

# **FINAL RESEARCH REPORT**

**By**

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## 1. ABSTRACT

This research project focused on two specific work related hazards of pipe installation, cave-ins and underground utilities. Both thrusts addressed the problems through technological interventions. This final report presents an exciting and successful endeavor that produced tangible results ready to be deployed in the field to save lives and increase productivity at the same time. The following will briefly discuss the most significant accomplishments.

Even though diverse support systems such as shoring, shielding, and sloping are to be applied during trench excavating and pipe laying operation, accidents still occur. The underlying concept for finding a remedy for this problem is to remove the need for people to enter the confined space through the use of a tele-robotic approach. In response to the many complexities in installing pipes of various types, two separate mechanisms were designed, fabricated, and field tested. While both were invented as attachments to backhoe excavators or cranes, the first device, labeled PipeMan, is capable of handling large and heavy concrete pipes used to build drainage systems. The second, called PipeMan Jr, is tailored to manipulate lighter but longer water or sewer pipes built with O-ring gasket joints also called push-on-joint type seals. PipeMan and PipeMan Jr each required a uniquely different technical approach to create a safe alternative to the present hands-on method. Tele-robotic systems are mechanical devices that combine human and machine intelligence to perform a task remotely with the assistance of various sensors, computers, man-machine interface devices, and electronic controls. The last generation of PipeMan utilized a fork and clamp system leading to a field assessed cycle time for laying one pipe segment of 3.6 min. Moreover, a crew of 3 is able to perform pipe installation instead of the conventional 5, which drastically increases productivity. It is estimated that Pipeman would be to lay 70 pieces of 8 ft (2.4 m) pipes per day if laid consecutively into an open trench.

Because of the requirement to apply significant normal forces for jointing pipes with O-ring gaskets the simple “push” approach of PipeMan was ineffective. PipeMan Jr draws on four key enabling technologies: 1) A hydraulically powered pipe-jointer, 2) compliant pipe carrier, 3) two powered struts to adjust the position of the pipe-end in x and z directions, and 4) wireless control interface for the operator. PipeMan Jr. was also repeatedly field tested with actual equipment operators performing the tasks.

Currently trenching contractors have to rely on color-coded markings applied by utility locators to know where utilities are buried in the ground. As accidents prove time and time again, this method is unreliable. The second main thrust of this project was to study the effectiveness of non-intrusive sensing systems to detect and locate buried utilities of all types, especially non-metallic plastic pipes. Furthermore, the final technology should be equipment-mountable and function like a fish-finder.

The Buried-Utility-Detection-System (BUDS) uses a multi-sensory approach to underground sensing. It is believed that more reliable results are possible because it decreases the degree of ambiguity and increases the probability. One example is the integration of the Electro-Magnetic-Induction (EMI) with spatial data from an actuator carrying the sensing antenna termed the Equipment-Mounted BUDS (EM-BUDS.) Software was programmed to control the manipulator while, in parallel, collecting and processing sensory data. A unique human-machine interface uses the manipulator as a “pointing stick” that tells the operator not only that there is a buried pipe but also where its approximate location is. This system was tested in the field.

Extensive experiments were conducted with Ground-Penetrating-Radar (GPR) technology since it promised to detect even non-metallic objects. Combined with the EMI and mounted on a mobile platform it was indeed able to distinguish between buried concrete with and without steel rebar.

The most critical progress in our ability to detect underground utilities was made in improving the effectiveness of processing GPR data. By using a wavelet based approach to filtering raw data from the GPR sensor we were able to make drastic advancements in pinpointing the location of buried pipes made of different materials.

A large pipe-laying project in connection with a new Chilled-Water facility on NC State's campus provided the testing ground for many of the technologies developed for this project. The most dramatic opportunity was to compare our utility sensing results with the actual situation found during trench excavation. It is anticipated that the analysis of the collected data will continue for years to come due to the fact that so much of it was collected during the extensive pipe-laying project.

## **2. HIGHLIGHTS/SIGNIFICANT FINDINGS**

The significance of the work presented in this report lies in four innovative technologies that have been designed, built, and tested in the field of construction. Two of the technological interventions replace the human laborers in a confined space with a tele-robotic device while, at the same time, increase the productivity of pipe-laying. The second set of innovations drastically advances the technological tool-box a pipe-laying contractor can deploy to detect and locate buried-utilities before and during excavation.

Two types of tele-robotic pipe manipulators were tested: 1) PipeMan handles large concrete pipes and 2) PipeMan Jr able to install long but small diameter pipes with O-ring gasket joint seals.

The work on improving underground utility detection technology resulted in an equipment-mounted device capable of sensing as well as physically pointing at the location of any metallic object within its area of influence. In tandem with this device, a drastic improvement in identifying the existence of any type of underground utility was made by processing GPR data with a wavelet-based filtering software.

## **3. TRANSLATION OF FINDINGS**

The developed and tested technologies are ready to be transferred into the industry. What is necessary are manufacturers willing to build and market the devices.

## **4. OUTCOMES/RELEVANCE/IMPACT**

This project proved the functionality and economic value of two sets of technological interventions designed to: a) eliminate deaths through cave-ins and b) drastically reduce accidents caused by damaging buried utilities during excavation.

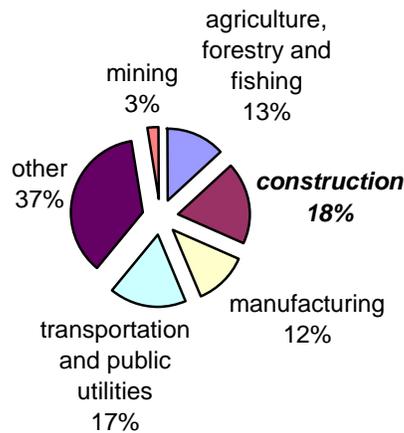
## **5. SCIENTIFIC REPORT**

### **5.1 Background**

Safety has become a major concern in the construction industry over the past few decades. According to the Bureau of Labor Statistics (1999), in 1997 there were 1,137 deaths in the construction industry. This number equals 18% of the total fatalities from all industries and indicates that construction has the highest number of fatalities as shown in Figure 1. Another source shows that the construction industry employed approximately 5% of the industrial work force, but generally accounted for nearly 20% of all accidental deaths

The reasons for the poor record for safety in the construction industry as compared to the manufacturing industry can be summarized as follows:

- 1) Large number of project participants opening the door for miscommunication (as shown by many accident reports.)
- 2) Lack of reliable and complete information about underground facilities that have been put in place decades or even centuries ago
- 3) Constantly changing and sometimes unpredictable working environment (e.g., soil conditions)
- 4) Increased complexity of the underground space as more facilities are being put underground.
- 5) Lack of technologies that can be used to do the difficult work of installing a large variety of pipes remotely.
- 6) Lack of reliable technologies that would enable the contractor to conduct his own investigation as he digs into the subsurface with his large equipment.



**Fig. 1. Industrial Fatalities (1997)**

A way to prevent construction accidents is to provide safe work environments and to establish safe systems of work. An analysis by the National Institute for Occupational Safety and Health (NIOSH) of workers' compensation claims for 1976-1981 shows that excavation cave-ins were the cause of about 1,000 work-related injuries each year. Of these injuries, 140 resulted in permanent disability and 75 in death.

Whether installing new utility lines or repairing old pipes, the process of excavation is an important component of civil infrastructure. However, because of the lack of information associated with the exact location and orientation of buried utility lines, there are many problems that arise due to line damage. Some of the construction dangers are fatal. Rupturing a gas pipe or large water main are too often examples of the potential dangers involved. People who rely on utility lines for life survival (dialysis machines or heart monitoring, for example) are gravely impacted by utility downtimes.

Hence, detection of a buried utility pipe is of utmost importance in excavation. Because the pipe may have been placed in a location that is different from the site plan or due to shifts in the ground, the exact location and orientation of a buried pipeline may be difficult to find. Abandoned utility lines and equipment that may be difficult to use also increase the number for mislocated utilities. The present method of utility location is the One-Call System. In the One-Call System, prior to digging, the contractor will call One-Call and then the utility owners will be notified. The utility owner will then send out a locating crew that will "mark out" the area where utilities are buried. The locators use various tools to locate the utilities including tracer wire locators, acoustic sensors, and ground penetrating radar. The tracer wire is the most common method. There are many mistakes associated with the markings which are due to a wide range of problems including workers not using the equipment correctly, marks being removed between the time the spot is marked and the time when the excavation occurs. Other reasons come from unexpected methods of utility placement including butt splices and looping. One way to circumvent these problems is to add an additional layer of protection and that is to place a sensor on the excavator to allow the operator to make a final scan of the area while digging. This layer doesn't eliminate the need for pre-dig location, but allows for a second check to determine if any mistakes were done.

