

Implementation of a PCB-Based IoT Smart Greenhouse Monitoring and Control System with Web Server Integration

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Abstract – The practical deployment of Internet of Things (IoT) technologies in greenhouse agriculture requires reliable hardware implementation in addition to real-time monitoring and control capabilities. Many existing IoT-based greenhouse systems are developed using breadboard-based prototypes and loosely connected components, which are prone to connection failures, increased maintenance, and reduced suitability for long-term agricultural use. To address these limitations, this paper presents the implementation of a printed circuit board (PCB)-based IoT smart greenhouse monitoring and control system using the ESP8266 microcontroller with web server integration. The proposed system emphasizes hardware-level design and deployment by developing custom PCB layouts for both sensor nodes and actuator nodes. The PCB-based sensor node integrates environmental sensors for measuring temperature, humidity, soil moisture, and light intensity, along with the ESP8266 for data processing and wireless communication. The actuator node is also implemented on a custom PCB and interfaces with relay circuits to control greenhouse equipment such as irrigation pumps and ventilation systems. The collected environmental data is transmitted through Wi-Fi to a web server, where it is stored in a database and made available through a web-based monitoring interface. This enables users to remotely observe greenhouse conditions and control devices as required. The use of custom-designed PCBs improves system compactness, reduces wiring complexity, enhances connection stability, and increases overall reliability compared to prototype-level implementations. The system was fabricated, assembled, and deployed in a greenhouse environment to validate its functionality under real operating conditions. Experimental observations confirm that the PCB-based system operates reliably, provides stable wireless data communication, and effectively controls greenhouse devices. The implementation demonstrates that PCB-based integration significantly improves system robustness and deployment feasibility. The proposed system offers a cost-effective, reliable, and deployment-ready IoT solution for smart greenhouse monitoring and control, supporting the advancement of precision agriculture and sustainable farming practices.

Keywords: Internet of Things (IoT), Smart Greenhouse, ESP8266, Printed Circuit Board (PCB), Web-Based Monitoring, Wireless Sensor Node, Precision Agriculture.

I. Introduction

Greenhouse technology plays a significant role in modern agriculture by providing a controlled environment that supports improved crop productivity, efficient resource utilization, and protection against adverse climatic conditions. Maintaining optimal environmental parameters such as temperature, humidity, soil moisture, and light intensity is essential for healthy plant growth and maximum yield. Traditionally, these parameters are monitored and controlled manually, which requires continuous human supervision and may lead to inefficient operation and delayed response to environmental changes. Manual monitoring is particularly challenging in large greenhouse environments, where maintaining consistent conditions

becomes difficult and labor-intensive. With the rapid advancement of the Internet of Things (IoT), automated greenhouse monitoring systems have been developed to enable real-time sensing, data transmission, and remote control of greenhouse devices. IoT-based systems use sensors and wireless communication technologies to collect environmental data and provide users with the ability to monitor and manage greenhouse conditions remotely through web-based platforms, thereby improving efficiency, reducing manual effort, and supporting precision agriculture.

However, many existing IoT-based greenhouse monitoring systems are implemented using breadboards and prototype-level circuit assemblies, which are primarily intended for experimental validation rather than practical deployment. These prototype implementations involve multiple external connections and loose wiring,

which can result in unstable operation, increased maintenance, and reduced reliability over long-term use. Such hardware configurations are often bulky, difficult to install and unsuitable for real agricultural environments where stable and continuous operation is required. Printed Circuit Board (PCB) technology offers a more reliable and compact solution by providing secure electrical connections, organized component placement, and improved structural stability. PCB-based implementation reduces wiring complexity, enhances system durability, and makes the system more suitable for real-world deployment. Additionally, integrating wireless microcontrollers such as the ESP8266 with PCB-based sensor and actuator circuits enables efficient data acquisition, processing, and wireless communication within a compact and cost-effective design.

This paper focuses on the hardware-level realization of a greenhouse monitoring and control system through custom PCB design using the ESP8266 microcontroller and integrated web server connectivity. In the proposed system, custom-designed PCBs are developed for sensor nodes and actuator nodes to improve hardware reliability and deployment feasibility. The sensor node measures environmental parameters including temperature, humidity, soil moisture, and light intensity, and transmits the collected data wirelessly to a web server for storage and monitoring. The actuator node controls greenhouse devices such as irrigation pumps and ventilation systems based on environmental conditions and user commands received through a web-based interface. The system focuses on hardware design, PCB fabrication, and real-time implementation to develop a stable and deployment-ready greenhouse monitoring solution. The proposed PCB-based system improves hardware stability, reduces system complexity, and provides a practical IoT solution for smart greenhouse automation and precision agriculture applications.

