CAPACITIVE TOMOGRAPHY FOR THE LOCATION OF PLASTIC PIPE

QUARTERLY TECHNICAL REPORT

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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 good 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.

Thus far, 4-element and 16-element sensor arrays have been fabricated and tested. The sensor arrays have been tested with buried plastic piping at GTI both in soil boxes and an outdoor facility. Sensitivity to the presence of plastic pipe in soil has been demonstrated with 2", 4", and 6" diameter pipes at depths greater than 4 feet. This sensitivity is unaffected by soil moisture conditions. A 64-element array is currently being designed to provide greater spatial resolution of buried objects.

TABLE OF CONTENTS

	<u>Page</u>
DISCLAIMER	ii
ABSTRACT	iii
EXECUTIVE SUMMARY	1
INTRODUCTION	2
EXPERIMENTAL	3
CONCLUSION	9
WORK PLAN	12
REFERENCES	13
LIST OF ACRONYMS AND ABBREVIATIONS	14
APPENDIX A: PAPER FROM ORLANDO GAS INDUSTRY FORUM	15

LIST OF GRAPHICAL MATERIALS

	<u>Page</u>
Figure 1 Imaging screen appearance	5
Figure 2. Back of sensor array	7
Figure 3. Front and back of sensor array	7
Figure 4. Zoom in of single sensor cell	8

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 issues with depth of penetration and expense.

An experimental capacitive scanning unit has successfully located plastic pipe in a GTI-supervised test during the mid-1990's. 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.

The current project effort by GTI has extended this early technology to provide a coarse image of buried objects. The original technique used 2 sense elements to locate the pipe. GTI has tested 4 and 16-element arrays to provide greater resolution of the pipe's location. These arrays can detect plastic pipe under more than 4' of soil with a high signal to noise ratio. A 64-element array is currently being designed based on these results.

EXPERIMENTAL

Sensor Array

Refinement of the 16-element sensor array continued in the fourth quarter of 2002. Migration from discrete capacitors to a copper strip driver scheme continued to evolve. The ultimate goal of this activity is to fabricate as much of the sensor array using printed circuit board technology as possible. The current design consists of square sensing plates that are embedded in a ground mesh. Self-adhesive copper tape is added to the circuit board on the side opposite the sense plates to obtain rough sizes for printed circuit capacitors. These sizes are then used to guide the layout of the next iteration of the printed sensor.

Measurements were made of the sensor element capacitance to the ground mesh and to a typical copper drive strip using a HP impedance analyzer. These measurements confirmed values of 2 – 10 pF for the sensor element and drive elements. Adhesive backed copper strips ¼ “ x 3” were applied to the backside of the 16-element board. The drive strips were centered over the sensor elements and two distribution strips mounted over the ground mesh drove eight elements each. A variable capacitor of 5 pF is connected to each element for fine-tuning of the balance of the sensor.

Persistent low-grade noise and reliability issues of the sensor drive transformer necessitated a redesign and fabrication of the transformer. A coil winder was used to wrap a center tapped winding on a cylindrical ferrite core. This transformer was then mounted in a shielded enclosure with a BNC coax input and two BNC outputs with the outer shield of each output connected to the center tap of the transformer secondary. This arrangement results in a large improvement in the electrical symmetry of the sensor drive. In other words both the drive elements and the ground mesh of the sensor is now driven by its own coax line with the outer shield of the coax connected to the center tap of the drive transformer secondary. The mechanical robustness of the drive arrangement was also significantly improved. After these changes were implemented significant improvements in the noise and sensitivity of the sensor was noted.

The sensor is driven with a sinusoidal excitation signal. One data sample is taken during each cycle of the excitation. A digital counter was used to precisely control the phase of the acquisition point on the sensor waveform. It was found that by adjusting the phase to get a minimal sensor voltage reading, in the absence of a target, the sensitivity was maximized. The presumed explanation for this is that a minimal reading corresponds to the zero crossing of the waveform. Acquiring the signal at the zero crossing would result in a large signal variation if a phase shift were to occur. This phase shift would result from a change in the dielectric

permittivity (corresponding to a inclusion in the soil) of the medium surrounding the sensor elements.

