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A Survey of Current Sensor Technology Research for the Detection of Landmines

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Abstract

Several promising (new) technologies for the detection of mines are in development, each with its strengths and weaknesses. We would like here to stress some of the basics and provide sufficient technical references, general as well as specific, for the reader to form his own opinion, look for more material if interested and get in touch with the right persons. It is of primary importance that scientists in each discipline and deminers share their knowledge and the result of their experience and experiments in order to design and test viable solutions for humanitarian demining.

1. Introduction

More than 100 million mines have been laid in the world, killing or maiming innocent civilians every day. Hence the need for the scientific community to use its knowledge to help stopping this plague for the humanity.

In the following paragraphs we review a number of technologies and projects on the subject of mine detection. We certainly cannot claim to be exhaustive: most of the projects conducted during the last years were targeted at military applications and detailed information is not always easily available.

Fortunately, a number of conferences specialized on this topic have taken place recently and help to have a clearer view of the research currently in progress. Some, such as the [SPIE9x] Series and [Mon96], are in fact more focused at military applications, whereas [Eur96] and SusDem’97 take into larger account the humanitarian demining needs and specificities.

It must be noticed that solutions developed for the military are normally not suitable for humanitarian demining. In the first case the goal is to make quickly a breach in a minefield to allow the troops to progress without delays. Mine finding or destruction rates of typically 80% are accepted. For humanitarian mine clearing it is obvious that the system must have a detection rate approaching the perfection (UN specifications require better than 99.6%). The armies being more and more implicated in peace keeping operations (Bosnia, Somalia), their requirements will surely come closer to the ones above.

The most interesting introductory and (technical) review articles we found, not always easily, are listed at the beginning of the **References**. [Mä95] contains a concise sensor review, whereas [Fee80], [Fee91] and [JPL95] deal with an in depth technical review of mine and UXO (UneXploded Ordnance) detection sensors. A good introduction to the landmine problem is given in [Ebl96], [Kin96], [Jas96] and [MIT96], and to sustainable humanitarian demining in [Nic96b], whereas [Cra94] and [Ham96] are somewhat more detailed. “New approaches” to humanitarian demining are proposed in [Jas96] and [MIT96]. The current activity in Europe is reviewed in [Nic96a], but this is, admittedly, a quickly changing scenario.

A list of *conferences*, *publications* and *links* dealing with the technical aspects of the subject is available starting from the DeTeC Web home page at http://diwww.epfl.ch/lami/detec/ The James Madison University (HDIC/JMU) is also setting up a Humanitarian Demining Information Center accessible online at http://www.hdic.jmu.edu/hdic/demining.htm

2. Sensors Currently Employed Manually

Demining teams use metal detectors that work by measuring the disturbance of an emitted electromagnetic field caused by the presence of metallic objects in the soil [Jas96] [MIT96].

Magnetometers are also employed, but almost exclusively for ferromagnetic objects (e.g. UXO). These sensors do not radiate any energy, but only measure the disturbance of the earth’s natural electromagnetic field [JPL95].

Both types of detectors cannot differentiate a mine/UXO from metallic debris. In most battlefields, but not only there unfortunately, the soil is contaminated by large quantities of shrapnel, metal scraps, cartridge cases, etc., leading to 100-1000 false alarms for each real mine. Each alarm means a waste of time and induces a loss of concentration [Ebl96].

Modern mines (Figure 1) can have almost no metal parts, the striker pin excepted for example. Although metal detectors can be tuned to be sensitive enough to detect these small items (current detectors can track a tenth of a gram of metal at a depth of 10 cm), this may not always be practically feasible, as it will also lead to the detection of smaller debris and increase considerably the false alarms rate.

Figure 1: A typical low metal AP mine (Type 72)

Whether or not the deminer can use a metal detector, he will sooner or later have to prod the ground. Using rigid sticks of metal, about 25 cm long, the deminer scans the soil at a shallow angle of typically 30°. Each time he feels something, he 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 straight to the operator [Nic96b].

3. Current Research and System Developments

From the above considerations it is obvious that new technologies must be developed to increase the detection rate and to automate these tasks whenever possible to preserve the life of the mine clearing personnel.

We list here a sample of the most important ones; other surveys can be found in the ***General References*** and have already been introduced.

