Humanitarian Demining : Sensor Systems, Mechanical and Robotics systems

Yvan Baudoin, Marc Acheroy, Eric Colon
Robotics Centre and Department of Electrical Engineering, Signal and Information Processing Centre
Royal Military Academy, Avenue de la Renaissance 30, B-1000 Brussels Belgium
phone: +32 2 737 6553
fax: +32 2 737 6547
Yvan.baudoin@mapp.rma.ac.be

ABSTRACT

In the current situation, there is a need to correctly define the usefulness and requirements of Sensor systems, Mechanical and Robotics systems that could speed the detection and the removal of the antipersonnel mines and unknown explosive devices disseminated in about 60 countries over the world. The Robotics systems may essentially be used in pre- and post-mine detection (minefield delineation and quality assurance), the Sensor systems in all detection procedures and the mechanical systems above all on very large infested areas (agricultural zones) but with a lower efficiency (estimated to 95 % instead of the 99.6 % imposed by the UN-standards). This paper summarizes some results of the research activities in Robotics , among onther conducted by the RMA. This paper also presents the status of sensor technology, including operational characteristics without aiming at being exhaustive. Signal processing aspects and important lessons on data fusion are also discussed briefly. The detection is considered as a global process in which the outputs of the sensors, considered as skilled specialists, are integrated in a fusion operation.

Keywords: Sensor Systems, Robotics, Image processing, Data fusion, Control.

1 INTRODUCTION

The terrible antipersonnel landmines plague represents a real challenge for the research community. Antipersonnel mines kill or mutilate tens of people every day. Humanitarian deminers still or often use classical manual methods because heavy demining vehicles cannot achieve a satisfying destruction percentage. This work is very slow, tedious, dangerous and costly. Furthermore, the detection is not always reliable. Improvements can be made by developing new sensors, by automating the detection sequence and by using different sensors simultaneously . The Royal Military Academy, leading the Belgian project Hudem, is focusing on the development of new data processing and fusion algorithms, on improvement of Ground Penetration Radar (GPR) and on robotics systems [17,18..23] that carry mines detection sensors.

2 SENSOR SYSTEMS OVERVIEW

2.1 General considerations

A huge amount of antipersonnel (AP) mines are polluting the environment in about 60 countries. Thanks to the Ottawa Convention, mine clearing operations have been organized in a more controlled and effective way. Nevertheless, mine clearance remains a very slow process. It is estimated that, on average, a deminer is clearing an area of 10 $m2$ every working day if he is using conventional tools, i.e. metal detectors and prodders. To give an idea of the extent of the problem, in Cambodia, only approximately 260 $km2$ have been cleared during the last ten years. Therefore, humanitarian mine clearance operations must be understood and designed correctly, keeping in mind that their main goal is to provide efficient aid to innocent people, who may be severely injured by this dreadful pollution. Furthermore, the analysis of actual demining campaigns not only reveals the far too long time needed to clear polluted terrain, but also brings to the fore a far too large false alarm rate, the threat of plastic mines (which are difficult to detect by classical means i.e. by metal detectors), and the large variety of mine clearance scenarios, depending on the country, the region, the climate and the place of the pollution (houses in villages, roads, agricultural fields, etc).
The important parameters, which characterize the mine detection problem, are the mine occurrence probability, the detection probability of a given material and the false alarm probability of a given material [9]:
_ The *mine occurrence probability* in a given position of a minefield expresses the local mine density of that minefield as well. Obviously, it is impossible to control this parameter because it depends on the reality of the terrain. Nevertheless, this parameter is very important for assessing the probability of an alarm in a given location of the minefield.
_ The *detection probability* is the probability of having an alarm in a given position of a minefield for a given detection material, if there is a mine in that position. This probability gives indirectly a measure
of the non-detection probability of that material as well.
_ The *probability of false alarm* is the probability of having an alarm, for a given material, in a given location if there is no mine in that location.
The two latter definitions are extremely important to understand the humanitarian demining problem and for designing demining systems. It is indeed particularly important that the detection probability should be as close as possible to one. It is easy to show that evaluating the detection probability also amounts to evaluating the risk of the occurrence of a mine which has not been detected. This risk is concerned with *human preservation* and is therefore of the utmost importance. No such risk is acceptable and it is therefore an absolute requirement that a demining system should decrease the probability of such a risk to the lowest upper bound possible.The false alarm risk is also a question of cost. Indeed, a demining method which minimizes the false alarm rate results in an acceleration of the demining operations which results in spending less money. Therefore, any demining operation enhancement must result in the highest possible detection probability (close to one) and in the smallest possible false alarm rate and that at the lowest price. Generally, it is accepted that the most efficient way for increasing the detection probability while minimizing

the false alarm rate consists in using several complementary sensors in parallel and in fusing the information collected by these sensors.