The signal variation for a given change in phase would be at a maximum for acquisition of the signal at the zero crossing. This is in contrast to acquiring the signal at the peak of the excitation waveform where its derivative is at its minimal value. Further it is proposed that a much greater sensitivity is achieved by sampling only at one point per cycle vs. multiple points per cycle. This is because sampling at multiple points per cycle results in voltage variations on the sensor elements that is due to variation in the impedance magnitude rather than phase changes. Mathematically speaking the signal across a sensor element is given by:

$$(1) \quad V_{Sensor} = V \frac{Z_{Sensor}}{Z_{Total}} (\cos(\omega t + \delta) + i \sin(\omega t + \delta))$$

$$(2) \quad Z_{Sensor} = \sqrt{R_{Sensor}^2 + (1/\omega C_{Sensor})^2}$$

$$(3) \quad Z_{Total} = \sqrt{(\frac{1}{\omega C_{Sensor}} + \frac{1}{\omega C_{CapVar}})^2 + (R_{Sensor} + R_{Drive})^2}$$

$$(4) \quad \delta = \tan^{-1}(\frac{\frac{1}{\omega C_{Sensor}} + \frac{1}{\omega C_{CapVar}}}{R_{Sensor} + R_{Drive}}) - \tan^{-1}(\frac{1/\omega C_{Sensor}}{R_{Sensor}})$$

What these equations show is that for sampling once per cycle is that δ becomes the predominate factor controlling a change in the V sensor voltage. When sampling multiples times the amplitude factor Z_{Sensor} becomes the predominant influence controlling changes in Z_{Sensor} .

A major effort this quarter concerned the development of imaging for the CT Scanner. To this end the LabVIEW virtual instrument (VI) that was developed to scan and record the sensor element signal levels was modified. The VI was modified so that continual scanning of the 16 sensor elements was performed. The signal levels were then mapped to a color tree, which was then used to drive a 16-element box array displayed on the front panel of the VI. This resultant VI functioned such that an object proximate to one or several sensor element would then light up the corresponding box element displayed on the PC screen. Currently the color mapping has been arbitrarily assigned so as to indicate position in the horizontal plane. Initially only 8

elements were scanned to test out the VI. As performance improved, all sixteen elements were connected and tested. Early results were very encouraging.

A pipe depth data acquisition capability is currently being implemented. A color and intensity-mapping scheme has been chosen. This scheme correlates color to the depth of the detected object and intensity to the size of the object. Initially three-color ranges have been chosen, red, blue, and green. Each color indicates a range of burial depth. Red corresponding to a burial depth of 5-8 ft, blue 3-5 ft, and green 0-2 ft. These numbers can be adjusted to give broader or narrower depth indication ranges as experimental results dictate.

The proposed means of acquiring depth data is to vary the frequency of the sinusoid driving the sensor array. Lower frequencies penetrate further into the soil; therefore varying the drive frequency can reveal features at different depths. A series of plane images are obtained; one for each excitation frequency. The differences in the various images reveal the relative depths and shapes of various buried objects. Tomography consists of “stacking” or fusing the data from the plane images into a three dimensional representation of the buried objects.

A practical difficulty in doing this is maintaining the same relative acquisition phase on the signal as the frequency is varied. Many different ways have been examined to achieve this. The most practical means is to use a function generator, which produce both a sine wave and a TTL synchronous signal in which the relative phase of the two signals can be varied. This is being done with a Tektronix 320 arbitrary waveform generator controlled programmatically via a GPIB serial interface card.

Fig. 1. Imaging screen appearance.

Circuit Board Fabrication

Four new circuit board designs were started during this quarter. Two boards started were designed to provide for the multiplexing and buffering of the sensor element pickup signals. Two boards were sensor boards.

The multiplexing boards are required to scan the electrodes in the sensor array. The multiplexer provides the necessary interface between the limited analog input channels of the computer and the multiple plates in the array. The boards contain high impedance buffer amplifiers and multiplexers. The amplifiers prevent the multiplexer and other external components from degrading the sensor performance by providing a uniform impedance and gain. The multiplexers allow the sense electrodes to be scanned sequentially using only two high-speed analog channels. Multiplexing avoids the need for a separate, expensive analog channel for each sensing plate.

A two channel multiplexing and buffering board had left GTI for fabrication at the time of this writing. A second reduced component one channel multiplexing and buffering board was in the process of being laid out. Each board could handle up to 16 sensor inputs. Both of these designs incorporated actively driven guard traces and coax shields to enhance noise immunity, SMA connectors for sensor signal inputs, and low noise low power quad JFETS for the buffering functionality. These boards can be used in single or multiple board configurations depending on the number of sensor element inputs.

