Metal Detectors in Civil Engineering and Humanitarian Demining: Overview and Tests of a Commercial Visualizing System

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Summary

After a brief introduction to Humanitarian Demining we will review the basic principles of the electromagnetic detection of metallic objects, especially induction devices ("metal detectors"), and see how they are applied in Humanitarian Demining and Civil Engineering, with emphasis on visualization techniques. We will then report on tests of a commercial "imaging metal detector" aimed at trying to assess its potentialities and understand in a broader sense if such systems, possibly in a modified form, could be useful to tackle some aspects of the Humanitarian Demining problem. The latter include the detection of non minimum-metal mines and shallowly buried Unexploded Ordnance (UXO).

Humanitarian Demining

The world's attention has been often captured, during these last years, by the landmine problem and its devastating effects on the civilian population. The latter can very well be indirect, in terms of denying access to arable land, infrastructure and housing for example.

These "weapons of terror", especially the antipersonnel (AP) mines, are indeed often cheap, easy to manufacture and exceedingly often used by the warring factions without keeping detailed records. Ordinary ("dumb") landmines can stay active for decades and, even if normally placed close to the surface (flush to some cm deep), can be displaced from their original position as a consequence of natural events such as floods or drifting sands. Unexploded Ordnance (UXO), i.e. munition which has not detonated (usually due to failure), has very often to be cleared as well before being able to declare an area as safe.

Needless to say, for humanitarian demining a detection rate approaching perfection, i.e. 100%, must be obtained. Time is less important than accuracy.

Detection and clearance are still being very often carried out using manual methods, whereby the problem is normally in the detection phase. Once a mine has been found, deminers know well how to remove it or blow it up. Metal detectors continue to be the industry's "workhorse" (see Fig. 1), whereby each alarm needs to be carefully checked until it has been fully understood and/or its source removed [1] [2].

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

This is normally done visually and by prodding the ground, i.e. scanning the soil at a shallow angle of maximum 30° using long rigid sticks of metal. Each time the deminers feel something, they must check the contour of the object to determine if it is a mine. This is dangerous because the mine could have moved and the sensitive surface turned towards the operator. Sometimes prodding is the only way to explore the ground.

The clearance rate achieved in this careful, thorough but slow way does not usually exceed 100 m^2 per deminer per day. Indeed, metal detectors cannot differentiate a mine or UXO from metallic debris (an example is shown in Fig. 2). In most battlefields, but not only there unfortunately, 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 [3].

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

In the following we shall more closely focus on metal detectors and how their use in humanitarian demining could be improved, possibly using input – especially visualization techniques – from other fields, such as civil engineering, in which similar devices are used with profit. Novel detection techniques, the use of dogs and mechanical demining are unfortunately outside the scope of this paper.

In particular we will try to assess the potentialities of a commercial "imaging metal detector", to understand if such systems, possibly in a modified form, could be useful to tackle some aspects of the humanitarian demining problem along the lines[1] proposed in [3]. In fact, given that spatial resolution and depth penetration constitute conflicting requirements, we do not expect them to

[1] "First generation equipment [] could provide the deminer with a visual image of shape and size of the metal signature."

be applicable to humanitarian demining "as is".

Results could be a priori expected for "larger" metallic objects of regular size which have to be differentiated from metallic debris often consisting of small metallic pieces scattered around. Examples are mines with an appreciable metallic content (some grams) such as the Russian PMN or PMN2, or shallowly buried Unexploded Ordnance (UXO) such as "bomblets" which still plague some areas (e.g. Laos). Minimum-metal mines such as the Chinese Type 72 (see Fig. 3) contain less than a gram of metal and seem much less likely to profit from such a system alone, in the sense that an image of a pointlike object would be of help to the deminer, but in itself probably insufficient to take a yes/no decision.

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

Electromagnetic Detection of Metallic Objects

The detectors we will consider are electromagnetic sensors which usually either exploit static magnetic fields, or 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 providing "limited" information on their nature (depth, shape, size, material, etc.). Direct contact with the surface is not necessarily required, but proximity might well be.

Magnetic Devices

Magnetic devices rely on the influence of nearby ferromagnetic objects, either via induced or via residual magnetization, on a magnetic field which they can generate themselves, or which can be naturally occurring.

Instruments of the first kind are active; they can for example measure changes in a magnetic circuit's properties, such as its magnetic reluctance, or directly map the deformation ("flux leakage") of the static magnetic field they produce [4]. They are being used or proposed for civil engineering applications (rebar locators, cover meters) [5].

Instruments of the second kind are passive, not radiating any energy, and typically measure tiny disturbances of the earth's natural magnetic field; they are called magnetometers, or gradiometers when used in a differential arrangement. These very sensitive devices are usually employed to detect large ferromagnetic objects such as UXO and can be effective to depths of several meters [6], but do not react to non ferromagnetic targets. They are only used in humanitarian demining when a real need exists.

