IoT-Driven Precision Agriculture using Communication Technologies for Crop Quality and Real-time Environmental Monitoring

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***Abstract*—This paper presents the development of an advanced system that merges real-time environmental monitoring and agronomical data analytics with yield and quality measurement to enable visualisation, analysis, modelling and long-term prediction of crop yield and quality based on environmental factors and farm practices. The system integrates Internet of Things (IoT) technologies and cloud-based analytics, incorporating Radio Frequency (RF) return loss measurements for non-destructive starch content assessment in cassava roots. The integrated data is transmitted through a custom-built pipeline to a web-based dashboard, offering real-time insights into the dynamic relationship between cassava yield and quality and environmental conditions. This system represents a significant advancement in the application of IoT for agriculture, providing a scalable framework for data-driven decision-making to enhance crop cultivation, with a potential impact on food security in cassava-dependent regions.**

***Index Terms*—Precision Agriculture, Cassava Cultivation, Starch Content Analysis, Environmental Monitoring, IoT, Cloud Analytics, ThingsBoard**

I. Introduction

Cassava serves as a critical food source for over half a billion people worldwide, particularly in tropical regions where it is a primary carbohydrate source [1], [2]. Its cultivation outcomes, in terms of both yield and quality, are deeply influenced by environmental variables, thus necessitating sophisticated approaches for optimal management [2], [3]. Established means of evaluating cassava quality, notably its starch content, are quite rigorous and do not afford the immediacy required for effective agricultural decision-making [4].

Precision agriculture, which leverages advanced sensor and analysis tools to enhance agricultural productivity, stands as a crucial solution to address the pressing challenge of meeting the escalating food demands of the world growing population [5], [6]. As climate change adds further complexity to traditional farming practices, precision agriculture data-driven approach is key to adapting agricultural production to environmental uncertainties. The deployment of Internet of Things (IoT) technologies, in particular, has emerged as a promising avenue for revolutionising farming practices through the provision of real-time data and analytics-driven insights [6]–[8], however, the adoption of such technologies in tropical agriculture, particularly cassava cultivation, has been limited, with Akilimo, an agronomic advisory service developed for and with smallholder farmers, being the primary resource available in this domain [9].

This paper builds upon the authors' previous pioneering work on estimating cassava starch content utilising a novel, non-destructive RF return loss measurement technique [4], [10]–[12]. This research has led to the design of a low-cost handheld IoT device, which estimates cassava starch and sends the data to a cloud database through an Android-based mobile app. In this paper, we report the extension of this foundational research through the introduction of an integrated system that combines environmental monitoring and agronomical data analytics, tailored specifically for the cassava crop [13]. This system, which features the a novel cassava-focused dashboard, marks a significant departure from existing studies by offering a holistic tool for real-time data visualisation and decision-making support. This platform combines starch content analysis from the previously developed portable RF device with comprehensive environmental and agronomical data gathering. This enables a detailed exploration of the dynamic relationship between cassava's growth conditions and its yield and quality at harvest, facilitating precise agricultural interventions for yield and quality enhancement.

The outline of this paper is as follows: Section II provides a comprehensive overview of the system architecture, and describes the key elements in the system. In Section III, the data integration pipeline is described, and the process of aggregating and transmitting data from the environmental sensors and quality measurement device to the web-based dashboard is outlined. Section IV presents a discussion on the overall functionality and merits of the proposed system and Section V concludes the paper.

II. System Architecture

The architecture of the proposed system represents a comprehensive integration of several cutting-edge technologies, designed to synergistically enhance cassava cultivation practices. Our multi-component system encompasses a cassava starch measurement unit, an array of environmental sensors, a mobile application for seamless data transmission, and a dashboard for data analysis and visualisation, developed on the ThingsBoard IoT platform [14]. The following subsections provide an in-depth exploration of each component and their interconnections within the system. The comprehensive integration of cutting-edge technologies within the system is shown in Fig.1, illustrating the synergy between the cassava starch measurement unit, environmental sensors, mobile application, and ThingsBoard dashboard.

