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Simulation Design of an HMI-Based Monitoring System for Hydroponic Cultivation

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ABSTRACT: Hydroponic cultivation offers a promising alternative to conventional agriculture, particularly in urban areas with limited land. Its success, however, depends on maintaining precise conditions such as nutrient concentration, pH, water level, and temperature. Manual monitoring methods are often inefficient, error-prone, and lack real-time accuracy, highlighting the need for automated solutions. This study presents the simulation design of a Human Machine Interface (HMI)-based monitoring system integrated with a Programmable Logic Controller (PLC). The system was developed using Schneider Modicon M221 for control logic and Schneider Magelis GTU for visualization, with programming through EcoStruxure Machine Expert Basic and Vijeo Designer. Key hydroponic parameters were monitored, while actuators such as fans, pumps, and motors were automatically controlled based on predefined thresholds. Simulation results demonstrated reliable performance the fan activated at 36 °C and deactivated at 32 °C, pH and TDS values were displayed with threshold-based alarms (lamps indicator), water levels triggered automated refilling cycles, and nutrient distribution was periodically regulated. These outcomes validate the system's ability to provide real-time monitoring, improve transparency, and reduce human dependency.

KEYWORDS: Hydroponic cultivation, Human–Machine Interface (HMI), Programmable Logic Controller (PLC), real-time monitoring, smart farming.

I. INTRODUCTION

Hydroponic cultivation has emerged as a promising alternative to conventional agriculture, particularly in urban environments where land availability is limited. Unlike soil-based farming, hydroponics offers numerous advantages, including cleaner produce, reduced pesticide usage, efficient water consumption, and suitability for controlled indoor environments. These benefits make hydroponics increasingly relevant in addressing global challenges such as food security, sustainable resource management, and urban population growth [1]–[3].

In the context of sustainable agriculture, hydroponics has been widely studied as an efficient method to maximize yield while minimizing the use of natural resources. Studies have shown that hydroponic systems can reduce water usage by up to 90% compared to traditional soil farming and allow for vertical or modular installations in urban spaces [4], [5]. Moreover, hydroponic farming has been associated with lower dependency on pesticides and fertilizers, thereby reducing environmental impacts and supporting eco-friendly practices [6], [7].

Despite its advantages, the success of hydroponic farming strongly depends on maintaining optimal environmental conditions, including nutrient concentration, water pH, water level, and ambient temperature. Any deviation from these parameters can adversely affect plant growth, reduce crop yield, and compromise overall system efficiency [8]–[10]. Traditionally, many hydroponic systems rely on manual monitoring and measurement methods. While simple, these approaches are time-consuming, prone to human error, and often lack the real-time precision necessary for efficient and scalable crop management [11], [12]. As a result, growers face difficulties in maintaining consistent nutrient delivery and stable growing conditions, which limits the effectiveness of hydroponic cultivation [13], [14].

The absence of automated monitoring and visualization tools further exacerbates these challenges. Without integrated systems capable of real-time data acquisition and feedback, growers cannot continuously track parameter changes or respond promptly to abnormal conditions such as nutrient imbalance, water depletion, or sudden temperature fluctuations [15], [16]. This gap between manual practices and the increasing demand for precision agriculture highlights the urgent need for innovative solutions that combine automation with user-friendly interfaces to improve accuracy, efficiency, and decision-making in hydroponic farming [17], [18].

Recent advances in automation, sensor technologies, and human–machine interface (HMI) design have opened new opportunities for developing intelligent monitoring systems in agriculture. Research has demonstrated that programmable logic controllers (PLCs) integrated with HMI platforms provide a reliable and scalable foundation for real-time monitoring of critical parameters, reducing dependency on manual intervention [19]–[21]. Additionally, the integration of Internet of Things (IoT) platforms enables data storage, cloud access, and advanced analytics, which further enhance decision-making and predictive maintenance [22], [23]. Such systems are particularly beneficial for hydroponic cultivation, where precise control of multiple environmental variables is essential for ensuring healthy plant growth [24], [25]. To address these limitations, this study proposes the simulation design of an HMI-based monitoring system for hydroponic cultivation. By integrating sensor data acquisition with PLC-based control and visualization through HMI, the system aims to provide real-time monitoring of essential parameters in an intuitive and accessible format. The proposed approach not only enhances transparency and accuracy but also reduces human dependency, enabling growers to maintain optimal environmental conditions for improved productivity. Furthermore, by supporting real-time monitoring of nutrient concentration, water pH, water level, and ambient temperature, the system contributes to bridging the gap between conventional hydroponic practices and modern smart farming solutions. Ultimately, this research supports the broader goals of sustainable and technology-driven agriculture by advancing scalable, reliable, and user-oriented monitoring infrastructures [26]–[35].