In the following we will therefore concentrate our attention on electromagnetic induction devices, which are technically similar and routinely used in both civil engineering and humanitarian demining.

Electromagnetic Induction Devices ("Metal Detectors")

Electromagnetic induction devices, which are the ones often referred to when speaking of "metal detectors", 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 (or incident) field reacts with the electric and/or magnetic properties of the target, usually the soil itself or a solid structure, and any metallic object contained in it. The target responds to it by modifying the primary field or, as a more accurate description, by generating a secondary (or scattered) 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 [7].

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. Target characterization is very difficult in the general case, but there are a number of situations where some (limited) statements on its nature can be issued.

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 due to the high value of their relative permeability (induced magnetization).

Eddy currents circulate mostly on the surface of the metallic target ("skin effect"), which explains why these devices are mostly surface area detectors. As a rule of thumb, larger objects will generate more eddy currents, but an object with twice the surface will not be found twice as deep.

Indeed, 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.

Note also that the primary magnetic field generated at the surface by a coil carrying a given current gets smaller as the coil gets larger, but decreases less rapidly with distance, and that smaller receiving coils pick up a correspondingly smaller fraction of the secondary field. Smaller coils provide therefore 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 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, measuring the (small) change in mutual inductance between the transmit and receive coil(s) caused by the presence of metallic or magnetic objects. A single coil can also be used, whereby its change in impedance is detected by measuring for example the damping of a (fixed frequency) resonant circuit, or the frequency shift of an oscillator in which the coil acts as the inductive element.

Information on the target's nature is contained in the amplitude and phase of the received signal, or equivalently in the real and imaginary part of the probe's complex impedance, as the detector approaches the target. Their measurement in background conditions can be used to reject part of the background signal itself, especially in areas in which the detector's performance would otherwise be seriously degraded, such as sea beaches (salt water is conductive) or strongly mineralized regions, which can be conductive or iron rich. Generally speaking, background rejection is more difficult in nonhomogeneous areas.

Time Domain Metal Detectors

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. A Time Domain metal detector measures in other words how quickly the momentarily generated magnetic field breaks down, which happens to be slower in presence of metal [7].

The eddy current decay time constant itself, some hundred μsec, depends (predominantly) on the target's conductivity, permeability and size. Low conductivity background and nuisance items, such as sea water and thin foils for example, have a very short decay time. A pulse detector, which is tuned to sample only a specific portion of the received signal, can therefore be "easily" made insensitive to them by an appropriate choice of the delay (some tens of μsec) between switch-off and sample. A similar argument applies to purely magnetic but nonconductive targets, which are magnetised by the transmit pulse but demagnetise just as promptly after switch-off. On the other hand overall sensitivity is probably reduced too in comparison with Frequency Domain detectors, and there can be problems in finding low conductivity metallic object such as those made of stainless steel.

Given that the transmit and receive phase are temporally separated, pulse detectors can use one and the same coil for transmitting and receiving; the decoupling of the two phases also allows to work with high power, and therefore to go deeper. Power consumption might obviously become an issue.

We shall now have a closer look at how metal detectors are actually employed in the domains of interest to us.

Metal Detectors for Humanitarian Demining

Metal detectors for humanitarian demining are remarkable active sensors capable of detecting tiny amounts of metal, from a fraction of a gram onwards, at shallow depths. Frequency Domain systems are often the choice because they seem to work well especially for very small and close objects, but they are being more and more challenged by pulse systems, and not only where ground conditions are severe. They share the following characteristics (true for most models):

- Weight: less than 2 kg.
- Size: round, oval or rectangular head. In the former case the diameter is between 20 and 30 cm, with thickness of about a couple of cm.
- Operating depth: shallow, i.e. from flush (even with the surface) down to about 10 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, from which an experienced operator can make some qualitative statement on the target and its position. In any case, 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, such as for example its depth, size or identity, albeit often for specific cases only (such as rebars embedded in concrete). Some systems capable of delivering a 2D "image" of buried metallic objects are available or under study, and on these we will focus our attention from now on.

Imaging Systems

"Conventional" metal detectors can indeed be used to generate bidimensional images of buried metallic objects, but up to now only a few (limited) practical implementations – which could be interesting for us – have been carried out. Most of them focus on the detection and imaging of larger objects such as UXO; we are aware of the following developments:

- ODIS (Ordnance Detection and Identification System) is a vehicular system conceived to provide the user with quantitative information (relying on database supported inversion) on shallowly buried ordnance and to deliver unprocessed images (not deconvolved) [8] [9]. The latter are very useful to spatially localize the single objects, which is essential in a real-time constrained vehicular operation. However, by themselves, these images probably do not allow to distinguish one object from another, except for "large" objects" (i.e. of size comparable to the detector's dimensions), because of their resolution. Further developments might have taken place since this information was published.
- Studies are being carried out on a "nearfield holographic" data processing technique aimed at reconstructing the magnetic field distribution in the horizontal plane at various depths in the ground, to localize and possibly resolve near-surface buried metallic objects [10] [11].
- Arrays of metal detectors have also been built, such as the Schiebel VAMIDS system [12], but their application as imaging detectors is limited.

