Perspective approaches to landmine detection, identification and positioning

Gennadiy Pochanin
Radiophysical Introscopy Department
O.Ya.Usikov Institute for Radiophysics and Electronics of the National Academy of Science of Ukraine
Kharkiv, Ukraine
gp.pochanin@gmail.com

Iryna Pochanina
Lab. of Mathematical Physics
O.Ya.Usikov Institute for Radiophysics and Electronics of the National Academy of Science of Ukraine
Kharkiv, Ukraine
irina_pochanina@ukr.net

Tetiana Ogurtsova
Radiophysical Introscopy Department
O.Ya.Usikov Institute for Radiophysics and Electronics of the National Academy of Science of Ukraine
Kharkiv, Ukraine
otn_tati@ukr.net

Fronefield Crawford
dept. of Physics & Astronomy
Franklin & Marshall College
Lancaster PA, USA
fcrawfor@fandm.edu

Lorenzo Capineri
dept. of Information Engineering
University of Florence
Florence, Italy
lorenzo.capineri@unifi.it

Timothy Bechtel
dept. of Earth & Environment
Franklin & Marshall College
Lancaster PA, USA
tbechtel@fandm.edu

2025 13th International Workshop on Advanced Ground Penetrating Radar (IWAGPR) | 979-8-3315-2335-0/25/$31.00 ©2025 IEEE | DOI: 10.1109/IWAGPR65621.2025.11109038

***Abstract*— In recent years, various approaches to mine detection have been introduced. To enhance the speed and safety of this process, systems such as remotely controlled flying drones and terrestrial robotic systems have been developed. These systems are equipped with a range of sensors that utilize different physical principles, including optical imaging, thermal imaging, LiDAR, magnetometry, metal detection, and various types of ground penetrating radar. Additionally, a global trend has emerged that involves the use of artificial intelligence to analyze the large volumes of data collected by these sensors. This paper presents a review of the latest methods for landmine detection, identification, and positioning.**

Keywords— surface and subsurface landmine, UXOs, sensors, robotic platforms, Unmanned Aerial Vehicles (UAV), data processing, artificial intelligence (AI), explosive hazards mapping.

I. Introduction

Ukraine currently holds the unfortunate distinction of being the most contaminated country in the world in terms of landmines and unexploded ordnance (UXO). According to estimates from Ukrainian officials, it could take around 700 years to completely clear the country of these hazardous materials. To help protect the public, the State Emergency Service of Ukraine (SESU) has created an interactive map (Fig. 1) that highlights areas potentially affected by explosive objects. This regularly-updated map displays locations where explosive items have already been discovered as well as areas where they may still be found, along with the level of threat they pose based on available information from the SESU. Please note that the map has a localization error of up to 30 meters.This highlights the need for developing effective mine detection and clearing methods over a vast area.

Heavy metals, sulfur, and chemical compounds from explosives pollute the soil and even make it unsuitable for agriculture in Ukraine [2] and this is already becoming a global problem. We must avoid destroying munitions in-place by blasting and instead, aim to clear soils by removing them whenever possible.

The authors acknowledge the financial support of the NATO/OTAN Science for Peace and Security (SFPS) Program for Project G7563- “Innovative Sensor Integration for Remote Landmine Detection” (https://www.natospsdeminingrobots.com/).

Fig. 1. Interactive map of areas that could potentially be contaminated by explosive objects [1]

There are many proposed and tested methods for detecting landmines. All of them are based on exploiting some difference in physical properties between mines and the surrounding media [3], [4], [5].

II. UAV-BASED MINE DETECTING SYSTEMS

The war in Ukraine has accelerated the development of flying Unmanned Aerial Vehicles (UAVs) with enhanced capabilities, such as accurate positioning, stabilization of orientation, and the ability to hold position despite wind and other factors. As UAVs work above the ground, they allow observation of significant areas without the risk of detonating landmines. Distant control makes it possible for operators to work safely far from dangerous territory. All of this attracted the attention of designers of mine detection systems and encouraged the use of UAVs for this purpose.

The author of the paper [6] selected four types of sensors that can detect dangerous objects on the soil surface (Fig. 2): visual imaging, thermal imaging, lidar, and magnetometry. UAVs can be readily equipped with these sensors. The paper discusses the advantages and disadvantages of various methods based on multiple tests conducted in specially designed test fields as well as in the fields of Ukraine.

