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.

Twelve months will be required to produce a prototype imaging system consisting of a flat sensor that can be laid on the ground to scan the volume immediately beneath it. During the first 3 months of the project a 4-electrode array was fabricated and tested. This array, as described in the first quarterly report, was able to detect the position of a plastic pipe in air. This second quarterly report covers months 4 through 6 of the project. Experiments with the plastic pipe buried in soil are cover in this report.

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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 during the final quarter of 2001 was to replicate these results with up-to-date equipment. To this end, a 4-element capacitive array was constructed and tested using standard laboratory instruments for electronic support. This setup was shown to be sensitive to the location of plastic pipe, but required some refinements. This report details these refinements and experiments with pipe in soil.

EXPERIMENTAL

Refinement of Experimental Setup

The major work focus for January was removing a common mode voltage problem, optimal balancing of the bridge, and realistic testing of the sensor on plastic pipe in soil. The four-element bridge was configured with two discrete capacitors as the two top drive elements in the bridge and the bottom elements being the sensor plates on the printed circuit board (PCB). The typical drive signal was 100 kHz at 100 VAC rms. Voltage measurements across the bridge elements were taken in order to determine the voltage distribution ratios. Maximum sensitivity occurs when the bridge is operated close to the balance point. Thus there would need to be 50 volts across each of the bridge elements for optimal bridge sensitivity. Referring to Figure 1, discrete capacitor values C1 and C2 were adjusted to give a fifty-volt drop.

Figure 1. Patent Diagram from “Buried Pipe Locator Utilizing a Change in Ground Capacitance”

The common mode voltage issue needed to be resolved as a part of optimal bridge balancing. The majority of operational amplifier circuitry needs supply voltages in the plus or minus 20-volt range. Differential signals that were in the 40 mV to 500-mV range were being detected across the bridge. This small differential signal was on top of the 50-volt common mode bias signal. Distortion would occur when the detected signal was input to the AD621 first stage instrumentation amplifier. This occurred because the 50-volt common mode signal voltage exceeded the supply voltage to the instrumentation amplifier.

Several alternative circuit designs were tried to remove the common mode voltage with various levels of success. A small toroidal pickup transformer was constructed and the primary tied across the midpoint of the bridge. The secondary was then tied across the input to the AD621 instrumentation amplifier. The common mode voltage problem was solved by this modification, but noise and desensitization of the bridge were unacceptable. Consideration was also given to using high voltage bipolar or mosfet transistors to level shift the signal. A flying capacitor type of topology was also considered.

A Burr Brown INA 117 difference amplifier was a workable solution to the common mode voltage problem. This op amp utilizes a balanced high precision resistor network that enabled it to handle common mode voltage up to 200 volts. Using this part as the first stage in the signal conditioning electronics resulted in a reduction of the common mode voltage to within the range of the instrumentation amplifier used to produce the difference signal. The INA 117 also produced a large improvement in the signal to noise ratio.

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.

In March, an intermediate frequency (IF) transformer was constructed as another means of addressing the common mode voltage. 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. This arrangement eliminated the need for an INA 117 amplifier for each channel. 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.

From this point extensive testing and refinement of the sensor and the associated electronics took place. Various cabling and grounding arrangements were evaluated in order to minimize signal losses and noise sources. Discrete resistors and a multi-turn potentiometer were used instead of discrete capacitors to drive the sensor. This was done in order to make it easier to balance the bridge. Static electricity is an issue since residual charge on the sensor plates result in a dc offset on the conditioning circuitry. Using resistors rather than capacitors gives the static a discharge path

Various modifications to the PCB sensor were tried. Various means of focusing or directing the field lines were considered and attempted. Copper tape strips, driven from a high impedance voltage source, were placed around the sensor plates in order direct the electric field lines out perpendicularly away from the plates and to minimize fringing effects. These modifications resulted in marginal improvements in the spatial sensitivity.

At the end of January 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 2, enables repeatable experiments by holding constant the separation between the ground surface and the surface of the sensor.

In February the work focused on confirming and extending the initial soil pit lab test results. 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 the sensor was centered directly over the plastic pipe.

Figure 2. Close up of sensor on sliding frame

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.

Transitioning to Digital Instrumentation

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. Dell workstation was purchased with a 2.2 GHz CPU, a SCSI hard drive interface and a second dedicated hard drive for data storage. LabVIEW 6.1 Professional and MatLab were installed.

The present plan is to interface each of the four sensor plates of the capacitive sensor to each of the four analog channels of the DAQ. A LabVIEW Virtual Instrument (VI) will be constructed to allow the sensor signal data to be digitized and streamed to the hard drive in the PC. Going into the future it is anticipated that a 16-element sensor will be fabricated. A four to one multiplexing will be implemented to map the 16 array plates to the 4 DAQ analog channels. Multiplexing of the sensor data will either be achieved through a discrete chip analog multiplexer or a PCI based multiplexer board.

Initial development of the VI for the NI 6115 DAQ went forward in March after the 6115 arrived and was installed in the workstation. Evaluation of possible data acquisition and processing algorithms has begun. The board and software drivers were installed and initial tests were performed to verify operation. Various LabVIEW VI's were loaded and the DAQ was tested with these VI's with a 100 kHz signal input. Stream to binary read and write VI's were tested. Various scan rates and data refresh rates were tried to find the optimal settings for good signal representation. Various data storage protocols were examined for their efficiency, speed, and readability. Storing the captured data to spreadsheet format allows one to export the data to third party applications such as Excel and MatLab. The stream to binary data storage protocol is fast and efficient, but currently only Lab View can read this data.

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.

RESULTS AND DISCUSSION

Initial results from the indoor soil pit testing were very encouraging. A very 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 5. 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. This result is in direct agreement with the predicted conclusions of the last quarterly report.

Figure 4. 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 5. 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 5 was generated from this type of configuration.

Another configuration consisted of the four square sense elements configured as two half bridges, driven by two discrete 10 k ohm resistors. Each adjacent pair of plates makes up the two halves of a sense capacitor. One plate is driven and the other forms the return path for the excitation signal. The square perimeter plate connected as a guard electrode, to confine or reduce the electric fringe fields. A graph of signal voltage versus position is shown in Figure 6 for this arrangement. A close examination of the data around the zero horizontal displacement point shows some indication of signal lobes associated with the sensor plates. As would be expected a maximum is found at approximately the center of one of the sensor plates at -6 inches. A local

minimum is seen at the zero point, but the expected maximum at +6 inches is not symmetrical with that seen at -6 inches.

Figure 6. 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.
- 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.

Work Performed in the 1st Quarter of 2002

Task 1: Research Management Plan

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

Task 2: Design and Prototype Sensor Array

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

Task 3: Design and Prototype Support Electronics

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

Task 4: Construct Field-Ready Mat Prototype

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

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 2nd Quarter Of 2002

The following items are planned for the next quarter:

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

REFERENCES

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

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

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

LIST OF ACRONYMS AND ABBREVIATIONS

CT - Capacitive Tomography
COR – Contracting Officer’s Technical Representative
DOE - Department of Energy
FERC – Federal Energy Regulatory Commission
GPR – Ground Penetrating Radar
GRI – Gas Research Institute
GTI - Gas Technology Institute
IGT – Institute of Gas Technology
IRNG –Infrastructure Reliability of Natural Gas