

We find the highest focus on the **Ground Penetrating Radar (GPR) technology**: 20 organisations declared to be working on or with GPR. The second highest score goes to the **Metal Detector (MD)**, mentioned by 15 organisations. **Infrared (IR)** technology is mentioned in 6 entries distributed over different European countries. The 7 entries mentioning **Dogs** for mine clearance are also spread over the whole of Europe. Research on **Nuclear Quadrupole Resonance (NQR)** is conducted mainly in the UK at several institutes, at one organisation in Italy and one in Switzerland.

## 4. THE STATE OF THE ART IN EUROPE

This paragraph has been mostly drafted on the basis of the direct interviews carried out during the EUDEM study (the complete list of interviews is given in Annex 4, a summary of the interview contents can be found in Annex 8). The organisations and individuals we encountered include industrial companies, operators, key research centres, university laboratories and government agencies active in humanitarian demining, as well as some organisations not yet active in the field but showing relevant interest and/or innovative ideas. We concentrated mostly on detection, and partly on clearance and destruction equipment technologies; other aspects of the mine action process were partly investigated with the operators themselves, as well as with some government agencies. The organisations previously mentioned can be subdivided as follows:

ORGANISATIONS	TYPE	Interviews
<b>Industry</b>	Equipment manufacturers (for humanitarian demining)	6
	R&D	9
<b>Operators</b>	NGO	3
	MAC	4 (Geneva, Croatia)
	Commercial	2
<b>Research centres</b>	Supra-national	2 (ISL, JRC)
	National	7
<b>University laboratories</b>		4
<b>Government agencies</b>	MOD, Foreign Affairs, Development Aid	5

Table 1. Types of organisations and number of corresponding interviews

### 4.1. Current Equipment in the Field

#### 4.1.1. Mine Dog Programs

Dogs can and are used to smell explosive vapours and/or traces, similarly to what is done at airports and in other security applications. Examples of application go back to the Second World War and in more recent times to the Vietnam War. Dogs were first employed for humanitarian demining in Afghanistan, which nowadays features one of the largest and most successful programs.

**Dog training** is extremely difficult and time-consuming, and lasts up to 3 years. Two dog-training centres were visited, one hosted by the Swedish Army and a commercial one, also located in Sweden. The training in the country of origin is essential and should be continued in the country where the dog has to work to ensure the adaptation to different working, soil, vegetation and weather conditions and also to a new local handler. The handler and the dog form the demining “system” and cannot perform well without perfect matching.

The price of a good dog is very high. Other **limiting factors** are unfavourable climatic conditions (such as excessive heat, too much wind or wind coming from the wrong direction), thick vegetation, as well as dense and/or mixed (AT and AP mines) minefields that can confuse the dogs. Daily working hours are also relatively short, but dogs can easily cover several thousand square meters per day (figures vary sharply).

The use of dogs is far from being a perfect science, and the detection rate (efficiency) of a dog-handler pair is subject to rather wild guesses. Nevertheless, well run dog programs are nowadays generally accepted by most humanitarian demining organisations for **area verification** (e.g. *Quality Control* after mine clearance activities) and **minefield delineation** (i.e. *area reduction*). For these applications, important time gains are obtained compared to manual clearance. The use of dogs for individual mine detection is somewhat more controversial (although examples exist: e.g. rescue operations, mine clearance in Afghanistan). In general, mine dog programs

seem to be expanding (see for example the Swedish contribution to the establishment of a program in Cambodia). Handicap International estimates that *less than 500 dogs are currently in use world-wide*<sup>6</sup>.

*Intensively discussed issues are the lack of coherent and universal testing protocols for dogs and the insufficient local training for the dog and its new handler. The systems differ from organisation to organisation. An important discussion point is also the lack of agreement on a Standard Operating Procedure (SOP). A number of scientific studies (e.g. FOA in Sweden) try to clarify what dogs actually detect (minute amounts of explosive, or a composite odour in higher concentrations, etc.).*

An *excellent report* has been published by Handicap International on the subject: “The use of dogs for operations related to humanitarian mine clearance”, (2nd quarter of) 1998, ISBN 2-909064-33-6, 229 pp, ed. by Chris Horwood, Bill Howell, Robert Keeley, Dr. Jean-Baptiste Richardier.

#### 4.1.2. Manual Demining

Detection and clearance in Humanitarian Demining very often rely on manual methods as the *primary procedure*. The problem resides primarily in the detection phase: once a mine has been found, deminers know well how to remove it or blow it up<sup>7</sup>. When operating in this way *the detection phase still relies heavily on metal detectors*, whereby each alarm needs to be carefully checked until it has been fully understood and/or its source removed. This is normally done visually, and by *prodding and excavating* the ground. Sometimes this is the only way to explore the ground, for example when the area is saturated with metallic debris or when the soil is too conductive or magnetic.

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

We have not gone into the details of *incremental improvements* to the current field procedures, and we left aside the discussion of SOPs and the specific procedures to take care of intelligent devices, booby traps, vegetation cutting, trip wires, etc. We would like, however, to point out the importance of continuous developments to improve several pieces of equipment (e.g. protection items, more effective prodding and excavation tools, or vegetation cutting equipment) that, far from being spectacular, can make a difference in the field and bring *real short term added-value*.

#### 4.1.3. Metal Detectors

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

##### Magnetic Devices

Magnetic devices rely on the influence of nearby ferromagnetic objects, either via induced or via residual magnetisation, on top of the Earth 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 at depths of several meters, but do not react to non-ferromagnetic targets. They are only used in humanitarian demining when a real need exists (e.g. deeply buried UXO).

##### “Metal Detectors” (Electromagnetic Induction Devices)

Electromagnetic induction devices, which are often referred to as “metal detectors”, are active devices capable of detecting tiny amounts of metal (from a fraction of a gram onwards) at shallow depths. They are still to the best of our knowledge, apart from dogs, *the only detectors really being used in the field*, and are probably going to remain in use for some time. Frequency Domain systems have often represented the choice because they seem to work well especially for very small and nearby objects, but they are being more and more challenged by

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<sup>6</sup> Ben Lark, Proceedings, Demining Technologies - International Exhibition, Workshops and Training Courses, A. Sieber (Ed.), 29 Sept. – 1 Oct. 1998, Ispra (VA), Italy, p 101, EUR 18682, 1998.

<sup>7</sup> Which does not mean that new, cheaper and/or safer disposal methods are not welcome as part of the overall demining tools.

pulse systems, and not only where ground conditions are severe (e.g. sea-water or laterite soils, see Explanation Box).

European metal detector manufacturers are well established at international level and include *Ebinger, Förster and Vallon in Germany, Schiebel in Austria, and Guartel in the UK*. Most of these companies are small, and jealously guard the secrets of the trade; technical and scientific documentation has unfortunately been rather rare up to now. Production has been in general mostly geared towards the military market. Recently several systems that take into account the humanitarian demining needs have seen the light. Metal detectors designed for humanitarian demining usually share the following characteristics:

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

To the best of our knowledge no current metal detector for humanitarian demining applications delivers some quantitative information on the object under analysis. This is astonishing at first view, since there are other disciplines like Non Destructive Testing where this is the case. It can probably be explained by the urgent priority to enhance detection performance through better background rejection (i.e. reduction of the metal detector false alarm rate) and achieving higher sensitivity, as well as by the need of being very precise whilst usually not having any a priori information on the object under analysis.