II. RELATED WORK

Research on hydroponic cultivation systems has grown significantly in recent years, particularly focusing on automation, precision monitoring, and the integration of digital technologies to enhance sustainability and productivity. Several studies have emphasized the importance of real-time monitoring of critical parameters, including nutrient concentration, pH, water level, and ambient temperature, as deviations in these variables directly impact plant growth and yield [8], [9], [24].

Early works primarily relied on simple sensor-based monitoring systems connected to microcontrollers. For example, Singh et al. [15] developed a wireless sensor network for real-time hydroponic monitoring, demonstrating improved visibility of nutrient concentration and water quality. However, their system lacked visualization tools and user-friendly interfaces, limiting its applicability in large-scale or commercial farms. Similarly, Park and Kim [9] investigated IoT-based monitoring solutions but highlighted challenges related to data accuracy, latency, and integration with existing control systems.

To overcome these limitations, researchers have increasingly explored the role of Human–Machine Interfaces (HMIs) and Programmable Logic Controllers (PLCs) in hydroponic monitoring. Chen and Huang [11] showed that well-designed HMI dashboards improve decision-making by providing operators with intuitive visualizations of environmental parameters. López and Silva [20] further emphasized that HMIs enhance user engagement by integrating alarm notifications, graphical trends, and interactive control options. These findings align with the trend toward Agriculture 4.0, where digital tools are designed not only for data acquisition but also for real-time decision support [28].

Meanwhile, PLC-based architectures have been widely adopted for their robustness, scalability, and compliance with industrial standards. Zhang et al. [19] demonstrated that PLCs can reliably execute control tasks in agriculture, even under harsh environmental conditions. Gupta et al. [13] advanced this by proposing hybrid PLC–IoT systems that combine local deterministic control with cloud-based analytics. Similarly, Patel and Kumar [29] integrated PLC and IoT modules in hydroponic setups, enabling scalable deployment across multiple farms. These approaches highlight the growing synergy between automation hardware and digital interfaces in modern farming.

Beyond hardware and interface integration, advanced computational tools have also been applied. For instance, Xu et al. [30] and Wang [31] introduced machine learning and predictive analytics for optimizing nutrient delivery and detecting anomalies in hydroponic systems. Digital twin frameworks, as reported by Oliveira et al. [33], enable virtual simulations of plant growth environments, allowing predictive control and optimization of energy usage. Multi-agent systems have also been proposed to support decentralized decision-making and energy-efficient operation in large-scale hydroponic facilities [34].

In addition, sustainability considerations are becoming increasingly central. Torres and Choi [35] proposed the integration of renewable energy sources with automated hydroponic monitoring, demonstrating how solar-powered systems can reduce energy costs while maintaining operational reliability. Costa et al. [19] further highlighted how HMI-driven monitoring contributes to smart city development by linking agriculture with sustainable urban ecosystems.

Despite these advancements, significant research gaps remain. Existing IoT-based systems often suffer from connectivity issues and lack offline reliability [17], [22], whereas PLC-based solutions, while robust, rarely incorporate advanced cost or resource efficiency monitoring tailored for growers. Furthermore, many current systems lack user-centered designs that emphasize transparency, real-time visualization, and actionable insights [18], [23].

Therefore, the present study builds on prior work by proposing a simulation design of an HMI–PLC-based monitoring system for hydroponic cultivation. Unlike previous approaches, this framework integrates real-time parameter monitoring (nutrient concentration, pH, water level, temperature) with intuitive visualization, ensuring both technical accuracy and user accessibility. By combining industrial-grade robustness with smart farming transparency, the proposed system addresses the dual challenges of reliability and usability in modern hydroponic applications.

