AVE Trends in Intelligent Applied Sciences

Assessing the Efficiency of Thermal Imaging and Advanced Scanners for Rapid Landmine Detection: A Case Study of Large-Area Surveying

J. Adeline Sneha[1], Jouma Ali Al-Mohamad[2,*], Ahmed Samir Naje[3], Ijaz Ahad[4], Omar Muhammed Neda[5], Wilhelmus De Wilde[6]

[1]School of Computing, Asia Pacific University of Technology and Innovation, Bukit Jalil, Kuala Lumpur, Malaysia.
[2]Department of Computer and Mobile Communication Engineering, Faculty of Information Engineering, Al-Shahbaa Private University, Aleppo, Aleppo Governorate, Syria.
[3]Department of Water Resources Management Engineering, College of Engineering, Al-Qasim Green University, Al-Qasim, Babylon Governorate, Iraq.
[4]Department of Computer Systems Engineering, University of Engineering and Applied Sciences, Swat, Khyber Pakhtunkhwa, Pakistan.
[5]Department of Electrical Power Engineering, Sunni Diwan Endowment, Baghdad, Iraq.
[6]Faculty of Architecture and the Built Environment, Delft University of Technology (TU Delft), Delft, South Holland, The Netherlands.
adeline.john@apu.edu.my[1], jalmohamad@su.edu.sy[2], ahmed.sameer@wrec.uoqasim.edu.iq[3], ijazahad@ueas.edu.pk[4], omar.muhammed@imamaladham.edu.iq[5], pioneertech@tudelft.nl[6]

*Corresponding author

Abstract: After over 15 years of fighting, over 15.4 million Syrians are in danger of injury or death from explosive threats. Traditional manual demining procedures, while effective, are slow, laborious, and dangerous, covering only 50–100 square meters each day and making large-area surveys a multi-decade process. This paper compares thermal imaging with advanced scanning technologies such as magnetometry, ground-penetrating radar (GPR), and multi-sensor fusion for rapid landmine detection in large-area surveying applications, using Syria's pioneering November 2025 drone trial as a case study. Through examination of each detection modality's physical principles, empirical performance data from controlled trials and field deployments, and Syria's operational experience with German-supplied systems, this study shows that thermal imaging offers the fastest large-area survey capability, with UAV-based systems covering up to 20 hectares per day and achieving detection accuracies of 83.7–96.14% under optimal conditions. Thermal imaging detection rates decline to 31% for deeply buried mines at 15 cm depth, compared with GPR's 87% under the same conditions, due to environmental factors, burial depth, and diurnal timing. Magnetometer-based devices identify metallic targets better at 6–7 meters but not non-metallic mines. Based on the research, a multi-sensor fusion strategy including thermal imaging, magnetometry, and GPR is the best way to detect large-area mines quickly and accurately. The research recommends wide-area thermal screening, targeted magnetometer verification, and high-resolution GPR confirmation for large-area survey activities in Syria. The findings apply to Syria and other conflict-affected nations using advanced sensing technologies to accelerate humanitarian demining.

Keywords: Landmine Detection; Explosive Ordnance; Thermal Imaging; Ground-Penetrating Radar (GPR); Multi-Sensor Fusion; UAV-Based Detection; Humanitarian Demining.

Cite as: J. A. Sneha, J. A. Al-Mohamad, A. S. Naje, I. Ahad, O. M. Neda, and W. D. Wilde, "Assessing the Efficiency of Thermal Imaging and Advanced Scanners for Rapid Landmine Detection: A Case Study of Large-Area Surveying," *AVE Trends in Intelligent Applied Sciences*, vol. 2, no. 2, pp. 98–110, 2026.

Journal Homepage: https://www.avepubs.com/user/journals/details/ATIAS

Received on: 04/02/2025, **Revised on:** 03/04/2025, **Accepted on:** 04/06/2025, **Published on:** 05/06/2026

Copyright © 2026 J. A. Sneha *et al.,* licensed to AVE Trends Publishing Company. This is an open access article distributed under CC BY-NC-SA 4.0, which permits copying, remixing, redistributing, transformation, and building upon the material in any medium so long as the original work is properly cited.

DOI: https://doi.org/10.64091/ATIAS.2026.000359

1. Introduction

Landmines and explosive remnants of war (ERW) are among the most durable and lethal legacies of armed conflict, continuing to threaten civilian lives long after active hostilities have ceased. “Explosive contamination is different in nature from many other effects of war; it can last for decades and restrict access to agricultural land, roads, residential areas, schools, health-care facilities, and essential infrastructure [1]. The continued presence of mines and unexploded ordnance also poses major challenges for humanitarian assistance, return of populations, reconstruction and economic recovery. According to the Landmine Monitor, 4,710 casualties from mines and ERW were recorded globally in 2022, up from 5,757 casualties in 2023 [2]. These Figures 1, 2, 3, and 4 highlight the disproportionate humanitarian impact of explosive contamination, with civilians accounting for some 84% of reported casualties in 2023, and children accounting for 37% of civilian casualties. These persistent dangers expose the limits of conventional mine-action approaches and create an urgent need for technologies that can map polluted areas faster, more safely and more accurately [3]. The landmine problem is global. An estimated 100 million landmines are buried around the world, a legacy of the heavy use of cheap explosive devices in past and present wars. It is estimated that about 26,000 people are directly exposed to landmine explosions every year, with children being especially vulnerable. The conventional clearance process remains demanding, as each suspected hazardous area must be surveyed, identified, verified and then cleared using carefully controlled procedures. Traditional manual demining methods depend heavily on trained personnel using metal detectors, probing equipment and visual inspection [4].

Although these methods remain important for confirmation and clearance, using them across very large contaminated territories is inherently slow and poses significant risks to personnel [5]. A conventional manual deminer may clear approximately 50–100 square meters per day depending on terrain, vegetation, soil conditions, contamination characteristics and operational procedures. As a result, surveying large contaminated areas using conventional techniques alone could take many years, or even decades. Conventional clearance cost estimates often range from US$300 to US$1,000 per mine and involve high human costs. The constraints have raised interest in remote sensing, uncrewed aerial vehicles (UAVs), artificial intelligence and multi-sensor detection technologies as complementary tools to accelerate the survey and prioritization stages of mine action [6]. The need for faster detection is especially urgent in Syria, where nearly 15 years of conflict have created a massive and geographically widespread explosive ordnance contamination crisis. Syria has suffered from long periods of military operations, displacement of population, destruction of infrastructure and extensive use of mines, improvised explosive devices, unexploded ordnance and other explosive hazards. According to the 2025 Humanitarian Needs Overview, more than two-thirds of the population, or over 15.4 million Syrians, are at immediate risk of injury or death from explosive ordnance. The contamination directly threatens civilians returning to previously inaccessible communities, and it is a major obstacle to agricultural recovery, reconstruction, transportation, humanitarian access and the restoration of essential public services [7].

