Metal Detectors for Humanitarian Demining: from Basic Principles to Modern Tools and Advanced Developments

Claudio Bruschini

EPFL-LAMI, INF-Ecublens, CH-1015 Lausanne, Switzerland

Tel. +41 (0)21 693 3911, Fax. 5263

E-mail: Claudio.Bruschini(AT)epfl.ch, Web: http://diwww.epfl.ch/lami/detec/

ABSTRACT: We will focus on the low frequency electromagnetic detection of metallic objects, concentrating in particular on induction devices ("metal detectors") and their application to Humanitarian Demining. We will begin by reviewing the basic principles of such systems, having a look at some features of the primary and secondary magnetic field and of the induction mechanism.

The introductory part will be followed by a description of present-day commercial systems, which are the result of many years' efforts in increasing sensitivity and autonomy, and mastering background rejection and ergonomics. The last section will then focus on advanced developments and how they could be used with profit in Humanitarian Demining, possibly in selected scenarios.

Keywords: humanitarian demining, metal detectors, electromagnetic induction, imaging systems

Introduction

Detection and clearance are still being very often carried out in Humanitarian Demining using manual methods as the *primary procedure*. *When operating in this way* the detection phase still relies heavily on metal detectors (see Fig. 1), whereby each alarm needs to be carefully checked until it has been fully understood and/or its source removed [1]. This is normally done visually, and by prodding and/or excavating the ground.

Unfortunately, metal detectors cannot differentiate a mine (see Fig. 3) or UXO from metallic debris (an example is shown in Fig. 2). In most battlefields, but not only there, the soil is contaminated by large quantities of shrapnel, metal scraps, cartridge cases, etc., leading to between 100 and 1,000 false alarms for each real mine. Each alarm means a waste of time and induces a loss of concentration [1]. When manual methods follow other procedures, such as mechanical clearance, constraints on the need to check each alarm are often somewhat relaxed.

In the following we shall more closely focus on metal detectors and how their use in humanitarian demining could be improved, possibly using input from other fields in which similar devices are used with profit.

Theoretical Background

The detectors we will consider are electromagnetic sensors exploiting low frequency electromagnetic fields up to some hundred kHz roughly. These sensors are capable of detecting metallic objects buried in the ground at usually shallow depth, whilst indirectly providing "limited" information on their nature (depth, shape, size, etc.). Proximity to the surface is usually required.

Fig. 1: HALO Trust deminer in Cambodia, checking the ground with an Ebinger 420SI metal detector

Fig. 2: Example of metallic debris (ruler: 25 cm long)

Fig. 3: Chinese Type 72 mine minimum-metal AP mine (78 mm large, 38 mm high)

Metal Detectors (Electromagnetic Induction Devices)

Metal detectors, actually electromagnetic induction devices, are usually composed of a search head containing one or more coils carrying a time-varying electric current. The latter generates a corresponding time-varying magnetic field which “propagates” towards the metallic target (and in other directions as well). This primary field reacts with the electric and/or magnetic properties of the target (the soil itself or any metallic object), which responds to it by modifying the primary field or, as a more accurate description, by generating a secondary magnetic field. This effect links back into the receiver coil(s) in the search head, where it induces an electrical voltage which is detected and converted, for example, into an audio signal [2].

The secondary field depends, both temporally and spatially, on a large number of parameters such as the distance, material type, orientation, shape and size of the buried object, but target characterisation is very difficult in the general case. The secondary field is due to eddy currents, which are induced by the primary field in conductive materials. Low conductivity metals, such as some alloys and stainless steel, are in general more difficult to detect, whereas the detector’s response is magnified for ferromagnetic objects (induced magnetisation).

In the case of a circular coil of radius R for example, the primary field behaves at a distance z on the coil axis as $1/(R^2+z^2)^{3/2}$, i.e. decreases with the cube of the distance far away from the coil. Given that the secondary magnetic field has to “propagate” all the way back to the receiver coil(s) it is not surprising that the “art” of building metal detectors consists, in a certain sense, in discriminating small target signals from background signals. Smaller coils provide better sensitivity (at closer ranges) and spatial resolution, but do not allow to go as deep, and scan as fast, as the larger ones.

