HIRT: Hybrid Impedance-Resistivity Tomography System

A Low-Cost, High-Resolution Subsurface Imaging System for Archaeological, Forensic, and Humanitarian Demining Applications

HIRT Development Team

Version: 2.0 | **Date:** January 2026 | **Status:** Technical Introduction

Abstract

The HIRT (Hybrid Impedance-Resistivity Tomography) system represents a novel approach to subsurface imaging that combines Magneto-Inductive Tomography (MIT) with Electrical Resistivity Tomography (ERT) in a crosshole configuration. Unlike conventional surface geophysical methods, HIRT places sensors directly into the ground volume being investigated, enabling true tomographic reconstruction with 2-5x better resolution than surface methods at depths exceeding 2 meters. The system is designed as a low-cost alternative to commercial solutions, with a complete 25-probe array costing $1,800-3,900 compared to $50,000-200,000+ for commercial systems. HIRT addresses the critical global challenge of unexploded ordnance (UXO) detection, with applications extending to WWII-era bomb sites, aircraft crash investigations, clandestine burial detection, and environmental site characterization. The system's development was motivated by the ongoing humanitarian crisis in regions like Poland's Kozle Basin, where thousands of unexploded bombs from WWII Allied bombing campaigns remain buried, posing continuous risk to civilian populations.

Keywords: crosshole tomography, electrical resistivity tomography, magneto-inductive tomography, UXO detection, humanitarian demining, subsurface imaging, WWII unexploded ordnance

1. Introduction: The Global Unexploded Ordnance Crisis

Undiscovered military explosives pose a continuing social and environmental burden in war-affected regions worldwide. More than 60 countries remain contaminated with unexploded ordnance (UXO) and explosive remnants of war (ERW), placing over 100 million people at risk—more than half of whom are children. Between 1999 and 2023, recorded casualties from mines and ERW exceeded 159,000 people, with the true toll likely far higher due to underreporting in conflict zones [1].

The legacy of World War II bombing campaigns presents a particularly persistent challenge. Post-war estimates indicate that 10-15% of aerial bombs failed to detonate, leaving millions of unexploded devices buried across Europe and Asia. In Germany alone, approximately 2,000 tons of WWII munitions are discovered annually—averaging 15 explosive devices requiring professional defusal every day. Since 2000, eleven bomb disposal technicians have been killed in Germany, and experts estimate bombs will continue to be found for another 200 years [2].

1.1 The Kozle Basin: A Case Study in Persistent Danger

The Kozle Basin (Cosel in German) in Upper Silesia, Poland, exemplifies the scale and persistence of the UXO problem. This region was home to the largest synthetic fuel production complex in the Third Reich—the Blechhammer facilities—which produced the majority of Germany's aviation gasoline. Between 1944 and 1945, Allied forces conducted intensive bombing campaigns against these strategic targets, dropping approximately 39,137 bombs across the basin [3].

Recent research by Waga et al. [3] using LiDAR scanning has mapped approximately 6,000 well-preserved bomb craters in the region, with some areas containing up to 77 craters per hectare. Based on the 10-15% historical failure rate, the researchers estimate that 4,000-6,000 unexploded bombs remain buried in the basin. Of 403 depressions investigated, 46 were classified as high-probability UXB sites and 134 as lower-probability candidates requiring further investigation.

The human cost of the original bombing campaign was devastating. The Blechhammer complex employed approximately 48,000 forced laborers, including 2,000 British prisoners of war and thousands of Jewish prisoners from the Auschwitz satellite camp system. Nearly 200 prisoners died while being forced to locate and defuse unexploded Allied bombs after raids. In January 1945, 4,000 prisoners were forced on a death march lasting 13 days, during which 800 were killed [4].