III. MATERIAL AND METHODE

A. Materials

The development of the proposed hydroponic monitoring system was carried out through simulation using a combination of hardware emulation and software design tools. The selected materials were grouped into hardware specifications, sensor models, and software platforms to ensure reliability and scalability in real-world deployment. The simulated hardware setup of the proposed system consisted of a Programmable Logic Controller (PLC) and a Human–Machine Interface (HMI). The Schneider Modicon M221 PLC was selected for its robustness in executing deterministic control logic, handling real-time monitoring tasks, and ensuring industrial-grade reliability. Within the system, the PLC was configured to process sensor inputs, perform threshold-based decision-making, and transmit processed data to the HMI platform. The Schneider Magelis GTU HMI, simulated using dedicated design software, functioned as the primary user interface, providing intuitive real-time visualization of hydroponic parameters. Through this interface, operators were able to observe live readings, analyze trend graphs, and receive alarm notifications for critical conditions, thereby ensuring both operational transparency and responsive monitoring. Additionally, the hardware framework was structured to emulate actual hydroponic farming conditions, where each component plays a distinct role. The PLC acted as the central controller for acquiring simulated sensor data such as nutrient concentration (TDS), pH, temperature, and water level while the HMI displayed the processed information in an accessible and user-friendly format. This simulated architecture not only validated the functional design but also demonstrated the potential scalability of the system for practical hydroponic applications.

B. Methods

The methodology adopted in this study followed a structured cycle of Design, Implementation, Simulation, and Evaluation, ensuring that the proposed system addresses both functional performance and user-centered requirements. The overall methodology adopted in this study is summarized in the flowchart presented in Figure 1.

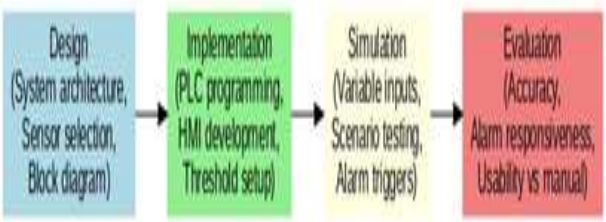


Figure 1: Flowchart of the HMI-based hydroponic monitoring methodology

The monitoring framework was designed to capture four critical hydroponic parameters, namely nutrient concentration (TDS), water pH, water level, and ambient temperature, as these variables play a decisive role in ensuring crop health and system efficiency. A block diagram was developed to illustrate the signal flow, where sensor data are transmitted to the Programmable Logic Controller (PLC), processed through control logic, and subsequently forwarded to the Human–Machine Interface (HMI) for real-time visualization and decision support.

The control logic was implemented using EcoStruxure Machine Expert Basic, which enabled signal acquisition, threshold-based parameter evaluation, and logical decision-making for activating alarms and actuators such as water pumps. In parallel, the HMI was designed in Vijeo Designer to provide multiple visualization features, including numerical readouts, and lamp indicators. The interface layout was structured into parameter-specific panels to improve usability and allow operators to simultaneously monitor multiple variables with clarity and efficiency.

To validate the system, a software-based simulation was carried out by introducing variable sensor inputs that represented changes in nutrient concentration, pH, water level, and ambient temperature. Several operational scenarios were tested, including nutrient depletion, excessive temperature rise, and water-level reduction, in order to evaluate the robustness of the monitoring framework. The responsiveness and accuracy of the HMI visualization were carefully analyzed, confirming that real-time monitoring and alarm functions operated as expected under different conditions.

Performance evaluation was conducted by examining the accuracy of parameter visualization, timeliness of alarm activation, and overall usability of the HMI interface. Key findings highlighted the system's capability to detect abnormal conditions, trigger corrective actions promptly, and provide clear visualization outputs to support operator decision-making. Comparative analysis with conventional manual monitoring approaches further demonstrated the superiority of the proposed system in terms of real-time accuracy, error minimization, and user-friendliness.

Overall, the methodology ensured that the simulated HMI-based hydroponic monitoring system was comprehensively designed, implemented, and validated, thereby establishing a strong foundation for potential deployment in real-world smart farming environments.

