CAPACITIVE TOMOGRAPHY FOR THE LOCATION OF PLASTIC PIPE

QUARTERLY TECHNICAL REPORT

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Principal Investigator: Brian J. Huber
Project Manager: Christopher J. Ziolkowski

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

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Submitted by

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

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

DOE Project Officer
Anthony Zammerilli

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ABSTRACT

Throughout the utility industry, there is high interest in subsurface imaging of plastic, ceramic, and metallic objects because of the cost, reliability, and safety benefits available in avoiding impacts with the existing infrastructure and in reducing inappropriate excavations. Industry interest in locating plastic pipe has resulted in funding available for the development of technologies that enable this imaging. Gas Technology Institute (GTI) proposes to develop a compact and inexpensive capacitive tomography imaging sensor that takes the form of a flat plate or flexible mat that can be placed on the ground to image objects embedded in the soil.

A compact, low-cost sensor that can image objects through soil could be applied to multiple operations and will produce a number of cost savings for the gas industry. In a stand-alone mode, it could be used to survey an area prior to excavation. The technology would improve the accuracy and reliability of any operation that involves excavation by locating or avoiding buried objects. An accurate subsurface image of an area will enable less costly keyhole excavations and other cost-saving techniques.

Ground penetrating radar (GPR) has been applied to this area with limited success. Radar requires a high-frequency carrier to be injected into the soil: the higher the frequency, the greater the image resolution. Unfortunately, high-frequency radio waves are more readily absorbed by soil. Also, high-frequency operation raises the cost of the associated electronics. By contrast, the capacitive tomography sensor uses low frequencies with a multiple-element antenna to obtain better resolution. Low-frequency operation lowers the cost of the associated electronics while improving depth of penetration.

The objective of this project is to combine several existing techniques in the area of capacitive sensing to quickly produce a demonstrable prototype. The sensor itself will take the form of a flat array of electrodes that can be inexpensively fabricated using printed circuit board techniques. The image resolution is proportional to the number and spacing of the electrodes in the array. Measuring the complex impedance between adjacent electrodes at multiple frequencies forms the image. Simple location of plastic pipe with a two-electrode array has already been demonstrated.

Twelve months will be required to produce a prototype imaging system consisting of a flat sensor that can be laid on the ground to scan the volume immediately beneath it. Following a successful demonstration of this prototype, the application of this sensor to the surface of a backhoe will be addressed.

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EXECUTIVE SUMMARY

Excavation is an inherently expensive and risky operation that utilities seek to minimize. The cost of an excavation can range from $500 to $5,000 depending on the size and location. Extremely small (or, keyhole) excavations require very accurate targeting to be effective. Full-size excavations need to span the desired subsurface features in the first attempt, and rework of any type of excavation is expensive and disruptive. Less easily quantified are the losses incurred during dig-ins or impacts with the existing buried infrastructure resulting from faulty location data. These incidents require the mobilization of whatever resources are required to effect immediate repair, disrupting other operations. A release of gas, water, or a breach of an electrical main can severely affect the safety of workers and the public.

Directional boring is another technology that is being used to reduce the number of excavations. In this operation, a boring tool is used to create a pilot tunnel between two widely spaced pits. The boring tool is then pulled back to the entry pit drawing new plastic pipe with it. There have been instances of plastic pipe inadvertently intersecting clay sewer lines during the directional boring operation. When attempts were made to clear the blocked sewer line, the plastic gas pipe was breached, filling the sewer system with gas. There is at least one documented instance of an explosion caused by this situation. This hazardous situation could have been prevented with better subsurface imaging. Specifically, there is a need to accurately image non-metallic sewer lines as well as the plastic pipe.

In light of the consequences of faulty location data, the gas industry would be quick to adopt a subsurface imaging technology that meets their criteria. GTI industry advisors have identified this area as a high priority as demonstrated by the efforts expended on it to date. Current subsurface technologies to image non-metallic pipes, such as GPR and acoustic locators, are in limited use. A better technology would have excellent prospects for commercial deployment.

