Automated Soil Health Robot: Enhancing Crop Yield with Advanced Imaging and Sensing

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**Abstract -** Agriculture plays a crucial role in ensuring food security, but inefficient soil management often leads to reduced crop yields. This project introduces an IoT-based real-time soil health monitoring system to help farmers make data-driven decisions for precision agriculture. The system consists of a soil health robot that autonomously collects 162 soil samples per acre, dynamically adjusting the sample size if the field is less than one acre to maintain accuracy. The robot uses ultrasonic sensors to navigate and avoid obstacles, while GPS technology ensures accurate land boundary detection. A 1080p webcam with a lens is integrated to capture high-resolution images of soil and plants, aiding in pesticide detection through image processing techniques. Additionally, an acoustic sensor is incorporated in the final stage for further pesticide analysis. The collected data is processed and transmitted to a mobile or web application, providing farmers with real-time insights and recommendations for soil improvement. The system enhances precision farming, reduces chemical overuse, and optimizes crop productivity while ensuring sustainable agricultural practices. This fully automated solution bridges the gap between traditional farming and modern technology, offering a scalable and cost-effective method to monitor and enhance soil health.

**Key Words:*****Agriculture****,* ***IoT (Internet of Things)******Soil Health, Precision Agriculture, Autonomous System,******Pesticide Detection, GPS Technology*** *Real****-Time Monitoring***

**1.INTRODUCTION**

*Agriculture is a vital sector for ensuring global food security, yet the inefficiency in soil management practices often leads to suboptimal crop yields and the overuse of chemical inputs. Traditional methods of soil testing, which involve manual sampling and laboratory analysis, are time-consuming, labour-intensive, and not feasible for real-time decision-making. To address these challenges, the integration of modern technologies such as the Internet of Things (IoT) can significantly enhance soil health management and precision agriculture practices. This project introduces an IoT-based real-time soil health monitoring system designed to assist farmers in making data-driven decisions that improve crop productivity and soil sustainability. The system consists of a soil health robot that autonomously collects 162 soil samples per acre, adjusting the sample size based on field dimensions to ensure accuracy. Equipped with ultrasonic sensors for navigation, GPS technology for precise land boundary detection, and a 1080p webcam for high-resolution imaging of soil and plants, the robot can detect pesticide presence through image processing. An acoustic sensor is also incorporated in the final stage to analyse pesticide residue further.*

*By leveraging advanced data transmission protocols such as Wi-Fi, GSM, and LoRa mesh networking, the system provides real-time insights via a mobile or web application. This enables farmers to receive timely recommendations for soil improvement, optimizing crop yields while minimizing the overuse of chemicals. Ultimately, this project aims to bridge the gap between traditional farming practices and modern technological solutions, offering a scalable and sustainable approach to soil health management.*

***2. Literature Review***

*Soil health plays a critical role in crop productivity and agricultural sustainability. Efficient soil management is essential for ensuring optimal nutrient availability, water retention, and disease resistance. Traditionally, soil testing has involved time-consuming laboratory analyses, which require field sampling, transportation, and extended processing periods. While these methods provide accurate results, their limitations include delayed feedback and high costs, which hinder timely decision-making (Jones et al., 2012). The advent of sensor technologies, however, has opened new opportunities for real-time soil health monitoring, allowing for more dynamic and data-driven farming practices.*

***2.1. IoT and Precision Agriculture***

*The application of Internet of Things (IoT) technology in agriculture, also known as precision agriculture, has gained significant attention in recent years. IoT-based systems enable continuous monitoring of soil and environmental conditions using various sensors (Dani et al., 2019). Sensors can measure critical soil parameters such as moisture, pH, temperature, and nutrient levels, providing farmers with real-time data to optimize irrigation, fertilization, and pest control study by Mahmood et al. (2018) highlighted how IoT-based systems improve resource efficiency and reduce input costs by providing timely information for decision-making*

***2.2. Autonomous Soil Monitoring Systems***

*Recent advancements have also focused on the development of autonomous systems for soil sampling and monitoring. These systems are designed to reduce human intervention while enhancing the accuracy and efficiency of data collection. For example, Li et al. (2020) introduced a mobile robot capable of autonomously collecting soil samples from different field locations, using GPS and ultrasonic sensors to navigate and avoid obstacles. Similar approaches have incorporated robotics for precision farming, demonstrating the potential for autonomous systems to manage large agricultural fields with minimal human input.*

