

Integration of an electromagnetic sensor and neutron-based sensor for enhanced unexploded ordnance detection.

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ABSTRACT: Explosive ordnance used in World War I (WWI) and World War II (WWII) continue to be discovered in the form of unexploded ordnance (UXO) across various regions worldwide. These UXOs may reside at depths of up to 10–20 meters, depending on factors such as ordnance size, soil type, release height, and aircraft speed. While most research on UXO detection focuses on near-surface to moderate-depth targets, the detection of deeply buried UXOs (DB-UXOs) remains an ongoing challenge due to signal attenuation at depth when surface geophysical detection techniques are used. Currently employed DB-UXO detection methods, such as layer-by-layer surveying, Magcone probing, and borehole logging, are costly, time-consuming, and often yield high false alarm rates. This study explores a novel dual-sensor system mounted on a drill for improved DB-UXO detection. The paper presents a simulation-based assessment of two selected sensors: an electromagnetic (EM) sensor and a neutron generator paired with a scintillator detector for gamma-ray detection. EM sensor outputs were simulated using ANSYS Maxwell, while Geant4 was used to model neutron-induced gamma-ray spectra. Twenty-five distinct objects, including five UXO-like targets, were simulated buried in a 500mm x 400mm x 500mm size soil cube with burial depths of 100 mm from the surface, replicating a small-scale buried environment. Results indicate that the EM sensor alone yielded a 36% false alarm rate and failed to detect one target due to a non-conductive metal casing. The neutron-based system achieved a 12% false alarm rate, primarily due to the presence of carbon-rich materials in the soil but successfully identified all UXO-like objects. The combined analysis of EM and gamma-ray data significantly reduced false positives, improving overall detection accuracy.

KEYWORDS: Unexploded Ordnance, Deeply buried UXO detection, ANSYS Maxwell, Geant4, Dual sensor system.

1 INTRODUCTION

Morikawal, Taylor and Persons (1998) describe UXOs as ‘silent killers’ that continue to pose threats long after conflicts have ended. It is commonly estimated that around 10 per cent of the ordnance deployed during World War I (WWI) and World War II (WWII) remained unexploded (Cooper and Cooke, 2018; Stone et al., 2009). However, Busé, (2000) offers a differing interpretation, arguing that this estimate is based on the limitations of defence technologies available at the time. Busé, (2000) suggests that the true proportion could be as high as 30 per cent. Despite these debates, Zetica UXO, a leading UXO removal company in the United Kingdom (UK), recorded the removal of over 7,500 items, including small-arm ammunition, in 2023. Figure 1 illustrates the munitions disposal activities completed by the Explosive Ordnance Disposal (EOD) and Search Regiment over the past decade, up to September 2024. Although a centralized data system for UXO incidents does not yet exist, these statistics highlight the ongoing severity of the problem.

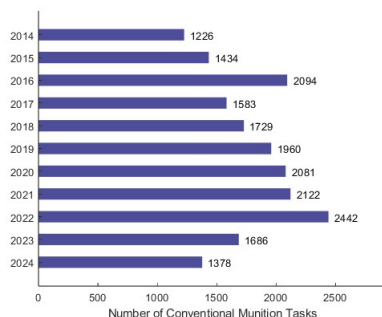


Figure 1. Conventional munition tasks are completed by the EOD and Search Regiment in the UK. The data does not distinguish between buried UXO, washed away UXO with ocean current, or items discovered on private property. Small arms ammunition and shotgun rounds are excluded. Data were requested from the UK Ministry of Defence under the Freedom of Information Act.

UXO encounters on land can occur from surface level down to 15 to 20m in depth, as shown in Figure 2. UXO burial depth can vary due to several factors like the ordnance type, release height, aircraft speed, and soil type (Stone et al., 2009).

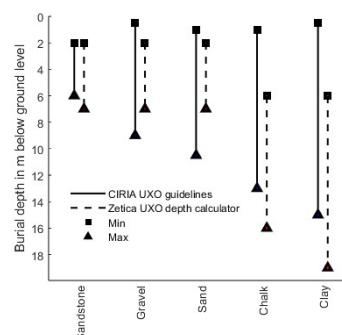


Figure 2. Depth variation of UXOs ranging in size from 50 kg to 1000 kg. The data, abstracted from CIRIA guidelines, are originally based on empirical records from the Ministry of Home Security (1941) (Stone et al., 2009; Gask & Moran, 2023). The Zetica UXO Depth Calculator, also known as the Unexploded Bomb Depth Calculator (UXB-DC), is an analytical tool developed by Zetica Ltd. to estimate the maximum potential penetration depth of UXOs (ZeticaUXO, n.d.).