3.1 Ground Penetrating Radar (GPR)

GPR works by emitting into the ground, through a wideband antenna, an electromagnetic wave covering a large frequency band. Reflections from the soil caused by dielectric variations such as the presence of an object are measured. By moving the antenna it is possible to reconstruct an image representing a vertical slice of the soil; further data processing allows horizontal slices or 3D representations [Dan96] to be displayed.

This technology has been used for about 15 years in civil engineering, geology and archeology for the detection of buried objects and soil study. A lot of research is conducted in these domains [GPR96] [WebGPR], but these systems usually lack automatic recognition algorithms.

Although this technology is promising, its intrinsic limitations must not be forgotten. In particular the resolution needed to cope with the small objects considered enforces the use of frequencies of some GHz, limiting the penetration depth and increasing the image clutter. The price of current equipment is also a limitation for humanitarian applications, compared to the cost of standard equipment.

Man portable solutions are developed among others by FOA (Sweden) [Eri97], GDE [GDEWeb] and Coleman Research [Bar95] (both financed by the US Army). A vehicular based radar, targeted at AT mines, is commercialized by ELTA [ELTAWeb].

In order to decrease the size and price of this type of sensor the Lawrence Livermore National Laboratory (LLNL) has developed and patented the Micropower Impulse Radar (MIR). The small footprint of the antennas (less than 50 cm^2) should allow to build quite easily an array for a faster and simplified scan of the minefield [Aze95].

Other GPR-like variations, using modulated microwave retinas and tomography imaging, have been pioneered by SATIMO [Gar96].

Another approach with GPR is to look for complex resonances, specific to each target type, in the spectrum of the reflected signal. A study conducted in the 1970's at the Ohio State University has already demonstrated the possibility of recognizing targets of about 30cm buried in clay [Pet94]. Collaboration with Battelle has lead to a portable standoff equipment utilizing a parabola to focus the radar beam [Shu96]. EG&G conducts also research in the same direction [Sow95], and FOA (Sweden) has been very active too looking for characteristic mine signatures (Web page at [Eri97]).

Raton Technology Research exploits variations of the frequency of a resonance cavity in presence of buried objects; first results are encouraging [Sto96].

3.2 Advanced Applications of Metal Detectors

Some interesting studies have been and are being carried out to see if it is feasible to discriminate mines/ UXO from metallic clutter with metal detectors, reducing the false alarm rate. For example, [Sow95] used an impulse MD looking for a characteristic decay curve and compared it to the ones stored in a library. Problems come from the fact that the response curve depends on several factors, e.g. the orientation of the metallic object, the exact metal type, etc., and that the matching is done only with objects known a priori. This approach could nevertheless be promising in specific situations. For earlier work see [Fee91].

Somewhat along the same line [Tra97] studied in the laboratory the possibility of characterizing objects/mines by measuring the eddy frequency response over a large frequency range. Interesting results were obtained for objects with some metallic content such as a PMN (Figure 2).

Figure 2: Metallic content of a PMN AP

Work is also ongoing on an advanced Active/Passive Magnetic Gradiometer combining sensitive magnetic sensors (e.g. magnetoresistive sensors capable of working over a broad frequency range, starting from DC) with advanced techniques of applied field rejection, as described in [Czi96].

Another interesting and unconventional application is represented by the Meandering Winding Magnetometer (MWM) described in [MIT96]. The device has the characteristic of using a square wave winding conductor in order to generate a spatially periodic electromagnetic field, whose spatial wavelength depends only on the primary winding spatial periodicity. It can, in principle, detect several characteristics of a buried metallic object (size, shape, etc.), and its application to humanitarian demining is currently being investigated.

The idea of using metal detectors to actually locate nonconducting targets, or more generally "cavities" in the soil, is also not new, as a (large) nonconducting target does indeed alter locally the natural ground conductivity, and has led for example to the patent ("cavity detector") described in [Mil96]. The system should probably work best for large objects in soils with high natural conductivity ("background" signal).

Arrays of metal detectors, to quickly scan a large path for example, have also been built, such as the Schiebel VAMIDS system. Figure 3 shows an image corresponding to data from the scan of a Field Calibration lane (low metal clutter) during tests at Ft. A. P. Hill, VA, Nov. 95, using a 2 meter array mounted on the multi-sensor VMDT vehicle (Vehicular Mine Detection Testbed) [Bro96]. The large signals are due to metallic mines and the smaller ones to shallowly buried APs.

