Developing Advanced Electromagnetic Induction Methods for Landmine Detection

Davorin Ambruš, Darko Vasić, Vedran Bilas[1]

Abstract

Conventional metal detectors used in humanitarian demining feature high sensitivity to extremely low quantities of metal, but also introduce enormous false alarm rate due to their inability to discriminate between metal parts of a mine and metallic clutter. In this paper we present the current state-of-the-art in the field of advanced electromagnetic induction (EMI) methods for landmine detection. We focus on the two research topics that have the potential to significantly improve the detection of low-metal content landmines: metallic object characterisation and model-based compensation of soil effects. Also, some of the key technical issues related to the practical implementation of advanced EMI detectors are briefly discussed. At the end, the main outlines of the project DEMINED, carried out by the University of Zagreb, are presented.

1. Introduction

In the recent years, there has been numerous research efforts worldwide directed towards the development of new and improved landmine detection methods. Technologies based on various sensing modalities have been developed and tested, such as metal detectors (MD), electrical impedance tomography (EIT), ground penetrating radar (GPR), acoustical/seismic methods, electro-optical (remote sensing) techniques, nuclear quadrupole resonance (NQR) sensors, explosive vapour detection systems, smart prodders, etc. [1]. Amongst these, MD and GPR devices are still at the forefront of research and are the only ones that are currently used for close-in mine detection in the field.

The ongoing research in the scientific community in the field of landmine detection is mainly focused on the two interrelated tracks. The first one deals with improvements of existing individual technologies and devices such as MD and GPR. The second one is concerned with integration of different sensing modalities into multi-sensor systems utilizing data fusion algorithms [1].

Modern metal detectors work on a principle of low-frequency electromagnetic induction and have basically changed very little since the World War II. Their strengths and weaknesses are well-known in the humanitarian demining community, especially in terms of a trade-off between their high sensitivity and a large false alarm rate. The inability of such detectors to reliably discriminate between metal parts of a mine and harmless pieces of metallic clutter is a major problem that needs to be addressed in order to improve the overall mine detection procedure.

2. Advanced EMI methods – state-of-the-art

There is a noticeable contrast between a modern metal detector as a rather basic induction tool and advanced induction-based tools and methods of geophysical, nondestructive testing (NDT) and security applications. Such tools normally use multiple coil arrays, complex excitation patterns, advanced signal processing and inversion algorithms in order to obtain information on shape, dimensions, position, orientation and material properties of an object under inspection [2] – [5].

Some of the interesting applications of EMI methods and their technical features that could be potentially employed for landmine detection are summarized in Table 1.

Table 1. Applications of advanced EMI methods / tools.

Application	Methods and tools with possible application in humanitarian demining
Geophysical measurements	- Inductive measurement of electromagnetic properties of rocks and buried objects - Devices with multi-coil configurations and multi-frequency excitations - Fast methods for solving 'soft-field' electromagnetic inverse problems
Nondestructive testing (NDT)	- Novel inductive and magnetic sensors and sensing configurations - Application of sensor arrays - Image reconstruction techniques
Treasure hunting	- Detectors optimized for different types of metals and with different depth profiling capabilities - Original ground compensation techniques - Detector-operator interfaces
Security systems	- Metal characterization and identification methods based on dipole inversion schemes (e.g. airport security systems) - Advanced visualization techniques

In general, a promising opportunity arises for a transfer of knowledge and experience from these applications in order to improve EMI methods in humanitarian demining. Such an advanced EMI mine detection would reduce the false alarm rate compared to the conventional metal detection because it would provide not only an indication of the metallic object presence but also information on its geometry and material properties.

2.1. Metallic object characterisation

Commercial metal detectors used in field operations of humanitarian demining are usually required to conform to the CWA 14747 standard [6]. The standard defines the basic technical and operational requirements for a metal detector, as well as detector-operator interface. In general, the inclusion of additional quantitative information about the buried

[1]All authors are with the University of Zagreb, Faculty of Electrical Engineering and Computing (FER), Department of Electronic Systems and Information Processing, Advanced Instrumentation Group (AIG), Zagreb, Croatia.

object (in addition to the standard-defined audible signal) could potentially help the operator with a desicion in a classic „mine or clutter“ problem.

