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Article

A Survey of Research on Sensor Technology for Landmine Detection

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1. Introduction

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According to official figures, more than 100 million landmines lie buried around the world. Although intended for warfare, these mines remain active after warfare ends. Each day these mines are triggered accidentally by civilian activities, ravaging the land and killing or maiming innocent people. To help stop this destruction of the environment and humanity, the scientific community must develop effective humanitarian demining. Mine detection is especially vital to humanitarian demining. The goal of military demining is to clear enough mines quickly to allow troops through a land area. Military demining usually requires mine destruction rates of 80%. The goal of humanitarian demining, in contrast, is to clear enough mines to permit normal civilian use of the land (e.g., construction or agriculture). Humanitarian demining thus demands a destruction rate approaching perfection: UN specifications require a rate better than 99.6%. Of course, a critical aspect of mine clearance is mine detection. Before one can remove mines, one must locate them. To aid scientific inquiry into mine detection, this paper reviews the major current and developing technologies for mine detection. We do not claim to include every technology. Often the details of research intended for specific military applications are difficult to attain. This paper highlights significant studies of mine detection technologies, discussed in several recent conferences and in many recent articles and reports, to show promising directions for future research.

Before we begin our review, we want to mention a few relevant introductory and review technical articles already in the literature. Featuring a concise sensor review are (Mäc, 1995) and (McFee and Das, 1980), while (McFee and Das, 1991) and (Jet Propulsion Laboratory, 1995) contain a thorough technical review of mine and UXO (UneXploded Ordnance) detection sensors. An effective introduction to the general landmine problem is given in (Eblagh, 1996), (King, 1996), (JASON, 1996)and (Tsipis, 1996) and to sustainable humanitarian demining in (Nicoud, 1996b). More detailed discussions of humanitarian demining appear in (Cra94) and (Hambric and Schneck, 1996). New approaches to humanitarian demining are proposed in

(JASON, 1996) and (Tsipis, 1996). The current activity in Europe is reviewed in (Nicaud, 1996a). Because the European scenario changes quickly, this article might not be current.

2. Current Technologies: Manual Mine Detection

Prodders
At present, the most common techniques for mine detection are manual, using either prodders or metal detectors. The most basic approach to mine detection is prodding. Using prodders, rigid sticks of metal about 25 cm long, the deminer scans the soil at a shallow angle of typically 30°. Each time he detects an unusual object, he assesses the contour, which indicates whether the object is a mine. Though effective, this technique is slow and dangerous. The deminer might encounter mines that have moved or have been placed so that they are triggered by prodding (Nicoud, 1996b). **Metal Detectors**
Another current technology used for mine detection is the metal detector. The basic metal detector used for mine detection measures the disturbance of an emitted electromagnetic field caused by the presence of metallic objects in the soil (JASON, 96) (Tsipis, 1996). Magnetometers also are employed but almost exclusively for ferromagnetic objects (e.g. UXO). Radiating no energy, the magnetometers measure only the disturbance of the earth's natural electromagnetic field (Jet Propulsion Laboratory, 1995).

Metal detectors pose problems for mine detection. Both types of detectors identify all metallic objects; they cannot differentiate a mine or UXO from other debris. The large quantities of shrapnel, metal scraps, cartridge cases, and other metal debris in most battlefields leads to false alarms: 100-1000 false alarms for each real mine detected. False alarms interfere with effective mine detection because they waste time and disrupt the deminers' concentration (Eblagh, 1996).

Another problem is that many mines contain little metal. Many modern mines (Figure 1) have almost no metal parts except for the small striker pin. 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), such sensitivity detects more metal debris and increases considerably the rate of false alarms. Increasing the sensitivity of metal detectors, therefore, does not solve the problem of nonmetal mines satisfactorily.



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

In short, the current technologies, metal detectors and prodders, are problematic. Although they are accurate, they slow the mine detection process and endanger deminers.

3. Current Research and System Developments

To increase the speed and safety as well as maintain the accuracy of mine detection, researchers are developing new technologies. This paper describes the most significant innovations.

3.1 Advanced Applications of Metal Detectors

Some interesting studies investigated whether metal detectors can discriminate mines and UXO from metallic debris, reducing the false alarm rate. For example, (Sower and Cave, 1995) used an impulse metal detector (MD) looking for a characteristic decay curve and compared it to the curves stored in a library. The study highlighted some problems. Capturing the response curve depends on several factors, e.g. the orientation of the metallic object, the exact metal type. Also, the approach is effective only with objects whose decay curves are known already. Nevertheless, this approach holds promise for specific situations. For earlier work in this area, see (Defence Research Establishment, 1991).

Similarly, (Trag, Czipott, and Waldron, 1997) studied the possibility of characterizing objects through measurement of the eddy current frequency response over a large frequency range. The study yielded interesting results for objects with some metallic content such as a PMN (Figure 2).

