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A survey of land mine detection technology

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This paper describes the state of the art in land mine detection technology and algorithms. Landmine detection is a growing concern due to the danger of buried landmines to people's lives, economic growth and development. Most of the injured people have no connection with the reason why the mines were placed. There are 50–100 million landmines in more than 80 countries around the world. Deactivation is estimated at 100 000 mines per year, against the nearly 2 million mines laid annually. In this paper we describe and analyse sensor technology available including state-of-the-art technology such as ground penetrating radar (GPR), electromagnetic induction (EMI) and nuclear quadrupole resonance (NQR) among others. Robotics, data processing and algorithms are mentioned, considering support vectors, sensor fusion, neural networks, etc. Finally, we establish conclusions highlighting the need to improve not only the way images are acquired, but the way this information is processed and compared.

1. Introduction

Land mine detection is a constantly growing concern due to the danger that buried land mines represent to people. Land mines affect people and civilians all over the world. Due to the long life of these mines, the victims often have no relation to the original motivation for the mines. Most victims are children (Kowalenko 2004).

To begin this research, we define a land mine as a device designed to kill or injure anyone that comes in contact with it through direct pressure or a trip-wire (Habib 2001). Antipersonnel land mines originated in the Second World War, where Germans and Italians improvised antipersonnel land mines with grenades and fuses in order to prevent allied soldiers from deactivating antitank mines placed on already determined defense lines (Russel 2003). Land mines can be categorized into two types: anti-tank (AT) mines and anti-personnel (AP) mines. AT mines are larger, i.e. 20–30 cm in diameter, whereas AP mines are approximately 5–15 cm in diameter (Gader 2002). In fact, there are more than 350 types of antipersonnel land mines being developed in more than 50 countries (Wen-Hsiung *et al.* 2007). Certain studies point out that there are around 50–100 million AP mines in more than 80 countries around the world. These mines kill or injure a person every 20 minutes—70 persons a day, or more than 20 000 people a year (Kowalenko 2004). The cost of producing a mine is as little as $3, but it can cost as much as $1000 to remove it.

The presence of landmines threatens people's lives, and also prevents much-needed economic growth and development. Long after wars are over, landmines

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make land unusable for farming, schools or living, preventing people from rebuilding lives torn apart by conflict.

If the current land mine detection and deactivation rate of 100 000 mines per year continues, it is estimated that the time needed to remove all existing mines, not counting new ones yet to be placed, will be at least 500 years. Nieman *et al.* (2002) point out that this horizon will retreat further, mainly because of new mines being constantly laid, and also because of the very limited use of technology for mine detection and clearance, and due to the lack of funds for detection.

It is expected that antipersonnel landmine use will decrease due to the 1997 Ottawa treaty that forbids new placement of mines. Additionally, the Nobel Prize for Peace award given in 1997 to the International Campaign to Ban Landmines (ICBL) has helped people to promote a better awareness of the problem, which has led to a new fund assignment to develop new techniques in this area.

On the other hand, at a technical level, mine detection is a very complex problem far from being solved. Schreiner (2002) identifies two main obstacles to this:

a) Land mines made today contain less metal and more plastic, making identification more difficult.
b) Mined areas may have metallic debris to avoid detection and identification, increasing false alarms.

Conventional antipersonnel mine detection has not evolved as much as one would like. The most widely used method for detecting and removing antipersonnel mines follows the same techniques developed during the Second World War, and directly involves human beings. Metal detectors for identification are used and a detailed and slow analysis of the affected zone is made. Every suspicious element found is meticulously checked.

In this paper we describe the remote sensing technology available, data processing and algorithms, and finally we present conclusions about the state of the art in landmine detection.

2. Remote sensing technology

A very thorough review of satellite and airborne sensors for remote sensing based detection of minefields and landmines was carried out by Maathuis and van Genderen (2004), focusing on multi-temporal aerial photographs and satellite images. Their paper makes a good analysis of the structure and composition of minefields and patterns that can be obtained for minefield detection. It also describes available methods and elements for this detection. Our work complements the aforementioned study because we focus on some of the most common ‘direct’ remote sensing technologies in landmine detection, defining ‘direct’ as a technology used in actual humanitarian demining processes.

