

From Soil to Sensor: AI Robotics Transforming Agriculture

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Abstract

AI-powered robotics is transforming soil sensing by enabling real-time, non-destructive and precise analysis of soil properties. By integrating artificial intelligence, advanced sensors and autonomous robotic platforms, soil parameters such as moisture, nutrient levels, electrical conductivity, compaction and temperature can be monitored efficiently across large agricultural fields. Unlike traditional laboratory-based methods, robotic systems provide rapid in-situ data collection with minimal soil disturbance. Machine learning algorithms further enhance decision-making by predicting soil health trends and optimizing resource use. This technology supports precision agriculture, improves crop productivity, reduces environmental impact, and promotes sustainable land management for future farming systems.

Keywords: Artificial Intelligence, Robotic Soil Sensing, Precision Agriculture, Soil Health Monitoring, Autonomous Robotics, Machine Learning, Smart Farming

Introduction

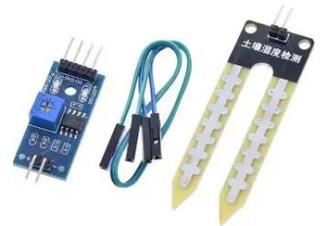
Soils constitute a fundamental resource for sustainable agriculture, global food security, ecosystem stability, biodiversity conservation and carbon sequestration. Accurate characterization of soil physical, chemical and biological properties is essential for informed land management and optimized crop production. Conventional soil assessment methods primarily rely on manual sampling followed by laboratory analysis, which are time-consuming, spatially limited and often disruptive to soil structure. Recent advancements in AI-powered robotics have introduced innovative approaches for in-situ, non-destructive and real-time soil sensing. By integrating artificial intelligence algorithms with autonomous robotic platforms and advanced sensors, high-resolution spatial and temporal data can be acquired efficiently. These systems enable comprehensive assessment of soil parameters, thereby enhancing precision agriculture practices. Consequently, AI-driven robotic soil sensing represents a significant advancement toward sustainable resource management and improved agricultural productivity.

Soil Sensing Techniques and Sensors Applied in Sensing Soil Properties with Robots

1. Soil moisture Sensor

Soil moisture sensing refers to the quantification of volumetric water content within the soil profile using diverse measurement techniques.

Among advanced methods, neutron scattering has been employed to estimate soil moisture and has been successfully integrated into robotic platforms for field-based applications, as demonstrated



by J. Pulido Fentanes and colleagues. A widely adopted conventional approach is the electrical resistance method, which determines soil moisture by measuring changes in the soil's resistance to an applied electric current. Since soil water enhances electrical conductivity, variations in resistance provide reliable estimates of moisture content under different field conditions.

2. Soil electrical resistivity/ conductivity sensor:

Soil electrical resistivity ($\Omega \text{ m}$) represents the ability of soil to oppose the flow of electric current, whereas soil electrical conductivity (S/m) describes its capacity to conduct electricity and is mathematically the reciprocal of resistivity. These properties are widely used to assess soil characteristics such as moisture content, salinity, texture and compaction.



Measurement techniques include the four-electrode (four-point probe) method, electromagnetic induction and electrical resistivity tomography (ERT). These approaches operate by introducing an electrical current into the soil and recording the resulting potential difference or induced electromagnetic response to determine subsurface properties.

3. Ion selective electrode

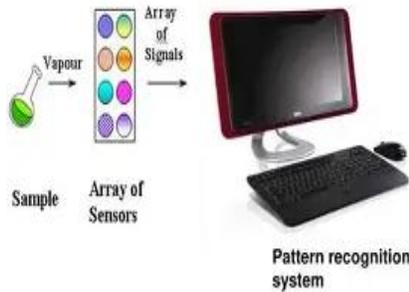
Ion selective electrodes are analytical sensors used to quantify specific ionic species in soil samples. In this method, soil is first extracted using an appropriate solvent to form a

solution containing dissolved ions. The electrode system then measures the electrochemical potential difference generated between a selective sensing electrode and a reference electrode. This potential is directly related to the activity or concentration of target ions such as nitrate (NO_3^-), ammonium (NH_4^+), potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}), which are essential nutrients for optimal plant growth and soil fertility management.



4. Electronic noses (e-noses)

Electronic noses (e-noses) are sensor-based systems designed to detect and characterize volatile organic compounds (VOCs) emitted from soil. These VOCs are primarily generated by soil microorganisms, plant roots and organic matter decomposition. By analyzing variations in VOC profiles, e-nose systems provide valuable information regarding microbial activity, biochemical processes and overall soil health. Changes in the composition and concentration of emitted gases can serve as indicators of soil quality, nutrient dynamics and environmental stress conditions, thereby supporting precision soil management and sustainable agricultural practices.



5. Soil compaction and cone index

Soil compaction and cone index, which indicate soil mechanical resistance and root penetration capacity, can be evaluated using multiple sensing techniques. Common methods include cone penetrometers that measure penetration resistance, soil pressure sensors that assess load bearing characteristics and shear strength sensors that determine the soil resistance to deformation under applied stress. These measurements provide critical information on soil structure, traffic-induced compaction and overall soil physical health.



