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Research Article

Digital Twin Prototype in Unity 3D: Real-Time Greenhouse Monitoring and Control

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ARTICLE INFO

Article history:

Received 19 May 2025
Received in revised form 19 July 2025
Accepted 8 August 2025
Available online 30 September 2025

Keywords:

digital twin, embedded system, greenhouse monitoring, smart agriculture, Unity 3D.

Doi: 10.24012/dumf.1702307

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ABSTRACT

The increasing global population, combined with the impacts of climate change and global warming, has made the production of high-quality agricultural products at lower costs a critical necessity. Addressing these challenges requires leveraging emerging technologies. This study presents a prototype system that integrates digital twin technology into greenhouse farming. A physical greenhouse was equipped with a Raspberry Pi and various environmental sensors to collect real-time data. This data is visualized and managed through a Unity 3D-based digital twin, enabling automated control via rule-based decision logic. Monitored parameters include temperature, humidity, light intensity, and soil moisture, which dynamically trigger irrigation, ventilation, and lighting mechanisms. The system was tested over a seven-day period under different lighting scenarios. Results showed consistent system performance, demonstrating its viability for educational use and small-scale agricultural applications. Furthermore, the flexible architecture of the system suggests potential for future extension toward predictive modeling and adaptive control strategies.

Introduction

As the global population continues to grow, increasing agricultural production to meet rising food demand has become an inevitable necessity (Viana et al., 2022). In this context, both traditional farming methods and modern technological applications have been employed to make agriculture more efficient and sustainable. However, the cost and complexity of technological investments often limit the adoption of these innovations, particularly in developing countries.

Today, the agricultural sector is undergoing a transformation driven by the integration of technological innovations. This transformation, particularly through the convergence of digital twin technology and smart farming practices, enables significant progress in increasing productivity, reducing costs, and achieving sustainability goals. A digital twin is a virtual representation of a physical entity (Cor et al., 2021; Junfang et al., 2024). Continuously updated through real-time data streams, it provides a dynamic simulation of the physical environment. This technology serves as a powerful tool in agriculture for reducing environmental impact, optimizing resource use, and enabling real-time monitoring of field conditions (Jose et al., 2024; Gomes, 2023).

Agriculture and forestry face complex challenges, including increasing food demand, land scarcity, the effects of climate change, and loss of biodiversity (Moreno et al., 2024). Digital technologies play a critical role in addressing these challenges by offering solutions for enhanced productivity and sustainable resource management (Silveira et al., 2023). Through smart farming, technologies such as sensors, artificial intelligence, and big data analytics are employed to monitor field conditions and optimize agricultural operations (Nipuna et al., 2022). These technologies provide farmers with a wide range of data—from soil moisture to plant health. When integrated with digital twins, this data is visualized in real time within a virtual platform, making agricultural management more interactive, data-driven, and precise (Warren and Thomas, 2023; Pajpach et al., 2022; Zhang et al., 2023).

Since the introduction of the Digital Twin (DT) concept by Grieves, it has been applied across diverse domains including aerospace, automotive, manufacturing, construction, real estate, healthcare, education, and agriculture (Attaran and Celik, 2023; Chamara et al., 2022; Li et al., 2022; Pajpach et al., 2022; Sun et al., 2022). A growing body of research has focused on agricultural digitalization through advanced technologies (Pylianidis et al., 2021; Delgado et al., 2019; Purcell and Neubauer, 2023;

Verdouw et al., 2021; Nasirahmadi and Hensel, 2022). Digital twin technology shows great promise in providing optimal growth conditions for plants and in promoting sustainable development through more efficient energy use (Zihua et al., 2023; Roger et al., 2022; Jiayao et al., 2023). For example, the study by Alves et al. (2023) demonstrated the potential of digital twins to improve agricultural operations and reduce water consumption by enabling real-time data processing and testing of irrigation strategies. Isied et al. (2022) proposed a genomic-driven digital twin framework to optimize the design and energy management of agrophotovoltaic greenhouse systems, aiming to achieve a balance between plant growth and energy production. Liu et al. (2023) presented methods for developing sustainable plant factories using digital twin technology to support smart agriculture through continuous data flow.

