Excavator-Mounted Ordnance Locating System for Remote Excavation

Steven J. Lorenc
Leonhard E. Bernold
Construction Automation & Robotics Laboratory
Department of Civil Engineering
North Carolina State University
Raleigh, NC 27695-7908
sjlorenc@eos.ncsu.edu

Abstract

This paper presents a novel approach to solving the problem of detecting, locating, and removing buried unexploded ordnance. The locating system consists of an active electromagnetic sensor coil mounted on a backhoe excavator. The system has the unique ability that the coil is capable of eliminating the metallic effect of the backhoe and be lowered into a trench during the digging process. An algorithm can analyze the data from the coil in real time and determine the location of the ordnance.

1: INTRODUCTION

There are in excess of twenty million acres of bomb and artillery ranges under the control of the Department of Defense (DoD). Each year some 200,000 to 500,000 acres are turned over to civilian (private or commercial) use. Some of this land is contaminated with buried unexploded ordnance (UXO). These UXOs present a safety hazard and raise many environmental concerns.

In the coming years, this land must be cleared of all underground contaminants before the land can be deemed fit for commercial use. Safe, quick and cost effective means of UXO remediation are required to accomplish this. [2] [6], [7] Because of this pressing need, proven technologies that can be applied to this problem should receive primary consideration.

Possibly the most promising approach to the UXO remediation problem is the use of remotely controlled excavators to dig up and remove the buried ordnance. [11] [12] These excavators have the advantage of keeping the operator at a safe distance from the potentially deadly explosive blast. Every attempt needs to be made to make the task of removing explosive ordnance as easy as possible for the remote operator to control.

In addition to inaccurate locating, one of the most difficult aspects for the operator is the inability to see the target ordnance while it is covered with soil and debris. A system needs to be developed that can detect a buried piece of metal located in the path of the excavator's bucket. Also, the system should be able to determine the precise location of the ordnance relative to the excavator's bucket. This information would allow the operator not only to avoid striking the ordnance during the digging operation, but also to expose the object by removing the soil material around it. This technology could also located small unexploded ordnance which can be buried within the spoil material. Potentially, this may result in savings of millions in operating costs and prevent the damage or loss of equipment. Currently, a wide variety of sensing technologies are being used for the purpose of subsurface mapping of buried utilities and UXO's. [1] [3] [5] [10] They range from ground penetrating radar to hand held magnetic locators. The magnetic locators are able to use the magnetic field of a ferrous or non-ferrous metallic object as an indicator. The basic system consists of a search coil, a power source, and a control unit. Some of the more sophisticated systems are mounted on remotely controlled vehicles capable of locating their positions using GPS. [8] One of the drawbacks of these systems is the fact that they operate only from the surface, thus limiting the possible depth of accurate detection. Thus, ordnance that are buried deeper then the sensing depth cannot be located accurately from the surface.

One way to circumvent the depth limitation is to find a method that would allow a metal detection device to be lowered into a trench or ditch created by the excavator in order to scan the area ready to be excavated next. Furthermore, it would be very desirable to integrate the sensory output with the actual operation of the equipment. It is apparent that the excavator arm could serve as a means to position a search coil within the already excavated area. However, one key problem is the fact that traditional excavator arms are made of steel, thus causing the metal detector to sense metal at all times.

The goal of this research was to apply an excavator-mounted metal detection system to the problem of locating and avoiding buried unexploded ordnance during digging operations. More specifically, the research concentrated on the development of the capability of scanning of the soil immediately ahead of the next cut. Reliable detection of the ordnance within a minimal soil overburden of two feet was strived for.

2: SYSTEM DESCRIPTION

This section will discuss the equipment and experimental setups which were used in this project. Tests were conducted with a total of three setups. Initially, experiments were conducted on a lab-constructed excavator. A mockup of the Caterpillar 325L stick was built on a field site for further experiments. Finally, the last experiments were conducted on a John Deere 690C backhoe excavator (on loan from Wright Laboratory).

2.1: Electromagnetic Sensor Coil

The metal detection system used in this project was developed by Pulse Technology, Ltd. [4] [9] It consists of a control unit and an electromagnetic sensor coil. The sensor coil is of the pulse-induction type. A single electromagnetic coil is used to both create and sense the induced fields. The advantage of this type of sensing coil is that very little calibration is needed and it is not very sensitive to vibration nor noise.

The sensor coil works by first creating a magnetic field about itself. This field is called the 'primary field' and it induces eddy currents into a nearby conductive object which will create a 'secondary field'. The current in the coil is then removed and the voltage across the coil is then affected by both fields. Since the 'primary field' depends on constant properties of the sensor circuit, it can be deemed a constant effect. The effect of the 'secondary field' is dependent on properties of the object being detected, such as size, shape, distance, and orientation. The decay of this field is what is measured. Specifically, one point in the decay is read and recorded.
The rest of the detection system consists of an analog-to-digital converter and a PC computer which allows for interpretation of the data. The main advantage of using this type of detection system for our application is its ability to "filter out" the effect of existing metal within the environment. By taking advantage of this capability, the sensor coil can be mounted onto a backhoe excavator and be used to detect buried unexploded ordnance.