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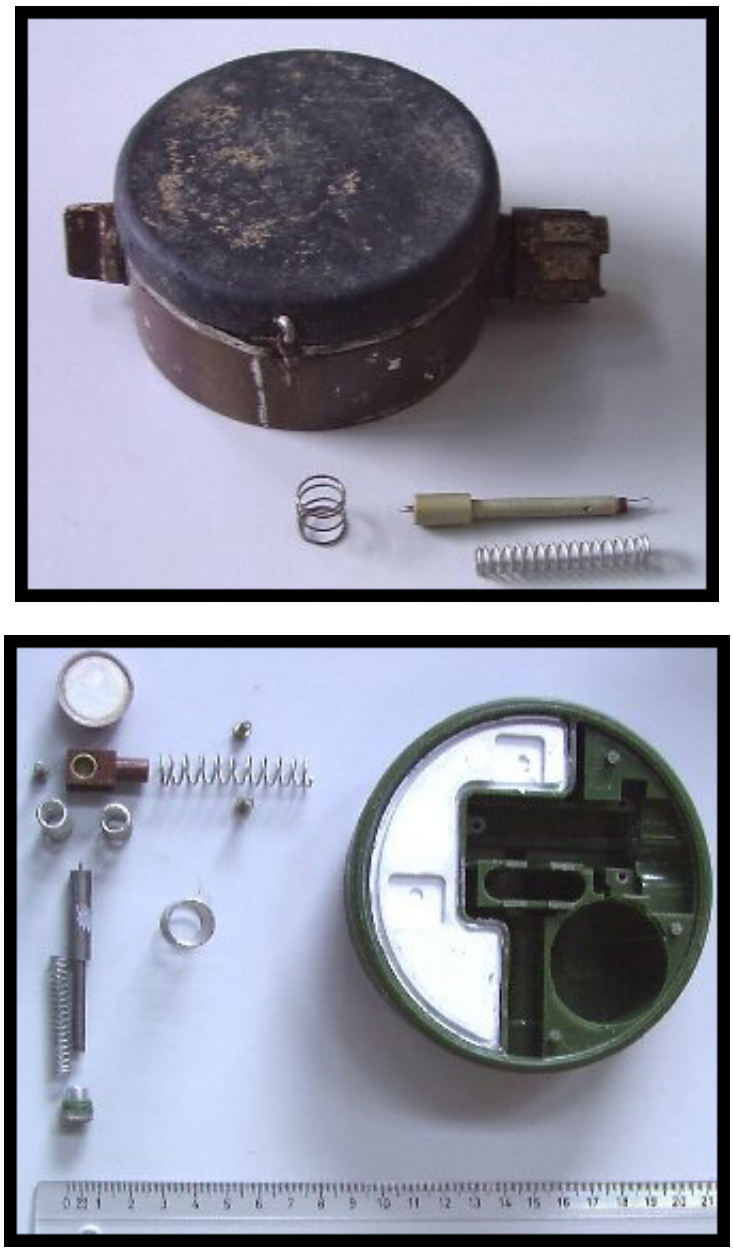


Figure 2: Metallic content of a PMN AP (top) and a PMN2 AP (bottom)

Also being developed is an advanced Active/Passive Magnetic Gradiometer, which combines 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 (Czipott and Iwanowski, 1996).

An unconventional technology involving metal detection was developed by the Meandering Winding Magnetometer (MWM), as described in (Tsipis, 1996). The device uses a square wave-winding conductor to generate a spatially periodic electromagnetic field. The electromagnetic field's spatial

wavelength depends only on the primary winding spatial periodicity. This method, in principle, can detect several characteristics of a buried metallic object (size, shape, etc.). The application of this method to humanitarian demining is under investigation.

A more conventional but promising metal-detection application locates nonconducting targets, or more generally "cavities" in the soil. This technology relies on the principle that a large nonconducting target locally alters the natural ground conductivity. A patented version of this technology ("cavity detector") is described in (Mills, 1996). The cavity-locating system most effectively detects large objects in soils with naturally high conductivity ("background" signal).

Additionally, researchers have built arrays of metal detectors. An array of metal detectors, such as the Schiebel VAMIDS system, scans a large area quickly. Figure 3 shows an image derived from this system during tests at Ft. A. P. Hill, VA, in November, 1995. The image corresponds to data from the scan of a Field Calibration lane (area with low metal clutter) with a two-meter array of metal detectors mounted on the multi-sensor VMDT vehicle (Vehicular Mine Detection Testbed) (Brown, 1996). The large dark areas indicate metallic mines and the small dark areas signal shallowly buried APs.

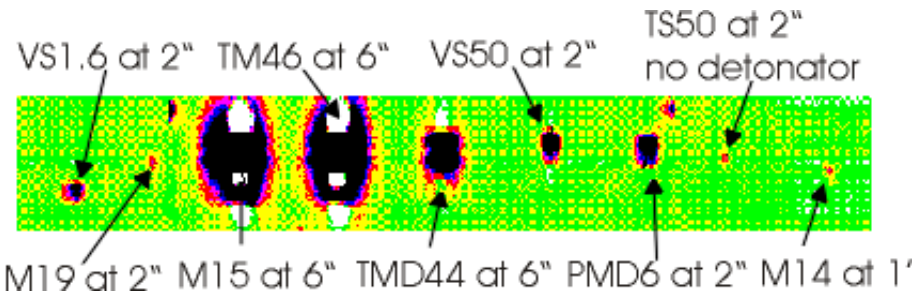


Figure 3: VAMIDS image from VMDT vehicle (D. Brown, SAIC (Brown, 1996))

Another recent development involving metal detectors is the ODIS vehicular system at DASA-Dornier (Borgwardt, 1995) (DASA-Dornier, 1996) has demonstrated potential for identifying and classifying shallow unexploded ordnance from recorded source data. In its current version, the system can detect metal parts of less than $1cm^3$ at a penetration depth of 50cm. Using database-supported inversion, the system computes an object's magnetic center(±2cm), depth (±10%)and magnetic volume as a measure of object size. Because this technology is so new and under investigation, further significant developments might have occurred since the publication of this article.

