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Sensors for close-in detection of explosive devices

Current status and future prospects

Abstract—**This paper presents a brief overview of sensor technologies for close-in detection of buried explosive devices and describes the research and development activities planed to be carried-out in the framework of FP7/SEC-2011/TIRAMISU project to advance the state of the art in this area.**

I. INTRODUCTION

Landmines are used as tactical weapons during wars. To be effective, landmines should be hidden (usually buried) turning difficult its detection by potential targets. Just like landmines, a large amount of other explosive devices, such as cluster munitions, explosive remnants of war (ERW) and improvised explosive devices (IED) are left on field after conflicts, causing victims and restricting land usage in dozens of developing countries with scarce resources. Cleaning post-conflict areas has for long time been identified as one of the most serious and urgent humanitarian problems to be solved by humanity, but the large amount of affected areas, sometimes of difficult access, and the lack of efficient sensing technologies are major difficulties to solve this problem effectively.

The detection and localization of a specific explosive device (ED) is usually done at short distance, by a process called close-in detection (CID). Tools currently used to perform close-in detection include metal detectors (MD), either hand-held or vehicle-mounted, vehicle-mounted ground-penetrating radars (GPR), hand-held detectors combining metal detectors and ground-penetrating radars, and vapor detection methods with or without animals. Sweeping a handheld metal detector and prodding manually a suspected area is still the most frequent technique employed by deminers. This is a trusted, but very slow procedure, since metal detectors are prone to provide a very high false alarm rate – on one hand post conflict areas may contain large quantities of metal debris generating frequent alarms by metal detectors, on the other hand stones can provide a prodding response similar to potential landmines.

According to the Geneva International Center for Humanitarian Demining (GICHD) an area can only be considered clean when all ED have been removed and destroyed – this requires a detection rate of 100%. The United Nations (UN) set a less ambitious, although still difficult to achieve detection target of 99.6%. All above detection tools exploit some kind of signature provided by the ED (e.g., metal content, dielectric discontinuity, explosive trace vapors, shape, etc.), but on one hand these signatures can also be found in non-explosive devices giving rise to a potentially high false alarm rate (FAR), on the other hand, the searched signature provided by some ED may be too weak to be detected by the CID tool, giving rise to a lower than unity probability of detection (POD).

Addressing these problems require better sensors and/or using multiple sensors simultaneously and fusing their output in order to obtain higher POD and lower FAR. The efficiency of CID tools can additionally be increased through the use of large arrays with high detection width, able to cover wider areas in the same or lower cost (be it time, involved persons or resources in general).

The remaining sections of this paper describe and analyze the conventional close-in detection techniques and commercial systems currently employed by humanitarian demining teams and surveys the latest advances in sensor technologies, still in an early research phase or being tested through prototypes. Particular emphasis will be devoted to sensing technologies developed in the framework of the TIRAMISU project, namely intelligent prodders, capable to automatically and safely detect and recognize the material in contact, chemical sensors for explosive vapours, advanced metal detector arrays, capable to identify the type of detected metal, and GPR arrays, for close-in detection and identification of buried explosive devices. A detailed survey is out-of-scope of this paper. For deeper treatment on the subject the readers are invited to check the following references [Robledo 2009, Kasban 2010].

II. METAL DETECTORS

The metal detector is the main tool used in manual humanitarian demining. This technology, invented during World War II, was very effective when the landmines contained large amounts of metal (e.g., a metal case), but modern landmines may contain only fractions of a gram, which significantly complicates their detection.

Conventional metal detectors employ the principle of electromagnetic induction, using a secondary coil to detect the disturbances produced by metallic or conductive objects in the continuous wave field generated by a primary coil. In

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modern metal detectors this basic principle may be implemented in different ways (e.g., pulse induction). A comprehensive overview of metal detectors technology and their use for humanitarian demining can be found in [Guelle 2003].

Metal detectors come from many different manufacturers. They may include features such as soil compensation algorithms (to reduce the influence of soil on detection) or discrimination features (to make the difference between different types of metal). Although being the tool of choice they do have some limitations. A heavy concentration of metal scraps can create a lot of unwanted alarm indications. Magnetic soils can reduce their detection. Soil with high concentration of salt and with high soil moisture, such as at sea beaches, can have a high conductivity which makes detection difficult because of additional alarm indications. Techniques implemented within metal detectors to compensate for the effect of soil may reduce sensitivity. High electromagnetic fields, such as what can be found near power lines, can create interference. In addition, some operators do not know that the sensitive area of a metal detector decreases with depth. [GICHD 2006].