Given the substantial risks associated with unexploded ordnance (UXO) contamination, conducting comprehensive surveys in suspected areas is essential (Owen, McNamara and Panchal, 2019). A significant challenge in UXO detection is the presence of metallic debris, which contributes to high false alarm rates (Butler, Bennett and Ballard, 2006). In some cases, the cost of removing scrap metal, frequently mistaken for UXO, can account for up to 70% of total remediation expenses (Lieblich, 2004).

Furthermore, increased burial depth complicates detection due to greater signal attenuation. To mitigate this effect, one widely used method for detecting deeply buried UXOs (DB-UXOs) is layer by layer scanning. In this approach, each soil layer is

scanned using geophysical investigation techniques like metal detectors, electromagnetic (EM) sensors, and ground penetration radar (GPR). The scanned layer is then excavated to a specified depth, and the process is repeated. After scanning, the excavated soil is used to backfill the area. Figure 3 illustrates the cost variation associated with conventional detection and the layer-by-layer scanning approach at increasing depths, based on a case study by MacDonald and Mendez (2005).

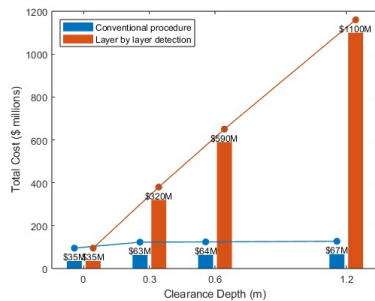


Figure 3. Cost variation in UXO removal between the conventional technique and the layer-by-layer soil removal method. In the conventional approach, referred to as the military protocol, the site is first scanned using the best available detection techniques. Detected anomalies are then removed, and construction support is provided for addressing any UXO discoveries encountered during ongoing excavation activities.

Therefore, this paper proposes a conceptual design setup aimed at enhancing detection accuracy through a simplified technique rather than layer by layer detection, MagCone or borehole logging for identifying DB-UXOs. The following section provides background analysis supporting sensor selection. The methodology section then outlines the procedure used to evaluate the effectiveness of the proposed approach. Finally, the paper presents a conceptual design for a DB-UXO detection system, followed by results and discussion.

2 BACKGROUND

Ongoing research and development efforts have significantly enhanced the accuracy and efficiency of UXO detection techniques. However, most of these advancements have primarily focused on near-surface detection, particularly in the context of humanitarian explosive ordnance clearance. This has resulted in a noticeable gap in the development of methods for detecting deeply buried UXO (DB-UXO), where improvements in accuracy and efficiency remain limited.

Figure 4 illustrates the evolution of UXO detection techniques. As shown, early methods for detecting DB-UXO involved the layer-by-layer removal of soil to a predetermined depth. In more recent years, two techniques have gained popularity for detecting deeply buried ordnance: MagCone and borehole logging.

The MagCone method, also known as the ‘push technique’, involves pushing a cone-mounted magnetometer into the ground, similar to cone penetration testing (Khater, Al-Nuaimy and Eriksen, 2019; Smith et al., 2013). In this setup, data are transmitted via cables to the surface. As depicted in Figure 4, because the system relies solely on a magnetometer, it can only detect ferrous objects, which often results in false positives. Moreover, this method is both expensive and time consuming, and its effectiveness is significantly reduced in hard or compacted ground, making penetration extremely challenging.

In contrast, borehole logging involves first drilling a borehole, then removing the drill bit and inserting a casing to prevent collapse. A magnetometer is then manually lowered

into the borehole to detect possible UXO targets (Khater, Al-Nuaimy, and Eriksen, 2019; Smith et al., 2013). This technique offers an advantage in penetrating harder ground. However, it shares the same limitations of high cost and slow operation with the added risk of hitting undetected UXO.

Given these challenges, Khater and Al-Nuaimy, (2019) propose an alternative approach inspired by the oil drilling industry, the Measurement While Drilling (MWD) technique. In their study, they suggest implementing a telemetry system capable of near real-time data transmission during UXO surveys, potentially improving both efficiency and cost-effectiveness in DB-UXO detection.