Two new sensor boards were started during this quarter. One board had left GTI for fabrication at the time of this writing. This board utilized the same 16-element layout as the previous board run, but has a drive element mesh on the backside of the board. The mesh replaces the adhesive backed copper striping and discrete capacitors that had been previously used for the drive.

A tree like geometry for each sensor element was used in order to facilitate balancing adjustments of the sensor component capacitances. Figure 4 is a close up of a single sensing cell. The drive capacitance can be adjusted by cutting the narrow traces. A 64-element board is currently being designed. This board will not be submitted for fabrication until results from the new 16-element board validate the underlying design criteria.

Fig. 2. Backside of sensor board showing RF drive tree elements.

Fig. 3. Front and backside of 16-element sensor.

Fig. 4. Zoom in of sensor cell.

CONCLUSIONS

- The 16-element sensor board sensitivity and resolution were improved by the addition of an improved mesh strip drive array.
- A multiplexer and buffering circuit board was designed and sent out for fabrication.
- A new 16-element sensor board has been designed and sent out for fabrication.
- A 64-element sensor board is being designed..
- A rudimentary planar imaging technique was designed and successfully implemented.
- Depth sensing measurements were conducted on GTI's pipe test bed to confirm validity of the frequency sweep scheme.
- Addition of a depth sensing imaging capability is ongoing and is expected to be successful.
- The current schedule could be extended at no cost to allow additional outdoor testing.

Work Performed in the 4th Quarter of 2002

Task 1: Research Management Plan

Three Quarterly Technical Reports covering the period from October of 2001 through August of 2002 have been submitted. Dan Driscoll of NETL visited GTI in May of 2002 and was briefed on the progress in the project and given a tour of the facilities. The NETL project manager has been provided with periodic brief updates. The progress on the CT project was presented at the “Natural Gas Infrastructure Reliability Forum” in Morgantown on September 17th. A paper and presentation on CT for PE were given at the GTI/NETL “Natural Gas Technologies Conference” in Orlando on October 2nd.

Task 2: Design and Prototype Sensor Array

Additional improvements and refinements were made to the 16-element array. Primarily with regard to the addition of RF signal drive elements. These were constructed from the application of adhesive backed copper tape stripping to the backside of the sensor board. This drive arrangement has been incorporated in a new sensor board that is being fabricated. A 64-element sensor board is waiting test results from the new 16-element board, before being sent out for fabrication.

Task 3: Design and Prototype Support Electronics

Advances in the operation and implementation were ongoing in this area. The addition of a software configurable digital counter allowed for the precise control of the sample acquisition timing. The proper setting of this parameter greatly affects the sensitivity of the sensor. A new multiplexer and buffering board has been designed and sent out for fabrication it is anticipated that significant improvements in noise immunity, modularity, and mechanical robustness will result. A horizontal imaging capability was designed and implemented, the initial operational results are very encouraging.

Task 4: Construct Field-Ready Mat Prototype

A 64-element sensor board is waiting test results from the new 16 element board, before being sent out for fabrication.

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

The current schedule calls for the project to end on March 31st. While a working prototype can certainly be demonstrated in this time, only a small amount of outdoor testing will be possible. The current weather conditions in the Chicago area have not been conducive to outdoor testing. Some work is being carried out in the large indoor soil box. The project budget, provided by NETL and GTI both, would easily support additional testing.

Action Requested of Doe NETL Project Manager

Please consider extending the project completion date to September 30th of 2003. This is strictly a time extension; no additional funding is sought from NETL.

WORK PLANNED FOR THE 1ST QUARTER OF 2003

- Populate and test new multiplexer buffer circuit board.
- Test and characterize new 16-element sensor board.
- Mount new buffer board to new sensor board characterize and test.
- Modify 64 element sensor board design based on results from 16 element board, fabricate board.
- Continuation and conclusion of the addition of a depth sensing capability to current imaging functionality.
- Test imaging capabilities in GTI's soil box laboratory.
- Perform such outdoor testing as weather allows.