3.2 Ground Penetrating Radar (GPR)

Basic Definition and Assessment
GPR emits 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. Moving the wideband antenna reconstructs an image that represents a vertical slice of the soil; further data processing allows the display of horizontal slices or three-dimensional representations (Daniels, 1996).

Used for about 15 years in civil engineering, geology, and archeology to detect buried objects and to analyze soil, this technology is well-researched (GPR Conference, 1996)(WebGPR). This abundant research, however, does not include GPR systems that use automatic recognition algorithms, a feature important to applying GPR to mine detection. Researchers need to investigate the application of GPR to mine detection.

Although promising, this technology has limitations. In particular, the resolution needed to detect small objects involves GHz frequencies, which decreases soil penetration and increases image clutter. Another constraint is cost. Compared to other technologies, especially the ones currently used, GPR systems are expensive: beyond the budget of most demining operations.

Specific GPR Systems
Many GPR options are available. Many outfits, such as FOA (Sweden) (Ericsson and Gustafsson, 1997), GDE (GDE Homepage), and Coleman Research (Barrett, 1995) (both financed by the US Army), develop portable solutions. Offering a vehicular-based radar, targeted at AT mines, is the company ELTA (ELTA Home Page). To decrease the size and price of GPR, the Lawrence Livermore National Laboratory (LLNL) developed and patented the Micropower Impulse Radar (MIR). The small footprint of the antennas (less than 50 cm^2) might allow a faster and more simplified scan of a minefield (Lawrence Livermore National Laboratory, 1995). Other GPR-like variations, using modulated microwave retinas and tomography imaging, have been pioneered by SATIMO (Garreau et al., 1996).

A possible future application of GPR involves discerning complex resonances, specific to each target type, in the spectrum of the reflected signal. A study conducted in the 1970s at Ohio State University has already demonstrated the possibility of recognizing targets buried in 30cm of clay (Peters, Daniels, and Young, 1994). The university, in collaboration with Battelle, developed portable standoff equipment that focuses the radar beam through a parabola (Shubert, 1996). Conducting research in the same direction are EG&G (Sower and Cave, 1995) and FOA (Sweden)(Web page at (Ericsson, 1997).

Raton Technology Research exploited variations of the frequency of a resonant cavity to detect buried objects and yielded encouraging initial results. (Stolarczyk and Mack, 1996).

3.3 Infrared (IR) Imaging

Basic Description and Assessment

Mines retain or release heat at a rate different from their surroundings. Infrared (IR) cameras create images that reveal the thermal contrast between the soil immediately surrounding a buried mine and the top layer of soil. When this contrast results from the presence of the buried mine (alteration of the heat flow), it is a *volume effect*. When the contrast results from the disturbed soil layer above and around the mine (because of burial), it is a *surface effect*. The surface effect is detectable for weeks after burial and enhances the mine's signature. A thorough explanation of the various thermal mechanisms affecting the temperature contrast is given in (Simard, 1996).

The application of IR imaging to mine detection presents some problems, however. Note that IR imaging requires sensitive cameras (DeltaT<0.1C) with sufficient spatial resolution (see also (Defence Research Establishment, 1991)). This technology consequently measures mines at a maximum burial depth of 10-15 cm. In addition, the results of passive infrared imagers depend heavily on environmental conditions (see also (Russell, McFee, and Sirovyak, 1997)). During cross-over periods (morning and evening), the thermal contrast is negligible, rendering mines undetectable through IR. The presence of foliage also impedes accurate IR imaging.

Specific IR Systems

IR systems hold the most promise as a support technology for specific mine-detection situations, such as 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 declined 40° from a horizontal plane, appear in Figures 4 and 5 (courtesy Dr. John McFee, Defence Research Establishment Suffield (DRES), Defence Research and Development Branch, Canada).

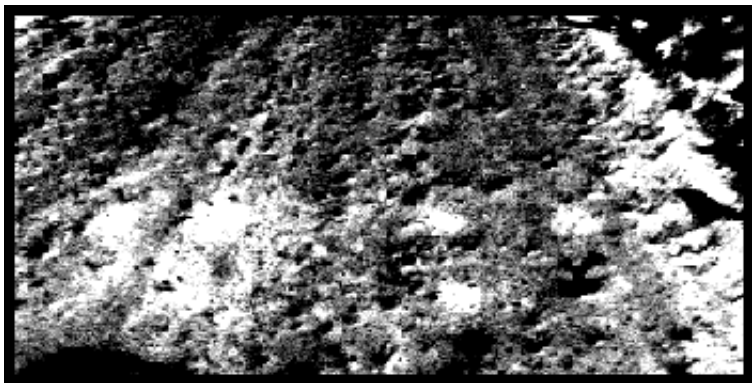


Figure 4: Daytime IR image (14.15), DRES, Aug. 1996 (J. McFee, DRES (Russell, McFee, and Sirovyak, 1997))