II. Related Work

The application of Internet of Things (IoT) technology in greenhouse monitoring has been widely explored to improve agricultural efficiency and automation. Devanath et al. [1] developed an IoT-based greenhouse monitoring and control system using the Arduino platform to measure environmental parameters such as temperature and humidity and control greenhouse devices. Their system demonstrated the feasibility of using IoT for greenhouse automation; however, the implementation was based on prototype-level hardware, which may limit reliability and long-term deployment. Similarly, Van et al. [2] proposed a wireless sensor network-based greenhouse monitoring system that enabled real-time environmental data collection and control. Their work highlighted the importance of wireless communication in greenhouse environments but primarily focused on communication performance rather than hardware design and deployment stability. Rathore

and Mishra [3] presented a wireless sensor network-based greenhouse monitoring system incorporating IoT technology for environmental monitoring and automation. Their study emphasized the effectiveness of IoT in improving monitoring efficiency, but the hardware implementation relied on conventional development boards without addressing the need for compact and deployment-ready hardware. Miao et al. [4] implemented an IoT-based smart greenhouse system capable of monitoring environmental conditions and controlling greenhouse devices; however, their implementation involved multiple external components and lacked hardware integration using custom-designed circuit boards.

Several studies have also emphasized the importance of greenhouse technology and IoT in modern agriculture. Pardossi et al. [6] discussed the role of greenhouse systems in improving agricultural productivity and environmental control, highlighting the need for efficient monitoring systems. Survey studies conducted by Al-Fuqaha et al. [7] and Atzori et al. [13] explained the significance of IoT in enabling real-time monitoring, remote access, and automation across various applications, including smart agriculture. Wireless sensor networks have also been widely used for environmental monitoring due to their ability to provide distributed sensing and wireless communication [10], [12]. Belgibaev et al. [14] presented the design of smart greenhouse systems with improved monitoring capabilities, emphasizing the importance of system reliability and cost-effectiveness. In addition, advancements in sensor web enablement and data integration technologies have further enhanced the capabilities of IoT-based monitoring systems [15].

Despite these developments, most existing greenhouse monitoring systems are implemented using breadboards or prototype-level hardware, which are not suitable for long-term deployment due to loose wiring, increased maintenance, and reduced reliability. The use of electronic design automation tools such as KiCad enables the development of custom Printed Circuit Boards (PCBs), which improve hardware stability, reduce system complexity, and enhance deployment feasibility [9]. PCB-based implementation provides secure component connections, compact design, and improved durability compared to conventional prototype-based systems. Therefore, there is a need for greenhouse monitoring systems that focus not only on sensing and communication but also on reliable hardware implementation. To address this gap, this paper presents a PCB-based IoT smart greenhouse monitoring and control system using ESP8266 with web server integration, focusing on hardware design, fabrication, and deployment to develop a stable and practical solution for precision agriculture.

III. Methodology

The proposed system adopts a distributed Internet of Things (IoT)-based architecture for real-time greenhouse monitoring and control using ESP8266 microcontroller modules. The methodology consists of environmental data acquisition, wireless data transmission, web-based data processing and storage, and remote actuator control. The overall system architecture consists of independent sensor nodes, actuator nodes, and a web server integrated through Wi-Fi communication, as shown in Fig. 1.

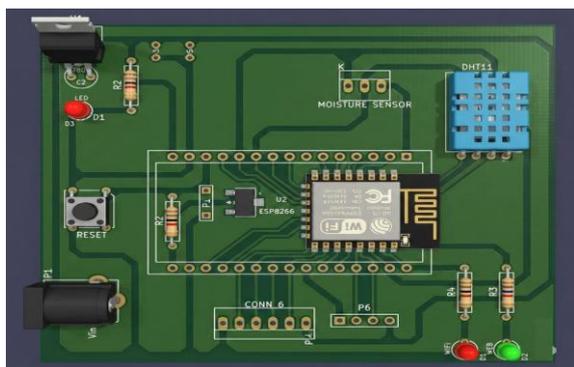


Fig. 1. PCB layout and implementation of the ESP8266-based sensor node

PCB design and development are carried out using KiCad electronic design automation software. The circuit schematic is first created by integrating the ESP8266 microcontroller, sensor interfaces, power supply circuits, and relay control circuits. Component footprints are assigned, and the PCB layout is generated by placing components and routing conductive tracks to establish electrical connections. The PCB layout is optimized to minimize signal interference and ensure proper electrical isolation between low-power and high-power sections. After completing the design, the PCB is fabricated and assembled with electronic components. This PCB-based implementation improves structural integrity, reduces loose wiring connections, and enhances overall hardware reliability compared to prototype-level breadboard circuits.

