Humanitarian De-mining and the Quest for Better Ways of Locating Buried Non-Metallic Objects

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1. Introduction

Land mines are scattered across many countries. Most of these countries are poor and developing countries with meager resources to develop technologically sophisticated solutions for mine detection and removal. These mines are leftovers of conflicts, both large and small. Some land mines have been in place for as much as half a century. One such nation is Egypt, where millions of mines remain from World War II. Others have been placed very recently, as in some central African nations. Most of these mines are buried in soil at depths of less than 15 centimeters. The removal of these land mines is a mandatory requirement for using the affected land. Until they are removed, people are in danger and millions of acres of potentially productive land lies fallow and/or unavailable for grazing. Thousands of people including children are killed or injured each year by these mines.

Mines are difficult to detect and remove. De-mining is mostly a manual process. Metal detection and hand prodding remain the widely used approaches for locating mines. We still lack technological expertise when it comes to low risk, non-invasive, stand-off detection of mines. At the current rate of removal, several centuries will elapse before minefields become usable. The Ottawa Treaty of 1997 designed to ban the introduction of new mines has no effect on the existing minefields. Some nations (e.g., the US) have not joined the Treaty; furthermore, the absence of inspections and enforcement makes the possibility of violations rather likely.

Any nation that has a land mine problem has already been disrupted to its core by conflicts that led to the placement of mines in the first place. The presence of mines leads to loss of agriculture, as well as infrastructure such as roads, bridges and sanitation systems. Often there has been displacement of population with related problems of unemployed and homelessness. While these structural problems are visible and quantifiable, the social effects of the tragedy inflicted by land mines in the post-war period upon these citizens who are trying to reconstruct their lives cannot be measured and are seldom publicized.

In this article, we discuss the magnitude of the mine infestation problem and attempt an assessment of the state of mine detection technologies that are currently under development or are already available.

2. Mines, Mines and Mines ...

The number of land mines[1] that need to be cleared to restore land for civilian usage is not exactly known. There are more than 750 varieties of known land mines. The US GAO[2] and the

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[1] Land mines can be anti-tank mines, anti-personnel (AP) mines and unexploded ordnance (UXO), which refers to any explosive device found in an apparently abandoned condition. A large portion of the anti-personnel and anti-tank mines are devices in plastic casings with very low metal content. Among the most difficult to detect are mines with low metal content, which are abundant. A typical plastic AP mine costs less than $ 3 to make. Estimated cost of retrieval/mine is ~ $1,000 or more.

International Campaign to Band Land mines estimate that there are some 127 million land mines that must be neutralized in as many as 88 countries. Some of the heavily mined nations with estimates of mines in parentheses in alphabetical order are:[3] Afghanistan (~ 10^7), Angola (1.5×10^7), Bosnia-Herzegovina (3×10^6), Cambodia (6×10^6), China (10^7), Croatia (3×10^6), Egypt (2.3×10^7), Eritrea (10^6), Ethiopia (0.5×10^6), Iran (1.6×10^7), Iraq (Kurdistan) (10^7), Mozambique (3×10^6), Rwanda (0.25×10^6), Somalia (10^6), Sudan (10^6), Ukraine (10^6), Vietnam (3.5×10^6).[4]

3. Mine Casualty Data

The global average number of casualties per year resulting from mine accidents is unknown. An estimate of total number of casualties per year is between 15,000 and 20,000.[5] The casualty data for calendar year 2000 as released by the International Campaign to Ban Landmines (ICBL) reveal the following numbers: Angola – 840, Bosnia-Herzegovina – 92, Chad ~ 300 over the past 24 months, Democratic Republic of Congo – 189 since 1997, Eritrea – 49 in May and June 2000. Lebanon – 113, Somalia – 147 in just two central regions, Sudan –321 between September 1999 and March 2001, Tajikistan – 58 between August 2000 and early May 2001. Thailand – 350 over the past 24 months.

4. Challenges of Exploring a Complex System

Our understanding of the mechanical and electrical properties of complex granular materials such as soil is limited (Bonner et al. 2001, Liu and Nagel 1993, Rogers and Don 1994, Sinkovits and Sen 1995, Muir 1954, Hoekstra and Delaney 1974, Wang and Schmugge 1980, Campbell 1990, Wensink 1993). High resolution imaging of shallow buried objects in soil remains an unresolved problem. It is not a surprise that small AP mines are most difficult to detect using available technologies. As stated above, most humanitarian de-mining operations rely upon the use of metal detectors and hand prodding. De-mining operations occasionally employ specially trained dogs to sniff out explosives. Besides, there are at least 20 different kinds of technologies specifically aimed at detecting buried mines that are currently either under development or are potentially available.[6] However, all of these technologies have their limitations and none of them can be used alone as a reliable mine detection tool. Further, de-mining is not only about digging out mines (King 1998). It also includes detection of ground based trip wires and of clearing vegetation and other elements that can potentially render many technologically sound methods practically useless (King 1998).

