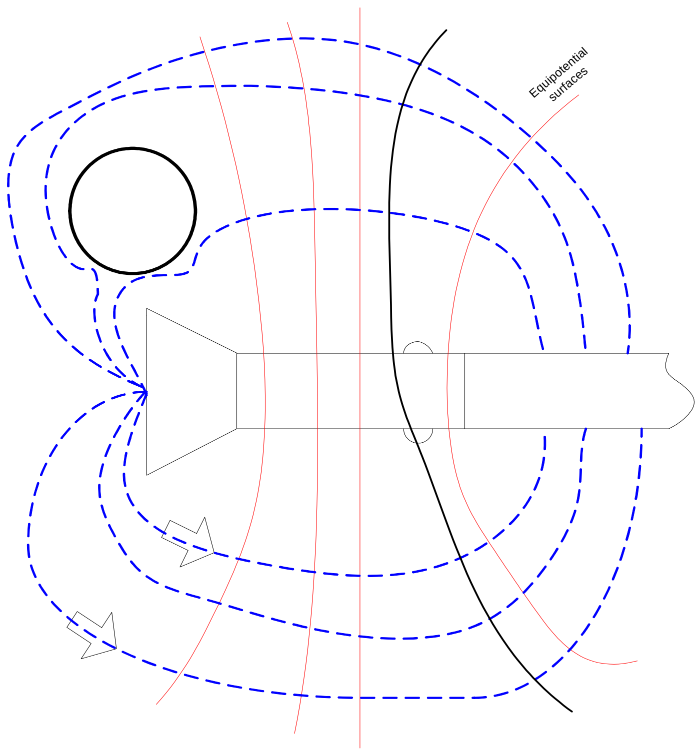

Figure 12. Equipotential lines of symmetric axis with obstacle introduced

The second version of the prototype is shown in Figure 13. 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.

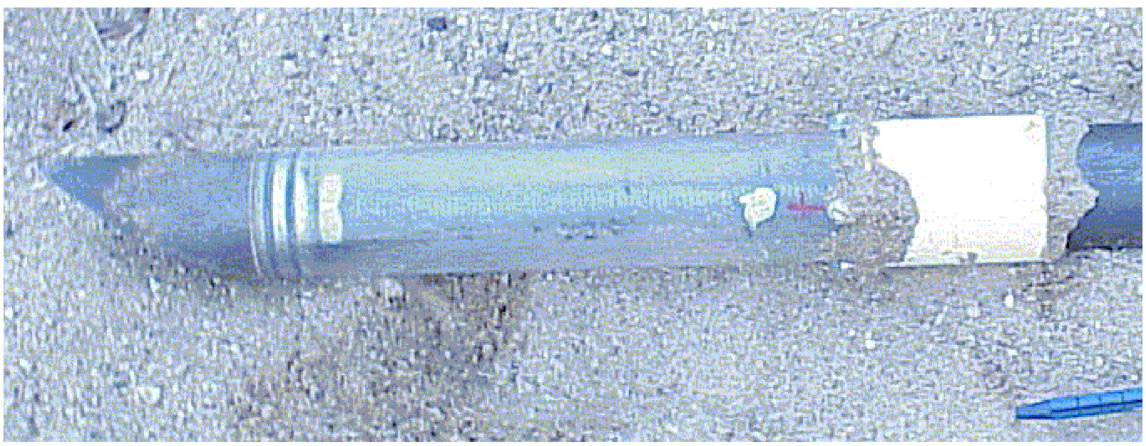

Figure 13a and 13b. Second Prototype

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.

Figure 14. Third prototype

The next version of the prototype is shown in Figure 14. The major changes included:

- 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 uses 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.

Some slight modifications were made to the prototype in this quarter (Figure 4). Steel shim stock pieces were added to the setscrews to increase the surface area of the sense elements. To insure some of the signal wasn't "bleeding" directly from the threaded rod to the sense elements, the threaded rod portion of the pod was shielded by applying a layer of electrical tape, a layer of metallic tape connected to the drill stem/ground, and another layer of electrical tape.

