Security
of Infocommunication Systems
and Internet of Things

2025 Vol 3, No 1

https://doi.org/10.31861/sisiot2025.1.01010

Received 04 June 2025; revised 25 June 2025; accepted 28 June 2025; published 30 June 2025

Perspectives on the Development and Use of Nuclear Methods for Detecting Landmines and Minefields: A Review

Artem Kasianchuk*, Halyna Lastivka and Andrii Samila

Department of Radio Engineering and Information Security, Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine

*Corresponding author (E-mail: kasianchuk.artem@chnu.edu.ua)

ABSTRACT Landmines remain a deadly legacy of past and present conflicts, with these hidden explosive devices causing thousands of casualties each year. In addition to the existing mainstream methods of detecting landmines and minefields, several new technologies are being investigated, such as nuclear mine detection methods, namely nuclear quadrupole resonance (NQR) and neutron detection. Both NQR and neutron techniques are quite promising and offer powerful advantages in detecting landmines and minefields, although they have certain draw-backs in practical use. Artificial intelligence can significantly mitigate these shortcomings through advanced signal processing, adaptive algorithms, etc. The purpose of the article is to analyze, research and systematize available information on the positive effectiveness and feasibility of using nuclear methods (NQR and neutron-based) to detect mines and minefields, as well as to improve the accuracy and effectiveness of using these methods using artificial intelligence.

KEYWORDS nuclear quadrupole resonance, neutron-based detector, landmines, mine-fields detection, artificial intelligence.

I. INTRODUCTION

Landmines remain a deadly legacy of past and ongoing conflicts, with an estimated 110 million active landmines scattered across about 60 countries. These hidden explosives cause thousands of casualties each year – in 2022 alone, landmines and explosive remnants of war killed or injured over 4,700 people, the vast majority of them civilians (about half of the victims were children) [1]. Beyond the human toll, landmines impede economic recovery by rendering farmland and infrastructure unusable. Removing mines is painstaking and expensive (a mine that costs as little as $3 to produce can cost up to $1,000 to safely remove). Both military engineers and humanitarian demining organizations employ a range of detection technologies to locate mines and clear contaminated land [1]. However, no single detection method is perfect – each has its own strengths and limitations, and often multiple techniques are combined for greater effectiveness. This article provides an overview of current technologies for detecting landmines and minefields, covering both widely used operational tools and promising experimental methods, namely a detailed review of detection methods such as nuclear quadrupole resonance (NQR) and neutron-based detection methods (neutron activation). It also examines how artificial intelligence (AI) is being integrated into these technologies and how AI can further improve mine detection through computer vision, robotics, signal processing, and predictive modeling.

II. AN OVERVIEW OF THE METHODS OF LANDMINE AND MINEFIELD DETECTION UNDER RESEARCH

For military purposes (e.g., during conflict or immediate post-conflict operations), speed and operator safety are paramount – armies may use armored vehicles with detectors or mechanical demining devices to quickly break through minefields, sometimes taking on greater risk of missing mines in order to advance more quickly. In civilian humanitarian demining, the priority is to achieve nearly 100% clearance with minimal risk, even if it takes a long time. Deminers must work in a variety of environments, from dense jungles and deserts to urban ruins, and often deal with a combination of anti-personnel and anti-tank mines placed in unpredictable locations [2]. This variety of scenarios has led to the development of numerous detection methods, from simple metal detectors to modern sensor arrays. Below is a list of few main detection technologies used today [2-4]:

A. Metal Detectors.

- **Principle:** Electromagnetic induction to sense metal in mines. Handheld coil emits a magnetic field, induces currents in metallic objects, and detects the response.
- **Advantages:** Lightweight, low-cost, and easy to operate; highly sensitive to metal fragments, able to find very small metal pieces (e.g. detonator parts); proven in decades of field use (standard tool worldwide).
- **Limitations:** Cannot detect non-metallic mines (minimal metal mines are challenging); very high false alarm rate: shrapnel and debris trigger signals (e.g. in Cambodia only 0.3% of 200 million metal signals were actual mines); performance is degraded in mineralized soils (magnetic soils cause noise).
- **Typical Use Cases:** Humanitarian demining: primary tool for manual deminers, swept inch-by-inch to pinpoint mines; military engineers: used in breaching operations and route clearance for metallic mines/IEDs (often alongside other sensors).

