LANDMINE DETECTION TECHNOLOGIES TO FACE THE DEMINING PROBLEM IN ANTIOQUIA

TECNOLOGÍAS PARA LA DETECCIÓN DE MINAS FRENTE AL PROBLEMA DE DESMINADO EN ANTIOQUIA

LORENA CARDONA
Ph.D.(c), Universidad Nacional de Colombia, lcardon0@unal.edu.co

JOVANI JIMÉNEZ
Ph.D., Universidad Nacional de Colombia, jajimen1@unal.edu.co

NELSON VANEGAS
Ph.D.(c), Universidad Nacional de Colombia, nvanegas@unal.edu.co

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ABSTRACT: This paper presents a review of existing landmine detection techniques. The review is made with an analysis of the strengths and weaknesses of each technique in relation to the landmine detection problem in Antioquia, which ranks first in Colombia by the number of victims from landmines. According to the uniqueness of landmines and terrains in Antioquia, this paper suggests some research topics that may help in the demining task for this affected department.

Key words: ammonium nitrate, APM, demining, explosive detection, IED, improvised explosive devices, landmine, landmine detection.

RESUMEN: En este artículo se hace una revisión de las técnicas existentes para la detección de minas antipersona. La revisión se acompaña de un análisis de las fortalezas y debilidades de cada técnica frente al problema de detección de minas en Antioquia, el departamento con mayor número de víctimas por minas antipersona en Colombia. De acuerdo a las características de las minas y de los terrenos antioqueños, se sugieren áreas de investigación que pueden ayudar a resolver el problema de desminado en este departamento tan afectado.

Palabras clave: AEI, artefactos explosivos improvisados, desminado, detección de explosivos, detección de minas, MAP, minas antipersona, nitrato de amonio.

1. INTRODUCTION

Landmines are weapons, usually buried, that explode when stepped on and are designed to injure or kill, leaving long-term psychological effects and posing a financial burden to the community [1]. Colombia ranks second in victims from landmines [2]. From 1990 to April 2011, Colombia recorded 9.277 victims, and 22.68% of them were in Antioquia [3], the most affected department. Colombia is seriously affected by this problem because landmines are currently used by groups outside the law to protect coca plantations and to counter the army [4].

Colombian mines usually include some elements that complicate the wounds caused by the explosion, as feces, glass and plastic scrap, which cause infections due to fragments that are not detected by x-rays [4]. In addition, these mines are enclosed in casings of various shapes, materials and sizes (e.g. wooden boxes, PVC pipes, glass and plastic bottles), that may contain more explosive: while conventional mines contain from 30 to 520 g, mines in Colombia usually contain from 250 g to 4 kg, and some have been found with more than 20 kg [4]. Due to government controls, the mines of illegal groups rarely contain military explosives, instead they contain ANFO (Ammonium Nitrate/Fuel Oil) [5] to which some products, like coffee or paint, are added to avoid canine detection. Due to the characteristics of Colombian landmines mentioned above, these are called improvised explosive devices (IEDs) [6].

A crucial step to prevent further victims from landmines and IEDs is to detect them and destroy them. Today, detecting IEDs is a problem in Antioquia due to the characteristics of these devices and of the land where they are buried. Here, a review of landmine detection technologies is made, in order to orient future research in the topic.

2. EXPLOSIVE DETECTION

2.1. Explosive trace detection

These technologies detect traces of explosives on the soil surface or in the air. The explosive's transportation from the mine to the soil surface begins with the diffusion of the explosive vapor through the mine casing or through its cracks and seals. About 95% is absorbed by the ground, and only 5% migrates towards the surface as vapor (although much is lost in degradation processes [7]). Several factors affect its arrival to the surface: diffusion is inversely proportional to mine casing density, casing paint absorbs chemical signals [7]; explosive degradation increases with temperature, moisture and organic matter; and finally, soil disturbances generated by mine burying can cause dispersion of chemical signatures [8]. Explosive residues in the soil are not uniform and the highest concentrations are not always at the mine location [9]. Additionally, the vapor pressure for most common explosives is very small, requiring highly sensitive sensors [10].

