Design and Implementation of an Intelligent Environmental Monitoring System for Fruit and Vegetable Preservation Using Virtual Instrumentation

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Abstract: - The preservation of fruits and vegetables requires precise environmental control to prevent premature degradation caused by temperature and humidity variations. This paper presents the design and implementation of an intelligent environmental monitoring system using virtual instrumentation techniques. The system integrates temperature and relative humidity sensors, a data acquisition interface, and a LabVIEW-based software platform to provide continuous environmental supervision. The software architecture consists of a Front Panel for real-time visualization and operator interaction, and a Block Diagram implementing acquisition, signal processing, logical evaluation, and decision-support functionality. The system continuously compares environmental parameters against predefined thresholds and provides visual warnings and corrective recommendations when deviations occur. Experimental evaluation confirms reliable performance, accurate monitoring, and effective user interaction. The proposed system provides a scalable and efficient engineering solution for fruit and vegetable storage monitoring and preservation.

Key-Words: - Environmental monitoring, virtual instrumentation, LabVIEW, fruit preservation, humidity sensing, temperature sensing, data acquisition systems

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1 Introduction

Fruits and vegetables are perishable biological products, whose post-harvest quality and shelf life depend strongly on environmental storage conditions [1]. Temperature and relative humidity directly influence respiration rate, enzymatic activity, microbial growth, and moisture loss. Improper storage conditions accelerate physiological degradation processes, resulting in reduced freshness, loss of nutritional value, and increased economic losses throughout the supply chain [2], [3].

From an engineering perspective, maintaining optimal environmental conditions requires continuous monitoring and rapid detection of deviations [4]. Conventional monitoring approaches rely on standalone instruments or manual inspection, which lack automation, real-time analysis, and integrated operator guidance. These limitations increase the probability of delayed response to environmental fluctuations, negatively affecting storage efficiency [5], [6].

Recent advances in sensor technology and virtual instrumentation platforms have enabled the development of intelligent monitoring systems, capable of continuous supervision and automated evaluation [7]. Virtual instrumentation environments, such as LabVIEW, allow the implementation of graphical software systems that integrate sensor acquisition, data processing, visualization, and decision-making into a unified platform.

The objective of this work is to design and implement a real-time environmental monitoring system specifically intended for fruit and vegetable storage applications. The system integrates environmental sensors, a data acquisition interface, and graphical programming software to provide continuous monitoring, threshold-based evaluation, and operator guidance. The engineering design emphasizes reliability, modularity, scalability, and ease of use [8], [9].

2 System Architecture and Hardware Implementation

The developed system consists of three primary hardware components: environmental sensors, a data acquisition interface, and a computing unit. These components operate together to acquire environmental data, convert physical parameters into electrical signals, and transmit information to the software environment for processing and visualization.

Temperature sensing is implemented using an electronic temperature sensor capable of converting ambient temperature into an electrical signal proportional to the measured value. The sensor operates based on semiconductor temperature-dependent electrical characteristics, ensuring high sensitivity and measurement accuracy. Accurate temperature measurement is critical because even small deviations can significantly affect fruit and vegetable respiration rates and preservation duration.

Relative humidity sensing is implemented using a humidity sensor that detects the moisture content of the surrounding air. The sensor operates based on capacitive or resistive measurement principles, where the electrical properties of the sensing element vary according to atmospheric moisture levels. Maintaining proper humidity levels is essential to prevent dehydration or condensation, both of which can accelerate spoilage.

The analog signals produced by the sensors are transmitted to the data acquisition interface, which performs signal conditioning and analog-to-digital conversion. Signal conditioning ensures proper voltage levels, noise filtering, and signal stability before digital conversion. The analog-to-digital converter transforms continuous electrical signals into digital values that can be processed by the software.

Sampling rate selection is an important engineering parameter that determines how frequently environmental measurements are acquired. The selected sampling rate ensures adequate monitoring resolution while maintaining efficient computational performance. Proper grounding and electrical isolation techniques were implemented to minimize noise and ensure signal integrity.

The hardware system was designed for continuous operation within storage environments. The modular architecture allows future expansion through integration of additional sensors such as gas concentration sensors, airflow sensors, or automated control actuators.

3 System Design and Architecture

The developed virtual instrument consists of two primary components: The Front Panel, which provides the graphical user interface and system visualization, and the Block Diagram, which implements the internal functional logic, data acquisition, signal processing, and decision-making mechanisms [10].