5. The Global Budget for Humanitarian De-mining

According to ICBL,[7] the total investment (including equipment purchase, maintenance, salaries, R&D, etc.) on "humanitarian mine action" in 1999 was $211 million. However, this amount is

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[2] US General Accounting Office Report to the Chairman, Subcommittee on Military Research and Development, Committee on Armed Services, House of Representatives, "Land mine Detection - DOD's research program needs a comprehensive evaluation strategy," US GAO-01-239 (2001).

[3] Data quoted from Annex A of "Hidden Killers 1998: The Global Landmine Crisis" available in http://www.state.gov/www/global/arms/rpt_9809_de-mine_nxa.html

[4] The available data is incomplete. It is known for instance that much of Falkland Islands is heavily mined yet such information is not easy to come by in many publications. For details see the following on-line article by J.C. Ruan and J.E. Macheme, "Landmines in the sand: The Falkland Islands" in the Journal of Mine Action, http://maic.jmu.edu/journal/5.2/focus/falklands.htm.

[5] http://www.icbl.org/lm/factsheets/va_sep_2001.html

[6] http://www.humanitariandemining.org/catalog/fcover.htm

[7] http://www.icbl.org/lm/2000/keyfindings.php3

meager when one considers the overall cost of de-mining, some $1-2 million/sq. km (Trevelyan 1998). The stated amount includes the costs of operating an overall de-mining program in a typical third world environment. Hence, it would be incorrect to associate the $211 million figure with resources available for developing improved approaches to the problem of mine detection, deactivation and certification.

6. A Brief Survey of the Technologies

Electromagnetic Approaches

There are some eleven distinct technologies that are based upon sending electromagnetic energy into soil for mine detection.[2] There are four technologies that are based upon reflecting electromagnetic energy off the mine. These technologies radar, light detection and ranging (LIDAR), Terahertz imaging and X-ray backscatter. There are two technologies that rely on detecting an electromagnetic field. These technologies are a conductivity/resistivity based approach and metal detectors. In addition there are five different technologies that somehow react with the explosive contained in the mine. These technologies are electromagnetic radiography, gamma ray imaging, microwave enhanced infrared, quadrupole resonance and X-ray fluorescence.

Mine detection using electromagnetic radiation is based on the difference between the electromagnetic properties of the target and the ground. We first mention the approaches that rely upon the reflection of electromagnetic energy off the buried mine. Usually, shorter wavelengths that afford higher resolutions attenuate rapidly in soil. The strength of each technology relies upon penetrability versus resolution for specific soil conditions. The radar-based technology relies on the microwave part of the spectrum and hence can penetrate some distance into the soil. However, because of the rather large wavelength, ground penetrating radars offer limited spatial resolution. They are also unable to penetrate water-saturated soils. The LIDAR, terahertz imaging and X-ray backscatter approaches use shorter wavelengths and hence suffer from significant limitations in soil penetration (typically a few centimeters).

Among the electromagnetic radiation based approaches that involve interaction with the explosives, the one based on quadrupole resonance appears to hold promise. Many of these approaches do not have the drawback of getting too many false positives due to clutter and debris content of the soil. The quadrupole resonance approach is already used to detect explosives at the airports. In this technique a long wavelength pulse causes nitrogen nuclei to emit a pulse of energy that is characteristic of the molecule (e.g., nitrogen in TNT emits a unique pulse). The primary limitation of the quadrupole resonance approach is that the detector head must be very close to the target and the procedure is slow. In addition, it may not be easy to identify the signatures from specific suspect molecules. Quadrupole resonance is a mature technique and the Naval Research Laboratory has played a major role in developing this approach. Electromagnetic radiography scans the ground with long wavelength microwaves and excites target molecules at certain atomic levels, which in turn results in a spectrographic signature of the target substance. The electromagnetic radiography approach appears to be in a relatively early stage of development. In the microwave enhanced infra-red approach, the thermal signature and infra-red spectra of chemical explosives can be detected. One limitation of this approach is that it cannot detect metallic mines because microwave energy cannot penetrate metal. In addition, the speed and standoff distance at which this method can operate are concerns. In illuminating the ground with X-rays, one causes a series of changes in the electron configuration of the target atoms that results in X-ray fluorescence. This approach detects molecules of explosives that are emitted from the mine and the amount of fluorescence depends upon the target molecule. Standoff and penetration remain serious issues in the application of this technology to mine detection. Finally, gamma-ray imaging is a fifth technology being explored under this category. In this approach, an electron accelerator produces gamma rays that interact with the chemical elements in the explosives to generate a unique signature. Due to the short wavelength of this approach, proximity to the target is essential.

