Influence of Internal Structure on Landmine Radar Signatures

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***Abstract*—Cheap and easy to use, landmines are among the favourite weapons in civil wars and wars of insurgency and are used by governments and guerrillas alike. These "eternal sentinels" stand guard long after the conflicts have ended and kill and maim without mercy or discrimination. Therefore, there is a pressing need to remove these devices and to clear the contaminated land. As many landmines have low metal content they are difficult to detect using traditional techniques such as metal detectors, hence Ground Penetrating Radar (GPR) is an attractive tool in landmine clearance. Many investigations of landmine detection using GPR make use of surrogate landmine targets, since real landmines are difficult to obtain. This paper investigates the importance of the fidelity of such surrogates in terms of their external design, internal structure and explosive content.**

Keywords*— Radar; Landmines; Target signature; Target characterisation;

I. INTRODUCTION

Landmine contamination represents one of the more dangerous and unpleasant problems of our times. These devices have been spread over vast regions in an uncontrolled manner throughout several decades, including recent conflicts. A huge factor contributing to landmine production and planting is the terrorist warfare against civilians and between terrorist groups. Of course, although governments may sign on to the International Campaign to Ban Landmines, terrorist groups do not conform as such [1]. Regardless of the questionable immediate gain, their long term life ensures that they will be an impediment to survival and development to local communities and wildlife. United Nations organisations estimate that there are more than 600 different types of antipersonnel landmines, which are contaminating and blocking access to more than 700,000 acres of land for a total estimate of 110 million of devices still lodged in the ground. These correspond to 1 landmine laid for every 16 children in the world [2].

Modern landmines are fabricated with sophisticated non-metallic materials, posing new challenges to the traditional mine clearance techniques that use magnetic induction metal detectors and hand-held mine probes [3]. This necessitates the development of advanced detection technologies, which attempt to exploit disturbances in the background [4] [5].

Among all available techniques, Ground Penetrating Radar (GPR) is expected to provide a unique detection capability and to achieve operationally useful performance [6] [7]. Widely accepted as a near surface geophysical sensing tool, GPR uses high frequency electromagnetic waves to image the shallower layer of the earth [8], it is sensitive to changes in permittivity, conductivity and permeability of a medium and thus it is capable of detecting both metallic and non-metallic objects [9][10]. The principal limitation of GPR is its prohibitively high false-alarm rates, due to its capability of imaging any anomaly in the subsurface [11]. Therefore, the knowledge of the radar signature is almost essential for increasing the efficiency of GPR in discriminating between targets of interest and clutter objects, whether manmade or natural [12], and achieves significant detection performance [13].

A mine may have a number of scattering centres, each with their own angular radiation pattern and, in the case of plastic landmines, the internal structure of the mine may generate additional scatterers [14]. Most plastic landmines may be considered as multiple layered dielectric cylinders, of which each interface causes a reflection, the impact of the small internal metallic fuse being minimal. Since real inert landmines are objects that are difficult to obtain, most of the research has been conducted using mine simulants, objects which attempt to replicate landmines within a certain degree of accuracy [15] [16]. Since the radar response of a target is dependent both on physical and dielectric properties, the target echo could be significantly affected by any approximations [17] [18].

The aim of this paper is to qualitatively and quantitatively investigate the effects that the internal structure of a landmine, in terms of filling materials and inner assemblies, has on the radar response. The experimentation takes advantage of the availability of a real device (including explosive content and detonator assemblies) to compare its signature to the one obtained using a high fidelity 3D printed version filled with a comparable mixture of substances, and a simple rubber surrogate. Responses at different aspect angles are also explored to give a further characterisation and comparison.

II. TARGETS DESCRIPTION

First of all, it is necessary to understand the characteristics of mines, in terms of their shapes, case material and explosives. The features that impact the radar signature of a landmine can be divided into two categories, (1) the outer casing, which includes the main body, the fuze pressure plate and the handling devices, and (2) the internal structure, consisting of the main charge, the firing mechanism and the detonator.

A. Landmine Cutaway

Fig. 1 shows a disassembled Italian VS-50 with all the major features highlighted. In particular: the safety pin housing (A), which places the mine in a live state, the trigger assembly, which includes the release sear (B), the firing pin (C) and the rubber bellows (D). From an external view, the rubber pressure plate (E), the plastic case chamber (F) and the handling device (G).

Except for a stiff compression spring, that supports the pressure plate and determines the load required to trigger the mine, and the firing pin, responsible for initiating the detonation process, there is almost a null metal content.