Metal Detectors for Civil Engineering Applications

Smaller objects such as reinforcing bars, widely employed in civil engineering, are closer to what might be interesting for us. They are mostly made of steel, cylindrical, with diameter between 6 mm and 50 mm, and usually located from just underneath the surface to 18 cm maximum in depth (the shallow location being more frequent).

Rebars in concrete can be detected and characterised using metal detectors, whose task is definitely eased by the rebars' ferromagnetic nature. The stainless steel ones, which are often used for specialized applications, represent in fact a problem of their own for low frequency electromagnetic detection, given that they are poor electrical conductors and usually (austenitic alloy) non magnetic too [13]!

Simple instruments are only able to locate the rebars, whereas more advanced ones can also calculate the distance ("cover") from the surface to a rebar of known size and characteristics (this allows to precalibricate the instruments), usually operating by direct contact on a flat surface. Precision on cover measurement can attain some percent of cover, down to about one mm in the most favourable cases.

The most recent instruments, such as the one shown in Fig. 4, are also able to estimate both cover and rebar size (diameter) by taking at least two measurements of the same rebar under different conditions. Several techniques are available[2], such as [4]:

- Taking the second measurement with the search probe spaced away from the surface by a known amount (or by employing two coils one on top of each other).
- Rotating the search probe by 90° ("orthogonal" measurement using a directional search probe).
- Scanning the probe across the bar and analysing the width of the response, which has been shown to be a simple function of the effective width of the search probe and the distance from the surface to the centre of the rebar.

Fig. 4: An example of an advanced cover meter: Protovale CM9 CoverMaster®

Different head sizes are sometimes proposed by the manufacturers, and 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, which is especially useful in "congested" situations, but lack in depth of penetration given that the detection range is strongly related to the coil dimensions.

Such systems, especially when applied as imaging tools, can indeed exploit the fact that rebars are shallowly placed regular structures composed of ferromagnetic objects, usually lying in a plane, whereas the humanitarian demining world is obviously much more complex (small and irregular objects, ground inhomogeneities, large number of varying scenarios, etc.). The rejection of the background signal, for example due to moisture, is therefore also somewhat less problematic in civil engineering applications.

Imaging Systems

Work on "imaging" devices is indeed in progress, with at least a couple of systems on the market. Note that single sensors have normally to be scanned on the area of interest, which can be time consuming; devising a simple and accurate tracking and positioning system is also far from trivial. Multi-sensor systems can ease the task at the price of higher cost and somewhat increased complexity. Example of developments include the following:

- The University of Kassel has been working on an imaging inductive rebar locator, which uses IR sensors for accurate position measurements (0.5 mm) on a 2D grid of lines [14] [15]. Priority has then been moved to data analysis and sensor optimisation[3] rather than on imaging aspects (although, concerning the latter, interest in a high resolution tracking system remains).
- The University of Manchester is working on an inductive rebar locator and on image processing (enhancement) techniques, such as deconvolution (*Fig. 5c,d*) using an accurately modelled response function, to sharpen the response. This might require the knowledge of the object's depth. Their laboratory prototype uses a high resolution positioning frame and a sensor which is physically much smaller than a "conventional" metal detector (*Fig. 5a*), to improve spatial resolution [16] [17]. The development of a multi-array sensor with a new sensor head is currently being pursued (see also [18]).

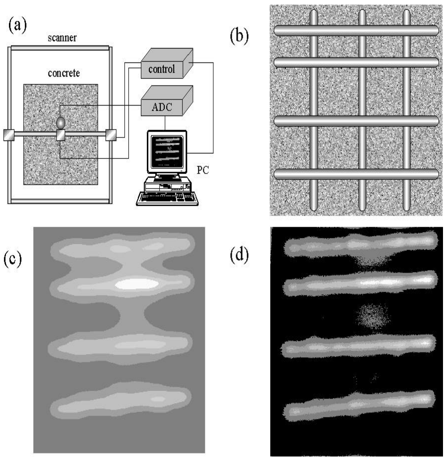

Fig. 5: Prototype high resolution imaging metal detector (F. Gaydecki, Manchester [17])

- The Profometer4 cover meter developed by Proceq. In addition to the usual functions it is possible to fit its probe with a path measuring device and, after scanning a surface along the x and y direction, rebars can be located and displayed on a LCD monitor as shown in Fig. 6.

