CAPACITIVE TOMOGRAPHY FOR THE LOCATION OF PLASTIC PIPE

QUARTERLY TECHNICAL REPORT

(July 1 through September 30, 2002)

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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.

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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 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

The new 16-element array sensor was designed and fabricated during the June - July time frame. This sensor array is 24" x 24" and is composed of 16 4.5 inch square sense elements embedded in a $\frac{3}{4}$ inch ground mesh. Each element is driven through a capacitor. Presently the drive capacitor is a variable capacitor of 1.4 - 5 pf. Ultimately, this could be replaced with a fixed value discrete capacitor, or a copper metallic strip attached to the back sensor of the array.

Fig. 1. 16-Element Capacitive Sensor.

Testing and characterization work proceeded with the 16-element array. Two array elements were originally connected to two 5-pf capacitors driven at 100 volts rms and 100 kHz. Good sensitivity was observed with a 250 mV signal at 4 inches and 40 mV at 12 inches from the sensor plates by the motion of a hand. Plastic pipe at 4 inches gave a 40 mV signal. Note that these observations were made in air; signal strengths are considerably better in soil.

Driving all 16 elements with $\frac{1}{4}$ inch copper strips connected to 5 pF caps resulted in a significant reduction in sensitivity. Explanation for this would be increased undesired cross coupling between elements. Using 1-5 pf variable capacitors as drive elements resulted in sensitivity numbers in line with those first mentioned above.

Fig. 2. Sensor RF Drive Circuitry.

An electronic breadboard was constructed using 216 to 1 multiplexers. The multiplexers allow any one of 16 sensor elements to be chosen with a 4-bit address bus. This address bus is driven from the digital output lines of the National Instruments data acquisition board. After debugging and optimal signal level was achieved the breadboard circuitry was transferred to a Vector circuit board so that it could easily be mounted to the sensor. Each element was connected through shielded coax to a 0.1-inch center standard header mounted on the Vector circuit board.

Fig. 3. Sensor Element Signal Pick Up Block Diagram.

Significant cross talk signal degradation was encountered when the multiplexer board was attached to the sensor array. Ultimately this was traced to the connector that interfaced the sensor element pickup cables to the multiplexer board. After much effort this problem was traced to the length of the sensor elements pickup cables. Each cable has a capacitance of 30 pf per foot with the shields connected to ground. Prior to the multiplexer, coax cables of 3-5 feet were used to connect each sense plate to the instrumentation. This created a capacitive path to ground through the coax shield that helped to keep the signals isolated from one another. When these lines were shortened to accommodate the multiplexer board this isolation was lost. Signals could very easily cross couple on the multiplexer pins thus corrupting the sensor elements sensitivity. Electronic buffering via discrete op amps was considered as a solution to the cross coupling problem. Instead, since reasonably clean and strong signal levels were achieved with the longer sense pickup cables, testing of the sensor array proceeded using these.

Experiments at GTI Buried Pipe Facility

Initial tests were conducted with the array placed directly on the surface of the soil over the pipe. The center eight sensor elements were addressed by the operator one by one and the signal level recorded. The sensor elements initial signal balance was controlled by adjusting the variable capacitor mounted over each sensor element. Inconclusive results were achieved, due to a non-uniform zero signal level across the sense elements. This issue in particular will need to be addressed and resolved in order to successfully specify the pipes location. At this time it was decided that it was of higher priority to conclusively establish the sensor's capability to detect and spatially localize the plastic pipe. Therefore the previously utilized procedure of mounting the sensor to a wooden fixture that can be uniformly slid along a 4 ft. x 8 ft. wood frame.

