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Implementing a cost-effective soil monitoring system using wireless sensor networks to enhance farming practices for small-scale farmers in developing economy countries

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Abstract

Small-scale farmers in Africa often face challenges in monitoring soil and environmental parameters essential for informed agricultural decision-making. This study addresses this issue by developing a cost-effective soil monitoring system utilizing Wireless Sensor Networks (WSN). Our approach integrates real-time data analysis and visualization components to offer timely insights into soil conditions, weather patterns, and crop development, thereby enhancing agricultural decision-making processes. While commercial soil monitoring systems exist, their high cost presents a barrier to widespread adoption, particularly in African contexts. To address this issue, our proposed system utilizes WSN sensor nodes transmitting data to a central database via Arduinos functioning as web servers. This innovative approach extends monitoring capabilities to remote areas beyond the reach of individual nodes, thus promoting accessibility and affordability through the utilization of open-source software. In conclusion, our study aims to revolutionize farming practices in Africa by providing an affordable solution that empowers farmers with actionable insights for optimized agricultural outcomes, thereby aligning with the distinctive African perspective on the theory and practice of information systems.

Keywords: small-scale farmers, wireless sensing networks, soil monitoring systems, affordable technology, Wireless Sensor Networks (WSN), agricultural data, open-source software.

Introduction

The integration of wireless sensing network technology into soil monitoring systems marks a significant evolution from traditional methods, providing automation to reduce human laborand enable data collection from distant locations. Soil monitoring systems, equipped with distributed sensors within wireless sensor networks (WSNs), are capable of collecting and broadcasting weather data automatically, even in remote locations[1]. Typically housed in mast-mounted, weatherproof enclosures, a soil monitoring system comprises essential components such as a data recorder, rechargeable battery, telemetry (if desired), and meteorological sensors[2]. The system's configuration may include solar panels or wind turbines, allowing for flexibility in data storage or almost real-time reporting over a web server[3]. Historically, automatic soil monitoring systems were constrained to locations near electrical and communication infrastructure. However, advancements in solar panels, wind turbines, and mobile phone technology have liberated these systems from reliance on the electrical grid or landline telecommunications network[1].

To address these challenges, we propose a novel system, Implementing Soil Monitoring System with Wireless Network, designed to electronically and continually communicate meteorological and climate parameters across diverse geographic areas[4]. This innovative technology enables meteorology agency controllers to remotely access weather climate nodes, enhancing efficiency and conserving time and energy[4]. The proposed system mitigates common difficulties faced by soil monitoring systems, including energy depletion, packet loss, gateway failure, and sensor node failure[1]. Although the supplied data is well-structured, the implementation of data analytics becomes essential for deriving insights into the soil monitoring system's health[5]. Challenges during data reception, such as a rise in data volume, transmission, or arrival rates, and potential data loss at the receiving end due to packet dropping, necessitate effective management strategies[5].

Given the widespread accessibility of news media outlets and the prevalence of communication devices in households, our suggested soil monitoring and detection system strategically employs sensor nodes in fields. These nodes, transmitting data through a multi-hop sensor network, facilitate real-time communication of soil condition updates to individuals in affected areas via Short Message Service (SMS)[6]. In cases of potential emergencies, the sensor nodes relay critical data to the central station, which undergoes additional processing to alert locals about potential threats[6]. Leveraging WSN technology, an online monitoring framework emerges as a promising solution, overcoming challenges associated with wired systems[3]. Applications in agriculture, such as tea plantation monitoring, showcase the potential of wireless sensor networks. Image processing techniques are applied to tea leaves tracked by sensors, with wireless communication to the central station determining ripe areas for harvesting[7]. This paper emphasizes the pivotal role of WSNs in creating integrated information and production-based agricultural systems, ultimately contributing to increased farm productivity and efficiency.

In light of the distinctive African perspective on the theory and practice of information systems, we emphasize the relevance of our work to the African context. Africa, with its unique agricultural challenges and technological landscape, stands to benefit significantly from the adoption of innovative soil monitoring solutions utilizing WSN technology. By addressing the specific needs and constraints faced by African farmers, our proposed system aims to contribute to the advancement of agricultural practices and enhance food security across the continent.