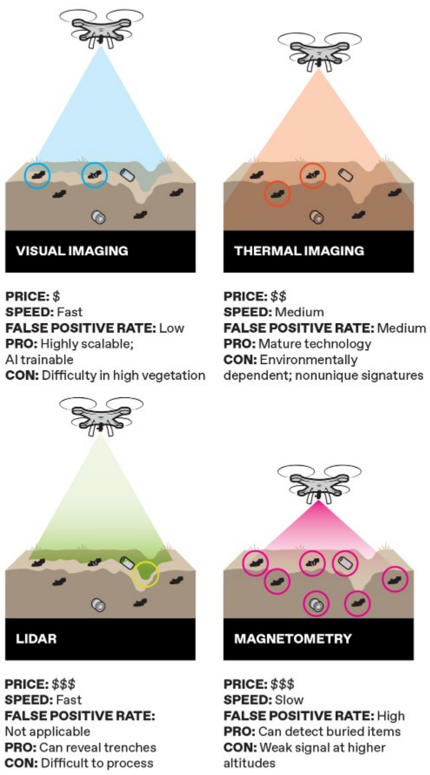

Fig. 2. Four types of sensors for hazards detection in the technology demonstration set up by the United Nations. (Cited from [6])

As follows from the paper [6] fusion of data collected by these sensors and processed with an artificial intelligence (AI) algorithm allows detection of up to 23 objects.

The web site [7] reports on testing organized by the United Nations Development Programme (UNDP) in Ukraine in May 2024. This testing of mine detection innovations revealed promising advances in the methods used to detect landmines and other explosive remnants of war (ERW). The participating organizations demonstrated the advances of integrating electro-optical sensors with AI for surveys of hazardous areas (Fig. 3).

Fig. 3. Example of equipment used in tests (Cited from [7])

III. UAV-BASED GPR SYSTEM

None of the sensors currently available are effective at detecting subsurface plastic mines. However, because of the difference in dielectric constant between plastics and damp soil, ground penetrating radar (GPR) can be used to locate buried plastic mines. A comprehensive review of 14 UAV-based GPR systems as well as methods of processing the data collected by these systems is presented in review paper [8]. Some of these GPRs are applicable for detecting objects under the soil surface.

Conceptually, a UAV-based GPR system can be understood as a UAV whose payload is a GPR module. In the review [8, 10], most UAV-based GPRs use frequency bands higher than 2 GHz. Definitely, this allows application of small and lightweight antennas. However, effective signal penetration is very small due to attenuation of high frequency sounding signals. So, most of the systems are able to detect objects on the ground surface with significantly worse performance for buried objects.

It should be noted that detection is only the first stage. The second, and perhaps more important due to the ubiquity of war zone clutter, is object identification. Review of UAV-based GPRs indicates that this task currently remains unsolved.

The authors of [8] presented their own experimental results on detection of subsurface objects from a UAV-based GPR. The test was the detection of a metal plate of a size of 25 × 35 cm, which was buried into the ground at a depth of 30 cm. During the data acquisition UAV moved at the height 0.5 m above the ground. GPR data processing included microwave tomography-based imaging following commonly-used data preparation procedures.

Results of the GPR scanning are shown in Fig. 4. While the GPR did detect a quite large metal plate (mines are considerably smaller), the image still does not allow object identification. This is a promising initial result in need of deeper investigation.

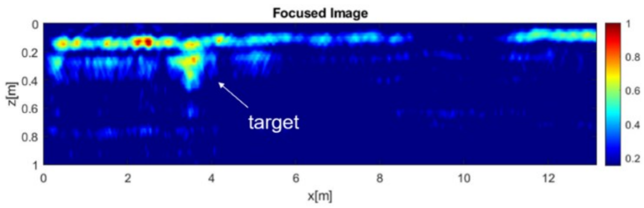

Fig. 4. Microwave tomography-based focused image (Cited from [8])

Despite advantages of UAV based systems (such as operator safety, quick data acquisition, relatively cheap observation procedures) the application of these systems requires further investigations that should address problems related to instability of flight trajectory, reduced penetration of sounding signal into the ground, and diffuse scattering by surface relief. Another problem is restrictions on payload of UAVs; especially small ones.

