Appendix A

ELECTROMAGNETIC INDUCTION (PAPER I)

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OPERATING PRINCIPLE

Electromagnetic induction (EMI) is the basis for the familiar handheld metal/mine detectors. The metal parts present in a landmine are detected by sensing the secondary magnetic field produced by eddy currents induced in the metal by a time-varying primary magnetic field. The frequency range employed is usually limited to a few tens of kHz. The primary field is produced by an electrical current flowing in a coil of wire (transmit coil), and the secondary field is usually detected by sensing the voltage induced in the same or another coil of wire (receive coil). Present research is investigating replacement of the receive coil with magnetoresistive devices. EMI detectors are often classified into two broad categories: “continuous wave” and “pulse induction.”

This appendix discusses EMI detectors primarily in the context of minimum-metal antipersonnel landmines encountered in humanitarian demining. Words such as “EMI sensors,” “EMI detectors,” “metal detectors,” and “metal/mine detectors” are used interchangeably throughout.

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STATE OF DEVELOPMENT

The basic technology is very mature. The EMI principle appears to have been used for landmine detection in World War I. EMI metal/mine detectors were further developed during World War II and have been routinely used to detect landmines since. The use of EMI to detect conducting objects is also well established in other application areas such as mineral exploration, nondestructive testing, treasure hunting, security and law enforcement, and food processing.

Although earlier development of EMI mine detectors was led by government agencies (examples include the development of the 4C and the AN/PSS-11), recent development of this technology has been driven, in large part, by the commercial interest of the private sector. As a result, a number of detector models from various companies worldwide are available as commercial-off-the-shelf (COTS) items. However, most of these items were not developed to meet any specific statement of requirement for mine detection.

The private sector has carried out product improvement through its own research and development (R&D). Government organizations in various countries have continued to conduct or sponsor research in areas of EMI mine/unexploded ordnance detection, which are considered to have low probability of success but high potential payoff.

CURRENT CAPABILITIES

Largely due to the advancement in electronics, the sensitivity, sophistication, and ergonomics of metal detectors have improved tremendously since their beginning in World War II. A good modern metal detector can detect extremely small quantities of metal (e.g., that found in an M14 or 72A antipersonnel landmine buried up to 10 cm) under various soil (e.g., magnetic) and other environmental (e.g., wet tropical) conditions. The speed at which a handheld metal detector can be used to sweep the ground is typically less than 1 m/second. However, the effective rate of area coverage will depend on many factors, which include the search halo of the detector, the frequency of occurrence of metal fragments and actual landmines, and the operating procedure employed.

The capabilities of COTS metal detectors vary over a wide range. Because most of these were not developed to meet any specific mine detection requirement and quality control standard, there is wide variability in the performance and quality among the various detector models. Developing and standardizing systematic testing and evaluation procedures to help select detectors best suited for a given set of circumstances will, in itself, represent a worthwhile contribution to mine detection.

LIMITATIONS

The most obvious and serious limitation of metal detectors used to detect landmines is the fact that they are *metal* detectors. A modern metal detector is very sensitive and can detect tiny metal fragments as small as a couple of millimeters in length and less than a gram in weight. An area to be demined is usually littered with a large number of such metal fragments and other metallic debris of various sizes. This results in a high rate of "nuisance" alarms since a metal detector cannot currently distinguish between the metal in a landmine and that in a harmless fragment. The more sensitive a detector is, the higher the number of nuisance alarms it is likely to produce in a given location. Operating a detector at a lower sensitivity to reduce the number of such nuisance alarms may render it useless for detecting the very targets it was designed to detect, that is, the minimum-metal-content landmines buried up to a few centimeters.

Electromagnetic properties of certain soils can limit the performance of metal detectors. Only a few detectors in the market are designed to and can cope with magnetic soils without serious loss of sensitivity. But not all of these detectors can cope with magnetic soils to the same extent. Because magnetic soils are found in most parts of the world that have landmine problems, the inability to operate satisfactorily in such soils is a significant limitation of some metal/mine detectors. Further, performance of some detectors could be severely limited by certain other environmental factors, such as accumulation of moisture on the detector head. However, this is not a limitation of the basic EMI technology.

POTENTIAL FOR IMPROVEMENT

Because metal detectors have been around for a long time and have been extensively researched, startling breakthroughs are not expected. It is doubtful if an order of magnitude improvement in metal detector performance is possible in the next two to seven years. However, sustained effort on a few fronts will contribute to a more efficient utilization of this technology in demining and to scientific progress in this area of sensing. A brief analysis of potential research areas, some of which are interrelated, and the expected results are described in the R&D outline that follows.

