Radar Systems for Landmine Detection

Invited Paper

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***Abstract*—This paper contains a review of various radar systems that are designed for the detection of landmines. The main principles of their operation, their methods of application, and their achievements are considered. We review both functioning systems and prospective future systems.**

Keywords—landmine, ground penetrating radar, holographic radar, demining, detection, humanitarian demining

I. Introduction

Twenty years ago, about half of the world's countries were contaminated by antipersonnel mines, and tens of thousands of people were killed and injured each year. The Anti-Personnel Mine Ban Convention (APMBC), which was adopted in 1997, put an end to the humanitarian tragedy caused by mines but did so only temporarily.

As shown in the report of the Geneva International Centre for Humanitarian Demining (GICHD), the level of contamination with explosive ordnance has increased significantly, owing to new armed conflicts in recent years. In the last five years, the number of victims has sharply increased, reaching the levels of 20 years ago [1].

With the financial support of the governments of 10 countries, humanitarian demining has been underway in the liberated territories of the Donetsk and Lugansk regions in Donbas, Ukraine. In 2019, 36 plots were cleared with an area totaling more than 250.7 hectares [2]. However, minefields in Donbas occupy about 700,000 hectares, illustrating the magnitude of the demining task in Donbas.

Particular challenges are plastic antipersonnel mines (APMs) and improvised explosive devices (IEDs). Plastic APMs cannot be detected by metal detectors (MDs). IEDs are difficult to defend against because they can be made in different ways, using materials that are intended to shield them from detection. NATO has considerable experience in this area, and Ukrainian sappers have adopted NATO approaches [3].

However, there still remains an urgent need to develop advanced productive systems for the detection of mines and IEDs.

II. Methods of Landmine Detection

The physical characteristic features of mines and explosive devices (EDs) are the primary means for reliably identifying them as dangerous items (versus harmless clutter) [4]. The main features of landmines or explosives, which almost always are identified, are:

- the presence of explosives;
- the presence of a localized mass of metal (even in so-called "non-metallic" mines);
- the characteristic shape and dimensions of mines;
- heterogeneity of the surrounding environment (anomalies in the soil surface or road surface, changes in the color or quality of vegetation or snow cover, etc.).

Additional identifying factors that may not always be present include:

- the presence of a wired control line;
- the presence of a clockwork or electronic timer;
- the presence of a seismic, magnetic, or optical sensor for targets detection;
- the presence of an antenna with a radio receiver.

Thus, a mine can be detected mainly through the presence of three factors

- the detection of a concentrated mass of explosives;
- the characteristic design of the mine (shape, body material, etc.);
- violation of the uniformity of the surrounding background (electrical or thermal conductivity, permittivity, permeability, and density, among others).

Table 1 summarizes the salient features of different mine types, including APMs and antitank mines (ATMs). Ideally, it is desirable to detect a mine from a safe distance (at least 70 to 100 meters from the sapper).

The various possible detection methods are shown in Fig. 1 [5]. Analysis of the methods for detecting objects of artificial origin shows that each method has certain limitations. Of course, it is useful to take into account both a-priori information about the object being probed (dimensions, materials, etc.) and the properties of the covering medium.

Moreover, a significant problem when probing electromagnetically for a mine is the recognition of the signal from the mine against the background of numerous

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interference signals from environmental heterogeneities and various soi inclusions (clutters).

TABLE I. CHARACTERISTIC SIGNS OF MINES AND EXPLOSIVE DEVICES (ED)

The contrast between the object and the surrounding medium due to	Search Object Type			
	APM	ATM	Mines and ED with electronic components	ED mines with a wired control line
Conductivity	+	+	+	+
Permeability	±	±	+	+
Permittivity	+	+	+	+
Thermal characteristics	±	±	±	±
Optical characteristics	±	±	±	±
Mechanical characteristics	+	+	+	+
The presence of explosive vapor	±	±	±	±
Nonlinear electromagnetic properties	±	±	+	±

- detectable with a radar system
+ –contrast is available
± –contrast is not always available

Requirements for detection reliability during humanitarian mine clearance grew from 90% in the early 1990s to almost 100% today (i.e., the UN standard specifies at least 99.6% detection rate. Usually, the depth of detection is also specified - typically at about 20 cm to 30 cm). These conditions require that mine detection systems have very high sensitivity. On the other hand, very sensitive devices will also detect many clutter objects in the ground. A large number of such "false alarms" (up to up to hundreds per several square meters) requires remarkable technological efforts for identifying the types of buried objects [6].