2.2 Sensor description

In this section, it will be tried to describe succinctly sensors of different types without claiming exhaustivity. we will subdivide the description into four categories:
1) Prodders, seismic and acoustic sensors
2) Electromagnetic sensors (Metal detector, GPR, Micro-wave radiometer, Electrical Impedance Tomography, Electrography, Imaging with handheld sensors)
3) Electro-optic sensors (visible, IR, multispectral, hyperspectral, LIDAR)
4) Explosive detectors (NQR, X-rays, Neutron activation, Biosensors, Trace explosive detection)

The three first sensor categories are not able to discriminate between an explosive material and any material with the same electro-magnetic, thermal and/or optical properties, but often offer good localisation capabilities as well as 2-D and even 3-D capabilities for some of them.

The last category aims at detecting explosive material, often offers poor localisation capabilities and often lacks for spatial resolution as well as for 2-D or 3-D capabilities. Most of the time these sensors require a long integration time, which makes them more suitable as confirmation device. In the latter case, they are used in combination with sensors of the three first categories.

For each of these categories, a table will describe for each sensor its status of maturity ("R&D", "in development, "in use"), its cost ("Low", "Low to medium","High", "Very High"), its clearance speed ("Low", "Low to medium", "High") and its effectiveness ("Unknown", "Low", "Low to medium", "High").

Metal detectors*:* There exist three families of metal detector: the first one, based on electromagnetic induction (EMI), sends a primary magnetic signal in the ground in an emitting phase during which it creates eddy currents in the buried metallic objects which in turn create a secondary magnetic field. During a listening phase, the emission is stopped and the system listens to the secondary magnetic field which induces eddy currents in the coils of the detector. These currents are characteristic of the buried metallic objects and of the soil. There exist two types of EMI devices: the first one sends a magnetic pulse, the second one a continuous wave at different frequencies in a stepped frequency mode. In the second family, the detector, called magnetometer, mesures the local perturbations of the earth magnetic field. In the third one, the detector, called gradiometer, measures the magnetic field gradient in a given direction depending of the sensor configuration. The most used family of detectors is the first one, based on EMI. Surprisingly, the metal detector of the first family (which is the most common detector), considered as an imaging device, can also provide very useful information on the shape of metallic pieces included in mines. Unfortunately, the point spread function (PSF) of a metal detector is a function of the depth (see Fig. 1) and of the nature of the buried metallic object (eddy currents are different in a close and in an open circuit) and the image formation process is non linear. However, the in depth modeling of the metal detector behavior as a function of the type of buried object by the RMA [13], has shown that it is possible to derive the depth of a buried object from the original data and thus to derive the corresponding PSF to allow a correct de-convolution. Further, information on the symmetry properties of the buried metallic objects can easily be extracted.

This subject is still under investigation. This interesting consideration shows that the metal detector, known as a cheap mine detection system, remains a promising device.

Table 1. Sensors development state

Sensor family	Sensor	Maturity	Cost	Speed	Effectiveness
Prodders & Acoustic	Prodder	In Use	Low	Very low	High
	Smart Prodder	In Use In devel.	Low to medium	Very low	High
	Seismic & acoustic	R&D	High	Medium	High (in wet soil)
Electro-Magnetic	EMI devices	In use	Low to medium	Low to medium	High
	Magnetometer	In use	Low to medium	Low to medium	High
	Gradiometer	In use	Low to medium	Low to medium	High
	GPR	In use	Medium to high	Low to medium	High
	MWR	In devel	Medium to high	Low to medium	Medium
	Electr Imp Tom	R&D	Low to medium	Low to medium	Unknown
	Electrography	R&D	Low to medium	Low to medium	Unknown
Electro-optic	Visible	OK	Low to medium	Medium	Low
	Infrared	OK	High	Medium	Medium
	Infrared Polar	R&D Prototype	High	Medium	Medium
	Multi & hyperspectral	R&D	High	Medium	Medium
	LIDAR	R&D	Very High	Medium	Low
	Terahertz	R&D	Very High	Medium	Low
	SLDV	R&D	Very High	Medium	Medium to high
Biosensors	Dog	OK	Medium to high	Medium to high	Medium to high
	Rodents	In devel	Medium	Medium to high	Medium to high
	Artificial nose	R&D	Medium to high	Medium	Medium
Nuclear and chemical	NQR	R&D proto	Medium to high	Medium	Medium
	TNA	R&D proto	High	Medium	Medium
	FNA	R&D	Very High	Medium	very high
	X-Ray backscattering	R&D proto	High	Medium	low
	X-ray fluo	R&D proto	High	Medium to high	Medium
	Chemical detectors	R&D	High	Medium	Unknown