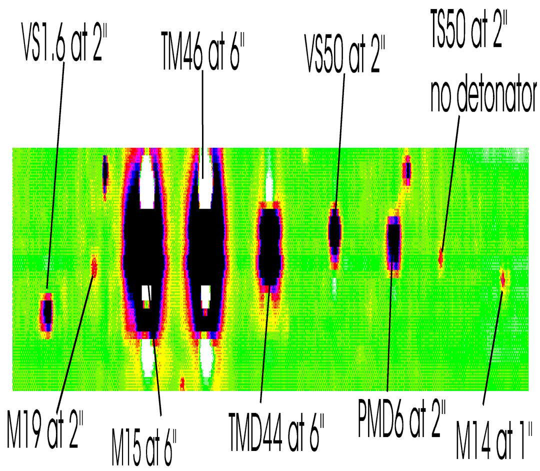

Figure 3: VAMIDS image from VMDT vehicle (D. Brown, SAIC [Bro96])

The ODIS vehicular system at DASA-Dornier [Bor95] [ODIS96] has demonstrated encouraging results in the identification and classification of shallow unexploded ordnance based on recorded source data. In its current version it is able to detect metal parts of less than 1cm^3. Penetration depth is about 50cm. Using appropriate software (database supported inversion), the system is able to compute the magnetic center of an object (±2cm), its depth (±10%) and its magnetic volume as a measure of object size. Further developments might have taken place since this information was published.

3.3 Infrared (IR) Imaging

Mines retain or release heat at a different rate than their surrounding, and during natural temperature variations of the environment it is possible, using IR cameras, to measure the thermal contrast between the soil over a buried mine and the soil close to it.

When this contrast is due solely to the presence of the buried mine (alteration of the heat flow) one speaks of a *volume effect*. When it is due primarily to the disturbed soil layer above and around the mine (resulting from the burying operation) one speaks of a *surface effect*, which can be detectable for some time (say weeks) after burial and enhances the mine's signature. A good explanation of the various thermal mechanisms affecting the surface temperature contrast is given in [Sim96].

Note that rather sensitive cameras ($\Delta T<0.1C$) have to be employed, with sufficient spatial resolution (see also [Fee91]). Maximum burial depth is estimated at 10-15 cm. In addition, results obtained with passive infrared imagers can depend quite heavily on the environmental conditions (see also [Rus97]), and there are cross over periods (in the evening and in the morning) when the thermal contrast is negligible and the mine undetectable. Foliage is also an additional problem.

Infrared systems look currently best in a support role, for example for the (standoff) detection of ATs on roads and tracks. IR images of a gravel road, taken with an IR camera positioned 3m above the ground and inclined downwards from the horizontal plane by 40 degrees, are shown below (courtesy Dr. John McFee, Defence Research Establishment Suffield (DRES), Defence Research and Development Branch, Canada).

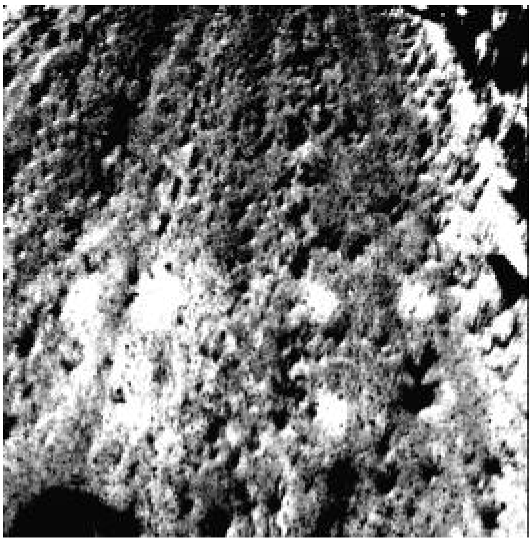

Figure 4: Daytime IR image (14.15), DRES, Aug. 1996 (J. McFee, DRES [Rus97])