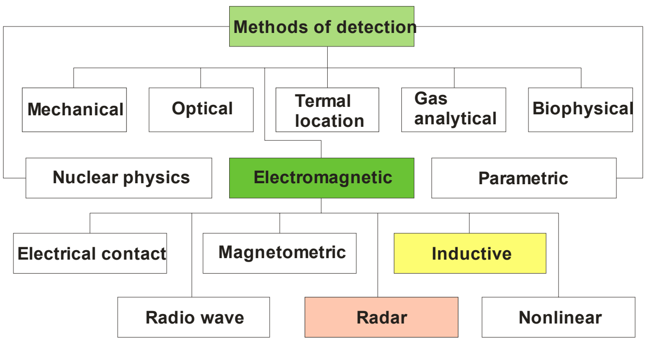

Fig. 1. Basic methods for finding hidden mines

Given these requirements, subsurface radar is the most promising mine detection tool. A recent paper [7] reports on the application of an advanced approach to mine detection that provides a detection rate of almost 90% with a false alarm rate of 0% on a controlled test site. Using a ballistic blanket allowed the authors to place a ground penetrating radar (GPR) antenna system directly on the ground to protect the antenna system from a possible blast. Close proximity to the soil provided greatly improved coupling for a dual-polarized high-frequency signal needed to reconstruct a 3D radar image, in which targets are recognized (but with no discrimination of landmines from clutter) using a specially developed algorithm based on convolutional neural networks.

However, despite ongoing research, none of the devices developed at the moment are able to detect the required percentage of explosive objects, and discrimination of harmless clutter from actual ED threats remains difficult.

Given the impossibility of providing reliable detection of 99.6% of mines with a low false alarm rate using only one type of detector, efforts have been made to combine two or more methods of detection on one platform. The use of several detection sensors makes it possible to detect not only mines installed in the ground but also those disguised on the surface. In addition, multiple sensors increase the detection efficiency of various types of mines (with both metallic and non-metallic casings).

III. CURRENTLY USED RADARS OR NEWLY DESIGNED SYSTEMS

A. Handheld and Vehicle-Mounted Dual Sensor Systems.

Advanced handheld equipment MD with ultrawideband (UWB) radar is currently available to detect subsurface objects as magnetic and/or electromagnetic anomalies [8].

A combined sensor using electromagnetic induction (EMI) and GPR is called a "Dual Sensor" instrument in humanitarian demining.

The integration of radar systems with MD started in 2008, and the benefit for detection has been demonstrated [9]. These systems have been designed both as a vehicle-mounted and handheld.

A vehicle-mounted system consisting of three transmitting-receiving antennas is shown in Fig. 2 [9]. This system acquires three data sets for one measurement position, which accelerates the survey progress. It should be noted that the antenna configuration enables common mid-point processing, increasing SNR and accuracy of depth calculation. It leads to the reduction of clutter generated by soil inhomogeneities. The system showed a high probability of detection and a low false alarm rate in outdoor testing despite the rough terrain and inhomogeneous soil.

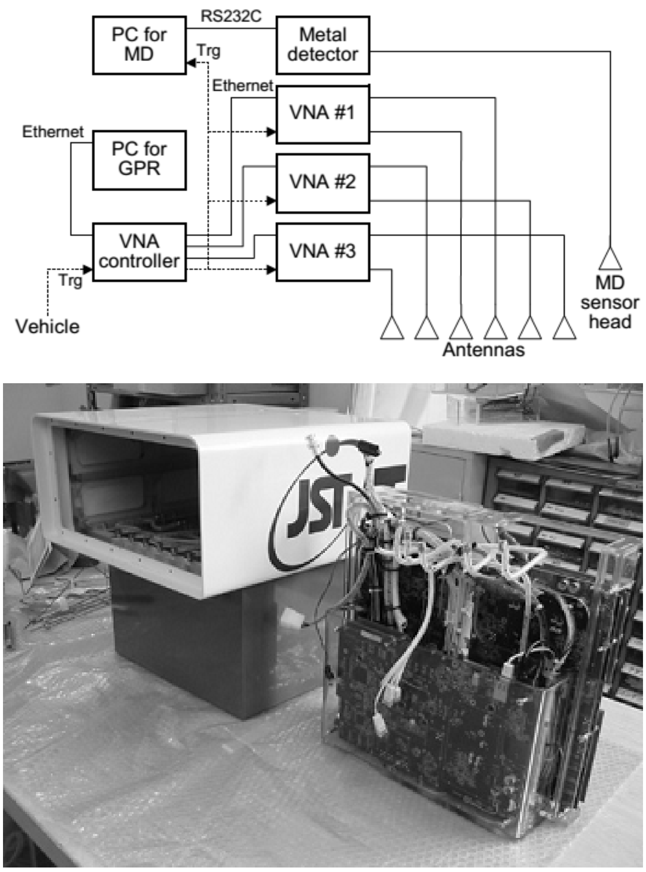

Fig. 2. System diagram and GPR design [9].