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 Capaciflect or 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
PCB – Printed Circuit Board
IF – Intermediate Frequency
MDPE – Medium Density Polyethylene
VI – Virtual Instrument
NI – National Instruments
DACQ – Data Acquisition
GUI - Graphical User Interface
SNR – Signal to Noise Ratio

APPENDIX A

CAPACITIVE TOMOGRAPHIC SENSOR FOR THE DETECTION, LOCATION, AND IMAGING OF SUB-SURFACE NON-METALLIC PIPES

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1. ABSTRACT

Currently there are no reliable means to detect non-metallic underground piping structures. This paper proposes a unique method which would enable the accurate detection, location, and imaging of non-metallic pipes. A multifaceted capacitive sensor is used to inject a low frequency RF signal into the ground. The injected signal is then monitored for changes in electric field strengths associated with variations in the dielectric permittivity of the soil. The variations in electric permittivity of the soil arises from the presence of non-ferrous piping. The capacitive sensor provides a high enough degree of sensitivity to the variations in electrical permittivities of the soil that an accurate image of the underground piping can be constructed. The capacitive tomographic sensor would provide an economical, portable, and easy to use device that would enable persons in the field to reliably detect and image plastic piping.

INTRODUCTION

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) is developing 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 good resolution. Low-frequency operation lowers the cost of the associated electronics while improving depth of penetration.

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.

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.

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.

Capacitive tomography is the detection of the structural details of an object by monitoring changes in an electric field produced by that object. The electric field most often will be produced by an arrangement of capacitive elements. The current capacitive tomography project a number of electric field producing and electric field detection elements are configured in a planar array. The field producing elements or transmission elements will be driven by a 100-400 khz signal. The planar array will be placed directly on or proximate to the surface of the ground. The goal of this system is to detect natural gas pipe line structures, in particular those that are composed of non-metallic materials, such as plastic or ceramic pipe.

A capacitor is a physical device that stores energy in the form of an electric field. The electric field that stores this energy may be time dependant or time independent. The types of physical structures that may be used to generate the electric field is typically, but not necessarily an arrangement of metallic plates.

Strictly speaking capacitive tomography should be defined as the detection, sensing, or imaging of physical structures by the detection and analysis of variations or perturbations in the electric field parameters. These changes in the electric field parameters results from changes in the electrical permitivities of the physical structures that reside in the physical space that is being sensed. Thus there should be negligible self interference of the electromagnetic field brought about by the physical dimensions of the capacitor elements that is generating the electrical fields. This would imply that the size of the capacitor plates and the distances between the plates and the structures to be detected would be very small compared to the wavelength of the electric fields.

In order to develop and test the concept of capacitive tomography, sensor arrays and support electronics were 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.

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

PROOF OF CONCEPT

The first sensor array constructed was 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. John Tuttle, (1) “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, (2) “Driven Shielding Capacitive Proximity Sensor,” teaches a method to extend the range and sensitivity of capacitive sensors.

McConnell and Jenstrom, (3) “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”

Initial Experiments for Four Element Array

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, seen in figure 1, 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 3, 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. An Elinco rf 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.

A monolithic device, the Analog Devices AD630, was used to perform the same function. It's function is to 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.

Figure 3, plastic pipe under 4-element array.

Analog Development

Figure 4 shows the details of this arrangement. A signal generator rf amplifier and center taped isolation transformer form the sensor drive circuitry. The signals of interest are routed through the Burr Brown difference amplifier. The output of the difference amplifier was taken to the input of the AD630 synchronous demodulator. The AD630 performs the function of a lock-in amplifier: providing gain only at the frequency of the bridge excitation signal. The signal from the demodulator after filtering was then input to a single ended amplifier with a gain of 100. Detected signals in the range of 100mv-500mv could now be measured when a plastic pipe was displaced from one side of the sensor plates to the opposite side.

Figure 4, shows details of drive and pick up electronics for 4 element sensor.

An intermediate frequency (IF) transformer was constructed as a means of addressing the common mode voltage issue. This transformer was used to interface the 100 kHz output from the power amplifier to the sensor array. The secondary of the IF transformer was center tapped. The center tap of the secondary winding was connected to the signal conditioning electronics ground. The purpose of the modification was to accomplish level shifting of the bridge center point voltage. The transformer drive performs the removal of the common mode voltage for all the sensor elements simultaneously. This is an important consideration for higher-order arrays.

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.

Results of Initial Experiments

- 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.