2.2: Lab Facility

Initially, a lab-constructed excavator was used to conduct preliminary testing on metallic objects such as pipes. A schematic of the experimental setup is depicted in Figure 1. The setup consists of a computer controlled excavator, a sensor coil, control unit, and an analog-to-digital interface. The sensor coil was mounted to the stick to allow the coil to swing (hand-operated) in order to conduct tests at different positions. The installation of a hinged joint allows active and fast scanning of the soil ahead of the bucket using an actuator capable of swinging the search coil. As shown in Figure 2, the signals picked up from the search coil during a fast forward and a slow backwards scan through zones 1, 2, and 3, clearly indicate the existence of a metal pipe. In fact, the intensity of the signal relates to the size of the pipes placed about two feet away from the arm and approximately seven feet away from the cutting edge of the bucket.

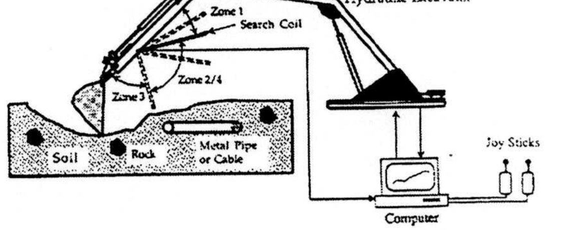


Figure 1: Schematic of Research Facility to Study Arm-Mounted Metal Detection

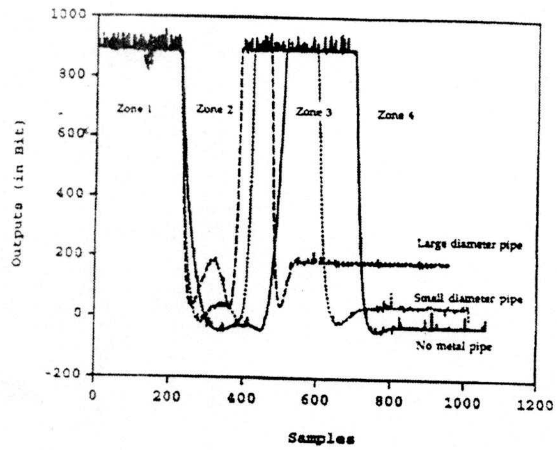
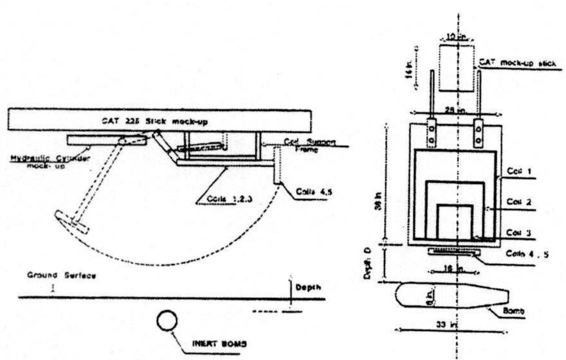


Figure 2: Sensory Patterns of Actuated Sensor Coil (Detection Distance = 2 Feet)

2.3: CAT 325L Stick Full-Size Mock-Up

A full size mock-up of the CAT 325L excavator stick including the hydraulic cylinder operating the thumb was built and installed in a testing field. The system consisted of a metallic rectangular tube measuring 10" x 14" x 12' and an attached metallic 'smart' cylinder. Also, the sensor coil mounted on the arm and the sand box which is used to bury the experimental inert ordnance, were built to simulate the actual field environment. Schematics of the experimental setup are shown in Figure 3, with coil dimensions shown in Table 1. An actual photo of the experimental setup is shown in Figure 4.



Side View **Top View**

Figure 3: Full-Size Stick Mock-Up

Table 1: Coil Dimensions

COIL #	DIMENSIONS
1	26" x 26"
2	20" x 20"
3	16" x 16"
4	15" x 11"
5	15" x 17"

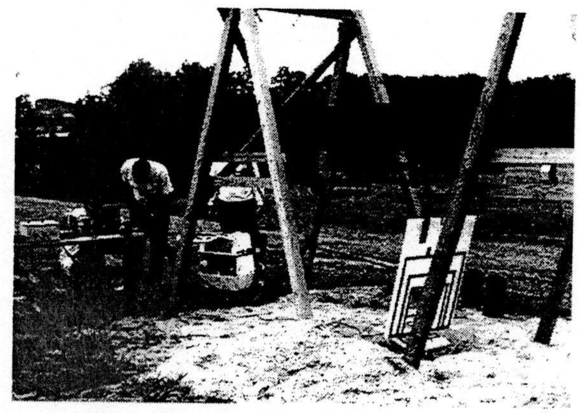


Figure 4: Photo of Full-Size Stick Mock-Up

2.4: Excavator Mounted Set-Up

The sensor coil was next moved to the John Deere 690C backhoe excavator on loan from Wright Laboratory. A smart cylinder was mounted on the stick of the excavator and connected to the hydraulic system of the backhoe. (see Figure 5) The cylinder was used to move the coil through an arc to scan the ground, both controlled from the cab of the excavator with a lap-top computer which was mounted in front of the operator. (The system can also be remotely controlled via an RF link or a cellular modem.)