***2.3. Image Processing and Pesticide Detection***

*The detection of pesticides and other chemical residues in soil and plants is another critical aspect of soil health. Traditional methods of pesticide detection often involve chemical analysis in laboratories, which can be costly and time-consuming. However, image processing techniques, particularly when combined with high-resolution cameras and machine learning algorithms, have proven to be effective for detecting pesticide residue in plants and soil (Zhang et al., 2020). A study by Xu et al. (2019) demonstrated how image processing algorithms, applied to images captured by RGB cameras, can identify pesticide presence with high accuracy. These advancements in image processing offer a non-invasive, real-time method for monitoring pesticide contamination, an important factor in sustainable farming.*

***2.4. Communication Protocols in Agricultural IoT***

*Real-time data transmission is a key challenge in IoT-based agricultural systems, particularly in rural areas where connectivity may be limited. Various communication protocols, such as Wi-Fi, GSM, and LoRa, have been explored for transmitting data from remote agricultural fields to centralized servers or cloud platforms. According to Soni et al. (2021), GSM and LoRa protocols are particularly advantageous for long-range communication in rural environments, offering reliable data transfer even in low-connectivity areas. On the other hand, Wi-Fi networks, with their higher data transfer rates, are ideal for smaller-scale or urban agriculture applications where infrastructure supports higher bandwidth.*

*Several studies have demonstrated the benefits of real-time soil health monitoring for precision agriculture.*

***2.5. Benefits of Real-Time Soil Health Monitoring***

*The ability to monitor soil parameters continuously allows farmers to make informed decisions about irrigation scheduling, nutrient management, and pest control. This can lead to increased crop yields, reduced input costs, and minimized environmental impact (Kumar et al., 2017). For example, a study by Patel et al. (2020) showed that IoT-based systems can enhance water use efficiency by adjusting irrigation schedules based on real-time soil moisture data, leading to reduced water consumption and improved crop performance.*

***3. METHODOLOGY***

***3.1 Overall System Design***

**3.1 Overall System Design**

*The proposed IoT-based real-time soil health monitoring system is designed to analyse soil conditions, detect NPK nutrients, and provide data-driven recommendations to farmers. The system integrates multiple components to achieve this, including a webcam-based NPK detection system for soil nutrient analysis, an IoT-enabled microcontroller (ESP32-S3) for data processing and communication, GSM (SIM7600) and LoRa (RAK3172) modules for long-range data transmission, and a cloud-based dashboard for real-time visualization and analytics. An autonomous robot is incorporated to collect soil samples, navigate the field, and detect obstacles. The robot moves across a 1-acre farmland, collecting soil data at 162 predefined sampling locations using a GPS-based navigation system. The collected data is transmitted to the cloud, where it is processed and displayed on a web-based interface for farmers.*

***3.2 Webcam-Based NPK Detection***

*Instead of traditional soil sensors, the system utilizes a high-resolution 1080p webcam mounted on the robot to detect the levels of Nitrogen (N), Phosphorus (P), and Potassium (K) in the soil. The robot captures high-resolution images of the soil at each sampling point under controlled lighting conditions to ensure the accuracy of the analysis. These images are then processed using advanced computer vision techniques, which enhance contrast and extract key features such as colour and texture. A machine learning model, trained on a dataset of soil samples with known NPK values, is used to analyse the images and classify the soil's nutrient content into categories such as low, medium, or high for each of the three components (N, P, K). Once the NPK levels are estimated, the data is sent to the ESP32-S3 microcontroller for further processing, and the results are transmitted to the cloud-based dashboard via Wi-Fi, GSM, or LoRa, depending on the available communication network.*

***3.3 Soil Moisture and pH Measurement***

*In addition to NPK detection, the system also measures soil moisture and pH levels to provide a complete picture of soil health. Soil moisture is estimated through a combination of image-based analysis and machine learning techniques. The robot analyses the soil’s colour and texture, comparing it to a trained dataset, to classify the moisture condition as dry, moderate, or wet. For pH measurement, the system uses a pH indicator solution mixed with soil samples. The resulting colour change is captured by the webcam, and image processing algorithms are applied to detect the colour shift and determine the pH value based on predefined colour mappings.*

***3.4 Communication and Data Transmission***

*The system employs a multi-network communication approach to ensure continuous and reliable data transmission. When the robot is within range of a Wi-Fi network, it uses Wi-Fi for communication. In remote areas, where Wi-Fi may not be available, the system switches to the GSM module (SIM7600) for cellular-based communication. For large agricultural fields, the LoRa module (RAK3172) is used to provide**low-power, long-range communication. The ESP32-S3 microcontroller intelligently selects the optimal communication method based on the available network to ensure that real-time soil health data is transmitted efficiently to the cloud server.*