This study proposes a greenhouse digital twin prototype developed in the Unity 3D environment and synchronized with physical sensors operating on a Raspberry Pi. Unity was selected due to its support for interactive 3D environments, suitability for scenario testing, and compatibility with real-time data streams (Unity, 2024). These features provide significant advantages for both educational use and user-centered monitoring systems.

The contribution of this study is not limited to a technical implementation; it also addresses the methodological challenges of achieving real-time synchronization between a physical greenhouse and its digital counterpart. The developed system goes beyond simple monitoring and data collection by offering a dynamic interaction layer that enables behavior modeling, user interaction, and decision-support mechanisms.

The Raspberry Pi, defined as a single-board computer equipped with ARM-based processors, offers the ability to interface with various external components through its general-purpose input/output (GPIO) pins (Raspberry Pi, 2024). These characteristics have made it widely used in fields such as computer science education, robotics, and digital prototyping.

In this study, the Raspberry Pi collects environmental data through sensors placed inside the greenhouse to monitor light, relative humidity, temperature, soil moisture, and air quality. This data is used to observe plant growth conditions and adjust factors such as lighting, irrigation, or ventilation as needed. The Unity 3D-based digital twin platform not only visualizes this data, but also provides an interactive virtual environment that responds to environmental changes in real time, maintaining synchronization with the physical greenhouse. The system integrates visualization, monitoring, and rule-based control processes in a unified architecture.

Section 2 details the project's methodology and research techniques; Section 3 provides a comprehensive overview of the implementation and testing processes; and Section 4 presents the results and discusses their implications.

Methodology

This study involves the development of an integrated, digital twin-supported system for monitoring and managing environmental conditions within a greenhouse setting. The system establishes real-time synchronization by enabling bidirectional data communication and control mechanisms between a physical greenhouse prototype and its digital representation. In addition to automated control, the architecture is designed to function as a basic decision support system by evaluating sensor data in real time and triggering rule-based responses. The main objective is to continuously monitor environmental variables such as temperature, relative humidity, soil moisture, air quality, and light intensity, and to manage microclimate conditions through rule-based automated responses derived from these data.

The study consists of three main components: (i) the setup of the greenhouse prototype and sensor integration, (ii) the digital twin environment developed on the Unity platform, and (iii) the bidirectional data communication and synchronization structure.

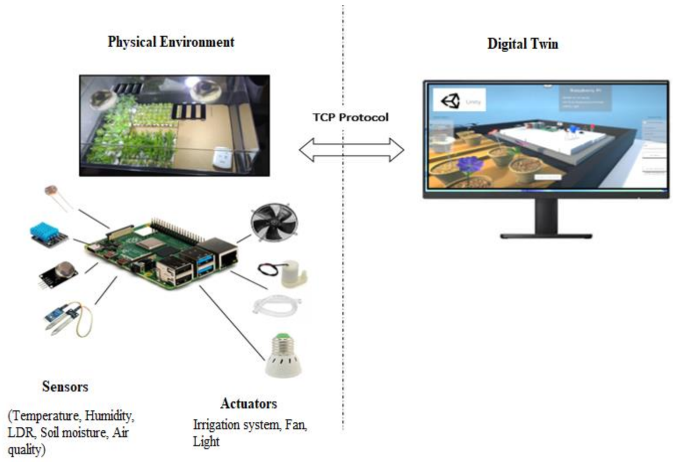

Figure 1. General architecture of the system.

Figure 1 illustrates the overall system architecture that forms the backbone of the proposed digital twin-supported greenhouse monitoring system. The left side of the diagram represents the physical environment, consisting of a Raspberry Pi connected to various environmental sensors (for temperature, humidity, soil moisture, light intensity, and air quality) and actuators (including a fan, light, and irrigation system). These components enable real-time data collection, environmental control, and data-driven decision making. The right side shows the digital twin developed in the Unity 3D environment, which mirrors the physical greenhouse and supports user interaction, behavior modeling, and scenario testing. Bidirectional data communication between the physical and virtual systems is provided through the TCP protocol, enabling synchronized operation, visualization and rule-based control decisions, and forms the basis of the system's decision support function.