Special attention should be paid to the paper [9] which is dedicated to achievements of UAV-based GPR for landmine detection. Recently, many advances were made for the application of UAVs for landmine detection. Current developers of UAV-based GPRs have moved from individual attempts to probe the soil with drone-based GPR to systematic in-depth studies on the use of various options for combining drones and GPRs: from equipping a drone with a ready-made GPR to designing special radars, and on to combining and unifying their navigation systems, and communication systems with the operator, etc. If earlier in the scientific literature one could find only isolated publications on this topic, then starting from 2020 there are already more than a hundred of them. Of particular interest are studies aimed at using methods for synthesizing the aperture of the antenna system [11], the possibility of which is due to the equipment that has recently appeared for fairly accurate determination of the location of the GPR in space.

It should be noted that not only down looking schemes for collecting radar data are considered, but also side view and an even more interesting option which is a Circular Synthetic Aperture Radar using a ultrawideband (UWB) radar antenna that irradiates the ground surface at an angle to the surface (Fig. 5).

Fig. 5. UAV with a UWB horn GPR antennas mounted for use in side looking mode. (Cited from [11])

Combining frequency-modulated sounding signals and irradiation of a focused area from all directions achieves a large enough dynamic range to receive reflections from subsurface objects and to obtain synthetic aperture radar (SAR) images of surface and subsurface landmines (Fig. 6).

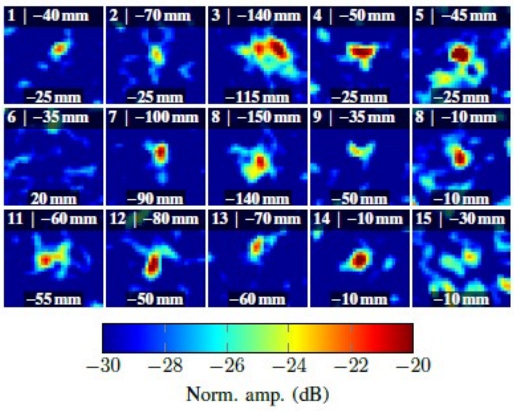

Fig. 6. Ground penetrating SAR images. 1) PMA-2, 2) C3A2, 3) Pressure Plate, 4) VS-50, 5) DM18B1, 6) VS-MK2, 7) PMN, 8) PT Mi-Ba-III, 9) PMA-1A, 10) PFM-1S, 11) PMN, 12) PPM-2, 13) Projectile, 14) PFM-1S, 15) M-14. Numbers 1, 2, 4, 6, 7, 8, 9, 10, 11, 12, 14 are plastic cased. Numbers 5, 13, 15 are metal. (Cited from [11])

This technology of circular SAR with UAV based GPR allowed detection of 11 of 15 antipersonnel landmines buried in sand. Positions of detected objects had accuracy measured in cm.

However, this is still an early-stage investigation and cannot yet demonstrate the possibility of subsurface object identification. Authors of paper [11] intended to continue their research in a realistic environment.

IV. GROUND BASED ROBOTIC SYSTEMS

Terrestrial robotic platforms equipped with GPR are pivotal in humanitarian demining, offering enhanced safety and efficiency in detecting landmines. These systems integrate advanced sensors and autonomous navigation to identify and map buried explosive devices. At present there are many companies that develop robotic platforms and some of them have equipped with GPR systems and other sensors for humanitarian demining operations [12, 13, 14].

The architecture of the multisensor robotic platform is described in [16]. It is based on the Industry 4.0 paradigm and is equipped with UWB impulse GPR, and Holographic Subsurface Radar (HSR) (Fig. 7). An example is presented which describes how to exploit the information from the multiple sensors with experiments carried out in a test field with landmine simulants (Fig. 8).

Fig. 7. Robotic platform 1 – Impulse GPR antenna system, 2 – Impulse GPR hardware unit, 3 – Holographic Radar, 4 – Robotic platform Jackal.