B. Ground-Penetrating Radar (GPR).

- **Principle:** High-frequency radio waves sent into the ground; detects reflections from buried objects with different dielectric properties. Often used in dual-sensor detectors (with metal detector).
- **Advantages:** Capable of detecting *non-metallic mines* (plastic, wood) by imaging the shape or detecting dielectric contrast with soil; provides depth information and target imaging (can distinguish object vs. soil layering); combining GPR with metal detection greatly reduces false alarms from metallic clutter.
- **Limitations:** Limited penetration in conductive or wet soils (signal attenuation in clay or moist ground); cluttered environments (rocks, roots, surface debris) produce confusing reflections; slower and more complex: requires signal processing expertise and generates large data volumes; typically short range – antenna must be close to ground, making fast scanning difficult.
- **Typical Use Cases:** Dual-sensor handheld units: e.g. US Army's HSTAMIDS detector (combines metal detector + GPR) used in Iraq/Afghanistan and by NGOs; vehicle-mounted GPR: used for route clearance (finding buried roadside mines/IEDs) on military vehicles (e.g. Husky mine-detection vehicles); surveying suspect areas: in humanitarian operations to detect low-metal mines after initial metal detection sweeps.

C. Infrared (IR) & Thermal.

- **Principle:** Passive thermal imaging (or active heating) to detect temperature differences in soil covering a mine. Buried mines alter the thermal conductivity and heat flow of the ground; at certain times of day, the ground above a mine may be warmer or cooler than surrounding soil.
- **Advantages:** Non-contact, standoff detection – can be done from a safe distance or aerial platform (drone, aircraft); can cover large areas faster than ground detectors when conditions are ideal; detects both metallic and non-metallic mines (based on thermal signature, not material).
- **Limitations:** Strongly dependent on environmental conditions: weather, soil moisture, time of day all affect thermal contrast; generally effective only for shallow mines. Mines deeper than ~10–15 cm may not produce a detectable surface temperature difference; yields false positives from natural temperature variations (rocks, sun/shade patterns) and is less useful in dense vegetation.
- **Typical Use Cases**: Aerial reconnaissance: drones or aircraft with IR cameras to scan open areas (e.g. desert minefields) at dawn or dusk for thermal anomalies; confirmation tool: used after clearing vegetation or in combination with other sensors to highlight likely buried objects. Mostly experimental or in pilot programs due to reliability issues.

D. Acoustic & Seismic.

- **Principle:** Acoustic or vibrational energy is introduced into the ground (e.g. via a loudspeaker, shaker, or seismic thumper). Buried mines resonate or reflect vibrations differently than soil. A sensor (e.g. laser Doppler vibrometer or geophone) measures the ground's response to detect anomalies.
- **Advantages:** Can detect *minimal-metal and plastic mines* by their mechanical signature, regardless of metal content; potential for standoff detection: modern systems use lasers to remotely sense vibrations from a safe distance, keeping operators out of the minefield; not as affected by metallic clutter or soil magnetism (mechanical properties are the focus).
- **Limitations:** Requires an external vibration source and sensitive sensors; setup can be complex and equipment heavy (vehicles, tripods often needed); surface conditions (vegetation, uneven ground) and soil type can interfere with vibration patterns, making data interpretation difficult; largely experimental; not yet widely deployed operationally. Scanning large areas can be slow.
- **Typical Use Cases**: Research prototypes: e.g. the University of Mississippi's LAMBDIS system uses a vehicle-mounted laser array to map ground vibrations in real time; potential military use: convoy-mounted acoustic detectors to find mines/IEDs from a moving vehicle. (Currently in testing); focused area confirmation: scanning suspicious spots identified by other methods to differentiate a mine from a rock via its vibration signature.