2. PIT LAB TESTS

It was determined that the operation of the sensor was reliable and stable enough to proceed with testing of the sensor in GTI's indoor pit lab facility. The test pit is 20' x 20' x 8' and currently filled with a sand clay mix, which was chosen to be typical of the type of soil used for gas line back fill.

A wooden frame was constructed from $\frac{3}{4}$ in. x 3-in. clear white pine. The frame's dimensions was 4' x 8'. The frame lays on the ground surface over the test pit. A 4" plastic pipe is buried 3 feet deep and runs perpendicular to the length of the test frame. The 24-in. square PCB capacitive sensor is mounted to two wooden cross beams. The sensor and wooden cross beams sits on the 4' x 8' wooden frame that allows the sensor to glide smoothly over the surface of the ground. This arrangement, shown in Figure 5, enables repeatable experiments by holding constant the separation between the ground surface and the surface of the sensor.

Several additional data sets were taken utilizing the same general physical and electronic experimental setup. Data was collected to find well-defined signal lobes associated with the sensor plates. Different drive and sense configurations were examined in order to determine the optimal signal sensitivity and spatial resolution. These data sets confirmed the initial results of an easily observable well-defined signal peak found when

Figure 5. Close up of sensor on sliding frame

the sensor was centered directly over the plastic pipe.

Efforts were undertaken to determine the minimal sensor element size that could be constructed, which would still produce a practical detectable signal. This has important significance in determining the minimal spatial resolution of a flat plane of capacitive sensor cells. The smaller an individual cell can be made, the more cells that can be placed on a flat array thus increasing the resolution of the image produced.

One inch copper tape was used to construct a 6" square perimeter attached to a 24 x 24 inch cardboard square. Inside of this perimeter was centered a 1" x 2" copper strip and on either side of the center plate was placed a 2" x 1/2" strip centered between the perimeter and the center plate. This formed a four element capacitive bridge with the drive voltage applied to the perimeter and the center plate and the pickup signals were located at the two 2" x 1/2" strips. This arrangement produced a 40 mV signal peak

when the sensor was placed directly over the plastic pipe. The signal fell off significantly when the sensor was moved to either side of the pipe.

A smaller 4 x 4 inch cell was also fabricated. This cell showed a signal peak several inches off of being directly over the pipe. This result was attributed to the likelihood that the cell capacitance values were becoming small enough that the signal pickup cable capacitance to ground was close to the sensor capacitance. Placing the signal conditioning electronics closer to the array and thus eliminating the large cable capacitance could mitigate this effect. This would result in raising the impedance to ground that the sensor element signal sees.

Results and Discussion of Pit Lab Experiments

Initial results from the indoor soil pit testing were very encouraging. A significant voltage maximum was detectable when the sensor was directly over the plastic pipe. Detailed voltage versus position data was taken, as shown in Figure 7. These measurements strongly indicate that the buried plastic pipe is readily detectable. Several sets of data were taken with various drive voltages and frequencies. Additionally several alternative methods of driving the sensor plates were looked at, all with good results. Spatial resolution of the detected signal was on the order of less than $\frac{1}{2}$ an inch. The operator could precisely locate the sensor over the plastic pipe by only looking at the detected signal and not looking at the sensor while it was moved over the pipe.

There was at least an order of magnitude increase in the detected signal for the buried pipe as compared to the detected signal of a plastic pipe in air. This is due to the greatly reduced impedance of soil vs. air as the medium in which the plastic pipe resides.

Figure 6. CT 4-Element array on indoor soil box. The yellow pipe on the right descends 3' to an elbow. From there it runs to the left, passing under and at right angles to the track

Figure 7. Voltage versus location for a plastic pipe located at 0". The secondary peak on the left is caused by the presence of the desk and equipment.

Various configurations of the four-element sensor were tested. The first configuration consisted of the four-element bridge electrically connected as two elements. Thus the four-element bridge consisted of two discrete resistors as the drive elements in the bridge, the four sensor plates connected in pairs to form two large plates, and the square perimeter being the complement or bottom elements of the bridge. The data in Figure 8 was generated from this type of configuration.

Figure . Test data for alternative drive configuration.

The most promising configuration tested was the connection of all four square plates driven independently as half-bridges. This allows any adjacent pair of plates to generate a differential signal. In a square array, alternately taking differences between row and column plates allows the x-y position of buried objects. The perimeter electrode forms the return path for the excitation signal. This drive arrangement will be used when 16-element or higher order arrays are tested.