Table 1. Types of sensors used and their purposes

	Sensor name	Features	Usage purpose
Temperature sensor	DHT11	- Measurement range: 0-50°C - Accuracy: ±2°C	Used to monitor temperature levels indoors.
Humidity sensor	DHT11	- Measurement range: 20-90% RH - Accuracy: ±5% RH	Used to monitor humidity levels indoors.
Light sensor	LDR	- Resistance varies with light exposure - High resistance in low light, low resistance in high light	Used to measure light levels and for applications dependent on daylight.
Air quality measurement sensor	MQ-135	- Detectable gases: NH3, NOx, alcohol, benzene, smoke - High sensitivity and fast response time	Used to measure environmental air quality and detect hazardous gases.
Soil moisture sensor	FC-28	- Measurement range: Typically from dry to wet soil -Output: Digital (High/Low) and Analog voltage that varies with moisture level	Used to monitor soil moisture levels to optimize irrigation in gardening and agriculture.

Greenhouse Prototype Setup and Sensor Integration

In this study, a small-scale greenhouse prototype was constructed, and various environmental factors such as soil moisture, relative humidity, air quality, temperature, and light intensity were measured using sensors configured on a Raspberry Pi. The types of sensors used and their corresponding purposes are presented in Table 1.

he FC-28 soil moisture sensor used in this study was configured to automatically trigger irrigation when soil moisture levels fall below a predefined threshold. This sensor provides both analog and digital outputs, with the digital mode selected for the current implementation. In digital mode, the output is either 0 or 1, depending on whether the soil moisture is below or above the user-defined threshold set via a built-in potentiometer. If the soil moisture level falls below the threshold, the sensor outputs a low signal (0), indicating insufficient moisture and the need for irrigation.

Monitoring environmental conditions such as temperature, relative humidity, and air quality inside the greenhouse is critical for maintaining optimal conditions for plant growth. When these factors exceed predefined thresholds, integrated ventilation systems are automatically activated. These systems operate to maintain environmental variables within ideal ranges. For instance, if the internal temperature or humidity is too high, or if air quality drops below acceptable levels, ventilation fans are automatically triggered. This process helps stabilize the internal environment, allowing plants to grow healthily without stress.

In addition, LDR (Light Dependent Resistor) sensors were used to measure light intensity within the greenhouse. These sensors detect changes in resistance based on ambient light levels. When light intensity falls below a specified threshold—potentially affecting plant development—supplemental light sources (LEDs) are automatically activated based on the input from the LDR sensors. This ensures that optimal lighting conditions are maintained inside the greenhouse, creating an ideal environment for plant growth while also optimizing energy consumption.

Finally, the physical greenhouse environment that houses all the technological components described above is shown in Figure 2. Through this integrated system, environmental variables within the greenhouse are continuously monitored and appropriate interventions are made when necessary.

Figure 2. Greenhouse prototype

Development of the digital twin environment

The digital twin environment developed on the Unity platform represents a virtual counterpart of the physical greenhouse prototype. Through this interface, users can monitor real-time environmental conditions, observe system responses, and conduct scenario-based experiments. Unity not only provides a visual representation but also processes real-time data streams to run a synchronized simulation that reflects the physical system within the virtual environment.

The system operates through bidirectional communication established between Unity's TCP client and the Raspberry Pi's TCP server. The Raspberry Pi collects environmental sensor data every 2 seconds and transmits it to Unity in JSON format. The Unity application processes this incoming data, visualizes it on the interface, and, if necessary, generates and sends control commands back to the Raspberry Pi. This continuous exchange ensures real-time synchronization between the digital twin environment and the physical greenhouse system. The digital twin scene shown in Figure 3 is an example of this interactive simulation.

Figure 3. Interactive digital twin scene developed in Unity 3D for real-time greenhouse monitoring and control

Data Communication and Synchronization

At this stage, bidirectional data communication is established between a TCP server running on the Raspberry Pi and a TCP client configured within the Unity environment. The Raspberry Pi is configured as a TCP server and periodically transmits sensor data representing environmental parameters—such as temperature, humidity, light intensity, and air quality—to the digital twin environment. The data are formatted in JSON and sent to the Unity application, where they are processed. Based on the processed data, Unity generates control commands that are sent back to the Raspberry Pi via the TCP client. The Raspberry Pi then interprets these commands and converts them into physical output signals to activate relevant hardware components (e.g., fan, LED, irrigation system).