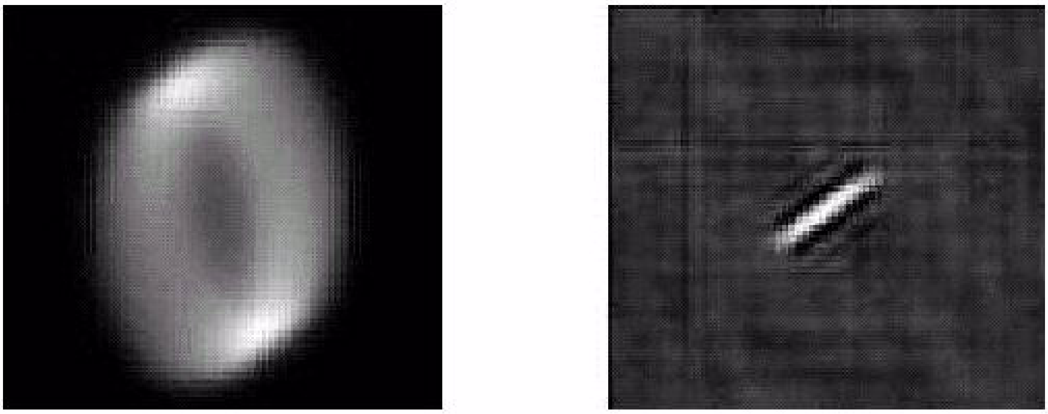
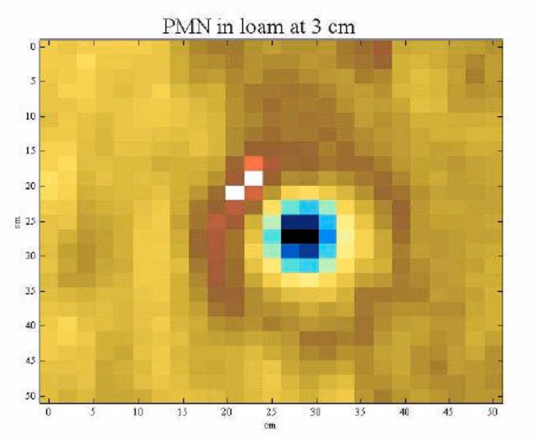


Fig 1: Metal detector : a straight metallic wire

***The ground penetrating radar (GPR)**:* Useful definitions to understand what follows have to be given first. An A-scan is a one-dimensional signal taken perpendicular to the ground surface and is the basic echo signal produced by a GPR. A B-scan is a two-dimensional signal resulting from a collection of adjacent A-scans along a straight line horizontal to the ground surface. A C-scan is a two-dimensional horizontal slice (parallel to the ground surface) in a set of adjacent B-scans. The GPR includes an emitting system (transmitter) and a receiving system (receiver). The transmitter emits a pulse wave or a continuous wave at given frequencies. The receiver collects the waves backscattered by discontinuities in permittivity. Discontinuities can be provoked by buried objects like landmines (useful signal) but also by natural discontinuities of the soil (clutter). This means also that a GPR is able to detect plastic objects buried in the ground. There are mainly two important types of GPR depending the emitted signal: the first one sends a short pulse into the ground (Ultra wideband pulse GPR), the second one sends a continuous wave in a stepped frequency mode. The advantage of the second type is that it provides directly the Fourier transform of the received signal and that more energy can be send into the ground at a given frequency. Ground penetrating radars and passive radiometers are intended to function as anti-personnel mine detectors. Their performances depend upon parameters such as type and texture of soil, soil water content, soil density and operating frequency. In order to evaluate the performances of microwave technologies in land-mine detection, the electrical properties of soils must be extensively evaluated (see [10]). Current GPR are working in a frequency range comprised approximately between 0.4 and 6.0 *MHz*.



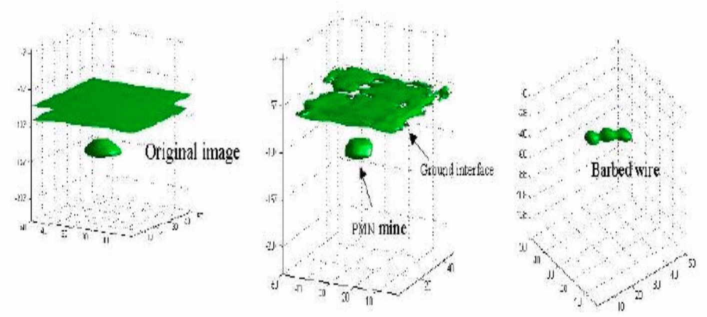


Fig 2. GPR-image (RMA)

Fig 3. GPR 3D algoritms

***Microwaves radiometers**:* The microwave radiometer is a passive ground penetrating radar (only receiving antennas are present) which uses the EM waves (a few K) emitted by the sky and reflected on the ground surface and subsurface. They also can generate clear two-dimensional images of surface, shallowly buried and buried objects (metallic and plastic). The spatial resolution and the penetration depend on the frequency. As for the GPR, the performances are also depending on the soil conditions: a high level of moisture can largely limit the detection capabilities. In the scope of the HOPE project[2], The DLR has developed a MWR which is capable to work at more than 32 different frequencies between 1 and 8 *GHz*.
***Other electromagnetic sensors**:* In Electrical impedance tomography, the soil impedance is measured between selected locations on the ground. By solving a non-trivial and non-linear

inverse problem, it is possible to detect anomalies. In electrography, the corona effect is used to detect explosives (typically TNT) in a liquid phase. The HOPE handheld system, project funded by the European Commission,
includes a metal detector (Vallon, GmbH & RMA), a stepped frequency GPR (RST, GmbH) and a multifrequency MWR (DLR), all with imaging capabilities through the use of a high precision positioning system (RMA)