2.1 *Electromagnetic induction*

Conventional mine detection has trusted mainly metallic mine detectors based on electromagnetic induction (EMI). This method is based on two bobbins, transmission and reception. The first one allows current to flow. The second one receives the induced current modified by the presence of a metal. Its main problem is its high false alarm rate due to the large amount of metallic objects or particles spread all over the field (Collins *et al.* 2001). This high false alarm rate makes detection slow, expensive and dangerous. Detectors can be adjusted to reduce the false alarm rate, but may then miss some mines, resulting in new victims afterwards. Metallic clutter interference in EMI responses has been studied and analysed through the incorporation of statistical signal processing in order to mitigate false alarm rates (Collins *et al.* 2001). This statistics-based approach involves detection and classification, incorporating independent component analysis in order to separate signals from multiple objects within the field of view of the sensor. Gao *et al.* (2000) incorporate a wideband frequency domain EMI sensor with an algorithm that considers uncertainties regarding target–sensor orientation and a theoretical model of the response of such sensors. This was reported to gain over 60% average improvement over traditional matched filters approach.

2.2 *Ground penetrating radar*

Difficulty in detecting tiny amounts of metal in a plastic land mine with a metal detector has led to the development of this technique which was first used on geophysical subsurface image acquisition and applications including utility mapping and hazardous waste container location. A radar signal is sent, and its reflected signal is analysed according to dielectric variations produced from reflections from the soil such as the presence of an object (Habib 2001). The resolution of the image is better if the wavelength is shorter; the shorter the wavelength, the better the soil penetration. Digital analysis of the signals plays a very important role in this kind of technology. Several good results have been obtained combining Ground penetrating radar (GPR) and EMI (Collins 2003). The great advantage of GPR is that it detects dielectric changes which are useful not only for metal detection but for a large variety of mine shields. A good point is that GPR can get horizontal sections of the subsoil at different depths, which constitutes a 3D image of the ground (Gader *et al.* 2002). Some of the main disadvantages are that inhomogeneous subsoil may cause a great amount of false alarms, and furthermore, performance is very complex according to complex interactions produced by metal content, radar frequency, soil mixture and soil surface smoothness (moisture, etc.) (Carin 2003, Ralston *et al.* 2003).

GPR is considered as one of the best techniques for subsoil research. However, mine detection using this technique becomes very complex when clutter is present, keeping good and useful results hidden. This clutter varies according to the soil surface irregularity and soil conditions, which implies adding uncertainty to the measurement. Soil moisture plays a fundamental role in the performance of GPR; therefore its results depend on the knowledge of the prevailing weather conditions, soil type and soil water content, all variables that will have a deep effect on GPR performance (Rhebergen 2003). For this reason it is necessary to have a good signal process in order to keep only mine generated signals. In order to reduce false alarms and detect real mines, several techniques have been developed. Some of the most important techniques include automatic target recognition (ATR), methods based on 2D and 3D texture analysis, subspace transformation techniques, background subtraction, hidden Markov models, wavelet decomposition, and several statistical approaches. Most of these methods work with the returning signal. In weak-contrast buried objects, especially buried objects under rough soil/air interface, discrimination is always difficult. Sato *et al.* (2005) present a statistical approach to obtain images forming from buried objects through a physical model using optics for surface representation and a Born approximation for weak contrast backscattered buried objects. The aim is to capture and relate the permittivity difference between the mine material and the surrounding soil. This statistical representation leads to reconstruction algorithms for buried objects.

Two methods for mine detection are proposed by Barkat *et al.* (2000), which are based on time-frequency analysis of the returned GPR signal. The first one uses instantaneous frequency (IF) of this signal, which consist of displaying the signal's spectral components using the peak of the Wigner-Ville distribution (WVD), with apparently good results. The other method is energy based detection using another time frequency approach to detect the presence of a buried target in the soil. This method is based on a discriminator algorithm that uses the WVD difference of a pair of signals, aiming to distinguish a buried target from the GPR trace from no target (Barkat *et al.* 2000).

Clutter reduction through data processing and parametric modelling is approached through an algorithm that improves signal processing techniques by incorporating an adaptive basis function for clutter representation, minimizing shallow depth objects returning image, and adding the use of a matched filter to account for uncertainty in the placement of the mine (Van der Merwe and Gupta 2000). Another approach to this subject focuses on clutter modelling using parametric modelling. A procedure called the Kalman method reduces most of the clutter to zero while preserving the shape of the original signal (Kempen and Sahli 2001).