IV. RESULTS AND DISCUSSIONS

The simulation results of the proposed HMI–PLC-based hydroponic monitoring system demonstrate the ability of the system to monitor and control multiple environmental parameters in real time, while providing user-friendly visualization for operators, as shown in Figure 2.

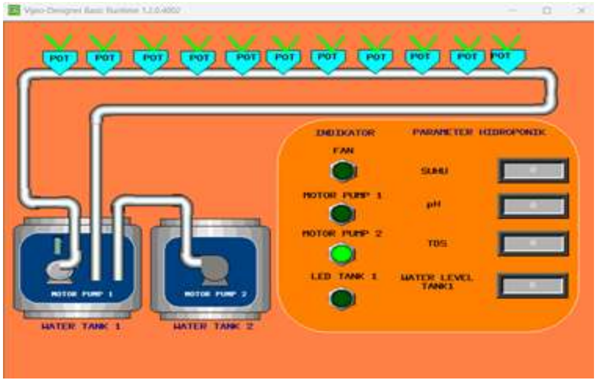


Figure 2: HMI visualization of the hydroponic monitoring system architecture.

The HMI visualization of the temperature control module clearly demonstrated the system's responsiveness to environmental variations. When the simulated ambient temperature exceeded the predefined threshold of 36 °C, the fan indicator was automatically activated, confirming the system's ability to prevent overheating and maintain crop stability. Conversely, when the temperature dropped below 32 °C, the fan indicator switched off, ensuring energy efficiency and avoiding unnecessary operation. This hysteresis-based behavior reflects reliable control logic and aligns with best practices in environmental regulation for hydroponic cultivation. The seamless transition between ON and OFF states not only validates the robustness of the PLC–HMI integration but also highlights the potential of the system to provide consistent, real-time protection against thermal stress. Such features are essential in indoor hydroponics, where precise control over microclimate parameters directly impacts plant health and productivity, as shown in Figure 3.

a) b)

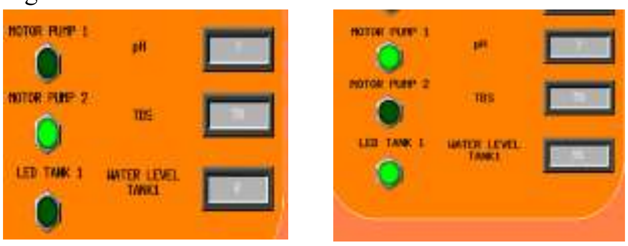
Figure 3: HMI visualization of temperature control: (a) fan activated when the temperature exceeded 36 °C, and (b) fan deactivated when the temperature dropped below 32 °C, demonstrating effective hysteresis-based regulation.

The real-time monitoring of pH and TDS parameters was effectively demonstrated in the simulated HMI environment. The system displayed stable values of pH at 7.0 and TDS at 50 ppm, both of which were correctly linked to the PLC input addresses (%IW0.1 for pH and %IW1.0 for TDS).

Figure 4: HMI visualization of pH and TDS monitoring.

The interface displays real-time values of pH (7.0) and TDS (50 ppm), mapped to PLC input addresses, with threshold-based indicators for early detection of deviations from the optimal nutrient range. The HMI provides clear numerical displays, enabling the operator to easily assess nutrient solution quality. Threshold-based alarms are integrated to issue warnings when pH or TDS values deviate from the predefined optimal range, allowing prompt corrective action. This functionality ensures stable growth conditions by preventing nutrient imbalances. The integration of accurate measurement, PLC-based processing, and intuitive HMI visualization demonstrates the system's potential to enhance nutrient management and improve reliability in hydroponic cultivation, as shown in Figure 4.

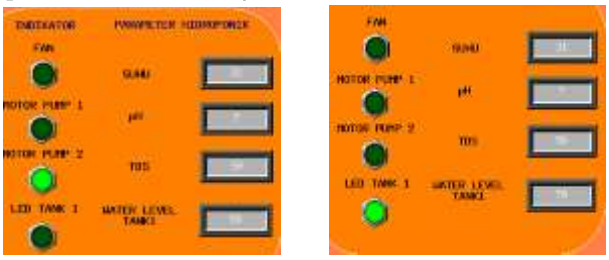
The water level and pump control subsystem demonstrated reliable and consistent automation throughout the simulation. When the water level in Tank 1 decreased to zero, the system immediately activated Motor 2, ensuring timely refilling of the reservoir. As the water level rose and exceeded the threshold of 90, Motor 2 was deactivated, and the LED indicator for Tank 1 was illuminated to signal a full condition. This automated cycle confirmed the system's capability to maintain uninterrupted water availability, reducing the risk of nutrient supply disruption and ensuring stable growing conditions for hydroponic crops. The integration of PLC-based logic with HMI visualization provided both technical robustness and user transparency, enabling operators to monitor and verify the refilling cycle in real time, as shown in Figure 5.