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2 Their transposition to humanitarian demining applications would indeed also deserve to be investigated in more detail!

3 W. Ricken, *Private Communication*, 9/1997.

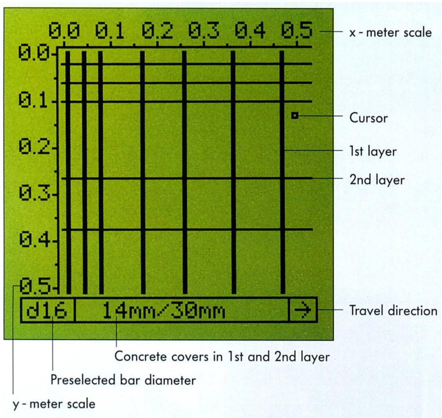

Fig. 6: Profometer4 rebar display (example over 50x50 cm)

- The Ferroscan system, developed by the HILTI Corporation, which will be detailed below.

As a last point note that the response curve of a sensor depends on its intrinsic resolution as well as on the object's depth, and that it will tend to broaden with increasing depth (*Fig. 7*), which can considerably affect the images if left untreated.

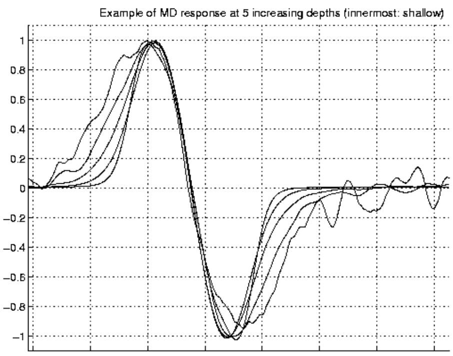

Fig. 7: Normalized response at increasing depths (general trend, differential sensor, line scan over the object)

The Ferroscan System

Ferroscan, manufactured by the HILTI Corporation (Schaan, Liechtenstein), has appeared on the market at the beginning of the '90s and is targeted at the visualization of steel rebars in concrete.

System Components

The heart of the system is represented by the RS 10 multi-sensor scanner (*Fig. 8*, right), of size 230x140x140 mm and weight 1 kg, which is able to scan a width of 15 cm.

Results are displayed on the RV 10 monitor (*Fig. 8*, left), of size 270x200x80 mm and weight 2.2 kg (accumulators included). Its backlight LCD works on 320x240 pixels using 9 grey levels. The monitor can be interfaced to a PC via a standard serial RS 232 interface to download the acquired data, with a maximum of 42 raw data files, each one corresponding to a full acquisition (i.e. up to 42 images can be stored). A PC version of the data processing software running on the monitor's 16 bit microprocessor is also available [19].

Fig. 8: Ferroscan RV 10 monitor (left) and RS 10 scanner (right) (ruler length: 30 cm)

Scanning Procedure

The maximum area which can be covered and analysed in a single image is 60x60 cm and has to be crossed horizontally and vertically, for a total of eight scans (four in each direction, see *Fig. 9).*

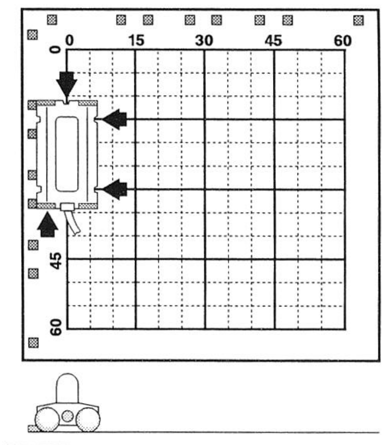

Fig. 9: Ferroscan scanning procedure, lengths in cm (from [20])

This because the system, due to its differential nature, is not able to find objects located parallel to the scanning direction. The latter is in fact strictly true only for rebars somewhat longer than the scan, in the sense that any object shorter than the scan length will produce at least a signal at its beginning and at its end; this will have some interesting implications on the objects of interest to us. Note that diagonally lying objects are displayed with slightly worsened resolution (fuzzier image).

The maximum scanning speed is 0.5 m/s, which looks quite sufficient for hand-held operation; a complete scan is therefore obtained rather quickly. Note that the area of interest can be smaller if necessary, but only sections containing both horizontal and vertical data are actually displayed and analysed [20].

The distance is measured along the track by odometry, using an optical encoder, given that the surface used is almost always flat. One set of two wheels is placed at each end of the scanner, the four wheels moving together to guarantee displacements as parallel as possible along the scanning direction.

Technical Details

From the Ferroscan patent [21] we know that the system is of multi-sensor and differential nature, basically measuring (an approximation of) the horizontal gradient, along the scanning direction, of the vertical component of the induced magnetic field.