2.1 Sensor Selection

Multi-sensor approaches have proven effective in reducing false alarm rates in UXO detection (Butler, Bennett, and Ballard, 2006; Hassan, Ahmat and Ouya, 2024).

Selection of the sensors was guided by material characteristics of historical UXO, which predominantly comprises steel, iron, or cast iron (Simms et al., 2004). Thus, a three-axis electromagnetic sensor was selected for its suitability in detecting such materials when integrated into a drilling setup.

However, electromagnetic sensors alone are prone to false positives due to metallic clutter. To enhance discrimination, a neutron-based technique is incorporated to identify key elemental signatures of carbon (C), hydrogen (H), nitrogen (N), and oxygen (O), which are the key elements in explosive materials (Mitra, 2013; Mitra and Dioszegi, 2012). These elements emit characteristic gamma rays upon neutron activation, specifically at energies of 4.4 MeV, 2.2 MeV, 5.11 MeV, and 6.13 MeV, respectively (Gozani, 2011; Mitra, 2013; Mitra and Dioszegi, 2012). By employing a 14 MeV neutron generator and gamma-ray scintillation detector, the system aims to distinguish UXOs from benign metal debris.

Therefore, this research focuses on a dual-sensor configuration that integrates a three-axis electromagnetic sensor with a neutron-based detection system to improve UXO identification accuracy in subsurface environments. In addition, the effectiveness of the chosen sensors via independent simulations is also assessed.

2.2 Conceptual Design

In this research, the integration of a magnetic sensor and a portable neutron generator with a scintillator detector onto a drilling machine for the DB-UXO detection is proposed. To minimise signal interference caused by metallic components, a non-metallic drill bit, preferably made of tungsten carbide, is recommended.

The Bartington MAG639 Time Domain Electromagnetic (TDEM) sensor is selected for its suitability in subsurface UXO detection. For a portable neutron generator, an inspiration was drawn from the work of Kerr et al., (2022), who developed a portable deuterium–tritium (D–T) neutron generator for neutron transmission imaging. A similar approach is expected to be used to create a portable 14 MeV fast neutron flux generator.

To analyse elemental composition via gamma-ray spectra, a scintillator-based gamma-ray detector will be employed. A suitable telemetry or data transmission system is currently under evaluation to enable near-real-time data transfer to the surface, akin to measurement-while-drilling (MWD) systems.

This paper presents a performance assessment based on simulated results, evaluating the combined use of EM sensing and neutron-induced gamma-ray detection for UXO identification.