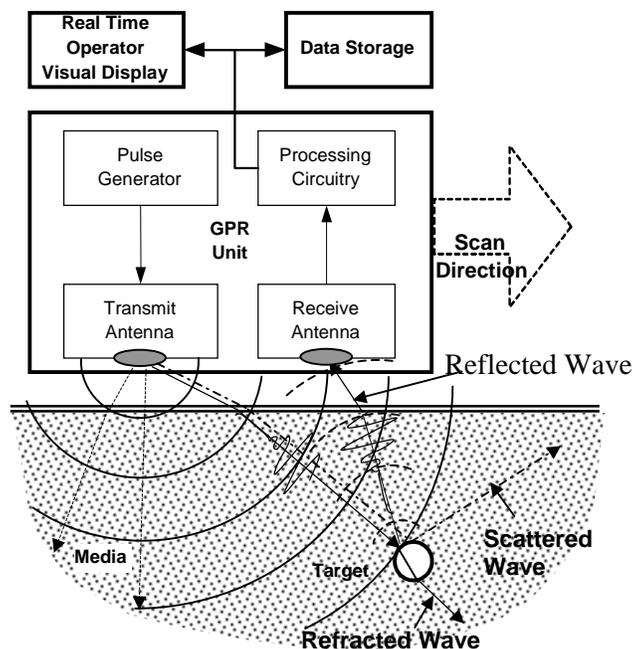
Trenching and pipe-laying are, without a doubt, some of the most dangerous operations in construction. Electro-mechanical devices that are able to reduce or eliminate the exposure of humans to these risks have the highest potentials to change the present situation.

## 5.2 Results that Address the Specific Aims

The following section will discuss the results of this project organized according to the 8 Specific Aims.

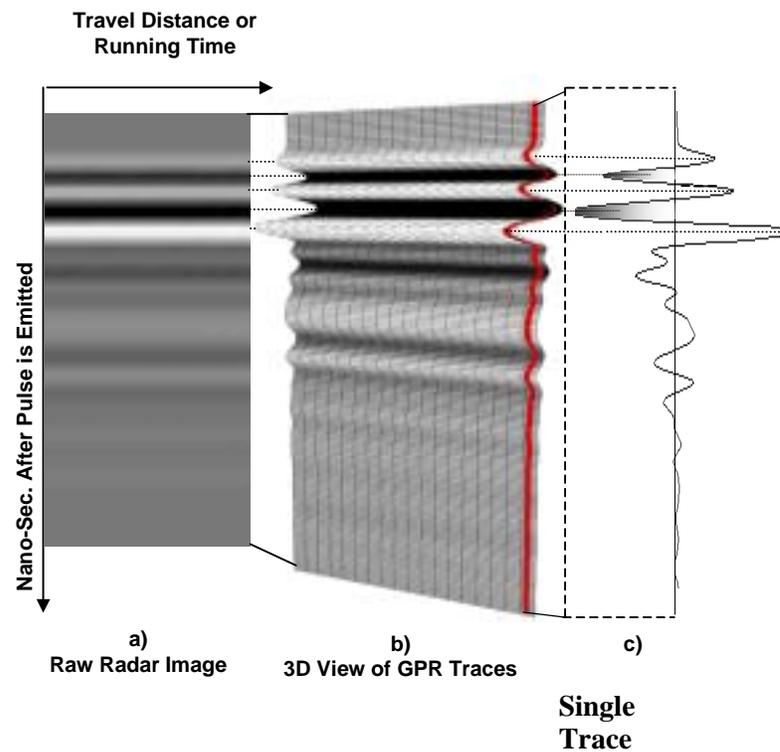
### 5.2.1 AIM 1: Address the need of detecting non-ferrous buried utility lines such as plastic and concrete pipes.

A main part of the project effort went into addressing this specific aim by experimenting with a Ground Penetrating Radar (GPR). Fig. 2 presents the key elements of a GPR unit: 1) Pulse Generator, 2) transmitter, 3) receiver antenna, and 4) processing circuitry. The main component of the Pulse Generator is a power source capable of transmitting an electrical signal with high peak voltage and short time duration. This signal is used to produce a non-sinusoidal electromagnetic (EM) pulse, which can be represented as a Gaussian waveform. The energy from the EM pulse is radiated outward in straight lines from the Transmit Antenna and reflected back towards the receive antenna by any media and/or targets in the transmission path.



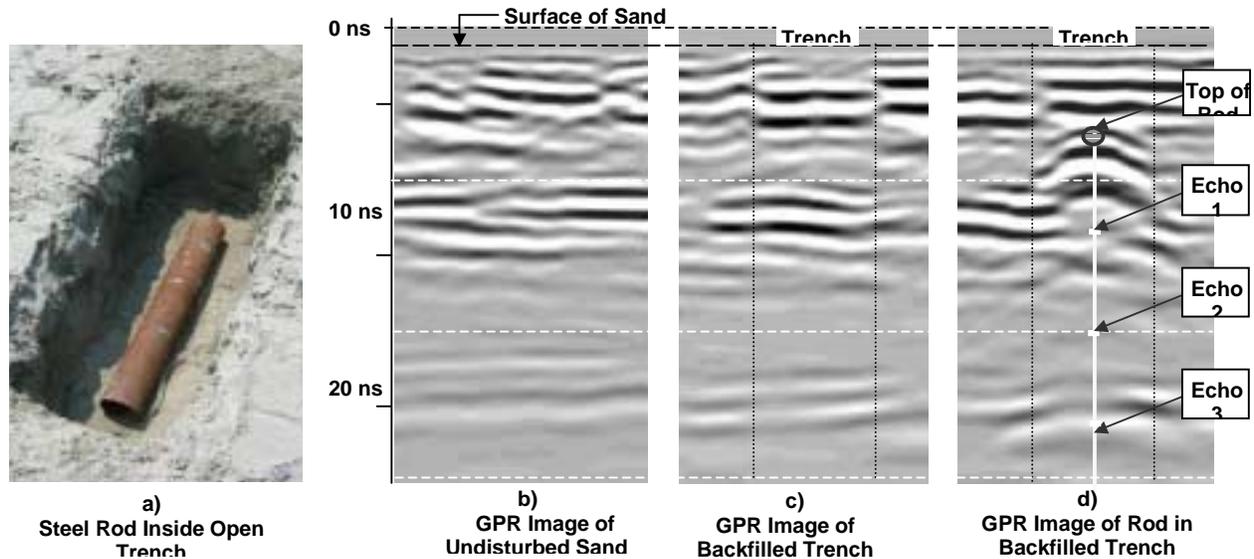
**Fig. 2.** Schematic of UWB impulse GPR unit and diffraction mechanism

Fig. 2 also highlights the three main scenarios of wave behavior. While certain pulses are being reflected back to the receiver, others are being scattered and refracted. The echo captured by the receiver is called a trace and represents the cumulative reflections over a short period of time (e.g., nanoseconds) in time after a pulse was launched from the transmitter. Fig. 3 presents the result of scanning across a homogenous half-space with a constant material property



**Fig. 3.** Three views of radar trace profiles in homogenous material

However, the world's underground is seldom homogenous especially in areas that have been “transformed” by humans. Layers of sands, clays, gravel, are mixed with stones, tree roots, construction debris, and of course, utilities of all kinds. The resulting radar images show streaks of black and white bands in various forms and shapes, magically split and joined at all angles. Sometimes, however, unique features appear such as the hyperbolically shaped stripes, shown in Fig. 4 d), which were created by the reflected pulses from a 2.5 inch (6.4 cm) diameter steel rod buried in 1 foot (30.5 cm) of sand.