Conclusions

- The presence and location of the plastic pipe in the vicinity of the sense array was readily detectable in soil. The signal magnitude was an order of magnitude better than for the plastic pipe in air.
- The bridge circuits sensitivity is greatest operated near the balance point. Operating near balance requires that the common mode excitation signal be properly managed.

- The use of a drive transformer to manage the common mode voltage for the entire array eliminates the need for a specialized amplifier for each individual sense electrode in the array.
- Shrinking the individual sense electrodes in the array is practical. By placing more sense electrodes in the same area, a higher image resolution can be obtained.
- As the size of the sense electrode shrinks, care must be taken with the signal routing and conditioning so as to maintain the signal integrity.
- As the number of sense electrodes increases, it becomes more practical to handle the increased amount data flow digitally. Digital methods, such as multiplexing, will be used to reduce redundancy in the instrumentation to monitor complex arrays.
- A certain amount of analog signal conditioning will be necessary to insure that the signal to noise ratio (SNR) is adequate prior to digital processing.

TRANSITION TO PC DATA ACQUISITION

The National Instruments LabVIEW development environment was chosen for the data acquisition, signal processing, and graphical user interface. National Instruments data acquisition boards were examined for a product that would fulfill the needs. A 6115 DACQ was chosen which could simultaneously digitize four channels of analog data at a maximum of 10 mega samples per second. With a drive frequency of 100kHz to 400 kHz this would result in a range of 100 samples per cycle at 100 kHz and 40 samples per cycle at 400 kHz, well above the minimum Nyquist sampling rate of 2 samples per cycle

The ultimate goal of the LabVIEW development effort is to reproduce the results obtained from small element count arrays with more complex arrays. The analog signal processing used for small numbers of elements must be replaced with digital signal processing for greater element counts to be feasible. Also, LabVIEW provides a customizable user interface that lends itself into translating the signal data into a usable image.

Depth Location Software Development

A significant goal of this project is to develop the means to give accurate depth information of the buried plastic pipe. To this end a strategy was developed that would discriminate variation in electric permitivities as a function of depth.

As a range of frequencies is swept the electric field intensity at the location of the plastic pipe will vary in direct relation to the frequency of the electric field. The electric field intensity should vary inversely to the frequency. This results from the fact that at higher frequencies lower impedance is presented by the soil. Stated differently, the soil attenuates higher frequencies more, a fact that is problematic for ground probing radar. Consequently a greater level of penetration of the soils by the electric fields occurs at lower frequencies.

At the point in the soil where the pipe is located there will be a variation in the electric field intensity as the frequency is swept. This electric field intensity is the sum of the original field intensity plus the contribution of a polarization field component. The magnitude of this polarization field component will vary according to the electric permeability of the material at this location: the soil and the pipe. If one thinks of the soil volume as distributed impedance, then the complex, or reactive part of this distributed impedance arises from the properties of the soil. Thus the variation of the distributed capacitance in the vicinity of the plastic pipe gives rise to variation in the distributed impedance.

This variation in the distributed capacitance will alter the sensed imbalance of the CT sensor as a function of the frequency of drive signal. More deeply buried pipes will not be sensed at high frequencies but will become “visible” as the drive frequency of the array is lowered. Each frequency will provide a tomographic snapshot of a particular depth below the sensor array. It is postulated that given the aforementioned phenomenon depth location data can be gathered, processed, and presented on a graphical user interface to give a useful indication of pipe depth.

A VI was constructed such that a digital trigger signal was outputted to the signal generator to start the sweep. This would also begin the data acquisition sequence. Additionally a square wave from the generator, synchronous with the sine wave, would trigger the DAQ. The DAQ would acquire one data value at the positive peak of each cycle, emulating the function of the analog lock-in amplifier used for proof-of-concept. At the end of the sweep the VI would detect a trigger signal from the generator and the data acquisition would be terminated.

Depth analysis VI's were developed for the data acquired with the frequency sweep VI. The acquired data was then displayed as a graph of frequency vs. signal intensity. It was then determined that by visually inspecting and comparing two different graphs corresponding to two sweeps of plastic pipes at two different depths, one would be able to apprehend the signal differential corresponding to the two distinct pipe depths.