Population movements and reconstruction activities have increased the need for accurate contamination mapping and rapid risk reduction. The problem has become increasingly important following changes in the security and political environment after the end of the Assad government in December 2024. Available incident data indicate the continuing severity of the Syrian explosive ordnance crisis [8]. From 8 December 2024 to 21 November 2025, UNMAS recorded 849 explosive ordnance accidents, which resulted in 1,568 casualties, including 581 people killed and 987 injured. The 2025 Landmine Monitor also recorded over 6,000 incidents in the previous year, resulting in approximately 1,945 deaths and 4,325 injuries. Other monitoring sources registered some 650 incidents of unexploded ordnance in the first nine months of 2025 alone, resulting in more than 570 deaths and 850 injuries. Mine action organizations have made great strides, surveying more than 2.9 billion square meters of land and destroying more than 27,000 explosive items, but vast contamination remains. Given the scale of the problem, how quickly hazardous areas can be identified matters as much as the physical clearance that follows [9]. Accurate survey information can help mine-action authorities prioritize high-risk locations, protect communities, support safe returns and guide limited clearance resources to locations where they can provide the greatest humanitarian benefit. In this context, thermal infrared imaging appears to be a promising technology for rapid, large-area mine detection. The core concept of thermal detection is based on the disparity of thermophysical properties of buried mines and the soil in which they are embedded [10].

Landmines contain casing materials, explosive components, detonators and other materials that may react differently to changes in environmental temperature than the surrounding soil [11]. These differences may produce measurable differences in surface temperature when the ground is heated by solar radiation or cooled under night-time conditions. Buried objects may be indicated by areas of thermal contrast on images generated by thermal cameras that detect infrared radiation. Thus, mines can be detected without direct physical contact with the ground. The success of this approach depends on environmental and physical parameters such as burial depth, soil composition, moisture content, mine size, surface conditions, weather, solar radiation and the time of image acquisition. The potential of UAV-based thermal imaging has been further enhanced by recent developments in artificial intelligence. Machine learning and deep learning-based algorithms can evaluate large numbers of thermal images and identify spatial patterns that correlate with suspected mines [12]. A study was performed in 2025 with thermal cameras on UAVs, and

the architecture MobileNetV3-Large was utilized. The training, validation and testing accuracies were 96.97%, 97.19% and 96.14%, respectively. Other studies reported a detection accuracy of 92.13% for plastic anti-personnel mines, while the sensitivity of thermographic images taken from UAVs was 82.4%. Average detection success rates of about 97.1% for images at one meter above ground level and 88.8% at higher altitudes have also been shown using UAV thermal systems. Studies across different observation periods show that evening thermal imagery can achieve detection accuracies of nearly 88%, underscoring the importance of thermal contrast and measurement timing. At the University of Twente, extensive field research has further investigated thermal imaging performance across multiple soil conditions, drone platforms, thermal cameras, landmine replicas, field campaigns and computational simulations [13].

Studies like these show the potential of thermal sensing coupled with convolutional neural networks to improve automated detection. But thermal imaging is not an infallible detection method [14]. The thermal signal is increasingly attenuated before it reaches the ground surface, so thermal contrast decreases with increasing burial depth. Furthermore, environmental conditions can greatly affect detection performance. Factors influencing the thermal response of contaminated ground include soil moisture, vegetation, surface roughness, solar radiation, wind, ambient temperature and cloud conditions. As a result, deep mines can be mistaken for natural thermal variations. This limitation is particularly apparent in experimental evidence; for example, thermal detection rates can drop to around 31% for mines buried at 15 cm depth, while GPR has achieved around 87% detection rates under similar conditions [15]. Thermal imaging should therefore be seen primarily as a rapid screening technology, not as a standalone clearance or confirmation technology. Its main advantage is that it can rapidly survey large areas and locate places for further detailed investigation. Magnetometry provides a complementary sensing modality because it measures magnetic, rather than thermal, anomalies. Metallic landmines and unexploded ordnance contain ferromagnetic materials that cause disturbances in the Earth's magnetic field, which can be detected by magnetic survey systems. Today's magnetometers are highly sensitive and can be combined with UAV platforms, so personnel do not have to enter dangerous environments. The German-supplied Setera drone tested in Syria has magnetometer-based scanning. It is said to detect mines, unexploded ordnance and other explosive remnants to depths of up to about six meters. The system can also estimate the depth, weight and size of detected objects [16].

These capabilities are especially useful for detecting metallic targets with weak or ambiguous surface signatures [17]. However, magnetometry has one important limitation: it relies on the target's magnetic properties. Plastic and other non-metallic mines may produce little or no detectable magnetic anomaly, so magnetometer-only surveys cannot fully cover all mine types. A complementary technique is ground-penetrating radar (GPR), which emits electromagnetic waves into the ground and measures the reflections caused by changes in subsurface material properties. GPR is sensitive to variations in dielectric properties and can detect both metallic and non-metallic objects, including plastic mines that conventional metal detectors or magnetometers may miss. GPR is especially successful in dry, non-conducting soils, where electromagnetic penetration is relatively good, and can investigate subsurface features to depths beyond what most traditional surface-based detection methods can achieve [18]. However, soil composition, moisture, terrain irregularities, vegetation, and subsurface clutter affect GPR performance. Complex GPR data also requires expertise to interpret and process, which can slow operational deployment. Also, GPR equipment used on UAVs can be heavy and bulky, reducing flight duration and increasing logistical requirements. Acquisition and maintenance costs can also be significant for mine-action programs operating under severe financial and technical constraints. Syria pioneered the drone trial on 16 November, 2025, demonstrating the practical relevance of these technologies. The Syrian Ministry of Emergency and Disaster Management, through the National Mine Action Center (NMAC), conducted the country’s first practical trial of an advanced German-made drone for landmine detection in the Drousha area of the Damascus countryside [19].

It was described as the first such trial in Syria and the broader Middle East. The Setera drone was equipped with thermal imaging, specialized cameras, high-precision sensors, and a magnetometer scanning system [20]. According to operational reporting, the system can detect buried explosive objects and estimate characteristics such as depth, weight and size while operating at speeds of up to about 8 km/h. In a field test, the drone surveyed about 10,000 square meters in just 35 minutes, demonstrating its potential to significantly speed up preliminary large-area surveys and reduce survey personnel's direct exposure to hazardous environments. But the Syrian trial showed that operational realities must be weighed against technological capability. GPS instability and poor internet connectivity were real challenges during testing, reflecting broader infrastructure limitations stemming from years of violence and damage [21]. These restrictions are essential because sophisticated UAV systems rely on accurate positioning, communication, data transmission, battery management, and technical support. Continuing the planned testing in Hassia City in the Homs countryside provides an opportunity to evaluate system performance under different environmental and terrain conditions. More generally, the Syrian experience reminds us that successfully implementing advanced mine detection technologies requires not only the right sensors, but also trained personnel, reliable communications, data-management systems, maintenance capacity, field protocols and integration into national mine action planning. Comparing thermal imaging, magnetometry, and GPR shows that each technology has distinct advantages and limitations [22].

Thermal imaging has strong potential for rapid, wide-area screening and can cover large areas using UAV platforms, but its performance depends heavily on environmental conditions and burial depth. Magnetometry is effective for metallic objects and

can detect targets at greater depths. However, it has limited ability to detect non-metallic mines. GPR can detect metallic and non-metallic targets and can provide useful information about what is underground [23]. Still, it is relatively expensive, requires technical expertise to operate, and can be sensitive to soil and terrain conditions. These differences explain why using a single sensing modality may yield incomplete or ineffective survey results. In contrast, integrating several complementary technologies can improve both coverage and confidence in the detection results [24]. This work thus proposes a fast, large-area mine-survey approach in Syria based on a multi-sensor system across three complementary operational levels. At the first level, UAV-based thermal imaging serves as a wide-area screening tool to rapidly locate potential thermal anomalies. The second level employs magnetometer-based scanning to confirm and characterize potential metallic targets identified in the initial screening. The third level uses GPR for high-resolution subsurface investigation, especially in areas where non-metallic mines are suspected, or where thermal and magnetic results are ambiguous. In this way, the speed of thermal imaging, the depth sensitivity of magnetometry, and the material-detection capabilities of GPR can be combined in this layered approach [25].