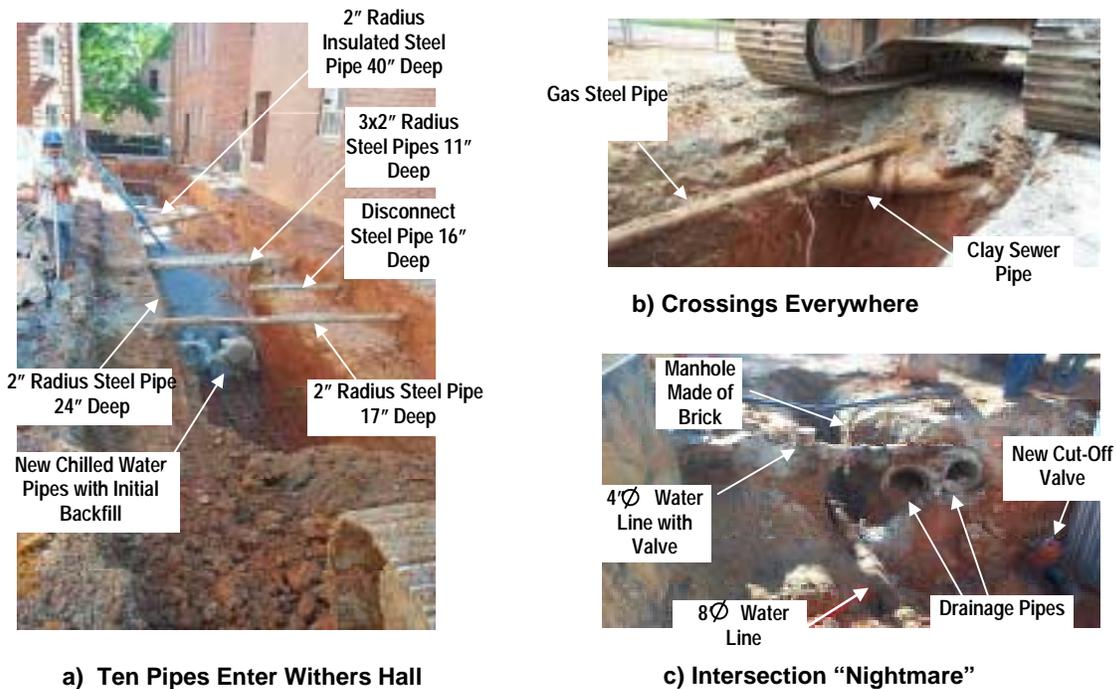


**Fig. 4.** Field tests with GPR in beach sand

While such a unique feature is readily recognizable within a semi-homogenous beach sand, smaller size objects within a messy subsurface are extremely difficult to discern. As a consequence it is desirable to remove, or filter, the effect of clutter on a GPR data set. The term clutter, often referred to as background, refers to any portion of a GPR trace that is unrelated to a target. The use of clutter suppression techniques allows persons who have never before worked with GPR data to identify targets that would normally be obscured. The clutter suppression methods presented in this paper are: 1) mean background trace subtraction (MBTS), 2) matched filter deconvolution (MFD), and 3) translation invariant wavelet packet decomposition (TIWPD). While MBTS and MFD are used to simply enhance the visibility of targets, TIWPD is used to reduce clutter by nullifying target-free GPR traces.

Over the course of the last decade a variety of signal processing routines have been developed and tailored for use with GPR. The goal of all these methods is to suppress background noise (or clutter) since it obscures a target's visibility.

In addition to test GPR in clay it was found necessary to use data from an urban setting where the underground has been previously disturbed. For this purpose, the research team collaborated with a pipe-laying contractor working on a new Chilled Water plant at NC State University that required the installation of a pipe system to circulate the water between the many buildings and the plant. This large scale excavation effort provided an excellent opportunity to collect real world data especially since the subsurface of a college campus contains a complex network of utilities both in use and abandoned. Due to the recognized importance of improving the technologies for locating underground utilities all of the involved agencies and companies agreed to let us scan the subsurface before excavation and identify the type, size, and the exact location of the exposed utilities after the trenching was complete. Fig. 5 presents three representative views open trenches with many invisible surprises.



**Fig. 5.** Exposed utilities during trenching operations on the NCSU campus

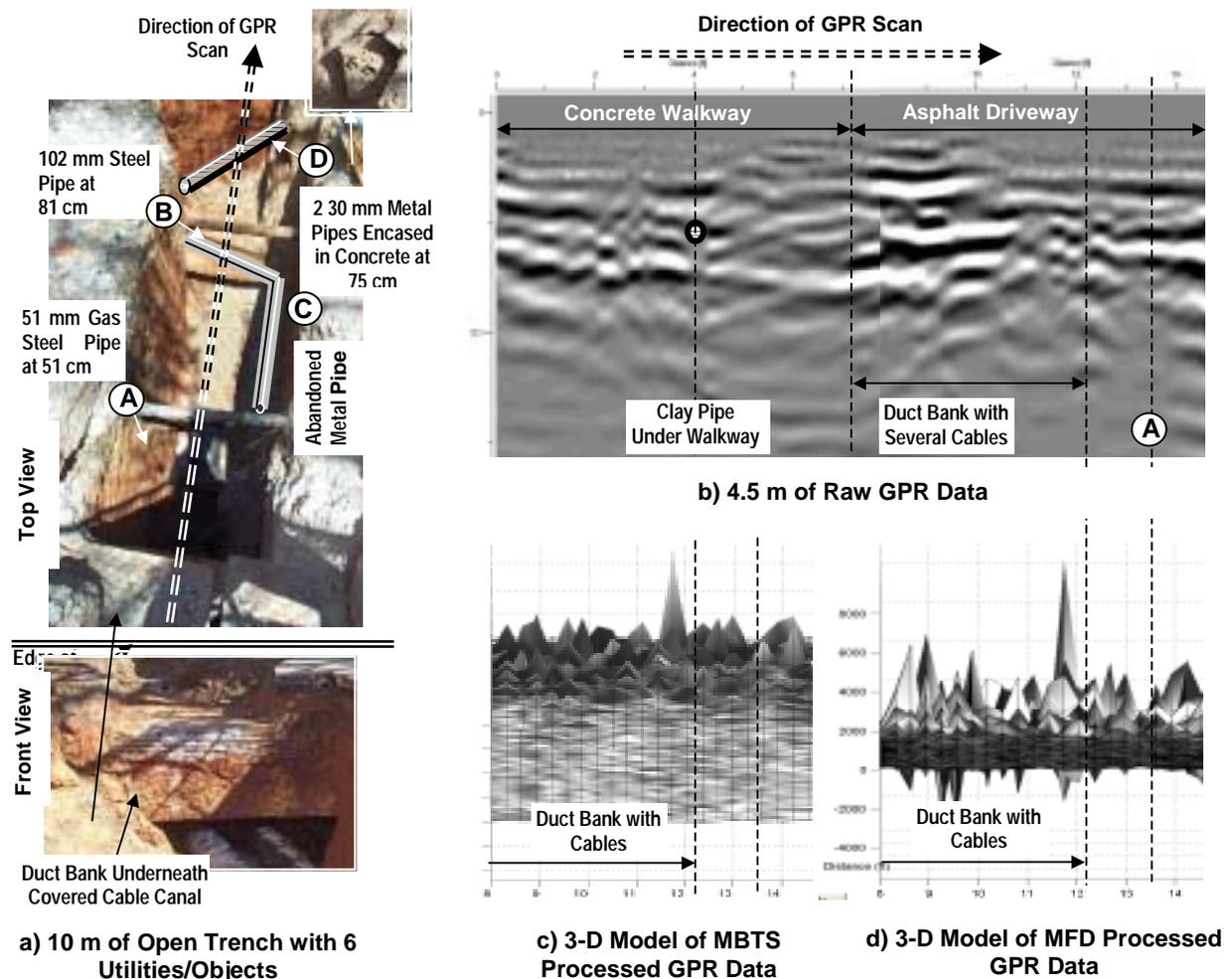
By observation (in color), one is able to recognize that the predominant soil found on campus is red Piedmont clay that made North Carolina the largest brick-producing state in the Nation. Buried pipes are made of a variety of material such as bore steel, ductile iron, terracotta, plastic, and concrete. The size varies from 1 inch (2.5 cm) to 2 ft (61 cm) diameters. In addition, one finds cables of all kinds. Another source of confusion are the many abandoned lines that nobody can identify and lay next or over "live" lines. Furthermore, the as-built drawings are outdated and mostly incorrect.

Prior to the start of the excavation, the subsurface to be trenched was scanned with a MALA Geoscience RAMAC/GPR with shielded 500 MHz antenna mounted on a mobile cart while the distance from the start was measured using an encoder attached to a wheel. It is interesting to note that, as the research team became more effective in interpreting the GPR data, the excavator foreman started to request that the team to mark their predictions on the asphalt.

The data collected during each scan, GPR traces and traveling distance, was stored on a laptop and processed in the office using the three filtering methods. As the excavating crew opened the trenches to visual inspection the unearthed utilities were photographed and their size and burial depth recorded. Unfortunately, utilities that had been previously abandoned were destroyed in the process. As a consequence, the visual inspection of the trench walls became an important step since they indicated where pipes or cables had been broken off. After a while, the excavator operator kept pieces of the destroyed utility for the research team to examine.