2.3 *Nuclear quadrupole resonance*

Nuclear quadrupole resonance (NQR) relies on observation of radiofrequency (RF) signals from the ^{14}N nuclei present in explosives. The frequency of these signals oscillates between 0.5 and 6 MHz, and they are characteristic of a given explosive. They provide not only a positive identification, but also an estimate of quantity or depth. Rowe and Smith (1996) established a procedure that behaves unlike the typical nuclear magnetic resonance technique as no static magnetic field is needed, so portable probes can be used. Signals are seen only as solid or solid-like materials, avoiding interference from other nitrogen-containing materials that may be present in the mine casing or surrounding areas. This technique has proved to be highly effective if the NQR sensor is not exposed to radio frequency interference (RFI). A robust detection method should be used, since RFI may be unavoidable (Yingvi *et al.* 2002).

2.4 *Infrared (IR) and hyperspectral methods*

Infrared (IR) and hyperspectral methods detect anomalous electromagnetic radiation variation reflected or emitted over the mine surface or soil immediately over the mine (Nelson 2000; Batman and Goutsias 2003). The idea is to get reflected energy from mined areas where its reflection differs from surrounding areas. We include thermal sensors that make use of the difference in temperature variations between the soil and the mines mainly due to the night and day thermal oscillation (Boras *et al.* 2000). This method has a high performance only in homogeneous soil. Laser illumination or high power microwave radiation may be used to induce these differences. They do not need to have physical contact with the surface, the equipment used is light, and image acquisition is fast. Its disadvantage is that that its performance is variable and depends on characteristics of the environment

(Ackenhusen 2003, Baertlein 2003). Some authors say that these sensors need to improve, so for the time being it is better to 'wait and see' (Boras *et al.* 2000).

Considering the risk in close detection, Shimoi *et al.* (2001) present a study in remote detection through IR cameras by peripheral temperature difference considering data between the ground and the mine. The use of infrared thermography is one of the greatest improvements for mine detection. Muscio and Mauro (2004) focus on the development of research tools where the chance of success can be enhanced. A two-dimensional axial-symmetrical thermal problem is obtained in order to define a procedure that would correlate field temperature measured indoors, in a test case, with reduced size and duration, and that obtained in an outdoor mine detection campaign, enabling them to produce enough reference data for theoretical comparison and experiments.

2.5 *Electric impedance tomography*

Electric impedance tomography (EIT) uses electricity to generate an image of the conductivity distribution. A bidimensional array of electrodes is placed over the surface to catch signals from the distribution of the conductivity that can give information about mine presence. This system allows detection of metallic and non-metallic objects due to conductivity anomalies. It behaves well in wet soil and the equipment is relatively cheap and light. A disadvantage is that sensors must be in contact with the surface, therefore increasing the risk of detonation. They do not work well in dry soil like desert or rocky surfaces because of weak conductivity. Moreover, it is useful only for objects close to the surface (Church 2003).

2.6 *X-ray backscatter*

X-ray backscatter (XBT) has the potential for low false alarm rates and high detection probability. This technique is used to obtain the image of an object through X-rays passing through matter with an attenuation consequence (i.e. absorbed or scattered) (Nieman *et al.* 2002). Since it is impossible to capture photons that penetrate the soil due to the impossibility of placing an X-ray detector under the mines, these systems use the 'Compton principle' of X-ray dispersion. This means that photons are captured from irradiation from the object. This allows having an emitter and a receiver over the surface (Grodzins 2003). The use of this technology has three main advantages (Nieman *et al.* 2002): scatter signal is directly proportional to the density of the material in the irradiated volume, it requires only single-sided access, and high image contrasts are achievable, meaning that XBT has a high potential for imaging purposes.

The use of this technology is limited by the depth of the mines, since mines buried deeper than an average of 10 cm will not provide an adequate level of noise signal. Furthermore, it will be necessary to implement procedures to avoid exposure to irradiation by handling personnel (Jacobs and Dugan 2003).

