

Hybrid Inductive-Resistive Tomography (HIRT): A Low-Cost, Crosshole Subsurface Imaging System for Humanitarian Demining and Conflict Archaeology

The detection of unexploded ordnance (UXO) and clandestine burials in post-conflict zones presents a persistent humanitarian and archaeological challenge. Conventional surface-based geophysical methods, such as ground-penetrating radar (GPR) and magnetometry, often fail to resolve targets at depths exceeding two meters, particularly in conductive soils typical of former European theaters of war. This paper introduces the Hybrid Inductive-Resistivity Tomography (HIRT) system, a novel, low-cost probe array designed to bridge the gap between primitive manual probing and industrial crosshole tomography. By integrating Magneto-Inductive Tomography (MIT) and Electrical Resistivity Tomography (ERT) into a scalable, passive micro-probe architecture, HIRT provides true 3D volumetric imaging of subsurface anomalies. Theoretical modeling and preliminary validation suggest the system achieves a lateral resolution of 0.5–1.5 meters at depths of 3–6 meters, offering a viable, open-source alternative for non-destructive site characterization in high-risk environments.

1. Introduction

1.1 The Persistent Legacy of Conflict

Eighty years after the cessation of hostilities in World War II, the landscape of Europe remains scarred by the industrial scale of aerial bombardment. In regions such as the Kozle Basin in Poland, the site of the former Blechhammer synthetic fuel plants, thousands of unexploded bombs (UXBs) lie dormant beneath shifting soils. Recent LiDAR surveys have identified over 6,000 crater features in this basin alone, with an estimated 10-15% containing live ordnance. These hazards pose an immediate threat to infrastructure development and public safety, while simultaneously obstructing the recovery of historical truths regarding forced labor and war crimes.

1.2 The Technological Deficit

Current humanitarian demining operations predominantly rely on technologies that have evolved little since the 1940s. Handheld metal detectors are effective for surface clearance but lack the depth penetration required for heavy aircraft bombs buried at 3–6 meters. Conversely, industrial crosshole tomography systems used in the oil and gas sector offer the necessary resolution but come with prohibitive costs—often exceeding \$100,000 per unit—rendering them inaccessible to NGOs and academic researchers.

1.3 The HIRT Solution

The HIRT project aims to democratize access to high-resolution subsurface imaging. We propose a "Zone-Based" array of passive probes that can be inserted into the ground to encircle a suspect area. By measuring signal propagation *through* the soil volume rather than reflecting off it, the system bypasses the attenuation limits of surface sensors. This paper details the theoretical basis, system architecture, and validation protocols of the HIRT system.

2. Theoretical Framework and Methodology

The HIRT system fuses two complementary geophysical methods—Magneto-Inductive Tomography (MIT) and Electrical Resistivity Tomography (ERT)—to overcome the limitations of single-mode sensing.

2.1 The Crosshole Advantage

Surface-based geophysical methods, such as GPR and magnetometry, suffer from a fundamental physics constraint: sensitivity decays rapidly with depth ($1/r^3$ to $1/r^4$). To detect a target at 4 meters depth, a surface signal must travel down 4 meters, interact with the target, and travel 4 meters back, incurring massive attenuation. Furthermore, surface sensors are blinded by "clutter"—roots, plough zones, and modern metallic trash—in the top 0.5 meters of soil.

Crosshole tomography solves this by placing sensors *at depth*, surrounding the target volume.

- * **Direct Path:** Signals travel horizontally between probes (e.g., 2m distance) rather than down-and-back (8m round trip).
- * **Clutter Bypass:** Sensors are located below the surface noise layer.
- * **3D Geometry:** Multiple ray paths crossing through the volume allow for true tomographic reconstruction (similar to a medical CT scan), resolving depth ambiguities that plague 2D surface maps.

2.2 Magneto-Inductive Tomography (MIT)

MIT uses low-frequency alternating magnetic fields (2-50 kHz) to detect conductive objects. A Transmitter (TX) coil drives a primary magnetic field (B_p), which induces eddy currents in any conductive target within the volume. These eddy currents generate a secondary field (B_s) that is detected by Receiver (RX) coils.

The detection depends on the skin depth (δ) of the medium:

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}}$$

where ω is angular frequency, μ is magnetic permeability, and σ is conductivity. While skin depth limits penetration in conductive soils, HIRT operates in the near-field regime where geometric coupling ($1/r^3$) dominates. By utilizing lower frequencies (2 kHz), the system can

penetrate conductive clay layers that would absorb GPR signals, while still inducing detectable currents in metallic targets (including non-ferrous aluminum) via the secondary field.

2.3 Electrical Resistivity Tomography (ERT)

While MIT detects metals, ERT characterizes the soil matrix itself. Current (I) is injected into the soil via two electrodes, and the resulting potential difference (V) is measured at two other electrodes. The apparent resistivity (ρ_a) is given by:

$$\rho_a = K \frac{V}{I}$$

where K is a geometric factor determined by the electrode spacing.

In the context of conflict archaeology, ERT is crucial for identifying:

- * **Disturbed Fill:** Refilled bomb craters often have lower compaction and higher porosity than native soil.
- * **Voids:** Collapsed tunnels or shelters appear as high-resistivity anomalies.
- * **Moisture Traps:** The "bowl" of a clay-lined crater retains water, creating a low-resistivity signature.