Because of its access to gas industry research, GTI is familiar with the merits and shortcomings of the various methods of subsurface imaging that have been attempted. The proposed capacitive tomography-imaging sensor directly addresses several deficiencies of the currently available technologies. The capacitive tomography technique is sensitive to the presence of plastic and ceramic piping materials. In addition, the thin-film nature of the sensor makes it adaptable to multiple applications. Also, capacitive tomography will give greater depth of penetration at a lower cost than ground-penetrating radar.

INTRODUCTION

The objective in this project is for GTI to apply existing research to reliably image subsurface features to benefit the natural gas distribution infrastructure. This innovation enables a compact low-cost sensor to be developed to detect buried plastic pipe, a long-standing challenge for the natural gas industry. A compact, low-cost sensor that can image objects through soil could be applied to multiple operations and will produce a number of cost savings for the gas industry. In a stand-alone mode, it could be used to survey an area prior to excavation. The technology would improve the accuracy and reliability of any operation that involves excavation by locating or avoiding buried objects. An accurate subsurface image of an area will enable less costly keyhole excavations and other cost-saving techniques.

The proposed technique performs a low-frequency impedance measurement using a multiple-element antenna array. The impedance of the soil and inclusions is sensitive to the dielectric properties of the inclusions as well as their conductivities. Thus, the technique is sensitive to plastic and metallic objects both.

A device that can reliably image objects through soil is a high priority for the gas infrastructure industry as indicated by the considerable effort already expended to develop locating and imaging subsurface technologies. The increased use of plastic piping materials has complicated this effort, and much existing technology is applicable only to metallic materials. The technology of GPR only partially fulfills this objective. While sensitive to plastic materials, GPR use has been limited due to its low depth of penetration and considerable expense.

GTI has been an active participant in the development of subsurface imaging technologies for the natural gas industry and has researched the strengths and shortcomings of the available technologies. Studies have found that techniques useful for the location of plastic piping are limited. Most of the prior locating technologies focused on metallic piping.

An experimental capacitive scanning unit has successfully located plastic pipe in a GTI-supervised test. From the outset, this technique has demonstrated sensitivity to plastic pipe materials. An acoustic method and GPR were also tested during the same project. The test involved technology providers performing a “blind” location on pipes buried on GTI property. GTI personnel knew the location of the buried piping and the technology providers did not. The rudimentary capacitive tomography device that was tested demonstrated good sensitivity and was simpler than the other devices that were tested.

EXPERIMENTAL

Setup of Experiments

In order to develop and test the concept of capacitive tomography, sensor arrays and support electronics must be constructed. The spacing of the sensor array elements sets the resolution of the system, allowing the use of long wavelengths. In fact, any desired wavelength can be used, allowing the technique to be tuned to a particular soil. Low-frequency operation simplifies the signal processing requirements. The measurement of the soil impedance at a particular frequency can be done with simple circuitry. Fabricating multiple circuits to simultaneously measure the impedance as seen by each antenna element will be economical.

Radar, by contrast, is a time-of-flight method requiring measurement of the interval between sending a radio pulse into the soil and the reflected echo from a buried object. This requires expensive, high-speed electronics. The expense of the electronics limits Ground Penetrating Radar (GPR) to operation at one or two fixed frequencies. GPR uses short-wavelength radiation to achieve good position resolution and imaging. These short wavelengths are attenuated more severely by the soil than are long wavelengths.