2.1.1. Biological methods

Dogs. Dogs outperform the best chemical sensors and can detect various byproducts from mine explosive degradation, however, they require constant training, and their performance decreases with time. In addition, they have mood and behavior variations difficult to predict [11], [12].

Rats. As an alternative to dogs, the use of giant African rats is being researched [13], [14]. They are trained with food to indicate the presence of explosives by scratching the ground with their feet. Rats have advantages over dogs: they are cheaper, can be deployed in large numbers, are lighter and resistant to tropical diseases [15].

Bees. Bees are trained to associate the odor of an explosive with food, by placing a mixture of sugar and the explosive nearby their hive. The use of bees is limited because they are difficult to track [16], can only work under limited climatic conditions, and their performance with multiple sources is unknown, being it possible that they only detect the strongest ones [15].

Ants. It has been found that ants can locate piles of explosives (TNT and RDX) and carried them to their ant hill. In [17], anecdotal evidence is discussed and in [18], a possible application is proposed for producing smart-landmines capable of self-passivation with time.

Bacteria. There are genetically modified bacteria that emit fluorescence in the presence of TNT [19]. A bacterial detection process involves spraying the bacteria in the minefield, letting them grow for several hours and then returning to search for fluorescence signals. It is possible to cover large areas rapidly with these bacteria [20], however they are highly sensitive to environmental conditions and false alarms of unknown cause have been found. Also, there is no known strain of bacteria capable of detecting other explosives than TNT.

Plants. *Aresa Biodetection* company has genetically modified a thale-cress plant called *Arabidopsis Thaliana* to change color when in contact with nitrogen dioxide emanating from explosives [21]. This technique has associated problems: nitrogen oxides are also formed by denitrifying bacteria, causing false alarms [22], these plants do not grow to be high, making it difficult to watch the results, and there is some concern about native plants contamination [21].

Human role. Humans play an important role in biological landmine detection, especially when dogs or rats are used. They are required for animal training and for interpretation of animal signals. A human and an animal comprise a unique team to perform the detection task together [23].

2.1.2. Chemical methods

Mass and ion mobility spectrometry. In mass spectrometry, a sample of air is introduced into a vacuum chamber where it is ionized. In ion mobility spectroscopy, ions are formed in a reactor. In both techniques ions are accelerated and separated according to their mass/charge ratio which is used for detecting explosives. However, these techniques have false alarms caused by non-explosive substances [24].

Infrared absorption spectroscopy. This technique relies on the fact that molecular vibrations have characteristic frequencies in the infrared spectrum. Resonant absorption of light by these vibrations is observed when the molecule dipole moment changes [24]. However, infrared spectra of large molecules can have broad bandwidths, leading to an indistinct spectrum. Also, many explosives decompose at the high temperatures needed to achieve the vapor pressure required for detection.

Opto-acoustic spectroscopy. This technique relies on the fact that optical energy absorbed by molecules is partially transformed into thermal energy by means of relaxation processes. Using pulsed radiation to excite the sample, pressure pulses are detected by sensitive microphones, yielding a photo-acoustic spectrum [25].

Raman scattering. Raman scattering is an inelastic scattering of light by molecules or atoms. During the interaction of light with the molecule, the energy of the vibrational and rotational states can be exchanged and a lower energy quantum of light is emitted. However, the Raman effect is extremely weak, having insufficient sensitivity for the landmine detection application [26].

Immuno-chemical sensors. Antigen-antibody complexes are formed for proteins containing the molecule of interest. When the substance is bound to an antibody, there is a change in some physical property which serves for detection. Although their selectivity, antibodies are not easily applied in field because they are not reusable [27].

Electronic noses. They are combinations of multiple sensors with pattern recognition algorithms, constituting an artificial olfactory system. They reduce the demand for highly selective sensors and put more emphasis on the algorithms to identify the sample [28]. Sensors used in electronic noses are: fluorescent polymers, optical fiber, polymeric films, gold nanoclusters, piezoelectric materials and micro-electromechanical systems [29].