A few large coil metal detectors, by Ebinger and Vallon for example, have been manufactured for the detection of larger metallic objects such as metallic mines or UXO. They can for example be employed as an alternative to magnetometers for the detection of ordnance that is not too deeply buried, or in cases where magnetometers can not be used (magnetic soil).

### **Metal Detector Arrays**

Most metal detector arrays, normally one to several meters wide, are derived from commercially available metal detector technology and are *usually employed for vehicle platforms to rapidly scan large areas*. Some of them can deliver information not only on the location of metallic objects but also on their depth and their approximate size, for example in the form of an “equivalent object volume” (which can be used to reduce the number of false alarms when looking for UXO for example). Some systems do also employ a special suspension system to make sure that the detectors are always parallel to the surface, and that a constant height is maintained.

*European manufacturers* include Förster (working within the ESPRIT LOTUS project), TZN and Vallon in Germany, as well as Schiebel in Austria. Förster is working on an extension of its portable MINEX 2FD two frequency continuous wave technology, using one large rectangular transmitter coil and 7 staggered (i.e. partially overlapping) differential receiver coil pairs; the final system should not be too expensive. TZN is a relative newcomer to the field, and is now commercialising the AMOS Unexploded Ordnance Detection System, which uses pulse induction and features a double layer coil system. Vallon and Schiebel arrays have been on the market for some time, whereby the Schiebel VAMIDS (Vehicular Array Mine Detection System) has been used in a number of projects; it employs combinations of 1 m wide flexible or rigid segmented arrays containing eight individual sensors.

Apart from the use in combination with other sensors, metal detector arrays can be used on their own, possibly for *Quality Control applications*, and the set-up/maintenance of a *data archive* in order to compare previously

executed searches with new searches<sup>8</sup> (suggestions by TZN). *Applications on road and road verge, or in combination with a magnetometer for the detection of UXO* are also feasible (suggestions by Förster). They obviously strongly depend on the end user and its SOP.

## EXPLANATION BOX

### Metal Detectors (Electromagnetic Induction Devices)

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

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

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

### Frequency Domain (Continuous Wave) Metal Detectors

Metal detectors can be subdivided in Frequency Domain, or Continuous Wave (CW), and Time Domain, or pulse, 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 the receive coil(s) caused by the presence of metallic or magnetic objects.

Information on the target's nature is contained in the amplitude and phase of the received signal, as the detector approaches the target. Measurements carried out 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 (seawater is conductive) or strongly mineralised regions, which can be conductive or iron rich. Generally speaking, background rejection is more difficult in heterogeneous areas.

### Time Domain (Pulse) 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 of obtaining a high slew rate to minimise the current switch-off transient time (a few  $\mu\text{s}$ ). Eddy currents are thus induced in nearby conductive objects and their exponential decay with time is observed. A Time Domain metal detector measures how quickly the momentarily generated magnetic field breaks down, which happens to be slower in presence of metal.

The eddy current decay time constant itself, some hundred  $\mu\text{s}$ , depends (predominantly) on the target's conductivity, permeability and size. Low conductivity background and nuisance items, such as seawater 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  $\mu\text{sec}$ ) between the time of switch-off and the sample acquisition. A similar argument applies to purely magnetic but non-conductive targets, which are magnetised by the transmit pulse but demagnetise just as promptly after switch-off.

A pulse systems is therefore the detector of choice when it comes to working in seawater or strongly mineralised soils (containing for example bauxite, laterite, magnetite or magmatite, which are conductive and/or magnetic) as found in parts of Cambodia, Mozambique and Angola. On the other hand, at least up to some time ago, overall sensitivity was probably low in comparison with Frequency Domain detectors, and there were problems in finding low conductivity metallic object such as those made of stainless steel.

Given that the transmit and the 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.

## 4.1.4. Mechanically Assisted Demining

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<sup>8</sup> Recording the data might in fact be useful in case of controversy at a later stage, i.e. after clearance, for "going over the books" easily.

A number of machines have been tested during the past years, partially adapting them from military designs. The general trend goes from “mechanical demining” towards “mechanically assisted demining”, adaptable to local circumstances. Without pretending to be exhaustive, the following systems are currently used (see *Humanitarian Mine Action Equipment Catalogue 1998/1999*, German Federal Foreign Office – second draft):

- **Vegetation cutters:** in many countries, and not only tropical ones, vegetation is a large problem and its removal (mine detectors have to be used in close proximity to the soil, and tripwires have to be detected) can take up a substantial fraction of the time. Vegetation cutters are used by several organisations to accelerate manual clearance and the work of sniffing dogs. In their simplest form they consist of adequately modified commercial devices (e.g. tractors or excavators).
- **Mine Clearing Flails:** clearance machine hitting and milling the ground with a series of flails (long chains with clearing elements, similar to hammers, attached to them). The flails are attached to a rapidly rotating drum, and *detonate the mines or break them apart*. Such systems have been in use for years for military applications, and a number of units have also been produced and tested during the last years for humanitarian demining. European producers include Aardvark in the UK, Hydrema in Denmark, Patria Vehicles in Finland, Technopol in Slovakia. Prices start from about 500 k EURO, and the systems are rather large, at least 15-20 t. Clearance depth is usually adjustable, and there is a trade-off between depth and forward speed. Several machines are in use, for example with NPA in Angola.
- **Mini Flails:** a smaller version of the flail system just described, with correspondingly reduced price and maintenance cost, designed in particular for vegetation clearance (see also the *Vegetation cutters* described above). Some systems should also be able to clear (shallow) landmines. Much development work is still going on (e.g.. in the UK at the Warwick University); some systems are operational (e.g. the Croatian MV2).
- **Earth Tillers:** rather large and bulky clearance machines employing one or more rotating horizontal drums with special teeth, capable of tilling the soil to a variable depth, detonating or disrupting mines as they move on the field. Weight is usually at least 30-40 t (some machines have been built around a tank chassis), and prices go from 1 M EURO upwards. European producers include amongst others MaK (Rhino system) and Krohn in Germany, Bofors (Mine-Guzzler) in Sweden. Some systems might be in use or being tested.
- **Wheel Shovel** (e.g. HALO Trust in Afghanistan) based systems for digging up mines that will be manually cleared afterwards, for the excavation and inspection of (urban) rubble, also for roads (road grader). A mesh basket is fitted over the shovel, which then shakes out the rubble; large ordnance and mines will remain held by the mesh in the bucket.
- **AP Mine Sifter** (e.g. MgM Foundation in Angola): a drum is used to pick up the contaminated soil; it then closes and rotates, and the loose soil falls out. The remaining debris can be visually inspected.
- **Mine Protected Vehicle:** MPVs are vehicles designed to resist AP and AT mine explosion. They can be modified, for example by replacing the tyres with large steel wheels or attaching devices such as steel disc roller sets, for mine clearance (e.g. Mechem - South Africa, also used in Croatia).