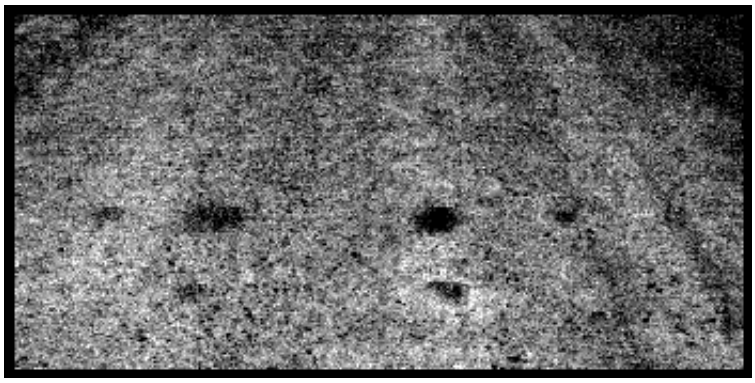


Figure 5: Nighttime IR image (04.45), DRES, Aug. 1996 (J. McFee, DRES (Russell, McFee, and Sirovyak, 1997)

The three dark spots in the lower left of Figure 5, a nighttime image, represent recently buried mine surrogates, with the larger spot corresponding to an AT surrogate and the other two to AP surrogates. In contrast, the three dark spots in the lower right represent long-buried surrogates (again, one AT surrogate and two AP surrogates). The same configuration of surrogates is more faintly evident in the daytime image of Figure 4.

A few IR projects aim at searching for individual mines. One such project is the effort of Martin Marietta Technologies, Inc. to develop a short range IR system for the US army. This technology is based on a commercial 8-12 micron IR sensor and uses neural networks to recognize patterns after segmentation of the image. In (Ngan, 1995), the company reported a mine-detection rate of 90%.

Finally, polarimetric IR has potential for detecting unburied "man-made" objects (e.g. mines) despite hindrances such as high grass and heavy background clutter (Barbour et al., 1996).

3.4 Trace Explosive Detection

Dogs

One way to identify mines is to detect the explosive material within them. A common method of detecting explosives is through trained dogs. Dogs can reliably detect 10^{-12} to 10^{-13} g of explosives. Exactly how dogs detect explosives remains a mystery. We do not know whether dogs use senses other than the olfactory sense. Also unclear is the substance that dogs detect, vapors or trace particles, and the concentration of the substance they detect.

Although dogs effectively detect the presence of mines, they cannot determine a mine's precise location. The odor of an explosive penetrates the ground and the vegetation up to 10 meters from the actual mine. Another hindrance to locating mines with dogs is the scattering of race explosive particles far from the actual mine. Finally, a mine's vapor-release rate changes significantly over time. One way to compensate for these hindrances

is to cover an area with several different dogs.

Identifying the precise location of mines is not necessary for vast stretches of land, however. Dogs accurately detect the general mined areas within these stretches. Deminers collect samples (possibly filtered to increase the concentration of any explosive material), then take them to the dogs for evaluation. Once the dogs identify the contaminated areas, deminers can concentrate on those areas with technologies that locate individual mines. To this respect, Figure 6 and Figure 7 illustrate MEDDS (Mechem Explosives and Drug Detection System) long used to verify whether a given area contains mines. In Figure 6 dogs assess MEDDS vapor absorbent filters, filled along a road. The filters shown on a stand represent 2.4 km of roads. Several dogs inspect each batch of filters. Results indicating a mined area are confirmed by a free running dog (a dog roaming the suspected mined area), as shown in Figure 7.

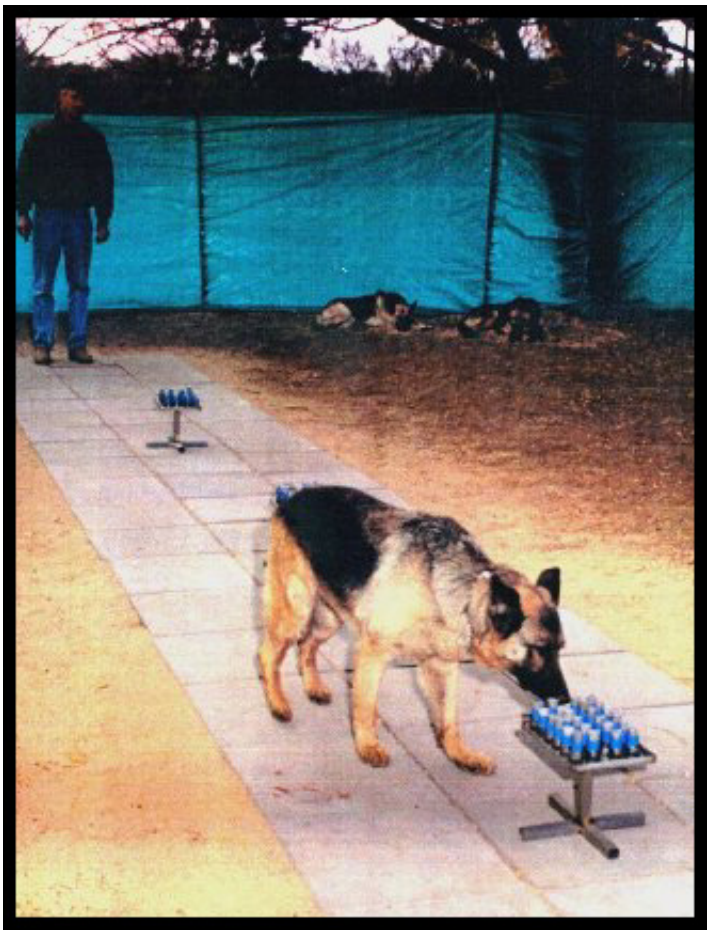


Figure 6: Checking vapor filters at a dog centre (V. Joynt, MECHEM)



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

Although somewhat effective, mine detection with dogs poses obstacles such as time and money costs for training dogs, the dogs' quickness to tire, and their sensitivity to environmental conditions.