2.1.3. Explosive trace detection techniques for IEDs detection in Antioquia

Most of the chemical and biological sensing research has focused on military explosives such as TNT, DNT, RDX, tetryl and PETN. Antioquia requires the development of new sensors capable of detecting Ammonium Nitrate (AN). However, AN is a common fertilizer and traces of it may be present around the minefield confusing such sensors. Moreover, vapor concentration of explosives depends on several factors that should be studied. It has been found that paint absorbs explosive vapors, preventing their escape to the surface, and it is usual to find a mixture of paint with the explosive in IEDs of Antioquia. The incidence of this mixture should be investigated, or perhaps exploited for IEDs detection. Also, explosive trace dispersion should be studied, since it is known that it could move within 10 meters from the mine location, and the current knowledge on vapor transportation from mines is insufficient for a reliable location [30].

Among biological systems, dogs and rats are the most suitable for IEDs detection in Antioquia, since bacteria are only able to detect TNT, plants suffer from high rates of false alarms and their effect on native plants has not been studied, and bees would be very difficult to track in the high vegetation lands of Antioquia; its use would depend on the development of new strategies for tracking bees in poor visibility conditions.

Currently dogs are used for IEDs detection in Colombia. Although reliable, dogs are slow and armed groups have begun to place anti-dog mines around IEDs, and also IEDs are being buried at greater depths to prevent explosive vapors from reaching the surface [6]. Alternatively, a research is being carried out on using *Wistar* rats for IEDs detection in Colombia [31]. According to the researchers, *Wistar* rats are better than African rats because African rats can damage the local habitat and they weigh three times more than *Wistar* rats, so they could trigger IEDs.

2.2. Bulk explosive detection

2.2.1. Neutron analysis methods

Thermal neutron analysis (TNA). In TNA neutrons are emitted and when absorbed by a nucleus, gamma rays are emitted with an energy that is specific to the nucleus. However, TNA cannot distinguish nitrogen oxides in the explosives from those in the surroundings, having a high rate of false alarms. In addition, its sensitivity is limited, its price is high and it is bulky and slow for use in field [32].

Fast neutron analysis (FNA). This technique uses high-energy neutrons to detect and differentiate gamma radiation at different energies. FNA technique is sensitive to almost all elements in explosives and allows their identification, but the equipment is usually complex and expensive [33].

Pulsed fast neutron analysis (PFNA). This technique applies the same concept of FNA, using a pulsed beam of neutrons. PFNA allows explosive composition to be determined, as well as its location and concentration, however, it needs large particle accelerators, which are bulky and expensive [34].

Pulsed fast thermal neutron analysis (PFTNA). PFTNA applies long-lasting beams of neutrons. Its main advantages are high reliability and mobile construction [34]. Its main disadvantage is an insufficient sensitivity to effectively detect the sub-kilogram amounts of explosive in the mines.

2.2.2. Nuclear quadrupole resonance (NQR)

This technique sends radio frequency pulses that excite nitrogen nuclei in the explosive, which induces an electric potential at a receiver coil. The spectrum recorded from each explosive is unique and thus the detection is highly specific and less susceptible to false alarms [34]. Its major drawback is a low signal/noise ratio (SNR) [30]. Also, it is affected by radio frequency interference (RFI), by the distance between the detection coil and the explosive, and by temperature [35].

2.2.3. Bulk explosive detection techniques for IEDs detection in Antioquia

Bulk explosive detection has advantages over trace explosive detection because the last one is affected by factors that are difficult to characterize, cannot locate IEDs accurately and suffers from insufficient sensitivity and false alarms because the pressure and concentration of the explosive vapors are too low.