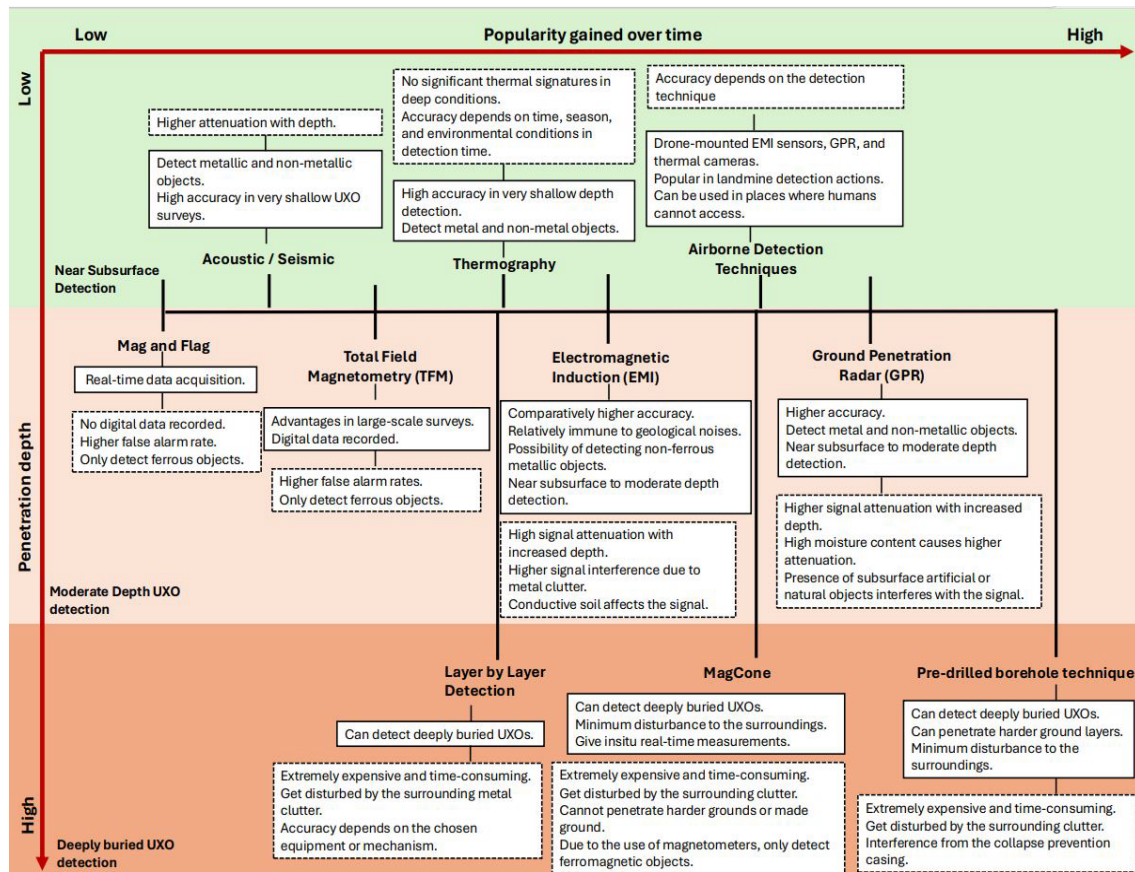


Figure 4. Evolution of UXO detection techniques with their detection depth variation.

Table 1: A detailed summary of the 25 test objects considered in Geant4 and ANSYS Maxwell simulations.

Sample No.	Overall dimensions (mm)	Material	UXO-like object	Weight (g)	Presence of H, C, N and O				Magnetic properties	
					H (%)	C (%)	N (%)	O (%)	Magnetic	Nonmagnetic
01	Φ90 x 250	Steel	-	1100	-	1	-	-	*	-
02	Φ86 x 260	Steel	-	1100	-	1	-	-	*	-
03	Φ74 x 200	Steel	-	550	-	1	-	-	*	-
04	Φ74 x 200	Cast Iron, Aluminium	-	550	-	3.2	-	-	*	-
05	Φ46 x 180	Aluminium	-	250	-	-	-	-	-	*
06	Φ90 x 250	Steel, Ammonium Acetate	*	2000	4.12	14.57	8.17	18.68	*	-
07	Φ86 x 260	Steel, Ammonium Acetate	*	2000	4.12	14.57	8.17	18.68	*	-
08	Φ74 x 200	Steel, Ammonium Acetate	*	1000	4.12	14.57	8.17	18.68	*	-
09	Φ74 x 200	Cast Iron, Aluminium, Ammonium Acetate	*	1000	4.12	15.78	8.17	18.68	*	-
10	Φ46 x 180	Aluminium, Ammonium Acetate	*	450	4.12	14.03	8.17	18.68	-	*
11	50 x 50 x 100	Iron	-	2000	-	-	-	-	*	-
12	150 x 150 x 15	Iron	-	2500	-	-	-	-	*	-
13	23 x 23 x 23	Iron	-	100	-	-	-	-	*	-
14	30 x 30 x 30	Iron	-	250	-	-	-	-	*	-
15	Φ110	Steel	-	1500	-	1	-	-	*	-
16	100 x 100 x 40	Glass	-	1000	-	-	-	-	-	*
17	100 x 100 x 20	Concrete	-	500	1	0.1	-	53	-	*
18	75 x 75 x 75	Concrete	-	1000	1	0.1	-	53	-	*
19	Φ110 x 100	Concrete	-	2400	1	0.1	-	53	-	*
20	50 x 50 x 50	Copper	-	1120	-	-	-	-	-	*
21	100 x 100 x 106	Polyethylene	-	985	14.4	85.6	-	-	-	*
22	Φ68 x 10	PVC	-	690	4.8	38.4	-	-	-	*
23	20 x 30 x 13	Tin	-	50	-	-	-	-	-	*
24	Φ20 x 100	Tin	-	230	-	-	-	-	-	*
25	100 x 110 x 50	Wood	-	250	6	49	1	44	-	*

3 METHODOLOGY

To evaluate the effectiveness of a dual-sensor approach combining a magnetic sensor with a neutron generator and gamma detector, two independent simulations were conducted using two different software tools. Magnetic responses of objects under the Earth's magnetic field were simulated using ANSYS Maxwell (Ansys, 2025), while neutron interactions and the resulting gamma-ray spectra were modelled using the Geant4 toolkit (Geant4 Collaboration, no date). A total of 25 test objects, as summarized in Table 1, were selected, including five small-scale UXO-like proxies, as well as magnetic and non-magnetic materials. These objects were independently modelled in both ANSYS Maxwell and Geant4 to generate relevant datasets.