Background: The agricultural landscape has undergone a transformative shift propelled by the rapid integration of Information and Communication Technology (ICT). The dissemination of crucial information, ranging from new agricultural products to market dynamics and research findings, has become widespread through the adoption of information technology within the farming and agricultural sectors[5,8]. Precision agriculture, a convergence of horticulture, engineering, and agriculture, leverages controlled environments to optimize crop yield, product efficiency, and overall crop enhancement. This involves meticulous management of variables such as illumination, nutrients, temperature, and humidity to sustain plant growth under controlled conditions[6,7]. Temperature and humidity, in particular, significantly influence plant-related processes, impacting germination, photosynthetic activity, and nutrient absorption[6,7]. Temperature variations affect plant respiration rates and sugar content, with a direct correlation between rising temperatures and increased breath rates. Conversely, lower temperatures lead to a decline in photosynthetic activity[6]. Humidity levels play a vital role in regulating both temperature and moisture loss experienced by plants. High humidity reduces evapotranspiration (ET), leading to less water absorption by leaves, while optimal moisture levels promote robust root development and overall plant growth[6,7].

The Green Revolution of the 1960s addressed the global demand for food and fiber through the development of high-yielding crop hybrids, increased use of farm inputs, and improved mechanization[7,8]. However, the environmental implications of extensive agricultural input applications became a growing concern in subsequent years[9]. The Speaking Plant Approach (SPA), conceived and refined by Japanese scientists since the 1980s, builds on the sensor-observed response of plants to ambient growth conditions[3]. This approach harnesses wireless sensor technology, incorporating components like radiofrequency receivers, sensors, microcontrollers, and resources. It serves as a user-preferred and cost-effective means of accessing and managing agricultural systems[3]. Environmental Sensor Networks (ESN), an application of Wireless Sensor Networks (WSNs) in environmental sectors, actively exchanges data in a Sensor Network Server (SNS). ESN enables intelligent network integration of autonomous sensors, strategically placed in fixed positions or on a mobility scale, to detect crucial environmental factors[2]. Studies have demonstrated that distributed ground soil monitoring systems surpass satellite-based data in accurately determining rainfall and soil conditions at various depths, providing invaluable insights for agricultural practices[3].

This background sets the stage for our exploration of wireless sensing technology in agriculture, emphasizing the pivotal role it plays in optimizing environmental conditions for enhanced crop productivity. Africa, with its unique agricultural challenges and environmental conditions, stands to benefit greatly from the adoption of wireless sensing technology in agriculture. By addressing specific environmental factors and optimizing agricultural practices, our research aims to contribute to sustainable agricultural development and food security on the African continent. Through the utilization of wireless sensor networks and environmental sensor networks, our study aligns with the objectives of providing innovative solutions tailored to African agricultural contexts, thus advancing the theory and practice of information systems in an African context.

Proposed Solution: Effective utilization of water resources and other agricultural inputs is paramount for developing sustainable agricultural systems on social, environmental, and economic fronts, particularly in African contexts where small-scale farmers predominate. Precision agriculture, involving the application of water and inputs with precision to enhance profits and environmental conservation, is crucial for growers[2]. Soil moisture detection technologies have demonstrated their potential to increase profitability and protect the environment[1]. However, small-scale farmers, often cultivating limited land with traditional methods, face challenges in adopting precision farming due to the cost of available soil monitoring systems[10,11].

This study proposes the development of a communication system for monitoring soil properties, specifically designed to empower smallholders[12]. The platform offers data gathering, viewing, and sharing options, utilizing open-source hardware and software to ensure affordability and simplicity[13]. To address the challenges of remote agricultural lands, supervisory software programs employing multi-terminal control frameworks are recommended[4]. Soil conditions are updated remotely, promoting flexibility and ease of monitoring systems through web accessibility. Open-source electronics, wireless data transfer, and Internet-of-Things technologies contribute to making soil moisture sensing devices more accessible and reasonably priced for small-scale growers[1].