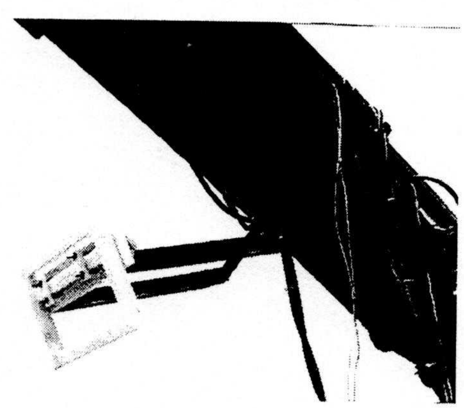


Figure 5: Sensor Coil Attached to the John Deere Excavator

The final major modification of the setup depicted in Figure 5 was to replace the smart cylinder with a hydraulic rotary actuator. A new bracket which attached the sensor coil to the actuator was fabricated and a potentiometer was mounted to the shaft of the rotary actuator in order to obtain angular position feedback from the actuator. (A photo of the new actuator and mount is shown in Figure 6.) This final modification increased the agility of the system. The scanning motion of the sensor coil was much smoother and the range of travel was increased greatly. The previous scanning range was roughly 90 degrees and limited by the smart cylinder. The scanning range of the current setup is only limited by interference with the boom stick and the bucket which will allow a maximum scanning range of roughly 180 degrees. The scanning capabilities of the new system are shown in Figure 7 in pictures of the coil in three separate positions.

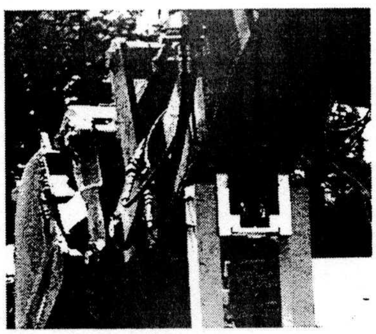


Figure 6: Photo of the Final Set-Up

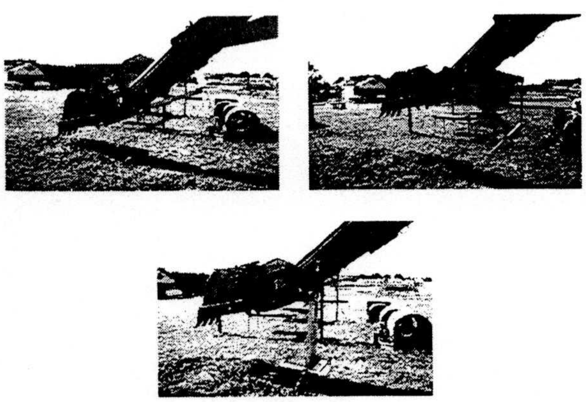


Figure 7: Enhanced Scanning Motion of the Excavator Mounted Sensor Coil

2.5: Computer Interface

The detection system is controlled via a laptop 486 PC computer mounted in the cab of the excavator. (see Figure 8) The comprehensive program for ordnance detection and actuator control is written in QuickBasic 4.5. The program uses an advanced artificial neural network to detect the underground ordnance and calculate the distance from the sensor coil to the ordnance under the conditions that the plane of the coil and the plane of the ordnance are parallel to each other. Additionally, it is assumed that the coil is directly above the ordnance. The software can display, in real-time, all the necessary information from the field. Figure 9 depicts the computer display in the metal detection mode while Figure 10 depicts the computer display in the dual mode. The information which is displayed includes:

- ordnance detector output;
- rotary actuator control keys;
- rotary actuator feedback;
- numerical value from the ordnance detector;
- ordnance detection, distance from the sensor coil to the ordnance;
- joint angles of the four rotational joints of the excavator;
- a field view which shows a relative location of the detected ordnance.

Figure 8: Photo of the Laptop Computer Inside the Cab of the Excavator

It is possible to switch between the two screen displays at any time. This provides more flexibility for the user to observe the current situation in the field.

The program has the additional capabilities of collecting data from all of the joint encoders mounted on the excavator and controlling the rotary actuator. The angular position of the rotary actuator (scanning position of the sensor coil) can be directly controlled through the program while collecting data. A start and end position can be programmed and the coil can scan through that region.