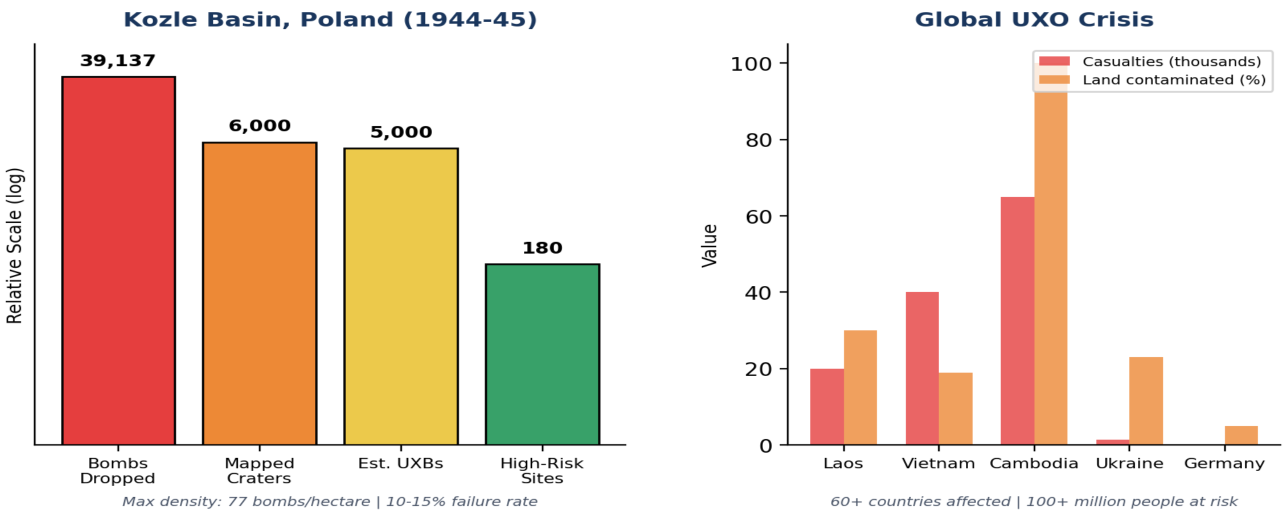

Figure 1. Scale of the unexploded ordnance crisis. Left: Kozle Basin bombing statistics showing bombs dropped, craters mapped, estimated UXBs remaining, and high-risk sites identified by Waga et al. [3]. Right: Global comparison of UXO-affected regions showing cumulative casualties and percentage of land area contaminated.

1.2 The Technology Gap in Humanitarian Demining

Despite decades of technological advancement in other fields, humanitarian demining continues to rely primarily on mid-century technologies: primitive handheld metal detectors and bayonet-style probing tools essentially unchanged since WWII. Human deminers using traditional methods clear only 10-20 square meters per day—a pace that would require centuries to address the global backlog. Even in Laos, where 80 million cluster submunitions remain from the Vietnam War era, clearance at current rates would take 100-1,000 years [5].

The barriers to technological innovation in humanitarian demining include military secrecy, lack of sustained funding, and the small commercial market for specialized detection equipment. Commercial crosshole tomography systems, which offer superior resolution compared to surface methods, cost $50,000-200,000+, placing them beyond reach for most humanitarian organizations and research institutions. The HIRT system was developed specifically to address this cost barrier while maintaining professional-grade detection capabilities.

2. Physics and Measurement Principles

2.1 The Crosshole Geometry Advantage

The fundamental advantage of crosshole geometry lies in the physics of electromagnetic and electrical field propagation. Surface methods must send energy down to a target and receive the return signal—doubling the path length and exponentially increasing attenuation. In contrast, crosshole methods send signals horizontally through the target volume, with sensitivity concentrated precisely where targets are located. Figure 2 illustrates this geometric advantage.