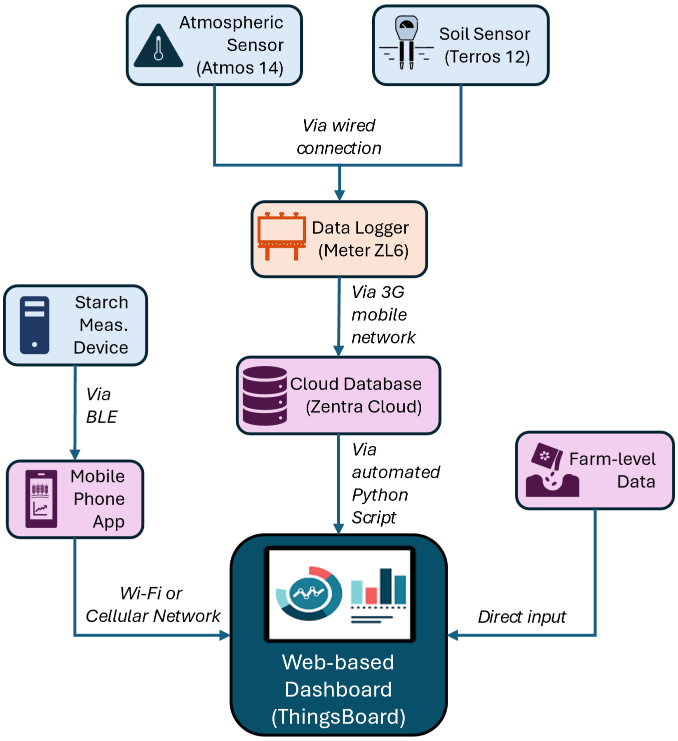

Fig. 1. Schematic diagram of the integrated system

A. Environmental Sensors Integration

The collection and management of environmental data is achieved through the integration of a subsystem with an array of commercially available sensors, designed for monitoring both Atmospheric and soil conditions. These sensors capture a diverse range of environmental parameters with precision and accuracy. In the proposed platform, the TEROS-12 soil sensor, which measures the moisture, temperature, and electrical conductivity of the soil [15]; and the Atmos-14 atmospheric sensor, which measures air temperature, relative humidity, barometric pressure, and vapour pressure, are employed [15], [16]. Both sensors are supplied by Meter Group, providers of advanced, cloud-connected, real-time plant-soil-atmospheric data systems [17]. The data collected by these sensors is transmitted through cables to advanced data loggers, which serve as the central hub for aggregating the data. The ZL6 data logger from Meter Group is employed in the proposed system [18]. The devices are solar-powered, capable of operating in diverse environmental conditions, and are designed for long-term deployment in the field. A key feature of these data loggers is their integrated 3G connectivity, which enables the seamless upload of data to cloud platforms. This capability eliminates the necessity for frequent manual data retrieval, thereby promoting continuous monitoring and enhancing the overall efficiency of the environmental data management system. The data from ZL6 is uploaded to the Zentra Cloud platform which is Meter Group's proprietary, subscription-based cloud database [19].

B. Cassava Starch Measurement Unit

The cassava starch measurement unit, which employs Radio Frequency (RF) return loss principles to estimate the starch content in cassava roots is used to provide quality measurement data to the dashboard [13]. Fig.2 shows this unit with top case open to reveal the internal PCB, with the various functional areas indicated [11].