Concerning the mine clearing vehicles in particular, one can say that usually the machines have to be backed-up by some manual method (full detection drill or visual inspection), dogs or a second machine in order to guarantee a satisfactory overall clearance rate. These systems are *employed for mine verification and area reduction tasks as well as clearance of actual minefields*. They are mostly used in wide areas (not in dense forests), and roads. Large mechanical systems, in particular the flail and tiller machines, do require substantial investments, not only for machine costs but also for logistics and maintenance, and can actually only be employed on a fraction of the total mined areas.

**Environmental effects, such as erosion and soil pollution** due to exploded mine residuals, have not always been duly studied. A confidential study on the effects of mechanical clearance on the natural ecosystem has been carried out in Norway. More emphasis should be attributed to this specific aspect of demining.

More information on Mechanically Assisted Clearance is available in the summer issue (June/July 1999) of the Journal of Humanitarian Demining (published by the Mine Action Information Center at the James Madison University, see <http://www.hdic.jmu.edu/hdic/journal/3.2/>), as well as from the ongoing study on Mechanical Support to Demining by Handicap International.

## 4.2. Emerging Sensor Technologies

Needless to say, *the detection capability, and corresponding false alarm rate, are only two of the many parameters that have to be considered.* Others, will also strongly determine if the system will ever be fielded, e.g. *importance of the target application, cost, size, complexity, penetration depth, simple and/or user friendly man machine interface (MMI), etc.* The risk of R&D is, as Colin King once put it, to devise systems which “work best where they are least useful”.

### 4.2.1 Enhanced Metal Detectors

These detectors have indeed become more and more refined and sensitive over the years. Although it has often been said that they have reached their limits, there are still opportunities for **improvement in background rejection**, helping in difficult soil conditions, and perhaps in **sensitivity**. Developments are ongoing, and partly financed by current EC R&D projects.

Next in the line of “realisable” items is probably the determination of the **object’s depth**. It could be delivered for example either by scanning the detector across the object and analysing the width of the response (or other parameters), or by taking at least two measurements under different conditions, for example by using two overlapping coils which is probably easiest. Some of these techniques are in use for Non Destructive Testing applications and UXO localisation.

Giving an estimate of the **object’s size** is next in the wish list. In principle the object’s size should represent an interesting piece of information, although opinions diverge. One way of estimating the size of an object could consist in measuring the magnetic field over an area in order to try to calculate the object’s magnetic dipole moment (typically using a simple, dipolar model), that gives an indication of its “magnetic” volume. Another way is to try to extract the information from the time behaviour (the pulse shape) of the received signal in a pulse detector for example. Again, technical feasibility as well as applicability in the field and sources of errors have to be very carefully studied. This development is also being looked into but is probably rather tough: a detector’s response contains a lot of information on the target, but depends on a series of parameters as well.

Another approach is to generate an **image**, for example by scanning a single sensor over a surface. Resolution enhancement techniques such as deconvolving the detector’s intrinsic response might also be tried. Whether this approach will be practically applicable in the field, from the point of view of the resulting resolution, scanning speed and cost for example, remains to be demonstrated. Imaging activities seem to be still at the research level.

Another interesting line of research is to investigate how concepts from **low-power electronic design** can be used to *increase autonomous operation time* (e.g. proposals exist for systems that are (partially) powered by movement).

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

It is interesting to see that *for most of these activities there does not seem to be a clear cut opinion neither on the technical aspects (realisable or not) nor on the actual applications and utility in the field.*

### 4.2.2. Passive Microwave Radiometers

Passive radiometers working in the microwave range of the electromagnetic spectrum have been suggested in particular for the detection of mines placed on the surface (but covered with light vegetation for example) or shallowly buried mines (some cm). The actual maximum detection depth is a strong function of the frequency being used, soil humidity and conductivity, material type (metal or plastic) and size (AT vs. AP Mine for example). Increasing the frequency, results in better spatial resolution, but soil penetration can be drastically reduced (especially for wet soils); the trend has been therefore towards lower operating frequencies, say below 10 GHz. We are referring here to close-in detection; distant detection of larger objects on the surface seems possible too, using millimetre wave devices (i.e. working at higher frequencies, for example 94 GHz).

Metallic targets do indeed have a low emissivity and strong reflectivity (acting like a mirror) in the microwave band, whereas soil has a high emissivity and low reflectivity. Soil radiation depends therefore almost entirely on

its physical temperature, whereas metal radiation depends mostly on the reflection of the low-level radiation from the (cold) sky which “illuminates” it. It is possible to measure this contrast between the “warm” ground and a “cold” mine (both temperatures as seen in the microwave band) using a passive radiometer; the latter basically consists of a receiving antenna measuring the microwave radiation coming from an object and functions like a microwave band power meter. The detection of plastic targets is also possible but more difficult, given that they produce a much smaller  $\Delta T$  (temperature difference) than the metal objects (they have much lower reflectivity and transparency to radiation rising from below them).

Passive microwave radiometers are simpler devices than the Ground Penetrating Radar and should suffer less from clutter problems. In principle it should be possible to build man portable systems using rather low cost materials. Like many other sensors, they could be scanned over the ground to generate bidimensional images, with best results in dry soils, and for metallic targets and/or large objects.

Work on passive microwave radiometers is also being looked into within current EC R&D projects (e.g. by ERA in the UK, DLR in Germany and Thomson-CSF Detexis in France), usually in conjunction with a Ground Penetrating Radar that might have problems with the detection of surface or shallowly buried objects. It will be interesting to verify if there are some applications where microwave radiometers can be used on their own.

#### 4.2.3. Infrared (IR)

Infrared (IR) cameras are passive devices sensitive to radiation in the infrared part of the spectrum (i.e. basically to the physical temperature of a body). They are capable of detecting under some circumstances *mines on the surface as well as buried mines*. The detection of buried objects might seem rather surprising, given that IR rays do not penetrate the ground and that it is therefore not possible to measure directly the temperature of a buried mine. What happens is in fact that mines do retain or release heat at a different rate than their surroundings. During natural temperature variations of the environment it is therefore possible, using IR cameras, to *measure the thermal contrast between the soil over a buried mine and the soil close to it*. The devices of potential interest do normally operate in the 3-5  $\mu\text{m}$  and 8-12  $\mu\text{m}$  atmospheric windows<sup>9</sup>, corresponding respectively to Medium Wave IR (MWIR) and Long Wave IR (LWIR).

When the previously mentioned thermal 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 which enhances the mine’s signature.