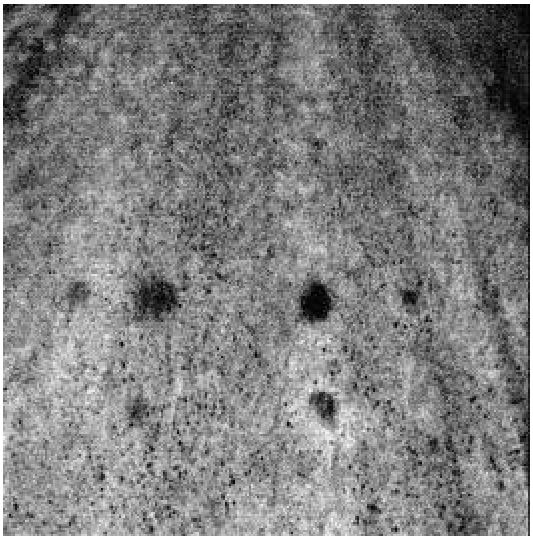

Figure 5: Nighttime IR image (04.45), DRES, Aug. 1996 (J. McFee, DRES [Rus97])

The three dark blobs in the left bottom of Figure 5 (imagine a left mirrored ┌) are caused by recently buried mine surrogates with the larger blob corresponding to an AT surrogate and the other two to AP surrogates. Likewise the three dark blobs in the right bottom (this time imagine a ┌) are caused by long-buried surrogates (again 1 AT, 2 APs). The same configuration of surrogates can be seen in Figure 4, but the blobs are light.

The development of a short range system for the US army by Martin Marietta Technologies Inc. is an example of the few projects aimed at searching individual mines. It is based on a commercial 8-12μm IR sensor and uses neural networks to recognize patterns after segmentation of the image. They reported 90% of target detection in [Nga95].

Polarimetric IR looks interesting for the detection of non buried "man-made" objects such as mines in the presence of high grass and heavy background clutter [Bar96].

3.4 Trace Explosive Detection

Dogs are used for the search of mines because their great smell sensibility (10^{-12} to 10^{-13} g of explosive) allows them to detect mines with a good reliability. Obstacles to be faced are, for example, dog training costs, sensitivity to environmental conditions, time necessary to train and the fact and they tire rapidly.

Nevertheless, dogs are known to work, under certain conditions, but it is not yet fully clear how (using also other senses?), nor what exactly they detect and in which concentration (explosive's vapours or other substances leaking from the mine or from its surface, trace particles deposited in and on the soil around the mine).

Localization accuracy is usually not very good (several meters), given that the explosive's odour can penetrate the ground and the vegetation in an area up to 10 meters from the real location of the mine after some months, and that trace particles might also be scattered around. The mine's vapour release rate can also change significantly over time after burial. Several passes with different dogs might be needed over a given area.

Precise localization is not a problem when verifying with dogs vast stretches of land, in order to save precious time by concentrating on areas which really need to de demined. This can be done in an indirect fashion, for example by collecting samples (possibly filtered to increase concentration) and taking them to the dogs for evaluation.

To this respect Figure 6 and Figure 7 illustrate MEDDS (Mechem Explosives and Drug Detection System), which has been used for quite some time with interesting results to verify if a given area has been mined or not. In Figure 6 MEDDS vapour absorbent filters, filled for example along a road, are being checked at a dog centre (each batch of samples by several dogs; for details see *V. Joynt*, these Procs.). In this case the filters on a stand represent 2.4 km of roads. Positive answers, indicating a suspected area, can be checked with a free running dog as shown in Figure 7.

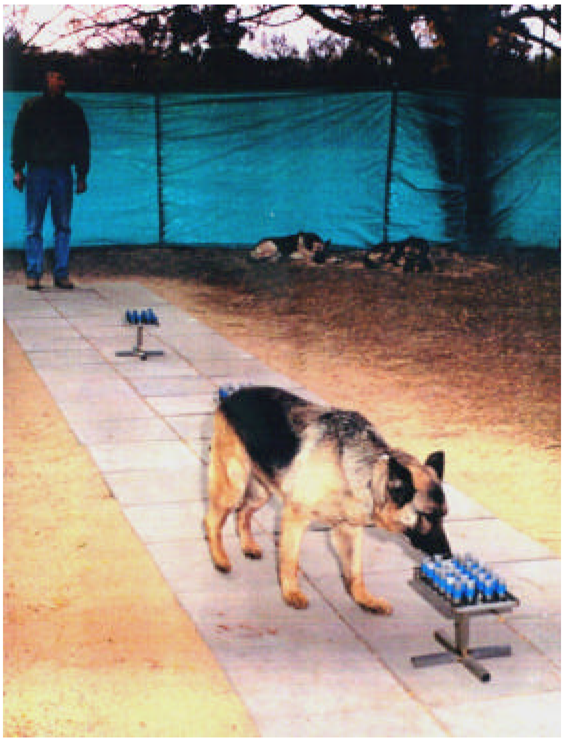

Figure 6: Checking vapour filters at a dog centre (V. Joynt, MECHEM)

Figure 7: Free running dog checking suspect area (V. Joynt, MECHEM)

Artificial odour or vapour sensors would constitute a valid alternative: in fact they exist and are already used in the chemical industry or in airports (chemiluminescence [Pat95] [MIT96], mass spectrometry, ion mobility spectroscopy, biosensors, electron capture [Jan92]). Good reviews are given in [Rou97] and [Jan92]. Unfortunately these sensors either have a too low sensibility, are too slow or too large to be used in field applications.