The deployment of Wireless Sensor Networks (WSNs) across vast monitoring regions is made efficient by linking dispersed

WSN base stations to an internet cloud server[3]. This allows users to access meteorological data through an online web service. WSNs, known for their low-power, low-cost, multi-hopping capabilities, offer an extended network without line-of-sight coverage, self-healing data paths, and independence from external service providers[2,3]. The use of mobile access and cloud computing further enhances the reach and convenience of the proposed system[4]. A mobile application, developed using 'MIT App Inventor 2,' facilitates easy access to the system. This solution leverages the Arduino UNO WiFi Rev2 board as a Web server, providing an interactive webpage displaying sensor values. Users can remotely perform manual actions or automate soil condition adjustments based on sensor values, offering a highly dependable, low-cost technology tailored for small-scale farmers[1,13].

This proposed solution not only addresses the challenges faced by small-scale farmers in adopting precision agriculture. By emphasizing affordability, simplicity, and accessibility, our work seeks to empower African smallholders with the tools and technologies necessary to optimize soil conditions and enhance agricultural productivity in a contextually relevant manner.

Web-Based Soil Management System: The integration of Information and Communication Technology (ICT) into small-scale farming practices has the potential to revolutionize crop and soil management, enhancing agricultural productivity, particularly in the African context where smallholder farmers are predominant. In recognition of the limited tech-savviness of the majority of farmers, the proposed portable sensing box aims to provide practical, seamless, and user-friendly ICT solutions for digital farming in rural areas. Aligned with the second Sustainable Development Goal (SDG2) of the United Nations, which focuses on ending hunger, achieving food security, improving nutrition, and promoting sustainable agriculture, the project specifically addresses the needs of marginalized areas, particularly in South Africa.

The key output of the portable sensing box is the development of a mobile soil management system, leveraging the Internet of Things (IoT). This system aims to support humanitarian technology by catering to the specific requirements of smallholder farmers. The soil monitoring system consists of three main components: the Sensor application, the Farmer application, and the selected crops. The Sensor application, integrated into an IoT sensing platform, utilizes various sensors to monitor crucial soil conditions and provide insights for crop growth. The system employs a web browser to request data from the IoT sensing platform, enabling the collection of parameters for all the sensors within the sensing box.

The IoT sensing platform, in conjunction with computer vision, offers data on pH, soil moisture, humidity, pressure, air temperature, and light conditions, providing a comprehensive understanding of soil features. The hardware of the platform is designed to withstand deployment environments, ensuring durability and ease of assembly and transportation within a protective shell. The operational logic involves sensors collecting data, transmitting it to an Arduino, which then uploads the data over Wi-Fi to a web server. An Android app reads this data from the web server and displays it using the MIT App Inventor, a user-friendly tool for creating Android apps. The MIT App Inventor enables non-programmers to develop mobile apps for Android smart phones through a graphical user interface, allowing users to drag and drop visual elements to design applications. The app can display readings and perform actions based on the collected data, making it an accessible tool for farmers.

The proposed web-based soil management system offers an innovative and user-friendly solution to empower smallholder farmers, contributing to sustainable agriculture and addressing the challenges of rural digitalization in the African context. By providing accessible and practical ICT solutions tailored to the needs of African farmers.

Material and Methods

This study adopts a Design Science Research (DSR) methodology to develop and evaluate a mobile sensing device and accompanying mobile application aimed at enhancing soil management practices for small-scale farmers, particularly within the African context. The methodology follows established principles within the DSR paradigm to design innovative artifacts addressing real-world agricultural challenges, with a focus on the specific needs and contexts of African small-scale farmers. The research begins by identifying challenges faced by small-scale farmers in Africa, particularly regarding soil management and agricultural productivity. Through a comprehensive literature review and stakeholder consultation, key issues are identified, motivating the need for real-time soil monitoring solutions tailored to the unique conditions and constraints faced by farmers in African regions. Clear research objectives are defined to guide the development process, with a keen emphasis on addressing the specific needs of African small-scale farmers. The primary objective is to design and evaluate a mobile sensing device and mobile application to provide real-time soil condition information for small-scale farmers in Africa, facilitating informed decision-making in agricultural practices.