A. *Metal detector array*

The use of double balanced receiving coils provide several advantages in terms of detection, namely the ability to cancel the background effect of the soil and the ability to identify the type of metal. TIRAMISU partner Vallon will investigate this metal discrimination ability with a metal detector array. This partner will develop lightweight modular system, containing from 2 to 16 coils, adaptable to the width of mobile robots and other mobile platforms.

III. Ground penetrating radars

GPR is a geophysical technology widely used for subsurface imaging. This method is based on the following principle: 1. A transmitting antenna emits short pulses of high-frequency electromagnetic waves. 2. The electromagnetic pulse is reflected from a buried object or a boundary with different dielectric constants. The reflected signals arrive back to the receiving antenna at different times, which depend on the depth of reflection. 3. The receiving antenna records samples of the time varying reflected signal providing a scan, called A-scan. 4. The A-scan provides information about variation of dielectric properties at different times of reflection. The time of reflection roughly represents the depth of reflection. However, there is no exact transformation due to the unknown properties of the materials where the signal is propagating. The frequency of the transmitted radio pulse determines its penetration depth. For the purpose of humanitarian demining GPR antennas with frequencies around 1-2 GHz are normally used. This allows detecting antipersonnel landmines up to the depth of around 30 cm. GPR data use to contain clear signatures of landmines or other man-made objects buried in clean soil. However, GPR is also sensitive to a large amount of clutter objects and any dielectric heterogeneity of the soil.

A. *Ground Penetrating Radar array*

A densely sampled GPR imaging approach to detection of small AP mines has been recently demonstrated by Prof. M. Sato (Tohoku University, Japan) in the development of the ALIS hand held combined GPR and MD sensor by CEIA [Sato 2008]. However, the ALIS GPR can only explore/image a very small area around the mine (e.g. 40x40 cm) and uses a simple threshold detection mechanism to declare the alarm.

TIRAMISU's partner IDS aims to extend the advantages of GPR imaging arrays, now proven in state of the art military systems, to a wider variety of targets (i.e., AP mines and small UXOs) and terrains while improving the automatic detection capabilities so that no operator interpretation skills will be required.

B. *Dual sensor systems*

A limited number of teams currently use dual sensors combining a metal detector and a ground-penetrating radar [Doheny 2005, Daniels 2005, Ishikawa 2009]. The detection range of ground-penetrating radars is reduced by certain types of conductive soils such as clay. Soil moisture has two effects on detection. On one hand it decreases the detection range into the ground by attenuating the microwave propagation, but on the other hand it increases the contrast between the mine and the surrounding soil, making the mine easier to detect. It is not clear which of this effect is preponderant in a given situation. Soil inhomogeneities, such as roots, rocks, and very uneven ground surfaces can create additional alarm indications. Since ground-penetrating radars are often used to discard an object based on its small size, detecting small mines can be a challenge. [GICHD 2006].

IV. Imaging radars for landmine detection

Ultra-wideband (UWB), ground penetrating radar (GPR) radiates a short pulse, pseudo-random coded sequence or frequency modulated burst of electromagnetic energy into the ground and detects the backscattered energy from the buried target. The radiated pulse is typically a wavelet of several nanoseconds duration and in the frequency domain, covers a wide range of frequencies in the region of a few hundred MHz to several GHz. Typically the spectral characteristics of the pulse consist of a series of individual frequencies whose spacing is related to the pulse repetition interval and whose envelope is related to the temporal characteristics of the wavelet. The power radiated per spectral line is in the order of a few nanowatts. For close-in systems the radar antenna beam is moved in a known pattern over the surface of the ground and an image of the ground can be generated, in real time, on a display either in gray scale or in colour. The image can be a cross-section or a plan view. The radar image is not identical to an optical image because the wavelengths of the illuminating radiation are similar in dimension to the target. This results in a much lower definition in the radar image and one that is highly dependent on the propagation characteristics of the ground. In addition the beam pattern of the antenna is widely spread and this degrades the spatial resolution of the image, unless corrected. For longer-range systems where the objective is to detect surface laid or very shallowly buried mines, synthetic aperture techniques are used. Radar systems may be hand held, vehicle mounted or airborne [Daniels 2002].