Artificial Sensors of Trace Explosives

Brief description and Assessment

An alternative to training dogs to use their natural senses is developing artificial odor or vapor sensors: some types of artificial sensors are used currently in the chemical industry and in airports (chemiluminescence (Patel, 1995) (Tsipis, 1996), mass spectrometry, ion mobility spectroscopy, biosensors, electron capture (Jankowski, Mercado, and Hallowell, 1992)). Informative reviews of these sensors are given in (Rouhi, 1997) and (Jankowski et al., 1992). These sensors, however, are not practical for mine detection. They lack sensibility, speed, and portability. Results from Trace Explosive Detection (TED) trials using several types of artificial sensors and the problems associated with them are described in one paragraph of (McFee and Carruthers, 1996), while (Defence Research Establishment, 1991) analyzes the general problem of using artificial sensors for mine detection.

Specific Artificial Sensors

In 1995 the Bofors company in Sweden launched a project targeted specifically at detecting antipersonnel mines through odor sensors based on antibodies (Brink, 1996). Their system measures the variation in the oscillating frequency of a piezoelectric crystal, the surface of which is covered by an antibody reacting with TNT molecules.

A simple and inexpensive (polymeric) sensor array ("nose-on-a- chip"), designed to identify and classify vapors, has potential for trace explosive detection, as described in (Lewis et al., 1997).

An interesting complementary approach is MEMS (Micro Electro Mechanical Systems), in particular an array of thermal sensors (bimetallic cantilever beams) (Fair, Pamula, and Pollack, 1997). The basic concept is ultrasonically stimulating a target area, which detaches explosive particles, and collecting them. The particles then are irradiated with selective infrared radiation and deflagrate, which releases heat. The heat is detected by the cantilever, as schematically illustrated in Figure 8 for one element of the array.

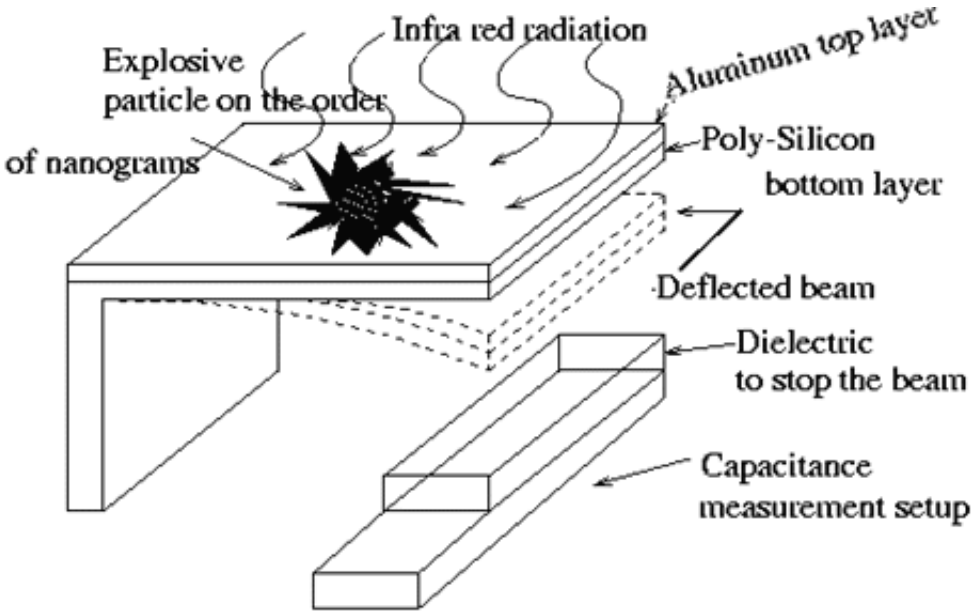


Figure 8: Schematic of MEMS trace explosive particle detector (V. Pamula, Duke (Fai97))

Finally, DARPA (Defense Advanced Research Projects Agency, http://www.darpa.mil/) recently began an ambitious three-year project (BAA 96-36), with a planned funding of 25 million US$, that aims to develop an electronic dog's nose. This project seeks technology for real-time, lightweight, low-power, and low-cost systems (referenced in (Rouhi, 1997)).

3.5 Bulk Explosive Detection

Brief Description and Assessment

Besides techniques for detecting trace explosives, interest is growing in techniques for detecting bulk explosives. These techniques are used in security (screening airport luggage (Novakoff, 1992) or mail) or Non-Destructive Testing. Applying these techniques to mine detection, which requires one-sided sensor configurations, operator security, equipment portability, and extensive soil penetration, is a challenge. However, some techniques, such as nuclear methods and NQR (Nuclear Quadrupole Resonance) appear promising.