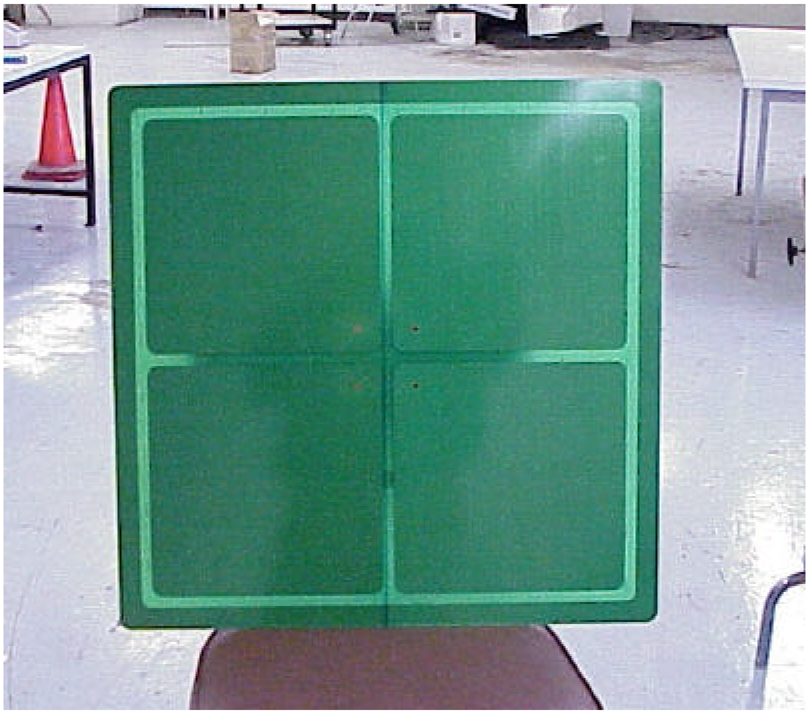

Figure 1. Experimental 4-Element Capacitive Tomography Array

Sensor Arrays

The proposed sensor array is a flat plate array of conductive electrodes. These electrodes allow signals to be capacitively coupled into the soil beneath the array. This geometry was chosen both on the basis of theoretical considerations and for ease of fabrication. In performing research on this problem, GTI identified existing technologies that can be rapidly applied to create an innovative sensor for subsurface feature detection and imaging. In particular, there are three patents that have a direct bearing on this development. Tuttle, “Buried Pipe Locator Utilizing a Change in Ground Capacitance,” teaches a simple method for locating plastic pipe. Tuttle’s device was the one tested at the GTI blind trials. The device does not perform imaging in its current form. McConnell and Vranish, “Driven Shielding Capacitive Proximity Sensor,” teaches a method to extend the range and sensitivity of capacitive sensors. McConnell and Jenstrom, “Steering Capaciflector Sensor,” extends this by teaching a method to control the directionality of capacitive sensors.

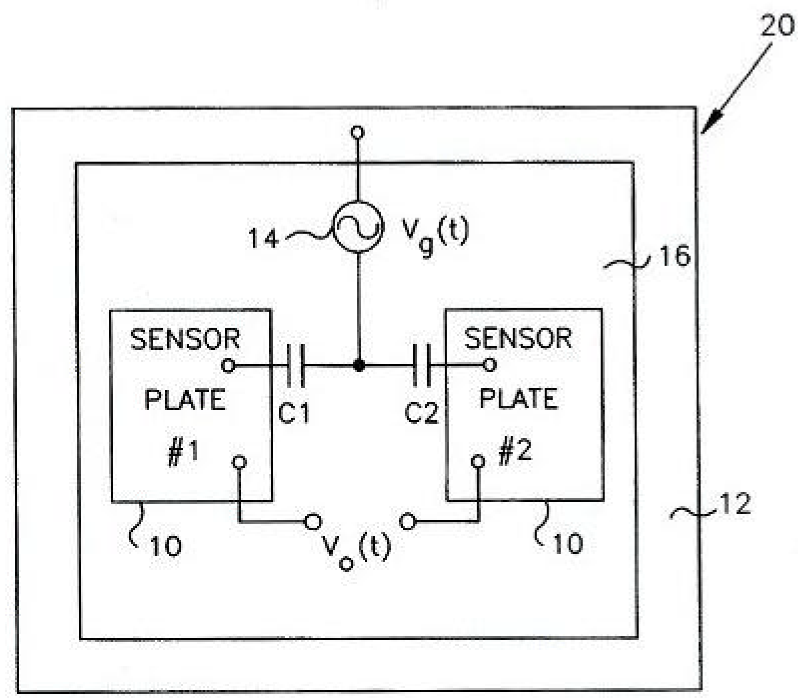

Figure 2. Patent Diagram from “Buried Pipe Locator Utilizing a Change in Ground Capacitance”

Support Electronics

The initial experiments made use of lab bench instruments rather than PC data acquisition equipment, as per the proposal. The following equipment was assembled for use in these experiments. All listed items were already in GTI's possession.