RESULTS AND DISCUSSION

There continues to be an issue with balancing the symmetric axis in a homogeneous soil condition. The data shown in the table below was taken with an excitation signal of 50 kHz and 5Vpp. These tests are with the shim stock already added to the setscrews to increase the surface area of the sense elements.

The sensor was placed equidistant from two pipes parallel to one another in the soil. One is the permanent pipe that exists in the soil test bed, and the other is a smaller length of pipe added into the soil. The two pipes are approximately 9 feet from one another with the sensor placed in the middle (4.5 ft from each). The depth of the smaller pipe was slightly shallower; it was only about 2 feet deep compared to 3.5 feet of the longer pipe. 0 degrees corresponds to the initial condition where the symmetric axis is parallel to both pipes. The (+) and (-) correspond to the polarity of the sense elements as they are connected to the instrumentation amp (AD621).

50 kHz 5Vpp	**0 deg**	**90 deg**	**180 deg**	**270 deg**	**360 deg**
AD 630 in pk-pk	23.6 V	23.6 V	23.6 V	24.0 V	23.6 V
AD 630 out mean	9.06 V	8.95 V	8.90 V	9.42 V	9.0 V
Filter out mean	9.85 V	9.76 V	9.77 V	10.3 V	9.80 V

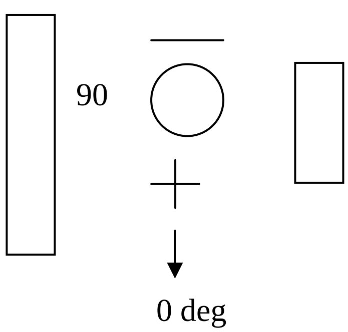

Table 1. Symmetric Axis Test - 50kHz, 9Vpp

Tests were repeated, but this time the sensor was rotated in the opposite direction. The values below, however, are listed in the same degree orientation as above (i.e. 90 deg corresponds to the (+) element facing the larger pipe).

50 kHz 5Vpp	0 deg	90 deg	180 deg	270 deg	360 deg
AD 630 in pk-pk	24.4V	22.8V	14.4V	24.0V	24.0V
AD 630 out mean	9.45V	8.73V	8.05	9.17V	9.54V
Filter out mean	10.4V	9.71V	9.0V	10.1V	10.5V

Table 2. Repeat Test of Symmetric Axis – 50kHz, 9Vpp

There are some items to note between the two experiments when comparing the filter out values. There is poor repeatability between the two when comparing exact values, but there is some commonality with the 90 and 180-degree orientations both being the lowest two out of the five values. But in comparing closely between the two tests, in test 1 the two are very close to one another with the 180-degree filter out being slightly larger. But in test two, the 180 degree value is lower than the 90 degree value, and significantly more so. In test 2, the 0 and 360 degree values are the highest, but in test 1, the 270-degree value is the highest. One would expect the signals to be more balanced in the 0 and 360-degree orientations since there are no obstacles in the viewing area in these cases. To sum up, a relative difference can be seen as the sensor is rotated, but there is not enough consistency among tests to be confident of the results, suggesting there are certainly still issues with either the circuit or configuration.

Tests were also done with the sensor on the other side of the large pipe. Results are shown below in Table 3. Note that the orientation is slightly different with respect to the (+) and (-) sense elements than the two tests above.

50 kHz 5Vpp	0 deg	90 deg	180 deg	270 deg	360 deg
AD 630 in pk-pk	12.0Vpp	17.6V	19.6V	20.0V	14.8V
AD 630 out mean	-7.51V	6.84V	8.08V	8.33V	7.20V
Filter out mean	-4.97V	7.70V	8.96V	9.20V	8.09V

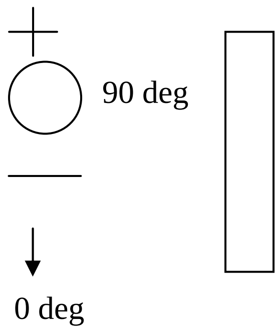

Table 3. Tests with sensor on other side of pipe

Note that when the (+) sense element is towards the pipe, the filter out values is higher than when the (-) element is toward the pipe. This is as to be expected. However, notice the difference between the 0 and 360 degree values. The expected outcome was that the signal should return to the level seen at the beginning of the rotation.