In both simulations, a small, buried environment was modelled using a soil cube with dimensions of 500 mm × 400 mm × 500 mm. Objects were buried 100 mm below the top surface of the cube. These dimensions were chosen to match those of a wooden box used in ongoing small-scale experiments. The size of the box was primarily constrained by the limited space available near the D-T neutron generator.

The ANSYS Maxwell simulations were used to distinguish between metallic and non-metallic objects. From the Geant4 simulations, gamma-ray spectra were obtained for each object. Within each spectrum, regions of interest (ROI) corresponding to characteristic peaks of carbon (C), nitrogen (N), and oxygen (O) were identified. Based on these ROIs, elemental count ratios such as C/N count ratio and C/O count ratio were calculated.

Finally, the data from ANSYS Maxwell (metal/non-metal classification) and Geant4 (elemental ratio analysis) were jointly analysed under predefined criteria to assess the likelihood of UXO threats.

3.1 Geant4 Simulation

To simulate neutron-based detection outputs, the Geant4 toolkit was employed. Geant4 is a widely used platform for modelling the interaction of particles with matter, including photonic and neutron interactions (Geant4 Collaboration, 2024). In this study, a 14 MeV Deuterium–Tritium (D–T) neutron generator and a CeBr₃ scintillator were modelled using Geant4. The CeBr₃ scintillator was simulated with a 4% energy resolution, incorporating random Gaussian noise to reflect realistic detector performance. Since the neutron energy of interest is 14 MeV and well below the 20 MeV threshold, the FTFP_BERT_HP physics list was used in conjunction with the G4NDL data library to ensure accurate modelling of high-precision neutron interactions. Figure 5 shows the schematic diagram of the Geant4 simulation setup used to generate output data. As illustrated, a point source emitting monoenergetic 14 MeV neutrons was implemented. To reduce the simulation time, a 100mm thick soil cube (500mm x 400mm x 100mm) was modelled instead of 500mm x 400mm x 500mm cube, and the objects were placed behind the soil cube, representing the above-mentioned small-scale buried environment.

To simulate realistic soil interference in gamma ray detection, the soil was modelled as a user-defined material composed of 10% air, 25% water, 60% mineral content, and 5% organic matter by volume. For simplicity, air was assumed to consist entirely of nitrogen (100% N₂), and water was considered pure H₂O, excluding any dissolved minerals. The mineral component was represented as 100% silicon dioxide (SiO₂), while the organic matter was approximated as 100% carbon (C). These assumptions provide a simplified yet practical basis for modelling soil composition in the Geant4 simulation setup in recreating the buried environment.

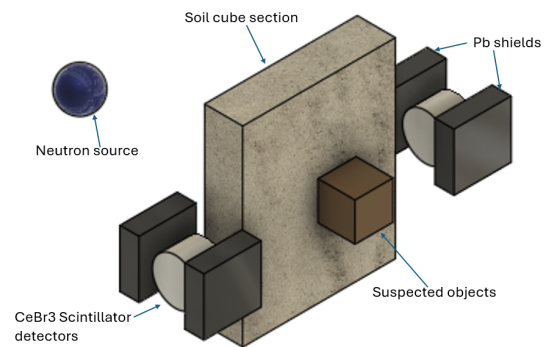


Figure 5. Geometric model and simulation setup for Geant4 simulation. suspected objects were placed behind a 100 mm-thick soil cube to minimise simulation time. Pb shields were used to reduce the noise due to background gamma rays.

3.2 ANSYS Maxwell Simulation

ANSYS Maxwell, developed by Ansys Inc., is a simulation software used to model electromagnetic field behaviour (Ansys, 2025). In this study, it was assumed that UXOs are induced solely by the Earth's magnetic field, which was modelled as a uniform and static magnetic field. To replicate this condition, a Helmholtz coil configuration was used to generate a uniform external magnetic field (Ansys, 2025). In each pair of coils, the current flows in the same direction, producing a tangential magnetic field equivalent to the Earth's magnetic flux components in the x, y, and z directions as tabulated in Table 2.