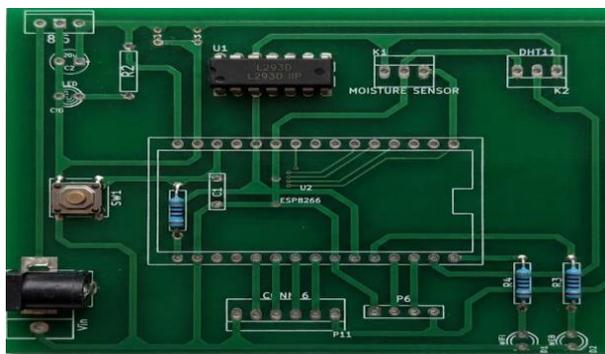


Fig. 2. Fabricated PCB of the ESP8266

The actuator node is implemented using ESP8266 integrated with relay driver circuits on the PCB. The relay module enables electrical switching of greenhouse

devices such as irrigation pumps and ventilation fans. Control commands are received from the web server through wireless communication, and the ESP8266 activates the corresponding relay based on the received instruction. The web server stores sensor data in a database and provides monitoring and control functionality through a web-based interface. The integration of sensing, processing, communication, and control functions into PCB-based hardware ensures compact design, stable operation, and deployment readiness for greenhouse automation applications.

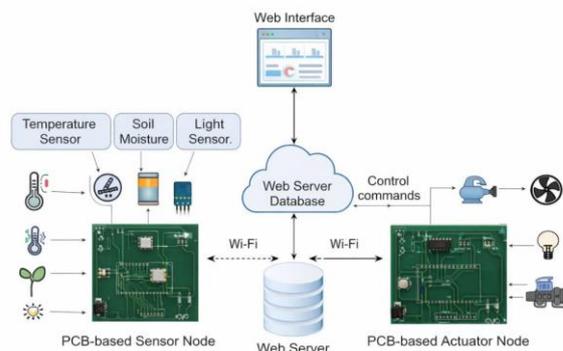


Fig. 3. Hardware architecture of the PCB-based greenhouse monitoring and control system

Algorithm 1: PCB Hardware Design and Implementation Procedure

- Step 1: Select ESP8266 microcontroller and required electronic components
- Step 2: Design circuit schematic using KiCad software
- Step 3: Assign component footprints
- Step 4: Create PCB layout and place components
- Step 5: Route electrical connections between components
- Step 6: Verify PCB design and correct errors
- Step 7: Fabricate printed circuit board
- Step 8: Assemble components on PCB
- Step 9: Test hardware functionality
- Step 10: Install PCB hardware in greenhouse environment

IV. Experimental Analysis

The experimental analysis was conducted to evaluate the operational performance, communication reliability, and hardware stability of the PCB-based greenhouse monitoring and control implementation. The fabricated PCB hardware was tested under continuous operating conditions inside the greenhouse environment. The ESP8266 microcontroller interfaced with the sensors through the PCB circuits and transmitted the acquired data to the web server through Wi-Fi communication. The performance of the wireless communication was evaluated by observing the successful transmission of data over time. The transmission success rate during operation is shown in Fig. 4. The results indicate that the PCB-based hardware maintained reliable wireless

communication throughout the test period. The integrated PCB design ensured stable electrical connections and supported uninterrupted data transmission.