Nuclear Methods

Nuclear methods include thermal neutron activation, neutron backscatter, and X-ray backscatter. They are reviewed in (Gozani, 1996) and, with emphasis on military applications and the detection of AT mines, in (Department of the Army, 1985) and (Department of the Army, 1991). (Defence Research Establishment, 1991) also provides thorough information about nuclear methods.

Thermal neutron activation (TNA) (Bach et al., 1996) relies on the activation, via neutrons emitted by a radioisotopic source or an accelerator of the nitrogen nuclei abundantly contained in most explosives. The activated nitrogen nuclei emit specific gamma rays, which can be detected quickly. The SAIC company has developed, using a Californium-252 source, a confirmatory device for the Canadian Improved Landmine Detection System (ILDS) (McFee, 1996) and for the VMDT vehicle already described (Brown, 1996).

In Figure 10, the TNA sensor head (weight around 180 kg) is attached to a translation frame as it undergoes field trials for the US Army. The sensor yielded good results for AT mines but not for APs, which contain a smaller explosive volume (Brown, 1996). Drawbacks of this method include system complexity and limited depth of soil penetration (10- 20 cm).



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



Figure 9b,c: The VMDT vehicle during field trials (D. Brown, SAIC)

A neutron backscatter application is described in (Leonhardt, Küster, and Neff, 1996). This technique thermalizes fast neutrons through the explosive's hydrogen nuclei and detects the backscattered slow neutrons. Because it relies on hydrogen nuclei, however, water, comprised of oxygen and hydrogen, impairs this system's ability to detect mines. This system is therefore probably most effective in dry environments.

X-ray backscatter techniques, mostly for the real-time detection of ATs, also are under investigation. Some developments are described in (Wehlburg et al., 1995) (Wehlburg et al., 1997) (Lockwood et al., 1997), with drawbacks similar to the ones described before for TNA. The prospect of a portable, safe, and reliable X-ray backscatter system that is used similar to a metal detector is detailed in (JASON, 1996) (Tsipis, 1996). X-ray backscatter systems also can provide two-dimensional images with a resolution of 2-3 cm. This use encounters problems in mine detection, however, from shallow soil penetration, sensitivity to soil topography, and variations in sensor height.

Nuclear Quadrupole Resonance (NQR)
NQR is "an electromagnetic resonance screening technique with the specificity of chemical spectroscopy" (Czipott and Iwanowski, 1996). Developed for airline security, this technique relies on the resonant response of certain nuclei possessing electric quadrupole moments. Research on this technology is documented in (Czipott and Iwanowski, 1996) (Kercel et al., 1997) (Rowe and Smith, 1996). (JASON, 1996) and (Tsipis, 1996) sketch a possible NQR for mine detection.

Because demining operations require one-sided (remote) implementation, adapting the technique to mine detection poses a problem. Another complication is that, although NQR detects RDX well, it does not efficiently detect TNT, the chief substance in mine explosives. Increasing the signal-to-noise ratio for TNT is, therefore, a priority in current NQR research.

3.6 Passive Millimeter Wave (MMW) Detection

In the millimeter wave band, soil has a high emissivity and low reflectivity, while metal has a low emissivity and strong reflectivity. Soil radiation depends, therefore, almost entirely on its temperature, and metal reflection relies mostly on the low-level radiation from the sky. It is possible to detect mines by measuring this contrast with a millimeter wave (MMW) radiometer. Passive MMW radiometers are relatively simple, less complicated than GPR. They also can generate clear two-dimensional images of surface or shallowly buried (centimeters deep) metallic objects, yielding best results in dry environments and for metal mines.

Tests in ideal laboratory conditions have demonstrated the capability of detecting metallic objects buried under 3 inches of dry sand working at 44 GHz (Yujiri, Hauss, and Shoucri, 1995). At this frequency, even a small percentage of water causes poor penetration of the soil, so this technology most likely is ineffective in wet environments.

Researchers also have tested the technology on plastic mines, which produce a much smaller DeltaT than the metal ones. Plastic mines have much lower reflectivity and transparency to radiation rising from below them. Using off-the-shelf components, these tests used frequencies of 44 and 12 GHz (Yujiri et al., 1996), and a recent test employed 5 GHz (Yujiri, Hauss, and Shoucri, 1997). The lower frequencies increase soil penetration, especially for moist soil, but decrease spatial resolution. These tests gathered radiometric data by scanning the area over a mine covered by leaves and shallowly buried in soil with varying degrees of moisture and used the data to form two- dimensional images.