### Analysis of GPR Data from Disturbed Clay

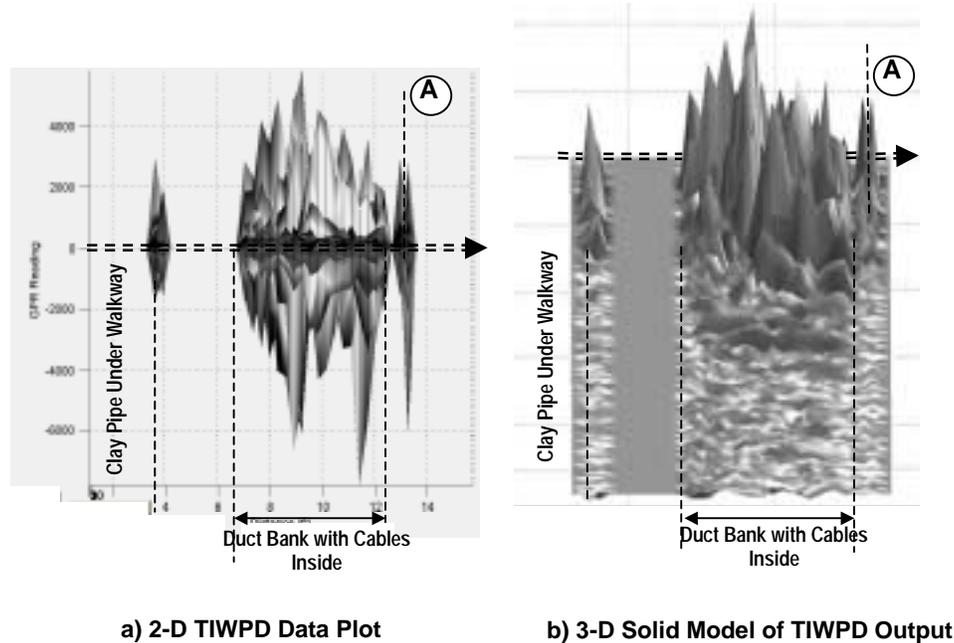
The GPR data sample used for this analysis was generated during the start of a scan behind Withers Hall, shown in Fig. 9 a). As the open trench in Fig. 10 a) shows the selected 10 meters contained a multitude of buried objects among them a terracotta pipe (not shown in picture), a concrete duct bank, and various pipe sizes at various depths. The utilities labeled C and D were destroyed during excavation but were drawn into the photograph for clarity. Indicated in the Figs. 6 a) and b) is the direction of the GPR scan which started approximately 1.8 m (6 ft) before the buried duct bank at the edge of a concrete walkway.



**Fig. 6.** GPR data from test area

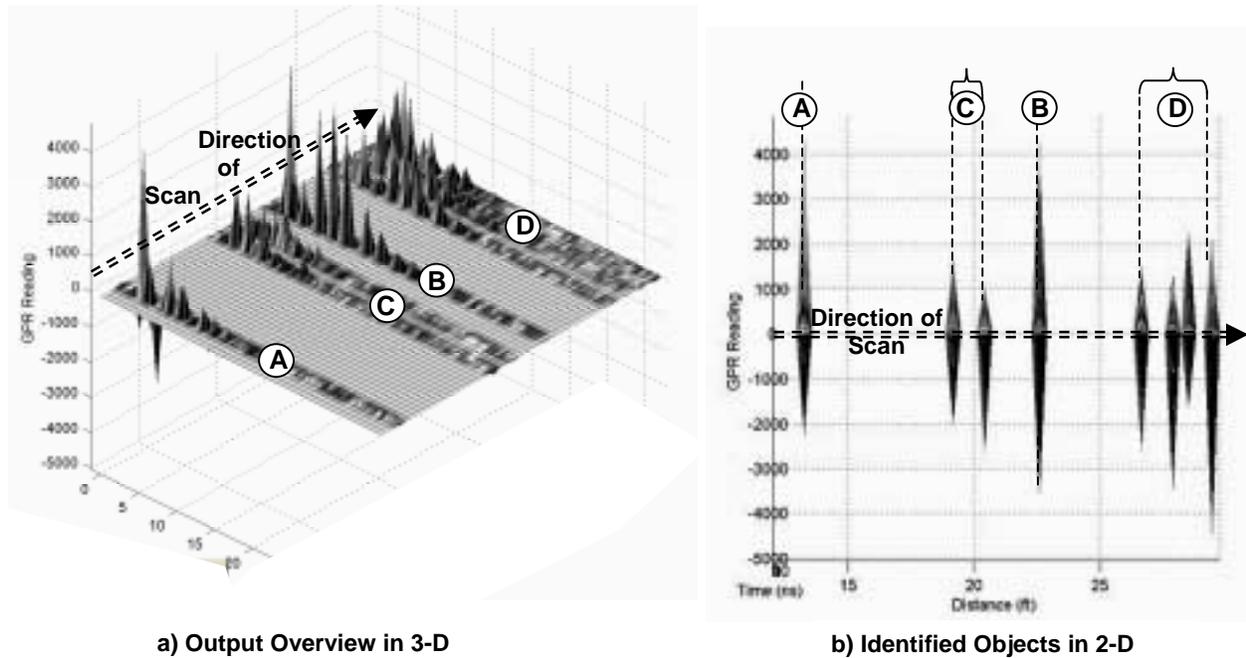
A comparison between the GPR data collected on the beach, shown in Fig. 4 b), and the path behind Withers Hall emphasizes the effect of a non-homogenous subsurface on the data. Without the a priori knowledge of what is buried where, it would be impossible to recognize the presence of objects. The same holds true after the raw data is filtered using the MFD and the MBTS methods both depicted in a 3-D view in Figs. 10 c) and 10 d). The usefulness of the MBTS and

MFD methods lies in their ability to reduce background noise by averaging  $N$  traces. However, the removing of background noise also lessens the already weak target signatures. As a consequence, duct bank as well as pipe A are impossible to be determined with accuracy. This situation changes drastically with the use of the TIWPD filtering method.



**Fig. 7.** The magic of TIWPD filtering

The difference in the meaningfulness of the data plots shown in Fig. 7 is self-evident. Both, in 2-D and the 3-D, the graphs clearly indicate the location as well as the boundaries of the objects. Most surprisingly, even the clay-pipe underneath the concrete walkway was clearly identified. Similarly, pipe A shows up separate from the duct-bank while the cables and pipes inside the duct, which could not be inspected, left their fingerprints on both plots. Fig. 7 b) gives a clear indication of the bottom of the concrete duct which could be turned into meters and feet if the velocity of the radar pulse could be determined. Because of the effectiveness of the TIWPD filtering method, only its results after processing the remaining data set will be discussed. First, Fig. 8 presents the outcome of filtering the residual GPR data collected in the 10 m section.



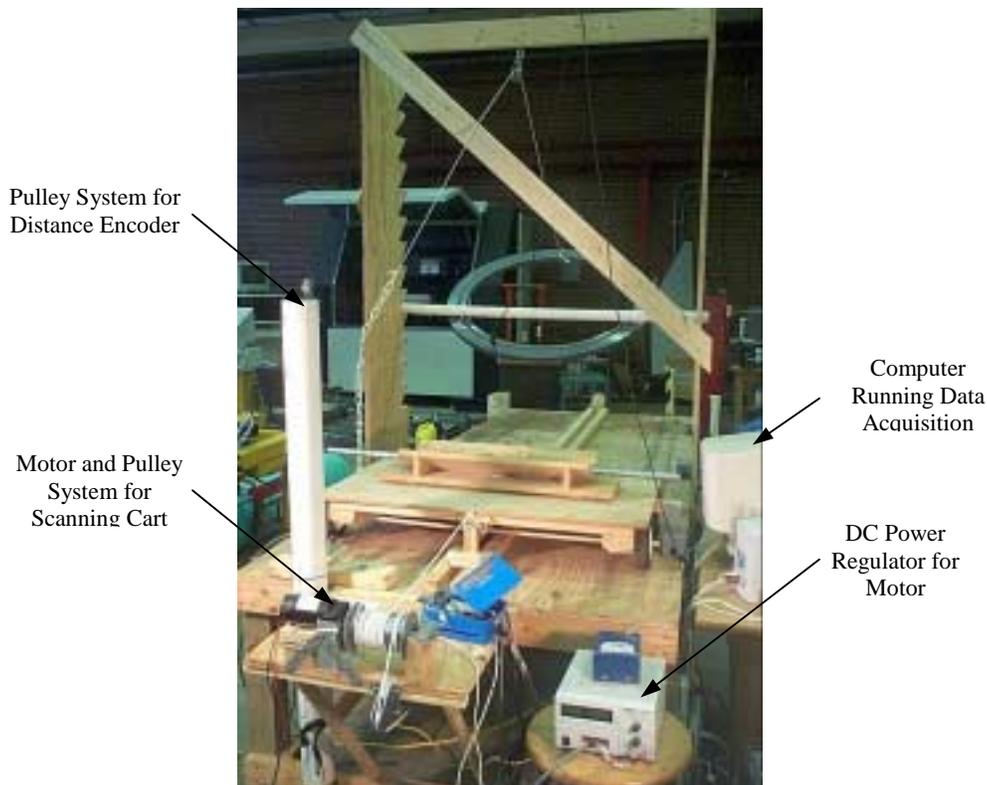
**Fig. 8.** Crisp object recognition with TIWPD

The outcome of processing the GPR data from beyond the concrete duct bank with TIWPD filter surfaced some interesting facts. Most importantly the four buried objects, A, B, C, and D, were clearly identified. However, it is interesting to note how the two pipes that did not cross the trench perpendicularly are represented. As indicated in Fig. 10 a) object D is made up of two steel pipes encased in concrete within a concrete pipe. In order to understand the occurrence of the four separate spikes one has to remind oneself that the TIWPD method focuses on detecting abrupt changes in signal strength through the use of test statistics ( $T_0$  and  $T_1$ ). Thus, each of the four peaks indicates a significant change in the subsurface. In the case of pipe D, the scan “cuts” in an approximate 45 degree angle through the elongated object experiencing four drastic changes in material that reflect or scatter a GPR pulse. First is the contrast between the surrounding clay and the concrete pipe, changing from a dielectric constant  $\epsilon_r$  of 30 of wet clay to 10 of concrete. The magnetic steel of the two pipes is causing another large discontinuity that is being recognized and repeated as the GPR crosses over the center of the encased set of pipes. As both plots in Fig. 12 highlight, the same phenomenon is being produced by object C. Here the concrete surrounding only one pipe was significantly smaller in radius thus creating only two peaks that are separated due the shallow angle of the scan. The latter explanation is rather hypothetical since the pipe was destroyed by the backhoe excavator.