E. Chemical Sensors (Trace Explosive Detection).

- **Principle:** Detecting vapor or microscopic particles emitted by explosives in a landmine. Methods include biological detectors (scent-detection dogs or rats) and electronic sensors ("electronic noses," ion mobility spectrometers, colorimetric kits, etc.).
- **Advantages:** Finds mines with no metal by sniffing the explosive itself – effective for minimum-metal or plastic mines that other detectors might miss; dogs (and trained rats) are highly sensitive and can cover ground relatively quickly by sampling air over large areas. A well-trained mine detection dog can indicate the presence of buried explosives with high reliability; some chemical sensors can confirm the type of explosive (e.g. TNT vs RDX) by chemical signature.
- **Limitations:** Many explosives have very low vapor pressure – a buried mine may emit only trace amounts, making detection difficult if the soil traps the chemicals; wind, rain, and terrain affect scent distribution; gaps in coverage can leave mines undetected if no odor reaches the sensor; dogs and other animals require extensive training, conditioning, and rest; their performance can vary and they may be distracted by other scents. Electronic detectors can be overly sensitive or give false alarms from chemical contaminants.
- **Typical Use Cases**: Humanitarian demining: commonly deploys mine detection dogs to "sniff" large suspect areas and flag-mine locations. Dogs are often used to systematically survey minefields before manual clearing; security/military: dogs and handheld explosive trace detectors are used at checkpoints or to search vehicles and buildings for explosive devices (including mines/IEDs); emerging: researchers are experimenting with drones carrying lightweight

chemical sensors or using biosensors (like bees or genetically engineered plants) to indicate explosives, but these are not yet field-proven.

Beyond the mainstream methods above, the next several novel technologies are being researched to overcome the current challenges in landmine detection: Advanced Sensor Fusion & 3D Imaging, LiDAR and Optical Methods, Nuclear Methods (NQR and Neutron), Biological Sensors, Quantum and Advanced Sensing [5].

Each of the above technologies has both significant advantages and disadvantages in the process of detecting landmines and minefields.

In this article, we will focus on and examine in detail the following methods: NQR and Neutron-Based Detection Methods (Neutron Activation).

F. Nuclear Quadrupole Resonance. NQR is a radio-frequency (RF) technique that can directly detect certain explosive molecules by their nuclear properties [6]. Nuclear Quadrupole Resonance exploits the unique electromagnetic resonance signatures of nitrogen nuclei commonly present in explosives like TNT, RDX, HMX, and PETN. NQR functions similarly to an MRI scan but at radio frequencies specific to nitrogen compounds found in explosives. It detects the resonance signals produced when nitrogen atoms, under specific radio-frequency pulses, respond with characteristic frequencies. A sensor placed close to or above the ground emits radio-frequency pulses [6]. If a landmine (containing nitrogen-rich explosives) is present, the nitrogen nuclei resonate and emit detectable signals.

The presented method has several significant advantages, namely: high selectivity – specifically detects the chemical composition (nitrogen-rich explosives), thus significantly reducing false positives from metallic or non-explosive clutter; non-metallic mine detection – capable of finding plastic or non-metallic mines since it directly detects explosive chemicals, independent of metal content; non-destructive and safe – doesn't use ionizing radiation, thus safe for operators and the environment.

Despite all its advantages, there are some challenges that this method faces in the process of detecting landmines and minefields, such as: weak signal and noise issues – NQR signals are inherently weak and easily obscured by environmental radio-frequency noise; limited detection depth – typically effective for shallow mines (within approximately 10 cm – 20 cm) [6]. Deeper mines may have resonance signals too faint to detect; slow scanning speed – early NQR systems required several seconds to minutes per measurement, making large-area surveys impractical; sensitivity to environmental conditions – soil moisture and temperature fluctuations can affect detection performance.

Although this method is still largely experimental, it has successfully demonstrated its positive effectiveness in research and limited military applications. Field tests have shown promise in distinguishing buried explosives from harmless objects with a low false alarm rate. For example, NQR has been tested in research projects funded by defense agencies such as DARPA and NATO to detect explosives in mine clearance and checkpoint screening applications.

G. Neutron-based detection. Neutron Activation involves interrogating the soil with neutrons to detect explosive materials by analyzing resultant gamma-ray emissions. Neutrons emitted by a portable neutron source interact with buried objects. These interactions cause the emission of characteristic gamma rays, particularly from nitrogen-rich explosives. In the technical application of this method for detecting landmines and minefields, there are two main approaches [7]:

- **Thermal Neutron Activation:** Low-energy (thermal) neutrons interact with nitrogen atoms, causing them to emit distinctive gamma rays.
- **Fast Neutron Analysis:** Higher-energy (fast) neutrons can penetrate deeper into the soil, generating gamma rays from elements like nitrogen, hydrogen, and carbon in explosives.