Note that rather sensitive cameras have to be employed, with sufficient spatial resolution; the maximum burial depth that still allows detection, is estimated at 10-15 cm. In addition, results obtained with passive infrared imagery can *depend* quite heavily on the *environmental conditions* and there are crossover periods<sup>10</sup> (typically in the evening and in the morning) when the thermal contrast is negligible and the mine practically undetectable. Other problems are due to the target object’s history, uneven surfaces, clutter and vegetation (which cause a number of secondary effects). *It remains to be seen if this heavy dependency on external conditions can be overcome in practical applications*, possibly enhancing the detection techniques. Two major approaches have been studied to enhance detection efficiency:

- The analysis of IR image sequences, showing the dynamic scene behaviour after or during time variant heating (e.g. solar illumination), as studied at VUB in Belgium, and BGT in Germany.
- The exploitation of an extra physical parameter, namely the polarisation of the IR radiation reflected and emitted by man-made objects, as studied at DERA in the UK, Thomson-CSF Detexis in France and Daimler Benz in Germany. A periodical image sequence can be obtained by continuously rotating the polarisation orientation.

Both methods are creating augmented contrast between the natural environment and man-made objects, by analysing *sequences* of images and combining them into one or a few parametric images.

Infrared systems have been and are being intensively investigated by a number of companies and research centres for defence applications, in particular for the *detection of mines and minefields* (mostly AT mines) *from airborne platforms*, and for the *stand-off detection from vehicles*, typically on roads and tracks again for AT mines. The only EC ESPRIT project which makes use of IR sensors is the LOTUS project (multisensor remote

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<sup>9</sup> The atmosphere is transparent to infrared radiation in these wavelength bands.

<sup>10</sup> When the soil above a mine changes from hotter than the surrounding soil to colder (thermal inversion), or vice versa.

controlled vehicle); IR sensors have also been used in the EC DG VIII pilot project “Airborne Minefield Detection in Mozambique”. In Europe we have not encountered activities using this type of sensor for man portable applications.

Direct measurements can be coupled to *thermodynamic soil modelling* programs, with models describing the heat transfer in the mine and the ground, as well as the heat exchange between ground and atmosphere. Depending on the model’s sophistication level they can simulate not only the heat flow in the ground but also the moisture flow. This type of study should allow predicting where and when the detection can be performed (FOA in Sweden is among the institutions working on this).

What speaks in favour of IR systems is their *imaging capability* (large field of view), and the recent technological progress yielding cheaper, more sensitive and larger sensor arrays moving towards an imaging quality comparable to current commercial digital cameras operating in the visible spectrum. High-end cameras are usually cooled so that the sensing element works at low temperature for maximum sensitivity; they are still rather expensive. Small, uncooled cameras are also starting to be industrialised and are definitely cheaper, but a factor 5-10 less sensitive.

#### 4.2.4 Multi-spectral Imaging Systems

In reconnaissance applications based on imaging sensors, for example minefield detection using airborne systems, it can be difficult to differentiate the mine from the background due to low contrast and the presence of highly textured backgrounds. Multispectral techniques can be used since they provide more information than images from common broadband cameras. The multispectral systems themselves operate over several wavelength bands, e.g. from ultraviolet to visible and thermal infrared (0.2-14  $\mu\text{m}$ ). Surface laid and buried mines can be found due to contrast variations in the collected multidimensional image. FOA in Sweden is investigating multispectral analysis for mine detection and minefield delineation. Note that *multispectral imaging has the advantage of measuring different physical parameters simultaneously, and without major spatial co-registration problems.*

#### 4.2.5 X-ray Backscatter Techniques

Backscattered radiation is detected during active illumination of the ground with X-rays, and basically determines whether or not an object is made up predominantly of light chemical elements (i.e. low atomic number Z). The technique is intended for real-time detection of AT mines. The system is said to be able (Thomson-CSF Detexis in France) to produce a 2D image with a resolution of some cm. Potential problems come from shallow penetration, system complexity, sensitivity to soil topography, sensor height variation, and safety aspects due to the use of ionising radiation. Outside Europe, research on the subject has been carried out during the last decade in particular by the University of Florida, mostly for defence applications. X-ray backscatter techniques are also used in geological studies.

#### 4.2.6 Ground Penetrating Radar (GPR)

##### Background

Ground Penetrating Radar (GPR) has been in use for at least 15-20 years in civil engineering, geology and archaeology for the detection of buried objects and soil study. The detection of landmines has been a subject of interest, in particular due to the radar’s potential for the detection of plastic mines. Today a very large number of organisations over all of Europe are working on different parts of GPR systems, and amongst the sensors encountered, *GPR is probably the most studied.*

GPR works by emitting an electromagnetic wave into the ground, rather than in the air as in most radar applications, using an antenna which does not need direct ground contact (in other domains direct contact is often required, e.g. Non Destructive Testing). GPR systems usually operate in the microwave region, from several hundred MHz to several GHz<sup>11</sup>. Buried objects, as well as the air-ground interface, cause reflections of the emitted energy, which are recorded by a receiver antenna. The antenna is indeed one of the crucial parts of the system. Most systems are low power ones and do not present any danger to the operator.

GPRs can be subdivided into four categories, depending on their operating principle. The first type is a *time domain* GPR with an *impulse system*, where the emitted pulse has a carrier frequency, modulated by a square envelope. This type of device operates in a limited frequency range, and has in most cases a mono-cycle pulse.

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<sup>11</sup> At 1 GHz, a frequency similar to the one used for mobile phones, electromagnetic waves have a wavelength of 30 cm in air and of about 10-15 cm in the ground.

The second type of *time domain* GPR is the so-called *Chirp Radar*, which transmits a pulse-train waveform where the carrier frequency of each pulse is rapidly changed across the pulse width. *Frequency domain* GPRs transmit a signal with a changing carrier frequency over a chosen frequency range. This carrier frequency can be changed, either continuously for example in a linear sweep (*Frequency Modulated Continuous Wave Radar*, or FMCW), or with a fixed step (*stepped frequency radar*).

The terminology *Ultra Wide Band (UWB) GPR* is used for a system having a fractional bandwidth, which is larger than 25%.

What particularly matters for detection is the difference between the electromagnetic properties of the target (in particular its dielectric constant) and those of the ground. The amount of energy reflected obviously depends also on the object's size and form, which is a prerequisite for reliable detection of small AP mines. Spatial resolution depends on the frequency used, and the resolution needed to cope with the small objects considered enforces the use of wide frequency bands (some GHz)<sup>12</sup>, with the higher frequencies being limited in penetration depth. Microwaves are indeed strongly attenuated by certain types of conductive soils, such as clay, and attenuation increases with frequency. Wet clay in particular provides an extremely tough environment (penetration is very poor).

### System Configuration

GPR systems for landmine detection are either designed *to provide detection warnings* (e.g. an audio signal as in MDs), or *to produce image data*.

In the first case, adequate signal processing should extract information on the target object from the return signal. The final aim is to detect the targets and, if possible, classify them<sup>13</sup>. The main problem is understanding if and how such information can be extracted in a usable and robust way, in particular if invariant features do exist (independent of target orientation and depth, soil type, etc).

In the second case, the area scanning should either be controlled or tracked so that the radar's pose is known for each of the acquired signals (in real time if necessary). Designing a *tracking system*, in particular for a handheld probe, is a complex task due to the required precision level and the area coverage. Several types of images representing the spatial structure of the measured data can then be produced, for example vertical slices (so called B-scans), horizontal slices (C-scans), or full 3D volume representations. The wavelength of the GPR radiation is comparable to the target object size (centimetres or tens of cm). *A radar image has therefore a totally different nature than an optical image* (lower spatial resolution, "fuzzy" aspect due to complex interaction of the emitted signal with the target objects, particular noise patterns due to scattering). In addition, GPR antennas normally have a wide beam pattern, which degrades the spatial resolution unless appropriately corrected.