The characterisation and identification of metal objects usually implies the determination of the following properties [2]:

1. Size (i.e. the approximate volume),
2. Principal shape (i.e. is the object round, flat or elongated?),
3. Spatial orientation,
4. Position (burial depth),
5. Material properties (electrical conductivity and magnetic permeability).

In a practical sense, most of the landmines have some common features with respect to the properties mentioned above; relatively small burial depth up to 20 cm, vertically oriented firing pins of cylindrical shape, etc. The estimation of these parameters from field measurements can be obtained by using two different approaches: the pattern recognition approach or the model-based approach.

Pattern recognition approach

The most commonly used methods of metal object characterisation for landmine detection based on the pattern recognition approach are summarized in Table 2 [2] [7].

Table 2. Methods of metallic object characterization based on the pattern recognition approach.

Method	Features	Problems
Statistical processing of raw detector signals	- Classification methods based on support vector machines (SVM) and similar algorithms.	- Large data sets needed. - Object libraries often not available.
Method using basic features of the detector response (phase-shift / decay constant)	- Coarse estimation of object size and material type (ferromagnetic or non-ferromagnetic). - Possible alternative: classification based on a time-frequency representation of a detector signal.	- Potentially useful method for a simple discrimination of UXO, not directly applicable to low metal content landmines.
Phase-plot method	- Specific target signatures give information on object size, shape and material type. - Intuitive visualization with 2D diagrams.	- Highly orientation dependent response. - Problems with elongated ferromagnetic objects.
EMI spectroscopy	- Classification based on object's complex spectral signatures. - Excitation spectrum typically between 30 Hz and 50 kHz.	- The same as for the phase-plot method. - Signatures not distinctive enough.
EMI imaging	- Image of the buried object produced by precise scanning over the suspected area with a known excitation field distribution.	- Low resolution. - High sensitivity to signal-to-noise ratio. - Very precise positioning of a detector needed.

This method is based on a comparison of the measured set of data obtained from the unknown object with a respective set of data corresponding to the known object. Some classification criteria are then applied in order to characterize the object under inspection. The first step in this process is usually to perform some kind of feature extraction in order to reduce the initial data set and loosen the requirements for the pattern recognition algorithms.

Model-based approach

State-of-the-art of the methods of inductive metallic object characterization relying on the model-based approach is given in Table 3 [8] – [10]. Simulation and evaluation of these methods is usually performed by using some numerical procedures, such as those based on the finite-element method (FEM).

Table 3. Methods of metallic object characterization relying on the model-based approach.

Method	Features	Problems
Simple analytical models	- Models of objects of canonical shapes (spheres and cylinders) in homogenous half-space. - Useful for physical insight of the problem	- Not directly applicable to the landmine detection problem.
Induced dipole model	- Object modeled by the magnetic polarizability tensor which fully characterizes the object properties in terms of size, shape, orientation, position and material properties. - Dipole approximation enables fast inversion algorithms. - Intuitive interpretation of the tensor elements.	- Further research needed on the method applicability to discriminating low metal content landmines from metallic clutter. - Potential problem with large/composite metallic objects.
Variations of the induced dipole model	- Models based on combinations of multiple dipole elements for better characterization of complex objects (quadrupole, dumbbell dipole models, etc.)	- Further research needed, not as straightforward as simple dipole models.
Standardized excitation approach (SEA)	- Method suitable for modeling large, heterogeneous objects (such as UXOs) where internal interactions between different metal parts of an object cannot be neglected (non-dipole effects).	- Fast inversion procedures more difficult to implement (when compared to simple dipole approximation).
Simple parametric models	- Object response most commonly described by a set of poles / own frequencies.	- Orientation dependent, suitable only for very simple targets.
Empirical models	- Object response is fitted to an empirically derived model featuring only a few model parameters.	- Orientation dependent, only valid for a very limited range of objects.

The aim of this approach is to reconstruct the unknown parameters of a mathematical model that relates the voltage induced in a detector coil with the geometrical and electromagnetic properties of a buried object. In other words, an inversion problem needs to be solved, which is for a general case of EMI detection non-linear and ill-posed [8]. Characterization and classification of metallic objects is then performed based on the estimated model parameters.