The Centre for Community Technologies (CCT) at Nelson Mandela University (NMU) has developed a cutting-edge mobile sensing device capable of real-time measurement of soil moisture, light, humidity, and pH levels. This device, housed in a portable sensing box, serves the primary purpose of providing small-scale farmers in Africa with immediate and accurate information about their soil conditions. The data collected by the sensors is seamlessly integrated into a mobile farming application, specifically designed to cater to the needs and preferences of African farmers. The design and development process follow a systematic approach within the DSR framework, comprising iterative stages of conceptualization, design, implementation, and evaluation, while ensuring cultural sensitivity and relevance to the African context. Ideation and brainstorming generate potential solutions to identified problems, with a focus on addressing the unique challenges faced by African farmers. Concepts are refined through extensive stakeholder engagement, ensuring alignment with user needs and cultural preferences.

Detailed design specifications are developed, including the selection of hardware components, sensor technologies, and software frameworks, taking into account the availability and affordability of resources in African regions. Emphasis is placed on usability, reliability, and scalability, considering the diverse socio-economic and infrastructural conditions prevalent in African agricultural settings. Prototypes of the mobile sensing device and mobile application are developed and rigorously tested to validate functionality and performance in real-world African environments, with a particular focus on usability and effectiveness in addressing the identified challenges. Feedback from end-users and experts, particularly those from African farming communities, informs iterative refinement, ensuring that the artifacts meet the unique needs and expectations of African small-scale farmers.

Continuous reflection and iteration refine the artifacts and address emerging challenges, with a commitment to ensuring cultural sensitivity and relevance to the African context. The research contributes to DSR and agricultural technology by presenting a novel solution for real-time soil monitoring tailored to the specific needs of African small-scale farmers. Implications of the research findings are discussed in terms of their potential impact on agricultural practices in Africa and future research directions, with a focus on promoting sustainable development and food security in African regions. The methodology outlined in this study follows established standards within the DSR paradigm, providing a rigorous framework for designing and evaluating innovative artifacts to address agricultural challenges in the African context. By adhering to DSR principles and prioritizing cultural sensitivity and relevance to the African context, this research aims to generate valuable insights and innovations to empower African small-scale farmers with actionable information for improved soil management practices.

Sensor Probe Collection: The mobile sensing box incorporates a range of sensor probes, each designed to measure specific soil parameters. To facilitate connectivity, the breadboard is employed to extend power ports, providing essential 3.3 V, Ground, SDA, and SCL lines from the microcontroller board. The Arduino board, central to the system, operates with a single I2C bus comprising two critical signals: SDA (Serial Data) for data transmission and SCL (Serial Clock) for clock synchronization. This configuration is vital for the proper functioning of three of the probes within the system. The proposed IoT Sensing Platform represents a comprehensive integration of sensor arrays as shown in Figure-1, corresponding software, and host hardware, all compactly housed within the portable sensing box. This platform aims to empower small-scale farmers by providing detailed insights into soil conditions, enabling informed decision-making for optimized agricultural practices. The IoT Monitoring System encompasses a detailed set of processes and diagrams, offering a comprehensive view of system assembly, design, Arduino handling, IP addresses, and MIT App Inventor integration. This system is meticulously designed to ensure the seamless functioning of the sensors, efficient data transmission, and user-friendly interaction through the mobile application. The combination of advanced sensor technologies, IoT integration, and user-centric mobile applications positions this technology as a transformative tool for small-scale farmers, bridging the gap between traditional farming practices and modern, data-driven agriculture.

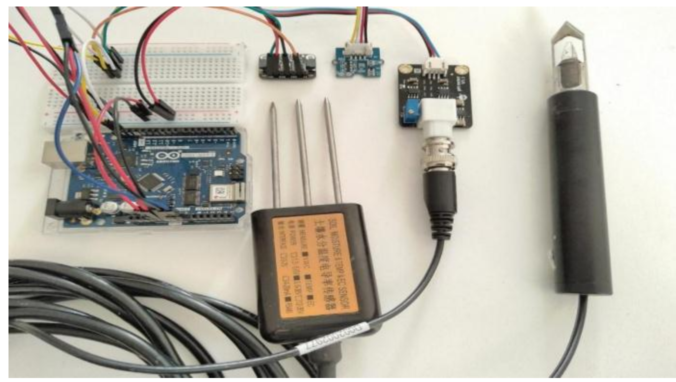

Figure-1: soil monitoring system Combined sensors.