6. Soil temperature sensor

Soil temperature is determined using temperature sensors or probes that are placed at specific depths within the soil profile. These instruments continuously record thermal variations, providing data on heat distribution and fluctuations influenced by environmental conditions. Monitoring soil temperature is essential for understanding seed germination, root development, microbial activity and overall soil biological processes.



System Configuration and Design of Robotic Soil Sensors Soil Sensing and Surface Management Unit

Autonomous UGV: A rugged Unmanned Ground Vehicle (UGV) designed for agricultural fields enables real-time soil monitoring. It operates on uneven terrain and carries multiple sensors for in-situ measurement of soil parameters.



Key Features:

- All-terrain design
- High payload capacity
- Autonomous navigation with GPS
- Remote monitoring
- Modular sensor integration

Robotic Manipulator Arm: A precision robotic arm mounted on the UGV ensures accurate probe placement and soil sampling at required depths.

Key Features:

- High accuracy
- Multi-degree-of-freedom movement
- Sensor-compatible modular design



Soil Sensing & Surface Clearing System: Includes a probe for measuring moisture, nutrients, and conductivity, and a blade for removing surface debris to ensure accurate readings.



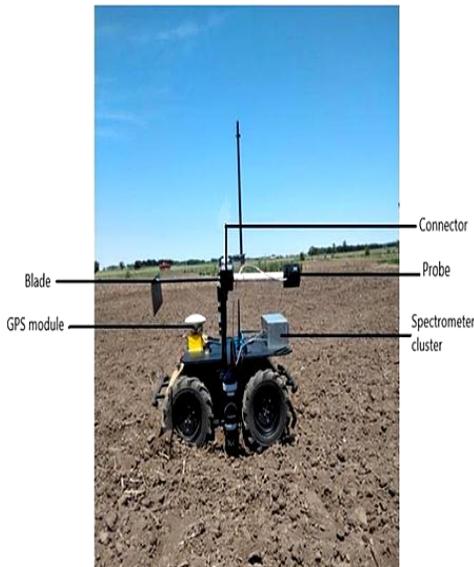
Soil Sensing and Surface Preparation Unit

The soil sensing and surface preparation module of the robotic system is designed to clear surface debris, biomass and obstacles before conducting soil measurements. The system enables soil spectroscopic analysis up to approximately 5 cm below the surface, ensuring accurate and reliable data collection.

The unit consists of two primary components:

I. Soil Probe

- Introduces electromagnetic radiation into the soil surface.
- Receives and analyzes the reflected signals.
- Enables assessment of soil properties such as moisture, nutrients and conductivity.



II. Surface Clearing Blade

- Removes debris, crop residues and surface obstructions.
- Ensures proper soil contact prior to spectroscopic measurements.
- Improves accuracy and consistency of soil data acquisition.

Challenges in the Adoption of Agricultural Technologies

1. High Initial Investment Costs

- Advanced agricultural technologies, including robotic systems and smart sensors, demand substantial upfront capital.
- Small and marginal farmers often face financial constraints that limit their ability to invest in such innovations without subsidies or credit support.
- Extended return-on-investment periods reduce the willingness of budget-constrained farmers to adopt these technologies.

2. Technological Reluctance

- Older generation farmers may be resistant due to limited exposure and familiarity with digital and automated systems.
- Doubts regarding the reliability, complexity and potential impact on traditional practices and employment further hinder acceptance.

Recommendations in the Adoption of Agricultural Technologies

1. Strengthening Research and Innovation

- Improve the efficiency and accuracy of soil sensors and robotic systems to generate detailed soil health data and promote optimal resource utilization.
- Design simple, user-friendly technologies adapted to local farming conditions and suitable for farmers with different educational backgrounds.

2. Institutional Support and Capacity Building

- Facilitate access to modern technologies through contract farming initiatives and agricultural extension programs.
- Provide structured training, technical guidance and continuous support to assist farmers in transitioning from conventional to technology-driven farming practices.

Future Perspectives and Opportunities

AI-driven robotics is transforming soil sensing by enabling real-time monitoring of soil moisture, nutrients and overall health to support precision farming. Robotic automation ensures accurate and consistent data collection over large fields, while predictive analytics assists farmers in making timely decisions. Integrated data systems and adaptive AI models enhance efficiency, optimize resource use, reduce operational costs, and promote environmentally sustainable agricultural practices.

Conclusion

AI-powered robotics is transforming soil sensing by enabling real-time, accurate and non-destructive monitoring of soil properties. Compared to traditional methods, robotic systems provide faster data collection, higher precision and better support for precision agriculture. Although challenges such as high costs and technology adoption exist, continued research and institutional support can enhance accessibility. Overall, AI-integrated soil sensing systems have strong potential to improve productivity, optimize resource use, and promote sustainable agricultural practices.

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