To better illustrate this interaction, a flow diagram showing the step-by-step data exchange and communication between system components is presented in Figure 4.

Figure 5 displays the latest improvements made to the user interface of the digital scene designed in Unity. These interface enhancements simplify system usability and improve the accuracy and realism of the virtual simulation of the physical environment. The improvements also help users better understand the system while supporting seamless and effective data exchange between the physical and digital domains.

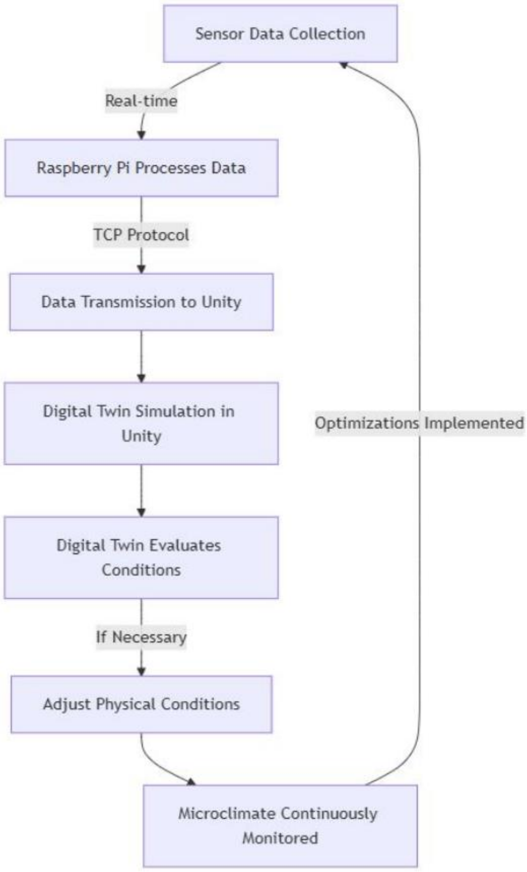

Figure 4. Bidirectional data flow between physical and virtual systems

The system is primarily designed to operate autonomously based on environmental parameters. However, the developed Unity interface also provides users with the ability to actively interact with the system. Through the graphical interface, users can dynamically modify threshold values for temperature, humidity, light, and soil moisture, thereby altering the system's behavior in real time. Additionally, users can manually trigger physical components such as the fan, LED light, or irrigation system, allowing for the testing of different scenarios.

This bidirectional control mechanism transforms the digital twin from a passive visualization tool into an interactive experimentation platform. Such flexibility is particularly valuable for educational and research purposes, as it not only allows users to observe the system's behavior visually but also to intervene directly and immediately observe the effects. This capability enables the system to be adapted to various user profiles—such as students, engineers, and farmers—and enhances its potential as a learning and development tool.