After more experimentation, it was discovered that values could be significantly different if one of the sense elements is in direct contact with the sidewall of the hole, compared to when there is a slight air gap caused from the rotation of the pod. The shim stock was added in the hopes of helping this, but the results show that it is not good enough. The increased surface area of the sense element does not decrease the sensitivity to these air gaps. This is the further indication that there is still a contact issue. One could of course make sure there is no air gap by re-compacting the soil after each quarter rotation, but in the field there is no guarantee that this will be the case. One can speculate that the drilling mud introduced in normal operation will prevent gaps, but this needs experimental verification.

After these tests, the 1MΩ resistors were added between the sense elements and the drill pipe. The thought was that lowering the resistance of the signal current path below the input impedance of the AD621 might improve the consistency of the results. Tests were performed again with the resistors added, but results were not any better. There was still an inconsistency with tests and an inability to establish a balanced condition and return to that condition after 360 degrees of rotation.

The resistance was measured between the sense elements and the drill pipe with the pod out of ground to determine if all are pretty close to the 1MΩ value expected. The measurement was performed with a Fluke True RMS Digital Multi-Meter model 111. The values were different from one another, suggesting there is indeed an imbalance problem:

Asymmetric (+) to pipe	1.08 MΩ
Asymmetric (-) to pipe	0.866 MΩ
Symmetric (+) to pipe	1.04 MΩ
Symmetric (-) to pipe	0.797 MΩ

Table 4. Impedance tests with resistors added between sense elements and pipe

The added shielding on the threaded rod portion did seem to help match the resistance values between the sense elements and the drill stem (out of the ground) better compared to Table 4. Only the (-) element of the symmetric axis is off. The readings this time around were:

Asymmetric (+) to pipe	1.090 MΩ
Asymmetric (-) to pipe	1.097 MΩ
Symmetric (+) to pipe	1.096 MΩ
Symmetric (-) to pipe	0.887 MΩ

Table 5. Impedance measurements with shielding added on threaded rod

Before the filtering circuit was altered to accept a lower range of frequencies, the frequency was swept to determine the filter characteristics. This was performed with the pod in the soil, and the frequencies adjusted discretely versus a continuous ramp. The signal did reach its lowest point at the higher frequencies. Looking at the output of the LF412 (after both filters), the signal was minimized at around 2 MHz when the output reached 25.9 mV. As the frequency was swept downwards, a discernible sine wave took form at around 700 kHz with an output of the 412 at 1.18V. The output reached its highest point around 50-100kHz, but the amplitude of the signal started decreasing again around 10kHz and below. Rather than a linear increase in the imbalance, a bell curve type characteristic was seen. This can be attributed to the fact that the lower frequencies are out of the range of the filter.

The calculated filter cut offs shown in Figure 3 are the “half-power” points on the filter characteristics. The expectation is that at these frequencies the gain of the filter stage would be 5 rather than 10. Going sufficiently above 284 kHz or below 500 Hz there will be a point where the gain of the LF412 stage will be less than 1 and actually be an attenuator. At frequencies above 284 kHz the gain bandwidth roll off of the amplifier will augment the low pass filtering. It is no surprise that the output is very small a 2 MHz. With decreasing frequency, the unity gain point of the high pass filter was seen at about 4.6 kHz. The overlap of the high and low pass characteristics was such that the gain in the middle of the pass-band was 7.5 rather than 10.

After the 560pF cap in the filtering circuit was changed to a 56nf cap to allow a lower frequency range, the LF412 had a truer gain of 10 and also there wasn’t as significant a high pass filtering effect leading into the 412. With the 560pf capacitor, an output of 960mV dropped to 140mV after the capacitor; the output of the 412 was only 1.04Vpp, yielding a gain of 7.4. With the 56nF capacitor, the signal remained at 960mV, with an output out of the 412 of 10.4V. This is a gain of 10.8. Also, previously if you dropped the frequency low enough, the output of the 412 was lower than the output of the AD621. With the newer capacitor, an output of the AD621 can drop to 156mV and still get a positive gain. It results in only a gain of 8.3. It is lower than the 10.8 above, but certainly better than the attenuation seen previously.

