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Intelligent Smart Farming Stick Using FPGA for Precision Agriculture and Crop Monitoring

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***Abstract*—Agriculture is increasingly challenged by inefficient resource utilization, un- predictable environmental conditions, and lack of real-time monitoring sys- terms. This paper proposes an intelligent smart farming stick that integrates FPGA-based processing with IoT-enabled sensors for precision agriculture. The system incorporates soil moisture, water level, and rain sensors to con- tenuously monitor field conditions. A Raspberry Pi with a camera module enables real-time crop monitoring and disease detection. The FPGA plat- form ensures low-latency processing and efficient control of irrigation systems based on sensor data. Furthermore, cloud integration allows remote monitoring and notification through a web interface. The proposed system reduces manual intervention, enhances water efficiency, and improves crop productivity. Experimental observations indicate that the system provides reliable and timely responses for agricultural automation, making it suitable for modern smart farming applications.**

***Index Terms*—Smart Farming, FPGA, Precision Agriculture, IoT, Crop Monitoring, Sensor Networks**

I. INTRODUCTION

Agriculture plays a critical role in sustaining the global population; how- ever, it faces numerous challenges such as inefficient water usage, unpredictable climatic conditions, soil degradation, and plant diseases. Traditional farming methods largely depend on manual monitoring and decision-making, which often leads to suboptimal resource utilization and reduced crop productivity. With the increasing demand for food production, there is a pressing need to adopt intelligent and automated farming solutions [13, 9, 14].

Recent advancements in Internet of Things (IoT), embedded systems, and edge computing have significantly contributed to the development of smart agriculture systems that provide real-time monitoring and control capabilities [6, 10]. Sensors can continuously measure environmental parameters such as soil moisture, water levels, and rainfall, enabling farmers to make data- driven decisions. Furthermore, wireless sensor networks (WSNs) have been widely adopted for agricultural monitoring due to their scalability and low power consumption [17, 12]. However, many existing systems suffer from latency issues, limited processing capabilities, and lack of seamless integration between sensing, processing, and actuation components [2, 7].

In recent years, artificial intelligence and deep learning techniques have also been explored for smart farming applications, particularly in plant dis- ease detection and crop monitoring [3, 8]. Although these approaches Domen state promising results, they often require high computational resources and may not be suitable for real-time field deployment without dedicated hard- ware acceleration [16, 18].

To overcome these limitations, hardware-based acceleration using Field Programmable Gate Arrays (FPGAs) has gained significant attention due to its parallel processing capabilities and low latency [4, 20]. FPGA-based systems enable efficient real-time processing of sensor data, making them highly suitable for time-critical agricultural applications such as irrigation control and environmental monitoring [19, 15].

In this work, an Intelligent Smart Farming Stick is proposed, which integrates FPGA-based processing with multi-sensor networks and cloud connectivity. The system leverages the high-speed processing capability of FPGA for real-time decision-making while utilizing a Raspberry Pi for image acquisition and high-level processing tasks. This hybrid architecture ensures efficient resource utilization and improved system performance.

The key contributions of this work are summarized as follows:

- Design and development of a multi-sensor based smart farming system using FPGA for real-time processing.
- Integration of Raspberry Pi for visual crop monitoring and potential disease detection.
- Implementation of automated irrigation control based on environmental conditions.
- Cloud-based monitoring and notification system for remote access.

II. RELATED WORK

Smart agriculture has gained significant attention in recent years, particularly in the domains of IoT-based monitoring and automated irrigation systems. Several research works have focused on improving crop productivity by integrating sensor networks and intelligent decision-making systems [9, 13].

Early approaches primarily relied on IoT-based irrigation systems using soil moisture sensors to automate water supply. For example, an automated irrigation framework was presented in [1], which improved water efficiency but depended heavily on microcontrollers with limited processing capabilities. Similarly, wireless sensor network (WSN)-based monitoring systems were explored in [2, 17], enabling environmental data collection; however, these systems lacked real-time responsiveness and efficient decision-making mechanisms.

With the advancement of computational technologies, recent studies have incorporated edge computing and artificial intelligence for smart farming applications. Machine learning-based plant disease detection systems, such as those presented in [3, 8], have demonstrated promising accuracy in identifying crop diseases using image data. However, these approaches often require high computational power and are not always suitable for deployment in real-time agricultural environments [16].