Electro-optic sensors:
Classical cameras have a poor detection capability even for mines laid on the ground and shallow buried objects. LIDAR and therahertz imaging systems have still to demonstrate their usefulness for mine detection. They indeed use shorter wavelengths than ground penetrating radar and hence suffer from significant limitations in soil penetration. Further, wild groing vegetation offers a strong limitation to most of electro-optic devices. Nevertheless, special attention must be paid to hyperspectral, thermal infrared sensors and Scanning Laser Doppler Vibrometry (SLDV).

Hyperspectral sensors*:* Hyperspectral techniques take into account the very selective properties of the material reflectivity. Laboratory experiments [7], in the course of which very narrow wavelength bands have been used, have demonstrate the capabilities of wavelength tuning to discriminate between different surface laid materials.

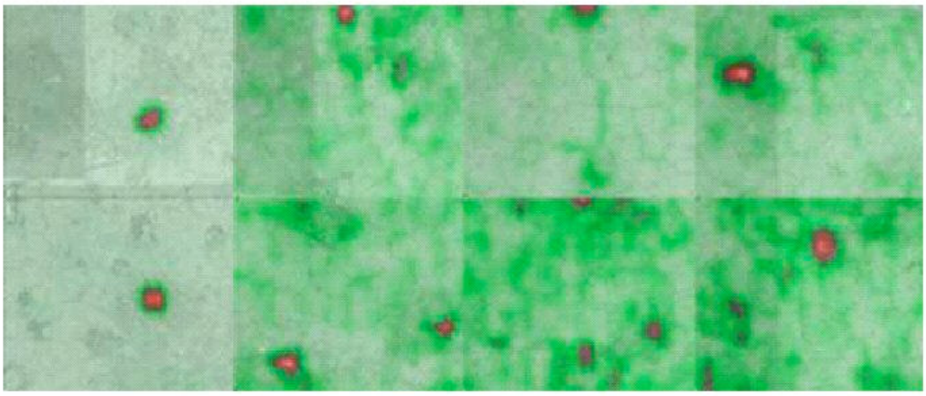


Fig 4.Buried mines acquired with SLDV (F Gan – Germany)

Thermal infrared*:* Mine detection by means of thermal infrared sensors can be achieved in two different approaches. The first approach consists in measuring the appearing temperature difference of the soil, induced by the differences in emissivity and/or by the differences in thermal flux due to the presence of a shallow buried or buried object [12]. A second approach consists to take advantage of the polarisation properties of manufactured surfaces, by analysing the information contained in the images of shallow buried mines produced by the three Stokes parameters which characterize the polarisation state, i.e. the degree of polarisation, the azimuth and the ellipticity. Those parameters can be evaluated by recording by means of a linear polarizer four different images corresponding to four different polarization directions [15].

Scanning Laser Doppler Vibrometry (SLDV): In this technology, which is not properly said an electrooptic technology, an acoustic power transmitter sends an acoustic wave in the ground. If an object is present in the soil, at the ground surface a backscattered wave induces soil vibrations measured by a laser Doppler vibrometer. This technique has been tried by FGAN (Germany) on a test site in ISPRA (European Commission Joint Research Centrum). Results are shown on next figure

Explosive detectors: biosensors
Dogs and educated rodents*:* Actually, one of the most efficient "sensor" for mine detection is the dog. But it appears that rodents are easier to educate and to feed and that they can work longer than dogs. Furthermore, the rodents are much lighter and have a better olfactory capacity and a better immunity. The non profit organization APOPO and the University of Antwerpen (Belgium) are currently making operational tests in six different countries, which are representative of the mine threat. Rats have already booked interesting results in Tanzania in 2002.

Artificial nose*:* Some reseach activities have been devoted to technologies that try to mimic the olfactory system of a dog. But up to now no significative results have been booked in the field of humanitarian demining. Another approach consists in using antibodies sensitive to TNT. these antibodies are fixed on a quartz crystal. When the sensor is in contact with TNT free molecules, the fixed antibodies leave the crystal. The result is that the weight of the quartz crystal is changed. This weight loss is measured by measuring the crystal frequency change. A relatively long integration time, due to the extremely low concentration of explosive vapours in the air, makes this technology more suited to confirmation than to the detection itself. Therefore, this technology should be accompanied by a detection equipment such as a metal detectors or a GPR or a combination of them.

Explosive detection: nuclear and chemical methods
This family of technologies includes Nuclear Quadripole Resonance, Thermal Neutron Activation (TNA), Fast Neutron Activation (FNA), Trace of explosive detection using chemical processes, X-ray backscattering and X-ray fluorescence. Again, the relatively long integration time needed to detect the explosive molecules and their high cost make this technology more suited to confirmation than to the detection itself. Therefore, this technology should be accompanied by a detection equipment such as a metal detectors or a GPR or a combination of them.