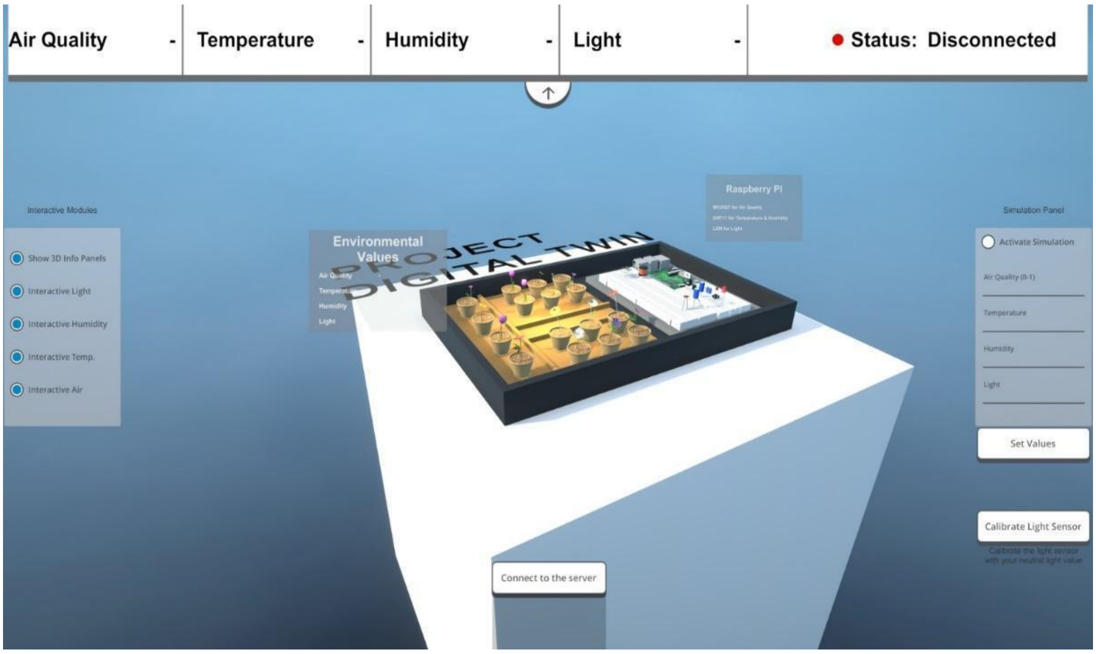

Figure 5. Unity digital twin interface with user control functions

Implementation and testing processes

In this study, the simulation and management of the environmental parameters of the physical greenhouse has been successfully realized through a digital twin developed on the Unity platform. The research is based on one-day data obtained in June conditions in Turkey, which were used to evaluate the effectiveness of the greenhouse lighting control mechanisms. In particular, during time periods of low natural light intensity, such as early morning and late evening, the LEDs were automatically switched on based on high readings from the LDR sensor. The graph in Figure 6 shows how the readings from the LDR sensor change throughout the day and how the LEDs are activated when they are above the threshold value set at 800.

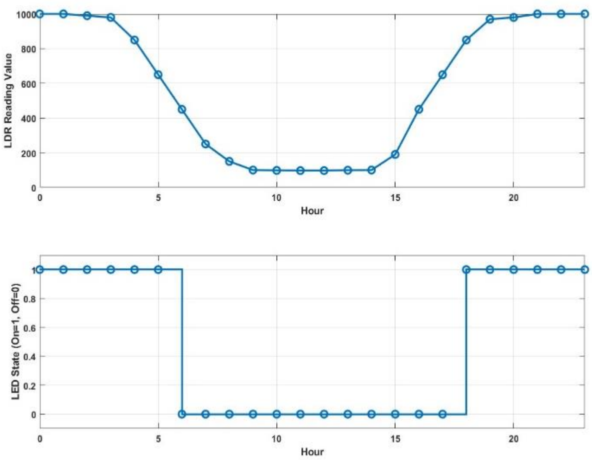

Figure 6. LDR Sensor Readings and LED Activation Based on Light Intensity Throughout the Day

This successfully demonstrates the capacity of the LEDs to provide the required light level for the plants, especially between 00:00 and 06:00 at night and after 20:00 in the evening.

In Figure 7, Unity 3D visually displays the moments when the LEDs are active in the digital twin environment. This simulation screen provides an interactive experience for the user to observe in real time when the LEDs are activated in the digital twin and the effect of this situation on the plants inside the greenhouse.

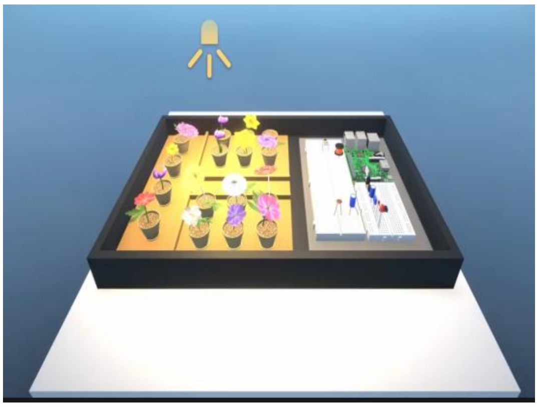

Figure 7. Real-Time LED Activation in the Digital Twin Environment Displayed in Unity 3D

In this study, data from temperature, relative humidity and air quality sensors were analyzed every hour for 24 hours and these data are presented in Figure 8. During the day, the temperature generally tended to increase, while the humidity showed a reverse trend and an increase was observed during the night hours. Air quality remained constant throughout the day. In the study, air quality is defined as a digital variable, where ‘0’ indicates good air quality and ‘1’ indicates poor air quality. The threshold values were used to analyses the changes in temperature and humidity.