- Princeton Applied Research Lock In Analyzer Model 5204
- Elinco 400W RF Amplifier
- Wavetek 175 Function Generator
- Tektronix TDS 320 Oscilloscope
- Tektronix Analog Oscilloscope
- Various multimeters and standard lab tools

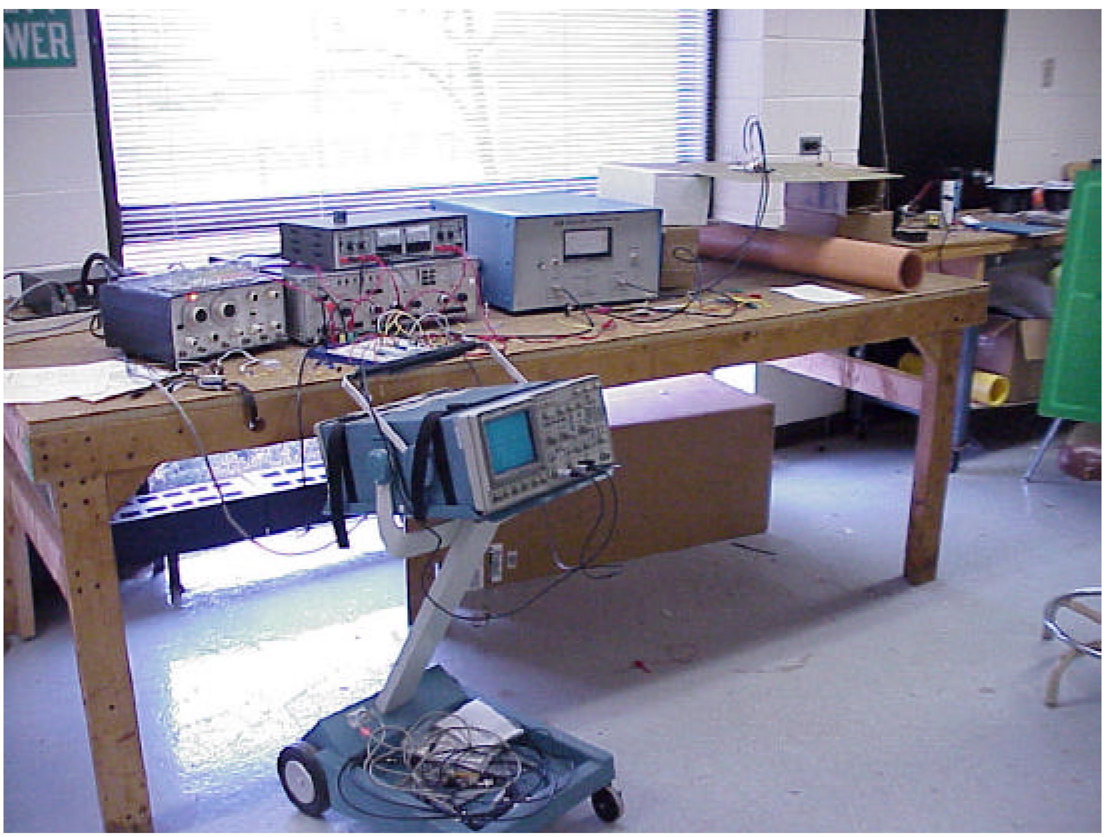

Figure 3. Initial Laboratory Apparatus

RESULTS AND DISCUSSION

Baseline Array Experiments

The first technical goal of the project was to fabricate and test simple CT arrays to gather baseline data. Replicating the results of Tuttle's 2-element system was the initial experiment to be performed. This system performed a differential measurement between two driven, or "hot", electrodes in contact with the earth. There is also a return, or "neutral" electrode in contact with the earth. The arrangement is depicted schematically in Figure 2. These electrodes form an AC impedance bridge. The advantage to the bridge approach is that background effects can be nulled out rendering the device sensitive to changes, or discontinuities in the soil.