X-ray backscattering*, for instance:* X-ray 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 bulk explosive detection, although AP mines have been imaged as well; smaller, man-portable detectors based on radioactive sources have also been proposed. The systems which have been developed are said to be able 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 [16].

2.3 Signal Processing and data fusion

For each type of sensor, specific signal processing techniques are used in order to extract useful information. The used techniques mainly include signal conditioning or preprocessing (*e.g.* signal detection, signal transformation, noise reduction, signal restoration and enhancement (see [2], [3] and [8], which are a very important steps before further processing) and pattern recognition techniques aiming at increasing the expertise of each sensor separately. Nevertheless, it has been shown in the previous section that no sensor is perfect for all scenarios and all conditions (moisture, depth, cost, etc). The analysis of the principles of operation of different sensors, their complementary information, and the factors that affect their operability, have led to the conclusion that their fusion should result in improved detectability and reduced number of false alarms in various situations.

Low level fusion can be performed even using a heterogeneous set of sensors if the data are co-registered. Our experience has shown that higher level data fusion is possible but accounting for the following facts:

Learning processes are very difficult and risky because of the inter and intra variability of the scenarios.

The heterogeneous character of a given minefield and of the huge set of possible minefields makes generalisation unpractical if not dangerous.

High level fusion must rely on qualitative instead of quantitative a priori knowledge, therefore methods like Bayes decision theory will often fail.

The absolute (objective) confidence in specific sensors resulting from extensive trials must be included in the fusion model (principle of objective discounting).

The relative (subjective) confidence that the deminer has in specific sensors must also be (interactively) included in the fusion model (principle of subjective discounting).

Since in this domain of application one has to deal with uncertainty, ambiguity, partial knowledge, ignorance and qualitative knowledge, it is important to chose for an approach where they can be appropriately modeled, e.g. belief functions within the framework of the Dempster-Shafer theory. A main motivation for working within this framework is to be able to easily model and include existing knowledge regarding: chosen mine detection sensors, mine laying principles, mines, and objects that can be confused with mines [11].

In any case, we need to be aware that the ultimate decision must belong to the deminer because his life is involved.

3 MECHANICAL MINECLEARERS AND ROBOTICS SYSTEMS OVERVIEW

The GICHD has published a ‘Mechanical Demining Equipment Catalogue 2003, available on www.gichd.ch includind several mine-clearers and their characteristics. But, as previouslay said, one has to make a clear difference between the mine-clearing and the humanitarian demining wherefor a higher efficiency or quality assurance (99.6 % clearing). Nevertheless, large areas (agricultural zones) may be quicly cleared with a high degree of confidence reaching about 96 % in the best cases: a post-scanning remains necessary, that could be entrusted to dogs, rodents or robotics systems.

The next scheme describes the modules included within a mechanical/robotics system During our RMA project we focused on the shaded modules. Other work groups of our Hudem-team focused on the other ones. Other R&D teams, in Europe , US and Japan follow the same scheme.

A mechanical mine-clearer, manned or unmanned, only include the left and right modules of the previous scheme. The most vehicles are equipped with detonating devices (flails, for instance). Even if still unsufficient, the effectiveness of such tools slowly increases for approaching the total quality (99.6 %). Unfortunately, their size limit their use to about 50 %

of the infested ‘accessible’ minefields. Their use in woods, urban zones, destroyed/unstructured fields, etc..still poses serious problems.