The advantages of the above-mentioned method in the detection of landmines and minefields are considered to be as follows: direct chemical detection – detects explosives based on their elemental composition, allowing discrimination between explosives and innocuous materials; effective at deeper depths – can detect buried mines deeper than methods like NQR, metal detectors, or GPR (over 30 cm); non-metallic mine detection – like NQR, neutron methods can find plastic and minimum-metal mines due to their chemical-based detection principle.

Like any method that, despite its relative success, is considered experimental, this method has certain limitations and challenges in its usage, like: use of radioactive sources – requires radioactive neutron sources (e.g., isotopes like Californium-252), raising regulatory, safety, and logistical challenges; heavy equipment and complexity – systems are often bulky and complex, limiting portability and usability in challenging terrains; slow scanning and data analysis – early systems required significant measurement time per location, slowing down overall clearance speed; gamma-ray background interference – background radiation can mask the signals, potentially leading to missed detections or false alarms [7].

This method has been successful mainly in experimental or limited applications for specialized military purposes, information about which is quite difficult to obtain, as it is classified. However, it is known that some neutron-based detection systems installed on vehicles have been tested by military engineers to clear routes or check for explosive objects at checkpoints [7].

Thus, each of the methods discussed above – both NQR and neutron-based methods – are similar in their general principle of operation, but they have both powerful advantages in detecting landmines and minefields and some scope for improvement, which is why these methods are used in a more experimental setting or in the military sphere (which, understandably, reduces the amount of publicly available information about the successful use of these methods for detecting landmines and minefields in practice). For a more detailed comparison of the two methods discussed, Table 1 below provides a comparative analysis of the characteristics of certain parameters of the methods under study and some common methods for detecting landmines and minefields [8, 9].

It should also be noted that the practical application of the above-described methods in detecting landmines and minefields requires the use of rather complex and expensive equipment. For NQR that for example [9]:

- **NQR RF Transmitter and Receiver:** Emits RF pulses at specific frequencies and detects resonance signals from nitrogen nuclei.
- **RF Coil/Antennas:** Transmit RF energy and receive resonance signals.
- **RF Amplifier & Low-Noise Amplifier:** Boost transmitted RF pulses and amplify weak NQR signals.
- **Signal Processing Unit:** Perform frequency-domain and time-domain analysis of resonance signals.
- **Environmental Noise Reduction Equipment:** Filters and shielding to minimize electromagnetic interference (EMI) from environmental sources (e.g., radio towers, electrical equipment).
- **Data Acquisition and Computing Hardware:** Capture, store, and analyze resonance data.

At the same time, Neutron-based detection method requires the following equipment for its practical implementation, albeit experimentally:

- **Neutron Source:** Generates neutron beams for interrogation.
- **Gamma-ray Detectors:** Detect gamma rays emitted by neutron interactions.
- **Gamma-ray Spectroscopy Electronics:** Analyzes gamma-ray spectra, identifies explosive-specific signals.
- **Moderators and Shielding:** Moderate fast neutrons and reduce radiation exposure to operators.
- **Radiation Safety and Monitoring Equipment:** Ensuring operator safety.
- **Robotic or Vehicle-Based Platforms:** Move neutron-based detectors safely across contaminated land.
- **Data Acquisition & Processing Computers:** Real-time data collection and analysis.

Therefore, in a sense, the use of these methods in the detection of landmines and minefields remains at the experimental level, due to the complexity and high cost of the equipment required for successful use in practice.

TABLE 1. Comparative analysis of the methods described above.