To address latency and performance limitations, FPGA-based solutions have been explored due to their parallel processing capabilities and deterministic performance. In [4, 20], FPGA platforms were utilized for real-time sensor data processing, showing significant improvements over traditional microcontroller-based systems. Despite these advantages, the integration of FPGA with IoT-based smart farming systems remains relatively underexplored [15].

Table 1 presents a comparative analysis of existing approaches and high- lights their limitations in terms of processing capability, real-time performance, and system integration.

Table 1: Comparison of Existing Smart Agriculture Systems

Ref	Tech	Features	Limitations	RT
[1]	IoT+MCU	Automated irrigation system	Limited processing capability	No
[2]	WSN	Environmental monitoring	No real-time control	No
[3]	AI/ML	Disease detection using images	High computational cost	Limited
[8]	DL	Image-based crop analysis	Requires GPU hard- ware	Limited
[4]	FPGA	High-speed data processing	No IoT/cloud integration	Yes
[17]	WSN	Scalable sensing net- work	Latency issues	No

From the above discussion, it is evident that existing systems either focus on sensing, processing, or intelligence individually, but lack a unified architecture that combines all these aspects efficiently.

To overcome these limitations, the proposed system integrates FPGA- based real-time processing with multi-sensor data acquisition and cloud connectivity. Additionally, the inclusion of a Raspberry Pi-based vision module enables crop monitoring and future scalability towards AI-based disease detection. This integrated approach provides a balanced solution in terms of performance, scalability, and real-time responsiveness.

III. SYSTEM ARCHITECTURE

The proposed Intelligent Smart Farming Stick is designed as an integrated hardware-software system that combines sensing, real-time processing, and cloud-based communication to enable efficient agricultural monitoring and automation. The system follows a layered architecture consisting of sensing, processing, and communication modules, which operate in a coordinated manner.

The sensing module is responsible for acquiring real-time environmental data from the agricultural field. It includes soil moisture, water level,

Figure 1: Latency comparison of different smart agriculture approaches showing the superior real-time performance of FPGA-based systems.

and rain sensors, which continuously monitor key parameters affecting crop health. The soil moisture sensor measures water content in the soil to sup- port irrigation decisions, while the water level sensor detects overflow or insufficient water conditions. The rain sensor identifies precipitation events to avoid unnecessary irrigation. These sensors generate analog or digital signals, which are interfaced with the processing unit through ADC and GPIO interfaces.

The processing module forms the computational core of the system and consists of an FPGA (Artix-7 EDGE board) and a Raspberry Pi 4 Model

B. The FPGA is responsible for real-time data acquisition and control operations. It processes sensor inputs using predefined threshold logic and generates control signals to operate irrigation components such as DC motors or pumps. Due to its parallel processing capability, the FPGA ensures low latency and deterministic performance, making it suitable for time-critical agricultural applications.

The Raspberry Pi complements the FPGA by handling high-level operations such as image acquisition, data communication, and cloud interaction. It interfaces with a camera module to capture real-time crop images, enabling visual monitoring and supporting future AI-based disease detection. Additionally, it manages communication with cloud platforms such as Azure, allowing remote monitoring through web interfaces and user notification systems such as SMS alerts.

The communication module enables seamless interaction between the system and end users. Processed data is transmitted to cloud platforms, where it can be accessed through web-based dashboards. This allows farmers to monitor field conditions remotely and make informed decisions without being physically present in the field.