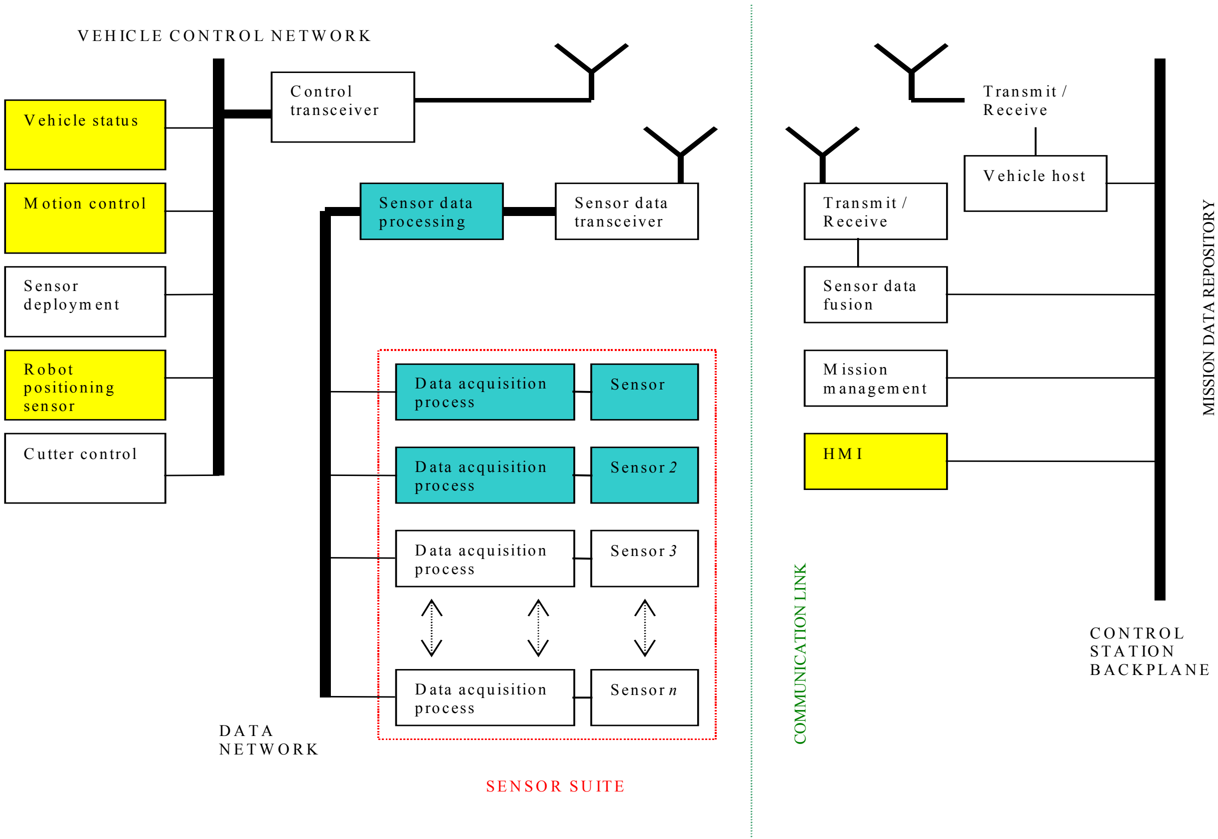


Fig 5. Modular definition of a Demining system

Scanning detection (manned) vehicles or (unmanned) robotic systems are at least composed of the following elements (fig 6 NL project) :

- The vehicles with their possible scanning device,
- The mine detection sensors,
- The tracking and location system.

Fig 6. The NL (TNO) project

The vehicle available in the project RMA (BE) , the Hunter (figure 7), the TRIDEM (wheeled robot) and the AMRUs (legged robots) , more recently the ROBUDEM (designed with Robosoft, FR) have been described in previous papers [17..25].Such robots need a control architecture and, consequently, introduce a more complex approach of the demining procedures: that explains (beside the costs) the poor penetration of robotics systems in the actual demining operations; another aspect lies in the immaturity of the outdoor (in unstructured and unknown fields) control of mobile robots
Among the different ways robots could help human deminers, the next scenarios are the most realistic. Small autonomous vehicles equipped with different sensors could run around an area to delimit the surface that is really polluted with mines. This phase when done manually is the most dangerous one because deminers are working faster and are taking more risks than during systematic detection.
Once the actual mined area is delimited, a systematic scanning process can begin. It has been proved that the use of different sensors could drastically improve the detection efficiency and reliability. However, the data fusion process requires the registration of the data acquired by the different sensors.
The last aspect considered , among others, in our RMA project is the determination of the robot's location in the field. This is required for navigation but also for automatic production of detection maps. For this purpose, a visual servoing system based on a pan-and-tilt colour camera has been developed. This system tracks a colour beacon mounted on the robot and sends in real-time the three-dimensional position of the sensor to the main control computer. Other R&D centers propose the use of GPS/DGPS (figure 8).