Feature	NQR	Neutron Methods	IR/Thermal	EMI (Metal Detectors)	GPR
Detection Principle	RF resonance of nitrogen nuclei	Gamma-ray emission from neutron interactions	Thermal contrast between soil and mine	Electromagnetic response from metallic objects	Reflection of radio waves from buried objects
Depth Penetration	Shallow (~10 cm – 20 cm)	Deeper (often 30+ cm)	Very shallow (~5 cm – 15 cm)	Medium (~10 cm – 20 cm, deeper for large metal objects)	Medium (~10 cm – 30 cm)
Speed of Detection	Generally slow; improving	Generally slow; improving	Fast (area surveys), slow for detailed analysis	Moderate	Moderate to slow
False Positive Rate	Low (chemical-specific)	Low (element-specific)	High; environmental variability	High; metallic clutter	Moderate; subsurface clutter and soil variability
Operational Complexity	Medium (electronics complexity)	High (requires neutron source)	Low to moderate; simple to deploy	Low; easy to operate	Moderate; requires trained operators
Safety and Environmental Issues	Safe (non-ionizing radiation)	Requires radioactive source	Safe	Safe	Safe
Current Status	Experimental with promising field tests	Military & experimental (limited humanitarian use)	Experimental; limited operational use	Widely operational	Operational in humanitarian and military contexts
AI Improvement Opportunities	High potential for AI in signal processing, noise reduction, and real-time adaptive scanning	High potential for AI in gamma-ray spectra analysis, robotic integration, and data fusion	High potential for AI in image processing, pattern recognition, and environmental compensation	Moderate potential; AI-enhanced signal processing, clutter discrimination, and sensor fusion	High potential; AI-driven image reconstruction, clutter reduction, and subsurface target identification
Dependence on Landmine Size	Low; chemical-specific detection largely independent of size, but small mines yield weaker signals	Moderate; better at detecting larger mines due to higher explosive content	High; smaller mines yield weaker thermal contrast and are difficult to detect reliably.	High; very small metal fragments can be detected, but difficult distinguishing mines from debris	Moderate; smaller mines harder to distinguish clearly from subsurface clutter, larger mines easier

III. IMPROVING THE PRESENTED DETECTION METHODS USING ARTIFICIAL INTELLIGENCE

AI is playing an increasingly important role in landmine detection, primarily by helping to interpret complex data and by enabling greater autonomy in search operations.

One of the strengths of modern AI, particularly deep learning, is analyzing imagery. In mine action, AI-driven computer vision can analyze aerial and satellite images to detect subtle signs of landmines or minefields. This might include recognizing patterns such as circular craters (from detonations), linear disturbances (rows of emplaced mines), or changes in vegetation and soil color that indicate buried explosives. For instance, the Demining Research Community developed a model using drone imagery where an AI algorithm locates surface mines; they achieved about 92% accuracy in identifying mines like the small green PFM-1 "butterfly" mine from images. Such accuracy is impressive given the difficulty for a human to spot these camouflaged objects in photos. Another organization, Mine Kafon, uses a dual-drone approach: the first drone maps the area in 3D, and the second collects data (visual, metal detection, etc.), which is then fed into mine-detecting software that marks likely mine locations on the 3D map. This process relies on computer vision algorithms to fuse sensor data with the visual map [10].

AI can also exploit spectral imagery beyond visible light. For example, feeding an algorithm multi-spectral data (infrared, thermal) allows it to learn the visual/thermal signature of mines at certain times of day, filtering out false signals from rocks or animal burrows. Satellite imagery, while lower resolution than drone footage, can cover huge areas. AI algorithms have been trained to scan historical satellite images to find clues of landmines – such as patterns of soil disturbances or even identifying old conflict fortifications (trenches, defensive lines) where mines are likely. Tech companies have collaborated with NGOs to apply AI on satellite data in places like Syria and Ukraine, flagging areas for ground teams to investigate.

A real-world example of AI in vision is the collaboration between the HALO Trust and Amazon Web Services in Ukraine: HALO is piloting AI to process drone and satellite imagery to identify debris of war and signs of landmine presence. The AI will highlight features like destroyed vehicles, craters, or suspicious ground scars near villages and roads – these can indicate either mines or other explosive ordnance. By automating the image analysis, HALO hopes to prioritize clearance tasks more efficiently. Another example is Safe Pro's SpotlightAI, reportedly used in Ukraine, which processes drone photos in seconds to detect surface-laid mines and mark their GPS coordinates [11].

Many mine detection sensors – especially GPR, acoustic, and multi-sensor arrays – produce complex signals or images that are not straightforward to interpret. AI and machine learning are increasingly used to analyze this raw data and pick out the signature of a landmine from background noise or clutter. This application of AI is more behind-the-scenes but critically important for improving detection rates and lowering false alarms.