The proposed framework treats advanced sensing technologies as force multipliers to improve prioritization, reduce unnecessary personnel exposure, and speed up the identification of areas requiring detailed clearance, but not as a replacement for conventional manual demining [26]. This study seeks to fill a major research gap: the lack of an integrated comparative assessment of these technologies for large-area mine surveying in Syria. To date, studies have focused on thermal imaging, magnetometry, or GPR alone. At the same time, the most recent reports on Syrian drone operations mainly present technological demonstrations rather than systematically comparing detection principles, operational performance, environmental constraints, and large-area survey potential [27]. This paper fills that gap by considering thermal imaging and advanced scanning technologies based on their underlying physical principles, empirical performance data, and practical experience from the Syria November 2025 Setera drone trial. The analysis is especially focused on the trade-offs between survey speed, detection reliability, target characteristics, environmental sensitivity, operational complexity and applicability to large contaminated areas [28]. The study correlates technological performance with the realities of Syria's mine-action operating environment to develop a practical three-tier framework that integrates wide-area thermal screening, targeted magnetometer verification, and high-resolution GPR confirmation [30]. The resulting approach aims to support safer, more efficient humanitarian mine action in Syria and to provide lessons that may apply to other conflict-affected countries facing widespread explosive ordnance contamination and limited resources for traditional large-scale surveying [29].

2. Literature Review

Landmines and explosive remnants of war (ERW) are among the most intractable and destructive legacies of armed conflict, remaining serious threats to civilian populations long after active hostilities have ended. According to the International Campaign to Ban Landmines, in 2022 there were 4,710 mine and ERW casualties globally, which increased to 5,757 in 2023, with civilians accounting for 84% of casualties and children making up 37% of civilian casualties (Landmine Monitor, 11,12) [1]. Alongside direct casualties and injuries, explosive contamination hampers humanitarian access, the safe return of displaced populations and agricultural production, infrastructure rehabilitation and economic reconstruction (UNMAS, 19; MAG, 17) [2]. The continued presence of contamination creates an urgent need for faster, safer survey technologies because traditional manual demining is labor-intensive, technically demanding and hazardous. Large contaminated areas are difficult to evaluate quickly, and traditional survey teams may cover only about 50-100 m2 per day [3]. Thus, UAV-based remote sensing, thermal imaging, magnetometry, ground-penetrating radar (GPR), artificial intelligence, and multi-sensor data fusion are promising approaches to accelerate humanitarian mine action (I-Corps, 27; Uncrewed Systems, 25). Syria is one of the most pressing settings for these technologies. The 2025 Humanitarian Needs Overview estimates that nearly 15 years of protracted conflict has resulted in widespread contamination, with more than 15.4 million Syrians believed to be at immediate risk from explosive ordnance. Between 8 December 2024 and 21 November 2025, UNMAS recorded 849 explosive ordnance accidents with 1,568 casualties, including 581 deaths and 987 injuries [4].

The 2025 Landmine Monitor also documented over 6,000 incidents during the reporting period, underscoring the crisis's continued scale [5]. However, humanitarian mine-action organizations have made significant operational progress, surveying more than 2.9 billion m 2 and destroying more than 27,000 explosive items, although widespread contamination remains a major barrier to recovery and safe population return. One potential solution is thermal infrared imaging that exploits the differential thermal properties of mines and surrounding soil. Objects buried in the soil may react differently to the surrounding soil when it is heated by the sun or cooled during night-time conditions, creating thermal contrasts that can be detected by infrared cameras. Detection performance depends strongly on burial depth, soil type, moisture, mine characteristics, weather conditions and the time of image acquisition. The recent incorporation of deep learning with thermal imaging has greatly improved automated detection. Heuschmid et al. [1] developed a UAV-based thermal detection method using the MobileNetV3-Large architecture and reported training, validation, and test accuracy of 96.97%, 97.19%, and 96.14%, respectively. Similarly, a study on thermographic detection of anti-personnel "leg breaker" mines reported 92.13% accuracy and 82.4% sensitivity under experimental conditions. UAV thermal detection has also had high success rates at different flight altitudes. Extensive field campaigns at the University of Twente examined multiple soils, drones, thermal cameras, landmine replicas and deep-learning

architectures to evaluate the robustness of thermal detection. However, thermal imaging is greatly influenced by environmental and burial conditions, and high accuracy in laboratory or controlled field conditions does not necessarily translate to equivalent performance under complex Syrian field conditions [11].

Magnetometry is a complementary method that measures disturbances of the Earth's magnetic field caused by ferromagnetic materials. UAV-mounted magnetometers can survey dangerous areas where humans are not required in suspected minefields and can provide information on the location and characteristics of metallic targets. UAV-based magnetometer surveys have demonstrated potential for mine detection, and machine-learning classification can further improve the identification of metallic landmines from magnetic signatures [7]. The Syrian Setera drone uses magnetometer-based scanning and claims to detect mines and other explosive remnants at depths of about six meters, estimating characteristics such as depth, weight, and size. However, magnetometry is limited in that it is effective only if there is metallic material to be detected, and may therefore be of little use in non-metallic mines. GPR complements this by sending electromagnetic waves into the subsurface and analyzing the reflected signals caused by dielectric contrasts. This allows GPR to detect both metallic and non-metallic objects and is especially important for plastic mines that magnetic methods might otherwise miss. Recent research on landmine detection using drone-mounted FMCW GPR, multi-channel UWB radar, and array-based signal-processing techniques shows ongoing technological progress in this area (Low-Cost Drone-mounted FMCW GPR, 33; Ground Penetrating Radar System, 34; Study on Signal Processing, 35). However, GPR performance may be limited by factors such as soil composition, surface roughness, subsurface clutter, equipment weight, processing requirements and acquisition cost that may limit rapid deployment over large areas. Therefore, comparative research has increasingly focused on integrating different sensing modalities rather than a single technological solution (Comparative Evaluation, 4; Automated Airborne Ordnance Detection, 5; Integrated Drone Solutions, 6) [9].

This approach was particularly relevant during Syria’s pioneering drone trial on 16 November 2025, when the Ministry of Emergency and Disaster Management tested a German-supplied Setera drone in the Drousha area of the Damascus countryside. The system used thermal imaging and advanced scanning technologies and surveyed approximately 10,000 m2 in 35 minutes at speeds up to 8 km/h, according to reports [4]. The trial showed UAV technology's potential to rapidly survey suspected contaminated areas and produce information on detected objects. However, GPS instability and poor internet connectivity showed the need to account for Syria's recovering communications and digital infrastructure when deploying advanced sensing systems. These results indicate a clear research gap: previous studies have focused separately on thermal imaging, magnetometry, GPR, UAV sensing and artificial intelligence, but few studies provide an integrated comparison of their large-area survey capabilities in the Syrian operational context. This study therefore compares thermal imaging, magnetometry and GPR in terms of detection principles, potential coverage, environmental sensitivity, target characteristics, operational requirements and applicability to Syria. This implies a multi-sensor approach in which thermal UAV imaging provides rapid, wide-area screening; magnetometry targets and verifies metallic anomalies; and GPR provides high-resolution confirmation. In this way, the complementary strengths of each technology are integrated, reducing dependence on the limitations of any one technology. Such an integrated framework can enable safer, faster and more systematic humanitarian mine-action operations in Syria and offer transferable lessons to other conflict-affected countries with extensive explosive ordnance contamination [6].