The *imaging approach* is appealing, but it requires a good analysis of scanning time, data processing, scene reconstruction, processing power and visualisation. Scanning time performance is less stringent for humanitarian demining than for military applications. Moreover using GPR arrays reduces the scanning time at the cost of increased processing complexity. Typical data *pre-processing* components are: regridding of the measured data to the image grid, clutter removal, correction of the varying distances between the antenna and the ground, pose correction (note that these pre-processing steps are also used when the GPR is configured as a detection warning device without imaging). Scene reconstruction for visualisation of the underground requires solving an ill posed mathematical inverse problem, which is a non-trivial numerical problem that cannot be solved without sufficient processing power. Direct feature extraction from the measured data followed by classification based on the extracted features is an approach, which does not necessarily require the scene to be reconstructed from the measured data. *Visualisation can either be an image of the reconstructed scene, the pre-processed data in the form of C-scans, or an image of the classification results*.

### European R&D

Nearly all EC *ESPRIT* projects on humanitarian demining are working on GPR systems, mostly for *handheld applications*. Results are expected within 1 to 3 years. Despite the 20 years of GPR experience in civil engineering, geology and archaeology, we should be careful not to be overoptimistic concerning the development times for GPR mine detection systems. In the former applications, GPR systems are used by specialists of visual GPR image interpretation, and for large objects the detection heavily relies on spatial correlation. For mine detection, however, small AP mines have to be detected in the presence of a complex

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<sup>12</sup> The shorter the pulse or the wider the bandwidth, the better the spatial resolution.

<sup>13</sup> Detection means telling that "there is something", classification means telling what it is (in the simplest case something like "dangerous, not dangerous, do not know", ideally something like "a stone, mine type A, mine type B, etc.").

underground (e.g. inhomogeneities, irregular surfaces, etc.). Providing light, user friendly and affordable systems with sufficient autonomy (prices of commercial equipment are gradually decreasing but still about a factor 5-10 higher than metal detectors) is also a main technical challenge. Tests in the field by end users should assess real system performances and limitations.

**Vehicle mounted GPR** systems are also under study for application on roads and tracks, usually with the main target of detecting AT mines or UXO (which should facilitate the task compared to the detection of AP mines). During the interviews two types of systems were mentioned, (i) an array antenna mounted in front of the vehicle to ensure sufficient coverage, combined with imaging techniques, and (ii) a forward looking UWB radar combined with analysis of target traces formed by the forward vehicle motion. One ESPRIT project, LOTUS (start: January 1999, duration: 3 years), investigates a vehicular approach, and several other efforts are ongoing at national level, mainly for defence applications. The latter might partially have an impact on the humanitarian demining scenario. Some *Quality Assurance/Quality Control applications* have also been suggested, for example road survey after clearance, and the establishment of records describing the history of the clearance task, in order to compare previously executed searches with new searches and to eliminate controversy after clearance<sup>14</sup>.

In several domains other than demining high tech GPR-like developments are ongoing, e.g. the modulated microwave array antennas (“retinas”) and corresponding tomographic, real time image reconstruction, as pioneered by SATIMO in France. Even without a specific programme targeted at humanitarian mine detection, it is useful to closely monitor these developments, so that specific humanitarian demining tests can be carried out once the technology is mature.

#### 4.2.7 Bulk Explosive Detection Systems

Techniques that detect the explosive itself, in bulk form, should not be confused with trace explosive detection such as carried out by sniffing dogs.

#### Nuclear Quadrupole Resonance (NQR)

Nuclear Quadrupole Resonance (NQR) is one of a few techniques capable of detecting the explosive in bulk form. Contrary to what its name might indicate, *NQR does not use radioactive sources nor produces any form of harmful radiation*. Instead it uses radio waves, somewhat higher in frequency than those of a pulsed metal detector.

NQR has been described as “an electromagnetic resonance screening technique with the specificity of chemical spectroscopy”. It 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, like Nuclear Magnetic Resonance (NMR). Problems are due in particular –as in most other sensing techniques for landmine detection – to the need for a one-sided (remote) implementation (it is impossible to put parts of the sensor on “the other side of the object”). *Encouraging results have been obtained with RDX. Increasing the signal to noise ratio for TNT, used in the majority of mines, is therefore one of the priorities in current research.*

Similarly to metal detectors, the generated and the received field decay very quickly with distance; detection depth will be limited (depending on the type and amount of explosive, and the measurement time – typically seconds to tens of seconds) and the equipment will have to be used in close proximity to the ground.

Concerning Europe, NQR for landmine detection has been intensively researched in the UK in the context of defence applications, in particular at King’s College in London (KCL) under sponsorship of DERA, at DERA itself and at ERA Technology (especially equipment manufacturing). No currently ongoing ESPRIT project covers NQR research. Whether there are at present any plans - apart from those of KCL - to transfer this know-how to humanitarian demining, is unknown to us. R&D was also carried out in the former Soviet Union, in Kaliningrad, already at the time of the Afghanistan War. In this case, present efforts are likely to depend strongly on the funding situation.

NQR systems are most likely to be used in combination with other sensors as *confirmatory devices*. The estimated cost is 5-10 times the price of current metal detectors.

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<sup>14</sup> As suggested by Mine-Tech (Zimbabwe) and TRICON (Germany) during informal discussions at a conference in 1998.

Finally, let us point out the *activities on handheld and vehicle mounted NQR systems*, currently being carried out in the US by Quantum Magnetics, under sponsorship from DARPA, the U.S. Marine Corps System Command and the U.S. Army. Initially aimed at military systems, these activities now seem to be extended to humanitarian demining.

## **Thermal and Fast Neutron Analysis (TNA & FNA)**

### **Background**

There are several neutron-based techniques for detecting explosives in bulk form. All systems are composed of at least a *neutron source* – continuous or pulsed, emitting in bursts – to produce the neutrons that have to be directed into the ground, and a *detector* to characterize the outgoing radiation, usually gamma rays<sup>15</sup>, resulting from the interaction of the neutrons with the soil and the substances it contains (e.g. the explosive). Amongst the generic neutron-based explosive detection techniques we have Thermal Neutron Analysis and Fast Neutron Analysis (a number of derivatives thereof do exist), which are described in the Explanation Box.

- **Thermal Neutron Analysis (TNA)** is probably the “easiest” and cheapest among the neutron-based techniques. It features *high sensitivity to nitrogen* concentration. On the other hand it is relatively slow, and is usually not suited for operation in real-time, like conventional metal detectors (second or even minute response times).
- **Fast Neutron Analysis (FNA)** has the potential of delivering better results than TNA, because it is *sensitive to nearly all elements in explosives* and opens the possibility of identifying the substance under analysis, but is usually far more complex and expensive. Note that in using pulsed FNA, (pulsed) TNA comes in “automatically” (TNA gamma rays can be detected after each pulse).