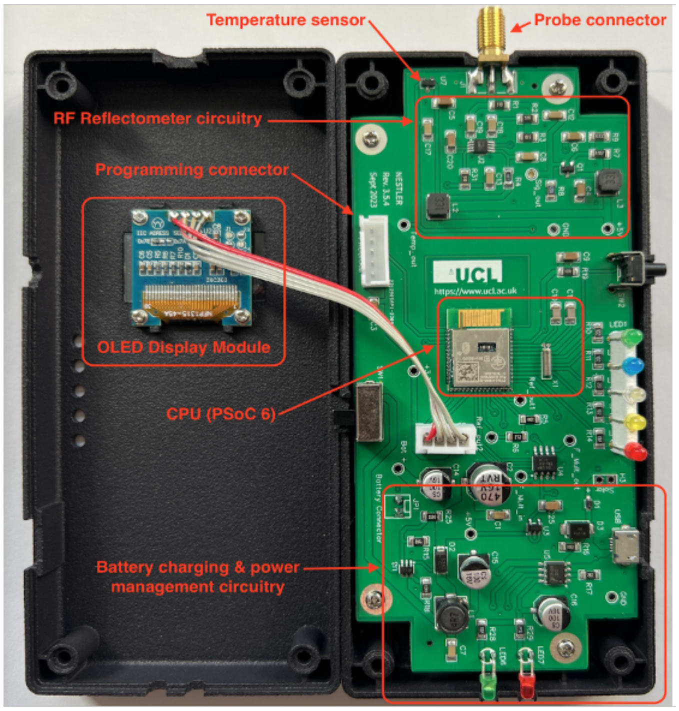

Fig. 2. The cassava starch measurement unit

The starch measurement unit contains a specially designed RF reflectometer circuit (Fig.2) that emits an RF signal into the cassava [13]. By analysing the reflected signal power level, the unit determines the return loss, which is correlated with the starch content in the cassava [12]. This process benefits from being non-destructive and provides rapid feedback on starch levels [4].

C. Other Data Sources

To capture farm-level data such as farm size, crop genotype, planting time, usage of fertilisers, and other factors that influence agricultural productivity, a provision is made for direct input of data to the dashboard. The system can also be readily modified to take additional data such as real-time remote sensing data and historical quality and yield data from existing repositories.

III. System Integration

The integration of the proposed system revolves around two primary aspects. The first aspect involves establishing an interface between the mobile application that aggregates the starch measurement data and the ThingsBoard platform. The second aspect focuses on creating an interface between the environmental sensing platform, specifically the Zentra Cloud—a proprietary web platform that consolidates data from the ZL6 data loggers—and ThingsBoard.

A. Mobile Application and Data Transmission

To bridge the gap between on-field data collection and cloud-based analysis, a dedicated mobile application was developed. This application serves as the conduit for transmitting data from the cassava starch measurement unit to the cloud. It employs Bluetooth technology to receive data from the measurement unit and utilises WiFi or cellular data to upload this information to the ThingsBoard platform.

The mobile application is designed with a user-friendly interface to simplify the process for end-users, allowing farmers and researchers to easily initiate measurements, view results, and sync data with the cloud. This ensures that data collected in the field is readily available for analysis, contributing to a seamless flow of information from the point of collection to the point of use. The interface of the mobile application, designed for seamless data transmission, is shown in Fig.3 [13].

Fig. 3. Starch measurement unit and Android smartphone App. The starch measurement unit transmits data to the smartphone via Bluetooth low-energy (BLE).

B. Environmental Data Integration Pipeline

A pivotal component of the integrated system is the bespoke data integration pipeline, which enables the flow of sensor data to the ThingsBoard platform. This pipeline represents a critical element of the architecture, ensuring the centralisation of data for real-time analysis and decision support.

The design of this pipeline was necessitated by the limitations encountered with direct usage of the Zentra cloud platform for comprehensive environmental monitoring [19]. While the Zentra cloud collects and stores data from the TEROS12 soil moisture sensor and Atmos14 atmospheric sensor, it presents challenges in terms of flexibility and integration capabilities for advanced analytics and custom dashboard visualization. These limitations prompted the development of a more versatile solution that could accommodate the specific needs of cassava cultivation research and monitoring.

The pipeline was designed and implemented using a Python script to automate the extraction of environmental data from the Zentra cloud, employing its API to access the latest readings. This data encompasses critical environmental parameters such as soil moisture levels, soil electrical conductivity, air temperature, relative humidity, and barometric pressure, which are instrumental in assessing the conditions affecting cassava growth and starch development.

Once retrieved, the data undergoes transformation to align with the ThingsBoard platform's ingestion requirements. This involves time-stamping and applying sensor-specific identifiers to ensure accurate representation and tracking within the system. The reformatted data is then transmitted to ThingsBoard through HTTP POST requests, facilitated by a secure access token that guarantees the integrity and confidentiality of the data transmission process.

The pipeline is deployed on PythonAnywhere, a cloud-based Python development and hosting environment, to leverage the capability for continuous operation that this plaform provides [20]. This ensures an uninterrupted data flow to the ThingsBoard platform, where real-time data visualization and analysis can occur. The flowchart of the code, illustrating the seamless integration from sensor data collection through to the visualisation on the ThingsBoard platform, is shown in Fig. 4.