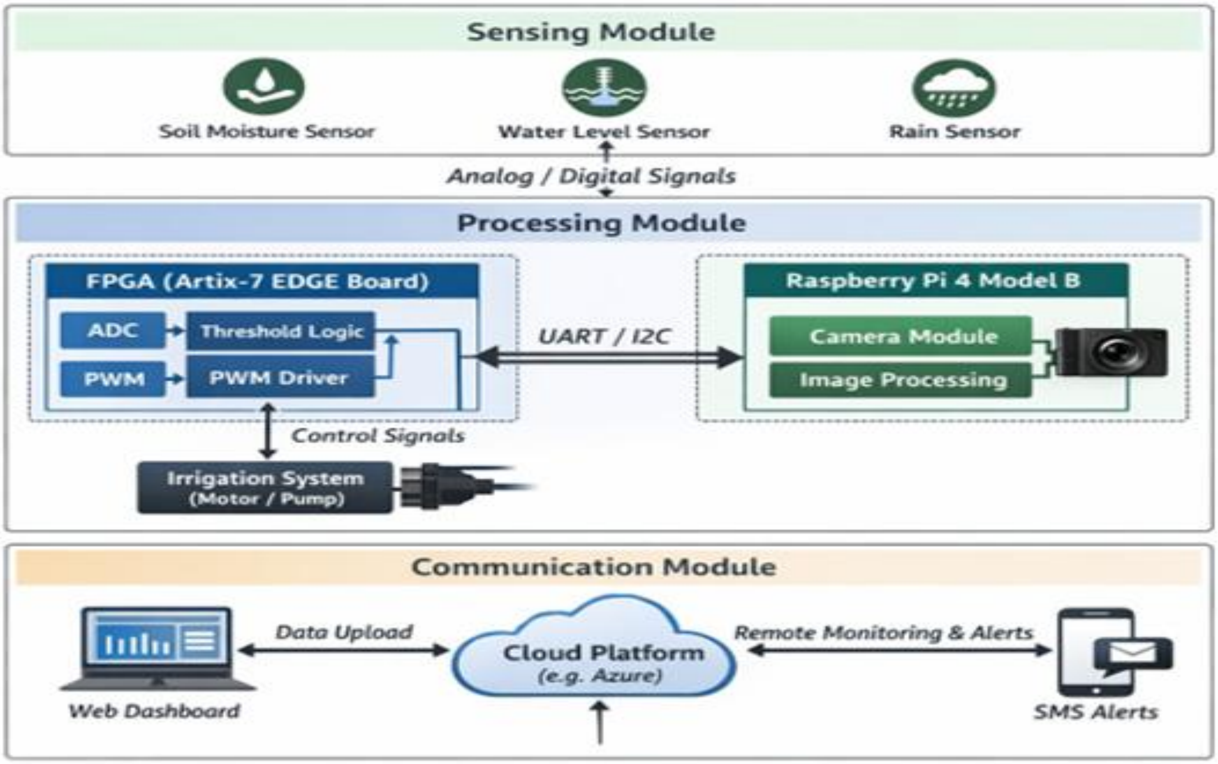

Figure 2: Integrated architecture of the Intelligent Smart Farming Stick showing sensing module, FPGA-based real-time processing, Raspberry Pi-based edge computing, and cloud-enabled communication.

The overall system operates as a hybrid architecture in which the FPGA performs time-critical control tasks, while the Raspberry Pi manages data processing, visualization, and connectivity. This division of functionality ensures efficient resource utilization and improves system performance com- pared to conventional microcontroller-based solutions.

IV. METHODOLOGY

The proposed system operates as an intelligent and automated framework that integrates real-time sensing, FPGA-based processing, decision-making, and cloud-enabled monitoring. The overall methodology is designed as a closed-loop system to ensure efficient irrigation control and continuous monitoring of agricultural conditions.

4.1 Data Acquisition

Environmental parameters are continuously monitored using soil moisture, water level, and rain sensors deployed in the agricultural field. These sensors generate real-time analog and digital signals corresponding to field conditions. Analog signals are converted into digital form using ADC mod- ules, while digital outputs are directly interfaced with the FPGA through GPIO pins for further processing.

4.2 Hardware Implementation

The hardware implementation of the proposed system is shown in Fig. 3. It consists of an Artix-7 FPGA development board, Raspberry Pi 4 Model B, sensor modules, interfacing circuits, and irrigation components such as DC motors or pumps.

The FPGA acts as the primary controller responsible for real-time processing and control operations. Sensor data is interfaced through ADC and GPIO connections, enabling continuous monitoring and fast decision-making. Based on processed inputs, the FPGA generates control signals to drive actuators through relay and motor driver circuits.

The Raspberry Pi is integrated into the system to perform high-level operations such as image acquisition and cloud communication. It communicates with the FPGA using protocols such as UART or I2C, ensuring coordinated system functionality.

4.3 Real-Time Processing and Control

The FPGA processes incoming sensor data in real time using predefined threshold values based on crop requirements. Due to its parallel processing capability, multiple sensor inputs are evaluated simultaneously.