Fig. 4, 16 Element Capacitive Sensor Array

Fig. 5, CT Sensor Array Plastic Pipe in Background Exiting Soil

Fig. 6, Sensor Array and Cart with Drive and Processing Instrumentation

Given the problems associated with placing the sensor directly on the ground surface, the sensor was mounted on the wooden slider frame used previously and incrementally moved over the ground surface at a distance of two inches above the ground. Differential signal levels were manually recorded at 1-inch intervals for the center 8 sensor elements. Analysis of this data strongly indicated the sensor elements were able to detect the plastic pipe. This process was carried out to verify that the sensitivity of the array is uniform for all the elements. In the final application, the CT array will be stationary on the soil and the array elements scanned electronically to produce an image of the volume beneath the array.

In order to increase the efficiency of this process, a software VI (Virtual Instrument) was constructed that would automatically scan the designated sensor elements display this data numerically, graphically, and store the data on file for later analysis. Figure 7 shows the graphical interface this VI presents to the user.

Front Panel

Fig. 7, Front Panel Virtual Instrument for 16-element sensor data acquisition.

Fig. 8, Code for above data acquisition VI.

This new VI proved to be very helpful in rapidly acquiring data and the file storage capability allowed for the quick display and analysis in an Excel spreadsheet document. This VI can readily be expanded for the scanning of many more elements and also provides the ability to take advantage of all of Lab View's processing capabilities. The following graphs were produced using the above VI for the data acquisition and an Excel spreadsheet.

Figure 9 can be understood by noting that the small diagram of the 16-element array as part of the key to the graph. The numbering of the elements corresponds to the scan traces as designated in the trace key of the graph. The manner in which the data was collected is shown below. Initially the array is positioned as indicated. The center of the sensor array is initially 44 inches away from the pipe centerline. The sensor is then moved in one inch increments with a scan of the sensor signal levels executed at each increment, as depicted in Figure 10. Moving the array with respect to the pipe is a test of the array sensitivity, not the intended mode of use for CT as an imaging technology.

Plates 6 & 7 and plates 5 & 8 correspond to the blue and pink trace respectively on the graph. These plates sense the pipe first and record their strongest signal variance when the pipe passes under the point between plates 6 & 7. This is to be expected, as this is where the differential signal between the adjacent plates should be strongest. Figure 11 shows these two signals alone. The presence of the plastic pipe creates a very strong valley in both signals when it is below these sense elements.

Fig. 9 Detected Signals for 6inch plastic pipe at a depth of 4 feet.

Fig. 10, Diagram of data collection method.

Plates 3 & 6 and 4 & 5 corresponding to the yellow and turquoise traces respectively respond to the presence of the pipe. A strong signal variance for these sets of plates occurs at approximately the center of the array. The same pattern of signal variances occurs for plates 1 & 3 and 2 & 4 corresponding to the brown and purple signal traces just past the center of the array. As can be seen these peaks in the signal differentials occur at the same intervals as the plate separation of on the sensor.

Fig 11. Detail of Data showing Plastic Pipe Detected by Two Adjacent Sets of Elements.

Improvements to the Electronics

An effort was begun to reduce spurious noise caused by physical motion of the sense element coax feed lines and sense element coax capacitance loading effects. Electronic buffering was introduced between the sense elements and the electronic multiplexer chip. This was accomplished using a standard follower op amp configuration. This immediately improved the sensitivity of the sense elements by an order of magnitude by eliminating the large coaxial capacitance loading on the bridge arrays. This modification had the unintended effect of making the balance of the sensor array more difficult to achieve and maintain. It is not entirely understood why this behavior is occurring. The best explanation is that the coaxial cable capacitance had the effect of damping the sensitivity of the sensor elements. It may be necessary to add some of this capacitance back. This could be achieved by including a small variable capacitor between the input terminal of the op amp buffer and ground for all of the sense elements. Adjustment of this variable capacitor would achieve the best balance, between sensitivity and a robust bridge balance.

Fig. 12, Picture of current CT sensor with op amp buffers and multiplexers.

