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BUILDING A HIGH-TECH CLOSED GREENHOUSE SYSTEM BASED ON IOT

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ABSTRACT

This paper presents the design and construction of a high-tech closed greenhouse system based on the Internet of Things (IoT) platform to automate the entire agricultural cultivation process. The system includes main components such as sensors, cameras, central controllers, care robots and smart control software. Environmental data such as temperature, humidity, light and CO_2 concentration are continuously collected and sent to the processing server, where algorithms for analyzing and recognizing plant status are executed. Based on the analysis results, the system automatically issues warnings, activates irrigation systems, ventilation fans, lighting or controls robots to perform plant care tasks. Test results show that the system is highly stable, with a sensor accuracy of over 96%, a pest detection rate of 93% and a 70% reduction in labor time compared to traditional methods. In addition, crop yields increased by an average of 10–20%, while water consumption was optimized thanks to the real-time automatic control mechanism. In addition, the model also integrated security and access authorization mechanisms to ensure data security and operation of the entire system. The proposed smart greenhouse system contributes to promoting precision and sustainable agriculture, while opening up new research and application directions in combining AI, IoT and agricultural robots to improve production efficiency in the digital transformation era.

Keyword: IOT, Greenhouse system, Agricultural Automation

1. INTRODUCTION

High-tech closed greenhouses play an increasingly important role in modern agriculture as the demand for both productivity and quality stability of agricultural products increases in the context of climate change, limited labor resources and pressure on water and fertilizer use. The transformation of traditional greenhouses into smart farming environments integrating the Internet of Things (IoT), edge/cloud computing, machine vision and care robots enables real-time monitoring, automation of irrigation, nutrition, disease prevention and harvesting decisions, thereby optimizing productivity and reducing operating costs. Recent reviews have pointed out the trend of combining multiple sensors, cameras and deep learning models to build smart platforms for greenhouses, while emphasizing the role of edge architecture to process data in real time and reduce bandwidth for large video/image streams [1]. An ideal closed-loop high-tech greenhouse system needs to perform a continuous chain of functions: multi-source data collection (environmental sensors, soil sensors, plant/branch/leaf surveillance cameras), processing and analysis to detect growth status and abnormalities (pests, water shortage/excess, heat stress), issuing warnings or control commands, communicating and coordinating IoT devices (irrigation valves, fans, shading systems), and finally performing physical actions through care robots (localized irrigation, fertilization, pruning, harvesting). These components must operate together in a secure architecture, with a decentralized and tightly secured mechanism to avoid risks from cyber attacks or sensor errors leading to crop losses. Recent studies describe the above functional blocks and highlight challenges in processing latency, reliability of wireless sensors (e.g., LoRaWAN), and the level of security required for agricultural IoT systems [2][3].

Greenhouse agricultural robots are gradually moving from single-task systems (harvesting only, spraying only) to multi-purpose platforms that can move flexibly in greenhouse corridors, recognize targets by vision, and interact directly with plants (cutting, pruning, pest control, localized irrigation). Recent reports and research papers describe the development of specialized robots for spot fertilization, precision spraying, and soft-gripper harvesting, showing great potential in reducing labor and post-harvest losses. However, lightweight mechanical design, precise positioning control in narrow spaces, and safe integration of human-machine interaction remain challenges. [10].

From the overview of the above studies, there are several research gaps that need to be filled: (i) seamless integration of plant state recognition by machine vision and robot actions for safety and efficiency in narrow greenhouse environments; (ii) an optimized hybrid (edge–cloud) processing architecture that balances latency, power consumption, and security; (iii) a lightweight yet robust security mechanism for real-time control channels in agriculture; and (iv) a comprehensive field trial framework to evaluate the economic impact and real-world yields of a closed-loop solution. These approaches have been discussed in many recent papers, but there are not many solutions that comprehensively combine hardware (robots, actuators), software (AI/ML, IoT operating systems), and security policies in a real-world testbed [1][4][7][10][11].

Based on technological achievements in IOT [11], image recognition and processing [12][13], audio processing [14], video processing [15]. This paper aims to propose and implement an IoT-based closed-loop greenhouse system architecture, combining multi-source data collection, deep learning image processing modules for plant status detection, device control mechanisms and robots to execute care commands, and integrating a security layer suitable for agricultural environments. The objective of the study is to illustrate the feasibility of this integrated platform through system design, simulation testing and laboratory-scale greenhouse experiments, and to evaluate the productivity benefits, resource savings and necessary security requirements. The expected outcome is to provide a reference framework for researchers and engineers to deploy smart greenhouses at different scales, and to open up further research directions for integrating safe interactive robots in closed-loop farming environments [1][9][10]. The specific objectives of this research include: (i) Design and implement a software capable of collecting real-time multi-source data from environmental sensors and surveillance camera systems; (ii) Build advanced data processing modules, using AI and computer vision to analyze, detect plant growth status, automatically issue warnings and generate control commands; (iii) Develop a centralized IoT interface that allows two-way communication, monitoring and controlling actuators such as irrigation systems, LED lights, ventilation fans and robots; (iv) Integrate an autonomous robot that can move flexibly in the greenhouse, receive commands from the central system to perform care activities (such as watering, local spraying) and interact directly with plants; and (v) Build a multi-layer security mechanism to control access and monitor the entire system operation, ensuring data integrity and security.