Before any sensors hit the ground, one key challenge is where to look for mines. AI is increasingly used to predict likely locations of minefields or even individual mines, using a combination of historical data, geospatial analysis, and pattern recognition. Essentially, this is about using algorithms to forecast risk: given everything we know about a region (battle history, terrain, prior finds, etc.), where are mines probably present?

Modern conflicts and historical ones leave data trails. For example, military records might indicate where defensive minefields were laid, or peacekeepers might have partial survey data. AI can take such structured data along with remote sensing inputs and output probability maps. A notable example comes from NEC Corporation's work with the International Committee of the Red Cross: they developed an AI system that, using open data (geological info, habitation locations, conflict history, witness reports), could predict areas with a high likelihood of landmines with about 90% accuracy. Their AI flagged both likely hazardous areas and likely safe areas, aiding efficient land release. This kind of model can be invaluable for prioritizing demining efforts – focusing resources on the most at-risk areas first [12].

Another example is a 2024 study that combined military expertise with machine learning to classify and predict mined areas by type and priority. They incorporated factors like proximity to strategic locations, vegetation cover, and terrain, using algorithms like XGBoost/LightGBM, and reportedly achieved ~97% accuracy in their predictions. This was validated by demining experts who agreed such a model could greatly reduce risk and cost, improving decision-making. Essentially, the AI was learning from both historical clearance data and expert input to forecast where mines are and even what types (anti-personnel vs anti-vehicle) might be present [12].

Applications of Predictive Modeling: Minefield Risk Mapping: AI can produce heatmaps overlaying a map, showing gradations of risk. For example, an AI might highlight old battlefields, former front lines, around military bases, along likely infiltration routes, etc., as high risk, while marking other areas as low risk. This helps land release: areas judged likely free of mines can be released for use after minimal checks, whereas high-risk zones get full clearance. This approach is encapsulated by tools like the Mine Action Decision Support Tool, which some researchers have proposed using AI and Geographic Information System (GIS).

Resource Allocation: In countries with vast contaminated land (like Angola or Cambodia), AI risk models can help decide where to send demining teams first or which communities are most in need of clearance (by predicting where accidents are likely if not cleared).

Operational Planning: If AI predicts that a certain valley is full of anti-tank mines because battles occurred there, clearance teams can gear up accordingly (bring heavy machinery or specific detectors, etc.). Conversely, if an area likely has only scattered anti-personnel mines, a different approach (dogs and manual clearance) might be planned.

Discovering Unrecorded Minefields: Often, combatants lay mines without maps. AI can pick up patterns from known minefields and scan unexplored areas for similar patterns. For example, if it learns that mines in a region are often laid near streams (perhaps to deter crossing), it can flag other similar stream crossings nearby that had no records but fit the pattern.

These predictive models often use GIS data layers: land use, soil type, slope, distance to villages, past conflict events. Machine learning algorithms like random forests or neural networks then find correlations. Some also incorporate social datasets – like where accidents have happened (crowdsourced reports of explosions), which could indicate presence of more mines in that locale. There's also an approach using Bayesian inference to update the probability of mines as new evidence comes in (for instance, every time a new mine is found or not found in a searched area, the model updates its confidence for neighboring areas) [13].

The following points should be emphasized regarding the improvement of the NQR potential through the integration of AI – Signal Processing Enhancement (AI can analyze faint or noisy resonance signals, greatly improving the signal-to-noise ratio and detection reliability), Real-Time Adaptive Scanning (AI-driven adaptive methods can optimize the scan strategy based on initial readings or ambient noise levels, improving detection speed) [14].

As for improving the potential of Neutron-Based Methods through the integration of AI, the following points should be highlighted – Gamma-Ray Spectra Analysis (advanced Machine Learning models (e.g., deep neural networks) can analyze complex gamma-ray spectra rapidly, enhancing the discrimination of explosive signatures from background noise), Predictive Modeling (AI algorithms can use historical detection data and neutron interaction modeling to predict probable mine locations, focusing neutron interrogation on high-risk spots), AI-guided neutron detection can enhance safety, consistency, and area coverage) [15].

One caution is that such AI predictions need ground truthing – they assist but don't replace surveys. Yet, even a 90% accurate model like NEC's means a huge improvement in efficiency. If we can tell with high probability which square kilometers out of a thousand are mined, we save enormous effort. In conclusion, AI in predictive modeling serves as a strategic tool, complementing the tactical tools. It helps answer "where should we look?" so that all the detection technologies (metal detectors, GPR, etc.) can then answer "what exactly is there?". Combining AI-driven predictions with AI-enhanced detectors creates a powerful pipeline: from broad planning down to pinpoint identification, AI can accelerate the journey towards a mine-free world.