The first sensor arrays tested were fabricated by applying metal foils to plywood backings. A simple 2-element array constructed in this fashion gave encouraging results. Simultaneous with this effort, a 4-element array was laid out for a 24" by 24" printed circuit board and the layout sent to a local fabricator. The rationale was that a 4-element array could easily be used as a 2-element array by electrically joining pairs of the plates. This would allow both the 2 and 4 element cases to be tested without repeating the fabrication step. Several 4-element PC board arrays were fabricated at once; Figure 1 depicts one of these.

The 4-element array was used in conjunction with the support electronics to determine the amount of bridge unbalance that could be induced with a plastic pipe. The experiments were carried out on a wooden table with the array resting on non-metallic supports. The purpose was to initially isolate the experiment from variables introduced by mixtures of target materials. A section of plastic pipe rolled under the prototype sensor array, as shown in Figure 4, to give a rough indication of sensitivity. The expectation is that this is a more difficult case than a pipe embedded in soil: the dielectric properties of air are closer to those of plastic than those of soil. The plastic pipe in soil is expected to have greater "contrast" with respect to its background.

Several signal conditioning arrangements were tested in this fashion. The array was driven with a sinusoidal excitation signal derived from the Wavetek function generator. The Elinco power amplifier boosted the excitation signal. Initially the signal from the array was applied directly to the inputs of the Lock In Analyzer. The results from this arrangement were adequate: if the bridge was perfectly balanced to begin with, the presence of the pipe was easily detectable. Several schemas for balancing the bridge were examined. A practical field device will need either a method for automatic balancing, or to be tolerant of some initial imbalance caused by varying soil types.