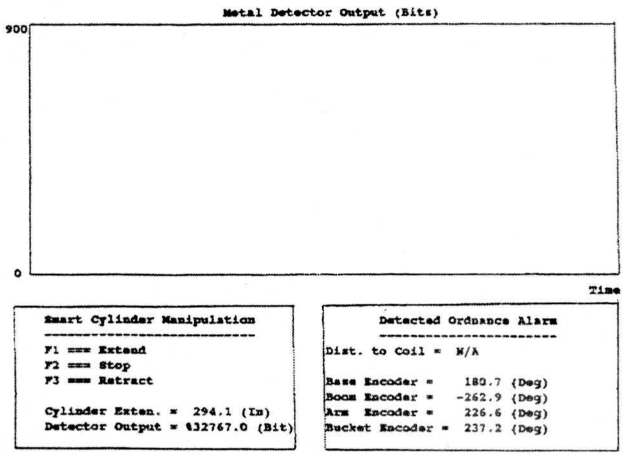


Figure 9: Screen Display in Metal Detection Mode

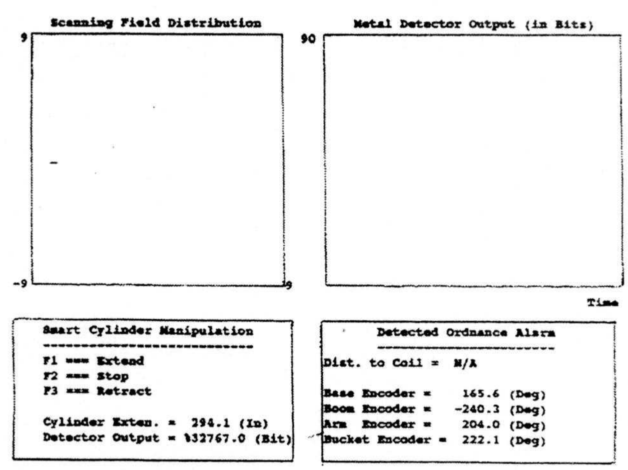


Figure 10: Computer Display in Dual Mode

3: EXPERIMENTAL RESULTS

3.1: Data Using the Laboratory Facility

Initial data was collected using the laboratory setup depicted in Figure 1. An ordnance was unavailable at the time so preliminary tests were conducted on two pieces of metal pipe. During these experiments the coil was configured as in Figure 1 with the edge of the sensor coil coming closest to the metal objects. Information was gathered as to how the signal changed during the scan. Prior to scanning, the metal detection system was initialized with the sensor coil at a position where it was perpendicular to the boom stick. This position translated to a rod extension position of about 11.5 inches. Figure 11 shows how the signal changed during the scan and the effect of the boom. It can be seen that the effect of the boom, measured as 750 bits disappears quickly at the beginning of the scan. Measurements would, therefore, be conducted only after the rod was extended more than 6 inches. This is the point where the effect of the boom is no longer seen.

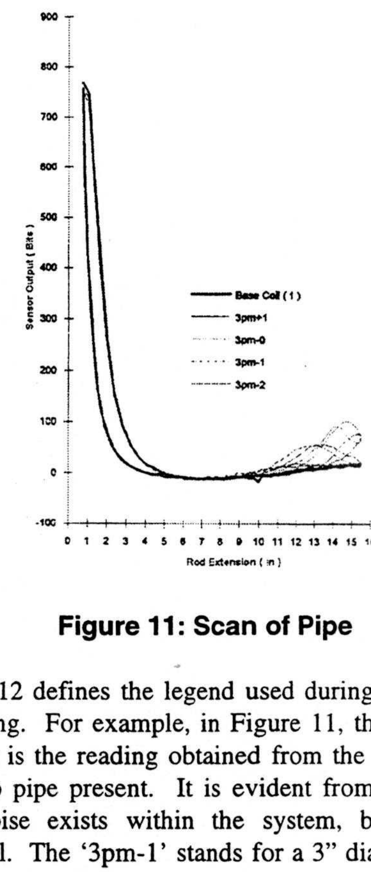


Figure 11: Scan of Pipe

Figure 12 defines the legend used during this phase of testing. For example, in Figure 11, the base coil reading is the reading obtained from the sensor coil with no pipe present. It is evident from the figure that noise exists within the system, but is very minimal. The '3pm-1' stands for a 3" diameter pipe in position pm-1 as defined in Figure 12. The pipe was positioned such that it was (p) perpendicular to the centerline of the boom, (m) middle of the pipe is along the centerline of the boom, and (-1) at position -1 which is located 1 foot to the right of the 0 position.