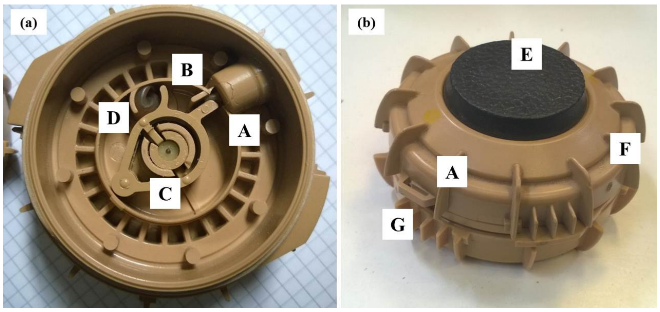

Fig. 1. Italian VS-50 landmine design. (a) Internal assemblies, (b) outer case.

Considering the characteristics of the main charge, it is commonly an explosive made up by a mixture of RDX, TNT and Composition-B, with a small percentage of paraffin. Table I lists the dielectric constant of the commonly employed materials in landmine design [19].

TABLE I. PROPERTIES OF LANDMINES MATERIAL

Material	Relative dielectric constant
Comp-B	2.7
RDX	3.1
TNT	2.9
Paraffin	1.9 – 2.5
Plastic	2 – 4
Resin	6
Bakelite	3.5 – 5

B. Surrogates and Replica

Most of the research on landmine detection has been based on the use of professional replicas or surrogates (Fig. 2), categories which both have their own strengths and weaknesses.

Essentially, replicas are accurately moulded from real mines for detection purposes, but the efficacy is limited by the fabrication material (commonly epoxy resin or solid aluminium with a permittivity quite far from the real values). The latter class, instead, are designed with a general simple shape but employing materials that claim to have realistic responses. Unfortunately, most of these devices are optimised for metal detectors rather than for GPR.

It is easy to infer that the heterogeneity of a landmine, both in terms of materials and design, could turn these two categories of simulant targets into useless, decreasing the efficacy and consistency of the research.

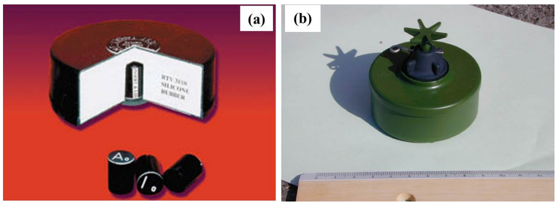

Fig. 2. Examples of (a) target surrogate and (b) professional replica.

III. METHODOLOGY

A set of free space measurements has been carried out to acquire the signature and compare the scattering features of a real inert landmine with two possible simulants. In particular, a 3D printed replica of the Italian VS-50 mine and a rubber hockey puck.

Concerning the internal content, the real device was filled with a training simulants for high explosives, with the same electrical properties of real substance, while the same amount of a homogeneous mixture of paraffin and dried peanuts was used to fill the printed replica. This mixture was chosen to effectively replicate the characteristics of the employed explosive. The surrogate was a homogeneous disk made of vulcanised rubber. Targets are depicted in Fig. 3 and described in Table II

TABLE II. TARGETS DESCRIPTION

Target	Dimensions [cm]	Outer case material	Inner filling material
Real VS-50	8 x 4.5	Plastic	Inert explosive
3-D Printed Replica	8 x 4.5	PLA	Mixture
Hockey Puck	7.6 x 2.5	Vulcanised rubber	Vulcanised rubber

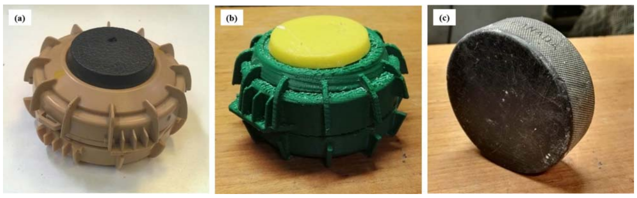

Fig. 3. Target description. (a) Real inert VS-50, (b) 3D printed replica, and (c) hockey puck.

The experimental set up is presented in Fig. 4(a). The acquisition equipment consisted of two horn antennas, in quasi-monostatic geometry, connected to a vector network analyser and transmitting at horizontal polarisation. The parameters and geometries of the acquisition are listed in Table III.

Targets were placed at a distance of approximately 150 cm from the antennas and their signature was measured at three different aspect angles to further quantify the impact of target inclination on the signature features. In particular, with reference to the activator plate, targets were oriented towards the antennas (Fig. 4(b), 0 degrees), pointing at 45 degrees (Fig. 4(c), 45 degrees) and side laying towards the antennas (Fig. 4(d), 90 degrees).

