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Design, Implementation, and Multi-Parameter Field Testing of Automated Greenhouse Environmental Control Systems

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Abstract: Greenhouse cultivation enables controlled agricultural production by mitigating adverse climatic conditions; however, conventional greenhouses rely heavily on manual monitoring and rule-of-thumb control, leading to inefficient resource utilization and inconsistent crop performance. Automated greenhouse environmental control systems offer a technology-driven solution by integrating sensors, actuators, and control algorithms to regulate critical growth parameters in real time. This study presents the design, implementation, and field testing of an automated greenhouse environmental control system capable of regulating temperature, relative humidity, soil moisture, light intensity, and carbon dioxide concentration. The system was developed using a modular hardware architecture and a rule-based control strategy tailored for low-to-medium scale agricultural operations. Field experiments were conducted over a full cropping cycle to evaluate system responsiveness, environmental stability, and energy efficiency. Results demonstrate significant improvements in parameter regulation accuracy, reduced manual intervention, and enhanced crop growth consistency. The findings confirm that automated greenhouse control systems can improve productivity while optimizing water and energy consumption, supporting sustainable protected agriculture.

Keywords: Automated Greenhouse Systems, Environmental Control, Precision Agriculture, Sensor-Based Automation, Controlled Cultivation

1. Introduction

Protected agriculture has gained increasing importance as climate variability, water scarcity, and land constraints threaten conventional farming systems. Greenhouses provide a controlled environment that enhances crop yield, quality, and seasonality by regulating key environmental variables such as temperature, humidity, and light intensity. However, manual monitoring and control practices often fail to maintain optimal conditions due to delayed response, human error, and limited data availability [1]. Automation in greenhouse systems introduces precision, consistency, and adaptability by enabling continuous monitoring and real-time control of environmental parameters. Advances in sensors, microcontrollers, and low-cost actuators have made automated systems increasingly accessible to small and medium-scale growers. This paper focuses on the engineering design and experimental evaluation of an automated greenhouse environmental control system with multi-parameter regulation capability.

2. System Architecture and Design Framework

The proposed system follows a layered architecture comprising sensing, control, actuation, and data logging modules. Environmental parameters were monitored using digital temperature and humidity sensors, capacitive soil moisture probes, light intensity sensors, and nondispersive infrared CO_2 sensors. These sensors were strategically placed within the greenhouse to capture representative environmental conditions. A

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microcontroller-based control unit served as the system core, processing sensor inputs and executing control decisions. Actuation mechanisms included exhaust fans, ventilation windows, irrigation pumps, shading screens, and supplemental lighting units. The system was designed to be modular, allowing easy expansion and maintenance.

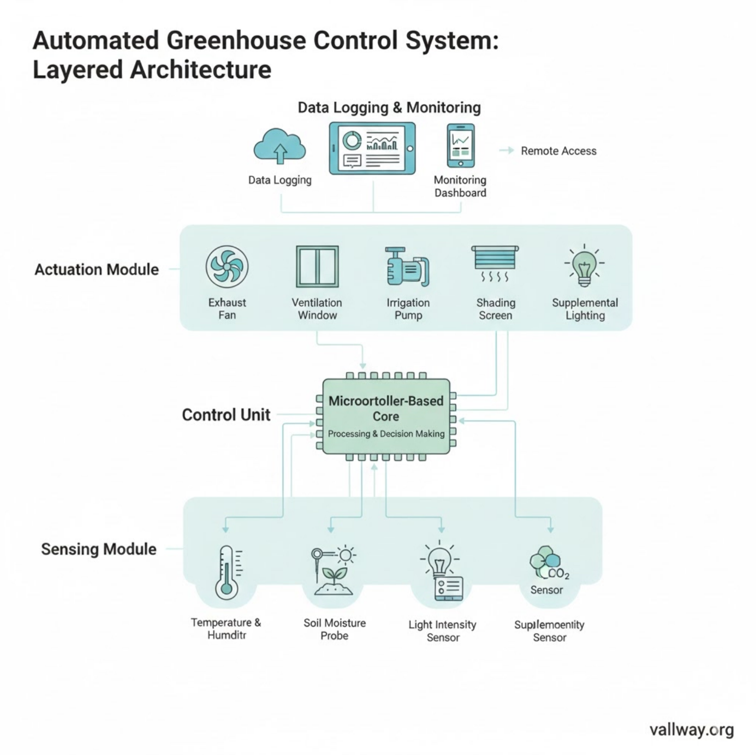

Fig. 1 Layered Architecture

3. Control Strategy and Software Implementation

A rule-based control algorithm was implemented to maintain environmental parameters within predefined threshold ranges suitable for vegetable crops. Control logic was developed using conditional statements that activated actuators in response to sensor readings exceeding or falling below set limits [2]. For example, ventilation fans were triggered when temperature exceeded the upper threshold, while irrigation was initiated based on soil moisture levels. Data logging functionality recorded environmental conditions and actuator states at regular intervals, enabling performance analysis and system tuning. Although advanced control techniques such as fuzzy logic and model predictive control exist, the rule-based approach was selected to ensure simplicity, reliability, and ease of adoption for resource-limited agricultural settings.

4. Field Testing Methodology

Field experiments were conducted in a naturally ventilated greenhouse covering an area of 120 m^2. The automated system was tested over a complete crop growth cycle of leafy vegetables. Environmental parameters were continuously monitored, and system response times were evaluated during sudden climatic changes such as midday temperature spikes and nighttime humidity increases. Manual measurements were periodically taken to validate sensor accuracy. Energy consumption of actuators and water usage for irrigation were recorded to assess resource efficiency.

5. Results and Performance Evaluation

Experimental results indicate that the automated system maintained temperature and humidity within desired ranges for over 90% of the operational time. Soil moisture levels were regulated effectively, reducing over-irrigation and water wastage by approximately 25% compared to manual practices. Light intensity control through shading and supplemental lighting improved uniformity of photosynthetically active radiation across the greenhouse. CO_2 concentration remained within optimal limits during daylight hours, contributing to improved plant growth rates. System response times were found to be adequate for real-time control, with most actuations occurring within seconds of threshold violations.

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6. Impact on Crop Growth and Resource Efficiency

Crop observations revealed improved uniformity in plant height, leaf size, and overall biomass compared to control plots managed manually. Automated irrigation scheduling contributed to healthier root development and reduced disease incidence caused by excessive moisture. Energy analysis showed moderate increases in electricity consumption due to automation; however, this was offset by gains in crop yield and reductions in labor requirements. The results demonstrate a favorable trade-off between operational costs and productivity gains [3].

7. Limitations and Future Enhancements

While the system performed reliably, limitations include dependence on fixed threshold values and lack of predictive capability. Future enhancements may incorporate adaptive control algorithms, machine learning-based decision support, and remote monitoring interfaces. Integration with weather forecasting data could further improve system responsiveness and energy efficiency.

8. Conclusion

This study demonstrates the successful design, implementation, and field evaluation of an automated greenhouse environmental control system capable of regulating multiple growth parameters. The system significantly improves environmental stability, resource efficiency, and crop performance, offering a practical solution for sustainable protected agriculture. The findings support broader adoption of automation technologies in greenhouse farming, particularly in regions facing climatic uncertainty.

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