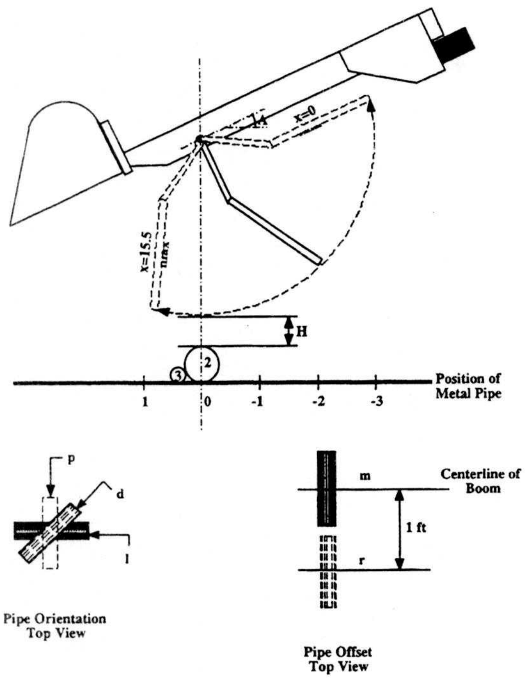


Figure 12: Schematic of Experimentation Legend

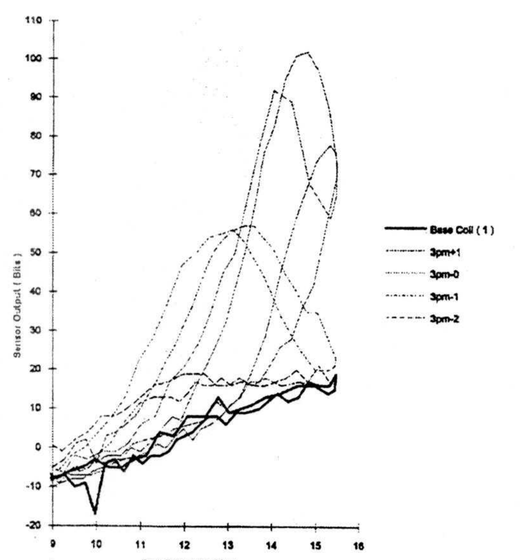


Figure 13: Zoom of Section of Figure 11

Figure 13 shows details of the effect of the metal pipe on the signal from the sensor coil by zooming in on the part of the figure which defines the pipe readings. This preliminary data showed that even a small section of pipe had a discernible effect on the sensor coil output and showed that the effect of the boom was negligible since the effect dissipated when the coil was moved only a short distance away (a distance which was far enough away from the detection area that the two signals could be quite easily distinguished from one another). Also, the sensor coil output begins to increase slightly towards the full extension of the rod because it begins to detect the bucket. It should be noted that the sensor coil reading at the initialization point, 11.5 in., has a reading of zero bits for the base coil curve.

3.2: Data Collected with the Full-Size Stick Mock-Up

The data collected with the full-size stick mock-up is described in this section. First, the data collected using the lab facility needed to be compared with the new setup. Additionally, a new sensor coil configuration was tested to determine the effect on the signal outputs. The new configuration consisted of three different sized coils configured as previously described with the addition of a fourth coil mounted perpendicularly to the other coils. (see Figure 3) During these experiments, an inert ordnance was now available and used for data collection. This ordnance was a 100 lb. ordnance on loan from Wright Laboratory.

Figure 14 illustrates the effect of the object size on the maximum sensor output data. Three different sized metal objects were compared: 1) short pipe, 4.5 in. diameter and 21 in. long, 2) long pipe, 4.5 in. diameter and 29 in. long, and 3) the inert ordnance. All were tested at the same burial depth of 21 in. using five different coil configurations. The goal was to compare the output data from previous lab tests using metal pipes, with the sensor output data when sensing the ordnance. The results were as expected. As the size of the detected object increases, so too, does the sensor output signal.

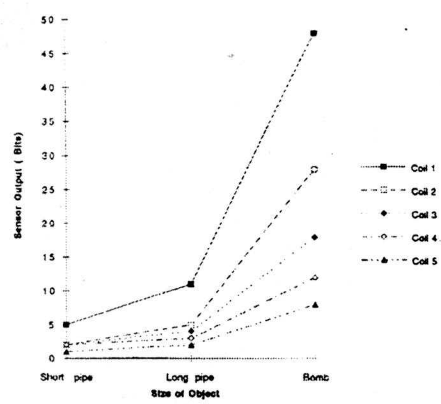


Figure 14: Combined Effect of Coil and Metal Object Sizes

Figure 15 illustrates the effect of the ordnance burial depth on the output signal using different coils. As the depth increases, the output signal decreases. This test reveals that it is possible to sense a buried ordnance within the 24 inch range which is required.

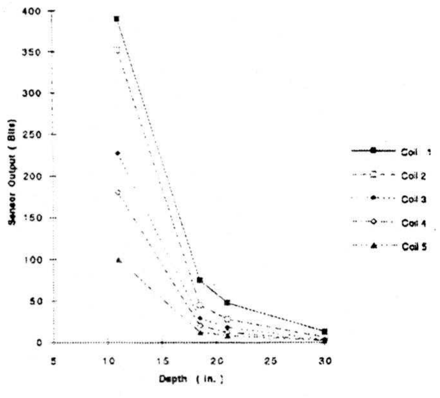


Figure 15: Different Coils Output Data for Various Burial Depths

Figure 16 illustrates the maximum sensor output of coil 4 detecting the bomb at different depths and different offset distances along the axis R. It is clear from the plot that as the offset distance increases, the sensor output decreases. Note that the change in offset distance has less effect on the output data than the change in depth.

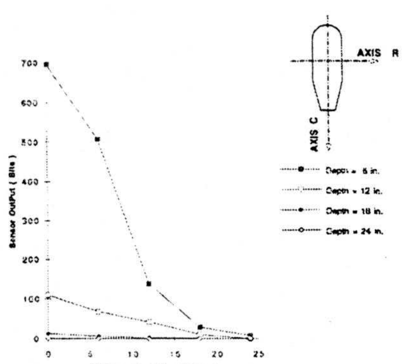


Figure 16: Effect of Horizontal Offset Along Axis R and Ordnance Depth on the Maximum Sensor Output

Figure 17 illustrates the maximum sensor output of coil 4 detecting the ordnance at different depths and different distances along the axis C. In the first curve, depth = 6 in.; the sensor output is the same from different offset distances, indicating that the coil reaches a state of saturation and cannot differentiate between positions. It is therefore necessary to reduce the coil sensitivity to obtain reliable output. In the second curve, depth = 12 in.; the output signal increased, and then decreased with the increase of the offset distance due to the variation of the ordnance shape.