3. Methodology

This study uses a mixed-methods approach, including a literature review, comparative technology assessment, case study analysis and quantitative performance evaluation, to assess the applicability of advanced sensing technologies for rapid landmine detection. The study includes thermal imaging, magnetometry and ground-penetrating radar (GPR), with particular emphasis on their prospects for large-area surveying in Syria. The main data include official statements from the Syrian Ministry of Emergency and Disaster Management, reports from the Syrian Arab News Agency (SANA) on the November 2025 drone trial, and technical specifications from the German manufacturer Setera. These sources provide the operational background, technical capabilities, and field experience surrounding Syria’s growing drone-based mine-detection activities. Secondary data is collected from peer-reviewed academic literature on thermal imaging, magnetometry, GPR, UAV-based sensing, and automated mine detection. This includes literature from IEEE Xplore, ScienceDirect and Springer. Further evidence is drawn from humanitarian mine-action reports published by organizations such as HALO Trust, Handicap International and UNMAS, Landmine Monitor 2023, Landmine Monitor 2025 and other relevant mine-action statistics.

The main case study is the field trial of the German-supplied Setera drone in the Drousha area of the Damascus countryside on 16 November, 2025. The study includes comparative field evaluations of UAV-based sensing modalities to provide a broader basis for assessing the technology's performance. Evidence collected is analyzed using five interrelated dimensions. First, physical principles cover the science underlying thermal, magnetic, and radar sensing. Second, detection performance measures reported accuracy, sensitivity, specificity, and detection depth. Third, survey speed and efficiency measure coverage rates and operational throughput. Fourth, environmental sensitivity considers the impact of soil properties, weather conditions, burial depth, and diurnal variation. Finally, operational requirements include equipment costs, infrastructure requirements,

communication systems, maintenance needs and technical expertise. Based on these dimensions, the capabilities and limitations of each technology are compared to determine their suitability for integrated, large-area humanitarian mine surveying in Syria (Figure 1).

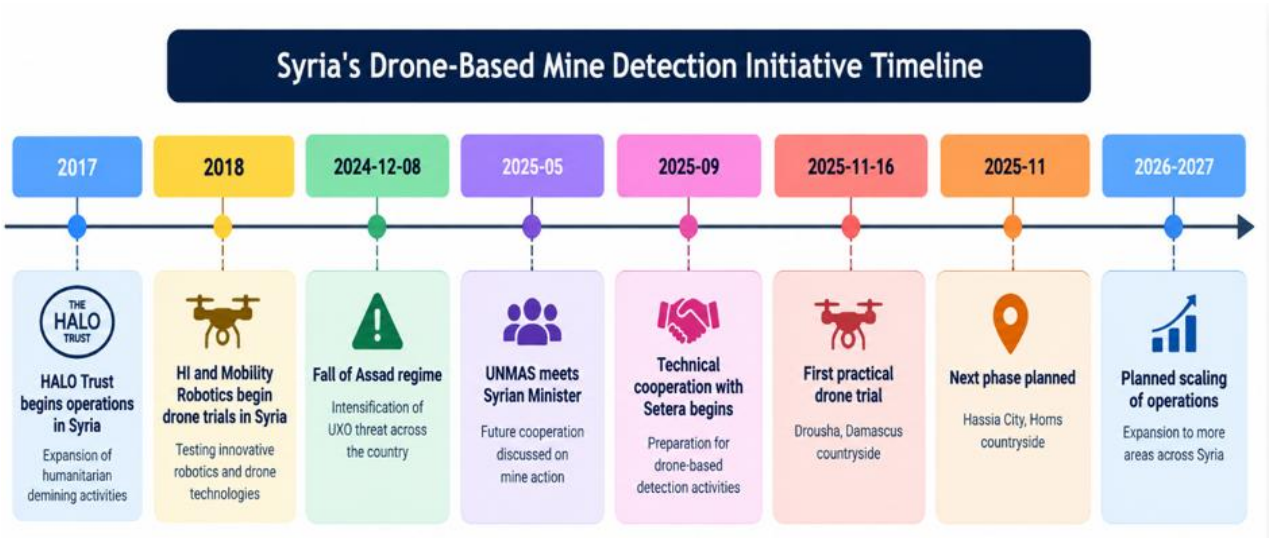


Figure 1: Timeline of Syria's drone-based mine detection initiative

4. Results and Discussions

4.1. Detection Technologies: Physical Principles and Performance Characteristics

Thermal Infrared Imaging: Thermal infrared imaging is used to detect the infrared radiation emitted by objects based on their temperature. Buried landmines and the surrounding soil have different thermal properties. Landmines are usually better thermal insulators than earth. As the ground warms under solar radiation or cools during the nite, mines and soil react differently, creating thermal contrasts that can be picked up by infrared sensors. Under ideal conditions, thermal imaging reports detection efficiencies of approximately 83.7–96.14%. Its depth capability is best for surface and shallowly buried mines (generally less than 5 cm), with performance degrading as burial depth increases. UAV-based thermal systems can quickly cover large areas (up to ~20 ha/day) and are therefore well suited for preliminary screening. Acquisition in the early morning, evening, and night-time may improve detection when thermal differences between buried objects and the surrounding soil are more pronounced. The major advantages are: rapid wide-area surveying, passive sensing without active signal emission, relatively low equipment costs and the ability to detect some non-metallic mines. However, thermal imaging is very sensitive to weather conditions, soil moisture, vegetation, surface conditions and daily temperature variations. False positives can also be caused by natural thermal anomalies. Burial depth can strongly affect detection reliability.

4.2. Magnetometry

Magnetometry measures the local variations of the Earth's magnetic field caused by ferrous materials. Metallic landmines and unexploded ordnance can therefore produce measurable magnetic anomalies which can be used to estimate their location and characteristics. Magnetometer-based systems can detect large metallic objects at depths of about 6-7 meters in favorable conditions, and are particularly efficient for metallic targets. During the Syrian drone trial, the system scanned about 10,000 m² in 35 minutes (with a claimed operating speed of up to 8 km/h) and provided estimated weight, depth and size for detected objects. Advantages of magnetometry include its ability to detect deeply buried targets, quantitatively characterize targets, remain relatively insensitive to weather conditions, and rely on well-established interpretation techniques. The technology is not reliable for detecting non-metallic mines, and magnetic background noise can affect the technology. Accurate interpretation requires proper personnel training, as weak-signature or small objects may go undetected. Ground Penetrating Radar (GPR) transmits electromagnetic waves into the ground and records reflected signals from structures below the surface. GPR can find both metal and non-metal objects because of the dielectric contrast between the soil and buried objects.

Under good conditions, GPR can detect objects meters below the surface and give some useful information about depth and structure. Reported experimental results indicate a detection rate of about 87% for deeply buried mines at 15 cm, highlighting its potential where thermal detection is less effective. GPR can provide high-resolution, possibly three-dimensional images of

subsurface structures, which helps with detailed confirmation. It can detect metallic and non-metallic mines, provide depth information and perform very well in dry, non-conductive soils. However, GPR systems tend to be bulky and heavy, which limits the UAV flight endurance and complicates the deployment. Penetration and detection performance can be severely degraded in soils that are moist or electrically conductive. Furthermore, GPR produces complex datasets that require specialized processing and interpretation, and acquisition, maintenance and operation costs can be relatively high.