Results from Trace Explosive Detection (TED) trials using several detector types and the problems associated with them are described in one paragraph of [Fee96]. [Fee91] gives an interesting overall analysis of the problem.

The Bofors company in Sweden has launched in 1995 a project targeted specifically at the detection of antipersonnel mines using odour sensors based on antibodies [Bri96]. Their system basically works by measuring the variation in the oscillating frequency of a piezoelectric crystal, whose surface is covered by an antibody reacting with the molecules of TNT.

A simple and inexpensive (polymeric) sensor array ("nose-on-a-chip"), designed to identify and classify vapours, could also be used to detect explosives and is described in [Lew97].

An interesting complementary approach has been proposed in the form of trace particle detection using MEMS (Micro Electro Mechanical Systems), in particular an array of temperature sensitive sensors (bimetallic cantilever beams) [Fai97]. The basic idea is to ultrasonically stimulate a target area, detaching explosive particles, and then to collect them. They are then irradiated with selective infrared radiation and deflagrate releasing heat, which is detected by the cantilever, as schematically illustrated in Figure 8 for one element of the array.

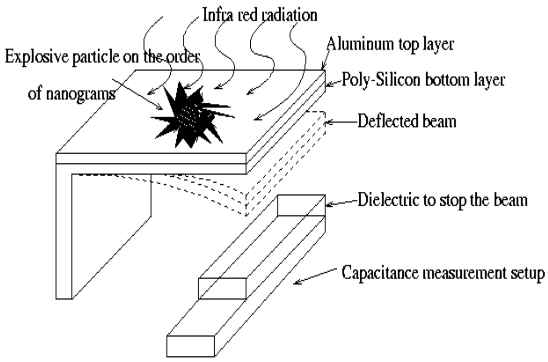

Figure 8: Schematic of MEMS trace explosive particle detector (V. Pamula, Duke [Fai97])

DARPA (Defense Advanced Research Projects Agency, http://www.darpa.mil/) has started an ambitious three year project (BAA 96-36), with a planned funding of 25 million US$, aimed at developing an electronic dog's nose that can be used reliably in the field, emphasizing technology for real-time, lightweight, low power and low cost systems (referenced in [Rou97]).

3.5 Bulk Explosive Detection

Interest is growing towards techniques that can detect the explosive itself, in bulk form as opposed to trace explosive detection, and which have found application in security (airport luggage [Nov92] or mail screening) or Non Destructive Testing applications. What makes the landmine detection problem formidable are, among others, the need for one-sided sensor configurations, operator security and equipment portability, and the limited soil penetration of particles/radiation.

Amongst the techniques which look most promising at the current stage of development we can list nuclear methods (neutron activation, X-ray backscatter) and NMR/NQR (Nuclear Magnetic or Quadrupole Resonance). The former are quite generally reviewed in [Goz96] and, with emphasis to military applications and the detection of AT mines, in [Mol85] and [Mol91]. [Fee91] provides also, again, a good discussion.

Thermal Neutron Activation (TNA) [Bac96] in particular relies on the activation, via neutrons emitted by a radioisotopic source or an accelerator, of the nitrogen nuclei abundantly contained in most explosives. Specific gamma rays are emitted and detected. The SAIC company has developed, using a Californium-252 source, a system to be used as a confirmatory device (detection can take of the order of a minute) for the Canadian Improved Landmine Detection System (ILDS) [Fee96] and for the VMDT vehicle already described [Bro96].

The TNA sensor head (weight around 180kg), attached to a translation frame, is shown in Figure 9 during field trials for the US Army. Good results where obtained for AT mines, whereas APs are much more difficult to detect reliably, as expected from the very reduced explosive volume [Bro96]. Drawbacks of this method include system complexity and limited depth of penetration (10-20 cm).