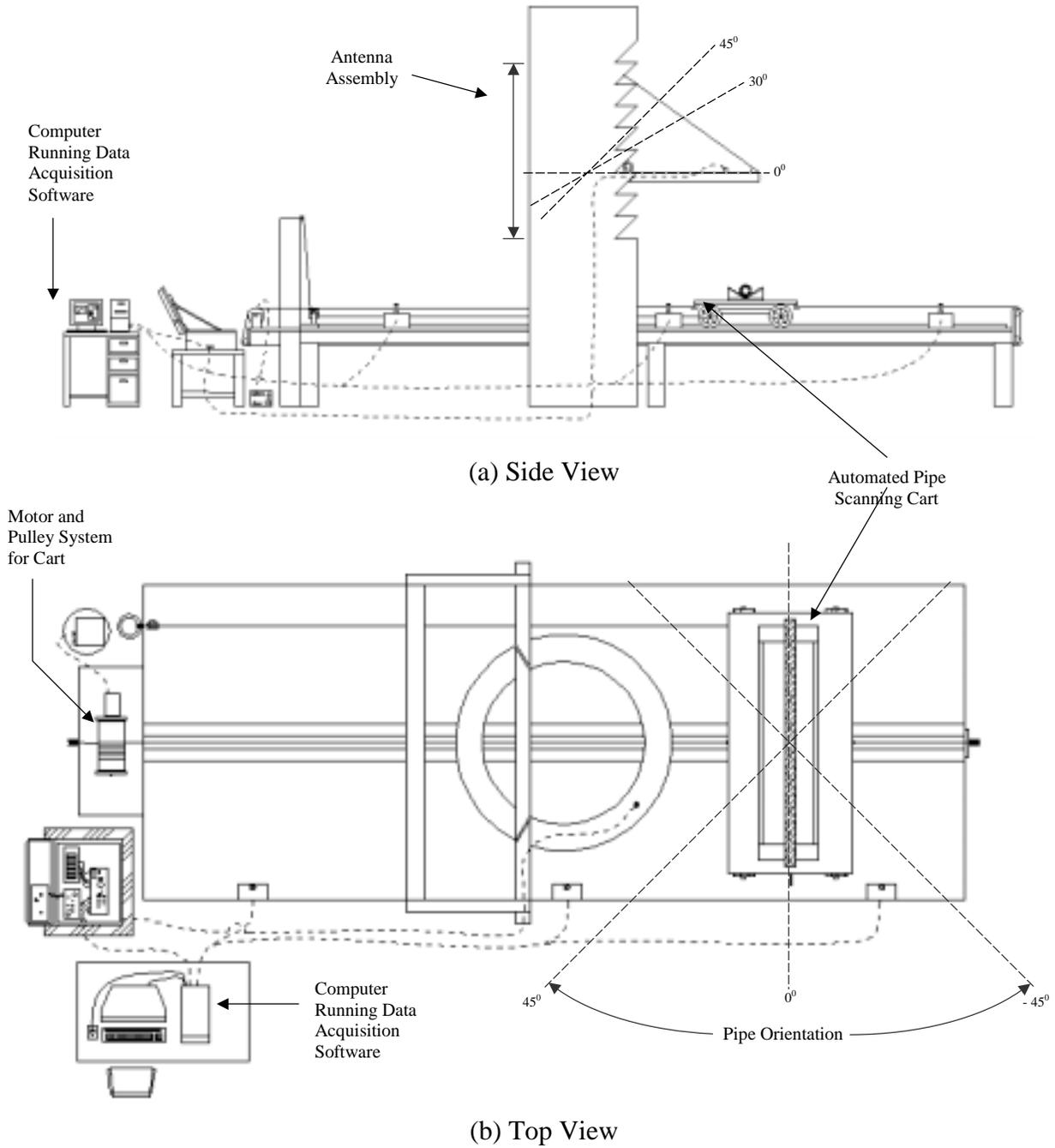
**5.2.2 AIM 2: Develop data processing and feature recognition capabilities that will enable the Excavator-Mounted Buried Utility Detection System (EM-BUDS) to locate as well as detect underground facilities in “real time”.**

To conduct experiments in the laboratory a facility that simulated the scanning procedure of the detection system over a pipe was built. The development of this facility involved fabrication of a wooden structure consisting of a) an antenna assembly, b) a track for an automated pipe scanning cart, and c) a data acquisition system (Figure 3.2). The antenna angles were made adjustable using a pulley system. Pipe orientation was done by means of a rotating pipe holder mounted on the cart.

The automated pipe scanning cart carries the pipe below the antenna simulating a scan. The cart is motorized and is controlled by the PC. A very accurate encoder attached to the cart measures its exact position. The cart table has limit switches so that the cart does not overrun the pathway. A Visual Basic program that also communicates with the Opto22 via the serial port recognizes the cart position through the encoders via the parallel port of the PC. This enables real-time data plotting and storage. The outputs to the motors are also through the parallel port.



**Fig. 9.** Overview of the experimental test facility



**Fig. 10.** Design of test facility

The laboratory tests were designed keeping in mind the objective, that is, for the accurate location and characterization of buried pipelines at the jobsite without any prior knowledge. For this objective to be achieved four important characteristics of the buried pipe need to be identified: Material, Size, Depth, and Direction.

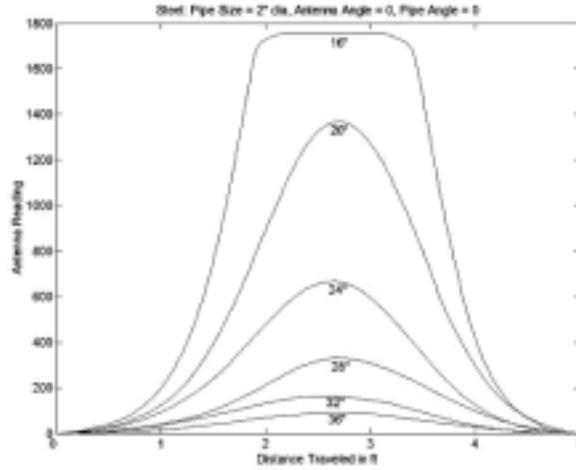
Several metallic pipes commonly used for laying underground pipelines were tested at the laboratory and included steel, cast iron and galvanized iron. Pipe sizes ranged from 0.5 inch to 4 inches in diameter, with an average length of 36 inches. Tests were conducted by placing a pipe on the cart shown in Figure 10, which was then moved under the antenna by the help of a motor from one end of the setup to the other, thus, simulating a sweep of the antenna over a pipeline. Results were recorded in both directions as a check for consistency. Each pipe was tested with the antenna placed at different heights and different angles. Antenna height ranged from 8 inches to a maximum height of 40 inches from the pipe. Antenna angles tested were 0, 30 and 45 degrees respectively. The maximum and minimum test heights of the antenna varied depending on the size of the pipes, as signal strength is directly proportional to pipe size. The pipes were also tested by being placed at 0 and 45 degrees respectively to the direction of movement of the cart.

Six steel pipes, four cast iron pipes and five galvanized iron pipes (Table 1.) were used for the experiments. Figs. 11, 12, and 13 show composite 2D plots of results obtained for the different pipes tested. In the plots, x-axis represents the calibrated antenna readings and y-axis represents the distance traveled by the cart in feet. From the plots it can be seen that at 8 inches height, peak antenna reading for all pipes are the same. But with increase in antenna height there is significant change in peak signal readings. From the tests conducted Steel provided the strongest signal readings, while Galvanized Iron provided the weakest.