IV. CONCLUSION

Landmine detection has evolved into a high-tech, multidisciplinary endeavor. Traditional methods like metal detectors and trained dogs, which have liberated countless communities from danger, are now augmented by ground-penetrating radar, thermal cameras, advanced chemical sensors, and robotic platforms. Each technology brings its own advantages – be it the simplicity of a metal detector or the ability of GPR to find plastic mines – and each has limitations that necessitate a complementary approach. In operational contexts, militaries and humanitarians alike are deploying multi-sensor solutions: a single demining operation today might involve manual deminers with dual-sensor detectors, mine detection dogs sweeping adjacent areas, a mechanical deminer clearing vegetation, and drones mapping from above. This integrated toolbox dramatically improves safety and efficiency compared to any one method alone.

AUTHOR CONTRIBUTIONS

A.K. – methodology, conceptualization, software, formal analysis, validation, resources, investigation, writing-original, draft preparation, visualization; H.L., A.S. – conceptualization, resources, validation, investigation, methodology, writing-review and editing, visualization, supervision.

COMPETING INTERESTS

The authors declare no competing interests.

ACKNOWLEDGMENT

The authors acknowledge the support from NFDU project №2023.04/0150 "Development of mobile radiowave source positioning and power measuring and visualising system".

REFERENCES

[1] J. Ishikawa and K. Furuta, *Anti-personnel Landmine Detection for Humanitarian Demining*. London: Springer, 2009, pp. 43–45, 132–148, doi: 10.1007/978-1-84882-346-4.

[2] M. Croll, *The History of Landmines*. London: Leo Cooper – University of Michigan, 1998, pp. 4–5.

[3] *ScienceDaily*, "Research uses lasers to detect landmines, underground objects," University of Mississippi, 2024, pp. 2–5.

[4] A. Peyton and D. Daniels, "Detecting landmines for a safer world," *Ingenia*, no. 75, 2018. [Online]. Available: https://ingenia.org.uk/articles/detecting-landmines-for-a-safer-world

[5] F. Lombardi, H. D. Griffiths, and M. Lualdi, "Characterization of the internal structure of landmines using ground-penetrating radar," *IEEE Geosci. Remote Sens. Lett.*, vol. 18, pp. 266–270, 2020.

[6] H. Kasban, O. Zahran, et al., "A comparative study of landmine detection techniques," Springer Science Business Media, LLC, 2010, pp. 102–109.

[7] L. Capineri, T. Bechtel, and G. Pochanin, "Holographic and impulse subsurface radar for landmine and IED detection," in *Physics and Biophysics*. Dordrecht: Springer, 2019, pp. 33–52.

[8] A. Kasianchuk and H. Lastivka, "Promising areas of integration of artificial intelligence technologies in unmanned aerial vehicles," in *Proc. SPIE*, 2024, doi: 10.1117/12.3008983.

[9] S. Anitei and K. Kezic, "Bees to detect landmines based on their keen," Oak Ridge National Laboratory, 2007, pp. 2–5.

[10] H. R. Pourghasemi and O. Rahmati, "Prediction of the landslide susceptibility: Which algorithm, which precision?," *Catena*, vol. 162, pp. 177–192, 2018, doi: 10.1016/j.catena.2017.11.011.

[11] M. McNabb, "Processes drone images to identify landmines: Saving lives in Ukraine," 2024. [Online]. Available: https://dronelife.com/2024/10/28/spotlightai-processes-drone-images-to-identify-landmines

[12] J. D. Kelleher, et al., *Fundamentals of Machine Learning for Predictive Data Analytics*, 2nd ed. Cambridge, MA: MIT Press, 2020, pp. 153–156.

[13] A. Saliba, K. Tout, et al., "Bridging human expertise with machine learning and GIS for mine type prediction and classification," *ISPRS Int. J. Geo-Inf.*, 2024, doi: 10.3390/ijgi13070259.