CONCLUSIONS

- The 16-element sensor array has successfully demonstrated the capability to detect and resolve plastic pipe for a range of pipe diameters and pipe burial depths. Plastic pipes 2", 4", and 6" in diameter have been successfully detected at depths of greater than 4 feet.
- An electronic buffering and multiplexer circuit board was constructed that enabled the rapid scanning of the sensor element signal amplitudes. This significantly improved sensitivity and the speed at which data can be taken.
- The sensitivity and signal to noise ratio of the 16-element array are sufficient that a 64-element array is feasible. The reduction in individual plate area to accommodate more elements will not degrade the system performance. Design studies for the 64-element array have been begun.

Work Performed in the 2nd Quarter of 2002

Task 1: Research Management Plan

Three Quarterly Technical Reports covering the period from October of 2001 through June 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

The sensitivity of the 16-element array was measured in single and multiple element drive configurations. Optimal drive capacitor values for the sense elements were also investigated. Measurements were taken both in an indoor laboratory setting as well as on the outdoor plastic pipe test bed.

Tests were done to determine the 16-element sensor’s capability to detect the presence of the 6, 4, and 2-inch plastic pipes at various depths. When optimally balanced the sensor was able to detect all of the pipes for the entire range of pipe depths. As expected signal levels were strongest for the larger diameter pipes and shallower depths. Signal levels fell off to the minimal levels for the 2-inch pipe at 4.5 feet.

Task 3: Design and Prototype Support Electronics

Two multiplexer circuit boards were constructed. The multiplexer was successfully integrated with Lab View operator interface. This interface enabled a rapid display and recording of sensor signal amplitudes. The second multiplexer board incorporated op amp buffers on the sensor elements, which significantly raised the sensor sensitivity.

Buffer and multiplexer interface board was consolidated onto a single circuit board and mounted directly to the center of the backside of the sensor array.

Task 4: Construct Field-Ready Mat Prototype

A 64-element sensor array design has been initiated. It will consist of a 2 to 4 layer board. This sensor will incorporate sixteen quad buffer op-amps, four 16 to 1 multiplexers, and printed circuit capacitors integrated into the board design to replace the discrete drive capacitors in the present design.

Significant additions and improvements to the LabVIEW user interface were performed. With one click of the mouse the user can start a sequential scanning of the sensor elements signal amplitudes. These signal are then graphically displayed. Additionally the data is stored on file for later analysis by a spreadsheet or MATLAB type analysis package.

Task 5: Demonstrate Mat Prototype

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

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 Planned For The 4th Quarter Of 2002

- Improve the sensitivity and resolution of the 16-element array. This may involve the design and fabrication of a custom circuit board to perform the buffering and multiplexing operations.
- Perform field tests for the detectability of metallic pipes by the 16-element sensor.
- Perform tests of 16-element array at varying frequencies to demonstrate depth-sensing capabilities.
- Develop an algorithm to assemble the array data taken at various frequencies into a color-coded image that displays the depths of various features beneath the array.
- Conclude the 64-element sensor array design studies and fabricate the printed circuit board.

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
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

Capacitive Tomography for the Location of Plastic Pipe

Christopher Ziolkowski
Brian Huber
September 16, 2002

Program Objective

- Develop a sensing system that can image plastic, ceramic, or metallic piping through common soils

Key Technical Issues

- Plastics require new methods of subsurface location and imaging
- The installed base of plastic piping is on the increase
- Low-dig installation and repair methods require precise location of facilities

Why Capacitive Sensing?

- Will sense objects with different dielectric properties than soils – not specific to metals.
- Very simple flat plate sensing array.
- One sensor array is operable over a wide range of frequencies.
- Plate spacing, not frequency determines resolution.

Simple CT Has Been Demonstrated

- A two-plate capacitive bridge sensor located plastic pipe in a GTI supervised test.
- The device was about the size of a lawn mower and was moved by the operator to scan the area.
- This device was demonstrated by J. Tuttle of the Aberdeen Proving Ground.
- The basic patent is assigned to the U.S. Government.