Given that such a system is targeted primarily at steel objects it can be built, in principle, either using a permanent magnet or an electromagnet as in conventional metal detectors used for humanitarian demining, in both cases spanning the scanner width. Corresponding sensors include field plates such as magnetically controlled resistors, or more conventional copper coils. A two dimensional arrangement of the sensors is in principle possible.

Data Processing

The sensor is obviously the central part of the system, but simple and elegant real-time data processing represents an important contribution to system performance too.

Using a differential sensor eases rebar localization, which can be obtained for example by looking for zero crossings in the received signals, or by further differentiation. The differentiated signal curves can then be used to produce, starting from the horizontal and vertical scans, a composite bidimensional grey scale image such as *Fig. 10*, bottom right [21].

The latter can then be further processed to look at different depth slices, as depicted in the first three images of *Fig. 10* (but always starting from 0, e.g. 0 to 20 mm or 0 to 35 mm etc.), using a simple and efficient menu driven interface and pushbuttons at the side of the screen [22]. Note that these images are binary (black/white). These impressive processing steps rely probably in a clever way on the characteristics of the rebars' response, which depends much more on its depth than on its size; as such they are not very likely, in their present form, to be generalized easily to other metallic objects.

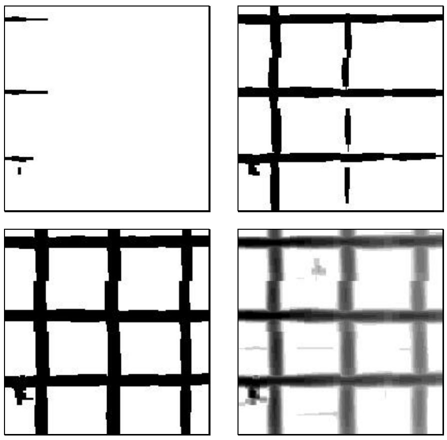

Fig. 10: Typical Ferroscan B/W rebar images at increasing depth range (0-20 mm, 0-35 mm, 0-50 mm), and overall grey scale image (all depths); 60x60 cm

It is well known that the signals received by metal detectors decay very rapidly with distance, spanning several orders of magnitude. Representing with a few grey levels an image of rebars at different depths requires therefore some form of nonlinear transformation to preserve the system dynamics. This has again implications on the visualization of objects of interest to us, especially small isolated ones. Adequate filtering is also necessary, especially for weak signals.

Note that we did have full access to the system's raw data thanks to the collaboration of HILTI, but that we did not know the exact details of the algorithm implemented in Ferroscan. We have therefore tried to reproduce it as simply as possible along the basic lines described above for the purposes of this study.

Data Analysis

Rebars of 6 mm diameter can be displayed nominally down to 130 mm, and those of 36 mm down to 180 mm. Indication of their depth and size is given only when reliable, which happens for somewhat smaller values of depth. Sensor resolution is such that two rebars should be distinguishable when their distance *d* is greater than their depth (cover) *T* (*d/T‡1*).

Note that processing is tuned to ferromagnetic objects; non ferromagnetic ones, e.g. aluminium or copper, do also produce signals, which can however not be evaluated. The corresponding images look somewhat like "negatives" of the expected ones. This does usually not represent a problem given that the analysis of such objects is not the primary goal of the system, and that they appear rarely in the context in which Ferroscan is used.

Note also that the magnetic field induced in the bar, or any other (linear) structure, radiates from its ends in all directions and is often detected in more than one sensor, which contributes to making the final image fuzzier [22]. This effect complements the one described in the ***Scanning Procedure*** paragraph.

Tests in the "Sandbox"

A number of objects were tested during 1997 in the EPFL "sandbox" at different depths. For this purpose we put a wooden plate directly on the flattened sand surface and moved the sensor over the plate in much the same way as would be done while scanning a standard wall (as described before). We do obviously NOT suggest here that this experimental practice is applicable "as is" to the detection of ordnance or landmines. On the contrary, as for other detectors which have to be scanned in a precise way over the object of interest, an adequate tracking system would have to be given careful attention and its implementation is far from trivial, but its development was not the aim of the present study.

The objects under analysis include (see the corresponding images on the following pages):

- *PMN* "like" AP mine[4] (origin: Cambodia): a "classical" AP mine, diameter 11 cm, height 5 cm, with cover retaining ring (ferromagnetic!) placed at about 1.5 cm from the top (height 5 mm, thickness about 2 mm, double i.e. bent twice). This mine has *usually* a steel striker composed essentially of two cylinders joined one to the other, the first of 19 mm length and 9 mm diameter, the second of 39 mm length and 5 mm diameter. This striker is located horizontally somewhat above the bottom. The one in our possession had in fact a slightly smaller, non ferromagnetic (alloy?) striker.
- *Small submunition*, steel (ferromagnetic), slight ellipsoidal shape (31x36 mm), 63 grams, internally prefragmented.
- *BLU 26 "bomblet"* (blue coloured, probably the training version), round (65 mm diameter), 430 grams. Its body is likely to be non ferromagnetic (e.g. aluminium), containing ferromagnetic shrapnel. Note that this might be different from the live (all steel?) version[5]. Large quantities of similar UXO are still found in Laos for example.
- *Mortar shell*: of total length 300 mm, its top half is steel (ferromagnetic), while the bottom half is aluminium.
- *20mm Projectile*: cylindrical, 20 mm diameter at the basis, 140 mm length, steel (ferromagnetic) with an aluminium tip.