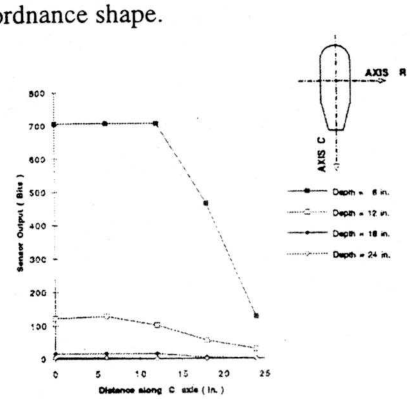


Figure 17: Effect of Horizontal Offset Along the Axis C and Ordnance Depth on the Maximum Sensor Output Data Collected with the Excavator Mounted System

The final data collection was performed with the coil mounted to the John Deere excavator. (see Figure 5) Tests were performed in which the ordnance was moved in a 4 ft. x 4 ft. plane below the sensor coil. The effect of the orientation of the ordnance on the sensor coil reading was tested. The first tests were conducted with the sensor coil parallel to the ordnance as shown in Figure 5.8.

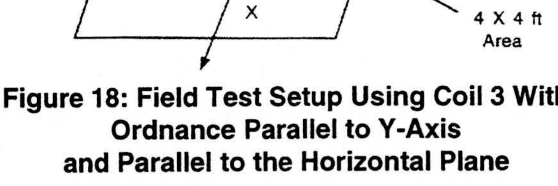


Figure 18: Field Test Setup Using Coil 3 With Ordnance Parallel to Y-Axis and Parallel to the Horizontal Plane

Figure 19 illustrates the sensor coil output data obtained from field testing using coil 3. The ordnance was moved in the X and Y directions and coil readings were taken. The three dimensional graphs show how the sensor coil reading changes with the distance from the ordnance with the highest reading when the ordnance is centered underneath the sensor coil.

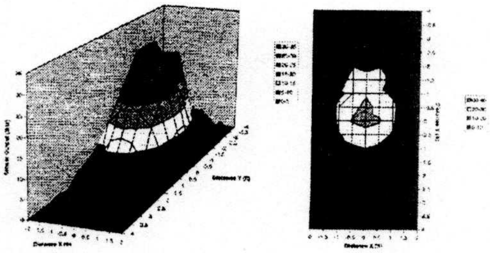


Figure 19: Field Test Data Using Coil 3 With Ordnance Parallel to Y-Axis

The ordnance was then rotated 90 degrees so that it was parallel with the x-axis. The test was conducted in order to determine whether the orientation within the plane had an effect on the sensor coil reading obtained.

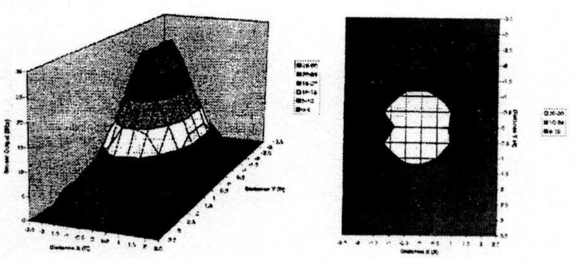


Figure 20: Field Test Data Using Coil 3 With Ordnance Parallel to X-Axis

By comparing Figures 19 and 20, it can be seen that the shape of the sensor coil has an effect on the reading. The base of the 'mountain' in Figure 20 has a circular shape while the base of the 'mountain' in Figure 19 has an elliptical shape. This difference is attributed to the shape of the field created by the sensor coil.

The next test conducted tested the effect of an 'out-of-plane' orientation of the ordnance with respect to the sensor coil. The test set-up is shown in Figure 21.

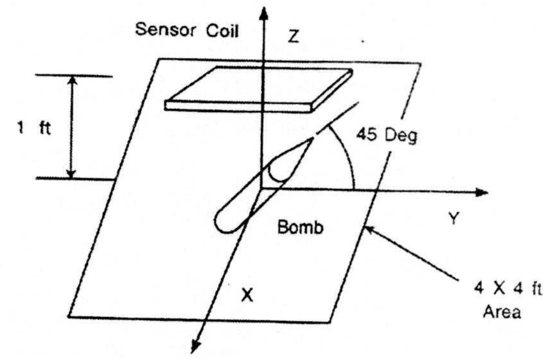


Figure 21: Field Setup Using Coil 3 With Ordnance Parallel to Y-Axis and 45 Degrees to the Horizontal Plane

Figure 22 illustrates the sensor coil output data obtained from field testing using coil 3. The ordnance was oriented at 45 degrees to the horizontal plane. The ordnance was moved in the X and Y directions and coil readings were taken. The highest reading in this test was shifted along the Y axis as a result of the ordnance being oriented at a 45 degree angle.

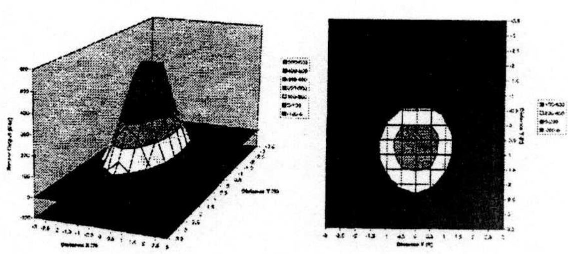


Figure 22: Field Test Data Using Coil 3 With Ordnance Parallel to the Y-Axis and at an Angle of 45 Degrees to the Horizontal Plane

4: Data Analysis

Tests were conducted to determine a functional relationship between the coil reading and the distance between the 100 lb. ordnance and the sensor coil. The experimental setup used is depicted in Figure 23. The sensor coil in this setup was mounted to the backhoe excavator. The offsets are measured from the tail-end of the ordnance and numerically defined as in Figure 23. The center of the sensor coil was positioned at each offset and readings were taken at different distances between the sensor coil and the ordnance. The distance was changed by raising and lowering the boom stick of the excavator.