2.7 *Acoustic and seismic systems*

Acoustic and seismic systems emit sound waves through speakers in order to get vibration over the soil. The sensors capture reflected waves from the soil and the mines. The difference in amplitude and frequency makes detection possible. There are special sensors that do not need to be in contact with the surface. Some studies point out that this technique is better for antitank mine detection (Sabatier 2003). These technologies capture mechanical differences between the soil and the mines, and they can complement the information obtained from EMI sensors. This system presents a low false alarm rate; however, bottles and cans may deceive the detector. Disadvantages are related to failure in detecting deeply buried mines and checking speed is extremely slow: between 2 and 15 min m^{-2} (Donkoy 2003). There is also some research in ultrasound use in order to characterize underground materials (Markucic 2002, Stepanic 2002). However, research is still needed to determine the operational framework for this technique.

2.8 *Vapour sensors*

A small percentage of the explosive manages to get out, as vapour, through fissures and shield structures of mines (Jenkins *et al.* 2003). The idea is to detect the presence of vapour from explosives. There are two research lines in this topic: biological and chemical.

Biological methods use animals (mainly dogs), insects and microorganisms to do the detection. They have the capacity to reduce false alarms since there are no similar explosives coming from rocks or debris (Burlage 2003). Dogs have had a good performance in detection. They can detect very low vapour concentrations (Phelan 2003). However, a large disadvantage is that this method depends on individual dogs in a heterogeneous universe. There is some research with bees and bacteria, but without positive results (Bromenshenk *et al.* 2003).

Chemical methods refer mainly to vapour from TNT, RDX and PET; therefore they may be considered as underground vapour sources. This vapour may be transported by phenomena such as molecular diffusion and turbulence processes (Jeremic and Nehorai 2000). The idea of this method is to build sensors capable of detecting smell using electromechanical principles, piezoelectric or espectropical (Jenkins *et al.* 2003, Swager 2003). There are still some limits in this research area due to the inability to establish a minimum detection level due to the variable nature of vapours.

2.9 *Robotics*

The option of detecting mines in a surface-laid minefield using autonomous robots is becoming more popular because it decreases the danger and the cost involved in manual detection (Acar *et al.* 2001).

Acar *et al.* (2001) have investigated some methods in path planning techniques in robotics. The first is sensor-based coverage according to exact cellular decomposition in terms of critical points. The robot executing the coverage algorithm incrementally constructs this cellular decomposition while it is covering the space with back and forth motions. The second technique, the probabilistic method, is for where time is limited and there exists *a priori* information about the minefield. This method works by minefield parameter extraction. Once the parameters are determined, the minefield layout is fixed, allowing opportunistic robot guidance to decrease demining time. Zhang *et al.* (2001) propose a probabilistic method for robot landmine search, focusing on optimization search strategy determining location of mines and/or unexploded ordnance. They first extract the characteristics of dispersion pattern of the minefield in order to construct a probability map and then design a path for the robot searching.

The development of lightweight, low-cost, semi-autonomous robots working together with a monitoring station (Personal Mine Explorers) is a well researched approached (Nicoud and Habib 1995). Robots search mines with such a low pressure that mine explosions are not triggered. In order to cover efficiently all mined areas, robots should adapt to accelerated exploration in order to increase efficiency, especially if any surveillance team exists.

Multi-robot systems for area reduction form the next step in landmine searching. Some research has been carried out on a multi-agent-based architecture responsible for coordinating a progressive stochastic analysis of the terrain (Santana *et al.* 2005). It includes a reactive obstacle avoidance method, and the development of mission control software to plan, configure and supervise operations. The system uses legged, wheeled and aerial robots. Finally, a sensorial payload system is described in this research with the use of Fourier analysis (Fourier transform) as the mechanism to effectively detect mines.

3. Data processing and algorithms

Data processing and algorithms will determine finally whether or not an object's image corresponds to a landmine. This aspect is probably the most important in landmine detection because technology is not currently showing big changes; however, detection algorithms will probably play a significant role in improving performance.

Support vector methods are interesting methods where anomalies in hyperspectral images are identified, therefore improving detection of the spectral signatures of unknown targets (Banerjee *et al.* 2006). The support vector data description is a technique that has been used in other domains such as faulty-machine-part detection and image retrieval.

Fusion is a developing technique in which information from several detection systems becomes relevant. Output information from different modules (systems) is grouped and compared, getting full potential from every available method, avoiding the weaknesses of each.

