

“Design and Experimental Evaluation of a Mobile Agricultural Robot for Soil Parameter Monitoring”

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ABSTRACT

Agricultural productivity is strongly influenced by the physical and chemical condition of soil. Conventional soil assessment generally involves manual collection of samples followed by laboratory testing. Although laboratory analysis can provide reliable information, the procedure requires considerable time, human effort and transportation of samples. The present work proposes the design and development of a compact mobile agricultural robot capable of moving through agricultural fields and collecting soil-related information at different locations. The proposed system integrates a mechanically fabricated mobile chassis with soil sensors, a microcontroller-based data acquisition unit, motor-drive arrangement and wireless data transmission.

The robot is intended to monitor important soil parameters such as soil moisture, soil temperature, pH, electrical conductivity, where a suitable calibrated sensor is available, nitrogen-phosphorus-potassium (NPK) indicators. Soil pH and EC are particularly useful indicators because pH is associated with nutrient availability and soil chemical condition, while EC can provide information related to soluble salts and salinity.

The proposed robot uses a four-wheel differential-drive configuration to achieve simple mechanical construction, adequate ground clearance and manoeuvrability. A sensor mounting mechanism permits the sensing elements to be positioned close to or inside the soil at selected measurement points. Preliminary/sample data presented in this paper demonstrate the proposed method of recording spatially varying soil parameters and generating a soil-condition map. The proposed system can reduce repetitive manual sampling and provide a foundation for precision agriculture, targeted irrigation and site-specific soil management.

Keywords: Agricultural Robot, Soil Monitoring, Soil Moisture, Soil pH, Electrical Conductivity, NPK, Mobile Robot, Precision Agriculture, Soil Sensing.

INTRODUCTION

Agriculture is increasingly influenced by the need to improve productivity while reducing unnecessary consumption of water, fertilizers and energy. Soil is one of the most important components of an agricultural ecosystem because it provides physical support, water and nutrients required for crop development. However, soil properties are not uniform throughout an agricultural field. Moisture, pH, salinity, temperature and nutrient availability can change considerably from one location to another.

FAO identifies soil-health assessment through a combination of physical, chemical and biological indicators. Parameters relevant to soil assessment include soil moisture and temperature as physical characteristics and pH, electrical conductivity and nutrient-related measurements as chemical indicators.

Conventional soil analysis normally requires an operator to select sampling locations, collect samples, label them and transport them to a laboratory. Laboratory analysis remains important when high-accuracy reference

measurements are required; however, frequent sampling over large agricultural areas can become laborious. A mobile robotic platform provides an alternative approach in which sensors can be transported automatically to several locations.

Recent research indicates that agricultural robots are being developed for navigation, monitoring, crop operations and information gathering. Modern field robots increasingly combine mobile platforms, sensing, localization, control and intelligent decision-making.

The objective of this work is therefore to develop a low-cost mobile agricultural robot for soil parameter monitoring that can be fabricated using commonly available mechanical and electronic components. The emphasis of the project is on mechanical design, mobility, sensor integration, field operation and data acquisition.

The proposed system is particularly suitable as an educational and research prototype for demonstrating the integration of mechanical engineering with electronics, embedded control and agricultural applications.

LITERATURE REVIEW

Agricultural robotics has developed from simple remotely operated machines to systems capable of autonomous navigation and environmental sensing. Reviews of agricultural robots identify mobile platforms, actuation systems, navigation, perception and task planning as important technological components. Fasiolo et al. reviewed technologies supporting autonomous mapping in agriculture and highlighted the importance of localization, mapping, navigation and sensing for ground robots operating in agricultural environments. Liu et al. reported that modern field robots increasingly incorporate intelligent sensing, decision-making, control, stable walking and cloud/edge technologies, while challenges remain in sensing accuracy, field operability and efficiency. Soil sensing from mobile machinery is not a new concept. Earlier research investigated contact and non-contact methods for sensing soil water content from mobile agricultural equipment. More recent robotic systems provide opportunities to combine several sensors on a single mobile platform. From the soil-science perspective, FAO identifies parameters such as soil texture, soil organic carbon, pH, electrical conductivity, bulk density, soil moisture and soil temperature as useful soil characteristics depending on the assessment objective. Electrical conductivity is particularly relevant to soil salinity assessment. FAO describes EC as an indicator associated with the concentration of salts in the soil solution, while also noting that EC is not a direct measurement of individual ions.