When soil moisture levels fall below a predefined threshold, the FPGA activates the irrigation system. Conversely, irrigation is automatically stopped when sufficient moisture is achieved or rainfall is detected. Control signals

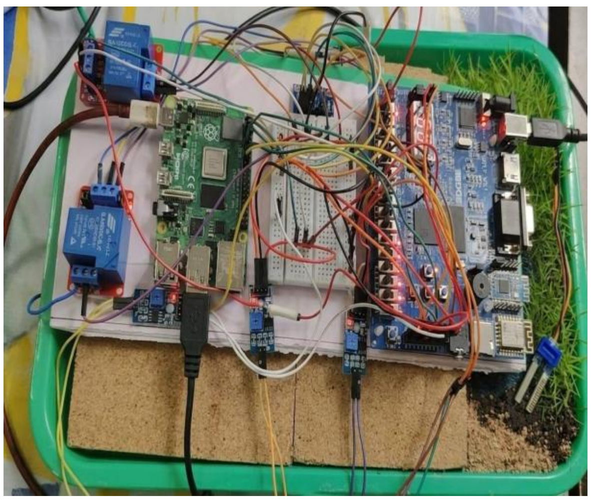

Figure 3: Experimental hardware setup of the proposed intelligent smart farming system showing FPGA board, Raspberry Pi, interfacing circuits, and irrigation control components.

are generated using PWM or digital outputs to drive actuators efficiently, ensuring optimal water utilization.

4.4 Image-Based Monitoring

The Raspberry Pi interfaces with a camera module to capture real-time images of crops. These images are used for monitoring plant conditions and identifying potential issues such as pest infestations. The system is designed to support future integration of artificial intelligence techniques for automated disease detection.

4.5 Cloud Integration and User Interface

Processed data is transmitted to cloud platforms for remote monitoring and analysis. A web-based dashboard provides real-time visualization of parameters such as soil moisture, rainfall intensity, and water levels. Additionally, pest detection results and alerts are displayed to assist farmers in taking timely actions.

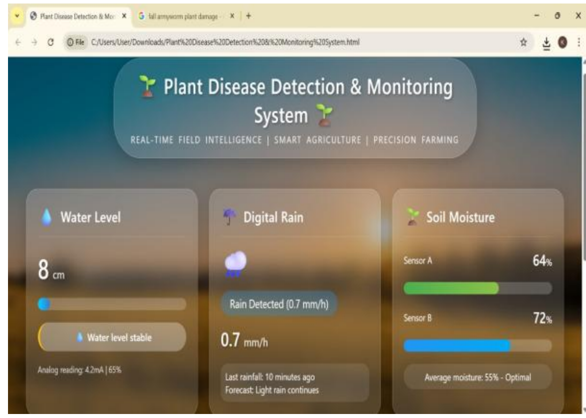

Figure 4: Web-based dashboard displaying real-time sensor data including soil moisture, rainfall detection, and water level monitoring.

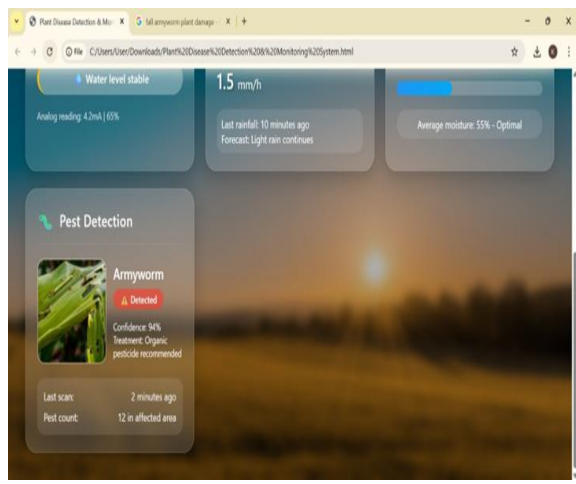

Figure 5: Pest detection interface showing identified pest (armyworm), confidence level, and recommended treatment details.

4.6 Overall System Operation

The complete system operates as a closed-loop architecture where sensing, processing, and actuation are tightly integrated. The FPGA handles time-critical control operations, while the Raspberry Pi manages data visualization, communication, and remote access.

This hybrid architecture ensures efficient resource utilization, reduces manual intervention, and significantly enhances agricultural productivity through intelligent automation.

V. RESULTS AND DISCUSSION

The performance of the proposed Intelligent Smart Farming Stick was evaluated based on real-time monitoring capability, irrigation control efficiency, and system responsiveness. The system was tested under different environmental conditions to analyze its effectiveness in practical agricultural scenarios.

5.1 Sensor Performance Analysis

The soil moisture sensor readings were continuously monitored, and irrigation decisions were made based on predefined threshold values. Table 2 presents the observed relationship between soil moisture levels and irrigation control.

