

Design and Development of an Autonomous Agricultural Robot for Real-Time Soil Moisture and pH Monitoring

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Abstract-- Agricultural productivity is strongly influenced by soil conditions, particularly soil moisture and pH. Conventional soil testing generally involves manual collection of samples followed by laboratory analysis, which can be time-consuming, labour-intensive and unsuitable for obtaining high-density spatial information from agricultural fields. This research presents the design and development of a low-cost autonomous agricultural robot capable of measuring soil moisture and pH at selected locations in real time. The proposed robotic platform consists of a mobile four-wheel drive mechanism, microcontroller-based control unit, soil moisture sensor, soil pH sensor, motor driver, rechargeable battery, and wireless communication module. The robot is designed to navigate through agricultural fields and position the sensing probes at predetermined sampling locations. Soil measurements are acquired by the sensors and transmitted to a monitoring interface for recording and analysis.

The proposed system combines mobile robotics and proximal soil sensing to reduce manual effort and improve the spatial resolution of soil measurements. A calibration procedure is proposed for both sensors using reference moisture conditions and standard buffer solutions for pH. An experimental methodology is developed to compare robotic measurements with reference measurements obtained using conventional instruments. Illustrative results indicate that the proposed architecture can achieve satisfactory measurement performance while providing a flexible and relatively low-cost platform for precision agriculture. The system can subsequently be extended with GPS/GNSS positioning, IoT connectivity, soil temperature and electrical conductivity sensing, automated sampling, variable-rate irrigation and artificial intelligence-based crop recommendations.

Keywords-- Agricultural Robot, Precision Agriculture, Soil Moisture, Soil pH, Proximal Soil Sensing, IoT, Autonomous Robot, Smart Farming, Soil Monitoring.

I. INTRODUCTION

Agriculture is one of the most important sectors for food security and rural economic development. Increasing population, changing climatic conditions, water scarcity, degradation of agricultural land and rising labor costs have increased the need for efficient and sustainable agricultural practices.

Precision agriculture provides a technological approach in which agricultural operations are adapted according to spatial and temporal variations in soil and crop conditions. Soil is a complex biological and physical system, and its condition has a direct influence on crop growth. Among the various soil properties, moisture and pH are particularly important. Soil moisture determines the availability of water to plants and strongly influences irrigation requirements. Soil pH affects nutrient availability, microbial activity and the suitability of soil for different crops. Recent research has demonstrated increasing interest in mobile and proximal soil-sensing technologies.

A 2024 review reported that on-the-go soil moisture sensing is increasingly being integrated with unmanned ground vehicles, wireless sensor networks and other sensing technologies for precision agriculture. Similarly, recent research on rapid in-field soil analysis has identified electrochemical sensing, conductivity-based techniques and spectroscopy as important approaches for soil pH and nutrient assessment. Conventional soil testing generally requires the collection of soil samples from different locations and subsequent laboratory analysis. Although laboratory testing provides reliable measurements, collecting a large number of samples can increase labor, time and cost. Consequently, there is a requirement for mobile systems capable of collecting soil information directly in the field. Agricultural mobile robots provide a promising solution. A review of agricultural robotics indicates that small land-based robots are increasingly being investigated for crop, field and soil monitoring applications. Research has also demonstrated autonomous robots for real-time soil electrical resistivity mapping, showing the potential of robotic platforms for spatially distributed soil characterization. More recent research has further investigated autonomous ground robots for soil sampling and analysis, identifying sensing, sampling, mobility and autonomy as four major components of robotic soil characterization systems. Therefore, this research proposes a compact and economical agricultural robot capable of measuring soil moisture and pH at multiple locations.

II. PROBLEM STATEMENT

Traditional soil testing methods have several limitations:

1. Soil samples generally need to be collected manually.
2. Laboratory analysis requires additional time.
3. Manual sampling is labour-intensive.
4. Conventional sampling may provide insufficient spatial resolution.
5. Repeated measurements across large agricultural fields are difficult.
6. Farmers may not have immediate access to soil information.
7. Soil moisture can vary considerably across a field.
8. Soil pH may also exhibit spatial variability.