Since for close-in scanning GPR the radar antenna is typically moved mechanically in close distance to the ground following a horizontal scan pattern, the lateral spatial resolution is limited to the average antenna footprint at a certain depth, but the depth resolution can be high due to the UWB signal character. A three-dimensional image can be formed by stringing together the lateral (horizontal) samples to form a two-dimensional image, and the third dimension is given by the vertical range profile for each lateral sample. For larger stand-off distances to the ground (several meters or even much more) the technique of synthetic aperture radar (SAR) can be combined with the use of UWB signals. The SAR principle requires a side-looking geometry for a moving radar, since the across-track image dimension and resolution are determined by the across-track antenna beam width and pulse length, and the signal bandwidth. The along-track image dimension and resolution are given by the length of motion and the along-track beam width of the antenna, and produced by coherent processing of the sampled signals. Hence in both horizontal dimensions a very high resolution can be achieved. The depth information as the vertical dimension is connected to the across-track or range information and cannot be unambiguously retrieved when only one antenna or antenna pair for transmit and receive is used.

Both imaging methods (close-in and stand-off) have been already extensively analyzed in the past for landmine or UXO detection and big progress has been achieved. However, the buried object detection still is a challenging problem due its enormous complexity, being expressed in the specific soil and target conditions, the background clutter, the resolution and sensitivity constraints, and the ambiguity impacts due to limited sampling and multipath effects. Furthermore the clear discrimination between a true threat and a false alarm is difficult, making the threat detection process very inefficient. Those problems can only be overcome by increasing as well the complexity of the radar sensors by using polarimetric information, multiple antenna systems and multi-static imaging geometries, and well-adapted waveform designs and signal processing methods. Work in that direction was and is done, but there is still a large requirement for further research and development.

A. TIRAMI-SAR

TIRAMISU's partner DLR HR-AS aims to develop high-resolution, high-sensitivity, ground penetrating imaging microwave radars (TIRAMI-SAR) following advanced Synthetic Aperture Radar (SAR) principles. The development shall consider suitable processing algorithms to be used for close-in stand-off ground penetrating radar to be installed on a moving vehicle.

V. Vapor detection

When EDs are deployed in the field, continuous release of trace vapours occur. These vapours, usually nitroaromatics like TNT or DNT, are signatures that can be used to identify dangerous fields or to localize approximately the corresponding ED. Some of the important and critical factors for this application are very low-detection limits (ppt), short-detector response time for operations, involving moving platforms, good baseline stability, and minimum interferences from environmental species and conditions.

A. Animal smell

Dogs can be used in different ways to detect explosives. The dog handler can stay at the border of the minefield and the dog walks in a lane through the minefield. This method is called the long-leash method. In another method the dog handler walks along the border on the minefield with the dog at his or her side but inside the minefield. This is called the short-leash method. In a third method the dog handler shows the locations to explore with a wooden stick and the dog studies that area. Training and operational procedures seem to be important to have an efficient detection. Dogs are said to be better for area reduction and delineation of minefield boundaries, mine and ERW verification, clearance of roads, quality assurance. There is a large influence of environmental parameters and target history on the explosive vapour and particle concentration. Weather and soil conditions can lead to samples not being reproducible. Direct vapour detection seems to be more difficult in arid areas. Cross-contamination and handling issues are of great importance. There are also possible problems due to interfering chemicals, and explosive residues due to devices that have detonated.

B. Chemical sensors

For chemical vapour detection, several techniques have previously been employed including electrochemical sensors, metal oxide sensors, laser Raman detection and fluorescence based sensors. When special class of plastic electronic materials is illuminated by UV or blue light, it absorbs the light and emits fluorescence [Thomas 2007]. If the film then comes into contact with very dilute vapors of TNT or a similar nitro-aromatic compound, some molecules of the vapor will adhere to the surface of the film and may penetrate deeper into the polymer. These TNT molecules act to quench the light emission through an electron-transfer process. The process is reversible and light emission returns when the sensor is isolated from the vapours. Such fluorescence sensing has been studied in laboratory conditions by several groups [Thomas 2007, Toal 2006] in the field as the Fido product by ICx Technologies. It was recently discovered that greater sensitivity is possible by using laser light from the polymer rather than fluorescence to detect explosives [Rose 2005].