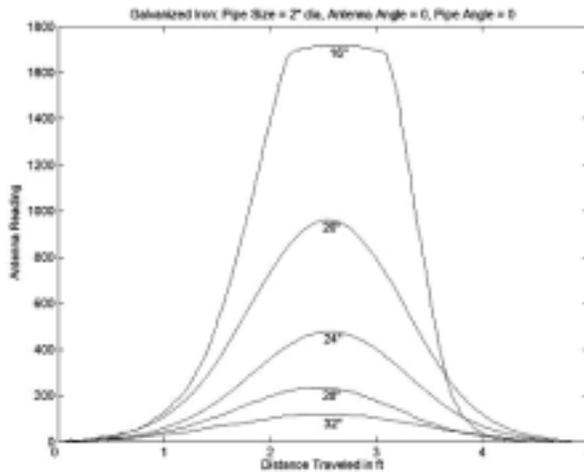
**Table 1.** Material and sizes of pipes tested

| Pipe Size       |  |  |  |  |  |  |  |  |
|-----------------|---|---|---|---|---|---|---|---|
| Material        | 0.5"  | 1.0"  | 1.5"  | 2.0"  | 2.5"  | 3.0"  | 3.5"  | 4.0"  |
| Steel           | ✓   | ✓   | ✓   | ✓   |   | ✓   |   | ✓   |
| Cast Iron       | ✓   | ✓   | ✓   | ✓   | ✓   |   |   |   |
| Galvanized Iron |   |   | ✓   | ✓   |   | ✓   |   | ✓   |

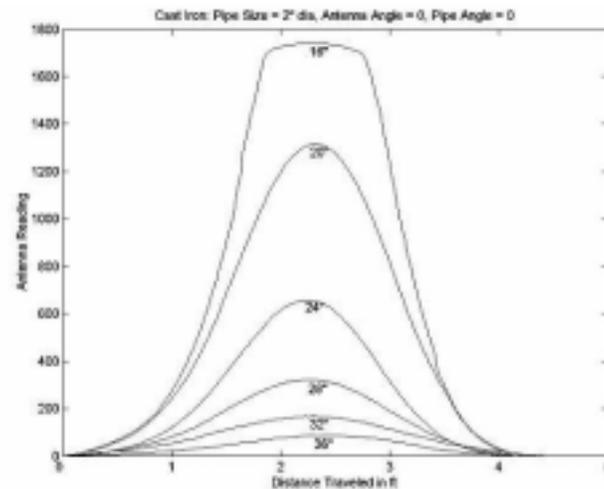
Note: Pipe Size – internal diameter of the pipes, in inches. Pipe thickness: ~ 0.3 in



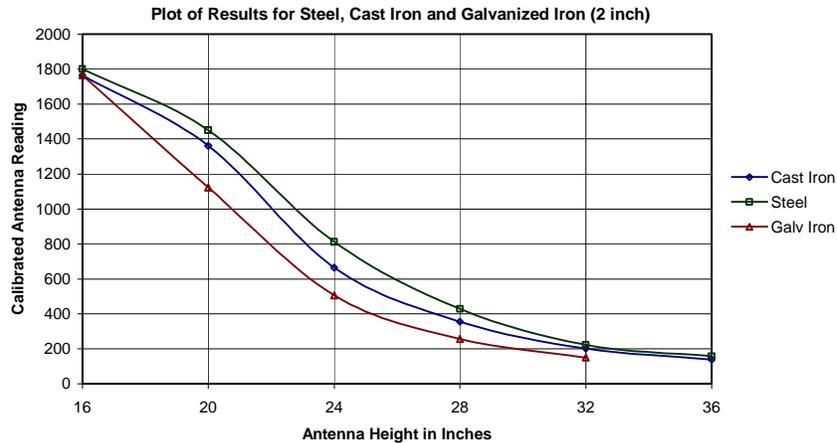
**Fig. 11.** Results for steel pipe at varying antenna heights



**Fig. 12.** Results for galvanized iron at varying antenna heights



**Fig. 13.** Results for cast iron at varying antenna heights



**Fig. 14.** Comparative plots of all metal pipes tested

### ***Real-Time Locating with EM-BUDS***

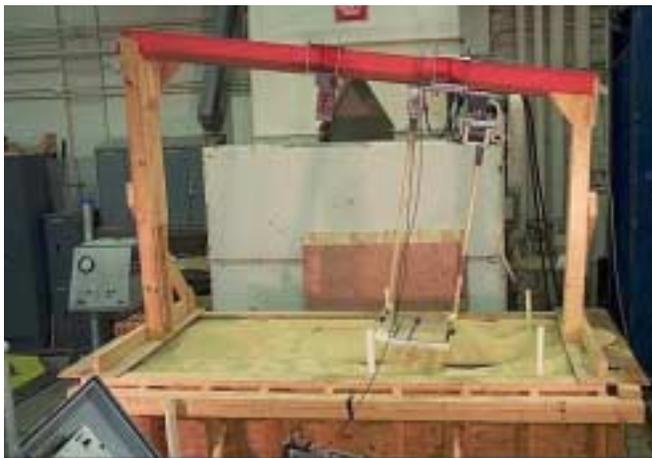
The Equipment Mounted Buried Utility Detection System or EM-BUDS consists of an antenna mounted on a mechanical arm that can be operated independently from the equipment. In the case of an excavator mounting, shown in Fig. 15, two hydraulic motors power the antenna movement, one in each plane of rotation. Proportional valves control the motors. The antenna position in space is determined by the two potentiometers mounted so that each measures the rotation of the antenna around the center axis of the motor. In its parking position the antenna is parallel to the beam held in place by a locking mechanism.



**Fig. 15.** EM-BUDS Antenna mounted on a backhoe

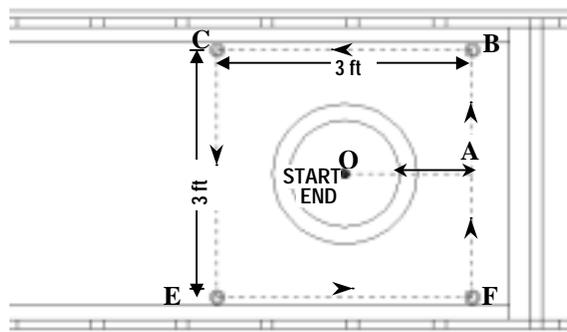
EM-BUDS has two modes of operation: a) Fast Scanning and b) Locating. The default mode is the Fast Scanning, where the antenna is released by the lock and one motor operates antenna through a swift arc and then returns. In the meantime, the data collected is immediately processed to assess if there is any utility in the vicinity. If the reading exceeds an empirically determined threshold value the operator is alerted and the system switches into a Locating routine. In this mode, the antenna moves in a near circular manner while collecting and processing the data to ascertain the exact location of the buried utility.

Fig. 16 depicts the laboratory prototype of the described concept. The set-up consisted of the EM-BUDS system mounted on a wooden beam which in turn was positioned over a sand box to facilitate the experiments with buried pipes. The antenna is attached to a hydraulically powered tow link mechanical arm.



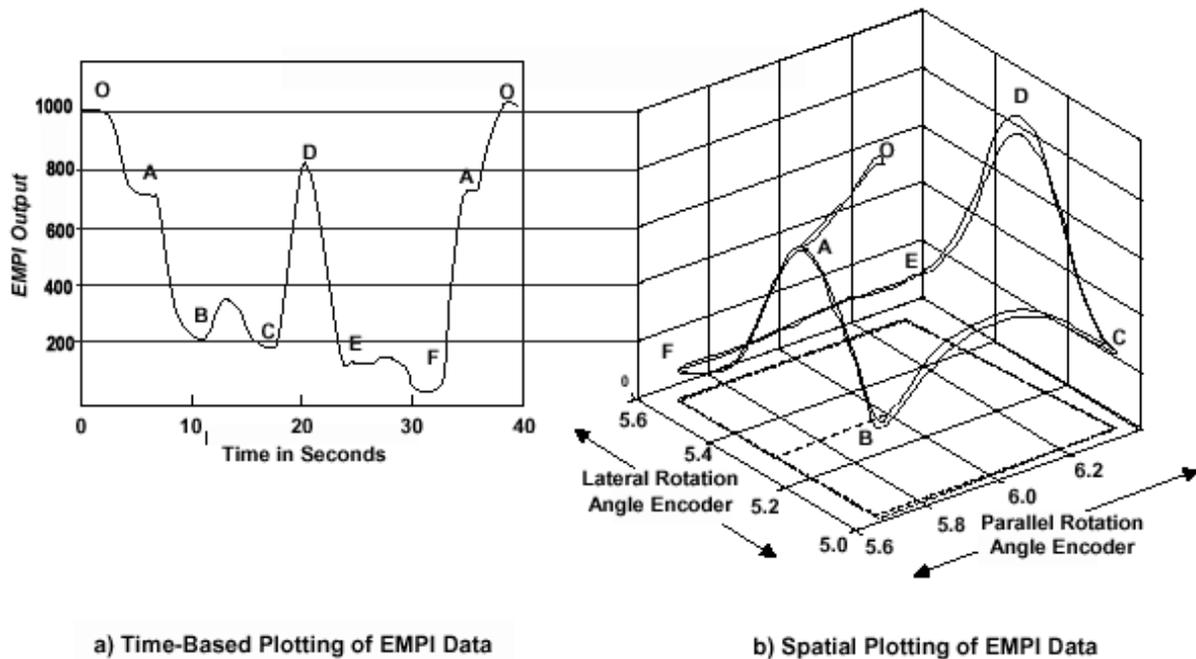
**Fig. 16.** EM-BUDS in laboratory set-up

The main interest of the laboratory work was in developing the locating module. For this purpose, the hydraulic system was programmed to execute a square routine 3 feet in each direction. A diagrammatic representation of the square routine is shown in Figure 17, where arrow marks trace the path of the antenna. After completing experimentations, the mechanical arm is moved to the 'lock' position. Here the arm moves backwards until it is parallel to the top beam, where a lock mechanism holds it in place.