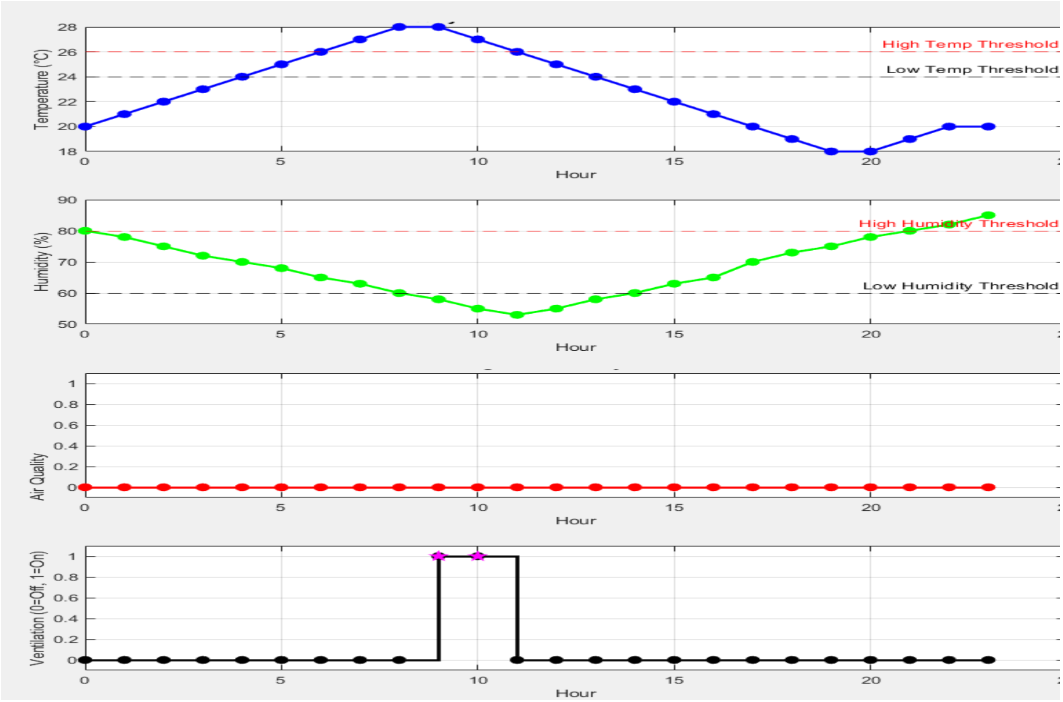

Figure 8. Hourly variation of temperature, humidity, air quality, and ventilation status over a 24-hour period

The low threshold value for temperature was set as 24°C and the high threshold value was set as 26°C. For humidity, the low threshold value was defined as 60% and the high threshold value was defined as 80%. As can be seen in Figure 8, the ventilation system was activated during the hours when the temperature and humidity threshold values exceeded the specified limits at the same time. The four sub-graphs in Figure 8 show the following: The first graph shows the temperature variations and their high and low threshold values. The second graph presents the relative humidity variations and the set high-low humidity limits. The third graph shows how the air quality changes in a digital form throughout the day. Here, an air quality of '0' represents a good condition, while '1' represents poor air quality. The fourth graph shows the activation status of the ventilation system. Ventilation is only activated when the temperature is above the high threshold and the humidity is below the low threshold. The purple markers highlight the times when these conditions are met and the ventilation is activated.

The measurements obtained from the soil moisture sensor show that the irrigation system is automatically activated and irrigation is performed for one minute for experimental purposes in case of moisture levels below the set threshold value.