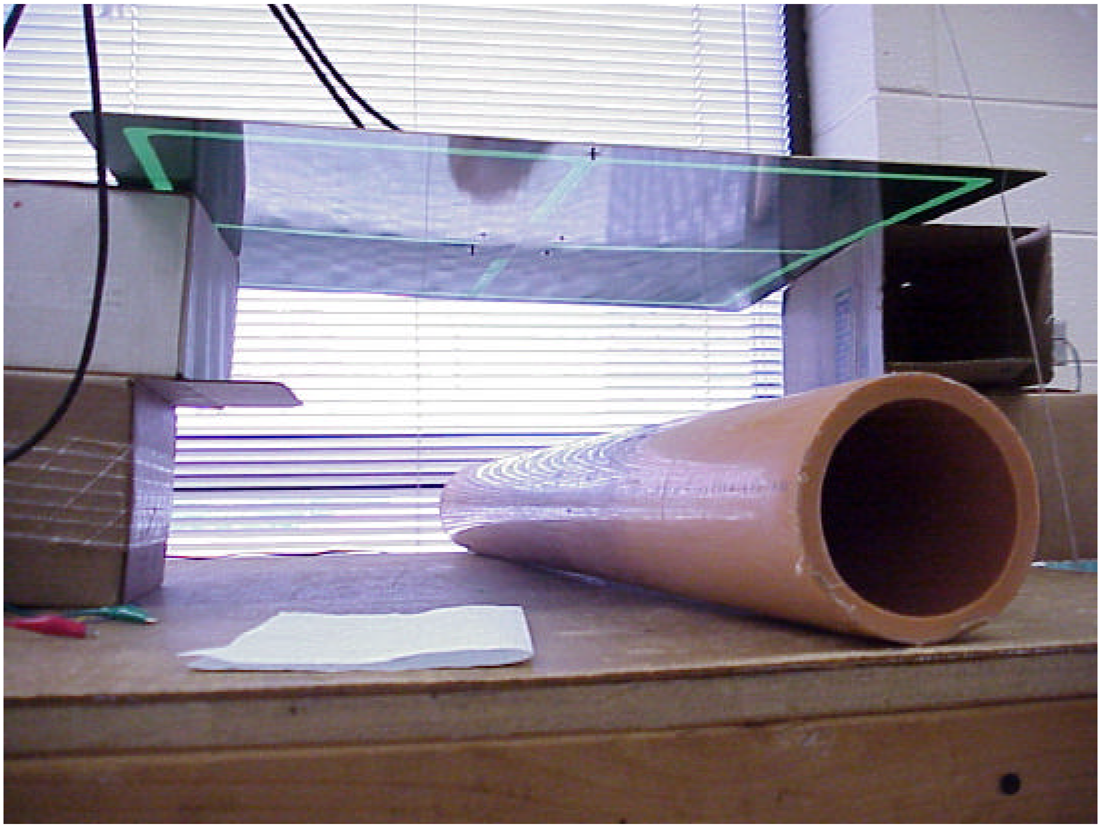

Figure 4. Plastic Pipe under 4-Element Array

It became apparent that the apparatus would benefit from some modifications to the first stage of amplification. The PR Lock In Analyzer is very sensitive to dc components or overload conditions. An instrumentation amplifier was inserted between the array and the Lock In Analyzer to remove some undesirable artifacts. This is a differential device that amplifies the unbalance of the bridge while subtracting out the common modes and offsets of the bridge.

This stage of preamplification did improve the results substantially: up to 100mV of difference signal could be observed as the pipe sample was moved from one side of the array to the other. Some other issues were flushed out in working with the preamp. The inputs to this preamp must be kept within the +20 to –20 volts supply range of the power supply; going beyond this overdrives the preamp and gives spurious results. This means that the magnitude of the excitation signal cannot be increased arbitrarily. Several means for keeping the array outputs "centered" in the appropriate range are being investigated. Again, a practical device needs have some tolerance for initial imbalance.

A substitute for the Lock In Analyzer was found and put to use in the December time frame. Even with the improved preamp, the Princeton Research Lock In Analyzer still was somewhat unreliable. A monolithic device, the Analog Devices AD630, was used to perform the same function. This function is measure the outputs from the array in synchronization with the excitation signal. This method is referred to as lock-in amplification or synchronous demodulation. The principle is that the signal of interest will be synchronized with some other known signal; in this case the drive voltage to the array. Sampling the signal of interest in sync with the excitation, and averaging many samples together greatly attenuates background noises. Stated another way, the signal of interest is of a known frequency and the lock-in amplifier provides a narrow band filter at this frequency. Because this filter is "locked" to the excitation signal, the frequency of excitation can be varied to suit varying soil conditions.

The best results were obtained using monolithic IC devices for the preamplification and the lock-in stages. The presence and location of the plastic pipe sample in air was easily detectable. The results of moving the pipe in the vicinity of the PC board array were observed as changes in signal levels viewed with an oscilloscope.

CONCLUSION

- Fabricating capacitive sense arrays on printed circuit board materials is a practical solution. Only rigid circuit boards were attempted during the first quarter.
- The presence and location of the plastic pipe in the vicinity of the sense array was detectable in air. This is projected to be a worse case than detection in soil.
- The best results were obtained using monolithic integrated circuits for the preamp and the synchronous demodulator.
- Some effort must be expended in developing an auto-balance for the sensing bridge or making the circuitry tolerant of some initial imbalance.

Work Performed in the 4th Quarter of 2001

Task 1: Research Management Plan

The draft "Research Management Plan" was written and submitted. A presentation was on Capacitive Tomography was prepared and presented at the project kick off meeting. An assessment of the state of the art in CT was prepared and submitted.