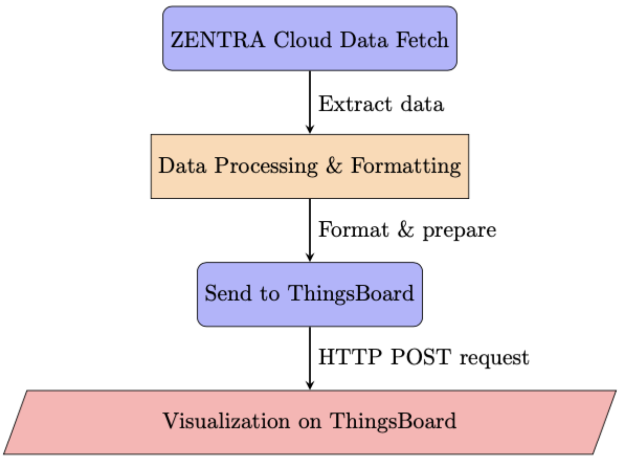

Fig. 4. Flowchart of the data integration pipeline.

C. ThingsBoard IoT Platform for Data Analysis and Visualisation

The system collects and sends data to the ThingsBoard IoT platform, where data from both the cassava starch measurement unit and the environmental sensors are aggregated, analysed, and visualised. ThingsBoard is a flexible and scalable platform for IoT, offering strong features for creating dashboards, analyzing data, and managing devices [14].

A custom dashboard was developed on ThingsBoard to present the collected data in an intuitive, easily interpretable