4.3. Multi-Sensor Fusion

Multi-sensor fusion combines data from multiple sensor technologies to achieve more comprehensive detection capability than a single modality. Possible combinations are magnetometry and GPR, thermal imaging and magnetometry, and thermal imaging and GPR. Multi-sensor systems employ multiple physical sensing mechanisms to enhance detection probability, reduce false alarms through cross-validation, and increase coverage of metallic and non-metallic targets at different burial depths. Thermal imaging enables rapid, wide-area screening; magnetometry locates and characterizes metallic anomalies; and GPR provides detailed subsurface confirmation of metallic and non-metallic objects. The main benefits of fusion are therefore complementary use of sensor strengths, increased confidence through cross-validation, complete target detection and greater adaptability to a variety of environments. However, multiple sensor systems also imply higher costs and more technical complexity (Figure 2).

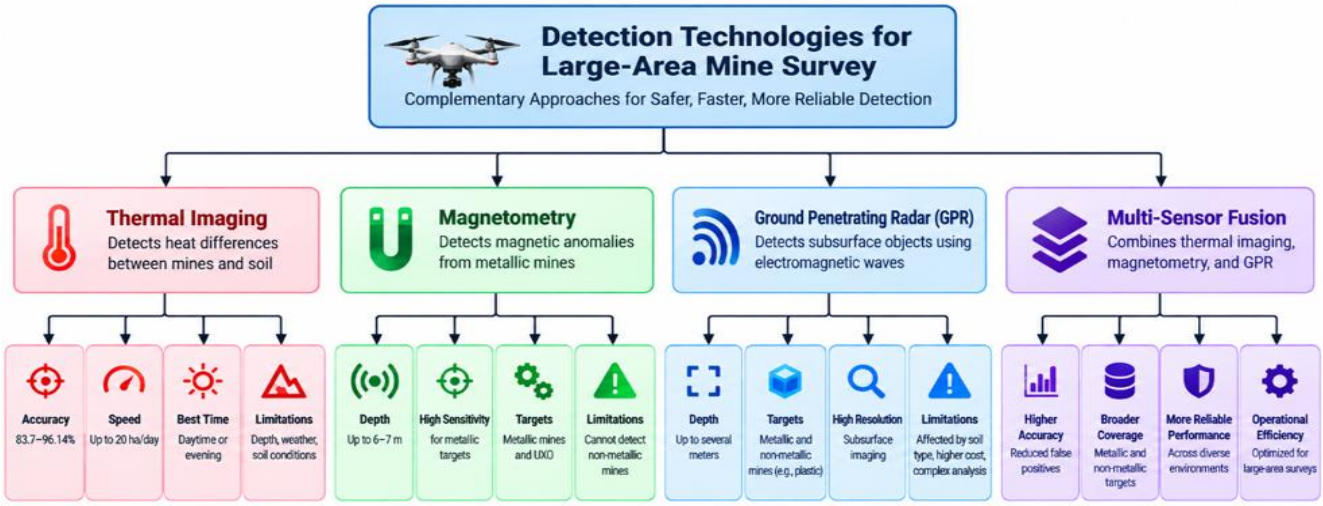


Figure 2: Detection technologies for large-area survey comparative overview

Successfully deploying this system requires sophisticated data-fusion algorithms, skilled technical personnel, appropriate calibration and reliable data-processing infrastructure. Using multiple sensors can also increase equipment weight, power consumption and UAV payload requirements, which may reduce flight endurance and operational flexibility. However, multi-sensor fusion provides a systematic basis for integrating rapid screening with targeted verification and high-resolution confirmation in large-area humanitarian mine-survey operations.

4.4. Comparative Performance Analysis

- **Detection Accuracy:** The Comparative Performance of different detection technologies varies significantly with target characteristics, Environmental Conditions, and Operational Parameters.
- **Survey Speed and Area Coverage:** Survey speed and area coverage vary dramatically across technologies.
- **Environmental Sensitivity:** Environmental conditions affect each technology's performance differently.

Table 1: Detection accuracy comparison across technologies

Technology	Best-Case Accuracy	Conditions	Reference
Thermal Imaging (DL)	96.14%	UAV-based, DJI Matrice 100, Zenmuse XT	Heuschmid et al. [1]
Thermal Imaging (MLP)	97.1%	1 m altitude, optimal conditions	Tenorio-Tamayo et al. [2]
Thermal Imaging	92.13%	Plastic AP mines, 260 test images	Kuru et al. [5]
Thermal Imaging	88.8%	Higher altitudes	Sherin et al. [6]

Thermal Imaging	88%	Evening hours	Alabi et al. [8]
Thermal Imaging	83.7%	UAV-collected, average detection	Baur et al. [4]
Thermal Imaging	75%	6 m altitude, 3 m/s speed	Kuru et al. [5]
Thermal Imaging	31%	Deeply buried at 15 cm	Kwon et al. [29]
GPR	87%	Deeply buried at 15 cm	Kwon et al. [29]

The comparative Tables 1 and 2 summarize the survey performance, environmental sensitivity and operating needs of several mine detection methods. As shown in Table 2, manual detection has a relatively low survey rate of about 50-100 m2/day and area coverage.

Table 2: Survey speed and area coverage comparison

Technology	Survey Rate	Area Coverage	Reference
Manual Detection	50-100 m²/day	0.005-0.01 ha/day	Kim and Choi [30]
UAV Thermal Imaging	Up to 20 ha/day	20 ha/day	Paun et al. [28]
UAV Magnetometer (Setera)	10,000 m²/35 min	~4.1 ha/hour	Yoo et al. [18]
UAV-based multi-Sensor	800 m²/hour	~0.08 ha/hour	Nikulin [22]

UAV-based thermal imaging can cover much larger areas, up to 20 ha/day, a major gain in operating efficiency. UAV magnetometry also enables quick coverage of roughly 10,000 m² in 35 min, or about 4.1 ha per hour. The multi-sensor UAV system records a survey rate of about 800 m²/hour and provides integrated detection capability. Table 3 shows that the performance of the different technologies is strongly influenced by environmental conditions.

Table 3: Environmental sensitivity comparison

Factor	Thermal Imaging	Magnetometry	GPR
Soil Moisture	High impact	Low impact	High impact (conductive soils)
Weather (Cloud/Rain)	High impact	Low impact	Moderate impact
Diurnal Timing	Critical	Not applicable	Not applicable
Vegetation	Moderate impact	Low impact	Low impact
Soil Type	Moderate impact	Low impact	High impact
Temperature	Critical	Not applicable	Not applicable

Thermal imaging is very sensitive to fluctuations in soil moisture, vegetation and temperature. These parameters have relatively little effect on magnetometry; however, magnetometry efficiency depends heavily on the presence of metallic objects. GPR can provide useful subsurface information, although it is more sensitive to soil moisture and conductivity. Table 4 also shows the different operational requirements of the technologies. Thermal imaging generally requires low- to moderate-cost equipment and intermediate technical skill, while magnetometry demands moderate- to high-level expertise. GPR's equipment and infrastructure requirements are somewhat higher because it requires heavier equipment and more complex processing.