The *gamma ray detector* is a key element of the system. According to the requirements its complexity can range from a simple counting device (registering only the amount of gamma photons) to the measurement of the energy (essential for chemical characterisation). A system with a pulsed source could in principle also deliver some timing information, from which the spatial position of the source of outgoing radiation can be determined. Such a system would therefore be able to determine the type of substances, where they are situated, and therefore generate an image.

### **System Configuration**

Neutron analysis systems could typically be combined with other sensors, and used in a confirmatory role. Amongst the drawbacks of neutron based systems we find usually system complexity and cost, radiation hazard, system weight (especially due to heavy shielding), power requirements. Depth of penetration also has to be carefully assessed, as well as minimum amount of detectable explosive. It remains to be established if such a system will be practical and fieldable, if the added performance will be sufficient to justify the extra costs, and if improvements can be obtained in special applications<sup>16</sup>. Some FNA based systems are in use for the detailed discrimination of ordnance containing explosives, inert substances and chemical warfare agents, whereby the corresponding companies mostly provide a service rather than sell a product.

### **European R&D**

Nuclear sensor systems are studied and designed, notably in France (EPPRA, SODERN), Germany (I.U.T.), Italy (INFN), Russia and the US.

Problems for landmine detection include: the need for a one-sided sensor configuration, operator security, equipment portability, and limited soil penetration of particles/radiation. To the best of our knowledge, no one has yet produced a fieldable and effective system for humanitarian demining applications. EPPRA (France) is working on neutron based techniques within the EC MINESEYE project. INFN (the Italian National Institute of Nuclear Physics) is engaged in an internal collaborative research program, called EXPLODET (EXPLOsive DETection), over the period 1998-2000. The involvement of other organisations with the necessary background is likely to be strongly dependent on the financial resources made available. Note that INFN includes in its project budget about 25 kEURO exclusively for material costs associated to a TNA system that is probably the “easiest” among the neutron based systems. FNA systems are likely to be much more expensive.

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<sup>15</sup> Gamma rays are similar to X-rays, but of higher energy, and are emitted in radioactive decays and reaction between nuclei.

<sup>16</sup> TNA sensors have been tested for example for the confirmation of the presence of AT mines on roads.

#### EXPLANATION BOX

**Thermal Neutron Analysis (TNA)** relies on the elevated nitrogen concentration of most commonly used explosives, and is based on the detection of characteristic gamma rays emitted by the nitrogen nuclei in thermal neutron capture reactions. The thermal (i.e. slow) neutrons themselves can be produced by slowing down fast neutrons from low cost, small radioisotopic sources, such as  $^{252}\text{Cf}$  (Californium-252), or from portable electronic neutron generators<sup>17</sup> (e.g. small accelerators of the electrostatic Deuterium-Tritium or plasma-focus type). The “slowdown” takes place in a specially designed “moderator”, or in the target substance itself (the earth and the explosive in our case).

**Fast Neutron Analysis (FNA)** is based on the interaction of fast neutrons, mostly inelastic neutron scattering, with the nuclei of interest. During this process the high energy neutrons put elements in an excited, short lived state, in particular Carbon, Nitrogen and Oxygen of explosives and soils, by hitting their nuclei. The nuclei return to their initial state by emitting gamma radiation, whose energy distribution, or spectrum reflects the, chemical characteristics of each nucleus. In other words, by characterising the outgoing gamma rays it is possible to calculate the elemental proportions – how much of each element (C, N, O) is present with respect to the others – in order to determine the type<sup>18</sup> of substance under analysis (all explosives are composed of Carbon, Nitrogen, Oxygen, and Hydrogen that is not detectable by pure FNA).

**Neutron backscattering** is a different technique, where slow neutrons coming back in the direction of the source are detected, providing a measure of the hydrogen content of the material. Neutron backscattering is probably the simplest technique, but seems likely to only work in dry or slightly humid environments.

Note that the International Atomic Energy Agency (IAEA) in Vienna has quite recently started a **Co-ordinated Research Project (CRP)** on the *Application of Nuclear Techniques to Anti-Personnel Landmine Identification*. “The main objective of this CRP is to apply this knowledge to humanitarian demining and to make already existing prototype instruments ready for field deployment. The output of the CRP will be a report that describes the state of the art of nuclear techniques for identification of antipersonnel landmines. These research results will be made freely available for use by scientists and organisations involved in research, development and use of equipment for post-conflict humanitarian demining.” More information is available from the Scientific Secretary, Ulf Rosengard (email: u.rosengard@iaea.org, phone: + 43 1 2600 21753).

#### 4.2.8. Trace/Vapour Explosive Detection Systems

We already discussed the use of dogs (see 4.1.1. Mine Dog Programs) and pointed out their importance in particular for verification and area reduction purposes (i.e. when the focus is on verifying that a given area is mine/explosive free or not). Research on sniffing dogs and how to complement or replace them with adequate sensors is scarce in Europe, compared to the effort put into other sensors (most notably GPR). *More precise and clear quantitative information seems strongly needed.*

One way of approaching the problem is to *increase our knowledge on how exactly dogs work*, i.e. how (using also other senses?) and what exactly they detect and in which concentration (explosive vapours or other substances leaking from the mine or from its surface, trace particles deposited in and on the soil around the mine). Another way, complementary to the first, is to *study the different processes between explosives and the environment*, in particular the migration of explosives, leaking from a mine, in the soil and in the air. Long term research of this kind is carried out for example at FOA in Sweden.

Sensor systems for field application should have an appropriate **sampling system** (of the air or the soil), possibly including filtering to increase concentration. Up to now it seems that sensors either have a too low sensitivity, are too slow or too large to be used in field applications.

Note the existence of a large *three year project*, started in 1997 by DARPA (the US Defense Advanced Research Projects Agency) and funded at the 25 million US\$ level, aimed at developing an electronic dog’s nose that can be used reliably in the field (see also <http://www.darpa.mil/DSO/rd/Applied/UXO/index.html>). If and when the results of this project will be made available to the humanitarian demining community remains obviously to be seen.

<sup>17</sup> One of their advantages is not to be radioactive when switched off (a source is always radioactive).

<sup>18</sup> Examples of chemical compositions: TNT is  $\text{C}_7\text{H}_5\text{N}_3\text{O}_6$ , RDX is  $\text{C}_3\text{H}_6\text{N}_6\text{O}_6$ .

## Biosensor

The “biosensor” program of the Swedish Biosensor Applications AB (<http://www.bioapp.se/>), formerly a company of the Bofors group, seems to be one of the very few in Europe targeted specifically at humanitarian demining applications, and perhaps the most advanced (work has been ongoing since 1995).

Biosensor systems are used to develop portable vapour detection systems, sometimes also called “artificial dog noses”. The collection system collects air and the air sample passes a filter which absorbs the molecules of the target substance. The filter is purged of its contents and the collected molecules are dissolved in a fluid, the collection system concentrating a sample of 100 litres of air to 10 microlitres of liquid. The system also minimises the risk of contamination through its automatic clearing process. The droplet obtained in this way is then brought into contact with the actual biosensor, a piezoelectric crystal (actually a Quartz Crystal Microbalance), whose surface is covered by an antibody reacting with the molecules of TNT. The antibodies detach themselves from the sensor, whose variation in oscillating frequency is then measured.