To enhance durability and streamline integration, a 3D-printed protective shell shown in Figure-2 is recommended to house all hardware components, encompassing the single board computer (SBC), microcontroller, sensors, illumination, and mounting components constituting the IoT sensing platform. This protective shell ensures physical security while maintaining a compact and efficient design. Facilitating remote control and communication, the proposed sensor box leverages the Arduino UNO WiFi Rev2 board. This specific Arduino Uno variant integrates a WiFi module, allowing seamless wireless connectivity. With this configuration, the sensor box becomes remotely accessible, enabling real-time monitoring and control. To ensure autonomy and flexibility, the sensor box incorporates a battery to power the probes. This design choice allows the system to operate independently of external power sources, contributing to its versatility and suitability for deployment in various agricultural settings. By combining 3D printing technology for protective housing, Arduino Uno WiFi Rev2 for wireless communication, and a battery-powered setup for autonomy, the proposed sensor box stands as a robust and efficient solution for small-scale farmers. This integrated approach ensures not only the security and durability of the hardware but also the practicality of remote monitoring and control.

The proposed system utilizes the Arduino UNO WiFi Rev2 board in conjunction with the WiFiNINA library. This combination empowers the Arduino to effectively manage the connected sensors and gather readings from diverse sensor components. The culmination of these readings is employed to establish a user-friendly web server, constituting the interface for the sensor board. Upon successfully uploading the code to the Arduino UNO WiFi Rev2 board, users can initiate the Serial Monitor. The Serial Monitor provides a visual representation of the system's functioning and status. Figure-3 showcases the expected appearance of the Serial Monitor interface after the code has been uploaded. The primary interface for interacting with the sensor board is the established web server. Users can access this interface to monitor sensor readings, control functionalities, and obtain real-time information about the soil conditions. The web server, facilitated by the Arduino UNO WiFi Rev2, ensures a straightforward and accessible means of interaction. While the specific details of Figure-3 are not provided, it is expected to present relevant information and feedback regarding the sensor board's operation. The Serial Monitor serves as a valuable tool for debugging, system analysis, and real-time observation of the Arduino's activities. By seamlessly integrating the Arduino UNO WiFi Rev2 and WiFiNINA library, the system achieves a cohesive and efficient approach to sensor management, data collection, and web server establishment. This integration lays the foundation for a user-friendly and accessible interface for monitoring and controlling soil conditions in agricultural settings.

Upon successfully establishing the web server, users can access the sensor values through a web browser. The user copies the IP address provided by the system. This IP address is crucial for connecting to the web server hosted by the Arduino UNO WiFi Rev2 board. Users open a web browser of their choice (e.g., Google Chrome, Mozilla Firefox) and paste the copied IP address into the browser's address bar. After entering the IP address, the web browser loads a page displaying all the sensor values. Figure-4 illustrates how this page might appear. The depicted Figure-4 showcases the expected layout of the web page displaying sensor values. It provides a clear and organized presentation of information related to soil conditions, including moisture, light, humidity, and pH levels. By following these steps, users can effortlessly access real-time sensor data through a web browser, offering a convenient and user-friendly means of monitoring and analyzing soil conditions. The web page serves as a comprehensive dashboard, presenting essential information for informed decision-making in agricultural settings.