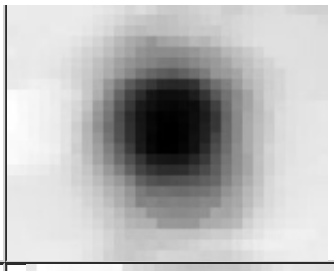
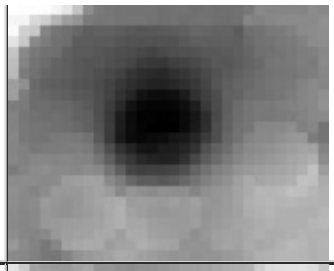
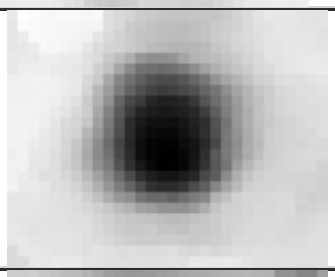
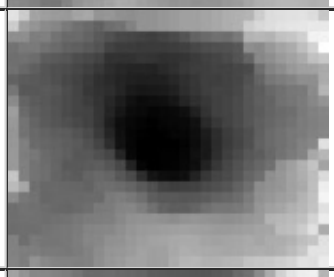
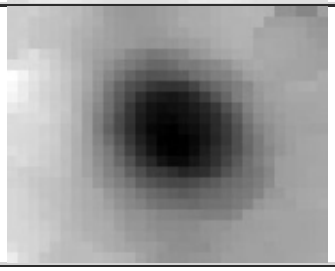
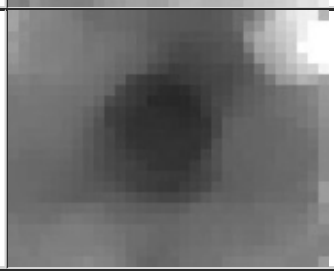
Mine Under Magnolia leaves		
Mine Under Dry Soil (1 to 3 cm) with $m_V < 0.05$		
Mine Under Soil (1 to 3 cm) with $m_V = 0.15$		

Table 1: Passive MMW Imaging at 5GHz: M-20 metallic AT (left), PMN2 plastic AP (right) (M. Shoucri, TRW (Yuj97))

(m_V : water volume fraction)

3.7 Ultrasound Detection

Conventional ultrasound detection involves the emission of a sound wave with a frequency higher than 20kHz into a medium. This sound wave reflects on boundaries between materials with different acoustical properties. Therefore, ultrasound systems effectively penetrate very wet and heavy ground such as clay, rendering them complementary to GPR. However, ultrasound systems encounter problems at the interface of air and ground.

Interesting results for mine detection with ultrasound were found in two significant areas of research. One area is the use of ultrasound to detect AP mines submerged in water, a simulation of mines thrown into rice fields (Ekstein, 1997) (Kempen, Nyssen, Sahli, and Cornelis, 1997). The research studies implement some methods of signal processing and pattern recognition to discriminate between AP mines and other objects. For example, the following figures show an AP mine (PRB M409) placed horizontally on a submerged soil surface. The top of the mine is 3 cm from the water surface. To obtain the figures, researchers used a 15 MHz probe and a scanning step of 0.6 mm. Figure 10 represents a horizontal scan along the X and Y axis at a fixed depth. The image is two-dimensional and displays the top of the mine. Figure 11 represents a scan that includes the Z axis. The image is thus three-

dimensional. The high frequencies used to obtain these images are effective only in water, not in soil.

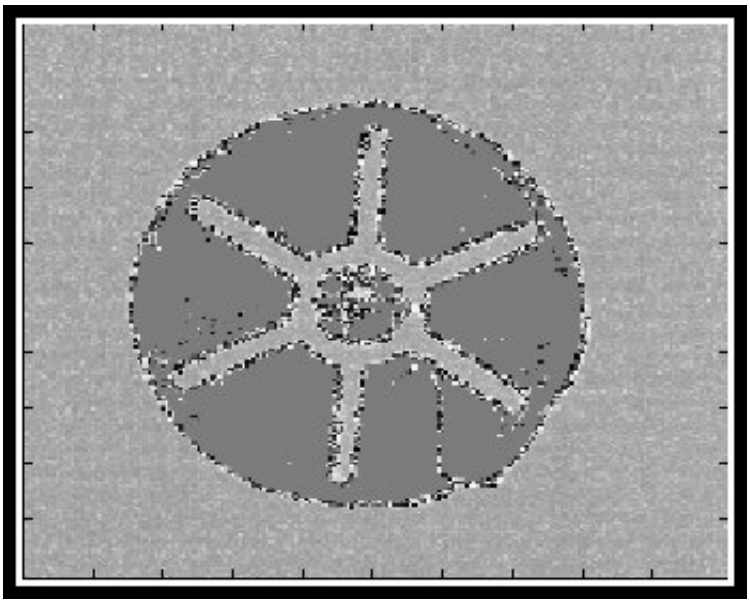


Figure 10: Two-dimensional image (horizontal slice) of an AP mine in water (H. Sahli, VUB Univ. (Kem97))

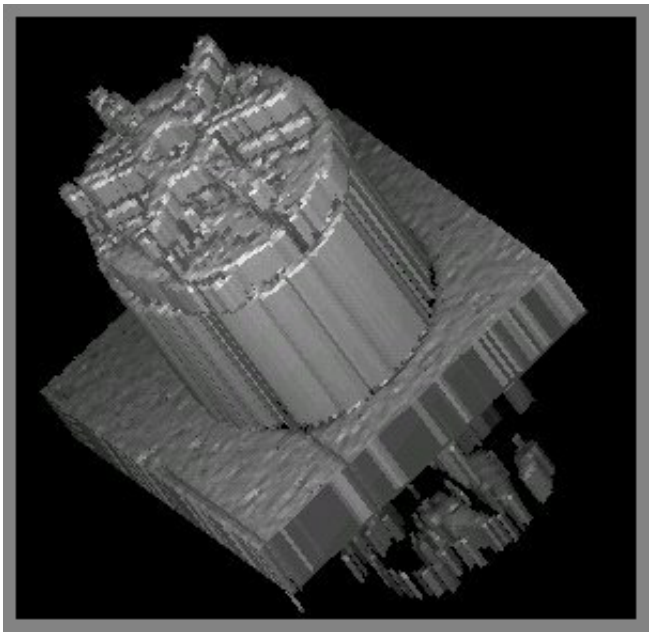


Figure 11: Three-dimensional image of an AP mine in water (Kempen, Nyssen, Sahli, and Cornelis, 1997))