In the category of approaches that detect electromagnetic fields, metal detectors are most widely used for de-mining. These detectors generate a magnetic field that reacts with the electrical or magnetic properties of the target. This reaction causes the generation of a second magnetic field, which is received by the detector. Metal detectors are not very reliable when detecting low metal mines and must be operated at close range. In the conductivity/resistivity based approach, a current is applied to the ground using a set of electrodes. Then the voltage is measured between various other sets of planted electrodes. The voltage measured is affected by objects in the ground including landmines. This technique was originally developed to locate minerals, oil deposits and groundwater supplies. The need to place the electrodes in or near the ground is a concern for landmine detection.

In addition to the eleven technologies referred to above, there are four passive electromagnetic technologies that do not actively illuminate the targets but are based on detecting energy emitted or reflected by the mines. These technologies spot either a contrast between the energy emitted or reflected from the mine and that of the background or the contrast between the disturbed soil immediately surrounding the mine and the top layer of the soil. Infra-red, millimeter wave and microwave based technologies typically provide good stand-off. Multispectral infra-red approaches gather information in several infra-red wavelength bands at the same time. These approaches are, however, strongly sensitive to temperature variations during the day. A fourth passive approach that detects energy produced by the circuitry in advanced mines that contain sophisticated fuses is also under development.

Acoustics Based Approaches

A long history of theoretical and experimental work dating back to the 1950s shows that a mine sized object in soil causes persistent measurable changes in the local elastic properties of the ground, which can be detected by acoustic probing.

The acoustics based attempts to mine detection fall into three categories, "ground sonars," i.e., Rayleigh wave based forward propagation and echo technique, low frequency (typically in the range between 150 and 300 Hz or so) resonance based attempt in which a selected low frequency is transmitted such that it resonates with the natural vibration of the soil-shell interface of a buried compliant object and impulse backscattering based approach, in which signals are sent through the granular contacts for directly imaging buried metallic and non-metallic objects using backscattered signals.

In the ground sonar approach, the shallow depths of soil (meaning a floppy three dimensional network of air channels and soil grains) is insonified with low frequency vibration pulses. This can be accomplished by using speakers. The buried mines, which possess mechanical impedance contrasts relative to the undisturbed soil, generate backscattered waves that reach the surface. Eventually, the entire soil column above the object will be set into vibration. The surface vibrations can be sensed by a spatially distributed array of sensors/receivers or via more sophisticated analyses such as one involving how light rays incident on a vibrating surface will get scattered as in laser Doppler vibrometry. The measurements are typically done in "near-field," meaning within a few centimeters from the target. Typical depths that can be probed by this technique do not exceed 15 cms. A different approach currently under investigation, proposes to send two differing frequencies from a transmitter and bounce them off a buried object such that the difference frequency is received by a receiver. The key idea is that the frequency difference can be crafted in such a way that a specific material of known geometry can respond to the transmitted signal while other objects would not. The method has the potential to discriminate different materials in soil. However, it is not appropriate for imaging and its usefulness in de-mining operations is unclear. The propagation of mechanical impulses in soil exhibit very different behavior compared to sound propagation. Unlike sound propagation in soil, which disperses as it travels horizontally or vertically through soil, impulses travel as weakly dispersive energy bundles. The velocity of an impulse depends upon the amplitude of the impulse and impulses backscatter efficiently from any object that possesses a density contrast with respect to that of the soil grains. The backscattered signals can be received at the surface using appropriate ground contact sensors, which in turn can allow one to reconstruct an image of the buried object.

Neutron Activation

Explosives in mines possess a much higher concentration of nitrogen and hydrogen than in naturally occurring chemicals. In this approach, a continuous or pulsed neutron source that emits bursts of neutrons in sent into the ground. A detector is used to characterize the outgoing radiation, which are predominantly gamma rays that result from interactions of neutrons with soil and substances such as explosives. The main limitation of the neutron activation approach is that it cannot be used in stand off mode. The neutron source and detector must be directly above the target. It is also unclear as to how deep the neutrons can penetrate and as to whether the approach would be capable of detecting small antipersonnel mines. The neutron activation detector is likely to be used as a confirmatory detector.