[14] S. Lameri, F. Lombardi, P. Bestagini, et al., "Landmine detection from GPR data using convolutional neural networks," in *Proc. IEEE*, 2017, pp. 3–5.

[15] K. Gholamnia, T. G. Nachappa, et al., "Comparisons of diverse machine learning approaches for wildfire susceptibility mapping," Univ. of Salzburg, Salzburg, Austria, 2020.

Artem Kasianchuk

Received a first master's degree in Cybersecurity in 2020 and the second master's degree in Telecommunications and Radio Engineering in 2023 from the Yuriy Fedkovych Chernivtsi National University in Chernivtsi, Ukraine. He is currently pursuing a PhD degree in Telecommunications and Radio Engineering at Yuriy Fedkovych Chernivtsi National University in Chernivtsi, Ukraine.

ORCID ID: 0009-0007-3428-7731

Halyna Lastivka

Received BS and MS degrees in Radio Engineering from ChNU, Ukraine. She received a Ph.D. in solid state electronics from ChNU. She is currently an associate professor of the Radio Engineering Department of ChNU. Her research interests include methods and means of radio spectroscopy, their application for research of sensory properties, structures, defects of layered and organic semiconductors.

ORCID ID: 0000-0003-3639-3507

Andrii Samila

Yuriy Fedkovych Chernivtsi National University. D.Sc. (Engineering), Full Professor, Head of Radio Engineering and Information Security Department of Yuriy Fedkovych Chernivtsi National University. Research interests: IoT, Microelectronics & Electronic Packaging, Signal Processing, Computer Hardware Design, Robotics, High Energy & Nuclear Physics. Author of nearly 200 publications in this research area.

ORCID ID: 0000-0001-8279-9116

Перспективи розвитку та використання ядерних методів виявлення наземних мін та мінних полів

Артем Касьянчук*, Галина Ластівка, Андрій Саміла

Кафедра радіотехніки та інформаційної безпеки, Чернівецький національний університет імені Юрія Федьковича, м.Чернівці, Україна

*Автор-кореспондент (E-mail: kasianchuk.artem@chnu.edu.ua)

АНОТАЦІЯ Наземні міни залишаються смертельно небезпечною спадщиною минулих і поточних конфліктів, за оцінками – близько 60 країн мають приблизно 110 мільйонів активних наземних мін на своїх територіях. Ці приховані вибухові пристрої щороку спричиняють тисячі жертв – лише у 2022 році наземні міни та вибухові залишки війни забрали життя або поранили понад 4700 осіб, переважна більшість з яких були цивільними особами (приблизно половина жертв – діти). Окрім людських жертв, наземні міни перешкоджають економічному відновленню, роблячи сільськогосподарські угіддя та інфраструктуру непридатними для використання. Знешкодження мін є кропіткою та досить дорогою справою (безпечне знешкодження міни, виробництво якої коштує всього 3 долари, може коштувати до 1000 доларів). Як військові інженери, так і гуманітарні організації з розмінування використовують цілий ряд перевірених часом методів та технологій для виявлення та безпечного знешкодження наземних мін та мінних полів на великих ділянках територій. Окрім стандартизованих методів виявлення наземних мін та мінних полів, для подолання сучасних викликів у даній сфері – досліджуються такі нові технології, як: вдосконалена сенсорна інтеграція та 3D-візуалізація, LiDAR та оптичні методи, ядерні методи, біологічні методи виявлення, квантові сенсори. Однак, жоден метод виявлення не є ідеальним – кожен має свої сильні сторони та обмеження, і часто для більшої ефективності поєднують кілька технік. У цій статті подано огляд сучасних технологій виявлення наземних мін і мінних полів, що охоплює як широко використовувані оперативні інструменти, так і перспективні експериментальні методи, а саме детальний огляд та порівняльна характеристика таких методів виявлення, як: ядерний квадрупольний резонанс та методи виявлення на основі нейтронів (нейтронна активація). Також розглянуто, як штучний інтелект (ШІ) інтегрується з методами по виявленню наземних мін та мінних полів та як ШІ може ще більше покращити процес детектування наземних мін за допомогою комп'ютерного зору, обробки сигналів та прогнозного моделювання.

КЛЮЧОВІ СЛОВА ядерний квадрупольний резонанс, нейтронний детектор, наземні міни, виявлення мінних полів, штучний інтелект.