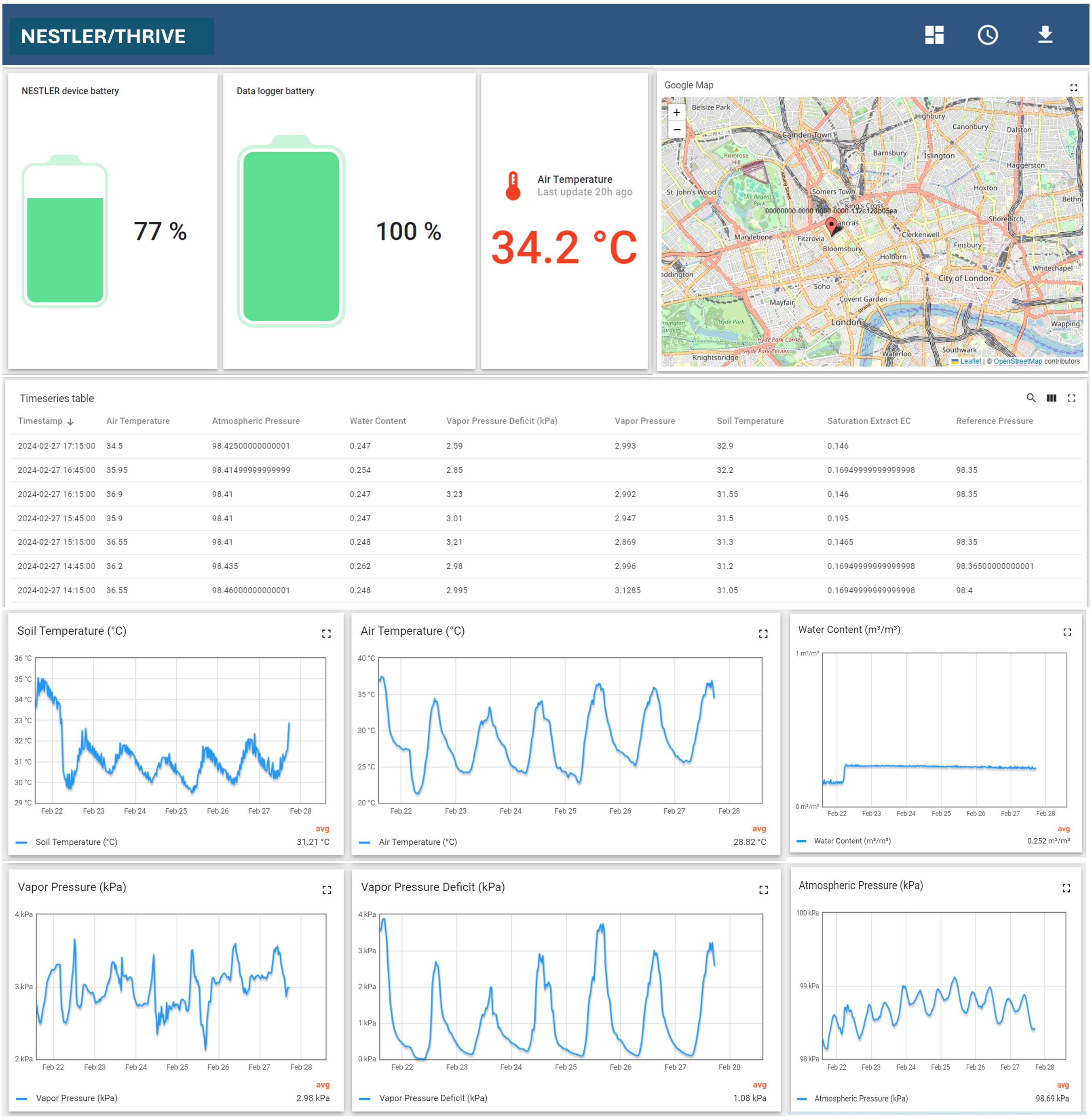

Fig. 5. Web-based dashboard that aggregates environmental sensing and cassava quality measurement data provisioned on ThingsBoard. The dashboard displays device status and real-time time series data from field sensors capturing soil temperature, soil water content, air temperature etc at 15-minute intervals.

format. This dashboard offers real-time visualisations of starch content measurements alongside environmental parameters, enabling users to observe patterns, correlations, and insights that inform decision-making processes in cassava cultivation. The ability to monitor these variables in real-time facilitates a proactive approach to agricultural management, where interventions can be made promptly to optimise growing conditions and improve crop outcomes. Fig.5 presents the custom dashboard developed on ThingsBoard, highlighting the real-time visualization capabilities for starch content alongside environmental parameters.

IV. Discussion

The integrated system described in this paper represents a significant advancement in precision agriculture, specifically tailored to optimise cassava cultivation. Through the integration of real-time environmental monitoring, agronomical data analytics, and quality measurement facilitated by cutting-edge IoT technologies, the system offers a holistic approach to enhancing cassava production.

A notable feature of the proposed platform is the integration of IoT and cloud analytics. The implementation of a custom pipeline, linking proprietary platforms like Zentra Cloud, not only enhances the dashboard's versatility but also broadens the potential for integrating data from similar platforms. This design enhances the system's capacity to derive actionable insights from the relationship between environmental factors and yield and quality performance. The real-time visualisation capability of the dashboard is envisioned to enable farmers and researchers to make informed decisions promptly, optimising cassava cultivation practices.

As a pioneering effort in cassava-focused precision agriculture, this research opens avenues for future exploration. The subsequent phase of this research initiative involves the integration of additional data sources, such as real-time remote sensing and historical yield data. This expansion aims to further refine the system's modelling and predictive capabilities, enhancing its overall utility and effectiveness. Simultaneously, ongoing research endeavours are focused on extending the application of the system to other crops and in diverse agricultural contexts, thereby contributing to the broader landscape of sustainable and technology-driven farming practices. This comprehensive approach is aimed to drive continuous improvement and adaptability, ensuring that the benefits of precision agriculture can be extended to a wider array of crops and agricultural settings in the future.

V. Conclusion

This paper presents a pioneering integrated system designed to optimise cassava cultivation through precision agriculture. The system's advanced approach combines real-time environmental monitoring, agronomical data analytics, and non-destructive quality measurement using IoT technologies. This holistic system, showcased through a web-based dashboard, offers farmers and researchers a powerful tool for optimizing cassava production. The system integrates IoT and cloud analytics through a custom pipeline, enhancing flexibility for cassava cultivation research. Future plans include incorporating real-time remote sensing and historical yield data, with ongoing research aiming to extend the system to diverse crops and agricultural contexts, advancing agricultural technology.

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