TABLE III. EXPERIMENTAL CAMPAIGN

Acquisition Parameters and set up	
Frequency range [GHz]	5 – 8.5
Frequency step [MHz]	0.4375
Resolution [cm] (in air)	4
Antenna dimension [cm]	9 x 12
Antenna offset [cm]	9
Antenna polarisation	Horizontal

Targets were mounted on a radar-transparent styrofoam cone with a plate to allow target rotation (visible in Fig. 4(a)).

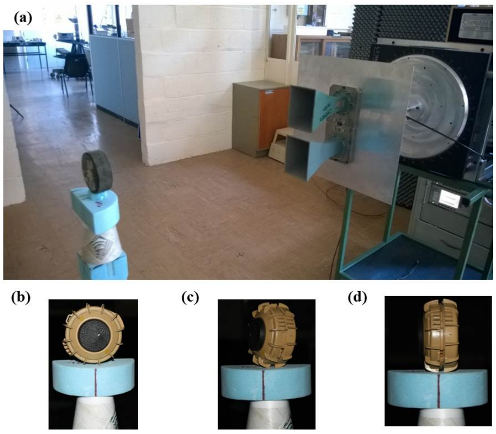

Fig. 4. Measurements set up (a) and target positioning. (b) 0 degrees, (c) 45 degrees, and (d) 90 degrees aspect angle,

A measurement of the background was taken in order to remove all stationary clutter from the target signature. Each signature has been normalised to its own maximum to help the comparison process and displayed in the time domain.

IV. RESULTS

The acquired signatures exhibit a high degree of complexity, effectively supporting the hypothesis of the significant impact that internal assemblies and outer design has on the radar target signature.

The response of the real inert VS-50 as a function of the aspect angle is presented in Fig. 5.

The high complexity of the real device signature strengthens the concerns on the meaningfulness of target simulants. Target heterogeneity is clearly visible, especially when the target is aligned with the antenna plane (Fig. 5(a)), showing several reflection layers. While the first peak could be identified with the activator plate, the second interface could belong to the air gaps which allow the activation of the detonation, or to the detonator itself. The last peak is due to the bottom of the landmine. These considerations do not hold true when the target is inclined: Fig. 5(b) shows only the top and bottom of the landmine, with a relevant homogeneous propagation between them, while when the target is vertically oriented (Fig. 5(c)), there are several internal reflections due to the internal bouncing of the radar wave. These multiple reflections are likely due to the high contrast with free space.

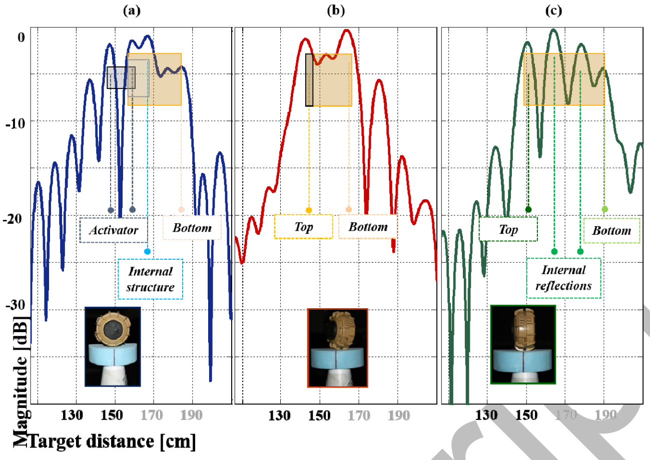

Fig. 5. Real landmine signature. (a) 0 degrees, (b) 45 degrees, and (c) 90 degrees oriented.

A comparison between the signature of the real device and the printed replica filled with the mixture is presented in Fig. 6.

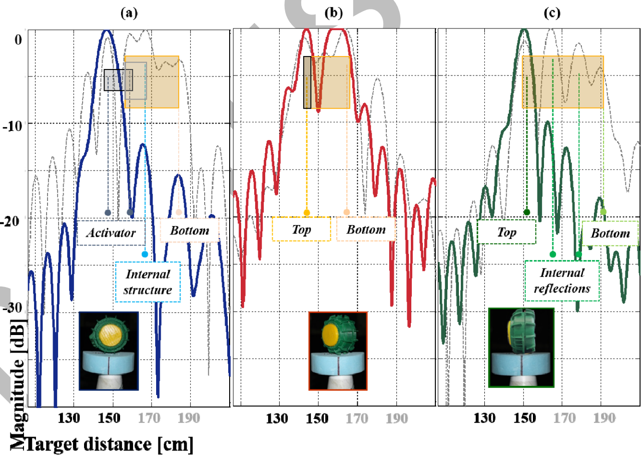

Fig. 6. Printed replica signature. (a) 0 degrees, (b) 45 degrees, and (c) 90 degrees oriented. The gray dashed line represents the real device counterparts.