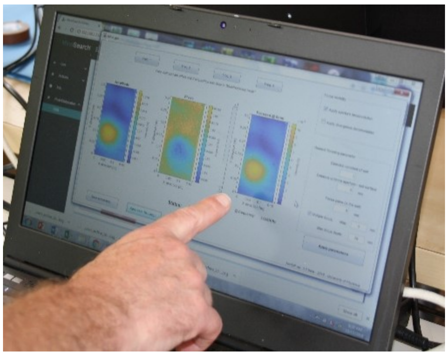

Fig. 8. Holographic image of subsurface antipersonnel mine

The next step, which is intended to increase reliability and probability of detection, is to extend the number of sensors and apply sensors of a different nature. Of course, mounting several sensors on the same platform makes data acquisition more complicated and slower. Therefore, the approach of using multiple robots [17, 18, 19] became the preferred solution.

The goal of cooperative demining robots with specialized sensors [18] is to investigate a field and detect plastic with metal components as subsurface treats using UWB impulse GPR, a Metal Detector, and with subsequent scanning with HSR to identify the type of subsurface object (i.e., dangerous or clutter). This system was developed in the framework of the NATO SPS project G5731 “Multi-sensor cooperative robots for shallow buried explosive threat detection”.

The all-terrain navigation used by the mobile robots is attained by a novel embodied reactive obstacle avoidance method [19]. A Control Mission software package has been developed to plan, configure, and supervise the operation. Highly compliant legged and wheeled platforms have been developed, accomplishing low-cost all-terrain robots in this work.

The primary sensors available in [19] include metal detectors, GPR, and explosive vapor sensors. Sensor fusion will serve as the means to integrate the data from these sensors. The main outcomes of the project outlined in the paper are as follows:

- Heterogeneous mobile robots, designed for specific conditions, offer significant advantages by reducing complexity through specialization;

- The expensive task of robot localization can be addressed using external tracking methods. Combining external positioning tracking with a stochastic approach for terrain coverage provides a cost-effective solution.

The multi-robot system AIDEDeX [17] includes unmanned aerial and ground vehicles equipped with advanced sensors and AI-based sensor fusion algorithms. This initiative aims to significantly improve operational efficiency, safety, and effectiveness in hazardous environments.

V. USE OF AI FOR DATA PROCESSING

Detailed manual or non-automated processing of data collected during GPR sounding is a very time-consuming procedure, since there is a lot of data and, in addition, it is necessary to detect all mines and at the same time ensure a minimum of false alarms. Therefore, automatic algorithms should be used to process the observation results. One of the promising options is the use of AI or artificial neural networks (ANN). The advantage of this approach is that even a set of data that characterizes an object not accurately (with some errors) allows trained networks to predict the correct solution with a fairly high probability.

Authors of this paper have experimented with data collected with UWB impulse GPR at a realistic test field in Ukraine. Results of this research are presented in paper [20]. This work uses the ANN method to recognize hidden objects. A large set of false objects for training the neural network gave good results in recognizing anti-personnel mines and showed excellent stability in determining the position and type of the object even in the presence of interference with a high signal-to-noise ratio.

Using a fully connected neural network with five hidden layers of neurons improves reliability of recognition. It was determined that the use of artificial intelligence gives good results in recognizing underground objects if a high-quality training data set for the artificial neural network is previously prepared. Satisfactory performance even with noisy signals is shown, which is promising for further testing of the developed method applied to subsurface radar in real experimental conditions.

In study [21] we have developed a novel real-time surface landmine detection system integrated within a demining robot. This system is notable for its ability to operate in real-time, achieving a processing speed of 2.6 frames per second. It is designed for accessibility and ease of use, functioning on both computer web browsers and smartphone devices.

In this approach, the emphasis was on the operational speed of surface landmine detection. This resulted in a system with an extended operational duration compared to UAV-based systems, which are typically limited by battery life.

A critical aspect of this system is its approach to handling false positives, a common challenge in detection systems. The false positives generated by our system can be quickly and efficiently evaluated by a human operator using a smartphone. This approach significantly reduces the risk of missing actual threats, minimizing potential harm to both the robot and human operators.

In contrast to [20] where ANN is trained on a set of combinations of A-scans, the author of the paper [22] uses B-scans as images for training. Such an approach makes it necessary to adjust the size of the image corresponding to the object (landmine).

Another paper [23] uses B-scans of buried objects for deep learning of AI. The authors stated that their approach outperforms other methods when the number of training data is small and when some of them are mislabelled.