Table 2. Summary of Earth's magnetic field in X, Y and Z directions and the current flows modelled in the transient simulation.

	X	Y	Z	X: Y: Z
Magnetic field (nT)	17500	1250	46000	14: 1: 36.8
Current (A)	27.3	1.95	71.76	14: 1: 36.8

Subsequently, a soil cube measuring 500 mm × 400 mm × 500 mm was modelled, as shown in Figure 6. The objects were buried inside the soil, with the centre of each object positioned 100 mm below the surface. A transient simulation setup was then used to generate the corresponding magnetic flux output data.

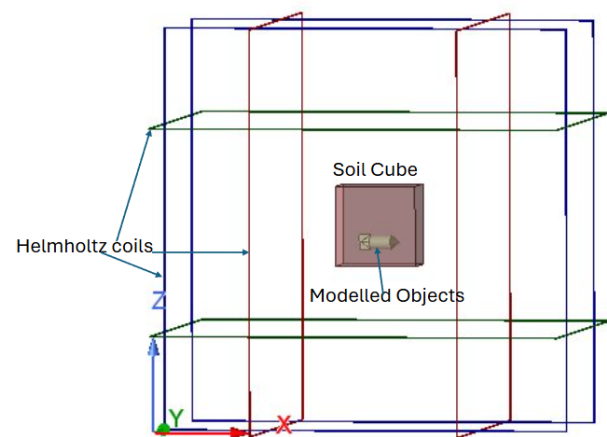


Figure 6. ANSYS Maxwell simulation setup with Helmholtz coils. In the middle of the coils a 500mm x 400mm x 500mm soil cube was modelled. Objects were buried in the soil 100mm inside the soil.

4 RESULTS AND DISCUSSION

Figure 7 illustrates the categorisation of Ansys Maxwell simulation data for 25 test scenarios involving 25 distinct test objects. Among the five UXO-like test objects, those with ferromagnetic casings were identified and classified as threats. In contrast, the object with an aluminium casing, despite containing explosive chemical components, fell outside the classified threat zone. Based on the Ansys Maxwell simulation results, the system produced a 36% false alarm rate and failed to detect one of the UXO-like objects.

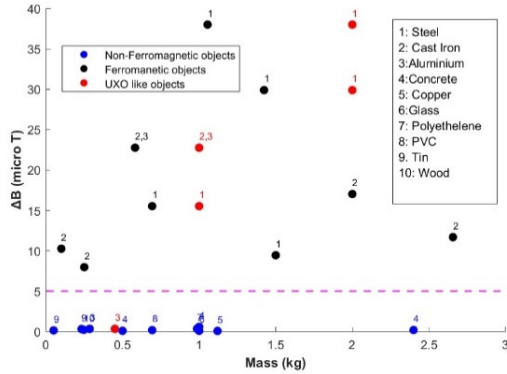


Figure 7. Suspected object classification depending on ANSYS Maxwell data outputs for 25 different test objects. The line at 5 μ T is the decision-making cutoff line defined.

In this simulation, the objects were buried 100 mm beneath the surface of the soil cube. The cutoff value shown in Figure 7 was determined based on the empirical relationship between magnetic field strength and distance relative to ordnance size, as described by Benson et al. (1982), in conjunction with the theoretical model presented in Equation 1, where r is the distance.

$$B \propto 1/r^3 \quad (1)$$

The gamma spectrum generated from Geant4 simulations demonstrates a pronounced influence from soil composition, which affects the object's gamma ray spectrum. Materials such as PVC, polyethylene, and wood, characterised by high carbon content as presented in Figure 8 a), can produce spectral features that mimic those of potential UXO signatures. As illustrated in Figure 8b, the calculated carbon-to-oxygen (C/O) and carbon-to-nitrogen (C/N) gamma count ratios provide a basis for distinguishing between threat-relevant objects and benign metal clutter. Furthermore, the application of the neutron-induced gamma-ray technique allows for the detection of non-ferromagnetic objects containing explosive materials, enhancing the discrimination capability beyond magnetic properties alone.