Frequency and Time Domain Metal Detectors

Metal detectors can be subdivided in Frequency Domain, or Continuos Wave (CW), and Time Domain systems. Frequency Domain instruments make use of a discrete number of sinusoidal signals, very often just one. They can employ separate transmit/receive circuits, and the measurement of the amplitude and phase of the received signal in background conditions can be used to reject part of the background signal itself.

Time Domain, or "pulse", instruments work by passing pulses of current through a coil (typical repetition rate of the order of 1 kHz), taking care to minimise the current switch-off time (a few μsec). Eddy currents are thus induced in nearby conductive objects and their exponential decay with time observed. The eddy current decay time constant itself, some hundred μsec, depends (predominantly) on the target's conductivity, permeability and size. Pulse systems are the detector of choice when it comes to working in salt water or strongly mineralised soils.

Metal Detectors for Humanitarian Demining

Metal detectors for humanitarian demining are capable of detecting tiny amounts of metal, from a fraction of a gram onwards, at shallow depths. They mostly share the following characteristics:

- **Weight**: less than 2 kg. **Price**: in the 2000-4000 EURO range.
- **Size**: round, oval or rectangular head. In the former case the diameter is between 20 and 30 cm, to achieve sufficient depth and a reasonable scanning surface and speed.
- **Operating depth**: shallow, i.e. from flush (even with the surface) down to about 10-15 cm for minimum-metal mines, 20-30 cm for mines with an appreciable metallic content, and about 50-70 cm for large metallic objects such as UXO or metallic mines.
- **Electrical/Mechanical**: capable of working with standard cell batteries for a long time (tens of hours), and usually simple to use. Many demining teams pay more attention to the ergonomics rather than to the pure performances of the detector itself.
- **Output**: normally an audio signal, usually already the result of extensive internal data processing**,** from which an experienced operator can make some qualitative statement on the target and its position. When using manual methods as the *primary procedure*, **each** alarm is carefully checked until it has been fully understood and/or its source removed.

These detectors have indeed become more and more refined and sensitive over the years, and it has been often said that they have reached their limits. In fact there are a number of other technical fields in which metal detectors are used with profit to deliver additional information on the object under study, albeit often for specific cases only.

Imaging Metal Detectors: Input from Civil Engineering Applications

One of the fields mentioned above is civil engineering, in which we identified and tested a commercial "imaging metal detector" [2], trying to assess its potentialities and understand if such systems could be useful to "provide the deminer with a visual image of shape and size of the metal signature" [1] (being well aware that spatial resolution and depth penetration constitute conflicting requirements). Results could be a priori expected for "larger" metallic objects of regular size, such as UXO (Unexploded Ordnance), and to be useful in regions where only a few type of mines exist and one has to differentiate them from metallic debris.

Civil Engineering Applications

Cylindrical reinforcing bars in concrete are widely employed in civil engineering and are mostly made of steel. They can be detected and characterised using metal detectors, whose head sizes are normally much smaller than the ones employed in humanitarian demining. They are therefore more accurate at shallow depths (increased spatial resolution) and able to resolve closely spaced objects, but lack in depth of penetration given that the detection range is strongly related to the coil dimensions.

The Ferroscan System

The Ferroscan system (Fig. 4) is targeted at the visualisation of steel rebars in concrete; it uses a multi-sensor and differential detector, basically measuring (an approximation of) the horizontal gradient, along the scanning direction, of the vertical component of the induced magnetic field. The differentiated signal curves can then be used to produce a composite bidimensional grey scale image [3]. The data processing is tuned to ferromagnetic objects.