*Highly selective, sensitive, portable systems are under development*, and a prototype for TNT will be tested in minefields in 1999 and cross-checked with a dog based detection scheme (typically MEDDS employed by the South African Mechem). These systems could be used for verification and area reduction purposes. The quartz crystal has to be reloaded or changed after a few positive answers. So far research has mostly concentrated on the detection of TNT; this also implies that, given the antibodies’ specificity, the system will not detect other explosive substances. Therefore, even if TNT is present in most mines, the development and the application of antibodies for PETN and RDX are under investigation. Overall detection time is of about 2-3 minutes at present, and projected cost between 15 and 25 k EURO.

## Ion Mobility Spectrometer (IMS)

The Ion Mobility Spectrometer (IMS) is a detection system capable of identifying and quantifying chemical vapours in minute traces. Its strong points are ease of use, speed of analysis (quick answer), sensitivity (capable of measuring tiny quantities) and specificity (capable of differentiating well between substances). As usual, it is difficult to speak about detection limits, but *an IMS is believed to be up to 1000 times more sensitive than a mass spectrometer*, with relative detection limits (concentrations) at least in the ppb<sup>19</sup> range, corresponding to an absolute quantity of picograms ( $10^{-12}$  g) for some substances.

An IMS delivers as output a current value vs. a drift time, whereby the drift time allows identifying the substance, and the current is a measure of its quantity. IMS makes use of the different mobilities of ionised species in gases. Molecules enter the ionisation region in ambient air via an inlet membrane, where they are ionised by means of UV radiation or beta particles. Short periodical pulses on a shutter grid allow the produced ions to move into the drift tube, where different charged particles drift according to their specific velocities, arrive at characteristic times at the collector electrode and cause current pulses forming the IMS spectrum. The drift time depends on the ion mass and on its molecular structure, and allows the identification of the substance. The presence of several kinds of compounds in the probe sample results in an increased complexity of the ion mobility spectra, which often can not be interpreted exactly.

An IMS system has been for example developed by IUT in Germany (other manufacturers might be offering similar pieces of equipment) as a commercially available system, with a weight of about 6 kg and prices starting from 30 kDM. It is portable, can operate in field conditions from a battery pack for 6-8 hours, and measures signals quasi-continuously (near real-time) all 2-30 s. Note that a conceptually similar IMS system, the IONSCAN, is currently being developed and tested by Barringer in the US for the NVESD (US Army Night Vision Laboratories) in Fort Belvoir, VA, for the detection of landmines.

## 4.3. Multi-sensor Systems

A number of ongoing research projects are aimed at *combining several sensors in order to exploit complementary information* (each sensor measures different physical characteristics), and to enhance detection and even classification. Sensor fusion should guarantee that the multi-sensor system at least retains the probability of detection of each single sensor, and moreover reduces the false alarm statistics.

Since the objective of these systems is mine identification, it is important to take into account the relative strengths and weaknesses of the sensors, as well as the environmental conditions (e.g. type of soil, clutter,

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<sup>19</sup> Parts per billion, i.e. capable of detecting the presence of 1 molecule in  $10^9$  (= 1 billion).

humidity and vegetation) in which each sensor may be used. *The ultimate goal would be to fully integrate individual sensors*, physically as well as from the point of view of data fusion. Physical integration requires close collaboration between the manufacturers of individual pieces of equipment, to ensure technical compatibility and to avoid cross talk and measurement ambiguity due to spatio-temporal misalignment. This is probably easier to achieve than full data fusion (see 4.3.1 Data Fusion Methods).

To avoid full data fusion, *easier solutions are being investigated*, such as using one of the sensors as **primary detector** (typically the metal detector) and another as a **confirmatory sensor** (e.g. a GPR or an explosive detection system), possibly leaving the final decision to the operator. This can simplify to a great extent system design and analysis, and in a certain sense comes closer to current operational procedures, where “sensors” (metal detectors, manual prodding, sniffing dogs) are used sequentially. Generally speaking, in all systems an experienced operator is crucial for the overall performance.

Multi-sensor system design and data fusion are fashionable research topics, nowadays. The underlying rationale for this interest is that exploitation of different sensing principles leads to more reliable detection/classification results by combining different pieces of incomplete or imperfect information. *The risk of this approach is that combining insufficiently mature sensors yields an even more complicated problem than pushing individual sensor technologies up to their intrinsic physical detection limits.* This implies that research and development of single-sensor data processing and pattern recognition techniques for mine detection/classification should be continued, and that multi-sensor system design should carefully take into account the requirements of the target application, the operational procedures and the complementary properties of the sensing principles.

During our interviews we came across the following multi-sensor combinations: (i) MD, GPR, (ii) MD, GPR, microwave/millimetre wave radiometer, (iii) MD, IR, GPR, (iv) MD, GPR, NQR, (v) MD, GPR, Vapour/trace explosive detection, (vi) MD, FNA.

#### 4.3.1 Data Fusion Methods

The choice of a method for merging data in a multi-sensor system depends mostly on the data format of the signals, which can be a 2D image (e.g. IR), a 1D time series (e.g. GPR), or a scalar value which expresses the detection of the presence of explosive or metal for example. Three different types of *data fusion architectures* can, in principle, be used:

- **Pixel level fusion:** multiple images are combined to a single image, and each location in the combined image has an associated vector of measurements from each of the sensors. The new image is then processed by an algorithm such as target detection/recognition that simultaneously operates on the vector values. The problems of putting pixel level fusion into practice are due to the differences in field of view, in sensor orientation (e.g. forward looking, downward looking), in resolution, and in data format.
- **Feature level fusion:** features are extracted from each of the sensor data, followed by a registration step, usually carried out at the level of regions of interest or image segments containing more than one pixel. Such a co-registration of features from individual sensors is often easier to achieve than pixel level fusion. A detection/classification algorithm can then be applied on the combined feature vector characterising a region of a certain spatial extent.
- **High-level data fusion:** each sensor makes an independent decision based on its own observations and passes these decisions to a central fusion module where a global decision is made. Because the sensors have very different data characteristics, this kind of data fusion is probably the most accessible for a mine detection system.

The EU LOTUS and HOPE projects are studying, amongst others, data fusion techniques. The HOM-2000 project in the Netherlands has also scheduled data fusion for handheld and vehicle based systems in its starting second phase.

#### 4.3.2 Handheld Systems

Multi-sensor systems can be made portable, similarly to currently used metal detectors. The human operator is indeed still difficult to surpass when it comes to taking analytical decisions in a complex environment, and there will always be situations where portable equipment is needed. Problems lie in producing affordable (5-10 times the cost of an individual high-end metal detector?), compact and lightweight systems, with sufficient autonomy, improved productivity (reduced false alarm rate), ease of use (ergonomics), and overall performances justifying the price.