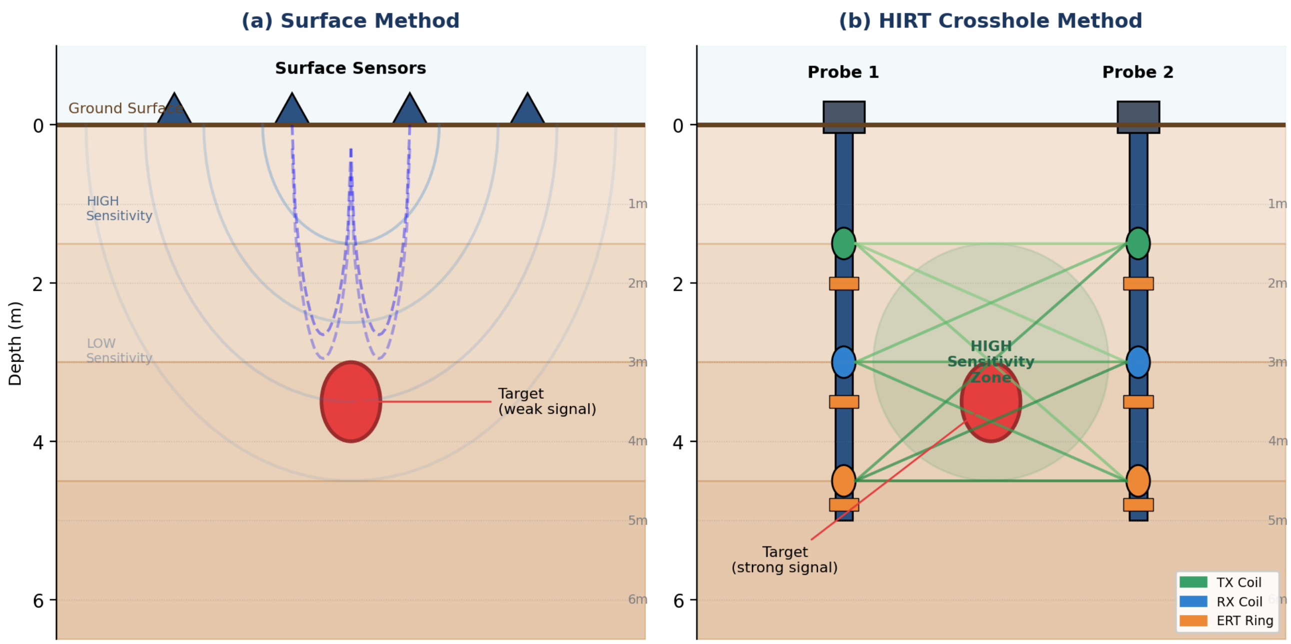

Figure 2. Comparison of (a) surface method versus (b) HIRT crosshole method. Surface sensors must contend with rapid sensitivity decay with depth ($1/r^2$ to $1/r^4$ falloff) and near-surface interference zones. Crosshole probes provide direct ray paths through the target volume with high sensitivity maintained at the investigation depth. The green ellipse in (b) indicates the zone of maximum sensitivity between probes.

The electromagnetic skin depth (δ) determines the effective penetration of MIT signals:

$$\delta = \sqrt{(2 / \omega\mu\sigma)}$$

where ω = angular frequency, μ = permeability, and σ = conductivity. At 10 kHz in typical soil (σ = 0.01 S/m), skin depth exceeds 50 meters. However, the practical limitation is coil coupling geometry, which scales as $1/r^3$ in near-field conditions. The effective MIT investigation depth is approximately 1-2x the probe spacing.

2.2 Dual-Channel Detection: MIT and ERT

HIRT employs two complementary sensing modalities. Magneto-Inductive Tomography (MIT) uses oscillating magnetic fields at 2-50 kHz to induce eddy currents in conductive targets, enabling detection of both ferrous and non-ferrous metals (including aluminum aircraft components that magnetometry cannot detect). Electrical Resistivity Tomography (ERT) injects small DC or low-frequency currents (0.5-2 mA) and measures voltage distribution, detecting resistivity contrasts from disturbed soil, moisture variations, voids, and grave shafts.

Parameter	MIT-3D	ERT-Lite
Operating Principle	TX coil magnetic field; RX measures eddy currents	Current injection; voltage measurement
Frequency Range	2-50 kHz	DC or 8-16 Hz
Detection Targets	Metal (incl. aluminum), conductivity anomalies	Disturbed fill, moisture, voids, grave shafts
Current Level	10-50 mA	0.5-2 mA
Key Advantage	Non-ferrous metal detection	Soil disturbance patterns
Resolution at 3m	0.75-1.5 m lateral	0.5-0.75 m vertical

Table 1. Comparison of MIT and ERT measurement methods. The dual-channel approach enables detection of targets that would be missed by either method alone.

3. System Architecture

The HIRT system follows an 'archaeologist brain first, engineer brain second' design philosophy, prioritizing minimal ground disturbance while maintaining measurement quality. The architecture employs passive micro-probes with centralized electronics, reducing per-probe complexity and cost while enabling robust, field-serviceable operation. Figure 3 shows the overall system architecture.