Biological sensors

All biological systems such as mammals and insects exploit the possibility of direct sensing of explosive compounds. This is, of course, the most direct route to exploring whether an object is an explosive and hence potentially dangerous. The commonly encountered difficulty in biological systems concerns translating relevant information from the dog, rat, bee or some other animal to the de-miner. Dogs are perhaps more reliable than others and are used routinely in de-mining operations. However, even with meticulous training and significant experience the information flow from the dog to the de-miner is not perfect. In addition, biological systems are very different than machines. The animals must be kept healthy, have fixed duty cycles and efforts must be made to keep them undistracted.

There have been several attempts to artificially accomplish the detection of explosive molecules by analyzing air samples in the vicinity of explosives. These attempts have exploited three distinct themes, the surface acoustic wave (SAW) devices, chemical resistor devices and ion-mobility spectroscopy. The SAW devices capture samples of the materials being sought and classify them by molecular mass. These devices capture the molecules of interest on a membrane. The membrane’s vibrational response spectrum is altered by the captured molecules. Appropriate signal processing techniques allow classification into molecular groups, from which the identification follows. The chemical resistor devices capture samples and classify the samples based upon how they affect the resistivity of the sampling probe. These devices are able to distinguish between closely related molecules with considerable precision. However, both the SAW devices and the chemical resistor devices need a substantial amount of any sample for reliable performance. In ion mobility spectroscopy, the samples are classified according to molecular mass, size and shape as all of these characteristics affect the drag forces on a molecule in a moving stream of gas. All of these chemical sensors can potentially be sensitive devices for mine detection. However, it is necessary to miniaturize these devices appropriately and improve their sensitivities for use in the context of de-mining. Some of that work is currently in progress.

7. Conclusion

In conclusion, the issue of automated detection of land mines in various kinds of soils and terrains remains an outstanding challenge to scientists and engineers. In many ways, this challenge is related to the fact that we still have much to learn when it comes to describing the propagation of electrical and mechanical energy in complex materials such as soil.

A suite of cost effective and reliable technologies is likely to be a crucial factor in humanitarian de-mining. To this end, a balanced collaboration between scientists, engineers, de-miners and social scientists is required. Humanitarian de-mining, a subject of great importance and enormous complexity, could profit from such an approach.

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References:

Bonner, B.P., P.A. Berge, C. Aracne-Ruddle, H. Bertete-Aguire, D. Wildenschild, C. Trombino and E.D. Hardy, “Linear and nonlinear ultrasonic properties of granular soils,” in S. Sen and M.L. Hunt Eds. “The Granular State,” *MRS Symp. Proc.* **627**, pp. BB. 3.7.1- 3.7.6 (MRS, Warrendale, 2001).

Campbell, J.E. “Dielectric properties and influence of conductivity in soils at 1-50 MHz,” *Soil. Sci. Soc. Am J.* **54**, pp. 332-341 (1990).

Hoekstra, P and A. Delaney, “Dielectric properties of soils at UHF and microwave frequencies,” *J. Geophys. Res.* **79**(11), pp. 1699-1708 (1974).

King, C. “De-mining: Enhancing the process,” pp. 1- 9 in “MD98- Proceedings of the 2nd International Conference on the Detection of Abandoned Landmines,” *IEE Conf Publ.* **458**, pp. 23-27 (IEE, London, 1998).

Liu, C-h. and S.R. Nagel, "Sound in a granular material: disorder and nonlinearity," *Phys. Rev B* **48**, pp 15646-15650 (1993).

Muir, J. “Dielectric loss in water films absorbed by some silicate clay minerals,” Chemical Society of London, *Faraday Trans.* **50**, pp. 249-254 (1954).

Rogers, A.J. and C.G. Don, "Location of buried objects by an acoustic impulse technique," *Acoustics Australia* **22**, pp 5-9 (1994).

Sinkovits, R.S. and S. Sen, "Nonlinear dynamics in granular columns," *Phys. Rev. Lett.* **74**, pp 2686-2689 (1995).

Trevelyan, J. “Technology Transfer in Humanitarian De-mining,” pp.23-27, in “MD98- Proceedings of the 2nd International Conference on the Detection of Abandoned Landmines,” *IEE Conf Publ.* **458**, pp. 23-27 (IEE, London, 1998).

Wang, J.R. and T.J. Schmugge, “An empirical model for the complex dielectric permittivity of soils as a function of water content,” *IEEE Trans on Geosci and Rem. Sens. GE*-**18**(4), pp. 288-295 (1980).

Wensink, W.A., “Dielectric properties of wet soils in the frequency range of 1-3000 MHz,” *Geophysical Prospecting* **41**, pp. 671-696 (1993).