Most handheld multi-sensor systems include a metal detector in their set-up. Most of the mines still contain some metal, even if sometimes in reduced quantities. In addition, metal detectors are still the only sensors really used in demining practice. Their inclusion should therefore facilitate the transition from single sensor to multi-sensor systems and guarantee system acceptance.

Ground Penetrating Radar is also well positioned in the list of preferences, followed by bulk explosive detectors (e.g. NQR) and vapour trace detectors. Other sensors being studied are infrared devices, which have the potential of detecting the object from a standoff position (e.g. mounted on the protection helmet of the operator). Microwave radiometers can be particularly useful for the detection of surface or shallowly buried objects, where radar might have problems.

#### **4.3.3. Vehicle Platforms**

Vehicle platforms are typically used for rapid surveying of large areas, in particular roads or moderately off-road areas. Sensor choice as well as sensor performance are usually not constrained by power and computational requirements. Sensor arrays are usually employed. Position tracking equipment and platform stability control systems are also extremely important. Usually a combination of forward looking (e.g. IR, visual, multispectral cameras, UWB radar) and downward looking sensors (e.g. GPR array, MD array) are used. Near “real-time” processing and decision taking might be necessary at high vehicle speeds. In some cases remotely controlled vehicles are used.

Most of the encountered vehicle based projects are military oriented, apart from the EC LOTUS project.

#### 4.4. Technological Maturity

From the discussion during the interviews, the EUDEM database, the bibliographic analysis of the state of the art, and the equipment specifications provided by the manufacturers, we have tried to make some inferences about the maturity of the mine detection technologies described above, as well as their cost. The resulting list is undoubtedly subjective, and open for criticism, because (i) we must rely on indirect evidence due to the absence of well established definitions of equipment performance, (ii) most of the results of independent performance tests are not publicly available, (iii) we have not conducted performance tests ourselves, and (iv) we do not share the practical experience of deminers working in the field.

Technological maturity should be interpreted as a qualitative measure expressing a mixture of the:

- State of advancement of the R&D;
- Demonstration of detection capabilities useful for humanitarian demining;
- Demonstration of building a practical system.

Cost includes technological cost only, i.e. does not take into account the actual productivity in the field. Needless to say, innovation can very well come from technologies other than the ones listed below, for example other trace explosive sensors, or acoustical/seismic detection systems, etc.

Sensor technology	Maturity	Cost	Comments
Dogs	H	H-HH	Used in practice
Prodding/Excavation	H	LL	Used in practice
Magnetic devices	H	M	Used in practice (Magnetometers, Gradiometers)
Metal detectors	H	L	Used in practice
Metal detector Array	H	H-HH	(Used in practice?)
Passive mm wave	L-M	HH	EU HOPE project claims low cost Handheld multisensor probe including radiometer
mm wave radar	L	HH	Cost figure based on lab equipment
Passive infrared	M-H	H	Cost is decreasing
Polarised infrared	M	HH	
Multispectral	L	HH	
Ground Penetrating Radar (GPR)	H	M-H	
Ultra-wideband radar (UWB)	L-M	H-HH	
GPR Array	M-H	HH	
Nuclear Quadrupole Resonance (NQR)	M	H	
Thermal Neutron Analysis (TNA)	M	HH	
Fast Neutron Analysis (FNA)	L-M	HH	
Ion Mobility Spectrometer (IMS)	M	M-H	
Biosensor	M-H	M	

Table 2. (Qualitative) Maturity and Cost evaluation for the previously mentioned technologies. Maturity indication ranges from Low (L) to Medium (M) up to High (H); Cost indication uses L  $\approx$  4000 EURO (price of a high end metal detector), M  $\approx$  2 to 5 times L, H  $\approx$  5 to 10 times L, and HH  $>$ 10 times L.

#### 4.5. EC projects

The following table very briefly summarises the largest European R&D projects on humanitarian demining, as well as some primarily defence oriented projects. More details are usually available in the interview reports (for the EC projects see also <http://www.cordis.lu/esprit/src/hphdhome.htm> ).

Project	Prime contractor	Sensors	Start	Duration, Partners*	Comments
<b>GEODE</b>	Dassault	pulse GPR (EMRAD), FMCW GPR? (ELTA) + MD (Förster) + IR (Marconi)	Jan. 98	15, 4P + 2A	Vehicle
<b>MINEREC</b>	EMRAD	GPR (EMRAD)	Jan. 98	18, 2P	GPR array, real time
<b>Airborne minefield detection in Mozambique</b>	ITC	ZeissLMK2000(optical), LeicaRC30(optical), VOS80C(digital), ReconCA860(thermal), AES-1(SAR)	Feb. 98	18, 12P	Pilot project EC DG VIII + some EC countries
<b>HOPE</b>	Vallon	pulse MD (Vallon) + stepped frequency (imaging) GPR (RST) + radiometer (DLR)	Jan. 99	24, 7P + 7A	Portable
<b>PICE</b>	Celsius Tech	pulse MD (Schiebel) + stepped frequency (no imaging) GPR (Celsius Tech)	Jan. 99	24, 5P + 4A	Portable
<b>INFIELD</b>	Detexis	pulse GPR (ERA) + continuous wave MD (Ebinger) + radiometer (ERA?)	Jan. 99	18, 3P + 1A	Portable
<b>LOTUS</b>	Detexis	pulse GPR (EMRAD) + MD (Foerster) + IR (Marconi)	Jan. 99	36, 4P + 1A	Vehicle
<b>DEMINE</b>	TUI	GPR (all)	Feb. 99	24, 6P	GPR only
<b>MINESEYE</b>	EPPRA	neutron (EPPRA) + digital MD (?)	Feb. 99	30, 5P	Portable, vehicle
<b>HOM2000</b>	TNO	GPR, MD, IR, ...		National Dutch project	Mostly Hum. Dem.
<b>HUDEM</b>	RMA	GPR, MD, IR, robotics, ...		National Belgian project	Purely Hum. Dem. mostly academia
-----	FOA	GPR, MD, IR, multi-spectral, explosive det. ...		National Swedish project	Mostly Hum. Dem. Portable, Airborne
<b>EXPLODET</b>	INFN	TNA, FNA	1998	36, 10P	Purely Hum. Dem
<b>(several projects)</b>	DERA	GPR, UWB, MD, IR, pol. IR, NQR, mm wave, ...		UK MoD sponsored	(nearly entirely) Defence: Portable, Vehicle, Airborne
<b>MMSR, DMH</b>	MaK, BGT (?)	GPR, MD, IR, multispectral, ...		German MoD sponsored	Defence: Vehicle, Airborne
<b>(several projects)</b>	Detexis?	GPR, MD, IR, ...		French DGA sponsored	Defence: Vehicle, Airborne

**Table 3. Largest European R&D projects on humanitarian demining, as well as some defence oriented projects.**

NOTE: DERA: Defence and Research Evaluation Agency (UK), Detexis: Thomson-CSF Detexis, FOA: Swedish Defence Research Establishment, INFN: Italian National Institute for Nuclear Physics, RMA: Royal Military Academy (Brussels), TNO: Netherlands Organisation for Applied Scientific Research, TUI: Techn. Universität Ilmenau (Germany).

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