Another significant area of research is the difference in acoustic impulse between a mine and soil. One study used ultrasound pulses of 1 msec to measure the difference successfully (Don, 1994). This study encountered

difficulty with distinguishing small object pulses from other signals and accounting for ground contours and irregularities. To overcome this difficulty, the study developed a procedure for subtracting background signals. A mine image obtained with ultrasound pulses (1 msec) is shown in Figure 12. The 12 cm plastic mine is buried 5 cm deep in lightly compacted, loamy garden soil. The arrival time of the surface reflection reveals the position of the surface.

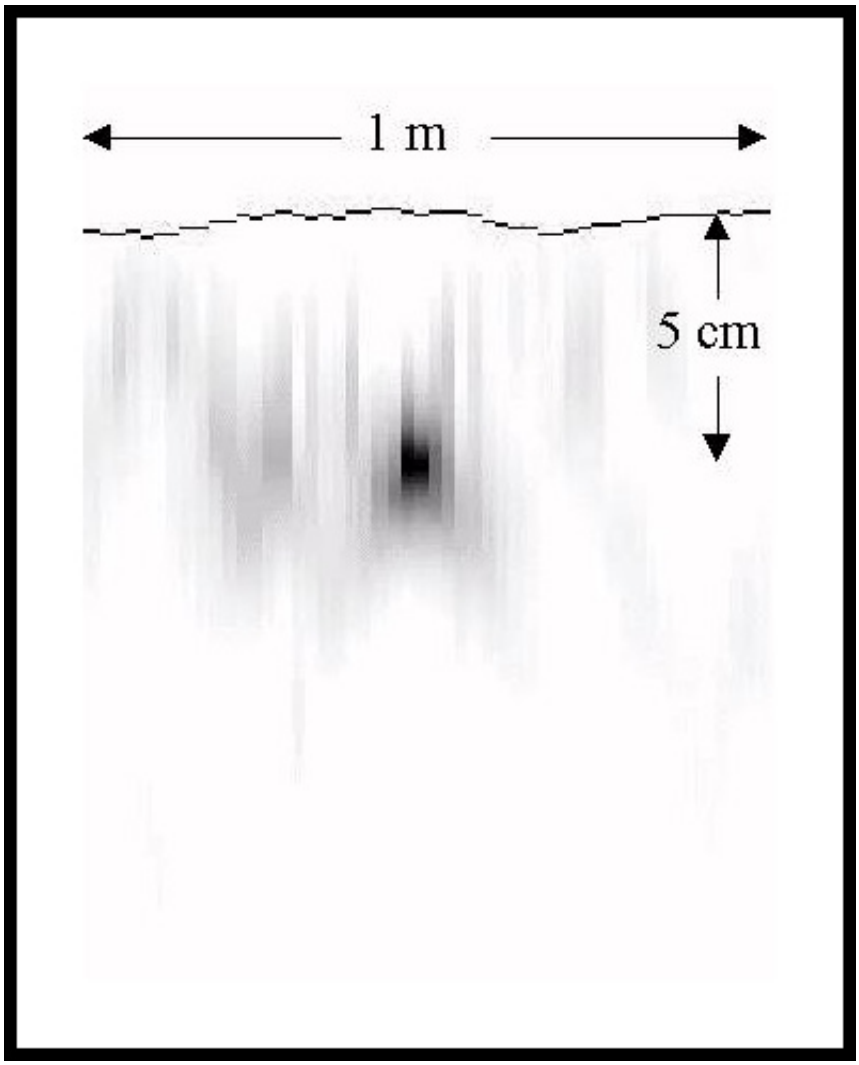


Figure 12: Line scan of a plastic AP using 1 msec acoustic pulses (C. Don, Monash Univ.)

Finally, a proposed area of research is the use of swept acoustic systems to find mine signatures (resonances) efficiently (JASON, 1996) (Kercel et al., 1997).

4. Conclusions

A NATO report published in March 1996 (NATO Defence Research Group, 1996) classifies these potential technologies for mine detection according to their maturity, cost, and complexity (Table 2). Though many technologies

show promise, none of these technologies seems capable of accurate mine detection in various environments with few false alarms. Most likely research will produce not a single panacea technology for mine detection but many technologies refined for specific situations. To progress toward more effective mine detection, researchers and operators need to exchange information about their studies and experiences. An efficient way to share information is through the global Internet. The Internet features many valuable resources for demining, including mine detection, such as the DeTeC web site http://diwww.epfl.ch/lami/detec/ and James Madison University's Humanitarian Demining Information Center.

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

Table 1: Demining Technology as measured by Maturity as well as Cost and Complexity.

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