Recall that the added shielding around the threaded rod helped with matching the impedance values of the sense elements (between sense elements and the drill stem) out of the soil. However, with the sensor in the soil, there was a significant discrepancy in the impedance readings. This occurred both when measuring impedances between the sense elements and the drill stem as well as between the sense elements and the drill tip. The sense element to drill stem values had larger discrepancies, with one reading even showing negative.

There was a thought that there might be a problem somewhere in the circuit that was causing the imbalance, but when the pod was taken out of the soil there was a good balance seen in the signal on the oscilloscope. When placed back in the soil, the signal became imbalanced regardless of the orientation of the sensor.

The discrepancy in the impedance readings further support that there is indeed a contact issue with the current sense element configuration. As a final check, large 4' x 4'x 1/4" plastic panels were placed equidistant around the sensor. The thought here was to force a boundary condition around the sensor, uniform in all directions. Even with this formation, a balance could not be achieved in the soil. In case there was uneven moisture content throughout the test area, the soil was saturated. Again, there was still a discrepancy. Resistances in this formation were:

Asymmetric (+) to drill stem	44.8 kΩ
Asymmetric (-) to drill stem	10.68 kΩ
Symmetric (+) to drill stem	11.5 kΩ
Symmetric (-) to drill stem	18.5 MΩ
Asymmetric (+) to tip	750 kΩ
Asymmetric (-) to tip	863 kΩ
Symmetric (+) to tip	809 kΩ
Symmetric (-) to tip	630 kΩ

Table 6. Impedance measurements for plastic sheet boundary test

It is obvious that there is a contact issue with the sense element portion of the pod. It was decided in the next quarter to try going back to a capacitive sense element pickup. The sensing signal injection will still be through resistive contacts from the drill tip to the drill pipe. This coupled with capacitive sense elements represents a hybrid approach, combining the best features of the original and current configurations.

Tests in earlier quarters showed a slightly better range of pickup using capacitive sense elements, but there was a concern using the capacitive drive and sense configuration when a long length of drill stem would be added on the aft portion of the sensor. The new drive configuration is proving to be an improvement as seen by the balance with the sensor out of the soil as well as with the shielding to reject noise (recall from previous quarters that there was a large DC drift in the signal).

The sense configuration will be changed to a capacitive setup in the next quarter. Similar to figure 7, the sense elements will be inside the lexan tube. However, in that formation there was an air gap between the sense elements and the lexan tube wall. There was concern that having two dielectrics of the air gap and lexan between the sense element and the soil was causing some of the sensitivity issue seen previously.

Realizing that the upcoming quarter will be the last, a new staff member is being allocated to help with the mechanical fabrication of the device. This will enable more prototypes to be built at a faster pace if quick changes need to be made. The new prototype was just starting to be built at the very end of this quarter. Not only is the prototype being made to incorporate the new sense element design, but serious thought about the robustness of the pod is also being incorporated.

CONCLUSIONS

- Shielding the threaded rod portion of the pod did help some characteristics, but there is still a problem with achieving a balance state along the symmetric axis in a homogeneous soil.
- Extensive tests with the larger sense elements and with the pod inside and outside the soil show there is a contact issue that appears to be causing the balance issues.
- Changing back to capacitive coupling for only the sense elements should minimize the soil contact problems.
- The shielding used in the setup is doing a good job of rejecting noise so that will stay. But the sense configuration needs to be changed.

Work Performed in the Ninth Quarter

Task 1: Research Management Plan

The eighth 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 the large indoor soil test bed.

Task 3: Demonstrate Obstacle Detection in Ground

Tests in this quarter were performed exclusively in the large indoor soil test bed. If the changes to the sense element design are promising, and there is enough time left in the next quarter, a horizontal directional drill will be rented to also test the robustness of the pod.

Technical Problems Encountered

It is proving difficult to balance the symmetric axis signal in the homogeneous soil condition. The cause of this is almost certainly a contact issue with the sense configuration. A new design 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

The sense element configuration will be changed to go back to a capacitive configuration, but the drive configuration will remain the same. If time allows and the new sense configuration works, a horizontal directional drill may be rented to test the robustness of 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.