Figure 1 illustrates the Front Panel of the developed monitoring system. The Front Panel serves as the human–machine interface and enables real-time monitoring of environmental parameters within the fruit and vegetable storage environment. It includes numerical indicators displaying temperature and relative humidity values, acquired from the sensors through the data acquisition interface. These indicators are continuously updated within the execution loop, ensuring real-time visualization of environmental conditions.

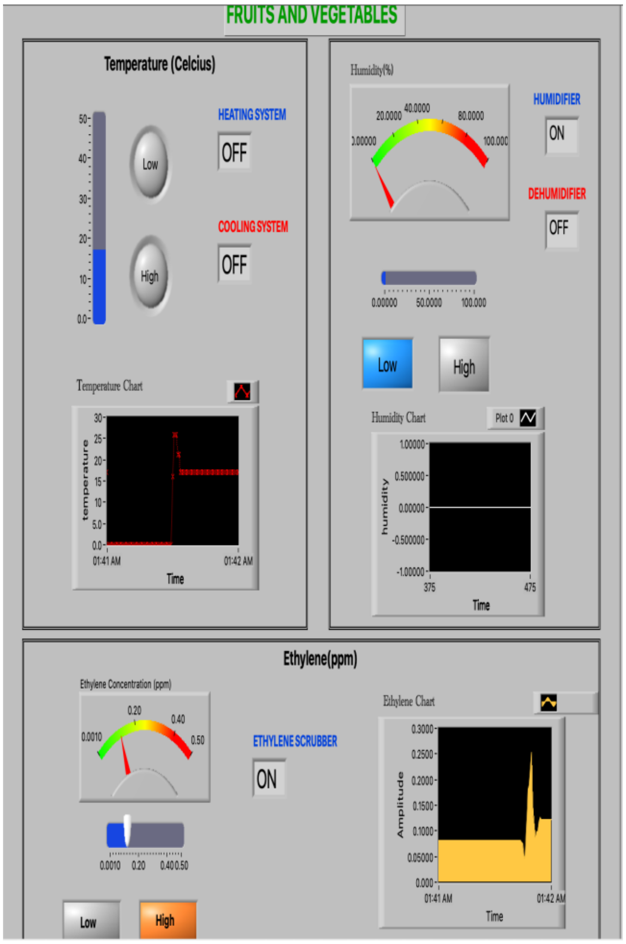

Fig. 1: Front Panel

From an engineering perspective, the numerical indicators function as calibrated display modules that present sensor measurements in engineering units. The temperature indicator displays values in degrees Celsius, while the humidity indicator displays values in percentage relative humidity. These indicators are directly connected to the acquisition and scaling functions in the Block Diagram, ensuring measurement accuracy and synchronization between acquisition and display.

The Front Panel additionally incorporates continuous visual supervision through dynamically updated monitoring elements. The temperature and humidity indicators operate synchronously with the acquisition loop, allowing operators to observe environmental trends in real time and rapidly identify abnormal fluctuations. The update frequency was selected to balance visualization smoothness and computational efficiency, ensuring stable operation during continuous monitoring.

From an operational perspective, the Front Panel acts as an intelligent supervisory interface rather than a simple display instrument. The arrangement of indicators follows a hierarchical visualization strategy in which critical alarm conditions are visually prioritized through Boolean warning LEDs and advisory text messages. This design minimizes operator reaction time and improves decision-making efficiency during environmental disturbances.

Furthermore, the interface architecture supports future integration of historical trend graphs, statistical indicators, and predictive analytics modules. Such extensions would enable long-term storage analysis and early detection of environmental instability patterns, affecting fruit and vegetable preservation performance.

In addition to numerical indicators, the Front Panel incorporates Boolean LED indicators that represent system status conditions. These LEDs function as visual alarms and are activated when environmental parameters exceed predefined threshold values. The use of Boolean indicators provides immediate visual feedback, without requiring interpretation of numerical values, improving operator response time and reducing the risk of delayed intervention.

The Front Panel also includes text-based status messages that provide operator guidance. These messages are dynamically generated by the logical decision structures in the Block Diagram. When environmental conditions deviate from acceptable limits, the system displays advisory messages, recommending corrective actions, such as reducing temperature or adjusting humidity levels. This functionality transforms the system into an active decision-support interface rather than a passive monitoring instrument.

The Front Panel is designed according to engineering ergonomics principles, ensuring clarity, intuitive operation, and efficient visualization. The graphical layout minimizes cognitive load and allows operators to quickly assess system status.