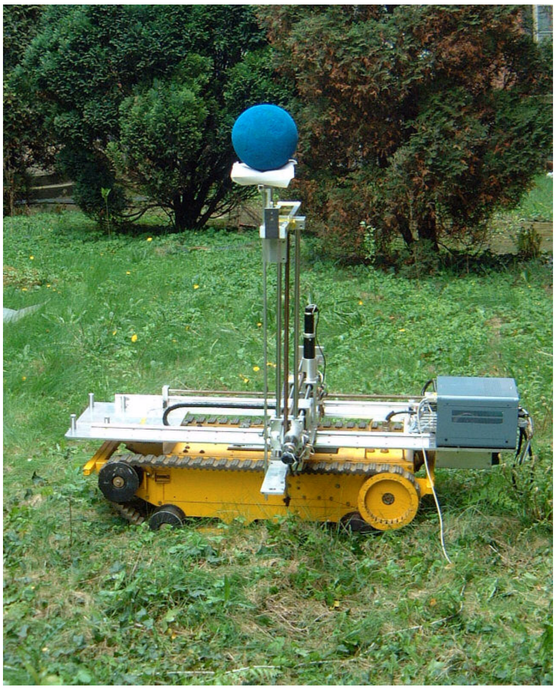


Fig. 7 The Hunter with a blue beacon

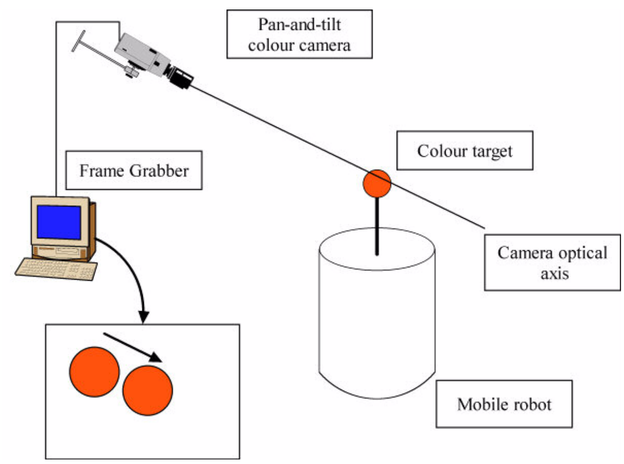


Fig. 8 The tracking system principle

3.1 The components of the control architecture

As an example, we describe here the control architecture of the robot Hunter developped by RMA.The whole system has a multi-processing architecture and comprises the following components (figure 9):

- The HMI (CORODE –Control of Robots for Demining) computer,
- An embedded computer for data acquisition and communication with the HMI computer,
- The motion controller (microcontroller),
- The visual tracking and location computer.

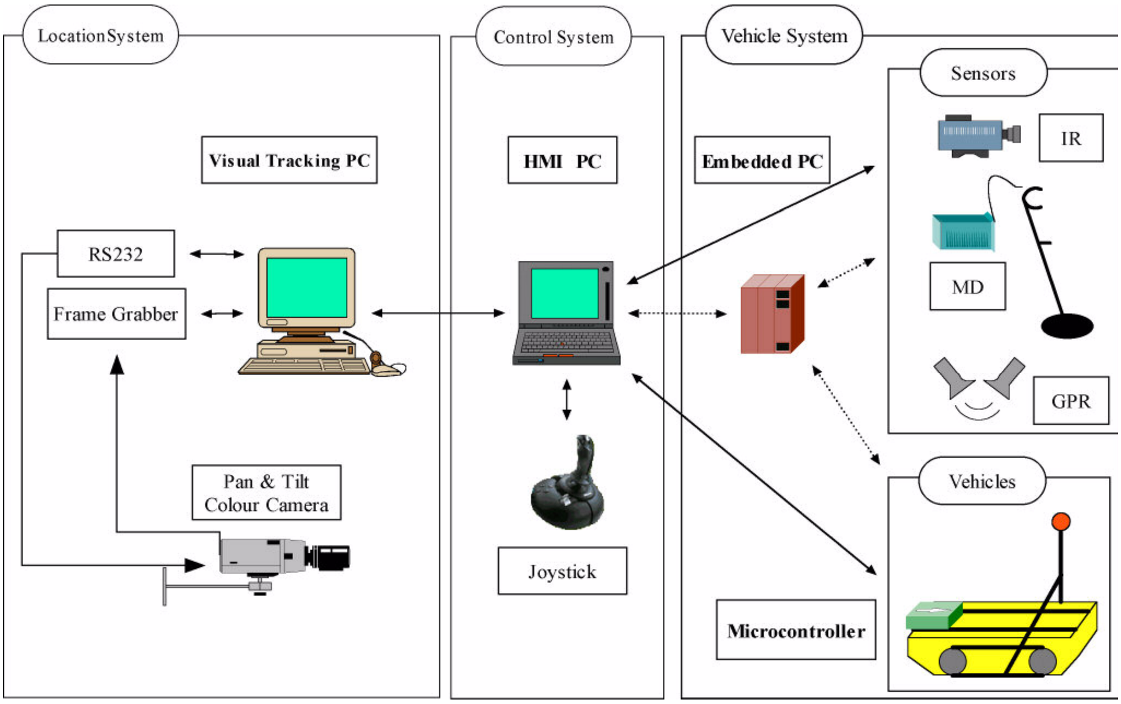


Figure 9. The general system architecture

3.2 Sensors and acquisition interfaces

Three different sensors , described in the previous section and specifically developped at the RMA or with RMA-partners, have been successfully used in the project: a metal detector (MD), a Ground Penetration Radar (GPR) and an infrared camera. The data acquisition process requires different interfaces: the metal detector has a serial interface, the GPR data are read through the GPIB interface of a high speed oscilloscope, the images coming from the infrared camera are captured with a frame grabber (through a cable or a wireless connection). We will see in the subsection 3.7 how the sensors' characteristics influence the scanning process and the way the control is realised.

3.3 Communication

A serial communication allows the transmission of commands between the Master PC and the microcontroller (the transmission speed is 9600 baud). Radio Ethernet links (protocol 802.11) are used to communicate between the HMI PC and the embedded PC.

3.4 Human Machine Interface

The graphical user interface of the control program CoRoDe is shown in figure 10. This program offers the following functions: Control of the vehicle, Configuration and control of the scanning system, Configuration of the sensors, Data visualisation, Data archiving, Mapping.