Table 4: Operational requirements comparison

Requirement	Thermal Imaging	Magnetometry	GPR
Equipment Cost	Low-Moderate	Moderate	High
Technical Expertise	Moderate	Moderate-High	High
Infrastructure Needs	Low (UAV, battery)	Low (UAV, battery)	High (heavy equipment)
Processing Complexity	Moderate	Moderate	High
Deployment Speed	Rapid	Rapid	Slower

Thermal imaging and magnetometry can be deployed rapidly, whereas GPR typically takes longer to operate in the field. The comparison clearly shows that no single detection system works for all environmental and operating conditions. Integrating complementary technologies, especially UAV-based multi-sensor systems, can improve survey coverage, detection reliability and operating efficiency while overcoming the constraints of individual sensing approaches.

4.5. Syria Case Study: The November 2025 Drone Trial

- **Operational Context:** The 16 November 2025 Drone Trial in the Drousha Area of Damascus Countryside Represented a Landmark Achievement for Syria and the Wider Middle East. The Ministry of Emergency and Disaster Management

conducted the trial through its National Mine Action Centre, with Technical Cooperation from the German Company Setera.

- **Technology Employed:** The German-Supplied Drone is "Equipped with Thermal Imaging and Advanced Scanning Technology". The Primary Detection System is a "Magnetometer System Capable of Detecting Landmines, Unexploded Ordnance, and Other Remnants of War at Depths of Up to Six Meters Below Ground". The system can "Determine the Weight and Depth of Detected Objects with High Accuracy".
- **Performance Results:** The Trial Demonstrated the Drone's Ability to "Survey About 10,000 Square Meters in Only 35 Minutes". Deputy Minister Hossam Hallak Confirmed that the Trial "Has Proven Successful in Accurately Identifying Contaminated Objects, with the Ability to Provide Data on Their Weight, Depth, and Size".
- Despite the Success, the trial revealed operational challenges, including "GPS Instability and Weak Internet Connectivity—Issues Expected in a Country Whose Infrastructure is Still Recovering After Years of War".
- **Implications for Large-Area Survey:** The Trial Demonstrates the Potential of UAV-based magnetometer systems for Rapid Large-Area Survey. However, the Technology's Limitation to Metallic Targets Means It Cannot Detect the Full Range of Explosive Hazards. As Noted in the Literature, "Landmines are Made from a Variety of Materials, Including Wood, Glass, Metal, and Plastic."

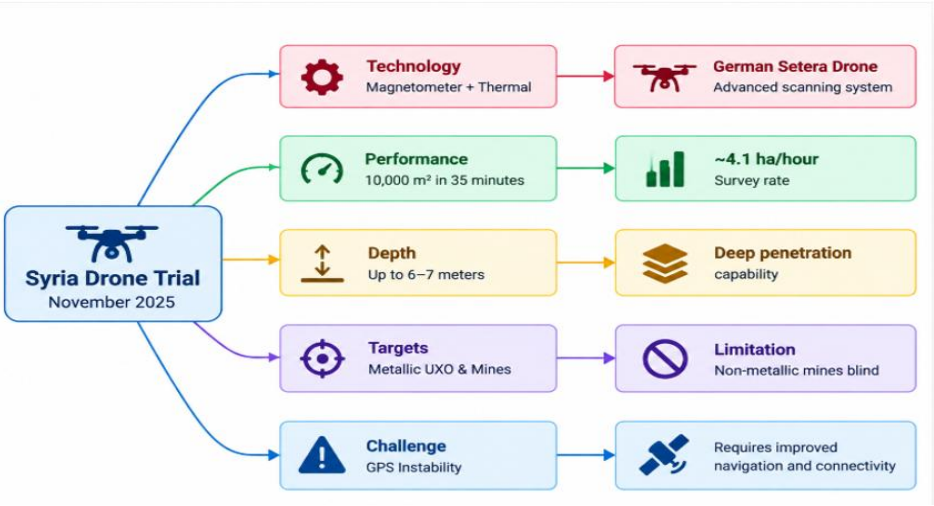


Figure 3: Syria drone trial – key performance indicators

The Syria Drone Trial in November 2025 proved the potential of sophisticated UAV-based detection technologies for large-area mine surveys. The German Setera drone combined magnetometer and thermal scanning capabilities and surveyed nearly 10,000 m2 in 35 min, which is a survey pace of roughly 4.1 ha/h. The technology displayed a deep-penetration capacity of 6-7 m and could recognise metals, UXO and mines. The system was nonetheless limited by its inability to detect non-metallic mines, showing that magnetometers alone cannot provide complete mine detection. The trial also identified operational issues related to GPS instability, navigation and connectivity, indicating a need for improved positioning and communication technologies to support successful deployment in broad and potentially challenging survey contexts (Figure 3).

4.6. Discussion: Multi-Sensor Framework and Comparative Evaluation

The comparative analysis shows that the three detection technologies have different strengths and limitations for large-area mine surveying in Syria. Thermal imaging offers the fastest wide-area coverage, with a survey speed score of 95% based on reported coverage of up to 20 ha/day, a detection accuracy of 90%, and a best-case accuracy of 96.14%. However, it has relatively limited depth capability, scoring 40% because thermal detection works best for surface and shallowly buried mines. It is also less environmentally robust (50%) because weather, soil moisture, vegetation and diurnal temperature variation can affect performance. Thermal imaging, however, has a high cost-effectiveness (85%) and deployability (90%). Therefore, UAV-based thermal systems are better suited for initial wide-area screening. Magnetometry has a different performance profile. Its survey-speed score is 85%, and it is reported to be able to survey 10,000 m 2 in 35 minutes, or about 4.1 ha per hour. Its detection accuracy is rated at 75% (the technology is mostly effective for metallic targets). In comparison, its depth capability is given a high score of 95% (indicating the potential for detection of large metallic objects at depths of approximately 6–7 m). Magnetometry also shows relatively high environmental robustness (85%) because its performance is less sensitive to thermal and diurnal conditions. The cost-effectiveness and ease of deployment score 70% and 80%, respectively. GPR offers a different,

complementary performance profile, with a lower survey-speed score of 50% due to equipment weight, operational complexity and data-processing requirements.

However, its detection accuracy is 85%. Detection rates for deeply buried mines at 15 cm depth are approximately 87%, and it scores 90% for depth capability. GPR can detect metallic and non-metallic targets and provide detailed information about subsurface and 3D structures. The environmental ruggedness rating is 60%. This is because soil moisture, conductivity and ground conditions can significantly affect performance. It scores relatively low, at 40%, on both cost-effectiveness and ease of deployment because of higher equipment costs, technical complexity and the need for specialized interpretation. These results show that no single sensing technology can simultaneously achieve full coverage, reliability, depth capability and operational efficiency. Thus, multi-sensor fusion is an important means of overcoming the limitations of individual technologies. Previous work shows that combining different sensor detection capabilities improves accuracy by providing complementary information and enabling more informed decisions. Studies on data fusion also show that fused classifiers outperform systems based on individual GPR or electromagnetic features. In the Syrian environment, thermal imaging can quickly screen and detect wide areas of surface or shallow thermal anomalies, magnetometry can detect deeper and quantitatively characterize metallic targets, and GPR can investigate non-metallic targets and provide detailed subsurface structural information. Based on this, a three-tier framework for the large-area survey operations in Syria is suggested (Figure 4).