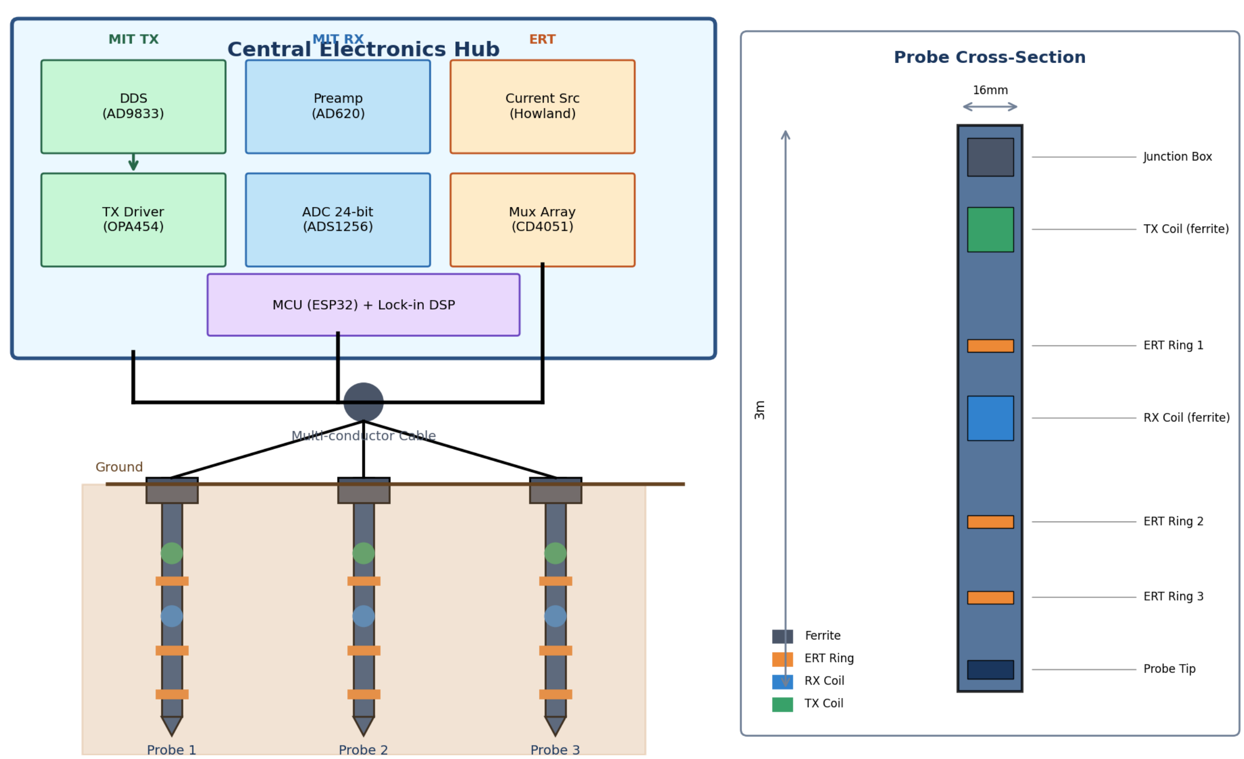

Figure 3. HIRT system architecture. Left: Central electronics hub containing DDS signal generator, TX driver, RX signal chain, ERT current source, and ESP32 microcontroller with lock-in DSP. Multiple probes connect via multi-conductor cables. Right: Detailed probe cross-section showing TX/RX coil positions, ERT ring electrodes, and modular threaded construction. Each probe is 16mm diameter fiberglass with no active electronics.

3.1 Micro-Probe Design

Each probe is a 16mm outer diameter fiberglass rod containing only passive sensors: ferrite-core MIT coils (TX and RX) and stainless steel ERT ring electrodes at fixed depths. The modular design uses M12x1.75 threaded connectors allowing field assembly to achieve desired depths (typically 1.5-3.0 meters). With no downhole electronics, probes are robust, waterproof, and inexpensive ($75-120 each). The 16mm diameter creates approximately 10x less ground disturbance than traditional geophysical probes.

Specification	Value	Notes
Rod Outer Diameter	16 mm	~10x less disturbance than traditional
Required Hole Size	18-20 mm	Hand auger or push-rod insertion
Material	Fiberglass (G10)	Non-conductive, RF transparent
Segment Lengths	50, 100 cm	Modular field assembly
Coil Inductance	1-2 mH	200-400 turns on ferrite core
ERT Ring Positions	0.5, 1.5, 2.5 m	From probe tip
Weight	~50-100 g/m	Lightweight for transport

Table 2. HIRT micro-probe physical specifications.

4. Performance Comparison

The crosshole geometry provides significant performance advantages over surface methods, particularly for targets at depths exceeding 1.5-2 meters. Research on crosshole ERT and electromagnetic tomography demonstrates 2-5x better resolution than surface methods at these depths [6,7]. Figure 4 compares the effective depth of investigation across common geophysical methods.