Paper [24] compares convolutional networks deep learning methods based on all possible data such as A-scan, B-scan, and even C-scan. The material of the paper is based on a long list (dozens) of quite fresh references (dated from 2015) and show advantages and disadvantages of mentioned methods. In the authors' opinion C-scan is the most effective element for AI training. However, it requires very high accuracy radar data to be collected.

Finally, it is necessary to consider a system with combined Electromagnetic Induction (EMI) and GPR sensors. This is the Advanced Landmine Imaging System (ALIS) developed in Japan between 2002 and 2004 [25]. Since then, it has been deployed in mine-affected countries around the world. The advantage of ALIS is that it produces 2-D images of the detected subsurface object which allow identification of the object based on whether it is metallic or nonmetallic, and the displayed plan-view shape of the object. AI is now being developed for use with ALIS images.

VI. Conclusions

The aim of the work in this paper is the collection and analysis of information which is useful for understanding approaches for landmine detection both on the surface and underground, as well as designs of UAV and ground based robotic platforms suitable for sensor mounting.

All authors are of the opinion that GPR is one of the single best methods for detecting the most dangerous plastic-cased and low metal content mines. Thus, GPR should be used in each mine detection system.

It is clear now that the best algorithms of GPR data processing for the landmine detection, positioning, and identification use an AI approach. Unfortunately, it is premature to state that AI is ready for widespread use in this way. Future investigations will be necessary to enhance this capability.

References

[1] "Demining Ukraine," *Dsns.gov.ua*, 2025. https://mine.dsns.gov.ua

[2] Maia Orel, " Ammunition against fertile soils: why Ukraine can lose the status of the breadwinner of the world," *hromadske*, Aug. 04, 2023. https://hromadske.ua/ru/posts/boepripasy-protiv-plodorodnyh-pochv-

pochemu-ukraina-mozhet-poteryat-status-kormilicy-mira

[3] L. Capineri et al., “NATO Advanced Research Workshop on Explosives Detection,” *NATO science for peace and security series. B, Physics and biophysics*, pp. 1–32, Jan. 2019, doi: https://doi.org/10.1007/978-94-024-1729-6_1.

[4] G. Fedorenko, H. Fesenko, and V. Kharchenko, “ANALYSIS OF METHODS AND DEVELOPMENT OF THE CONCEPT OF GUARANTEED DETECTION AND RECOGNITION OF EXPLOSIVE OBJECTS,” *Innovative technologies and scientific solutions for industries,* no. 4 (22), pp. 20–31, Dec. 2022, doi: https://doi.org/10.30837/itssi.2022.22.020.

[5] I. E. Ментус, В. А. Ясько, and Є. Ю. Саприкін, “Mine detection methods for humanitarian demining: an overview,” *Ukrainian journal of remote sensing*, vol. 11, no. 3, pp. 31–39, Sep. 2024, doi: https://doi.org/10.36023/ujrs.2024.11.3.271

[6] J. Baur, “Ukraine is Riddled with Land Mines: Drones and AI Can Help,” IEEE Spectrum, vol. 61, no. 5, pp. 42–49, May 2024, doi: https://doi.org/10.1109/mspec.2024.10522930

[7] C. Noviello et al., “An Overview on Down-Looking UAV-Based GPR Systems,” *Remote Sensing*, vol. 14, no. 14, p. 3245, Jul. 2022, doi: https://doi.org/10.3390/rs14143245.

[8] Y. Álvarez-López, María García-Fernández, G. Álvarez-Narciandi, and F. Las-Heras, “Unmanned Aerial Vehicle-Based Ground-Penetrating Radar Systems: A review,” *IEEE Geoscience and Remote Sensing Magazine*, vol. 10, no. 2, pp. 66–86, Jun. 2022, doi: https://doi.org/10.1109/mgrs.2022.3160664.

[9] “Humanitarian mine action trials show promise of innovation in Ukraine,” *UNDP*, 2024. https://www.undp.org/ukraine/press-releases/humanitarian-mine-action-trials-show-promise-innovation-ukraine.

[10] Y. Sh. Alqudsi, A. S. Alsharafi, and A. Mohamed, “A Review of Airborne Landmine Detection Technologies: Unmanned Aerial Vehicle-Based Approach,” *IEEE Xplore,* Jul. 01, 2021. https://ieeexplore.ieee.org/abstract/document/9493528.