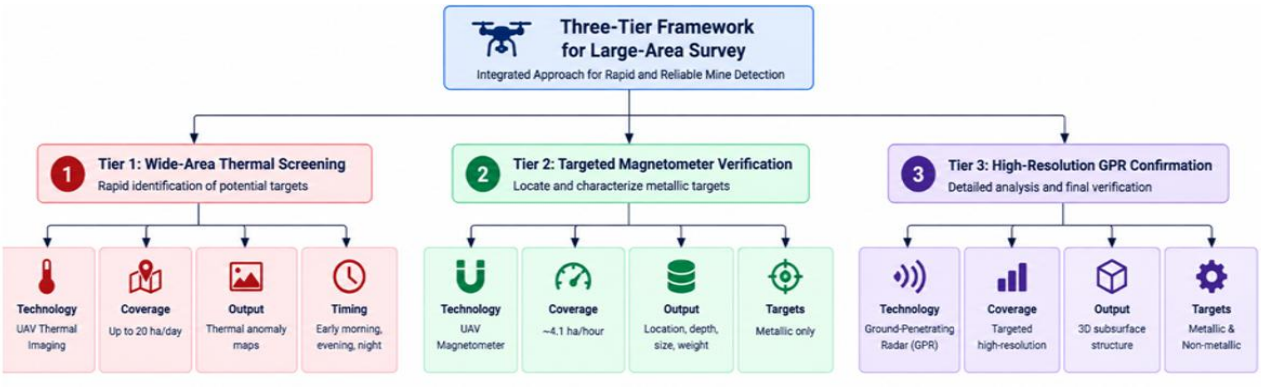


Figure 4: Three-tier framework for large-area survey operations

Tier 1 includes thermal screening at wide-area scales using UAV-mounted thermal cameras to rapidly identify suspected areas, with potential coverage of 20 ha/day and thermal anomaly maps. Surveys should preferably be done in the early morning, evening or night when thermal contrasts may be maximized. Tier 2 - Focused magnetometer verification of areas identified during the initial thermal survey. Magnetometers can characterize metallic targets from a UAV platform, such as the Setera system or similar. Target survey rates are expected to be around 4.1 ha/hour, with output being the estimated location, depth and size of detected objects. Tier 3: High-resolution GPR confirmation of priority targets requiring detailed investigation. Ground-based or UAV-mounted GPR can provide high-resolution subsurface information and three-dimensional structural characterization while supporting the identification of metallic and non-metallic objects. The sequential framework provides an integrated approach to safer, more efficient humanitarian mine surveying over large areas in Syria, combining the speed of thermal imaging, the depth capability of magnetometry, and the material-detection and structural capabilities of GPR.

5. Conclusion

Syria's landmine contamination crisis—with over 15.4 million people at immediate risk and the country on course to record the highest number of landmine casualties globally in 2025—demands innovative solutions for rapid large-area survey. Traditional manual methods, while effective, are too slow and too dangerous to address the scale of the challenge. The November 2025 drone trial in Syria marked a historic milestone, demonstrating the operational feasibility of UAV-based detection and surveying 10,000 square meters in just 35 minutes. This paper's comparative assessment shows that thermal imaging offers the fastest large-area survey capability, with UAV-based systems covering up to 20 hectares per day and achieving detection accuracies of 83.7–96.14% under optimal conditions. However, thermal imaging performance is highly sensitive to environmental factors, burial depth, and diurnal timing, with detection rates dropping to as low as 31% for deeply buried mines. Magnetometer-based systems perform best for metallic targets at depths of up to 6–7 meters but cannot detect non-metallic mines. GPR offers comprehensive detection of both metallic and non-metallic targets, with 87% detection rates for deeply buried mines, but it faces challenges with equipment weight, cost, and complexity. The analysis demonstrates that no single technology is sufficient for comprehensive large-area survey. The optimal approach is a multi-sensor fusion strategy combining the strengths of complementary technologies. The three-tier framework proposed in this paper—wide-area thermal screening, targeted magnetometer

verification, and high-resolution GPR confirmation—provides a practical pathway for integrating these technologies into Syria's mine action operations. As one analysis observed, "by shifting the paradigm from reactive clearance to predictive, data-informed humanitarian response, the system enhances the safety and sustainability of land release operations." Assessing thermal imaging and advanced scanners for rapid landmine detection is a critical step toward this paradigm shift. The decisions made in the coming years will determine whether Syria can leverage these transformative technologies to accelerate the clearance of landmines and explosive remnants of war, enabling the return of displaced populations, the rehabilitation of agricultural land, and the reconstruction of communities devastated by nearly 15 years of conflict.

5.1. Recommendation

The study finds that a combination of advanced detection technologies is needed to support large-area mine inspections in Syria, as each technology has significant strengths and limitations. UAVs with thermal imaging capability are suitable for broad first-pass screening because they can cover large areas quickly and screen far more area than manual detection. Thermal imaging may reach detection accuracies of about 83.7–96.14% under ideal environmental conditions, especially in the early morning, evening, and night. However, its effectiveness declines with increasing burial depth and is strongly affected by weather, soil quality, vegetation and temperature. Magnetometry provides a complementary method to confirm metallic targets and can detect metallic objects at much greater depths; the November 2025 trial of the Setera drone proved the feasibility of UAV-based magnetic surveying by covering approximately 10,000 m² in 35 minutes. However, magnetometry cannot guarantee full detection, as it cannot accurately detect non-metallic mines. This limitation can be overcome by the use of Ground Penetrating Radar (GPR), which can detect both metallic and non-metallic subsurface objects and has shown useful detection performance for deeply buried targets. However, its deployment can involve higher equipment costs, greater technical expertise, heavier equipment and more complex data processing. Moreover, evidence from comparable contexts including Ukraine, Cambodia, Colombia, Iraq, Lebanon and other contaminated environments indicates the potential utility of combining different sensing modalities depending on local operating conditions. These results suggest that Syria could develop a large-area survey strategy that uses thermal imaging for broad initial screening, magnetometry to confirm and characterise metallic targets, and GPR when deeper investigation or detection of non-metallic targets is required.

Multi-sensor data fusion could merge information from multiple technologies, improving the reliability of survey results while reducing the constraints of individual methods. Syrian authorities should develop standardised processes for survey prioritisation, data collection, processing, interpretation and reporting and allocate funds to procure and maintain suitable UAV, thermal, magnetometer and GPR devices. Technical training must be strengthened to build local capacity in UAV operation, sensor calibration, data processing and interpretation, equipment maintenance and the integration of multiple sensors. International partners can support this through technical assistance, financing, equipment, training, technology transfer and research support tailored to Syria-specific environmental and operational conditions. Cooperation with technology providers, academic institutions and international mine-action organisations could further aid the development of acceptable survey standards and operating procedures. Humanitarian organisations should provide advanced detection technology for applicable mine-action initiatives, promote local capacity-building, build relationships with Syrian technical institutions, and ensure systematic recording of operational experience and lessons learned. Continued international coordination would also be important to avoid duplication, to ensure that technology support is aligned with stated operational requirements, and to promote the exchange of information with other conflict-affected nations. Overall, the results suggest that a phased, integrated strategy using thermal imaging, magnetometry, GPR, trained staff and multi-sensor data analysis would provide a more complete framework for large-area mine surveys than relying on any single detection method.

Acknowledgement: The authors gratefully acknowledge Asia Pacific University of Technology and Innovation, Al-Shahbaa Private University, Al-Qasim Green University, University of Engineering and Applied Sciences, Sunni Diwan Endowment, and Delft University of Technology (TU Delft) for their valuable academic support, guidance, research resources, and institutional assistance throughout this research.

Data Availability Statement: The data supporting this study can be obtained from the corresponding author upon reasonable request.