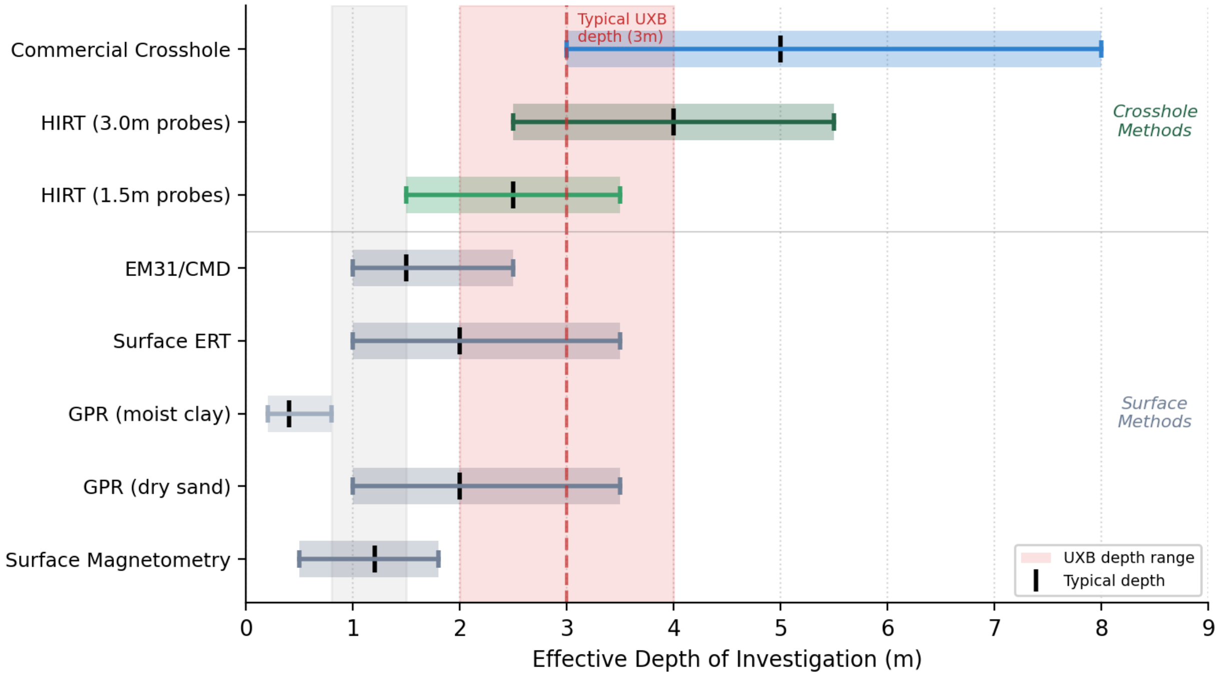

Figure 4. Effective depth of investigation comparison across geophysical methods. Horizontal bars show the range from minimum (poor conditions) to maximum (optimal conditions) depth, with vertical markers indicating typical performance. The red shaded zone indicates typical UXB burial depths (2-4m). HIRT crosshole methods maintain high-confidence detection throughout this critical range, while surface methods show significant degradation.

4.1 Cost-Effectiveness

A complete HIRT starter kit (25 probes, central electronics hub, cables, and tools) costs $1,800-3,900, representing a 95%+ reduction compared to commercial crosshole systems ($50,000-200,000+). This cost structure places professional-grade subsurface imaging within reach of research institutions, humanitarian organizations, and archaeological teams that could not otherwise afford crosshole tomography capabilities.

5. Application Scenarios

HIRT is optimized for three primary deployment scenarios, each with specific configuration recommendations. The system's dual-channel MIT+ERT approach enables comprehensive target characterization across diverse site conditions. Figure 5 illustrates the deployment strategies.