[11] M. Schartel, R. Burr, Rik Bähnemann, W. Mayer, and C. Waldschmidt, “An Experimental Study on Airborne Landmine Detection Using a Circular Synthetic Aperture Radar,” *arXiv (Cornell University*), Jan. 2020, doi: https://doi.org/10.48550/arxiv.2005.02600.

[12] P. Dasgupta, J. Baca, K. R. Guruprasad, A. Muñoz-Meléndez, and J. Jumadinova, “The COMRADE System for Multirobot Autonomous Landmine Detection in Postconflict Regions,” *Journal of Robotics,* vol. 2015, pp. 1–17, 2015, doi: https://doi.org/10.1155/2015/921370.

[13] S. Munir, “Demining Robots: Jackal UGV & OutdoorNav Utilized For Advanced Landmine Detection - Clearpath Robotics,” *Clearpath Robotics,* Oct. 2023, doi: https://doi.org/10/15212702/20221011_135753-scaled.

[14] R. M. Williams, L. E. Ray, and J. Lever, “An autonomous robotic platform for ground penetrating radar surveys,” Jul. 2012, doi: https://doi.org/10.1109/igarss.2012.6350750.

[15] Emanuele Vivoli, M. Bertini, and L. Capineri, “Deep Learning-Based Real-Time Detection of Surface Landmines Using Optical Imaging,” *Remote sensing*, vol. 16, no. 4, pp. 677–677, Feb. 2024, doi: https://doi.org/10.3390/rs16040677.

[16] L. Bossi *et al*., “Design of a robotic platform for landmine detection based on Industry 4.0 paradigm with data sensors integration,” pp. 16–20, Jun. 2020, doi: https://doi.org/10.1109/metroind4.0iot48571.2020.9138227.

[17] “A multi-robot system for the detection of explosive devices*,” *Arxiv.org*, 2023. https://arxiv.org/html/2404.14167v1

[18] S. Munir, “Demining Robots: Jackal UGV & OutdoorNav Utilized For Advanced Landmine Detection - Clearpath Robotics,” *Clearpath Robotics,* Oct. 2023, doi: https://doi.org/10/15212702/20221011_135753-scaled..

[19] P. Saavedra Santana, J. Barata, H. Cruz, S. Martins, J. Lisboa, and Lucas Macrorie Flores, “A Multi-Robot System for Landmine Detection,” *Emerging Technologies and Factory Automation*, Sep. 2005, doi: https://doi.org/10.1109/etfa.2005.1612597..

[20] O. A. Pryshchenko *et al.*, “Implementation of an Artificial Intelligence Approach to GPR Systems for Landmine Detection,” *Remote Sensing,* vol. 14, no. 17, p. 4421, Sep. 2022, doi: https://doi.org/10.3390/rs14174421..

[21] Emanuele Vivoli, M. Bertini, and L. Capineri, “Deep Learning-Based Real-Time Detection of Surface Landmines Using Optical Imaging,” *Remote sensing*, vol. 16, no. 4, pp. 677–677, Feb. 2024, doi: https://doi.org/10.3390/rs16040677.

[22] S. Lameri, F. Lombardi, P. Bestagini, M. Lualdi, and S. Tubaro, “Landmine detection from GPR data using convolutional neural networks,” *IEEE Xplore*, Aug. 01, 2017. https://ieeexplore.ieee.org/abstract/document/8081259?casa_token=gmSeEe3AyhsAAAAA:oTH2OEUA7dJ7Q0GeyDTDYa2gbAIEwaoHd8EydlJ5TBzQuSa-e5qv-2wDo4dkMPAaK2-I6RgwZUjK (accessed Mar. 10, 2022).

[23] M. Sezgin and M. N. Alpdemir, “Classification of Buried Objects Using Deep Learning on GPR Data,” in *2023 IEEE International Conference on Advanced Systems and Emergent Technologies* (IC_ASET).

[24] . X. Bai et al., “A Comprehensive Review of Conventional and Deep Learning Approaches for Ground-Penetrating Radar Detection of Raw Data,” *Applied sciences*, vol. 13, no. 13, pp. 7992–7992, Jul. 2023, doi: https://doi.org/10.3390/app13137992.

[25] [1]M. Sato, “Introduction of the advanced ALIS: Advanced Landmine Imaging System,” Apr. 2018, doi: https://doi.org/10.1117/12.2303966.
.