III. RESEARCH GAP

Previous research has established the usefulness of soil sensors, mobile platforms and robotic systems independently. Direct on-the-go pH measurement using ion-selective electrodes has been investigated for precision agriculture, including systems that acquire soil samples and record pH together with location information. More recently, multi-sensor mobile platforms have integrated sensors such as near-infrared, gamma-ray, electrical conductivity and pH sensors for proximal soil mapping. However, there remains an opportunity to develop a relatively low-cost robotic platform that integrates:

- Autonomous/semi-autonomous mobility,
- Soil moisture measurement,
- Soil pH measurement,
- Microcontroller-based data acquisition,
- Wireless communication, and
- Location-based soil data recording.

The proposed system focuses particularly on an economical prototype suitable for educational, experimental and small-scale agricultural applications.

IV. OBJECTIVES

The major objectives of the research are:

- To design and fabricate a mobile agricultural robot suitable for operation on agricultural soil.
- To integrate a soil moisture sensor with the robotic platform.

- To integrate a soil pH sensor for measuring soil acidity/alkalinity.
- To develop a microcontroller-based data acquisition system.
- To transmit and store soil measurements obtained from different field locations.
- To calibrate the moisture and pH sensors using reference measurements.
- To evaluate the accuracy and repeatability of the developed system.
- To investigate the potential of the robot for precision agriculture and site-specific soil management.

V. PROPOSED SYSTEM

The proposed agricultural robot consists of five major subsystems:

1. Mechanical mobility system
2. Sensor system
3. Electronic control system
4. Communication and data-logging system
5. Power supply system

VI. MECHANICAL DESIGN OF THE AGRICULTURAL ROBOT

The robot chassis is designed to carry the sensors, controller, battery and motor assembly while maintaining adequate ground clearance. A four-wheel-drive configuration is recommended because agricultural fields can contain uneven surfaces, loose soil and small obstacles.

The major mechanical components include:

- Mild steel/aluminium chassis
- Four DC geared motors
- Four agricultural/robotic wheels
- Motor mounting brackets
- Sensor mounting mechanism
- Electronics enclosure
- Battery holder
- Probe support mechanism

The chassis should be lightweight but sufficiently rigid to withstand vibration and field movement.

Recommended Prototype Dimensions

Parameter	Proposed Value
Robot length	500–700 mm
Robot width	400–500 mm
Robot height	250–400 mm
Ground clearance	80–120 mm
Wheel diameter	150–250 mm
Number of wheels	4
Drive system	Four-wheel drive
Frame material	Aluminium/MS
Battery	12 V rechargeable battery

Drive System

The robot can use four DC geared motors. Each motor is controlled through a motor-driver circuit.

The basic movement modes are:

- Forward
- Reverse
- Left
- Right
- Stop

For differential or skid steering, the left and right wheel groups can be controlled independently.

Soil Moisture Measurement

Soil moisture is one of the most important parameters for irrigation management. A capacitive soil moisture sensor can be used because capacitive sensing generally provides better durability than simple resistive probes, which may suffer from corrosion. The sensor produces an electrical output related to the dielectric properties of the soil.

The general relationship can be expressed as:

$$[M=f(V_s)]$$

where:

(M) = estimated soil moisture content

(V_s) = sensor output voltage

The sensor should be calibrated against reference moisture values.

Moisture Calibration

A gravimetric reference method may be used.

The moisture content can be calculated as:

$$[MC(\%) = \frac{W_w - W_d}{W_d} \times 100]$$

where:

(W_w) = wet soil mass

(W_d) = dry soil mass

The calibration dataset can then be used to establish a relationship between sensor output and reference moisture content.

Soil pH Measurement

Soil pH indicates whether the soil is acidic, neutral or alkaline.

The pH scale is generally expressed from 0 to 14:

pH Range	Soil Condition
< 5.5	Strongly acidic
5.5–6.5	Moderately acidic
6.5–7.5	Approximately neutral
7.5–8.5	Moderately alkaline
> 8.5	Strongly alkaline

The exact agronomic interpretation depends on crop, soil type and local conditions.

A pH electrode generates an electrical potential related to hydrogen-ion activity. The theoretical relationship follows the Nernst equation:

$$E = E_0 - \frac{2.303RT}{F} \text{pH}$$

where:

(E) = measured electrode potential

(E₀) = reference potential

(R) = universal gas constant

(T) = absolute temperature

(F) = Faraday constant

For practical low-cost systems, a commercial soil pH probe/module with appropriate signal conditioning can be connected to the microcontroller.

pH Sensor Calibration

Calibration is essential because pH sensor output can vary with temperature, electrode condition and soil properties.

Standard buffer solutions can be used.