2. MODEL ARCHITECTURE

2.1. Overview of the System Design Process

The system development process is described as figure 1.

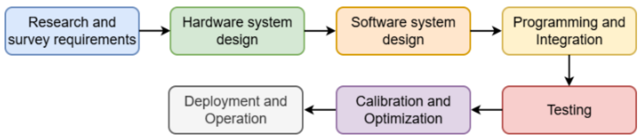

Figure 1. Overview of the proposed system

In the first phase, the research team gathered requirements from agricultural experts and greenhouse operators, identifying the environmental factors that need to be monitored (temperature, air humidity, light intensity, CO_2, soil moisture, pH, EC...) and the necessary control actions (irrigation, fans, lighting, cooling, misting). After identifying the requirements, the system was divided into two main parts: the hardware system (sensors, controllers, robots, actuators) and the software system (data collection, processing, display and control platform). These two parts were designed in parallel and integrated through a secure IoT platform.

2.2. Hardware system design

The system hardware is designed to meet the criteria of high reliability, continuous operation, reasonable cost and easy expansion. The overall hardware structure includes three layers: (i) sensor layer, (ii) central control layer, and (iii) actuator and robot layer.

a. Sensing Layer

The system uses a variety of sensors to collect data from the greenhouse environment. The common sensors used in this system are described in Table 1.

Sensor Name	Purpose
DHT22 Sensor	Measures air temperature and humidity.
CO_2 Sensor MH-Z19B	Monitors CO_2 concentration to support photosynthesis.
Capacitive Soil Sensor, Analog pH Sensor	Measures soil moisture and pH levels.
Camera OV264	Observes leaf and fruit conditions and detects plant diseases.

Table 1. List of sensors used in the greenhouse system and their corresponding functions.

b. Control Layer

The control center uses a microcontroller or an embedded computer with network connectivity. In this model, suitable options include a servo motor for a 4-axis flexible arm and a YoloBit Esp32 control system (as shown in Figure 2). The control center acts as a gateway, collecting data from sensors, transmitting it to the server, and receiving control commands from the software and sending them to the actuator.

Figure 2. Example with robotic arm

c. Actuation and Robotics Layer

The execution system includes:

• Smart drip irrigation system, controlled by solenoid valve.

• Ventilation system and cooling fan automatically controlled when temperature exceeds threshold.

• LED lighting system supplemented with light, turned on and off according to light sensor or time.

These components are powered separately via DC-DC converter module, with overvoltage/overcurrent protection circuit, ensuring safe operation.

In addition, the system also provides a security module to enter the door password to encrypt the security of the ability to connect to the warning system and control access to the greenhouse, protecting the safety of equipment and plants. Details of the devices and their functions are described in Table 2.

Device	Main Specifications	Primary Function
Greenhouse Care Robot	4-axis robotic arm, servo control, Bluetooth and remote operation	Automatic watering, pruning, and harvesting
Soil Moisture Sensor	Range: 0–100%, accuracy ±3%, power supply 3.3V	Measures soil moisture to adjust irrigation
Temperature Sensor	Range: –10°C to 60°C, error ±0.5°C, power supply 3.3V	Monitors greenhouse ambient temperature
Light Sensor	Range: 0–100,000 Lux, error ±5%, power supply 3.3V	Measures light intensity to adjust illumination
AI Surveillance Camera	1080p resolution, 30 fps, AI-based image recognition	Detects pests and monitors plant growth
Security Module with Keypad	4-digit password, high encryption capability, power supply 5V DC	Controls secure access to the greenhouse
IoT and Central Control Module	Supports MQTT, 2.4GHz Wi-Fi, real-time data processing	Enables remote system monitoring and control

Table 2. List of main devices in the smart greenhouse system with their specifications and functions

2.3. Software system design

The software is built on a three-layer architecture: (i) data acquisition layer, (ii) processing and control layer, and (iii) user interface layer.

a. Data acquisition layer

This layer receives data from sensors and cameras through the IoT gateway. Data is temporarily stored and sent to the server using the MQTT protocol, 2.4GHz Wi-Fi. For continuous signals such as images, the model uses image compression and sends important image regions (ROI) to save bandwidth.

b. Processing and control layer

Data is processed in two main directions: (1) sensor processing, (2) machine vision processing.

Sensor data is analyzed in real time to detect abnormalities, using statistical models or machine learning algorithms to predict environmental and crop conditions.

Images captured from cameras are processed using YOLOv8 or EfficientDet models to detect leaf diseases, determine growth status and calculate leaf area index (LAI).

When a value exceeding the threshold is detected, the system generates an alert or sends automatic control commands (e.g., turn on the irrigation system, turn on the fan, activate the robot to move to the diseased plant area).