Figure 9: Thermal Neutron Activation Sensor (D. Brown, SAIC)

A neutron backscatter application is described in [Leo96]: fast neutrons are thermalized by the explosive's hydrogen nuclei, and the resulting backscattered slow neutrons are detected. The system will probably work, however, only in dry environments (absence of water!).

X-ray backscatter techniques are also being investigated, mostly for real-time detection of ATs, and some system developments are described in [Weh95] [Weh97] [Loc97], with drawbacks similar to the ones described before for TNA. Ideas on a light man portable system, safe and reliable, meant to be used similarly to a metal detector, are detailed in [Jas96] [MIT96]. The system could also provide a 2D image with a resolution of 2-3 cm. Potential problems come once again from shallow penetration, and sensitivity to soil topography and sensor height variations.

Nuclear Quadrupole Resonance (NQR) has been described as "an electromagnetic resonance screening technique with the specificity of chemical spectroscopy", and relies upon the resonant response of certain nuclei possessing electric quadrupole moments. It is being developed in particular for airline security applications and has the fundamental advantage of not needing an external (static) magnetic field, contrary to NMR. Research work is documented in [Czi96] [Ker97] [Row96], with [Jas96] [MIT96] giving a practical sketch of a possible NQR application to humanitarian demining; problems are due in particular, as usual, to the need for a one-sided (remote) implementation. In addition, encouraging results have been obtained with RDX and not TNT, which is found in the majority of mines. Increasing the signal to noise ratio for TNT is therefore one of the priorities in current research.

3.6 Passive Millimeter Wave Detection

In the millimeter wave band, soil has a high emissivity and low reflectivity. On the other side, metal has a low emissivity and strong reflectivity. Soil radiation depends therefore almost entirely on its temperature and metal reflection mostly on the low level radiation from the sky. It is possible to measure this contrast using a millimeter wave radiometer device. Tests in ideal laboratory conditions have demonstrated the capability of detecting metallic objects buried under 3 inches of dry sand working at 44 GHz [Yuj95]. In fact, at this frequency even a water content of a few percent results in very poor penetration depth.

Tests have been carried out subsequently also on plastic targets, which produce a much smaller ΔT than the metal ones (they have much lower reflectivity and transparency to radiation rising from below them), working at 44 and 12 GHz [Yuj96], and recently also at 5 GHz [Yuj97], using off-the-shelf components. Note the trend towards lower frequencies, which present the advantage of increased penetration, especially in moist soil, at the obvious price of some loss in spatial resolution. In these tests radiometric data was used to form interesting 2D images by scanning the area over a mine covered by leaves and buried at shallow depth (1-2 cm), testing several degrees of soil moisture.

Passive MMW radiometers are simpler devices than GPR. They should suffer less from clutter problems and can be used to generate 2D images of objects placed on the surface (possibly under light vegetation) or shallowly buried (some cm), with best results in dry soils, and for metallic targets.

3.7 Acoustics

(Conventional) Ultrasound detection consists in the emission of a sound wave with a frequency higher than 20kHz into a medium. This sound wave will be reflected on boundaries between materials with different acoustical properties. Note that such systems should be capable of good penetration through very wet and heavy ground such as clay, which makes them somewhat complementary to GPR (although they are also likely to experience problems at the air-ground interface). We will illustrate in the following two interesting and rather different applications of impulse acoustics.

Experimental research has been conducted in the laboratory on the use of the ultrasound impulse echo technique for AP mine detection in the framework of a simulation of mines thrown into rice fields (i.e. under water) [Eks97] [Kem97]. Some signal processing methods and pattern recognition methods have been implemented to discriminate between AP minelike objects and other objects.

The following figures have been obtained by using a 15 MHz probe and a scanning step of 0.6 mm (along X,Y), placing a PRB M409 AP mine horizontally on a soil surface under water. The top of the mine is at a depth of 3 cm and is clearly visible in Figure 10, representing a horizontal scan at a fixed depth (the first echo of the object here). Figure 11 has been obtained under the same conditions, using all amplitudes along the Z axis (3D representation).