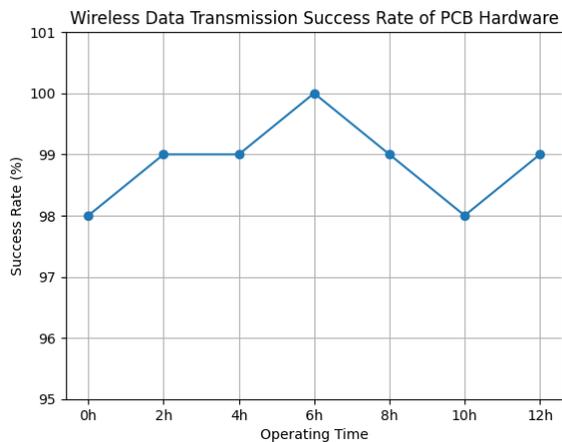


Fig. 4. Wireless data transmission success rate

The hardware stability of the PCB implementation was evaluated by monitoring continuous system operation during the experimental period under real greenhouse conditions. The PCB-based hardware was powered and operated continuously, and its performance was observed to verify reliable functioning of the ESP8266 micro- controller, sensor interface circuits, and wireless communication module. The PCB hardware operated without system restart, hardware malfunction, or communication failure during the entire testing duration. The integrated PCB design ensured secure electrical connections between components and minimized signal disturbances that are commonly observed in prototype-level circuits. The operational stability observed during the test duration is presented in Fig. 5, which shows consistent system uptime throughout the experimental period. The results confirm that the PCB hardware maintained stable operation and successfully supported continuous monitoring and communication functions. The use of PCB technology improved structural strength, reduced loose connections, and enhanced overall hardware reliability. In addition, the compact PCB design simplified system installation and reduced maintenance requirements. These results demonstrate that the PCB-based implementation provides stable, reliable, and deployment-ready hardware suitable for long-term greenhouse monitoring and control applications.

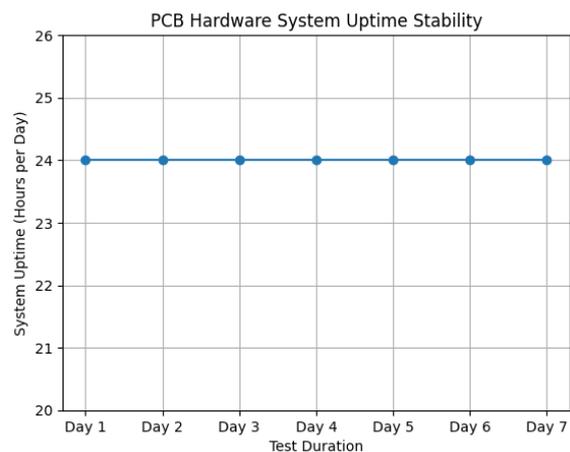


Fig. 5. System stability

The experimental results confirm that the PCB-based hardware implementation provides reliable communication, stable operation, and effective performance for greenhouse monitoring applications. The integration of sensing, processing, and communication circuits into a PCB improved system reliability and reduced hardware complexity. The ESP8266 microcontroller successfully supported continuous monitoring and wireless data transmission. The PCB-based implementation is therefore suitable for practical deployment in smart greenhouse monitoring systems.

V. Conclusion

In this study, a PCB-integrated IoT greenhouse monitoring and control hardware was implemented using the ESP8266 microcontroller and web server connectivity, with emphasis on developing a compact, reliable, and deployment-ready hardware platform. The hardware was designed using Printed Circuit Board technology to integrate sensor interface circuits, wireless communication, and actuator control components into a single structured unit. This integration improved electrical stability, reduced wiring complexity, and enhanced overall hardware reliability compared to conventional prototype-based implementations. The PCB-based hardware successfully interfaced with environmental sensors, processed the acquired data, and transmitted the information wirelessly to the web server for monitoring and control purposes.

The experimental analysis confirmed that the PCB hardware maintained stable operation and reliable wireless communication during continuous deployment in the greenhouse environment. The integrated PCB structure minimized loose connections and reduced the risk of hardware failure, ensuring consistent system performance. The compact design also simplified installation and improved the physical robustness of the monitoring hardware. In addition, the PCB

implementation improved system organization and made the hardware more suitable for long-term operation compared to breadboard-based systems.

This study demonstrates that PCB-based hardware integration significantly enhances the practicality, stability, and deployment feasibility of IoT greenhouse monitoring systems. By converting the monitoring and control circuit into a dedicated PCB design, the system becomes more reliable, easier to replicate, and suitable for real-world agricultural applications. The implemented PCB hardware provides a stable and scalable foundation for greenhouse monitoring and control, supporting the advancement of IoT-based smart agriculture systems.

VI. Future Scope

This study can be extended by integrating additional environmental sensors such as CO₂, soil nutrient, and pH sensors to enhance monitoring capability and provide more detailed greenhouse environmental analysis. The PCB design can be further optimized to support low power consumption and energy-efficient operation, enabling long-term and uninterrupted system deployment. Power management circuits and battery-based operation can also be incorporated to improve system portability and reliability.

The PCB hardware can be expanded to support multiple sensor and actuator nodes operating within a single greenhouse environment, allowing large-scale and distributed monitoring. Protective enclosures and improved PCB packaging can be implemented to enhance hardware durability under varying environmental conditions. Integration with cloud-based platforms and mobile applications can improve remote accessibility, real-time monitoring, and user control. These enhancements will support the development of scalable, reliable and fully deployable PCB-based greenhouse monitoring and control systems for smart agriculture applications.

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