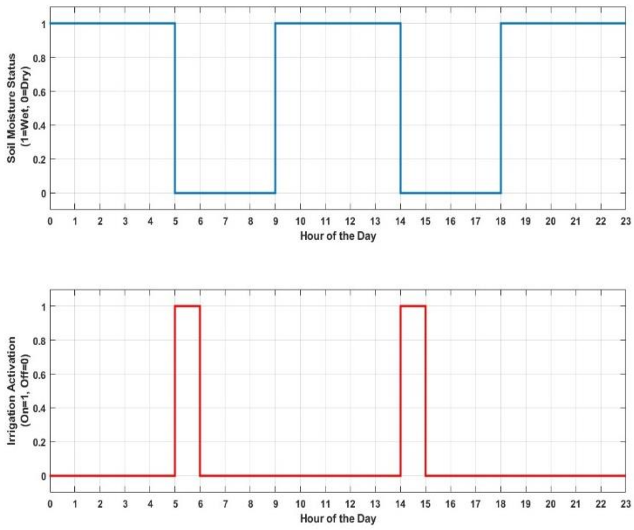

Figure 9. Irrigation System Activation Based on Soil Moisture Sensor Readings Below Threshold

Figure 9. visually presents the activation times of the irrigation system and how these activations are triggered when the moisture level falls below the threshold value. The irrigation system is activated as soon as the moisture level passes below the threshold value and remains activated for one minute, which is the specified experimental time, to maintain the moisture balance of the soil.

These control mechanisms, which are automatically triggered based on predefined sensor thresholds, demonstrate the system's functionality as a basic decision support system. By analyzing real-time environmental data and applying rule-based logic, the system can autonomously determine when and how to intervene, thus assisting in efficient greenhouse management.

Figure 10. Visualization of the Physical Greenhouse Environment and its Digital Twin

Finally, a visualization of the physical greenhouse environment and its digital twin is presented in Figure 10. Thanks to this integrated system, the variables inside the greenhouse are continuously monitored and interventions can be made when necessary.

Conclusions

This study presents the design and implementation of a real-time, interactive digital twin system developed on the Unity 3D platform for monitoring and managing environmental conditions in a greenhouse environment. The system processes real-time data from multiple sensors—including temperature, humidity, soil moisture, light intensity, and air quality—and simultaneously manages physical actuators such as fans, LEDs, and the irrigation system in both automatic and user-controlled modes.

Scenario-based experiments showed that the LEDs were automatically activated under low light conditions, the ventilation system was triggered when the temperature and humidity thresholds exceeded critical levels, and the irrigation system was activated when the soil moisture fell below a predefined limit. These applications indicate that the system effectively executes rule-based environmental control. Additionally, users were able to adjust threshold values dynamically and manually trigger physical components via the Unity interface, demonstrating that the system functions not only autonomously but also interactively.

The study presents a digital twin architecture that combines real-time environmental sensing, automated decision-making, and user-interactive control. The integration of a general-purpose game engine like Unity 3D with a physical greenhouse system in a synchronized and interactive manner offers a noteworthy example in terms of user experience, visualization capability, and educational usability. The system allows users to modify threshold values, perform scenario-based interventions, and observe the results in both the digital and physical environments simultaneously. Through its real-time sensor evaluation and rule-based control logic, the system also operates as a basic decision support system, assisting users in making timely and informed decisions for greenhouse management.

Thanks to its reusable, low-cost, and education-oriented design, the developed platform is not only a functional prototype but also a tool with potential for teaching, experimentation, and advanced research. The study demonstrates the feasibility of establishing an interactive closed-loop between simulation and the physical environment, and it offers a foundation that can be extended with AI-based decision support systems, cloud-supported data analytics, and large-scale agricultural applications.

Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared.

There is no conflict of interest with any person / institution in the article prepared.

Authors' Contributions

The conceptualization and design of the study were carried out by Ayçiçek and Özcan. Data collection was conducted by Ayçiçek and Özcan. Data analysis and interpretation were performed by Bal, Akpınar, and Yayla. The manuscript was drafted by Bal, and critical revisions were made by Bal, Akpınar, and Yayla.

Acknowledgment

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