RESEARCH AND DEVELOPMENT PROGRAM OUTLINE

This outline introduces the various potential research areas, makes a hypothesis about the possible improvement from each, recommends specific research goals, and indicates expected results. Because the author is not familiar with the cost of doing R&D in the United States, only a very crude guess of the level of personnel effort needed is included. As well, a level of priority on a scale of 1 to 3, with 1 being the highest, has been assigned to each research area with a brief explanation. This prioritization should help when a resource allocation choice has to be made.

Nuisance Alarm Reduction

A major improvement in the utility of a metal detector would be achieved if the number of nuisance alarms could be reduced without sacrificing detectability of the landmines. The following three general approaches address this issue: signal processing, imaging, and multiple sensors. Of these, the use of multiple sensors would likely have the *most* immediate impact. However the topic of multiple sensing is beyond the scope of this report and hence an R&D plan for it will not be included here.

Signal Processing. The signal-processing approach consists of analyzing the EMI response waveform of an object to distinguish it from other objects. It is highly unlikely that this approach will ever result in a standalone metal detector capable of reliably differentiating between landmines and metal fragments in a field situation. However, advancements in this area, expected to be slow, may provide synergistic improvement to other approaches. Research in this area has lacked experimental emphasis—many techniques have been proposed, but very little experimental validation exists. Potential improvement offered by this approach can only be established through a program of extensive experimentation that would include measurement and analysis of EMI response of a large number of objects under various conditions.

Recommended R&D: Conduct an extensive experimental study to measure EMI response of a large number of targets of interest—first with the targets in air and then buried. The focus of this study would be to validate or establish the limitations of proposed discrimination techniques. This study will also establish whether current EMI sensor technology is capable of providing the quality of data needed to apply these techniques.

Expected results: Antipersonnel landmine/metal fragments discrimination is considered high-risk and long-term research, and as such it is not expected that a fieldable method would emerge in the two-to-seven year time frame. However, the recommended research will answer important questions on the viability of the signal-processing approach.

Recommended level of effort: three to four person years (PYs) for five to seven years. Personnel: technologists, engineers, and scientists.

Priority: 2. This area has been researched for a while and past progress has been slow. However, this research should be sustained.

Imaging

Producing images, even crude ones, of the detected objects would reduce nuisance alarms. Even the ability to image some of the larger pieces near the surface would help. Imaging with EMI sensors is in its infancy. Some metal targets have been imaged in the laboratory using data from a metal detector scanned on a plane over the object. EMI imaging techniques, using data from an array of sensors, have also been proposed to image faults in nondestructive testing of metal parts. A basic requirement for imaging is the availability of response measurements as a function of sensor position. This can be achieved either by knowing the position of a single sensor as it is moved or by using a suitable array of sensors. Magnetoresistive sensor arrays appear to be an attractive option for the latter approach.

Recommended R&D: Investigate both of the above approaches to imaging for their applicability to landmine detection. This will entail both theoretical and experimental studies. Data gathering with a single detector as well as with proposed magnetoresistive sensor arrays should be investigated.

Expected results: As with discrimination through signal processing, the imaging approach is also high risk and long term. A fieldable imaging system is not expected in the two-to-seven-year time frame. However, this research should answer some crucial questions regarding this approach, such as: Are current sensors, including position sensors, capable of providing data needed to produce an image? What are the limits on the size and depth of objects for which such data can be obtained? How quickly can a needed data set be gathered and an image produced?

Recommended level of effort: three to four PYs for five to seven years. Personnel: technologists, engineers, and scientists.

Priority: 1. This area has not been explored much. If successful, the potential benefits would be high.

Enabling Technologies

New Sensors. Magnetoresistive sensors and sensor arrays may provide an attractive alternative to the conventional EMI sensors and merit a separate investigation. Potential advantages of this technology include small size, high bandwidth, and availability of an array with a large number of elements. Both individual and arrays of magnetoresistive sensors have been investigated to replace conventional wire coils. Work on sensor arrays has stopped over the past couple of years.

Recommended R&D: (a) Further investigate the development and testing of magnetoresistive sensor arrays[2] for landmine detection,

[2]Previously investigated by Blackhawk Geometrics and NVE.

and (b) characterize the performance limits of a single sensor as a replacement for a wire coil in a metal detector.

Expected results: This research will establish whether current magnetoresistive sensors and sensor arrays can provide signals of sufficient strengths from targets of interest in antipersonnel landmine detection. If they can, such sensors will be of great help to both signal-processing and imaging efforts already described.

Recommended level of effort: one to two PYs for two years. Personnel: technologists, engineers, and scientists. Development of the basic technology of magnetoresistive sensors will continue to benefit from a number of other applications.

Priority: 1. This area has not been sufficiently explored. This is truly a new area of research in EMI detection. In spite of known problems, this area should be explored extensively because the potential benefits would be high.

Positioning Systems. Light, inexpensive, and compact positioning systems that can be integrated to a handheld detector will enable those detectors to provide real-time EMI data as a function of sensor position. Such data are needed for imaging and target localization. A few systems have been proposed to address this requirement.