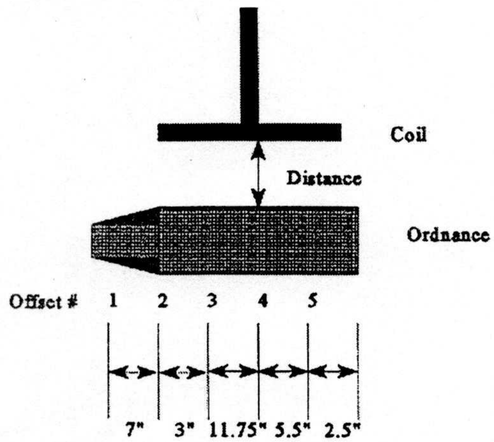
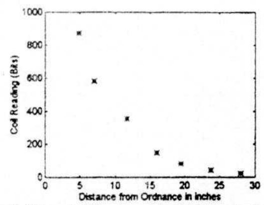
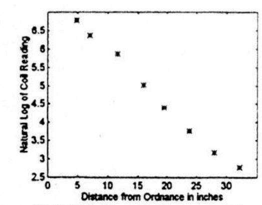


Figure 23: Configuration and Definition of Offsets

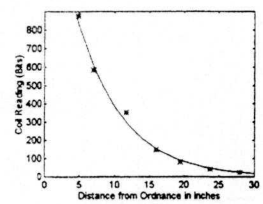
Figure 24(a) shows the data obtained at offset 3 where the coil is directly above the ordnance. This data is then manipulated by taking the natural log of the coil reading and plotting that, versus the distance. This plot is shown in Figure 24(b). The relationship is now seen to be a linear one. A first order polynomial is fit to this curve giving a functional relationship between the log of the reading and the distance. Therefore, a relationship is also known between the actual reading and the distance. This curve is plotted along with the data in Figure 24(c). The same procedure was applied to all of the offsets and it was found that within this range there was very little variation in the relationships. Therefore, data from all of the offsets was used to determine the function. This data and function are presented in Figure 24(d).



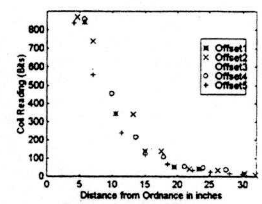
(a) Test Data at Offset 3



(b) Plot of Converted Data



(c) Plot of Function
Y = Exp(7.424-.1515 X)



(d) All Offsets
Y = Exp(7.5303-.1609 X)

Figure 24: Analysis of Test Data at Offset 3

Further data was then collected in order to confirm the functional relationship that was found. This allowed us to accurately locate the ordnance within a distance of about 30 inches from the coil. This relationship was further tested in the field by changing the distance from the coil to the ordnance and comparing the program's calculated distance and the measured distance. The error associated with the readings was on the order of 1/2 of an inch within a detection range of 10 in. to 36 in. coil to ordnance distance.

5: Search Methods

In order to locate the ordnance, searching strategies were developed. Due to the capabilities of the detection system, a dual search method was developed. The two types of search methods are: 1) Area Search and 2) Trench Search. Figure 25 depicts the two types of search methods.

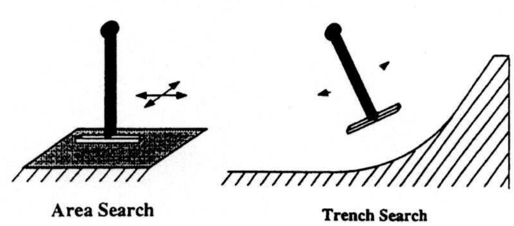


Figure 25: Schematics of the Two Types of Search Methods

The Area Search is used to scan the ground. The coil sensor is oriented to be parallel to the ground and the backhoe is used to scan the ground by rotating the base and driving the backhoe forward. The Trench Search is used while digging for an ordnance buried deep in the ground. In a Trench Search, the sensor coil is used to scan the ground in the manner shown in Figure 7.

It is apparent that the two search methods can be integrated, thus creating a very flexible detection tool. For instance, when the ground surface is flat, an Area Search is the most effective method. If a Trench Method was used in this scenario, a large amount of the area scanned would be air. It should be noted that from the data analysis, it was found that the sensor coil could detect the ordnance reliably within a distance of three feet between the sensor coil and the ordnance. By using a Trench Method, the immediate area would be searched. This is sufficient since the excavator bucket is only cutting through a two foot thick layer. Figure 26 illustrates the basic search scheme which should be used during ordnance location. It should be noted in Figure 26 that it is recommended that after a dig is made, the excavated material (dirt, sand, etc.) be scanned. This would ensure that small UXO's would not be left undetected in the spoil material.