Task 2: Design and Prototype Sensor Array

Some hand-made capacitive arrays were constructed and tested. Several identical 4-element arrays were fabricated for GTI by a local printed circuit board house. These were tested both in the 4 and 2 element modes. The PC board units were capable of detecting plastic pipe in air. It is expected that detection of pipe in soil will be easier due to the greater disparity between the properties of soil and plastic.

Task 3: Design and Prototype Support Electronics

Work was performed with both bench instruments and some prototype circuitry in support of testing the 4-element array. Progress was made in determining the parameters of importance that will improve the performance of the device. The operator interface to the experiment has been limited to oscilloscopes and metering device during the first quarter of the work. A computer based operator interface will be initiated next quarter.

Task 4: Construct Field-Ready Mat Prototype

This task is not scheduled to start for some time; no work has been performed under it as yet.

Task 5: Demonstrate Mat Prototype

This task is not scheduled to start for some time; no work has been performed under it as yet.

Technical Problems Encountered

No technical problems that will impact the ability to perform the project or project schedule have been encountered.

Project Management Problems Encountered

No project management problems were encountered this quarter.

Action Requested of Doe NETL Project Manager

There are no action items requested of the DOE COR.

WORK PLAN

Work Planned For The 1st Quarter Of 2002

The following items are planned for the next quarter:

- Test the 4-element array sensitivity to a plastic pipe buried in GTI's indoor soil box.
- Increase the array complexity to 16 elements and test the sensitivity both in air and in the soil box.
- Construct more complex targets by mixing different sizes of plastic pipe and metallic pipe.
- Begin creating a LabVIEW operator interface for the experiments.

REFERENCES

In a patent entitled " Driven Shielding Capacitive Proximity Sensor", patent number 5,166,679, dated November 24, 1992, inventors John M. Vranish and Robert L. McConnell have presented an invention for a capacitive proximity sensor that will detect the intrusion of a foreign object into the working space of an electrically grounded robotic arm. The capacitive proximity-sensing element is backed by a reflector that is driven by an electrical signal of the same amplitude and phase as that signal which is detected by the sensor. It is claimed that by driving the reflector plate with the same signal that is on the sense element significant increases in the sensor's range and sensitivity are accomplished.

In a patent entitled "Steering Capaciflector Sensor", patent number 5,363,051, dated November 8, 1994, inventors Del T. Jenstrom and Robert L. McConnell, present an invention that will allow for the steering of the electric field lines produced by a capacitive type proximity sensor. The inventors assert the claim that by steering or focusing the electric field will allow an increased ability to discriminate and determine the range of an object in the area of observation over that of previous capacitive sensors. Differential voltages applied to shielding plates spatially arranged around the sensor plate accomplish steering of the electric field lines.

In a patent entitled "Buried Pipe Locator Utilizing A Change In Ground Capacitance", patent number 5,617,031 dated April 1, 1997 inventor John E. B. Tuttle has invented a portable buried pipe detection device that utilizes changes in the electrical properties of the soils surrounding underground pipes. The detection method consists of the injection of a low frequency sinusoidal wave into the ground via an array of injector/sensor plates. Subsequent modification of the injected signal by variations in ground impedance brought about by the existence of buried piping structures will result. The modified signals will be detected by the spatially separated sensor elements located on the device. The injector/sensor elements are constructed in such a manner as to comprise a capacitive bridge circuit when viewed in conjunction with the ground. As the detection array is moved along the ground any occurrence of underground piping structures will imbalance the capacitive bridge and give rise to a detectable electrical signal.

LIST OF ACRONYMS AND ABBREVIATIONS

CT - Capacitive Tomography

COR – Contracting Officer's Technical Representative

DOE - Department of Energy

FERC – Federal Energy Regulatory Commission

GPR – Ground Penetrating Radar

GRI – Gas Research Institute

GTI - Gas Technology Institute

IGT – Institute of Gas Technology

IRNG –Infrastructure Reliability of Natural Gas