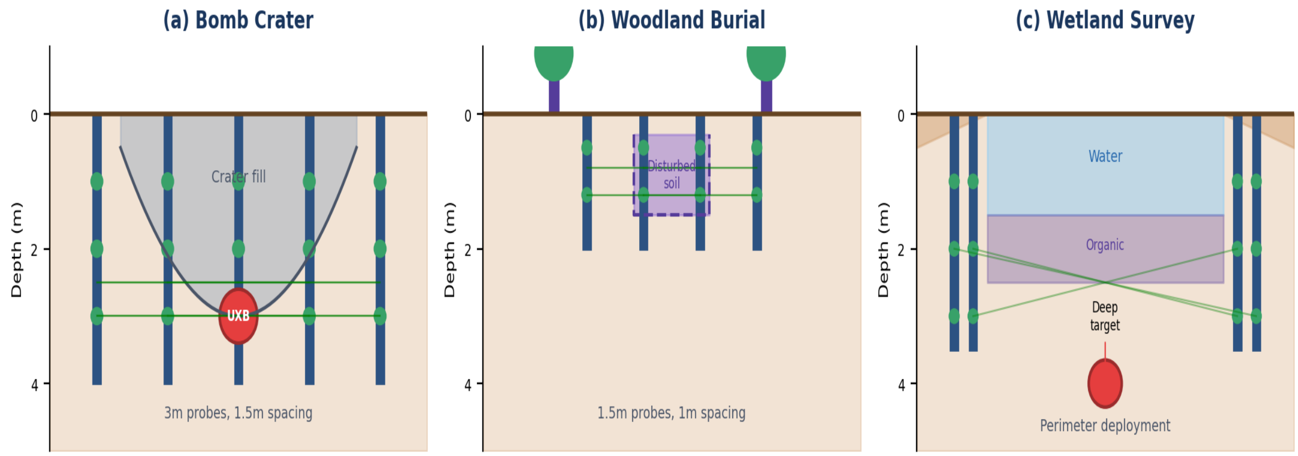

Figure 5. Primary HIRT application scenarios: (a) Bomb crater investigation uses perimeter probes (3m depth, 1.5m spacing) around suspected UXB locations with dense ray path coverage through the crater fill; (b) woodland burial search uses shallow dense arrays (1.5m probes, 1m spacing) to detect disturbed soil signatures; (c) wetland surveys deploy probes from accessible margins with long-baseline diagonal ray paths toward deep targets. Green lines indicate MIT measurement paths.

WWII Crash Sites and UXB Investigation: For craters 10-15m diameter with targets at 2-4m depth, use 3.0m probes at 1.5-2.0m spacing in a 5x5 or 6x6 array. MIT frequencies should emphasize lower ranges (2-10 kHz) for depth penetration. The combined MIT+ERT approach detects both metallic debris (MIT) and the disturbed fill boundaries of the crater (ERT).

Woodland Burials and Forensic Sites: For shallow targets (0.5-1.5m), use 1.5m probes at 1.0-1.5m spacing. Higher MIT frequencies (10-50 kHz) provide better near-surface detail. ERT excels at detecting the disturbed grave shaft signature while MIT identifies metallic artifacts such as belt buckles, buttons, or personal effects.

Wetland and Difficult-Access Sites: For targets exceeding 5m depth in areas with limited access, deploy probes from accessible margins. Use lowest MIT frequencies (2-5 kHz) with extended integration times (10-30 seconds). Diagonal ray paths from perimeter probes can interrogate central volumes that cannot be directly accessed.

6. Safety Considerations for UXO Sites

CRITICAL SAFETY REQUIREMENTS FOR UXO SITES

* Professional EOD clearance required before probe insertion
* No hammering or driving of pilot rods - soft insertion only
* Maintain 100m exclusion zone during insertion operations
* Perimeter-only deployment when UXB suspected at center
* Monitor groundwater conductivity: >5,500 uS/cm indicates elevated risk

Research by Waga et al. [3] documented a spontaneous UXB detonation in the Kozle Basin associated with elevated groundwater conductivity (>6,000 uS/cm) from industrial contamination. The electrochemical environment created by high-conductivity groundwater can accelerate corrosion of bomb casings and destabilize aging explosive fills. HIRT's ERT capability enables real-time monitoring of subsurface conductivity trends that may indicate elevated risk conditions.

7. Conclusions

The HIRT system addresses a critical gap between expensive commercial crosshole systems and limited-capability surface methods. By combining MIT and ERT sensing in a passive micro-probe architecture, HIRT achieves 2-5x better resolution than surface methods at depths exceeding 2 meters, while maintaining costs accessible to research institutions and humanitarian organizations.

The global unexploded ordnance crisis—affecting over 100 million people across 60+ countries—demands technological solutions that are both effective and deployable at scale. Traditional humanitarian demining methods clear only 10-20 square meters per day, a pace that would require centuries to address the existing backlog. HIRT offers a path toward more efficient detection and characterization of buried hazards, enabling prioritized clearance operations and reduced civilian casualties.

Key advantages of the HIRT approach include: (1) true 3D tomographic imaging rather than pseudo-depth estimation; (2) detection of non-ferrous metals that magnetometry cannot sense; (3) soil disturbance mapping independent of metallic content; (4) minimal ground disturbance (~10x less than traditional methods); (5) modular, field-serviceable design suitable for remote deployment; and (6) cost reduction of 95%+ compared to commercial alternatives.

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