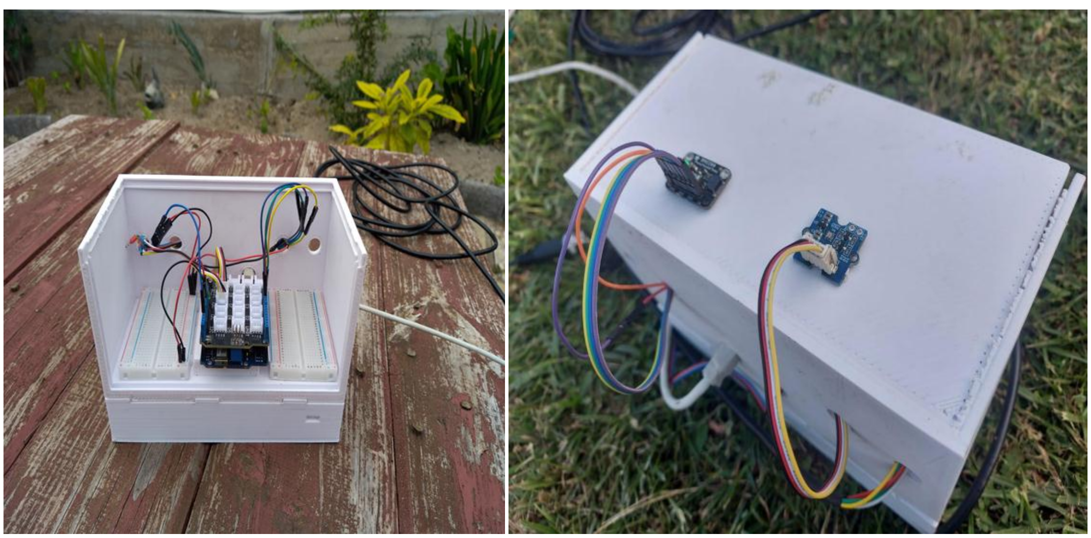

Figure-2: Showing the 3-D Casing design.

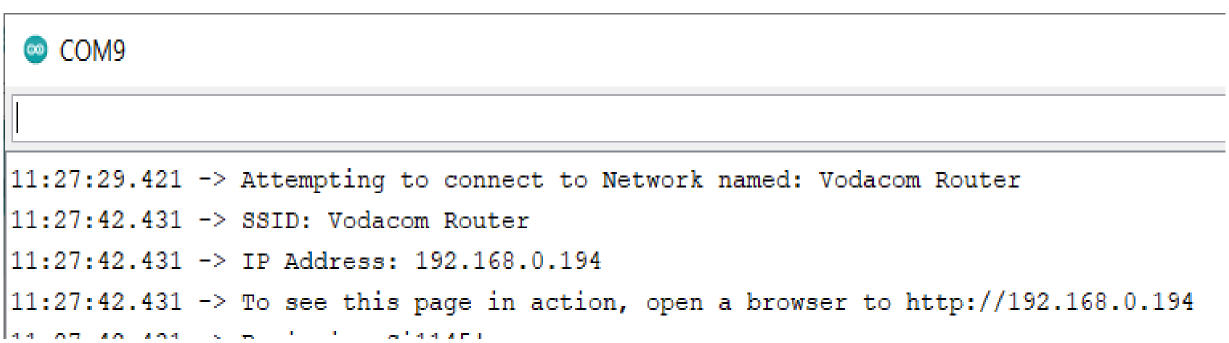

Figure-3: illustrating the serial monitor screen.

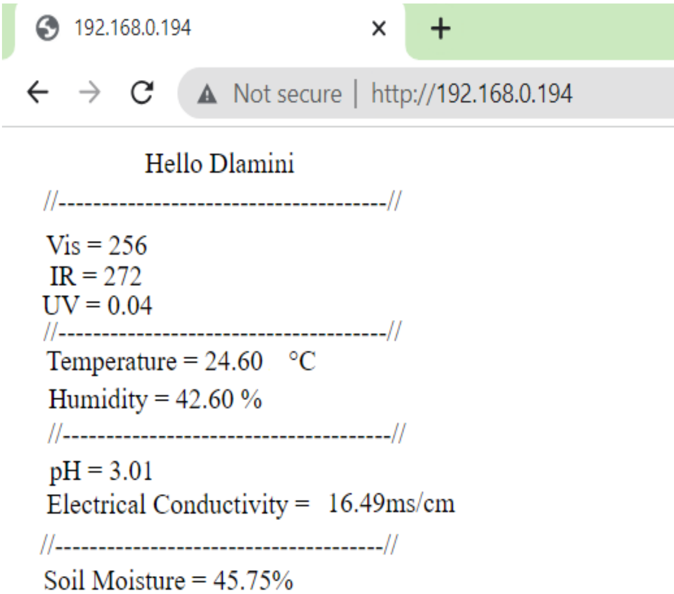

Figure-4: Web Browser Display of Sensor Values.