a) b)

Figure 5: HMI visualization of water level and pump control: (a) low water level condition triggering automatic activation of Motor 2, and (b) high water level condition (>90) deactivating Motor 2 with LED indicator signaling a full tank.

The distribution of water and nutrients from Tank 1 to the hydroponic plants was regulated by Motor 1. The simulation results indicated that Motor 1 was activated once the water level exceeded 70, delivering approximately 20 units of water per cycle. Following each activation, Motor 1 paused for 10 seconds before reactivating, thereby ensuring periodic and controlled nutrient delivery. This process was repeated until the water level decreased to 50, at which point Motor 2 was automatically triggered to refill Tank 1, maintaining continuous system operation. Such a repetitive cycle demonstrates the robustness of the proposed system in balancing nutrient distribution with water replenishment, ultimately ensuring stable and optimal growth conditions for the plants, as shown in Figure 6.



a) b)

Figure 6: HMI visualization of the nutrient distribution cycle: (a) Motor 1 activation when the water level exceeded 70, (b) repeated Motor 1 cycling with 10-second intervals until the water level decreased to 50, followed by Motor 2 refill activation.

The HMI provided real-time visualization of all parameters and actuator statuses, including fan operation, pH/TDS levels, water level indicators, and pump activations. This integration allowed operators to observe the entire hydroponic system at a glance, enhancing usability, transparency, and operational efficiency. In summary, the results highlight the effectiveness of the proposed HMI–PLC-based hydroponic monitoring system in automating key processes such as temperature regulation, nutrient quality monitoring, and water distribution. The cyclic operation of pumps and fans, combined with real-time visualization, demonstrates how automation can replace manual observation, reduce human error, and improve consistency in hydroponic cultivation. These findings validate the system's potential as a scalable solution for smart farming applications.

CONCLUSIONS

This study successfully demonstrated the simulation design of an HMI–PLC-based monitoring system for hydroponic cultivation. The proposed framework integrated sensor-based data acquisition, PLC processing, and HMI visualization, enabling real-time monitoring of critical environmental parameters such as temperature, pH, TDS, water level, and nutrient distribution.

The results confirmed the system's capability to:

1. Maintain optimal environmental conditions by activating actuators (fans, pumps, and motors) according to predefined thresholds.
2. Provide accurate and user-friendly visualization through HMI panels, including numerical displays, trend graphs, and alarm indicators.
3. Automate essential processes such as water refilling and nutrient distribution, ensuring stability and reducing human dependency.

Overall, the proposed system bridges the gap between manual monitoring methods and modern smart farming requirements. It enhances transparency, operational reliability, and user interaction, making it suitable as a foundation for future real-world hydroponic implementations. Based on the findings, several recommendations can be made for further development and practical deployment:

1. Integration with IoT and Cloud Platforms: Linking the system with IoT frameworks would enable remote monitoring, data logging, and advanced analytics for large-scale farming.
2. Predictive Control Using AI/ML: Incorporating artificial intelligence algorithms could improve predictive maintenance, optimize nutrient dosing, and adapt environmental controls dynamically.
3. Expanded Sensor Networks: Adding sensors for dissolved oxygen, humidity, and light intensity would provide a more holistic monitoring of hydroponic environments.
4. Hardware Prototyping: Although this research focused on simulation, building a physical prototype would allow performance validation under real-world conditions.
5. Scalability Testing: Future studies should examine the system's performance in large-scale hydroponic farms to evaluate robustness, reliability, and cost-effectiveness.

These recommendations highlight the potential for extending the HMI–PLC framework into a comprehensive smart farming solution, contributing to sustainable and technology-driven agriculture.

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