The development of a dual-sensor ALIS (Advanced Landmine Imaging System), shown in Fig. 3, started in 2002 in Japan, and the prototype of ALIS was completed in 2004 [10]. Since 2002, ALIS has been deployed in a number of mine-affected countries. The advantage of ALIS is that it produces "2D images" of the detected subsurface object. This allows the identification of the object using two criteria: the metallinon-metallicallic character of the object and the shape of the object.

Fig. 3. Dual-sensor ALIS.

In 2017 the combined selective two-channel mine detector PPO-2I was designed by the LLC "LOGIS" (Russia) to detect engineering ammunition in metallic and non-metallic cases, as well as metallic and non-metallic objects of various sizes located in non-conductive environments (soil, snow, freshwater, etc.) [11].

The device can operate as MD, as a GPR, or in a combined mode (with both MD and GPR).

B. Remotely Controlled Robotic Sensor.

The issue of safety must be given special attention in the development of systems for mine detection. Remote control is a method by which the safety of the sapper is maintained.

The next stage of development in the integration of sensors of different types on a remotely controlled robotic platform has been presented as part of the NATO SPS Multi-Year Project G5014 "Holographic and Impulse Subsurface Radar for Landmine and IED Detection" completed by authors of this paper in 2018 [12, 13]. The robotic platform, called UGO-1st ("*you go first"*) (Fig. 4), contains three sensors: a UWB impulse GPR, a holographic radar, and a Photonic Mixed Device (PMD) 3D camera. The design approach is based on the new paradigm of Industry 4.0 in which cyber-physical systems interact and share data, are reproducible everywhere, and are adaptable/expandable with different sensors and actuators. Robot remote control and data sharing are achieved by a sophisticated web-based software architecture that has excellent potential to migrate the procedures of explosive device detection toward completely remote and autonomous cooperative systems [14]. The impulse GPR with a specially designed "1Tx+4Rx" antenna system allows measurement of the 3D Cartesian coordinates of the detected object in the reference system, which is connected to the antennas in real-time. The holographic radar scans the area and subsequently produces plan-view images of the subsurface object detected by the impulse GPR. The olographic radar data can be elaborate to renconstruct the electromagnetic field distribution in the subsurface volume. The 3-D camera/scanner (PMD Pico Flexx) is an optoelectronic device that is necessary to monitor soil surface under antenna systems and the 3D data of the scene, by the holographic radar software, can be used for improve the discrimination of clutters from targets.

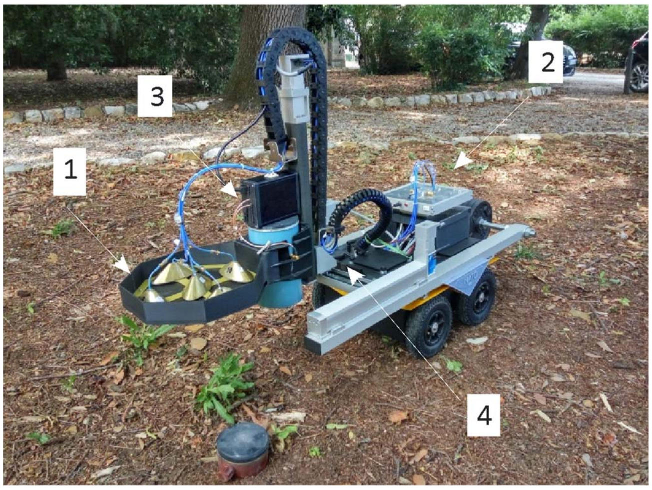

Fig. 4. Robotic platform UGO-1st with 1 – Impulse GPR antenna system, 2 – Impulse GPR hardware unit, 3 – Holographic radar, 4 – 3-D camera/scanner (PMD Pico Flexx)

C. Drones.

Starting from about 2010 there has been increasing interest in using drones for mine searches. This approach minimizes the risk for people and equipment engaged in demining operations.