Utilizing the MIT App Inventor, a sensor application has been successfully developed to enhance user interaction with the IoT sensing platform. The Web component plays a pivotal role in enabling users to access web-based features. The MIT App Inventor provides a user-friendly environment for creating Android applications. Users can leverage a visual interface to design and implement app functionalities. The Web component within the MIT App Inventor is a key element that facilitates web-based interactions. It empowers users to perform actions such as accessing URLs and posting text or files to web servers. The Web component grants users the fundamental features of a web browser. One of these features is the ability to utilize a URL to navigate to a specific page on the Internet. Through the Web component, users can post text or files to a web server. This functionality enhances the interaction between the sensor application and the IoT sensing platform.

The depiction in Figure-5 represents the MIT App Inventor interface, highlighting the integration of the Web component into the sensor application. This component enables users to access web-based functionalities seamlessly. The successful creation of the sensor application using MIT App Inventor enhances the overall user experience, providing a platform for convenient interaction with the IoT sensing platform. Through the Web component, users can harness the capabilities of a web browser, fostering a more intuitive and accessible application.

The development of the soil monitoring application was undertaken using the "MIT App Inventor 2," an open-source blocks platform-based environment endorsed by Google. This application, designed for Android devices such as tablets or smartphones, has been crafted by the Centre for Community Technologies (CCT) at Nelson Mandela University (NMU). MIT App Inventor 2 is a program that enables the creation of Android applications using a visual, blocks-based approach. It is an open-source platform supported by Google and is well-suited for developers aiming to build applications for Android devices
The smartphone application serves the purpose of providing valuable information to subsistence and small-scale farmers. Its primary focus is on educating farmers about practices that can enhance soil management, subsequently improving crop health and productivity. Recognizing that many farmers may lack literacy and e-literacy skills, special attention was given to ensuring the mobile application's user-friendliness. The design incorporates simplicity, making it easy for users to navigate and comprehend. Considering the potential literacy challenges, the application features text and images that are easy to read and view. This design choice enhances accessibility and ensures that information is effectively communicated to the target audience. The overarching goal of the mobile application is to empower farmers with actionable insights that contribute to the improvement of soil management. By providing relevant information in a user-friendly format, the application aims to positively impact crop health and productivity.

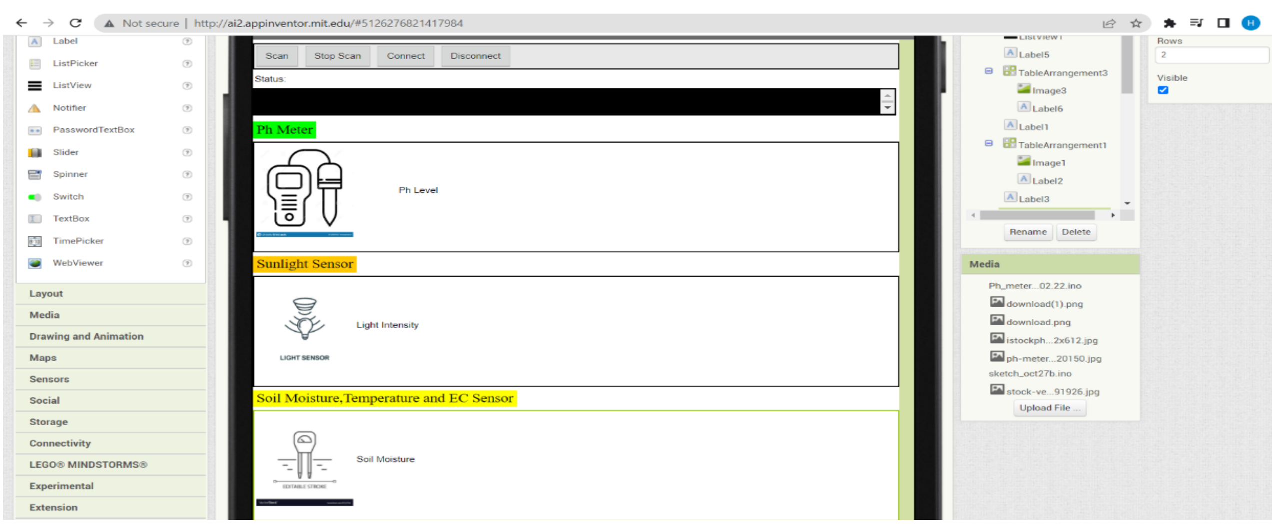

Figure-5: illustrating the MIT App Inventor.