With neutron analysis methods, there is a concern about the radiation dose that a human operator can receive, and even if it is within safe limits, a perceived risk may hinder its acceptance. Furthermore, it has been found that hydrogenated materials, such as water, can produce false alarms, preventing its use when humidity is above 20% [30]. It has also been found that by using neutron sources of low intensity to get a portable equipment, the detection task takes longer [30]. In addition, there are some concerns about the high cost of both neutron sources and gamma rays detectors. It would be necessary to study the incidence of the factors mentioned above in the detection of IEDs in Antioquia, and to determine infrastructure requirements to support research on neutron techniques.

NQR technique has the advantage of detecting the landmine explosive without emitting harmful radiation and with high chemical specificity. Despite of some drawbacks of this technique, much research has been carried out to deal with them [36], [37], [38]. These research results can be exploited to create a system for IEDs detection in Antioquia. However, in the literature, few works are found about AN detection by NQR [39], [40], [41] and none of them is related to landmine detection. Despite this, for NQR, AN detection is easier than TNT detection, the most used explosive in landmines [41].

3. MINE CASING DETECTION

3.1. Electromagnetic methods

3.1.1. Metal detector (MD)

MD measures the disturbance of an emitted electromagnetic field, caused by the presence of metallic objects in the soil. A major disadvantage of this sensor is that each piece of metal scrap triggers an alarm. The large number of false alarms makes the landmine detection task to be slow and costly [42].

3.1.2. Ground penetrating radar (GPR)

GPR emits radio waves into the earth and analyzes the returning signals produced by reflections at the discontinuities of the dielectric constant. Ultra-Wide Band Synthetic Aperture Radar (UWB SAR) with the ground penetrating capability has become an alternative way to detect landmines over large areas from a safe standoff distance [43]. The main drawback of GPR is that irregularities in the soil (e.g. roots, rocks) can produce false alarms [44]. Additionally, its performance is sensitive to complex interactions between mine casing material, soil texture and moisture, wave frequency and soil surface roughness. Another limitation is the detection of small shallow mines because the reflection at the soil surface masks the response of such mines [30].

3.1.3. X-ray backscattering

This technique exploits the fact that mines and soil have densities and effective atomic numbers that differ by a factor of two [45]. However, it is non-portable because of the size and weight of the x-ray generators, and of the power requirement to reach enough penetration [46]. Also, it emits radiation, hindering its acceptance.

3.1.4. Electrical impedance tomography (EIT)

EIT uses a two-dimensional array of electrodes placed on the ground to construct a map of conductivity distribution in which mines are seen as anomalies [47]. This technology is especially suited for wet soils, because water enhances conductivity. Also, EIT is cheap enough to be disposable and remotely inserted to improve safety [22]. The main drawback of EIT is that it requires physical contact with the soil. It cannot be used on very dry soils and it is sensitive to electrical noise. Its resolution does not reach that of a GPR [30].

3.1.5. Electromagnetic techniques for IEDs detection in Antioquia

Among the electromagnetic techniques, GPR is likely to be the most convenient for Antioquia. MDs are not suited because most IEDs have little or no metal content at all. X-ray backscattering equipment is not portable and in Antioquian minefields, it may be impossible to drive a bulky transportation platform. EIT requires physical contact with the ground and Antioquian lands are irregular, with high vegetation and IEDs can be activated with an uncertain weight.

GPR is regarded as one of the best subsurface investigation techniques and its potential application in Colombia has already been researched [48], [49]. As mine detection using GPR becomes very complex in the presence of clutter, its outcome depends on the knowledge of prevailing environmental conditions, soil texture and moisture [50]. These factors should be studied in the most affected areas of Antioquia (Tarazá, Guadalupe, Ituango, Toledo, Anorí and Campamento [3]), and tests should be made to validate GPR performance.

3.2. Mechanical methods

3.2.1. Seismic-acoustic techniques

Seismic-acoustic systems introduce sound and/or seismic waves into the earth that are partially reflected when they reach a landmine, causing vibrations at the soil surface. This technique has a low false alarm rate [51], however, sound waves are significantly attenuated by soil, so mines at depths greater than a mine diameter cannot be detected. Additionally, surface vibrations are small and difficult to measure when there is vegetation, turning it into a slow detection system. However the use of sensor arrays has proven to accelerate the detection [52].