Fig. 4: Ferroscan RV 10 monitor (left) and RS 10 scanner (right) (ruler length: 30 cm)

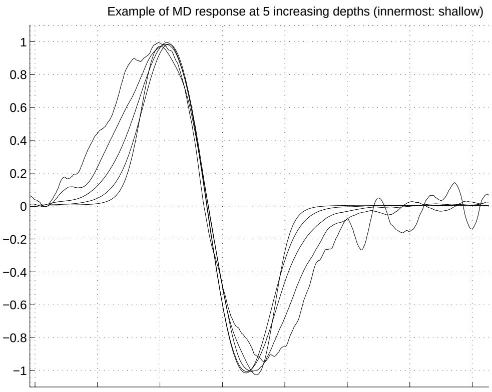

Fig. 5: Example of Metal Detector response at 5 increasing depths (general trend, differential sensor, line scan over the object)

Tests in the “Sandbox” and Discussion

A number of objects were tested in a “sandbox” at different depths, in particular (Fig. 6):

- *PMN* “like” AP mine: a “classical” AP mine, diameter 11 cm, height 5 cm, with cover retaining ring (ferromagnetic!) placed at about 1.5 cm from the top. The cover retaining ring is clearly visible (Fig. 6 left half), with the darker spot probably corresponding to the area around the pin used to secure the ring.
- *BLU 26 “bomblet”*, round (65 mm diameter), 430 grams. Large quantities of similar UXO are still found in Laos for example. Its mixed nature is probably at the origin of some of the complex image details displayed (Fig. 6 right half).

Images of the objects are shown up to a depth which gives roughly, *with the current hardware and data processing*, reasonable images, but which has not to be taken as a precise indication of the actual sensor performances. In general an object’s image gets larger with increasing depth, as expected (see also Fig. 5).

Preliminary Conclusions

We can summarise our findings as follows:

- Ferroscan images are indeed a precious aid in localising and interpreting the underlying metallic structure, without pretending to deliver a true representation of it. This task has been solved by employing multi-sensor hardware and simple and elegant data processing software. Imaging in civil engineering is “eased” by the fact that the nature of the problem is rather well defined a priori.

- The multi-sensor arrangement is practical to rapidly scan a large area, and its resolution looks indeed sufficient for large or extended objects such as AP mines with relevant metal content and UXO. On the other hand using more than one sensor, and the differential arrangement itself, have some side effects on the visualisation of smaller isolated (ferromagnetic) objects, for which the system was indeed not intended, and in presence of edges. In these cases a single sensor might be scanned in more detail over the object, possibly providing a more accurate image. In any way, the increased spatial resolution comes as expected at the price of decreased depth penetration.

The images obtained confirm that this approach is potentially interesting, especially if one has to look for (larger) ferromagnetic objects. Detailed imaging of smaller objects is and remains a very challenging task.

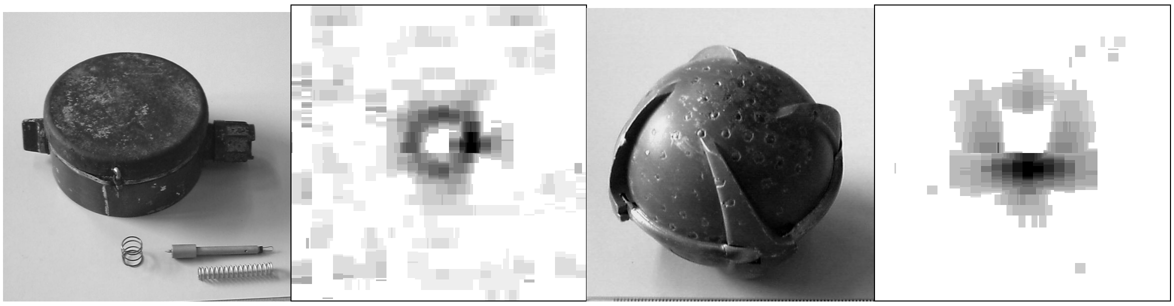

Fig. 6: PMN AP Mine, image at a depth of 1.6cm; BLU 26 "bomblet", image at a depth of 5cm (both: 60x60cm)

Imaging Metal Detectors: Deconvolution Approach

Another way of obtaining an "image" is to scan a single sensor over a surface to then try to deconvolve the detector's intrinsic response from the acquired data. A knowledge of the detector's response to a point-like object (Point Spread Function, or PSF) is mandatory in such a strategy, and can be obtained either theoretically by modelling the detector's response, or experimentally via direct measurements on small objects for example. We note in passing that the PSF will certainly be a function of the object's depth (see Fig. 5). Whether this approach will be practically applicable in the field, from the point of view of the resulting resolution, scanning speed and cost for example, remains to be demonstrated.