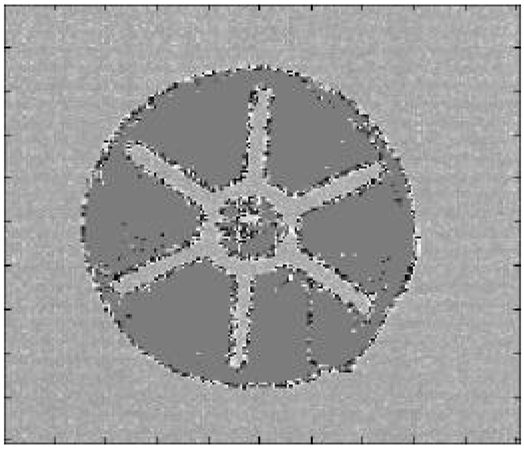

Figure 10: 2D image (horizontal slice) of an AP mine in water (H. Sahli, VUB Univ. [Kem97])

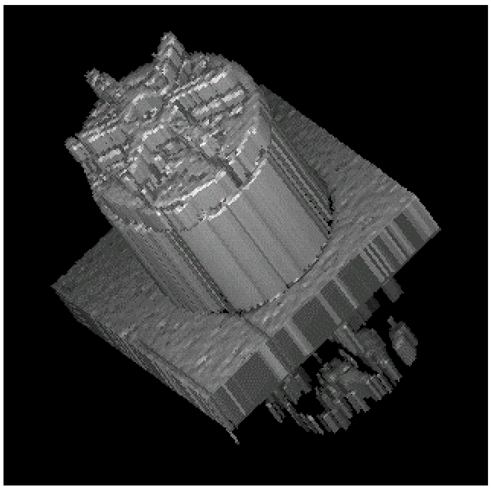

Figure 11: 3D image of an AP mine in water (H. Sahli, VUB Univ. [Kem97])

At such high frequencies ultrasound does practically not penetrate soil, which is the reason why such tests were targeted at finding mines in water.

A system using pulses of 1 msec in duration to measure the difference in acoustic impedance between a mine and the surrounding soil is described in [Don94]. The problem lies here in isolating small object pulses from other, often dominant, signals, and coping with ground contours and irregularities. A kind of “background signal subtraction” procedure is therefore necessary.

Figure 12 shows an image, obtained with such a system, of a 12 cm plastic land mine buried at a depth of 5 cm in lightly compacted loamy garden soil. The position of the surface is determined by the arrival time of the surface reflection.

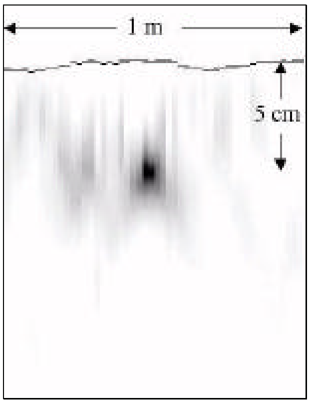

Figure 12: Line scan of a plastic AP using 1 msec acoustic pulses (C. Don, Monash Univ.)

Finally, note that swept acoustic systems have also been proposed to look for mine signatures (resonances) in a simple (?!) and unexpensive way [Jas96] [Ker97].

4. Conclusions

A NATO report published in March 1996 [NATO96] has made a classification of potential technologies, given in the following table.

None of the technologies presented seems in fact capable of reaching, in a very large number of situations, good enough detection while maintaining a low false alarm rate. Rather, each one will probably have to find, if it exists, a specific area of applicability, determined by technological as well as economical or even social factors, and possibly other sensors to work with using some form of “sensor fusion”. The need for a better exchange of information between the specialists in each category is obvious, using options such as data sharing on the Internet. If security, commercial and political issues will allow it, obviously…

Sensor technology	Maturity	Cost and Complexity
Passive infrared	Near	Medium
Active infrared	Near	Medium
Polarized infrared	Near	Medium
Passive electro-optical	Near	Medium
Multi-hyperspectral	Far	High
Passive mm-wave	Far	High
mm-Wave radar	Near	High
Ground penetrating radar	Near	Medium
Ultra-wideband radar	Far	High
Active acoustic	Mid	Medium
Active seismic	Mid	Medium
Magnetic field sensing	Near	Medium
Metal detection	Available	Low
Neutron activation analysis	Near	High
Charged particle detection	Far	High
Nuclear quadrupole reson.	Far	High
Chemical sensing	Mid	High
Biosensors	Far	High
Dogs	Available	Medium
Prodding	Available	Low

Acknowledgments

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§2 Sensors Currently Employed Manually

[ALL] > § Ref General

§3.1 Ground Penetrating Radar (GPR)

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