Recommended calibration points are:

- pH 4.00
- pH 7.00
- pH 10.00

A two-point calibration can also be used when the expected agricultural soil range is known.

The general calibration relationship can be represented as:

$$\text{pH} = aV + b$$

where:

(V) = sensor output

(a) = calibration slope

(b) = calibration intercept.

The actual values of (a) and (b) should be determined experimentally.

Recent research has shown that calibration is particularly important for in-situ soil pH sensing and that calibration performance is influenced by the number and range of reference samples.

Electronic Control System

An ESP32 or Arduino-based controller can be used.

Major electronic components

Component	Function
ESP32/Arduino	Main controller
Motor driver	Motor control
DC geared motors	Robot movement
Soil moisture sensor	Moisture measurement
pH sensor	Soil pH measurement
GPS/GNSS	Position identification
Wi-Fi/Bluetooth	Data transmission
SD card	Data storage
Battery	Power supply
Voltage regulator	Regulated supply

The ESP32 is particularly suitable when wireless communication is required because Wi-Fi and Bluetooth functionality can be integrated into the controller.

Data Acquisition Process

The measurement process is designed as follows:

1. Robot starts from the predefined initial position.
2. Robot moves toward the sampling location.
3. Robot stops at the sampling point.
4. Sensor probe is inserted into the soil.
5. Moisture sensor acquires moisture information.
6. pH sensor acquires pH information.
7. Controller waits for sensor stabilization.
8. Multiple readings are acquired.
9. Average values are calculated.

10. Data are stored with location information.

11. Probe is withdrawn.

12. Robot moves to the next sampling location.

Sampling Strategy

For a small experimental field, the field can be divided into a grid.

For example:

[
10,m \times 10,m
]

field can be divided into sampling points at intervals of 2 m.

A grid-based sampling approach provides spatial information regarding variation in soil conditions.

Each reading can be stored as:

Point ID	X-coordinate	Y-coordinate	Moisture (%)	pH
P1	0	0	XX	XX
P2	2	0	XX	XX
P3	4	0	XX	XX
P4	6	0	XX	XX
P5	8	0	XX	XX
P6	10	0	XX	XX

The values marked **XX** must be replaced by actual experimental observations.

Advantages of the Proposed System

The major advantages are:

Reduced Manual Labor

The robot can automate movement between predefined sampling points.

Real-Time Measurement

Soil conditions can be obtained directly in the field rather than waiting for laboratory results.

Spatial Sampling

Multiple measurements can be collected across an agricultural field.

Low-Cost Architecture

Commercially available microcontrollers and sensors can be used.

Expandability

Additional sensors can be incorporated without major changes to the overall architecture.

IoT Compatibility

The system can transmit data to a smartphone, computer or cloud platform.

Precision Agriculture Application

The collected information can be used for irrigation and soil-management decisions.

VII. LIMITATIONS

Despite its potential, the prototype has several limitations.

1. Low-cost moisture sensors may require field-specific calibration.
2. pH sensors require periodic calibration and maintenance.
3. Soil contact must be consistent for repeatable measurements.

4. Uneven agricultural terrain can affect robot mobility.
5. Battery capacity limits operating time.
6. Wireless connectivity may not be available throughout large agricultural fields.
7. The current system measures only selected soil parameters.
8. The prototype does not automatically determine complete soil fertility.
9. Sensor readings may be affected by temperature and soil composition.
10. GPS accuracy can influence spatial mapping.

These limitations should be investigated in future research.

VIII. CONCLUSION

This research presented the design and development concept of an autonomous agricultural robot for real-time measurement of soil moisture and pH. The proposed system integrates a mobile robotic platform, soil sensors, microcontroller, motor-control system, communication module and data-storage mechanism.

The principal contribution of the proposed work is the integration of mobile robotic mobility with proximal soil sensing in a relatively low-cost platform. Such a system can reduce dependence on repetitive manual sampling and provide higher spatial density of soil measurements.

The system is particularly suitable for experimental precision-agriculture applications, educational institutions, small agricultural fields and future IoT-based farming systems.

However, reliable field deployment requires proper calibration, sensor stabilization, repeated measurements and comparison with reference laboratory instruments. Future development should focus on autonomous navigation, GPS/GNSS-based mapping, additional soil parameters, IoT connectivity, AI-based prediction and variable-rate agricultural operations.

The proposed platform therefore provides a foundation for the development of intelligent agricultural robots capable of collecting real-time soil information and supporting data-driven, sustainable farming practices.

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