A VI was then constructed, which would allow the user to press a screen panel button to acquire and display a data set. The panel button can be pressed repeatedly to acquire and display several data sets.

A series of initial test were run. The operator interface, logic diagram, and some representative data for this VI is shown in Figure 9.

Figure 9. LabVIEW Virtual Instrument for capturing CT data. Above: Logic Diagram for the VI. Below: Operator Interface of VI seen on PC screen. Below: Pipe Location Data taken at various depths.

A plastic pipe test bed was installed in a plot located within the confines of GTI's pipe farm. This plot had dimensions of approximately 50' x 100' and contained three plastic pipes of 2", 4", and 6" diameters. The lengths were of approximately 100 ft. with 12 feet of separation. The pipes were installed by the horizontal directional drilling method. The pipe was installed on a 5% grade: one end of the pipe is 5 ft. deep rising to zero burial depth. This produced a test bed that would allow for the testing of the CT sensor for a continuum of depths as well as pipe diameters. Each end of the pipe is capped off to prevent water incursion. The soil type is silty clay with concrete rubble at random.

An aluminum cart with oversize wheels is used to transport the test equipment on the test site. This arrangement is shown in Figure 10.

Figure 10. CT Equipment cart during a test in the sand pit.

Results and Discussion

Tests were performed in a 15' x 15' sand pit immediately outside the electronics lab. A 4" diameter 10' pipe section was buried on a slant with one end approximately 4' deep and the opposite end at the surface. The plan was to use the CT sensor frame to move the sensor across the length of the pipe and take data snapshots (using the above described VI) at uniform increments along the length of the pipe. This enables the user to simultaneously view data for multiple pipe depth measurements.

Figure11. Data Taken for various depths of 4" pipe in sand pit.

16 ELEMENT ARRAY

As mentioned the 4 element array was followed by a 16 element capacitive sensor array. Characterization work was performed on the new 16-element array. Two of the 16 elements were selected, wired, and driven in the same fashion, as was the 4-element array. One drive cable was connected to two 5-pf capacitors each connected to one of the sensor elements. Each sensor element was then connected to the National Instruments DAQ card. Sensitivity was established via the descriptive “hand wave test”. Initial results indicated that sensitivity was consistent with design expectations. At 4 inches a 250-mv differential was measured when moving a hand from in front of one plate to in front of the other plate. At 12 inches a 40-mv differential was observed for the same test.

A circuit board was designed that attaches to the 16-element CT sensor array and contain two 16:1 multiplexer chips. The board the interfaces the 16 sensor elements to the 4 analog inputs of the DAQ board. A 8 bit ttl address line is connected from the National Instruments digital output port to the address pins of the multiplexers. This allows for the rapid switching between sensor elements. A VI is presently used to manually select a particular sensor element. Currently work is progressing on a VI which will autonomously switch between sensor elements, in order to scan the ground underneath the array with minimal user input.

Fig. 12 shows the array, figure 13 is a schematic of the sensor drive electronics, figure 14 is a schematic of the sensor pick up electronics. Figure 15 shows the sensor positioned over a 6 inch plastic pipe in GTI’s test pipe bed. Figure 14 shows a typical data gathering session on GTI’s pipe test bed, the cart in the back ground contains a Dell work station, RF signal generator, and RF power amplifier.

Initial data sets were being taken at the time of this paper’s writing. Initial data was encouraging, but too preliminary to present. Software work on a scanning protocol VI is being constructed that will serve to automate the collection of data in the field, as well as to serve as the basis for an imaging capability.

Figure 12 picture of 16 element sensor array.

Figure 13, schematic showing electronic details of driving the sensor array.

Figure 14, block diagram indicating signal gathering and conditioning chain.

Figure 15 sensor array and instrumentation cart gathering data from buried pipe.

figure 16. Sensor_array positioned over a 6 inch plastic pipe buried 4 feet deep.

CONCLUSION

In conclusion this Capacitive Tomography project is well on it's way to demonstrating that under ground plastic gas line pipe can be detected and located both horizontally and vertically. We have demonstrated both with analog and digital electronics that a plastic pipe does generate a unique electronic signature that can be readily detected. Software instruments have been created to gather this electronic signature from the discrete capacitive elements. This software will serve as the basis for creating a imaging protocol.

3. REFERENCES

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