3.2.2. Ultrasound

Emitted ultrasound waves are reflected at interfaces between materials with different acoustic properties, which could be used to create images of hidden internal anatomy. Its main advantage is the ability for good penetration into wet lands. However, the sound waves attenuate significantly at the soil-air interface [22].

3.2.3. Prodding

In prodding, a trained operator prods the ground with a stick of about 25 cm long, forming a small angle with the ground surface. Today, prodding the land is used to confirm the presence of a landmine and it is considered the only way to guarantee an exhaustive detection [53]. It is a very slow and dangerous technique because landmines can have any orientation due to soil movement or to nearby explosions and they can be detonated by the probe [46].

3.2.4. Mechanical techniques for IEDs detection in Antioquia

Ultrasound and acoustic/seismic systems have high probability of detection and low false alarm rate, however, they are not portable, seismic waves can detonate IEDs and they cannot detect deep objects. They also have issues with, dense vegetation, such as there is in Antioquia.

Prodding has several disadvantages, but it is still the quintessential confirmatory method for landmine detection. Although probes have been developed which can identify the landmine casing material, they are rarely used in field because, in the hands of a skilled operator, a normal probe may give enough information for landmine detection [46]. Moreover, instead of upgrading the probe for prodding, it would be ideal to have an alternative confirmatory method without the hazards of prodding. In this sense, NQR can constitute a reliable landmine confirmation system because of its high specificity and because its SNR increases with sensing time.

4. INFRARED AND HYPERSPECTRAL DETECTION

Infrared and hyperspectral methods detect abnormal variations in the electromagnetic radiation reflected or emitted by landmines or by the ground above them.

4.1. Millimeter wave radar (MMWR)

This technique relies on the fact that in the millimeter-wave band, soil has high emissivity and low reflectivity, while metals behave in the opposite way [54]. Active MMWR uses an excitation source while passive MMWR does not, relying only on environmental temperature. MMWR is a good technique for detecting metallic objects, but not for detecting plastic ones.

4.2. Infrared cameras (IR)

This is a thermal detection method that relies in the fact that diurnal temperature variations in areas close to landmines differ from surrounding areas [55]. By using high power radiation (i.e. active IR), these temperature differences can be induced [56], but a landmine could be detonated. IR performance is affected by factors such as weather conditions, landmine size and composition. IR sensors have trouble detecting deep objects and are most suited to detect mined areas than individual mines [22].

4.3. Laser induced breakdown spectroscopy (LIBS)

LIBS uses a high intensity laser to generate a micro-plasma at high temperatures, dissociating the material into atoms and ions. Electron-ion collisions produce a continuous spectrum whose analysis allows element identification. LIBS has been used in identification of different types of anti-personnel and anti-tank landmine casings [57]. LIBS is capable of in-situ point probing and of chemical sensing for landmine detection. It is being directed towards a development of a probe for prodding the soil that emits laser light and collects plasma emissions through an optical fiber [58].

4.4. Visible light

Mine detection by this technique involves the capture of light in the visible wave range using an optical system for imaging [59]. The main limitation of this technique is that it can easily be blocked by camouflage or foliage, so it can only be used on flat lands with little vegetation [22]. It is more suited to detect surface-laid mines.

4.5. Optical light detection and ranging (LIDAR)

LIDAR detects polarization changes in the back-scattered light after illuminating an object with linearly polarized light. Landmines on soil surface can be detected because of their smooth nature compared with the rough background [60]. This method is not capable of subsurface imaging, and does not work well when there is vegetation.

4.5. Infrared/hyperspectral techniques for IEDs detection in Antioquia

Passive IR methods are slow and not suitable for close landmine detection, and active techniques can detonate IEDs and require high power supply, which is difficult to provide in a portable system [46]. MMWR gets weaker signals than infrared ones and it is ineffective in detecting plastic landmines.