Sensor fusion in landmine detection states the difference between data fusion and data integration. With respect to data fusion, a multi system includes three main levels: raw data level, vector level and decision level (Rennie and Inngs 1997). In the raw data level the data from each sensor are combined. In the second level, each sensor analyses the raw data and produces a feature vector where its further coordinates will be combined to obtain a fused vector. Finally, in the third level, each sensor analyses the data, produces a feature vector, and then makes a decision of what feature vector is being described.

Neural networks are another approach for automatic target detection. Automatic target detection using entropy optimized shared-weight neural networks is an interesting method that compares standard shared-weight neural network performance (which is stated as inferior) with a morphological shared-weight neural network for automatic target detection (Khabou and Gader 2000). The first algorithm is improved by an entropy maximization term added to the method, and the results are compared between entropy trained and non-entropy trained datasets, concluding that the proposed optimization increases performance in detection.

Hidden Markov models (HMM) are used with some success through two and three dimensional vector sequences (Gader 2002). Gader *et al.* (2001) reported a method for detecting signatures through HMM. This method is evaluated with real data by transforming a GPR signal in a sequence of time dependent observation.

Bayesian network (BN) representation of a sensor's measurement process was developed so the problems of sensor fusion and management can be approached from a unified point of view (Ferrari and Vaghi 2006). This method uses *a priori* expert knowledge of the sensor's operating principle and available databases of actual sensor data to build a probabilistic model of the measurement process. This system works with GPR, EMI and IR sensors. It shows that BN models are capable of inferring target features by considering single or fused sensor measurement and known environmental conditions.

Decision fusion considers numerous detection algorithms and sensor modalities where detection algorithms are combined and fused into a common database. Liao *et al.* (2007) exploit the strengths of existing multisensor algorithms in order to achieve the required performance, exceeding those of isolation operating sensor algorithms. This approach is based on signal detection theory using the likelihood ratio. It considers a GPR and a metal detector.

Digital filtering for GPR signal enhancement was presented by Potin *et al.* (2006). It aims to reduce clutter noise in dielectric transmissions, as they constitute a major problem in shallow depth buried mine detection. Several other methods look for improvement in landmine detection like fuzzy clustering (Frigui *et al.* 1998), inductive learning as a fusion engine (Kercel and Dress 1997), ROC optimization (Wen-Hsiung *et al.* 2007), etc.

4. Summary

Humanitarian demining continues to be a world problem far from being solved. We have described some of the new technologies of landmine detection, some methods of processing and identification of landmines, and some algorithms. There is no single method for efficient landmine detection. Several technologies can be found, but their direct results cannot be generalized. There is work to be done in fusion of landmine detection technology in order to enhance its performance, since every approach has good results within limited conditions.

EMI and GPR have shown effective results. While the first is widely used, it presents several constraints when a non-metallic landmine is present. GPR has overcome the difficulties of detecting tiny amounts of metal contained in plastic mines by detecting both metal and non-metal kinds through the use of dielectric properties of objects. Despite this, serious limitations can be found when certain conditions are present that lead to mines being missed while allowing detection of debris or background conditions. This situation is presented in MacDonald *et al.* (2003), where GPR detects a wet spot in the sand, but does not detect a neighbouring landmine placed in the surrounding dry sand. In this case we can see how a system can be tricked.

Due to the aforementioned limitations, a multi-sensor system based on signal and algorithm fusion should be developed (Collins 2003, Russel 2003). Rather than focusing on individual technologies operating in isolation, mine detection research and development should emphasize the design from first principles and subsequent development of an integrated, multisensor system that would overcome the limitations of any single-sensor technology (MacDonald *et al.* 2003). Combining different kinds of sensors would certainly obtain better results in landmine detection. All this compels us to conclude that a single system should be produced, combining several kinds of sensors and detection algorithms. This 'system of systems' should consider algorithm fusion, integration of component technologies, detection technologies, data and feedback information management, all this under a continuous and financed effort. More information about costs and results can be found in MacDonald *et al.* (2003).

Finally, some more attention should be given to image processing techniques, especially segmentation, feature extraction, classification and post processing of characteristics, edge detection, texture, multiple view and digital image processing techniques including image restoration, enhancement, image processing and compression, wavelet transform, and object recognition. All these should help to discriminate useful data, which is critical as large numbers of false alarms increase uncertainty and limit future research.

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