Discussion

As hinted at before, a wooden plate was placed between the sensor and the sand (thickness 1.6 cm or 1.9 cm, indicated with "+1.6cm" and "+1.9cm" respectively). This thickness has therefore to be added to the depth indicated for each object, measured from its top, to obtain the actual distance from the sensor. "Flush" means (with the top) just underneath the surface level.

Each image is presented as the standard Ferroscan picture (compression of the intensity's dynamic range by default) and as obtained by us using a linear scale. The latter might be more appropriated to reproduce with greater accuracy an (isolated) object's shape.

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[4] It could be a Chinese Type 58 copy (Lyn Haywood, *Private Communication).*

[5] Lyn Haywood, Miltra Eng., *Private Communication.*

The objects are represented 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. Note also that the data has been acquired with two different sensors, with the second one possibly more noisy. All images are taken on the full 60x60 cm except where indicated.

Some of the interesting features of the images presented include the following:

- *PMN:* the cover retaining ring is clearly visible, with the darker spot probably corresponding to the area around the pin used to secure the ring (see the front of the corresponding picture).
- *Small submunition*: image size 30x30 cm.
- *BLU 26 "bomblet":* its mixed nature (ferromagnetic and non ferromagnetic material embedded in the same object) is probably at the origin of some of the complex image details displayed.
- *Mortar shell*: notice the "negative image" (void) corresponding to the bottom non ferromagnetic part, due to the processing algorithm tuned to enhance ferromagnetic objects and suppress non ferromagnetic ones.
- *20mm Projectile*: was lying diagonally along the axis NW-SE, which as expected somewhat degrades image quality. Note that a rebar of the same size would be visible, if orthogonal to one of the scanning directions, down to 160 mm.

Note that in general an object's image gets larger with increasing depth, as expected.

Concluding Remarks

The Ferroscan system is one of the few commercially available metal detectors capable of providing the user with visual information on the objects under study, in addition to "traditional" indications on depth and diameter. The Ferroscan images are indeed a precious aid in localizing 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, as far as we have been able to judge, simple and elegant data processing software. Imaging has also been "eased" by the fact that the nature of the problem is rather well defined a priori, i.e. mostly cylindrical parallel ferromagnetic objects placed horizontally in standard patterns at shallow depth.

Our preliminary tests were targeted at applying this existing system "as is" to the localization, and possibly visualization, of some AP mines with relevant metal content (e.g. PMN) and of shallowly buried UXO, mostly ferromagnetic. The size of such objects can vary rather widely, and they often do come isolated, placed at random.

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 UXO and rebars respectively. On the other hand using more than one sensor, and the differential arrangement itself, have some side effects on the visualization 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 case, the increased spatial resolution comes obviously at the price of decreased depth penetration, to nobody's surprise.

The images obtained confirm nevertheless that this approach is potentially interesting, especially if one has to look for ferromagnetic objects, and, once more, that the task we face remains a formidable one. Improvements on the range and sensor directivity could come from the data processing side, for very weak signals for example, and from the sensors, where it has been suggested to use smaller probes, e.g. magnetoresistive or miniature fluxgate elements[6] [23], or to alter the coil geometry [16].

Ultimately, feedback has to come from the people in the field, the end users of the equipment and those more directly concerned with its performances.

[6] Which obviously have to provide the required sensitivity and work at the required frequencies, not at DC as standard magnetometers.

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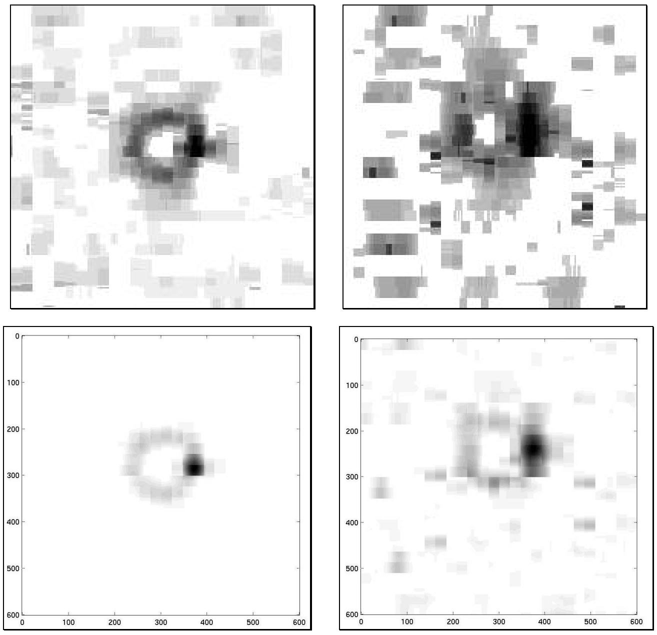
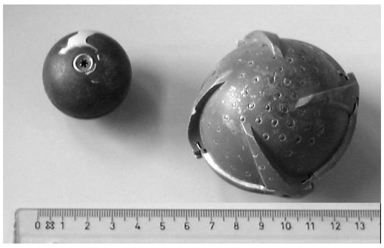
PMN antipersonnel mine