Research Gap

Based on the reviewed literature, several advanced agricultural robots employ sophisticated localization, perception and autonomous navigation systems. However, there remains an opportunity for a simple, economical and mechanically robust educational agricultural robot specifically designed around multi-parameter soil monitoring.

The research gap addressed in this work is:

- development of a compact mechanical platform suitable for agricultural soil;
- integration of multiple low-cost soil sensors;
- provision for repeatable sensor positioning;
- measurement at multiple spatial locations;
- recording and comparing soil parameters;
- development of a platform that can later be upgraded to autonomous navigation.

Problem Statement

Manual soil sampling requires repeated human intervention. When several points in a field need to be examined, the operator must physically travel to each location and perform or collect the measurements. The proposed problem can therefore be stated as: To design and develop a compact mobile agricultural robot

capable of traversing agricultural soil and measuring selected soil parameters at different field locations while recording the obtained data for subsequent analysis.

Objectives

The major objectives of the proposed research are:

1. To design a mechanically stable mobile agricultural robot.
2. To develop a suitable chassis and wheel arrangement for field movement.
3. To integrate soil sensors with the mobile platform.
4. To measure soil moisture, temperature, pH and electrical conductivity.
5. To provide an optional NPK sensing facility.
6. To acquire and store soil data at multiple locations.
7. To develop a low-cost prototype suitable for agricultural applications.
8. To evaluate the robot's mobility and sensing performance experimentally.
9. To develop a basis for future soil-condition mapping and precision agriculture.

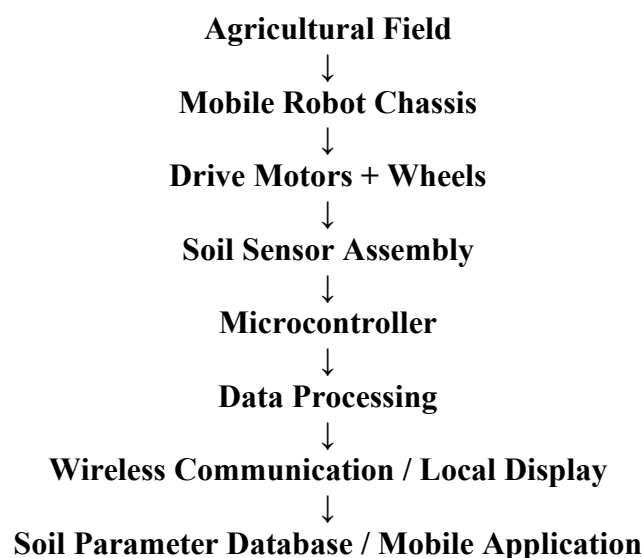
Proposed System

The proposed robot consists of five major subsystems:

1. Mechanical mobility system
2. Soil sensing system
3. Embedded control system
4. Power supply system
5. Data communication and storage system

Overall Architecture

The functional arrangement can be represented as:



The robot moves to a selected location and stops. The sensor assembly is then positioned at the required soil depth. After allowing sufficient settling time for the sensor output, the controller records the readings.

Mechanical Design of the Robot

Chassis

The chassis forms the primary structural component of the robot. A rectangular frame is proposed using mild-steel square tube or aluminium structural members.

For an educational prototype, mild steel provides:

- good availability;
- adequate strength;
- simple welding;
- relatively low fabrication cost;
- easy modification.

An aluminium frame can alternatively be used when lower mass is required.

Chassis Dimensions

Parameter	Proposed Value
Overall length	600 mm
Overall width	450 mm
Chassis height	180 mm
Ground clearance	100 mm
Wheel diameter	250 mm
Approximate robot mass	18 kg
Payload	5 kg

The ground clearance should be sufficiently large to avoid excessive contact between the chassis and soil or crop residues.

Wheel and Drive Arrangement

A four-wheel drive or four-wheel differential-drive arrangement can be used. In the proposed configuration, the left-side wheels operate together and the right-side wheels operate together. The robot can therefore move forward, reverse, rotate and change direction by controlling the relative speeds of the two sides.

For straight motion:

$$V_L = V_R$$

For turning:

$$V_L \neq V_R$$

For approximate in-place rotation:

$$V_L = -V_R$$

where:

- V_L = left-wheel velocity
- V_R = right-wheel velocity.