Figure 2 illustrates the Block Diagram of the developed virtual instrument, which represents the functional core of the monitoring system.

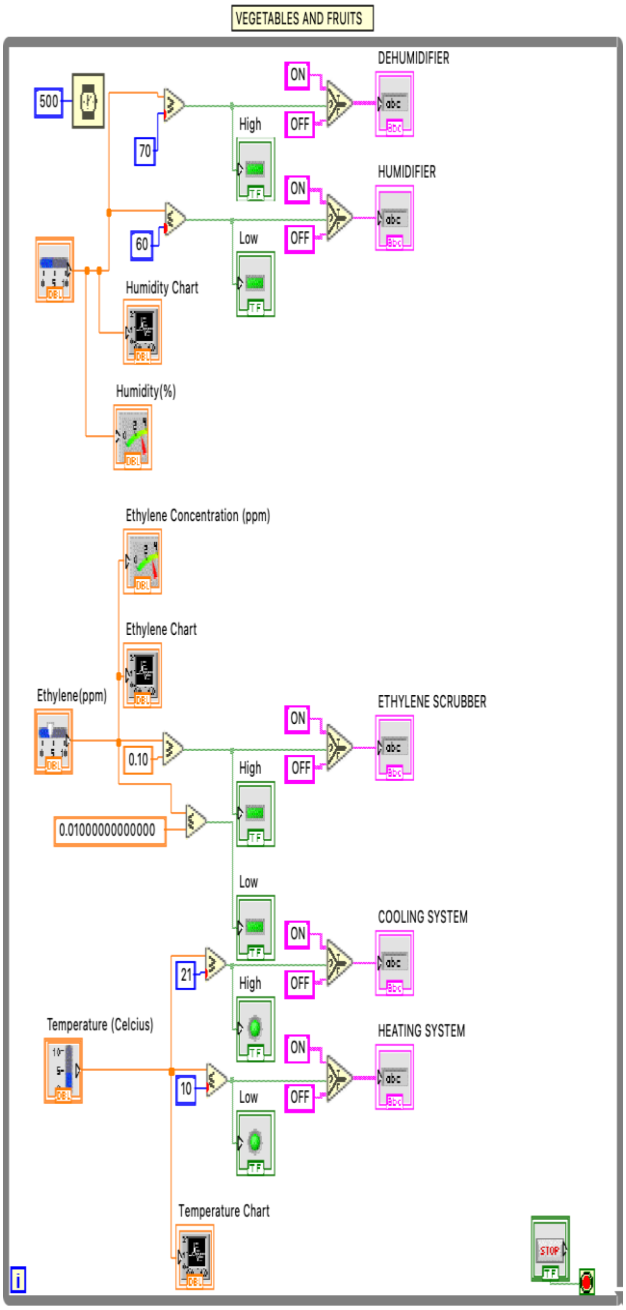

Fig. 2: Block Diagram

The Block Diagram implements the dataflow programming architecture, responsible for acquisition, signal processing, logical evaluation, and output visualization.

The acquisition stage consists of input nodes that receive sensor data through the data acquisition interface. These input nodes serve as the interface between hardware and software, transferring digital sensor values into the LabVIEW environment.

Following acquisition, signal conditioning and scaling functions convert raw sensor data into engineering units. These functions implement linear conversion algorithms that map input voltage values to corresponding temperature and humidity values.

Calibration constants are applied during this stage to ensure measurement accuracy and correct scaling.

The processed signals are then transmitted to comparison blocks, which implement threshold detection algorithms. These comparison blocks continuously evaluate sensor measurements against predefined minimum and maximum limits, corresponding to optimal fruit and vegetable preservation conditions.

The outputs of the comparison blocks are connected to logical decision structures, implemented using Case Structures. These structures perform conditional execution, based on the comparison results. When environmental parameters remain within acceptable limits, normal operation status signals are generated. When parameters exceed acceptable thresholds, warning signals are generated.

The decision outputs are transmitted to the Front Panel indicators, activating warning LEDs and advisory messages. This direct connection between logical evaluation and user interface elements ensures immediate feedback and rapid system response.

The entire system operates within a While Loop structure, which enables continuous monitoring and real-time operation. The loop executes repeatedly at a defined sampling rate, ensuring uninterrupted environmental supervision.