*(*visible ruler length: 16 cm)

Top row: original FS images. Bottom row: linear scale.

Depth from left to right: flush (+1.6cm), 3 cm (+1.6cm). Image size 60x60 cm.



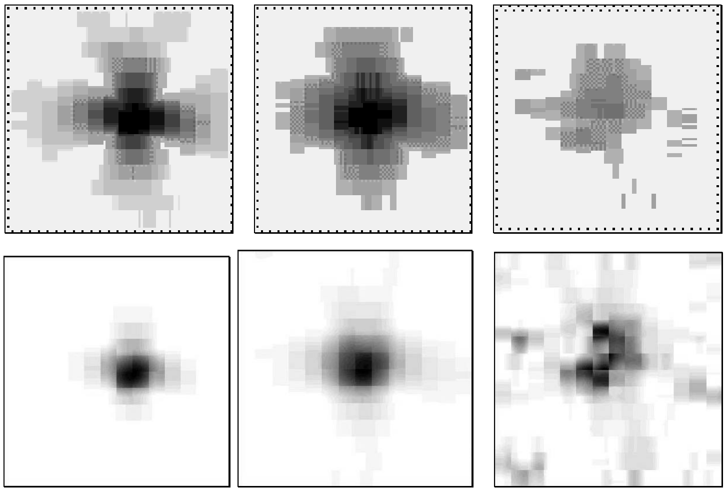


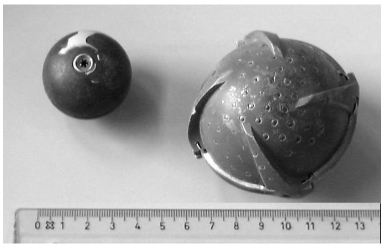
***Small submunition* (upper left of picture)**

(visible ruler length: 13 cm)

Top row: original FS images. Bottom row: linear scale.

Depth from left to right: flush (+1.9cm), 5 cm (+1.9cm), 9 cm (+1.9cm). Image size 30x30 cm.