**Fig. 17.** Top view of square routine mode of locating

The results of the test conducted with a steel pipe of internal diameter 1.5 inches are shown in Figure 18. The pipe was buried in the sandbox at a depth of one foot and positioned directly below the center of the antenna and parallel to the length of the sandbox. The x-axis in the plot denotes the time taken for the movement of the antenna in seconds, while the y-axis denotes antenna reading.



**Fig. 18.** Data collection during locating: steel pipe (1.5 in) in center of sandbox

The alphanumeric labels used to denote specific spots on the two plots in Fig. 18 correlate to the labels shown in Fig. 16. The start and end of the antenna scan is the location marked as O. Other intermittent points along the path of the antenna in the square routine mode have been marked A through F. The time-based plot of the EMPI readings shown in Fig. 18 a)) is the result of the antenna moving away, closer, or crossing the centerline of the buried pipe. For example, progressing from location O to A results in the EMPI signal getting weaker since the rotational motion of the plastic rods increases the distance between the antenna and the pipe. Based on the experiences from the experiments conducted earlier, this performance was expected. The weakening of the EMPI reading between position A and B reflects a further increase in distance when the antenna advances along a circular path brought about by the lateral rotation motor. While motion generally in- or decreases the EMPI readings stoppages create horizontal plateaus. This phenomenon is eliminated when the data is plotted against the two angle encoders as shown in Fig. 18 b). A visual comparison of the two plots illustrates instantly the benefits of the spatially integrated representation of the data. In particular, the human eye recognizes immediately how the peaks, A and D, belong to two symmetrical U-shaped curves resulting from the lateral paths C-E and F-B.

Lining up the two peaks, one is able to easily predict the centerline of the buried pipe as

parallel to the boom. The slight increase of the reading between B to C is again the result of the non-planar motion of the antenna along its path. However, between E to F no such increase is observable due to the fact that the limits of the lateral motor are not exactly symmetrical.

### ***Locating Routine***

Fig. 18) demonstrates the fact that the track scan supplies all the data necessary for calculating the direction and center location of a buried pipe. A search-subroutine can now be employed to find two peaks along its path that define two points that can be connected to establish the direction of the pipe. Next, a final sub-routine is launched to define the center and the perpendicular angle as the input for sending the antenna on a final path to define size and depth using look-up tables that are based on passing over the pipe perpendicularly.

### ***5.2.3 AIM 3: Create an operator-friendly interface for EM-BUDS to work similar to a “fish-finder”.***

Communicating the predicted direction, depth, and size of a located pipe is in fact a problem of how to present the output of the computer to humans. However, most research discussed in the literature focuses on maximizing the entering of data into the computer. The first basic question that arises is: “How do we inform the operator where a pipe is?” Display screens, commonly employed for such communications, face serious risks in a hostile environment that includes dust, heat, and dynamic shocks. The common saying “a picture is worth a thousand words” is certainly true when one has to describe the exact location and direction of a pipe buried in the ground to somebody else. While EM-BUDS does not change the way excavation takes place it does replace and drastically improve a laborer who scans the ground from inside the trench. Because OSHA rules prohibits entering the trench without protection utility locating is generally done visually by helpers who stand on the side of the trench looking for signs of a buried utility being unearthed. In that sense, the pre-computer human activity that is replaced and enhanced is: a) the “visual hunt” for a metallic pipe during excavation, b) warning of the operator when “something” has been detected, and c) communicating its location, including the depth, of the something. While a stop signal and the depth and size information can be easily substituted with simple electronic devices, such as a red lamp or digital numbers display, pointing with the arm has a 3-D component that can not be easily transferred into a graphical mode that is easily understood by the operator. Thus it was hypothesized that the best way to substitute the arm pointing by a helper was to turn the 2-D antenna assembly, shown in Fig. 16, into a “pointer”.

### ***Field Testing EM-BUDS***

In October of 2004 EM-BUDS was readied to be field-tested on an available JCB backhoe-loader. Fig.19 presents several pictures of the tests that were conducted in a fill area of a construction site. In particular Fig. 19 c) shows how EM-BUDS was mounted to the backhoe arm, using a clamp assembly consisting of four threaded rods and two plates. Hydraulic power was provided by a mobile pump. For the experiments, for each test a 0.5 inch (1.27 cm) pipe section was buried in the clay type soil found most often in the Piedmont area of North Carolina. While the EMPI is not impacted by the presence of soil one end of the pipe was left visible for the purpose of visually documenting the performance of the system. Fig. 19 a) illustrates how the

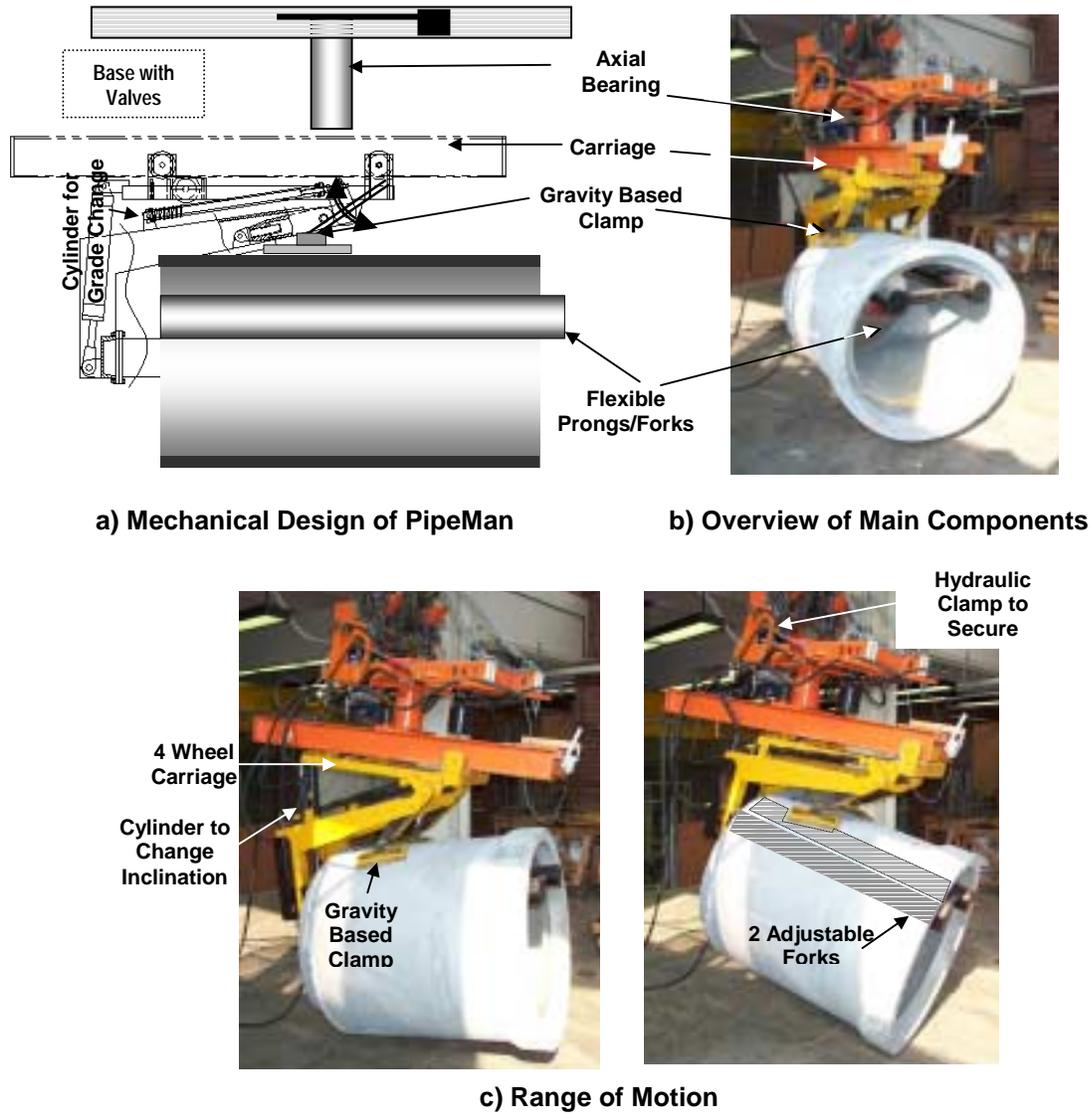
antenna followed the rectangle path marked as *a* through *e*. After reading the previous section, it is apparent that this very path had previously been developed and tested in lab experiments. Therefore, the same subroutines for analyzing the scan data could be used. In particular, the program was able to detect the peaks created by the EMPI output and calculate the mid-point and orientation of the pipe. Figs. 19 b) and c) document the final highlight of the project. Pipe 1, buried slightly off-center of the axis of a new trench, was detected and pointed to by the antenna. Pipe 2 was oriented almost perpendicular to the trench. As illustrated in Fig. 19 c), EM-BUDS not only detected the presence of the pipe but aimed correctly at the mid-point of the pipe within the space of the trench.