Conclusion

The integration of Information and Communication Technology (ICT) into small-scale farming holds significant promise for enhancing crop and soil management, thereby contributing to increased agricultural production, particularly within the African context. The adoption of precision agriculture, combining horticulture, engineering, and agriculture in a controlled environment, emerges as a vital strategy to maximize crop output and efficiency, aligning with the agricultural practices prevalent in many African regions. The Centre for Community Technologies (CCT) at Nelson Mandela University (NMU) has been at the forefront of developing practical and user-friendly ICT solutions tailored specifically for subsistence and small-scale farmers in Africa. One such solution is the soil monitoring application, crafted using the "MIT App Inventor 2" platform for Android devices. This application reflects our commitment to addressing the unique needs and challenges faced by African farmers, particularly those related to technological accessibility and usability.

The utilization of the Arduino UNO WiFi Rev2 board, in conjunction with the WiFiNINA library, forms the backbone of our soil monitoring system. This setup enables efficient sensor management, data collection, and the establishment of a user-friendly web server interface, catering to the technological capabilities of small-scale farmers in African rural areas. The soil monitoring application, designed specifically for Android devices, prioritizes ease of use and accessibility, ensuring that farmers with varying levels of technological proficiency can benefit from its functionalities. Our soil monitoring system integrates various sensors within an IoT sensing platform, facilitating the identification and addressing of soil requirements crucial for subsistence farming operations in Africa. Understanding the literacy and e-literacy constraints of small-scale farmers, our solutions emphasize simplicity, with text and images within the application designed for easy comprehension.
The overarching goal of our soil monitoring system is to contribute to humanitarian technology, particularly in marginalized areas of South Africa and other African regions. By empowering smallholder farmers with valuable insights for improved soil management, our system aims to enhance agricultural productivity and sustainability within the African context. In summary, the convergence of ICT solutions, precision agriculture, and practical design principles holds significant promise for transforming agriculture in rural Africa. The ongoing efforts by the CCT at NMU exemplify our commitment to leveraging technology for the betterment of subsistence and small-scale farming communities.

Future Work: The future development of the soil management system will focus on enhancing its functionality to better serve the needs of small-scale and subsistence farmers, particularly within the African context. This endeavor will involve the refinement and expansion of both the farmer and sensor applications, aiming to provide a comprehensive set of features tailored to the unique requirements of users engaged in agricultural practices in Africa. To ensure usability and effectiveness, two distinct Android mobile applications will be developed: one catering to farmers and the other to sensor applications. Detailed functional requirements will be defined for both applications, emphasizing a seamless and intuitive user experience. The sensor application will support the configuration of sensors, real-time observation of measurements (such as light, temperature, soil pH, and soil humidity), data logging, and data export functionalities. Additionally, a visualizer within the farmer application will assist users in capturing photos for soil type identification, leveraging the Zones of the Textural Soil Classification System.

Furthermore, the farmer application will incorporate user authentication features, enabling individuals to sign up, log in, and select between crops such as sweet potato and maize based on their cultivation site. Specific menus will be provided for each chosen crop, offering information on readings, pest and disease management, soil management practices, and fertilization techniques. Soil management menus will include submenus covering nutrient management, organic diversity, tillage methods, soil compaction mitigation, and strategies for adding organic matter to the soil. The system will also include a dedicated page focusing on soil nutrition, providing insights into various soil types and recommending actions to improve soil fertility. A weather page will be integrated, offering hourly, daily, and monthly weather readings to assist farmers in making informed decisions about agricultural activities. Leveraging the United States Department of Agriculture soil texture triangle acquisition system, the system will provide farmers with valuable insights into the type of soil present in their fields.

This future work aims to create a robust and feature-rich soil management system that empowers farmers with valuable information and tools for optimizing agricultural practices. By addressing the specific needs and challenges faced by small-scale and subsistence farmers in Africa, these envisioned developments underscore our commitment to technological advancements that contribute to the advancement of agriculture within the African context.

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