Table 2: Soil Moisture vs Irrigation Control

Soil Moisture (%)	Condition	Pump Status
20	Dry	ON
35	Moderate	ON
55	Optimal	OFF
75	Wet	OFF

The results indicate that the system maintains soil moisture within an optimal range of 50–60%, ensuring proper irrigation control. This automated regulation minimizes water wastage and prevents both over-irrigation and under-irrigation, thereby improving crop productivity.

5.2 Rain Detection and Water Conservation

The rain sensor accurately detected rainfall conditions and successfully prevented unnecessary irrigation. During experimental evaluation, the system avoided redundant water usage during rainfall events, leading to an estimated water saving of approximately 20–30%. This demonstrates the system's effectiveness in promoting sustainable water management.

5.3 System Response Time

The FPGA-based processing enabled fast and reliable decision-making. The average response time of the system was observed to be less than 1 second, which is significantly lower than traditional microcontroller-based systems that typically exhibit response delays of 2–5 seconds. The parallel processing capability of the FPGA allows simultaneous handling of multiple sensor inputs, resulting in improved system efficiency.

5.4 Comparative Analysis with Existing Systems

A comparative evaluation was performed to highlight the advantages of the proposed system over conventional microcontroller-based smart irrigation systems. The key differences are summarized as follows:

5.4.1 Processing Speed: The FPGA-based system provides faster response time (< 1 second) compared to microcontroller-based systems (2–5 seconds).

5.4.2 Parallel Processing: FPGA enables simultaneous processing of multiple sensor inputs, whereas microcontrollers process inputs sequentially.

5.4.3 Water Efficiency: The integration of rain detection and threshold- based control improves water conservation by approximately 20–30%.

5.4.4 Scalability: The proposed architecture supports integration of additional sensors and modules without significant performance degradation.

5.4.5 System Integration: The combination of FPGA, Raspberry Pi, and cloud connectivity provides a complete solution, unlike existing systems that focus only on sensing or control.

5.5 Discussion

The experimental results demonstrate that the proposed system offers significant improvements in terms of responsiveness, efficiency, and automation. The use of FPGA ensures deterministic and low-latency performance, which is critical for real-time agricultural applications.

The hybrid architecture, combining FPGA for real-time control and Rasp- berry Pi for high-level processing, provides an optimal balance between performance and flexibility. Additionally, the integration of cloud connectivity enhances accessibility, enabling remote monitoring and decision-making.

However, the current implementation has certain limitations, including dependency on network connectivity for cloud-based services and the absence of fully integrated AI-based disease detection. These limitations can be addressed in future work by incorporating edge-based AI models and offline processing capabilities.

VI. CONCLUSION

This paper presented an Intelligent Smart Farming Stick that integrates FPGA-based real-time processing with IoT-enabled sensor networks for precision agriculture. The system continuously monitors critical environmental parameters such as soil moisture, water level, and rainfall, and performs automated irrigation control based on predefined threshold conditions.

The use of FPGA enables low-latency and deterministic performance, ensuring rapid decision-making compared to conventional microcontroller- based systems. Experimental results demonstrate that the system effectively maintains optimal soil moisture levels, reduces water wastage by approximately 20–30%, and achieves a response time of less than 1 second.

Additionally, the integration of a Raspberry Pi and cloud-based monitoring provides enhanced accessibility through real-time data visualization and remote-control capabilities. The hybrid architecture improves system efficiency, scalability, and reliability, making it suitable for modern smart farming applications.

Overall, the proposed system offers a cost-effective and efficient solution for automated agricultural monitoring and irrigation management, contributing to improved crop productivity and sustainable resource utilization.

VII. FUTURE WORK

The proposed system can be further enhanced by incorporating advanced features to improve intelligence, scalability, and autonomy. Future developments may include:

- Integration of deep learning models for real-time plant disease detection and classification using image data.
- Expansion of sensor modules to include parameters such as pH level, temperature, humidity, and nutrient analysis for comprehensive soil monitoring.
- Implementation of wireless communication technologies such as LoRa or ZigBee for large-scale farm deployment.
- Development of a dedicated mobile application for user-friendly monitoring and control.
- Integration of edge-based AI processing on Raspberry Pi to reduce dependency on cloud connectivity.
- Incorporation of renewable energy sources such as solar power for energy- efficient operation.

These enhancements will further improve the system's capability, making it a fully autonomous and scalable solution for next-generation smart agriculture.

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