**Fig. 19.** EM-BUDS during field tests

**5.2.4 AIM 4: Drastically diversify the capabilities of PipeMan to handle a wide range of pipe sizes and materials. Add the ability to retrieve pipes and possibly lay pipes under water.**

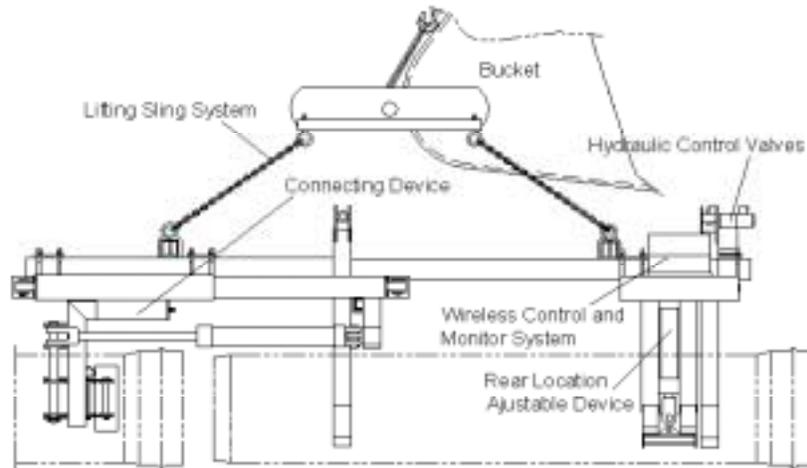
Fig. 20 presents the drastically upgraded PipeMan.



**Fig. 20.** Operational upgrades for PipeMan

While the first Pipeman prototype relied heavily on the movement of the bucket to align the grade, the new system provides the operator several tools to achieve proper line and grade. After the bedding has been properly established, using a laser beam as a guide, the two wireless video cameras and a laser target show the operator the orientation and position relative to the previous pipe and relative to a laser beam through the already installed pipes. Using the backhoe arm as well as the extra DoFs of the manipulator the pipe can be easily aligned.

The capabilities of the PipeMan concept was further diversified by building a second system, referred to as PipeMan Jr., able to join long pipes with O-rings. In addition, PipeMan Jr. should not depend on a backhoe excavator. As Fig. 21 shows, PipeMan Jr. consists of 5 main components: a) Hydraulic power, b) hydraulic actuators and controls, c) a wireless video and actuator control, d) lifting mechanism, and e) pipe clamp and connecting system.

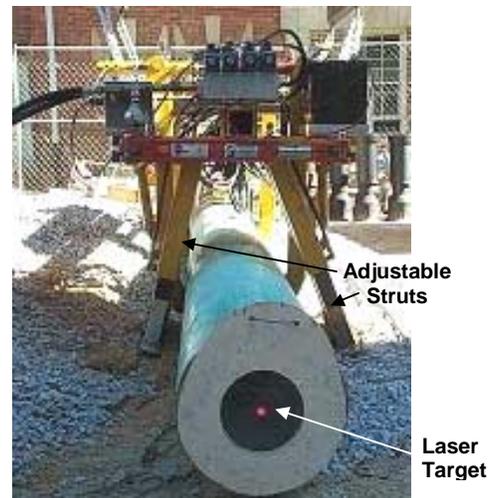


**Fig. 21.** Schematic of PipeMan Jr.

Fig. 22 ) demonstrates the basic operational concept of PipeMan Jr. After the device is being connected to the lifting equipment (e.g., backhoe) a new pipe segment is being secured by two clamps (in yellow). Subsequently, it will be lowered into the open trench while the jointing mechanism is used as a physical guide to align the previously laid with the new pipe. The line and grade is adjusted using the rear location adjustable device and the laser target, as shown in Fig. 22 b).



**a) Aligning of Pipes**



**b) Support Mechanisms to Achieve Line and Grade**

**Fig. 22.** Field testing of PipeMan Jr.

**5.2.5 AIM 5: Integrate the expanded EM-BUDS and PipeMan.**

This Aim was canceled due to lab closing by the department of Civil Engineering denying access to all researchers working on this project.

**5.2.6 AIM 6: Improve the human-machine interfaces for PipeMan.**

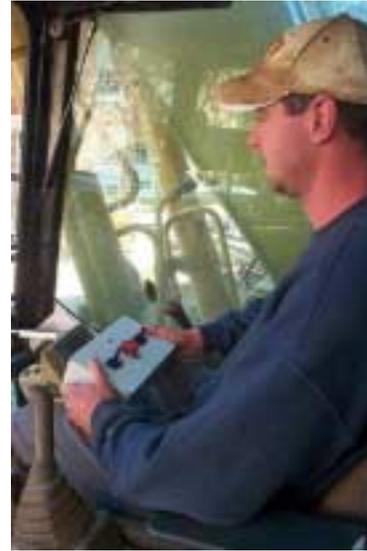
Both, PipeMan and PipeMan Jr. use the same human-machine interface and is presented in Fig. 23.



**a) Operator Interface During Field Test**



**b) Wireless Video Display**



**c) Wireless Controls**

**Fig. 23.** Field testing human-machine interface hardware for PipeMan

The operational control and the visual feedback are both wireless, a major improvement from the cable-based approach of the initial prototype. As Fig. 23 b) depicts, the video image of the jointing area is presented on a flat screen shadowed by an encasement. Despite these efforts, the image was not always as clear as desired which would make it desirable to use a head-mounted display or display glasses.

**5.2.7 AIM 7: Demonstrate the technologies to contractors nationwide in order to foster adoption of the research results.**

This Aim was canceled due to lab closing by the department of Civil Engineering denying access to all researchers working on this project.

**AIM 8: Disseminate information via journal articles, conference papers and on a website.**

This effort is still ongoing.

## 6. PUBLICATIONS

### Articles in Journals

1. Bernold LE: [2005] Accident Prevention Through Equipment-Mounted Buried Utility detection. International eJournal of Construction, Gainesville, FL: In Review.
2. Kim KT, Bernold L.E: [2005] A Comparison of Two Innovative Technologies- “Pipeman” and the Stewart-Gough Platform Based Pipe Manipulator. Automation in Construction: In Review.
3. Kolera BT, Bernold LE: [2005] An Intelligent Utility Locating Tool for Excavators. J. Constr. Engrg. and Mgmt., ASCE: In Review.
4. Lee J, Lorenc SJ, Bernold LE: [2003] A Comparative Performance Evaluation of Tele-Operated Pipe Laying. J. Constr. Engrg. and Mgmt., ASCE: 129 (1): 32-40.
5. Li, L. and Bernold, L E: [2005] Technological intervention to eliminate deaths During Pipe-Installation. International eJournal of Construction, Gainesville, FL: In Review.

### Proceedings paper (published)

1. Bernold LE, Li B [2004]. Robotic Technology for Pipeline Construction on Earth & in Space. In: Proceedings of Int. Conf. Engineering, Construction, and Operations in Challenging Environments, Houston, TX: ASCE, pp. 99-106.
2. Bernold LE, Immer M [2004]. Ground Penetrating Radar Technology to Locate Plastic Pipes and Lava Tubes. In: Proceedings of Int. Conf. Engineering, Construction, and Operations in Challenging Environments, Houston, TX: ASCE, pp. 24-31.
3. Bernold LE [2003]. Economic Impact Analysis to Optimize Investments in Damage Prevention for Pipeline Construction. In: Proceedings of New Pipeline Technologies, Security, and Safety, Baltimore, MD: ASCE, pp. 384-393.
4. Bernold L, Venkatesan L, Suvarna S [2003]. Equipment Mounted Multi-Sensory System to Locate Pipes. In: Proceedings of New Pipeline Technologies, Security, and Safety, Baltimore, MD: ASCE, pp. 945-952.
5. Bernold LE, Li B [2003]. Technology for the Tele-Robotic Laying of Large and Small Pipes. In: Proceedings of New Pipeline Technologies, Security, and Safety, Baltimore, MD: ASCE, pp. 400-407.