The internal dataflow organization of the Block Diagram follows a sequential acquisition-processing-decision architecture. Sensor signals are first acquired and scaled into engineering units, after which logical comparison algorithms evaluate whether the environmental conditions remain within predefined preservation limits. The resulting decision signals activate visual indicators and advisory outputs on the Front Panel.

The modular structure of the Block Diagram improves maintainability and scalability by separating acquisition, processing, and visualization functions into independent software layers. This separation reduces software complexity and facilitates future implementation of additional functionalities, such as automatic actuator control, wireless communication, cloud-based monitoring, and predictive environmental regulation.

In addition, the deterministic execution mechanism of the LabVIEW environment ensures that each processing node executes only after receiving valid input data. This behavior minimizes synchronization errors and guarantees reliable real-time system operation under continuous monitoring conditions.

From a systems engineering perspective, the Block Diagram implements a deterministic dataflow execution model. Each functional node executes only when its input data are available, ensuring reliable operation and eliminating execution conflicts. This execution model enhances system stability and ensures consistent real-time performance [11].

The modular structure of the Block Diagram allows future system expansion. Additional functional modules, such as actuator control, wireless communication, or data logging, can be integrated without modifying the core architecture.

4 Mathematical Modeling and System Performance Analysis

To provide analytical evaluation of the proposed monitoring system, mathematical models were used to describe environmental variation, sensor conversion, and system response characteristics.

The temperature dynamics inside the storage environment can be approximated using a first-order response model:

$$T(t)=T_{env} + (T_0 - T_{env})e^{-t/\tau} \quad (1)$$

where T(t) is the measured temperature, T_{env} is the equilibrium temperature, T_0 is the initial temperature, and τ is the thermal time constant.

Similarly, the humidity sensor output is converted into engineering units using a linear calibration model:

$$H = aV + b \quad (2)$$

where H is the relative humidity, V is the sensor voltage, and a, b are calibration constants.

The system continuously compares measured parameters with predefined threshold limits. The alarm condition is defined as:

$$A = 1, \text{ if } X > X_{max} \text{ or } X < X_{min} \quad (3)$$

$$A = 0, \text{ if } X_{min} \le X \le X_{max} \quad (4)$$

where A represents the alarm state and X corresponds to either temperature or humidity measurements.

Measurement uncertainty is influenced by sensor accuracy, analog-to-digital conversion, and electrical noise. The combined uncertainty can be estimated by:

$$U_c = \sqrt{U_s^2 + U_{ADC}^2 + U_n^2} \quad (5)$$

where U_s is sensor uncertainty, U_{ADC} is conversion uncertainty, and U_n represents noise effects.

The overall response time of the monitoring system is determined by sensor response, acquisition delay, and software processing time:

$$tr = ts + tDAQ + tp \qquad (6)$$

This analysis confirms that the developed system provides stable monitoring behavior, reliable threshold detection, and adequate response performance for fruit and vegetable preservation applications [12].

5 Conclusion

The system was evaluated under controlled environmental conditions, simulating fruit and vegetable storage environments. Temperature and relative humidity were continuously monitored, and system response was observed under both normal and abnormal conditions.

During normal operation, the system accurately measured environmental parameters and displayed values in real time on the Front Panel. Measurement accuracy and system stability were maintained throughout continuous operation.

When environmental parameters exceeded predefined threshold limits, the system immediately detected deviations and activated warning indicators. Advisory messages provided operators with appropriate corrective recommendations. The response time of the system was sufficient to enable rapid corrective intervention.

The graphical user interface provided clear and intuitive visualization of environmental conditions, improving operator awareness and response capability. The integration of measurement, processing, and visualization functions ensured reliable system operation.

Experimental observations indicated stable monitoring behavior under both steady-state and transient environmental conditions. During controlled environmental variations, the system successfully detected threshold violations without significant delay or instability. The measured response characteristics demonstrated that the acquisition and processing architecture maintained reliable operation during continuous execution. The implemented threshold detection mechanism exhibited high repeatability and low susceptibility to false alarm activation under normal operating fluctuations.

From an engineering standpoint, the system demonstrated reliable performance, accurate environmental monitoring, and effective decision-support capability. The modular architecture allows future integration of automated environmental control systems, enabling closed-loop control functionality.

The developed system provides a practical and scalable engineering solution for improving fruit and vegetable storage conditions. Continuous monitoring and automated warning generation reduce spoilage risk, improve preservation efficiency, and enhance storage reliability.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.