There was a research about LIBS in Colombia [61] intended to identify the polymers used for IEDs manufacture and for explosive trace detection, but it was concluded that LIBS has a limited use in Colombia due to the wide variety of IEDs, and to the low sensitivity of the technique at the explosive concentrations. A recent work on AN and fuel oil detection by LIBS [62] showed its ability to identify AN, but not to identify fuel oil when mixed with soil; they also found that the technique had trouble with wet soils and mentioned potential false alarms produced by fertilizers.

LIDAR and visible light techniques do not work well when there is vegetation. Even so, in [63] the images taken by an on-board camera were used, looking for texture and color abnormalities at the regions where the mines were buried. Tests were conducted on soil with gravel and short grass, demonstrating the feasibility of this technique for landmine detection.

5. SENSOR FUSION

A general conclusion of the reviewed papers about landmine detection is that no technology is capable of detecting all types of landmines under all environmental conditions and that there is a need for developing multi-sensor detection systems in order to overcome each sensor limitations [30], [46], [50], [64], [65].

Sensor fusion for landmine detection has been mainly dedicated to the combination of GPR and MD technologies, and in some cases IR sensors [66]. In Colombia, the Universidad de los Andes together with Indumil developed a detection system that combines a GPR with a MD [67]. However, they have not reported any experimental results.

Further research in sensor fusion is needed to include other technologies besides MD, even more so in Antioquia where most IEDs do not contain metallic pieces. A good solution could be to include an explosive detection technology, since it would decrease false alarms from non-explosive objects in the soil.

6. FINAL RECOMENDATIONS

In this paper a review was made about the existent technologies for landmine detection, showing their advantages and disadvantages and analyzing their prospect to become IEDs detection systems for Antioquia. It is concluded that no single technique is capable by itself of solving the IEDs detection problem and that the integration of two or more sensors is required. For Antioquia, the combination of GPR and NQR technologies is suggested. The reason is that GPR is a mature technology, portable equipment is available and there is research that shows its feasibility for IEDs detection in Colombia; and NQR detects the explosive inside IEDs, complementing GPR. However, there is a need for research on AN detection inside IEDs by NQR.

IEDs detection in Antioquia is a complex problem because of the difficulty accessing the areas, because IEDs are non-metallic and because they are currently being placed by armed groups that tailor IEDs to the current demining technologies in order to hinder their detection. But demining of out-of-conflict areas is possible if further research is carried out on adapting the existing technologies to the local problem. However, there is a barrier because the Army and the government do not seem to understand that research costs a substantial amount of money and that results are uncertain and will only appear over the medium to long term. Landmine clearance in Antioquia is subjected to the amount of investment in research on this topic.

In the development of a technology for IED detection in Antioquia it is important to maintain communication with the demining groups to meet their needs. According to [46], many scientists have attacked the problem without an ongoing discussion with users, and as a result, they have obtained technologies that cannot be used in the field.

The way information is presented to the operator is also an important research area. Most existing systems give a sound signal difficult to interpret and to hear in certain conditions. The advanced landmine imaging system (ALIS) [68], which shows images from two sensors (MD and GPR) in real time, is one of the most important contributions in this area.

Knowing the research carried out in Colombia in the context of demining is important to avoid repeated work [46]. Besides the works already mentioned (research using rats to detect explosives, the fusion of a GPR and MD, research on LIBS for the characterization of materials, and mine detection by surface image analysis), there are other two works developed in robotics: a remotely operated robot [69] and a study on snake-type modular robots for use in landmine detection [70]. These works are important for two reasons: first, some researchers might be encouraged to develop detection technologies that are not suitable for hand-held use, but that would be effective onboard a robot; and second because ideally, the mine detection task should be carried out by autonomous or semi-autonomous systems to prevent exposure of people or animals to the hazards of landmine detection.

Finally, current detection technologies are unable to detect mines at great depths and a sensor fusion will not solve this problem. This is a major research focus since IEDs are currently being placed by armed groups seeking smarter ways to make these artifacts difficult to detect.

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