This configuration reduces mechanical complexity compared with a conventional steering mechanism.

Motor Selection

The motor must provide sufficient torque to overcome:

- rolling resistance;
- soil resistance;
- slope resistance;
- acceleration forces;
- additional resistance caused by field irregularities.

The required tractive force may be approximately expressed as:

$$F_T = F_R + F_S + F_A$$

where:

- F_T = total required tractive force,
- F_R = rolling resistance,
- F_S = slope resistance,
- F_A = acceleration force.

The approximate wheel torque is:

$$T_w = \frac{F_T r}{\eta}$$

where:

- T_w = required wheel torque,
- r = wheel radius,
- η = transmission efficiency.

Calculation

Assume:

- Robot mass = 18 kg
- $g = 9.81 \text{ m/s}^2$
- estimated total resistance = 55 N

- wheel radius = 0.125 m
- transmission efficiency = 0.75

Then:

$$T_w = \frac{55(0.125)}{0.75}$$

$$T_w \approx 9.17 \text{ Nm}$$

Therefore, the drive system should provide approximately 9.2 Nm total wheel torque, with an appropriate safety factor.

Sensor Integration

The proposed robot can accommodate the following sensors.

Parameter	Proposed Sensor	Purpose
Soil moisture	Capacitive moisture sensor	Estimate volumetric/water-related condition
Soil temperature	Waterproof temperature sensor	Measure soil temperature
pH	Soil pH probe/module	Determine acidity/alkalinity
EC	EC sensor	Estimate conductivity/salinity
NPK	NPK sensor	Estimate nutrient-related parameters
Position	GPS/GNSS module	Location tagging
Robot orientation	IMU	Motion/orientation information

FAO's soil-data framework includes soil pH, EC, moisture and temperature among parameters used in soil assessment, although the appropriate measurement method depends on the intended application.

Soil Moisture Measurement

Soil moisture is one of the most important parameters for irrigation management. A capacitive soil-moisture sensor can be used instead of a simple resistive probe because capacitive sensing can reduce problems associated with direct electrode corrosion. The sensor is inserted into the soil to a predetermined depth.

Measurement procedure

1. Robot moves to sampling point.
2. Robot stops.
3. Soil probe is inserted.
4. Sensor output is allowed to stabilize.
5. Reading is acquired.
6. Value is transmitted/stored.
7. Probe is withdrawn.

8. Robot proceeds to next point.

Soil pH Measurement

Soil pH indicates the acidic or alkaline condition of soil and is important because soil pH influences nutrient availability and other soil processes. FAO identifies pH as one of the soil characteristics relevant to nutrient availability and notes its relationship to nutrient deficiencies and toxicities. The pH sensor requires appropriate calibration before measurement. A typical calibration procedure uses standard buffer solutions.

Recommended calibration

- pH 4 buffer
- pH 7 buffer
- pH 10 buffer, where appropriate

Electrical Conductivity Measurement

Electrical conductivity provides an indirect indication of the concentration of soluble salts in soil.

The EC value can be represented as:

$$EC = \frac{G}{K}$$

where:

- G = measured conductance,
- K = cell constant.

For actual experimental work, the unit and measurement method must be clearly reported because EC can be determined under different soil-water conditions. FAO provides an SOP specifically for soil electrical conductivity using a soil/water ratio method.

NPK Measurement

Nitrogen, phosphorus and potassium are major nutrients required for crop growth. An NPK sensor can be incorporated into the robot where the selected sensor provides sufficiently repeatable readings for the intended application. However, NPK values from inexpensive field sensors should not automatically be treated as laboratory-equivalent chemical analysis. The final paper should report the sensor model, calibration procedure, measurement principle and validation method.

Therefore, the final experimental section should contain:

- sensor manufacturer;
- sensor model;
- measurement range;
- accuracy;
- calibration method;
- reference measurement method;
- number of repeated readings.

Control System

An Arduino, ESP32 or similar microcontroller can be used as the central controller.

