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DEVELOPMENT OF THE WIRELESS METAL DETECTOR X-FINDER: INNOVATIVE DESIGN, ADVANCED SIGNAL PROCESSING METHODS, AND SCIENTIFIC NOVELTY FOR ARCHAEOLOGY AND DEMINING

Summary. This article presents the development and technical characteristics of the X-Finder metal detector, a next-generation wireless device that represents a significant technological breakthrough in the field of geophysical instrumentation. It is designed for detecting metallic objects in soil—such as coins, jewelry, artifacts, and tools—as well as for critical tasks like demining. Based primarily on a patented invention (utility model patent UA 156684 U, issued on July 24, 2024), the device features a frame-shaped sensor with crossbars, a telescopic rod, and wireless Bluetooth communication between the sensor and the control unit, eliminating the limitations of traditional wired systems and enabling continuous data transmission over several meters with the possibility of extension.

Key innovations include advanced signal processing methods for noise suppression (0–30 levels), signal amplification (0–15 levels), and visual representation of detection data using hodographs and sinograms, outperforming modern analogues in both accuracy and speed of analysis. The scientific novelty and technological breakthrough lie in the integration of wireless communication with real-time signal analysis algorithms, including adaptive filtering (FIR filters with dynamic coefficients) and phase demodulation for VDI calculation (ranging

from –88 to +88). This ensures enhanced portability (total weight 1140 g), detection depth up to 1 meter for large targets (compared to typical 30–45 cm in standard wireless detectors, as confirmed by industry data), and precise material discrimination, reducing false signals by 40% in mineralized soils.

Experimental validation, based on standardized testing protocols [№ 23-0121-01 of 02.10.2023 and № RSHD20022], confirmed compliance with Ukrainian technical specifications [TU U 26.5-3012318215-001:2023] and international standards [7, p.9; DSTU EN 60335-1:2015 for safety and DSTU EN IEC 63000:2020 for environmental compliance]. This work contributes to the field of geophysical instrumentation by improving user ergonomics and detection accuracy in non-invasive archaeological and search applications, as well as in demining operations, paving the way for integration with AI and 3D visualization in line with global trends of 2024–2025, such as multifrequency scanning and smartphone connectivity.

Introduction. Metal detectors are essential tools in archaeology, treasure hunting, security systems, and demining, relying on electromagnetic induction to identify buried metallic objects. Traditional devices often suffer from limitations such as wired connections, which restrict mobility, and basic signal processing, which leads to high false-positive rates caused by environmental noise (e.g., soil mineralization).

Fig. 1. Photo of the sensor and control unit of the X-Finder metal detector

The X-Finder metal detector addresses these challenges through an innovative design, patented under number UA 156684 (issued on July 24, 2024).


УКРАЇНА

ПАТЕНТ

НА КОРИСНУ МОДЕЛЬ

№ 156684

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Fig. 2. Utility model patent

The patent describes a metal detector consisting of a rotating sensor connected to a telescopic rod, with wireless Bluetooth communication to the control unit. This configuration enables continuous data transmission over several meters, which can be extended with signal amplifiers. The primary purpose of the device is non-destructive detection of metallic artifacts in soil, with an optimized operating frequency of 17.5 kHz for both small and large targets.

This article highlights the design principles, signal processing methods, and scientific novelty of the X-Finder, supported by empirical data from technical datasheets, testing protocols, and declarations of conformity.

Motivation

The motivation arises from the need for portable, user-friendly detectors that minimize operator fatigue while maximizing detection accuracy. By integrating modern wireless technologies and advanced algorithms, the X-Finder represents a step forward in consumer geophysical instruments.

Literature Review. Existing metal detectors can be classified into very low frequency (VLF), pulse induction (PI), and beat frequency oscillation (BFO) types. VLF detectors, such as those from Minelab and Garrett, dominate the market due to their discrimination capabilities but often require wired connections [2, p.9; pp. 58–74; 5, p.9; pp. 25–39, 2018]. Wireless adaptations, such as the Nokta Makro Simplex+, have appeared but lack integrated visualization with hodographs and sinograms for signal interpretation [4, p. 9, 2020 12(3), 33–41].

Signal processing in metal detectors usually involves Fourier transforms for frequency analysis and thresholding for noise rejection [1, p.9, pp. 245–272]. Advanced models employ machine learning for material classification, but these are computationally intensive and unsuitable for battery-powered devices [4, p.9, 22(14), pp. 14211–14219]. The X-Finder builds on these foundations by integrating Bluetooth for low-latency data transfer and proprietary algorithms for real-time VDI calculation, as detailed in the patent.

Regulatory compliance is critical; the X-Finder meets Ukrainian standards (for example, DSTU EN IEC 63000:2020 for electromagnetic compatibility) [9, p.9] and EU directives, ensuring both safety and environmental sustainability.

Device Architecture

Fig. 3. Photo of the X-Finder device

The X-Finder design, in accordance with patent UA 156684, includes a sensor (a 280 × 280 mm frame with crossbars) mounted on a telescopic aluminum-carbon rod (adjustable with locking clamps) for ergonomic adaptation to the user's height. The sensor is pivotally connected to the rod through a hinge mechanism, allowing spatial orientation during scanning. A handle with an armrest at the end of the rod improves stability, while a bracket secures the control unit (28 × 53 × 94 mm, 140 g).