Nevertheless a highly precise reproduction of the real target, some differences between the two signatures are evident at all angles. Even if the geometrical similarity locates the reflections almost in the same position of the real device, Fig. 6(a) and Fig. 6(c) demonstrate that the difference in the material completely changes the magnitude and trend of the peaks. The good agreement that occurs when the target is inclined (Fig. 6(b)) is due to the fact that this is the “simplest” configuration, in terms of layers and internal structures.

Considering the hockey puck signature, Fig. 7 shows its comparison with the real landmine.

When the target is in the same plane as the antennas (Fig. 7(a)), the two signatures are significantly different, in agreement with the absence of any internal structures or layers in the surrogate. Due to the different physical dimension of the two targets, a comparison of the result with the target looking aside (Fig. 7(b)) is not significant. A very high coherence is found analysing the signature of Fig. 7(c), probably due to the consistency in the dimension and dielectric properties of the two materials. This is consistent with the previous considerations, as this configuration yields less information on the inner composition of the landmine and the impact of the activation plate is almost negligible.

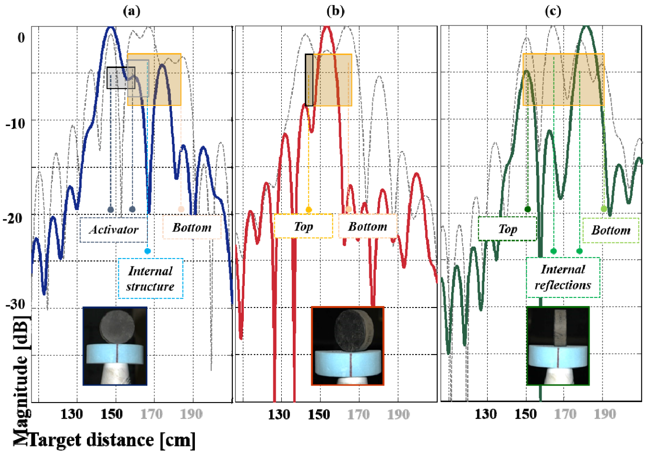

Fig. 7. Surrogate disk signature. (a) 0 degrees, (b) 45 degrees, and (c) 90 degrees oriented. The gray dashed line represents the real device counterparts.

V. CONCLUSIONS AND DISCUSSION

The research has provided a clear demonstration of the effects that the complexity, including the internal structure and the outer design, as well as employed materials, of a landmine has on its radar signature. This is critical for target characterisation and feature extraction purpose.

Three kinds of objects have been investigated: (1) a real inert device complete with all its parts and filled with inert explosive substance, (2) an accurate 3-D printed replica filled with a suitable material, and (3) a homogeneous rubber disk. Effects of aspect angle on reflections distribution have been evaluated as well to deeper characterise the radar signature, and it has been proved to be a further element to exploit.

The ensemble of the measurements have shown that, depending on the aspect angle of the target relative to the antennas, each of the two highlighted structures give a significant contribution to the overall response. Despite a physical or dielectrical similarity, both the analysed objects provided only a partial consistency with the real target. Hence, if one considers the well-known prohibitive false alarm rate of typical GPR systems, the need for real devices or a very accurate modelling of target structure and materials. The ability of discriminating between signatures lies in a very short edge, thus all the features that can characterise a landmine becomes of substantial importance.

Future work will include the evaluation of the radar signatures of real inert devices and simulants when targets are buried in soil to determine whether the highlighted behaviours are confirmed and, if not, to characterise the variations due to the wave propagation in soil. Significant changes are expected due to the reduced contrast between the target and the surrounding medium and to the increased data resolution. In addition, signature characterisation would further benefit from dielectric characterisation of the materials and substances.

ACKNOWLEDGMENT

The authors thank the Find A Better Way charity for their support of this research under the DETERMINE programme (grant number 2015/001D). We also thank the Defence Academy Ammunition Hall for providing the real landmines used for the experiments and Dr. Francesco Fioranelli for his help in the data collection.

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