In comparison with the pattern recognition approach, this method can potentially provide deeper insight into the nature of the buried object since it strongly relies on the physical background of the problem. However, the model-based approach is also more difficult to implement in a practical EMI detector. To the best knowledge of authors, besides some experimental prototypes built at universities and other research institutions (mainly for UXO detection), there are still no commercial EMI landmine detectors for humanitarian demining that utilize this principle [9].

Amongst all of the model-based methods of metal characterisation mentioned above, the method based on dipole inversion seems to be the most promising candidate for implementation into next-generation metal detector devices for humanitarian demining. Although the significant research is still needed on the dipole-based modelling of landmines (and clutter), the method looks fairly straightforward to implement and is already field-proven in other applications, such as security and geophysical inspection systems [5] [8].

2.2. Model-based compensation of soil effects

Modern metal detectors used in humanitarian demining and conforming to CWA 1747 standard always employ some sort of ground compensation technique in order to minimize the effects of non-cooperative soils on metal detector performance [6]. Ground compensation is usually performed in one of the following ways (with either manual or automatic controls) [2] [11]:

1. High-pass filtering of the detector signal which aims to cancel the slowly-varying signal component corresponding to variations of soil properties.
2. Subtraction of the soil signal component by applying a simple phase correction (soil signal is used as a reference for the synchronous demodulation).
3. Compensation techniques based on frequency-differencing approach (basically a subtraction of detector responses obtained at two different frequencies).
4. Techniques based on excitation pulses of variable duration in which the responses from metal targets and magnetic ground have different signal features, making them distinguishable in time-domain.

In general, the sensitivity of a metal detector to electromagnetic properties of soil is also influenced by the sensing head, i.e. coils design. All of the existing ground compensation methods have some apparent drawbacks. These are reflected either as a decrease of the detector sensitivity or in some cases as a loss of information on target material properties [2].

New approaches to compensation of soil effects rely on developing appropriate mathematical models of soil. These models describe the spatial variation of soil electromagnetic properties (electrical conductivity and frequency-dependant magnetic permeability). If the parameters of the soil model could be estimated from the detector measurements by a fast inversion procedure, then the soil EMI response could be subtracted from the total detector response without significantly affecting the metal detection and characterisation performance.

The models of soil related to the landmine detection problem that have been reported in the literature concentrate mostly on paramagnetic soils with viscosity effects (Cole-Cole model) [11]. In general, these types of soil correspond to a worst-case scenario for commercial metal detectors. The soil is usually modelled as a half-space (with a single or multiple layers). More complex models also take into account the roughness of the soil surface using some numerical procedures (e.g. the method of auxiliary sources, MAS).

3. Advanced EMI landmine detectors – implementation challenges

When it comes to practical implementation of the next-generation EMI landmine detectors (featuring inductive metal characterisation and model-based soil compensation), there are several critical design issues that need to be specifically addressed:

1. Sensing head position and orientation tracking system with sub-centimetre accuracy. This system is essential for the implementation of inversion procedures of metal characterization.
2. Accurate and field-proven model of soil including possible specific features of a particular mine suspected area.
3. Fast inversion algorithms that can operate in a real-time manner, determined by operational procedures and requirements for the existing handheld metal detectors.
4. Operator interface that features additional information without compromising the robustness and ease of use of existing devices.

4. DEMINED project

Having in mind the limitations of existing metal detector technology and based on its expertise in electromagnetic sensors and electronic systems, the Advanced Instrumentation Group (AIG) started the project DEMINED aimed at the development of an advanced EMI detector for landmine detection[2].

The expected results of the project are proof-of-principle and experimental demonstrator of the next-generation EMI detector. The detector would have the two main features: metallic object characterization (based on dipole inversion) and model-based ground compensation (based on field-proven model of soil). A new laboratory set-up will be developed for experiments with standard test targets that simulate metal components of mines (ITOPs [6]) and metallic clutter items. Developed tools and methods would be evaluated on HCR-CTRO test sites.

First prototype of a sensing head, developed by AIG is shown in Figure 1. The sensing head consists of two transmitter coils and a single receiver coil utilizing the magnetic cavity principle. The proposed design enables laboratory experiments with different excitation sources (both continuous and pulsed) and verification of novel concepts of model-based metal and soil characterisation. The final sensing head design will be optimized with respect to multiple criteria such as metal sensitivity and overall quality of sensor data needed for inversion procedures.