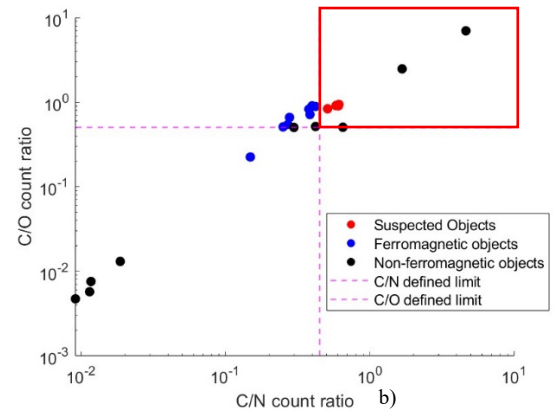
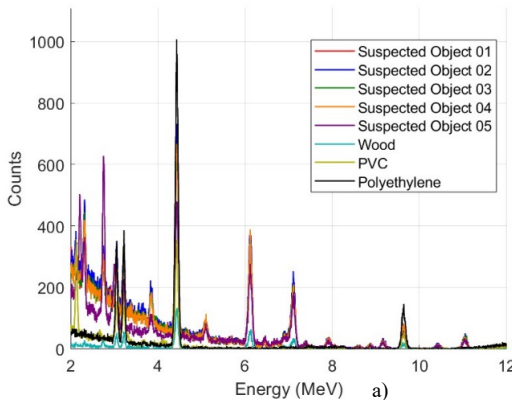


Figure 8. a) gamma ray spectra output for five UXO-like objects, PVC, polyethylene and wood. b) C/O count ratio vs C/N count ratio for 25 different objects when buried in the soil.

As expected, all five UXO-like objects fell within the region defined as the suspected object area based on the C/N and C/O count ratios. For this classification, the C/N ratio threshold was set at 4.5, and the C/O ratio threshold at 0.5 for objects buried under a 100 mm soil layer. None of the metal objects were located within this region, suggesting that metal clutter can potentially be distinguished from actual UXOs. However, PVC, wood, and polyethylene objects, which contain higher carbon percentages, exhibited C/N and C/O ratios when buried that could potentially lead to misidentification as UXOs as presented in Figure 8b).

After analysing the Ansys Maxwell simulation results in conjunction with the Geant4 output data, outlier objects exhibiting significant deviation were excluded from further consideration, as shown in Figure 9. From integrated analysis, all five UXO-like objects could be successfully discriminated from the metal clutter.

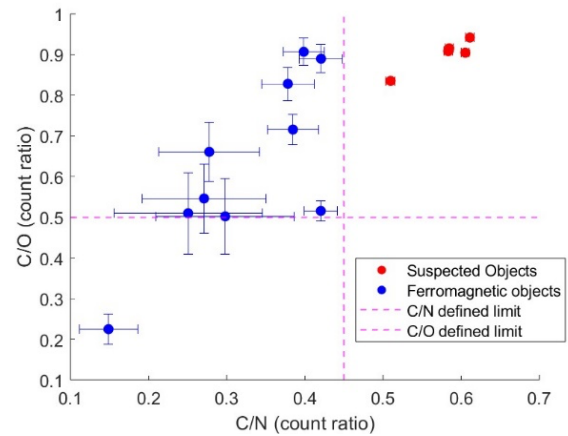


Figure 9: C/O count ratio vs C/N count ratio for threat object identification.

5 CONCLUSIONS

The simulation results demonstrate that soil significantly influences the gamma ray spectrum in neutron-based detection systems, which can lead to false alarms when objects with C, O, or N presence. Therefore, incorporation of techniques to mitigate soil effects on the resulting spectra in buried objects detection using a neutron-based technique would improve detection accuracy and system reliability.

In subsurface environments, neutron scattering significantly diminishes the effectiveness of using only a

neutron generator and a scintillator detector for object localisation, despite their demonstrated accuracy in discriminating threat objects from metallic clutter. Integrating an EM sensor with the neutron generator and scintillator detector is expected to provide complementary capabilities, enhancing detection, discrimination, and spatial localisation.

6 FUTURE WORK

Small-scale experiments are planned at the National Buried Infrastructure Facility (NBIF) and the Neutron Irradiation Laboratory for Electronics (NILE) to recreate a controlled buried environment for independent sensor testing. Data collected from these experiments will be used to validate the simulation results. Once validated, the proposed conceptual design will undergo large-scale testing at NBIF to assess its performance under more realistic conditions.

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