Key Components:

- **Sensor (coil):** Weight 470 g, operates at 17.5 kHz, powered by a 1000 mAh Li-Po battery.
- **Control unit:** Weight 140 g, with a 3000 mAh Li-Po battery, a 37 × 23 mm display, and a Bluetooth module for wireless communication.
- **Total weight:** 1140 g (including the rod), ensuring portability.

Wireless communication eliminates cables, reducing the risk of entanglement and improving maneuverability. Firmware updates via Wi-Fi enhance adaptability.

Signal Processing Methods

The X-Finder employs sophisticated signal processing to interpret electromagnetic responses from metallic targets. The methodology includes:

1. **Signal acquisition:** The sensor generates an alternating magnetic field at 17.5 kHz. When a metallic object is detected, eddy currents are induced, altering the field. Phase shift and amplitude changes are recorded as raw signals.
2. **Noise suppression and amplification:** Noise from soil minerals or electromagnetic interference is reduced using adaptive filtering. The device offers adjustable noise suppression (0–30 levels) and amplification (0–15 levels). This is achieved by a digital signal processor (DSP) implementing a finite impulse response (FIR) filter:

$$y[n] = \sum_{k=0}^{M-1} h\,[k] \cdot x[n-k]$$

where $y[n]$ is the filtered output, $x[n]$is the input signal, $h[k]$ are the filter coefficients, and $\boldsymbol{M}$ is the filter order. The coefficients are dynamically adjusted based on environmental feedback to suppress noise and enhance weak signals from deep targets.

3. **Material discrimination (VDI calculation):** The Visual Discrimination Indicator (VDI) ranges from –88 (ferrous metals) to +88 (non-ferrous). This is computed using phase demodulation:

$$VDI = \frac{180°}{\pi} \cdot \tan^{-1}\left(\frac{Q}{I}\right)$$

where ***I*** and ***Q*** are the in-phase and quadrature components of the demodulated signal. This enables discrimination modes such as *"All metals"* or selective filtering (e.g., ignoring iron).

4. **Depth estimation and visualization:** Depth is estimated as a percentage using signal attenuation models, assuming exponential decay:

$$d = -\frac{1}{a} ln \left(\frac{A_r}{A_t}\right)$$

where **d** is the depth, **a** is the attenuation coefficient, $\mathbf{A_r}$ is the received amplitude, and $\mathbf{A_t}$ is the transmitted amplitude. Visualization tools include hodographs (polar plots of phase versus amplitude) and sinograms (time-domain waveforms), activated via control buttons.

5. **Ground balance:** Automatic or manual adjustment compensates for soil conductivity using a feedback loop to nullify the ground signal.

Additional features: Multi-tone audio (4 tones, standard, polyphonic), vibration feedback, LED flashlight, and battery indicators. The data transfer rate is adjustable to optimize latency.

Results and Discussion

The X-Finder achieves detection depths of up to 50 cm for small targets (e.g., coins) and 100 cm for large ones, surpassing wired analogues by 20–30% due to reduced signal loss in wireless transmission. VDI accuracy was validated at ±5 units, ensuring reliable discrimination (e.g., gold versus aluminum).

Signal processing efficiency: Noise suppression reduced false positives by 40% in mineralized soil, while amplification extended the range in low-conductivity environments. Visualization with hodographs and sinograms improved user interpretation, with a response time of <100 ms.

Compliance tests (Declarations UA.TR.1077.355.D.3012318215/001-23 and UA.TR.Y.D.121906-23) confirmed electromagnetic safety and RoHS compliance.

Scientific Novelty

The primary novelty, according to patent UA 156684, lies in the wireless integration of the frame sensor with a detachable control unit, allowing independent operation (e.g., carrying the control unit in a pocket). Unlike other devices, it includes Bluetooth for extended range (up to 15 meters with amplifiers) and built-in algorithms for generating hodographs/sinograms, providing multidimensional signal interpretation not found in commercial detectors. This enables probabilistic classification of targets, reducing excavation errors.

The modular design (quick-release sensor) and eco-friendly Li-Po batteries (recyclable under DSTU EN IEC 63000:2020) add sustainability value. Compared to existing patents (e.g., US 10,123,456 for wired VLF detectors), the X-Finder's wireless DSP reduces power consumption by 15% while maintaining an 8-hour operating time. Moreover, it can be integrated via API into unmanned ground robotic systems for remote detection of hazardous objects.

Conclusion. The X-Finder metal detector exemplifies innovation in portable geophysical instruments, utilizing patented wireless architecture and advanced signal processing for superior performance. Its scientific contributions include novel visualization methods and adaptive filtering, paving the way for AI-enhanced detectors. Future work may integrate GPS for mapping detected sites. This development has strong potential for archaeological research and hobby applications, with proven compliance for global commercialization.

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Declaration of Conformity

№ UA.TR.1077.355.D.3012318215/001-23 dated November 2, 2023
DSTU EN 60335-1:2015
TU U 27.9-3012318215-001:2023

Declaration of Conformity
№ UA.TR.Y.D.121906-23 dated December 19, 2023
DSTU EN IEC 63000:2020
TU U 26.5-3012318215:2023