C. Polymer laser sensors

The organic Semiconductor Centre of the University of St Andrews (USTAN) is internationally recognised for their development of organic semiconductor lasers [Turnbull 2007] demonstrated laboratory prototype sensors for nitroaromatic explosive vapors, using plastic lasers based on the blue light-emitting materials polyfluorene [Yang 2010] and bisfluorene dendrimers [Richardson 2009] and will now work with the University of Coimbra to improve the prototype in on-the-(mine)field conditions. The majority of the research on light-emitting polymer chemical sensors to date has been laboratory based and materials oriented, while there are only a few examples of polymer laser based sensors. The work in the TIRAMISU project will make a step-change in progress beyond the state-of-the-art. It will advance the use of polymer laser sensors to on-the-mine-field detection conditions and will establish the feasibility for new modes of application of laser and fluorescence sensors in mine absence sensing for technical surveys.

VI. Mechanical prodders

According to [GICHD 2005] the most dangerous action for a deminer is prodding from the surface of the ground.

Usually very simple tools are used to probe the ground until a solid object is contacted. Then the material surrounding the buried object is carefully removed and the identification can be made. The process is repeated for each buried object until the area is cleared. Many attempts have been done to improve a classical prodder into a more complex sensors capable to safely detect and recognize the material in contact. Examples are the SmartProbe by DEW Engineering and Development Ltd., developed at Defence R&D Canada, using acoustic pulses to recognize the material. However After extensive field testing, it was concluded that the SmartProbe did not function as advertised and DEW discontinued the product [Melville 1999]. In 2001 HF Research Inc. improved the SmartProbe combining the acoustic pulse with a force feedback system [HF Research, 2002]. TNO-FEL conducted in 2003 extensive tests of the Instrumented Prodder, concluding that even if material identification of buried objects is feasible with the implemented technology, however it is not reliable [Schoolderman 2003]. Other works involved the development of rotary prodders to improve penetration into the soil, or prodder equipped via a microphone to give feedback of the contact sound to the operator [Gasser 1998]. In [Schade 2004] and in [Bohling 2006] preliminary results on the adoption of Laser-induced breakdown spectroscopy (LIBS) in combination with a conventional mine prodder for remote detection of explosives and mine housing materials are described. Fiber optics are used for guiding the laser pulses to the end of a modified conventional mine prodder and the LIBS signal back to the detector. In [Furihata 2005] two mechanical master-slave hands, named Mine Hand 1 and 2, to remotely prod to detect and to remove landmines and UXOs are proposed and experimentally tested. The University of Catania conducted intensive research activity in the development of tactile Measuring Systems for the Recognition of Unknown Surfaces [Baglio 2002, 2003]. In this work a novel smart tactile sensor that recognizes the nature of the surfaces was developed. The approach is based on the idea of analyzing the signal produced when the sensor touches and stimulates the surface. An "intelligent probing" system for material recognition has been developed. It is based on the use of bimorph piezo-ceramic actuators and sensors that allow the unknown surface to be stimulated and the response signal sensed. Two different experimental prototypes of the tactile sensing system have been realized and their performance has been characterized. Several interesting applications have been considered with particular emphasis on the problems of "humanitarian demining" and automatic waste material recycling. Experimental results are given to show the efficiency of the smart measuring system.

A. Smart prodder

The University of Catania will develop innovative prodders by the incorporation of new concepts and algorithms based both in ultrasound technology and in active prodding combined with force feedback, both containing touch sensors. This prodders will be able to be employed either by a human deminer or adapted to automatic demining systems and they will provide enhanced perception abilities about the kind of material that is being touched inside the ground as well as required penetration forces by keeping them within required safety margins. The advanced feedback provided by the smart prodder will be explored by CSIC to develop a haptic prodding interface.

VII. CONCLUSIONS

This paper discussed the established technologies for close-in detection of hidden explosive devices, namely metal detection, ground penetrating radar, vapour detection, and mechanical probing, and described the foreseen advances of these technologies in the framework of TIRAMISU project.

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