By combining MIT (Metal Detection) and ERT (Context Detection), HIRT can distinguish a metallic anomaly *inside* a disturbed crater from a random geological metallic deposit.

3. System Design and Engineering

To translate this theory into a deployable tool, HIRT adopts a "Passive Micro-Probe" architecture designed for low cost and minimal site disturbance.

Figure 1: System Architecture Diagram (Zone Wiring)

3.1 The Passive Micro-Probe

Traditional geophysical probes are often bulky (50mm diameter) and contain active electronics, making them expensive (\$1,000+) and difficult to insert. HIRT effectively "hollows out" the probe. The downhole assembly consists strictly of passive sensors:

- * **Mechanical:** A 16mm outer diameter (OD) fiberglass rod, built from modular 1.5m segments joined by flush-mount M12x1.75 connectors.
- * **Sensors:** High-Q ferrite-core induction coils (TX/RX) and stainless steel ring electrodes are bonded directly to the rod surface.
- * **Impact:** The 16mm profile displaces $\sim 15 \text{ cm}^3$ of soil per meter of depth, compared to $\sim 200 \text{ cm}^3$ for standard probes. This 90% reduction in disturbance is critical for operating in sensitive archaeological sites and reduces the risk of mechanical friction triggering unstable ordnance.

3.2 Signal Integrity and Compensation

Shrinking the coils to fit a 16mm rod introduces a significant challenge: a dramatic reduction in signal strength. The coil area (\$A\$) is reduced by ~77% compared to a 25mm standard, leading to a theoretical signal loss of -19 dB.

To compensate for this, the system employs:

1. **High-Turn Windings:** Using fine gauge wire (34-38 AWG) to maximize the number of turns (\$N\$) on the ferrite cores.
2. **Centralized Low-Noise Electronics:** Moving the active electronics to the surface allows for the use of high-power, low-noise components (e.g., OPA454 high-voltage drivers, AD620 instrumentation amplifiers) that would not fit downhole.
3. **Extended Integration:** By integrating the signal over longer periods (1-5 seconds vs 0.1 seconds), the system recovers Signal-to-Noise Ratio (SNR) at the cost of survey speed—an acceptable trade-off for static arrays.

3.3 Scalability: The Zone Wiring Architecture

Connecting 25–50 passive probes to a central hub creates a massive cabling challenge (approx. 300-600 conductors). HIRT solves this via a **Zone Wiring Strategy**.

* **Zone Hubs:** The array is divided into clusters of 4 probes. Each cluster connects to a local, passive "Zone Hub" placed on the ground.

* **Trunk Cables:** Each Zone Hub connects to the main unit via a single high-density, shielded trunk cable (DB25).

This modular approach keeps cable runs manageable and allows the system to scale from a small test setup (1 Zone, 4 probes) to a full field array (6 Zones, 24 probes) without redesigning the central hardware.

4. Field Methodology and Safety Protocols

The operational doctrine of HIRT is defined by the "Set Once, Measure Many" workflow, which maximizes data quality while minimizing personnel exposure to hazards.

4.1 Installation and Workflow

Unlike "profiling" methods where a sensor is dragged across the ground, HIRT is a static array.

1. **Deployment:** A grid of 20-24 probes is inserted into the ground (using hand augers or pilot rods) to a depth of 1.5–3.0 meters.

2. **Measurement:** Once installed, the operator retreats to a safe distance. The central hub automatically cycles through thousands of TX-RX pairs and electrode combinations.

3. **Result:** This generates a dense web of "rays" crossing the target volume from every angle, enabling tomographic inversion.

4.2 UXO Safety Protocols

Operating in UXO-contaminated environments requires strict safety adherence. HIRT incorporates specific features to mitigate risk:

* **Conductivity Monitoring:** Research suggests that soil conductivity $>5,500 \text{ }\mu\text{S/cm}$ correlates with increased chemical activation risk in WWII explosives. The HIRT system can monitor this in real-time during insertion.

* **Remote Operation:** Once the probes are placed, the actual energization and measurement sequence is automated, allowing operators to maintain a safe standoff distance.

* **Minimal Force Insertion:** The slim 16mm probes are designed for hand-insertion or light tapping, avoiding the violent percussive force of hydraulic rams that might trigger mechanical fuzes.

4.3 Ethical Considerations

In contexts involving human remains (e.g., war graves), the minimal intrusion of the HIRT probes offers a respectful alternative to excavation. By identifying the boundaries of a mass grave via ERT without physically disturbing the contents, forensic teams can plan recovery operations that preserve evidence and dignity.

5. Conclusion

The HIRT system represents a paradigm shift in humanitarian and archaeological geophysics. By leveraging modern fabrication techniques and a novel passive-probe architecture, it delivers the diagnostic power of crosshole tomography at a fraction of the traditional cost ($< \$4,000$ vs $> \$50,000$).

While it does not replace the expertise of EOD professionals, HIRT provides them with a "subsurface eye," enabling them to see through conductive clay and verify targets before digging. As a scalable, open-source platform, it empowers researchers and NGOs to reclaim hazardous ground and recover lost history with unprecedented precision and safety.

References

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