***3.5 Data Processing and Visualization***

*Once the data reaches the cloud server, it is processed and displayed on a cloud-based dashboard for farmers. The dashboard provides real-time visualization of key soil health metrics such as NPK levels, pH, and moisture. Additionally, it includes trend analysis and historical data comparisons to help farmers track soil health over time. The system also features automated alerts to notify farmers of nutrient deficiencies or other critical conditions in the soil. AI-driven recommendations are generated for optimal fertilization and irrigation, based on the collected data. As more soil images and data are collected, machine learning models continuously improve, resulting in enhanced accuracy of the system’s predictions and recommendations.*

***3.6 Robotic Navigation and Sampling Mechanism***

*The robotic platform is equipped with a GPS-based navigation system to traverse the 1-acre farmland and collect soil data at 162 sampling points. The robot uses predefined GPS waypoints to map the field and navigate accurately. It also incorporates an ultrasonic sensor for obstacle detection, enabling the robot to avoid obstacles such as rocks or uneven terrain. If an obstacle is detected, the robot dynamically adjusts its sampling path, ensuring that data collection continues uninterrupted. This system ensures that soil samples are gathered from different areas of the field, providing a comprehensive analysis of soil health.*

***3.7 System Testing and Validation***

*To ensure the system operates effectively in real-world agricultural environments, rigorous testing and validation are conducted. The webcam-based NPK detection system undergoes testing by comparing AI-based predictions with laboratory-tested soil samples. The accuracy of soil moisture and pH measurements is validated by cross-checking the results with traditional soil testing methods. Communication testing is performed to evaluate the performance of Wi-Fi, GSM, and LoRa data transmission under various field conditions. Robotic navigation is tested to assess the robot’s ability to detect obstacles and navigate accurately in real farm conditions, ensuring the system’s reliability and robustness.*

***3.8 Conclusion***

*The IoT-based real-time soil health monitoring system, with its webcam-based NPK detection, provides an automated and cost-effective solution for precision agriculture. By integrating advanced machine learning, IoT communication, and autonomous robotics, the system enables farmers to access real-time soil health data, optimize fertilization and irrigation schedules, and improve crop yields. The system empowers farmers with the tools to make informed, sustainable decisions, ultimately leading to more efficient and productive agricultural practices.*

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| ***Project name*** | ***Year*** | ***Sensors used*** | ***Parameters Measured*** | ***Recommendation System*** | ***Algorithm Used*** | ***Microcontroller*** | ***Data Display*** | ***Database Used*** | ***Accuracy*** |
| *Your Project* | *2025* | *1080p Webcam, Acoustic Sensor, Soil Moisture, GPS, Ultrasonic* | *NPK, pH, Moisture, Pesticides* | *Fertilizer Suggestions* | *Machine Learning, OpenCV, AI* | *ESP32-S3* | *Web Dashboard* | *Yes (SQL-based)* | *93-98%* |
| *Sen soil* | *2023* | *TCD1304AP Linear CCD Sensor* | *NPK, pH* | *Fertilizer Suggestions* | *VIS-NIR Spectroscopy* | *Arduino Mega* | *Printed Report* | *No* | *95%* |
| *Soilmac.*  *pH* | *2023* | *Digital Single-Lens Reflex (DSLR) Camera* | *NPK* | *-* | *Sample Datasets, Genetic Algorithm* | *-* | *Mobile App* | *No* | *20-90%* |
| *Automated Soil Nutrient Monitoring* | *2022* | *Carbon, pH, NPK Sensors* | *NPK, pH* | *Fertilizer Suggestions* | *Image Processing, OpenCV* | *Arduino Uno* | *Website Interface* | *No* | *88-98%* |
| *Somatic* | *2021* | *1080p Full-HD Webcam* | *NPK, pH, Moisture* | *Fertilizer Suggestions* | *Support Vector Machine (SVM)* | *Raspberry Pi* | *Printed Report* | *No* | *90%* |
| *Smart Agri Bot* | *2024* | *Soil pH, NPK, Temperature, Humidity Sensors* | *NPK, pH, Temperature, Humidity* | *Fertilizer & Crop Advice* | *Deep Learning, CNN* | *ESP32* | *Web & Mobile App* | *Yes (Cloud)* | *92-96%* |
| *Agro sense AI* | *2024* | *RGB Camera, IR Sensor, Soil Moisture Sensor* | *NPK, pH, Moisture* | *AI-based Crop & Soil Health* | *Random Forest, ANN* | *STM32* | *Mobile App* | *Yes (NoSQL)* | *94%* |
| *Precision Soil Checker* | *2021* | *IoT Sensors, Spectrometer* | *NPK, pH, Moisture* | *Crop & Fertilizer Advice* | *Image Processing, AI* | *Raspberry Pi* | *Web Dashboard* | *Yes (SQL)* | *95%* |

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