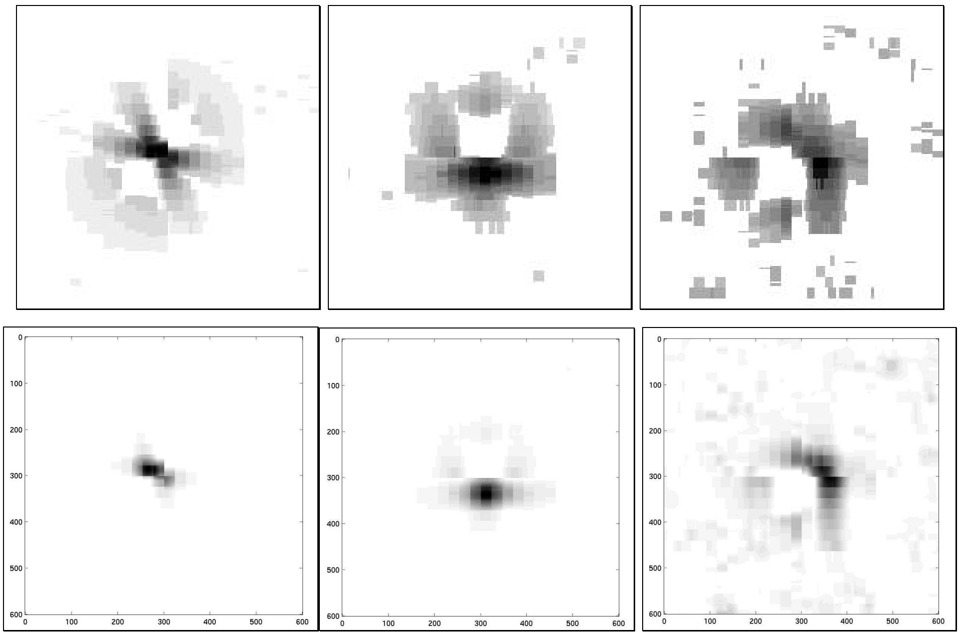


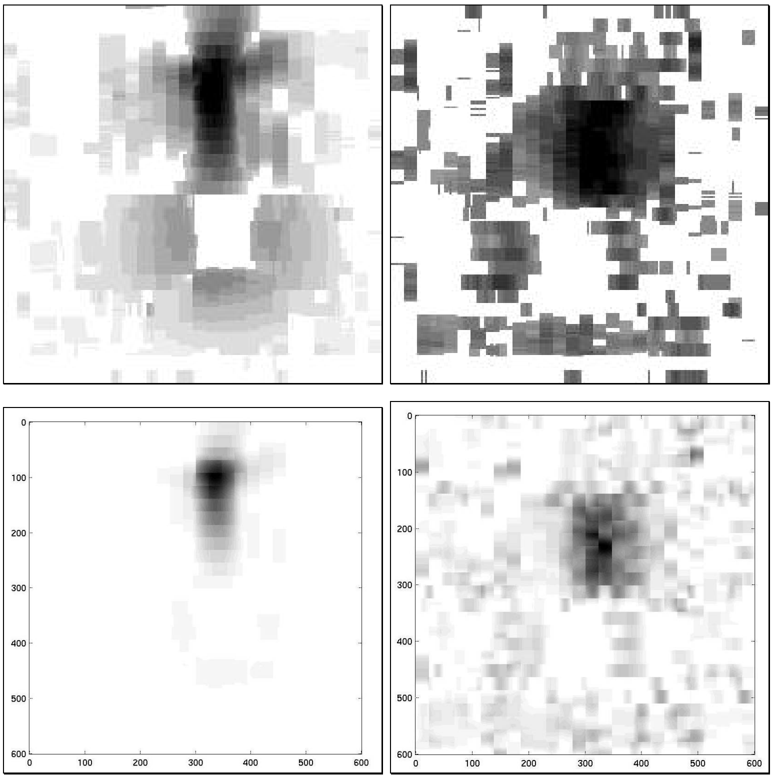
***BLU26 "bomblet"* (lower right of picture)**

(visible ruler length: 13 cm)

Top row: original FS images. Bottom row: linear scale.

Depth from left to right: flush (+1.9cm), 3 cm (+1.9cm), 5 cm (+1.9cm). Image size 60x60 cm.



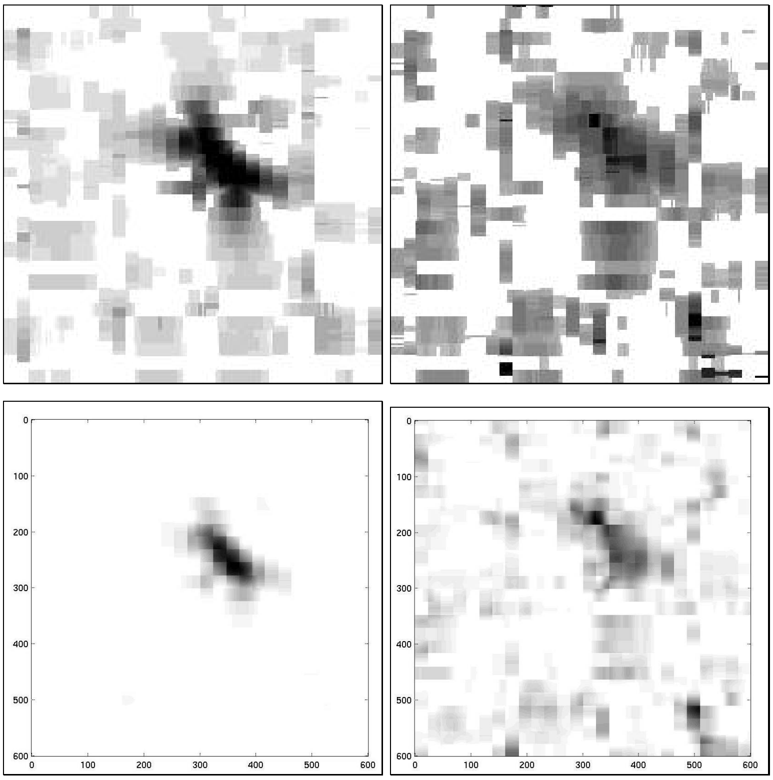


Mortar shell

(ruler length: 30 cm).

Top row: original FS images. Bottom row: linear scale.

Depth (of the uppermost parts) from left to right: 1-2 cm (+1.6cm), 10-12 cm (+1.6cm). Image size 60x60 cm.



20mm projectile

(visible ruler length: 14 cm)

Top row: original FS images. Bottom row: linear scale.

Depth from left to right: flush (+1.6cm), 6 cm (+1.6cm). Image size 60x60 cm.