Equivalent Circuit from Tuttle Patent

Scope of Work - Tasks

- 1. Research Management Plan
- 2. Design and Prototype Sensor Array
- 3. Design and Prototype Support Electronics
- 4. Construct Field-Ready Mat Prototype
- 5. Demonstrate Mat Sensor Prototype

Task 1. Research Management Plan

- Research Management Plan
- Kick-Off Meeting – November 2001
- Technology Assessment
- Three Quarterly Technical Reports
- Three Presentations

Task 2. Design & Prototype Sensor Array

- The initial array was 4 elements for proof of concept.
- Higher order arrays can readily be fabricated using circuit board technology
- GTI is currently working with a 16 element array.
- Flexible circuit board technology will be evaluated for applicability

CT Detail of One Electrode Pair

Task 3. Design & Prototype Support Electronics

- The 4-element array was tested with bench electronics.
- Higher order arrays require multiplexing in order to keep cost & complexity down.
- All signal processing will be at low frequencies, reducing hardware cost & complexity.
- Use LabVIEW front end to keep GUI cost & development time under control.

Multi-Element Array

Task 4. Construct Field-Ready Mat Prototype

- The sensor & support electronics must be field-hardened sufficiently for field testing.
- Power consumption must be managed for good battery life.
- Connector systems for field use require special attention.
- In general, the package must make a good impression on the field crews, even at the prototype stage.
- This unit will be tested on GTI pipe farm prior to any public demonstration,

Task 5. Demonstrate Mat Sensor Prototype

- GTI will schedule and coordinate a field test with a gas distribution utility.
- Several of our utility contacts have demonstrated interest in hosting a test.
- GTI personnel will transport, set-up, and demonstrate the mat sensor prototype.
- GTI will collect and report feedback from the field crews.

Task 2 Progress with 4-Element Array

- Several 4 element arrays have been fabricated.
- The instrumentation to evaluate these arrays was primarily analog.
- The array demonstrated sensitivity to PE in the lab.
- As predicted, the sensitivity was even greater with PE in the indoor soil box.

4 Element Array Fabricated on PC Board

Laboratory Set-Up to Evaluate 4-Element Array

PE Pipe Beneath Array

View of Array on Indoor Soil Box

Close-up View of Array on Slider

Task 2 Progress with 16-Element Array

- Several 16 element arrays have been fabricated
- The instrumentation to evaluate these arrays is primarily PC based due to the need for multiplexing
- The sensitivity to plastic pipe is still very good with the smaller size of individual elements

A 16-Element Array Fabricated on PC Board

16-Element Array and Multiplexer Under Test

Task 3. Progress – Support Electronics

- Analog support electronics was used for initial tests of 4-element array.
- LabVIEW is being used to test signal processing and develop graphical user interface.
- A multiplexer was constructed to interface the 16-element array to the PC.

Data Acquisition Station running LabVIEW

Sensor Array & Multiplexer tested on Pipe Farm

Task 4. Progress on Field-Ready Prototype

- An area of the GTI Pipe Farm has been set aside for this project.
 - Three, 100' runs of PE pipe were installed.
 - The PE pipes are 2", 4", and 6" in diameter.
 - Burial depth varies from 5' to 0' over the length
- The excitation drive circuitry has been modified to minimize the size and power consumption.

Installation of PE Pipe for CT Experiments

Detail of Drive Circuitry

Detected Pipe Signal Levels

SIX INCH PLASTIC PIPE AT DEPTH OF 4 FT.

Summary

- CT can detect plastic pipe in wet soils.
- Resolution is limited by electrode size, not wavelength, unlike GPR.
- The sensor was successfully transitioned from 4 to 16 elements.
- The signal to noise ratio is sufficient to make the elements smaller still.

APPENDIX B

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

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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.

1. 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 permittivities 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.

Figure 11. Data Taken for various depths of 4" pipe in sand pit.

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.

REFERENCES

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