Recommended R&D: Conduct a critical review of proposed systems and develop, if needed, light, compact, and inexpensive positioning systems to integrate with metal detectors.

Expected results: This research is considered low risk and short term. A suitable positioning system will greatly help target localization and imaging efforts.

Recommended level of effort: one to two PYs for two years. Personnel: technologists and engineers.

Priority: 2. There is some ongoing research in other countries that one may be able to harness.

Speed of Coverage Improvement

Current practice involves an individual deminer sweeping with a single detector and localizing targets manually using hand, ear, and eye coordination. Use of wide detector arrays as well as quick and accurate target localization should speed up the overall demining process.

Recommended R&D: (a) Develop wide detector arrays further to make them suitable for antipersonnel landmine detection, consider the possibility of person-portable arrays, and improve target localization algorithms for arrays; and (b) develop and integrate automatic target localization into current handheld systems possibly including overlaying of target positions with a photo of the scanned area. This research should be coordinated with research on positioning systems.

Expected results: This should be considered low risk and medium term. With proper focus, this research should result in fieldable improvements.

Recommended level of effort: On (a) three to four PYs for four to five years. On (b) one to two PYs for two years (this part would gain leverage from effort on positioning systems). Personnel: technologists, engineers, and scientists.

Priority: 2. Other countries are looking at some aspects of this.

Operational Improvement

Capabilities of available detectors vary widely. Proper equipment selection will make sure that the best that current EMI technology can offer is used in demining. To this end, development of an internationally accepted standard for scientific testing of EMI detectors for landmines will help improve quality and possibly speed of demining. The developed standard must include a method of unambiguously defining a "detection" that accounts for the effect of the operator. Normally an operator makes a "detection" or "no detection" decision by listening to the audio output from a detector. Such a process is obviously prone to variability introduced by the operator.

Recommended R&D: (a) Critically review existing test methodologies proposed over the years and contribute to current international efforts to coordinate development of a standard for metal detector testing for humanitarian demining. (This is considered low-risk but high-priority work.) (b) As a part of (a) or as an independent effort, develop computer processing techniques and/or experimental protocols to account for the influence of the operator.

Expected results: An objective standard for scientific testing of metal detectors used in humanitarian demining will help improve the average quality of COTS detectors.

Recommended level of effort: two to four PYs for two years. Personnel: engineers and scientists.

Priority: 1. This "low-tech" effort will have the most immediate impact on product improvement by the private sector and on humanitarian demining.

Soils Study

Analytical and Experimental Study. EMI sensors are affected by the electromagnetic properties of soil, particularly the magnetic susceptibility. Although a few detectors can cope with magnetic soils to a degree, the influence of soil electromagnetic properties on EMI sensors is not fully understood. Such an understanding will help us predict as well as improve the performance of EMI detectors in magnetic soils.

Recommended R&D: Conduct analytical and experimental study of the effect of soil electromagnetic properties (magnetic susceptibility and electrical conductivity) on EMI sensors in the specific context of landmine detection. An integral part of this work should be selection and/or development of suitable instrumentation to measure relevant soil properties.

Expected results: This research will involve significant intellectual effort from specialists and should produce: (1) a model to predict the sensor response as a function of soil electromagnetic properties and (2) a guide to characterizing soils in terms of their electromagnetic properties to help compare performance of different detectors in various soils. Results of this will also feed the effort on development of testing standards.

Recommended level of effort: three to five PYs for at least five years. Personnel: scientists and technologists.

Priority: 1. This long overdue and challenging research will provide important information of practical value.

Soil Database. An information database (and/or a soil map) of the electromagnetic properties of the top 50-cm layer[3] of soil of the landmine-affected regions of the world will be a very valuable resource. Such information will help planning of current demining operations as well as research on landmine detection.

Recommended R&D: Initiate and/or contribute to international efforts to develop an information database of the electromagnetic properties (initially magnetic susceptibility and electrical conductivity) of the top layer of soil in landmine-affected parts of the world.

Expected results: This will likely be an ongoing long-term effort. The information as it is gathered will populate an electronic database and will be immediately useful to researchers and planners.

Recommended level of effort: Cost will depend on scope of the project. Personnel: scientists, engineers, and technologists of multiple disciplines.

Priority: 3. This will be a project of large scope and some initial effort will go toward planning.

FURTHER READING

A vast literature exists on the many aspects, including field testing, of EMI detectors. The following is the latest multinational report describing comprehensive testing of COTS metal detectors for use in humanitarian demining:

Y. Das et al., eds., *Final Report of the International Pilot Project on Technology Co-operation (IPPTC) for the Evaluation of Metal/Mine Detectors*, EUR 19719 EN, June 2001 (published on behalf of the participants by the European Commission, Joint Research Centre, Ispra, Italy).

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[3]Such a database will also help R&D on other sensors.