Major functions

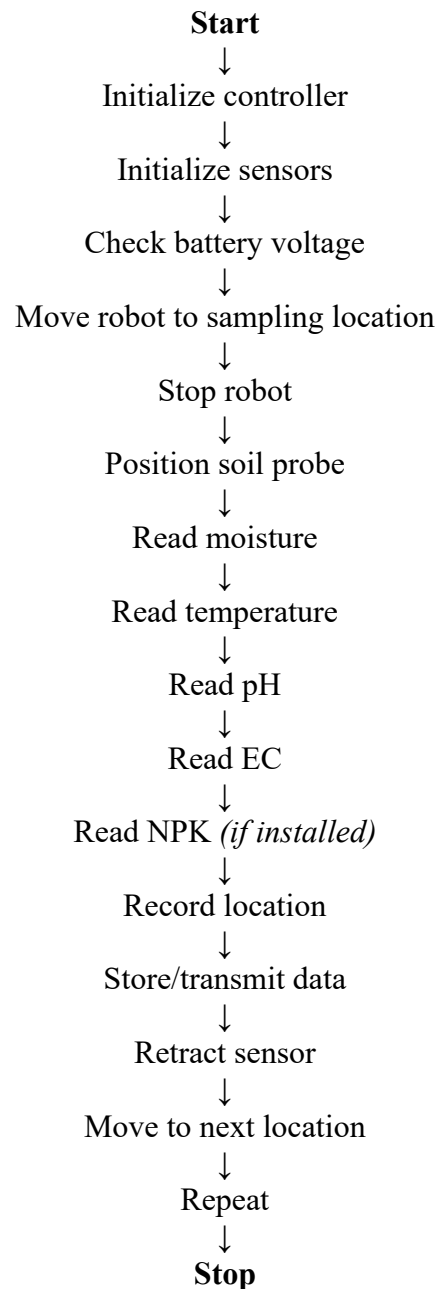
The controller performs:

1. Motor control
2. Sensor acquisition
3. Data filtering
4. Measurement timing
5. Location tagging
6. Wireless communication
7. Data storage

The ESP32 platform can be particularly useful when Wi-Fi/Bluetooth communication is required.

Data Acquisition Algorithm

The proposed algorithm is:



Experimental Methodology

The experimental study should be performed on a controlled agricultural test area or suitable soil bed. The test field should be divided into several sampling locations.

For example:

Point	X Coordinate	Y Coordinate
P1	0 m	0 m
P2	2 m	0 m
P3	4 m	0 m
P4	0 m	2 m
P5	2 m	2 m
P6	4 m	2 m
P7	0 m	4 m
P8	2 m	4 m
P9	4 m	4 m

At every point, at least three readings should preferably be taken.

The average value is calculated as:

$$X_{avg} = \frac{X_1 + X_2 + X_3}{3}$$

The standard deviation can be calculated as:

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n - 1}}$$

This provides an indication of repeatability.

Sample Soil Measurements

Location	Moisture (%)	Temperature (°C)	pH	EC (mS/cm)	N (mg/kg)*	P (mg/kg)*	K (mg/kg)*
P1	31.2	27.4	6.7	0.82	118	24	164
P2	34.6	27.1	6.5	0.76	126	27	171
P3	28.4	28	7.1	1.02	104	21	152
P4	38.1	26.8	6.4	0.69	132	29	178
P5	35.7	27	6.6	0.73	129	26	175
P6	25.9	28.3	7.2	1.08	97	19	145
P7	40.3	26.5	6.3	0.64	137	31	184
P8	36.9	26.9	6.5	0.71	131	28	177
P9	29.7	27.8	7	0.96	108	22	158

*NPK values are illustrative only.

CONCLUSION

This paper presented the design concept and development methodology for a mobile agricultural robot intended for soil parameter monitoring. The proposed system combines a four-wheel mobile platform, soil

sensors, embedded control, power electronics and wireless data acquisition. The robot is designed to measure selected parameters including soil moisture, temperature, pH and electrical conductivity, with provision for NPK sensing. The mechanical design emphasizes adequate ground clearance, mobility, stability, simple fabrication and modular sensor mounting. The sample experimental framework demonstrates how measurements from multiple field locations can be organized and analyzed to identify spatial variations in soil conditions. The proposed system provides a practical foundation for future development of autonomous soil-

monitoring robots. Integration with GNSS, IoT, artificial intelligence and automatic soil-probe mechanisms could transform the prototype into a more advanced precision-agriculture platform. The work is particularly suitable as a mechanical engineering student project because it integrates machine design, vehicle mechanics, fabrication, sensors, embedded systems, control and agricultural engineering within one application.

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