Other Advanced Developments:

Object Characterisation:

As we have seen in the introduction to metal detectors, their internal signals do depend on the nature of the object under study, its depth and size. It is therefore very tempting to try to harness at least part of this information. *Fig. 7* shows an example, for a two-frequency continuos wave instrument, of how information on the target's nature can be contained in the amplitude and phase of the received signal. Multifrequency systems might lead to some kind of "induction spectroscopy", and similar arguments are valid for pulse instruments.

In an ideal case one might provide object classification (mine or debris) or identification (mine type), possibly starting from a database of templates. Even without going that far it might still be possible to extract valuable additional information for the deminer, for example small object *vs.* large object. Problems with this approach are again represented by weak target signals and irregular background signals, nearby objects distorting the response, and obviously by the presence of unforeseen or unaccounted objects. The response signal does also depend on a large number of parameters such as the object's orientation, the exact metal type, etc.

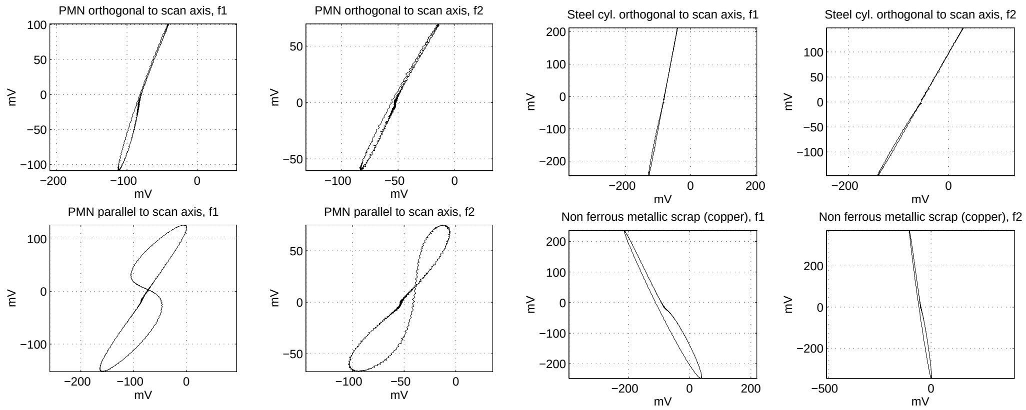

Fig. 7: Example of amplitude and phase dependencies when passing with a Continuos Wave detector, using two frequencies f1 and f2, over a PMN mine and two other objects.

Information on an object's depth should also be among the most easily recoverable object parameters. It could be delivered for example either by scanning the detector across the object and analysing the width of the response (or other parameters; see again Fig. 5), or by taking at least two measurements under different conditions, for example employing two overlapping coils. Some of these techniques are in use for Non Destructive Testing applications, but the need of having to be careful here can not be stressed sufficiently.

This last point is even more true when it comes to giving an estimate of the object's size, which would undoubtedly be an interesting piece of information. One way of doing it consists in measuring the magnetic field over an area in order to try to calculate an object's magnetic dipole moment (typically using a simple, dipolar model), which gives an indication of its "magnetic" volume. Again, applicability in the field and sources of errors have to be very carefully studied.

Sensors other than Standard Coils (Hardware Improvements):

It has been suggested to study sensors other than the ordinary coils currently used in metal detectors, for example giant magnetoresistive elements, or miniature fluxgate elements. They are expected to be broadband and provide better spatial accuracy; the construction of linear or bidimensional arrays should also be possible, delivering some kind of localised "image" of the soil metallic/magnetic contents. On the other hand their overall sensitivity is likely to be smaller, which might very well discourage their use for certain applications (their use might for example be envisaged for the detection of UXO or mines with a relevant metal content, but not for minimum metal mines).

Another direction of research could consist in the study of "improved" magnetic field shapes, for example more compact than what obtained with ordinary circular or rectangular coils, or featuring some other special structure (e.g. spatially periodic).

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