A drone being used to search for unexploded ordnance [15] is shown in Fig. 5.

Fig. 5. A drone being used to search for unexploded ordnance.

Ukrainian engineers, in collaboration with a foreign company, have developed an unmanned aerial vehicle (UAV) capable of locating explosive objects. Magnetometer sensors for UAVs detect ferrous metal parts of EDs. The sensors are suspended from the aircraft and scan the terrain, while it flies at an altitude of 5-10 meters. According to test results, the drone accurately identified mines of diameter 82 and 120 millimeters with an accuracy of a centimeter.

IV. Prospective Systems

A workshop reporting on results of projects supported by the NATO SPS Program that were devoted to the detection of explosives and mines was held in Florence on 18.10.2018. (see the book [16]). Although the reported results are tests of concepts, the workshop showed the feasibility of a variety of possible approaches and possible sensors that could be used for effective mine detection.

In the framework of one of the NATO SPS Multiyear projects, one team developed GPR attached to a hexacopter intended for automatic mine detection [16]. It uses both time domain, and frequency domain approaches. The first one requires a pulse with a short duration, typically a few 100 ps, and the other approach, which is easier to implement, is to observe variations in the amplitude and phase between the transmitted and received signals.

Advanced Detection Equipment for Demining and UXO Clearance [16] contains both dual-sensor and deep-search detectors. They can detect mines and explosives at a depth of between 0.5 and 1 m. (Fig.6)

One of the most difficult challenges is the detection of Improvised Explosive Devices (IEDs). It is conditioned on the unpredictable shapes, size, material of the device. Nowadays, we can see the beginning of developments of approaches to detect IEDs. Authors of the paper [24] have investigated of fundamentals and engineering challenges from an IED detection operational perspective. A vehicle-mounted 3D-RADAR GPR array was used to collect data from a pre-defined set of targets buried in four different test sites. This investigation showed that IEDs could be detected, but it is necessary to take into account the peculiarities of soil structure and conditions.

Fig. 6. Deep-search detectors.

Based on the experience of Project G5014, we can conclude that three sensors are already quite a big number to include on a single platform. These sensors can sometimes interfere with each other and prevent all of their potentials from being completely realized. The authors of this paper have, therefore, proposed using a swarm of specialized cooperative robots carrying each different sensors (Fig.7) in a recently approved proposal (NATO SPS Project G5731).

The main innovative aspect of the realized technological demonstrator is the capability to operate the system remotely for landmine and improvised explosive device (IED) detection and to provide data and 3D images from multiple sensors correlated in time and space. The system architecture can be enhanced to integrate other sensors - e.g., regular MD, and chemical, radiological, or environmental sensors - mounted on specialized robots that form the UGO swarm.

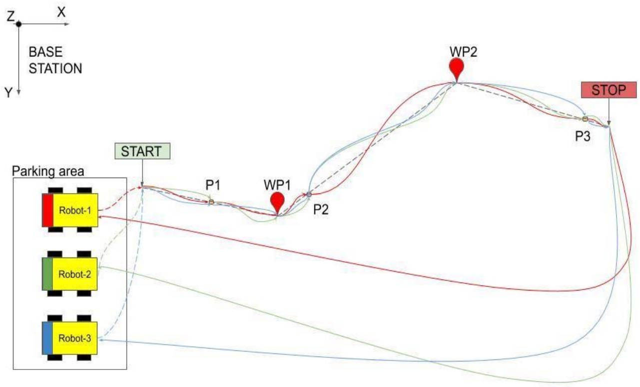

Fig. 7. Swarm of cooperative robots with different sensors.

V. Other researches in the world.

A search of related projects has produced the following links:

- Defense robots will automate military forces. The Pentagon has been working for several years on the Brigade Combat Team project, which aims to robotize most of their forces. [15]
- Russia orders a dozen new demining robots[16]
- Cambodian Virtual Reality Helps Train Bomb-disposal Techs [17]
- Security and Defense meeting, Brussels 22/11/2017 [18]
- MUSICODE – UGV stand-off multisensory platform for IED component detection (B 1465 GEM3 GP) Designing and developing a TRL 5 Technology Demonstrator of a UGV equipped with a variety of sensors for detection of IED components in support of Route Clearance Operations. [19]
- MINESWEEPERS TOWARDS A LANDMINE FREE WORLD [20] [21]

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