The software also has a robot coordination module, in which the path is planned based on the A* algorithm, combined with obstacle avoidance using ultrasonic sensors. Control commands are sent via Wi-Fi.

c. User interface layer (IoT Dashboard)

Operators access the interface via the web or the IoT Dashboard. The interface displays environmental information, real-time data charts, camera captures and system action logs. Users can adjust control thresholds, activate manual mode or view periodic reports. The software is developed on Node-RED platform connecting to SQLite database.

3. EXPERIMENT RESULTS

First, we tested the system and compared the expected results (with the small size we proposed) with the actual test results. To do this, we applied the system at the Center for Experimental and Technology Transfer - Tan Trao University, Tuyen Quang, Vietnam for 1 month and obtained the results as shown in Table 3.

The results in Table 3 show that the demo model and the experimental system have a high degree of similarity, proving that the design has good reliability. The continuous operation time and accuracy of the sensor are both maintained at above 95%, confirming the stability of the system. The pest detection rate reaches 93%, proving that the image processing and analysis capabilities of the AI model work effectively. Although the crop yield and water consumption are slightly different from the simulation (reaching 92% and 88.2% respectively), this reflects the influence of real environmental conditions. In particular, the system helps reduce about 70% of labor time, showing a clear efficiency in automation, although the actual number of maintenance is higher due to the outdoor equipment wear factor.

Next, we compared the use of the system with the traditional farming method (i.e., outdoor farming, using human labor). The results are described in Table 4.

Indicator	Demo Model (Small Scale)	Actual Experimental Result	Achievement Level (%)	Remarks
Continuous Operating Time (hours)	120	115	95.8	Nearly equal, system remains stable
Sensor Accuracy (%)	98	96	97.9	Sensor accuracy remains stable
Pest Detection Rate (%)	95	93	97.9	High detection accuracy

Crop Yield (kg/m²)	2.5	2.3	92	Actual efficiency slightly lower
Water Consumption (liters/day)	15	17	88.2	Requires more watering in practice
Labor Time Reduction (%)	75	70	93.3	Effectively reduces manual labor
Maintenance Frequency (times/month)	1	2	50	More frequent maintenance required in reality

Table 3. Comparison between the demo model and actual experimental results of the smart greenhouse system.

Table 4 shows that the automated method using robots combined with AI is more effective than traditional farming methods. Labor time is reduced from 150–200 hours to only 30–50 hours per hectare, demonstrating significant labor savings. Labor costs are also reduced by 60–70%, helping to optimize operating costs for farmers. At the same time, crop yields increase by 10–20% thanks to the system automatically adjusting environmental conditions to suit each growth stage. In particular, the uniformity and quality of products are significantly improved, thanks to the ability to precisely control factors such as temperature, light and humidity in the greenhouse. In short, the project brings about a significant reduction in costs and labor, increasing crop yield and quality. However, good investment in infrastructure and technical human resources is needed to optimize the system and overcome initial limitations.

Criteria	Traditional Method	Automated Method (Robot + AI)
Labor Hours per Hectare per Month	150–200 hours	30–50 hours
Labor Cost	High	Reduced by 60–70%
Crop Yield	Fixed, dependent on manual work	Increased by 10–20% due to optimized growth conditions
Uniformity and Quality	Low, inconsistent	High, thanks to precise environmental control

Table 4. Comparison of labor hours and efficiency between traditional and automated (Robot + AI) cultivation methods.

From there, we can draw out some advantages and disadvantages for the high-tech closed greenhouse system based on IOT as follows:

Advantages:

• Minimize manual labor hours thanks to automatic robots for watering, caring, and harvesting; estimated to save 70-80% of labor hours compared to traditional methods.

• Significantly reduce labor costs, because many stages are automated, human resources only need to monitor and intervene when needed.

• The greenhouse environment is stably controlled, ensuring optimal conditions for plants to grow evenly, with fewer pests and diseases thanks to AI monitoring and early warning.

• Increase crop productivity according to experimental models with stable output and better quality, because growing conditions are continuously optimized.

• The IoT dashboard system helps manage and monitor remotely quickly and accurately.

Disadvantages:

• Initial investment costs for hardware and software are still quite high, requiring large capital.

• Requires complex technical operation and maintenance of the system, requiring qualified personnel to handle problems.

• In the early stages, robots and AI systems may not be completely perfect, requiring regular calibration and monitoring.

• Some specific crops may not be suitable or require algorithm calibration to suit each type of plant.

4. CONCLUSION

The research results show that the proposed high-tech closed greenhouse system based on IoT has operated stably, meeting the requirements for automation and optimization of agricultural production. The integration of sensors, cameras, robots and IoT platforms helps to monitor, analyze and control the growing environment flexibly and accurately. The system not only significantly reduces labor costs and labor time, but also improves crop productivity, quality and uniformity. Practical experiments also demonstrate the scalability and high reliability of the model. In the future, the research team aims to integrate artificial intelligence more deeply in growth prediction and early detection of abnormalities, and develop energy optimization and automatic maintenance algorithms to improve overall operational efficiency.

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