Funding Statement: This research and manuscript preparation were completed without any financial support or external funding.

Conflicts of Interest Statement: The authors declare that they have no conflicts of interest related to this study.

Ethics and Consent Statement: The study was conducted in compliance with relevant ethical guidelines, and informed consent was obtained from all participants.

References

1. D. Heuschmid, O. Wacker, Y. Zimmermann, P. Penava, and R. Buettner, "Advancements in landmine detection: Deep learning-based analysis with thermal drones," *IEEE Access*, vol. 13, no. 5, pp. 91777–91794, 2025.
2. H. A. Tenorio-Tamayo, S. E. Nope-Rodríguez, H. Loaiza-Correa, and A. D. Restrepo-Girón, "Detection of anti-personnel mines of the 'leg breakers' type by analyzing thermographic images captured from a drone at different heights," *Infrared Physics and Technology*, vol. 142, no. 11, pp. 1–8, 2024.
3. A. Martinetti, F. Nex, and S. Askes, "Enhancing Landmine Detection Using UAVs with Thermal Imaging and Simulations," *University of Twente*, Enschede, The Netherlands, 2024.
4. J. Baur, S. Lekhak, G. Steinberg, A. Nikulin, T. de Smet, A. Brinkley, E. J. Ientilucci, F. Nitsche, H. Myers, J. Elliott, T. Bauch, N. Raqueno, and J. Frucci, "A comparative evaluation of UAV-based remote sensing and geophysical techniques for landmine detection on a seeded minefield," *Remote Sensing*, vol. 18, no. 13, pp. 1–38, 2026.
5. K. Kuru, D. Ansell, D. Jones, B. Watkinson, J. M. Pinder, R. Hamila, and C. Tinker-Mill, "Automated airborne ordnance detection using data fusion of magnetometer and ground penetrating radar," in *Proc. Interdisciplinary Conference on Electrics and Computer (INTCEC),* Chicago, Illinois, United States of America, 2025.
6. K. Sherin, N. Mithun Kumar, K. Rohith, and A. R. Darshika Kelin, "Integrated drone solutions for landmine detection," in *Proc. International Conference on Computing and Intelligent Reality Technologies (ICCIRT),* Coimbatore, India, 2024.
7. Syrian Arab News Agency (SANA), "Emergency Ministry conducts first practical trial using drone for landmine detection," *Syrian Arab News Agency (SANA)*, 2025. [Accessed by 01/12/2025].
8. R. Alabi, "Syria conducts first practical drone experiment for mine detection," *The Media Line*, 2025. [Accessed by 02/12/2025].
9. International Campaign to Ban Landmines, "Landmine Monitor 2023," *International Campaign to Ban Landmines - Cluster Munition Coalition (ICBL-CMC),* Geneva, Switzerland, 2023, [Accessed by 03/10/2024].
10. International Campaign to Ban Landmines, "Landmine Monitor 2025." *International Campaign to Ban Landmines - Cluster Munition Coalition (ICBL-CMC),* Geneva, Switzerland, 2025, [Accessed by 04/12/2025].
11. Karam Shaar, "The UXO threat: Syria's hidden war against landmines and explosives," *Karam Shaar*, 2025, [Accessed by 04/12/2025].
12. Syria Mine Action Area of Responsibility (AoR), "Syria Mine Action AoR: 2025—A Year in Review Info-Sheet," *ReliefWeb*, 2025. [Accessed by 05/12/2025].
13. Syria Mine Action Area of Responsibility (AoR), "Syria Mine Action AoR Situation Update No. 6: 2025—A year in review," *ReliefWeb*, 2025, [Accessed by 06/12/2025].
14. R. Ali, "A year after Assad's fall, explosive threats still stalk Syrians returning home," *Anadolu Agency*, 2025. [Accessed by 09/12/2025].
15. Mines Advisory Group (MAG), "One year on from the fall of Assad: A humanitarian emergency in Syria," *Mines Advisory Group (MAG)*, 2025. [Accessed by 10/12/2025].
16. Enab Baladi, "Syria tops list of countries most affected by landmines," *Enab Baladi*, 2025. [Accessed by 12/12/2025].
17. United Nations Mine Action Service (UNMAS), "Syria," *UNMAS Syria Mine Action Programme*, 2025, [Accessed by 13/12/2025].
18. L. S. Yoo, D. Jung, and Y. Choi, "Metallic landmine detection and identification using machine learning classification of UAV-based magnetometer data," *Journal of Electromagnetic Waves and Applications*, vol. 40, no. 15, pp. 2845–2873, 2026.
19. K. Moorthi, D. Harsathabinav, and B. Srivardhan, "Surveillance of landmine detection drone," in *Proc. International Conference on Computing and Communication Technologies (ICCCT)*, Chennai, India, 2025.
20. F. Samadzadegan, F. Qaderi, T. L. Haghighi, A. Toosi, and S. M. Mousavi, "Unmanned aerial remote sensing for unexploded ordnance detection: Concepts, methods, current status and trends," *Sensing and Imaging,* vol. 26, no. 10, p. 137, 2025.
21. C. Melton and A. Duncan, "Thermal, RGB, and Multispectral Unexploded Ordnance Data Collection," *Oak Ridge National Laboratory*, United States, 2026. [Accessed by 03/04/2026].
22. A. Nikulin, "I-Corps: Delivering integrated technology for automated wide-area humanitarian mine action surveys," *National Science Foundation*, New York, United States, 2024. [Accessed by 18/03/2025].
23. N. Flaherty, "IRIS uses AI to spot land mines," *Uncrewed Systems Technology*, 2024. [Accessed by 19/04/2025].
24. Syrian Arab News Agency (SANA), "Geneva conference on mine action in Syria opens with international participation," *Syrian Arab News Agency (SANA),* 2026. [Accessed by 11/04/2026].
25. Syrian Arab News Agency (SANA), "Workshop in Damascus advances national strategy on mine clearance," *Syrian Arab News Agency (SANA),* 2026. [Accessed by 13/04/2026].
26. Rebuilding Syria, "Launch of a Japanese funded mine clearance project," *Rebuilding Syria*, 2026. [Accessed by 16/04/2026].

27. Japan International Cooperation Agency (JICA) and United Nations Development Programme (UNDP), "JICA and UNDP showcase innovative Japanese technology to advance humanitarian mine action efforts in Ukraine," *United Nations Development Programme (UNDP)*, 2025. [Accessed by 21/12/2025].
28. M. Paun, R. Manda, and M. Hnatiuc, "Low-cost drone-mounted frequency-modulated continuous wave ground penetrating radar," in *Proc. International Spring Seminar on Electronics Technology (ISSE),* Budapest, Hungary, 2025.
29. J. H. Kwon, N. J. Kwak, S. J. Ha, S. H. Han, Y. S. Yoon, and D. Yang, "Ground penetrating radar system for landmine detection using 48 channel UWB impulse radar," *Journal of the Institute of Electronics and Information Engineers*, vol. 53, no. 12, pp. 3–12, 2016.
30. D. H. Kim and S. H. Choi, "A study on signal processing of array-type ultra wideband based ground penetrating radar for landmine detection," *Journal of the Institute of Electronics and Information Engineers*, vol. 58, no. 9, pp. 91–96, 2021.

Publisher's Note: *The publisher remains impartial concerning jurisdictional claims in published maps and institutional affiliations. Responsibility for the content rests entirely with the authors and does not necessarily reflect the publisher's perspectives.*