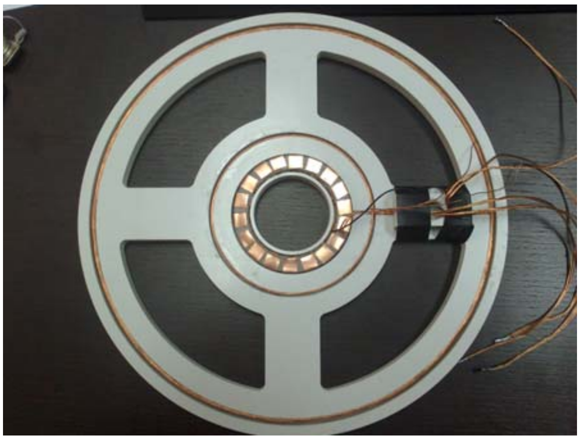

Figure 1. 1st prototype of a sensing head developed by AIG.

5. Conclusion

In order to overcome the well-known limitations of existing metal detector technology next-generation advanced EMI detectors are needed. These detectors incorporate some of the novel methods for metallic object characterisation, with a potential to significantly reduce the false alarm rate. The characterisation method based on dipole inversion is a promising candidate for practical implementation in the field. Furthermore, novel methods of ground compensation relying on field-proven models of soil could bring new possibilities in metal detector operation over non-cooperative soils. For a practical implementation of these novel concepts in humanitarian demining there are still numerous technical challenges to be resolved. DEMINED project is a small step in that direction.

---

2 Within the project scope, AIG is also collaborating with the research group from the University of Manchester, Sensing, Imaging and Signal Processing Group (SSIG).

Acknowledgment

This work has been supported by the European Community Seventh Framework Programme under grant No. 285939 (ACROSS). The research is also supported by Croatian Mine Action Center – Center for Testing, Development and Training (HCR-CTRO) through expertise and help during the testing phase. The presented work is a continuation of longstanding research activities in the field of landmine detection, led by the members of the HCR-CTRO Scientific Council professors Vladimir Knapp and Hrvoje Babić.

References

[1] K. Furuta, J. Ishikawa, *Anti-personnel Landmine Detection for Humanitarian Demining*, Springer-Verlag London Limited, UK, 2006.

[2] C. Bruschini, *A multidisciplinary Analysis of Frequency Domain Metal Detectors for Humanitarian Demining*, PhD Thesis, Vrije Universiteit Brussel, Belgium, 2006.

[3] D. Vasić, V. Bilas, "Application of stochastic inversion to casing effect correction in through casing induction logging", *IEEE Transactions on Instrumentation and Measurement*, 61 (2012), 5, pp. 1458-1465

[4] D. Vasić, V. Bilas, D. Ambruš, "Validation of a Coil Impedance Model for Simultaneous Measurement of Electromagnetic Properties and Inner Diameter of a Conductive Tube", *IEEE Transactions on Instrumentation and Measurement*, 55 (2006), pp. 337-342.

[5] L. A. Marsh, *et al.*, "Inversion of the Magnetic Polarizability Tensor at a Single Frequency from Walk-through Metal Detector Measurements", *6th International Symposium on Process Tomography*, 2012, Cape Town, South Africa.

[6] CWA 14747: Humanitarian Mine Action – Test and Evaluation - Metal detectors, CEN Workshop Agreement, CEN, 2003.

[7] I. J. Won, „Electromagnetic Induction Spectroscopy for Clearing Landmines“, *IEEE Trans. Geos. Rem. Sens.*, vol. 39, no. 4, pp. 703-709, April 2001.

[8] C. E. Baum, *Detection and identification of visually obscured targets*, Taylor & Fancis, USA, 1998.

[9] J.P. Fernandez„ *et al.*, „A Man-Portable Vector Sensor for Identification of Unexploded Ordance*", IEE Sensors Journal*, vol.11, no. 10, October 2011.

[10] F. Shubitidze, et al., „A standardized excitation approach for classification of buried UXO", *Proceedings of the Geoscience and Remote Sensing Symposium*, IGARSS, 2004.

[11] Y. Das, "Effect of Soil Electromagnetic Properties on Metal Detectors", *IEEE Trans. Geos. Rem. Sens.*, vol. 44, no. 6, pp. 1444-1453, June 2006.