Data acquired during the scan process are saved in two different formats: first as binary data for later processing (double for GPR, double word for MD) and as 8 bits grey scale raw images for direct visualisation. The data acquisition, scanning, location computation and vehicle motion are integrated into a sequence that is controlled by the user with button commands lying in a single toolbar. The interface is simple and intuitive thanks to the use of well-known symbols (VCR-like) and standard colours (see figure 10). In this application, it was a requirement to let the user keep the control of the process; at every moment the user can pause, resume or stop the operations.

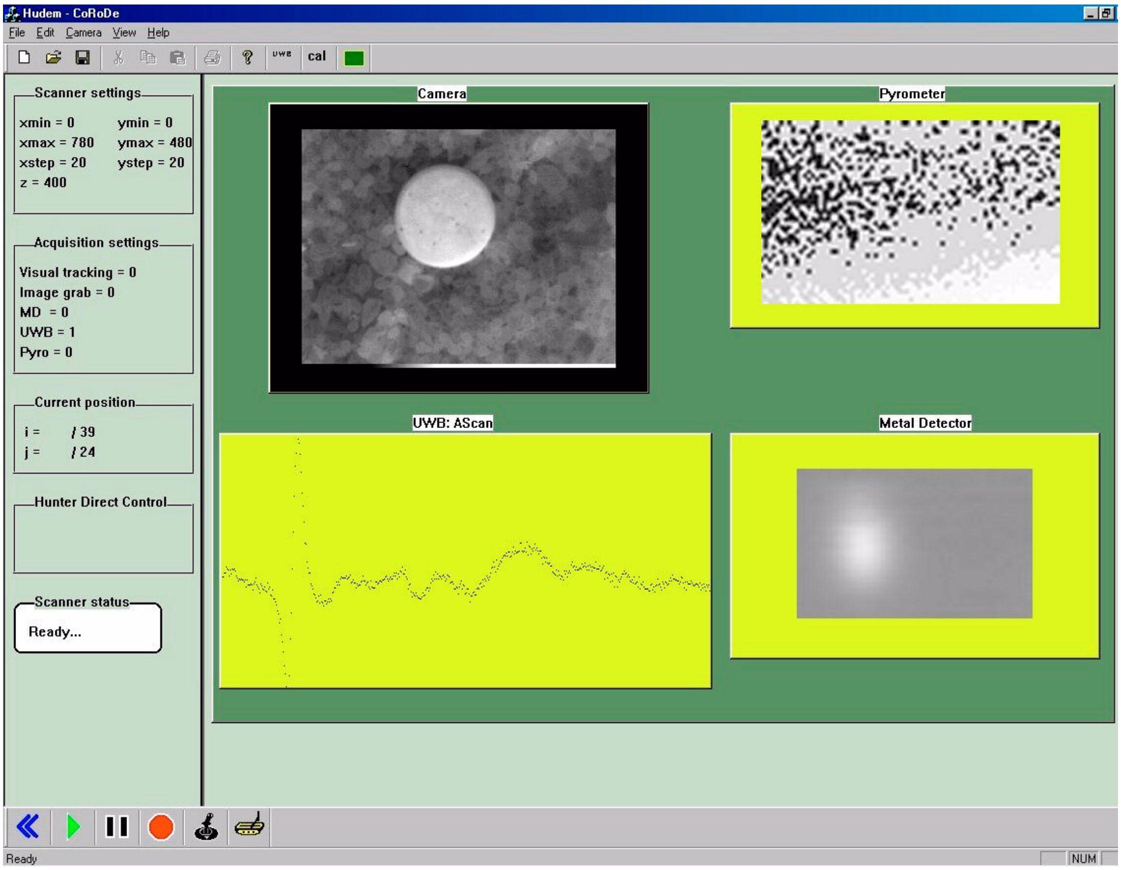


Fig. 10 The CoRoDe data visualisation window

It is also essential to provide information during internal processing or timeouts. In this case, sensors' data are drawn on the screen as the scanning progresses. The position of the scanner relative to the maximum positions, the status of the scanning sequence and the main options are also presented to the user and regularly updated. Finally the use of additional communication threads (see next section) preserves the interaction with the user interface. Ref [23] provides implementation details about the communication and the synchronisation of processes.

4 CONCLUSION

This summary has presented the results achieved by the Robotics and the Sensory Workgroups within the Belgian and European funded projects Hudem (now called BE MAT for Mine Action Technologies) and some other European projects. Robots using different locomotion techniques have been successfully used to acquire sensor data and to test and validate utilisation methods in different scenarios. In this summary, the control and programming architectures of these systems have been partially described. The use of object oriented techniques for application development and the reuse of the same control hardware may contribute to the success of projects based on a modular approach.

At this stage, it has not been proven that robotic detection of mines works better or faster than human deminers. But the obtained results are encouraging and pave the way for an integrated solution that will some day help to solve this terrible plague.

Furthermore, this paper presents the detection as a global process wherein the outputs of the sensors, considered as skilled specialists, thanks to their associated processing, can be integrated in a fusion process.

5 ACKNOWLEDGEMENTS

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