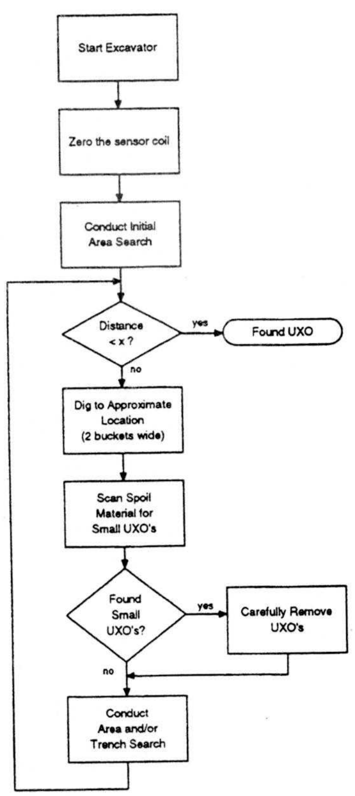


Figure 26: Flowchart of Search Scheme

6: Final Demonstration

A final demonstration of the system's abilities was presented at Wright Laboratory, Tyndall Air Force Base on June 24, 1996. The demonstration consisted of a field measuring 30' x 30' containing four inert ordnance of different sizes buried in unknown locations at a depth of about 18 inches. Additionally, a 250 lb. ordnance was buried in a 20' x 20' mound at a depth of about 5 feet.

The search method which was chosen was the simple Area Search. This method was chosen because the area which contained the four small UXO's was flat. A flowchart of the strategy is presented in Figure 27.

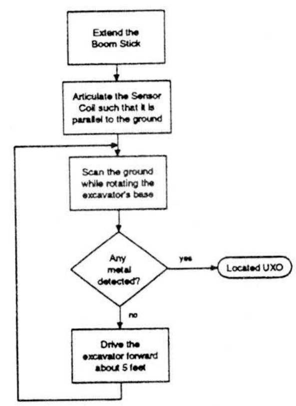


Figure 27: Flowchart of the Search Strategy for the Final Demonstration

Each of the four small ordnances were accurately located with the excavator mounted sensor coil. The exact distance from the coil to the small ordnances was only estimated from previous knowledge obtained during testing with the 100 lb. The system was capable of locating the ordnances in terms of allowing the operator to position the sensor coil directly above the ordnance.

7: Conclusions

The goal of this project of applying an excavator-mounted metal detection system to the problem of locating and avoiding buried unexploded ordnance during digging operations. The system which was developed is capable of detecting and locating a 100 lb. ordnance within a distance of 30 inches from coil to ordnance with an accuracy of ± ½ inch. It also has the capability of detecting even small shells. Additional research would be needed to improve the detection/location capabilities of the system in terms of obtaining the ability to distinguish between the different types of ordnance. There are a number of approaches to this problem. Some other improvements would be to also determine the orientation of the ordnance. Additionally, methods to search for UXO's has also been developed.

8: Acknowledgments

The authors wish to acknowledge the support of the U.S. Air Force Wright Laboratories, Tyndall Air Force Base, Florida.

9: References

[1] Das, Y., McFee, J. E., Toews, J., and Stuart, G. C (May, 1990), Analysis of an Electromagnetic Induction Detector For Real-Time Location of Buried Objects, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 28, No. 3, pp. 278-288.

[2] Kolcum, E.H., (April 27, 1992), "GPS, Other New Technologies Help Clear Ordnance From Kuwaiti Desert," *Aviation Week and Space Technology*, pp. 54-55.

[3] McDonald, J.R. and Robertson, R., (March, 1996), Sensor Evaluation Study for Use with Towed Arrays for UXO Site Characterization, *Proceedings of UXO Forum 1996*.

[4] Metalarm Series 3000 Operating Manual, (1993), Pulse Technology Ltd., Oxford, England.

[5] Pawlowski, J., Lewis, R., Dobush, T. and Valleau, N., (1995), An Integrated Approach for Measuring and Processing Geophysical Data for the Detection of Unexploded Ordnance, *Proceedings on the Application of Geophysics to Engineering and Environmental Problems*, pp. 965-983.

[6] Powers, M.B., (March 6, 1995a), "Cleaning up buried bombs may bust environmental budget," *ENR*, pp. 50-54.

[7] Powers, M.B., (March 6, 1995b), "Historic Hawaiian site about to be cleaned up for $400 million," *ENR*, pp. 52.

[8] Rankin, A.L., Armstrong, D.G., and Crane, C.D., (1994), "Navigation of an Autonomous Robot Vehicle," *Proceedings of Robotics for Challenging Environments*, pp.44-51.

[9] Thorpe, D.J. and Probert, P.J., (September, 1996), Quality Control Using Electromagnetic Induction Sensors, *Colloquium on Intelligent Sensors*, University of Leicester.

[10] Utility Technical Services (UTS), (1996), Basic Cable Locate 206 Manual, *North Carolina State University Utility Locating Workshops*.

[11] Waltz, W., (July, 1996), "Systems for Evaluating Site Remediation Technologies for Test Ranges Containing Unexploded Ordnance," *AUVSI*.

[12] Wetzel, J.P., (August, 1996), "Robotics to Support Hazardous Operations," *AIAA*.