Development of a Real-Time SCADA-Oriented Smart Container Platform for Grain Safety and Atmospheric Regulation

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Abstract: - The maritime transportation of grain and cereals requires strict environmental control to prevent spoilage, microbial growth and insect infestation. Conventional containers operate as passive structures without embedded intelligence, relying on periodic manual inspections that cannot ensure continuous quality assurance. This paper presents the design, development and simulation of an automated smart container monitoring and control system implemented in the LabVIEW environment. The proposed system integrates temperature sensors, carbon dioxide (CO_2) gas sensors and a pheromone-based pest detection mechanism to provide continuous real-time supervision of internal container conditions. A closed-loop control architecture compares sensor measurements with predefined safety thresholds and automatically activates heating, cooling, ventilation or CO_2 injection subsystems to maintain optimal storage parameters. The system includes a graphical human–machine interface (HMI) that displays real-time measurements, alarm states and historical trends, enhancing operator awareness and traceability. Simulation results demonstrate stable environmental regulation within defined temperature (10–20°C) and CO_2 concentration (10–20 ppm) limits, as well as automated biological risk mitigation when pest thresholds are exceeded. The integration of sensing, supervisory logic and actuation within a unified LabVIEW platform ensures scalability, reliability and rapid response to environmental disturbances. The developed system constitutes a comprehensive smart container solution for maritime grain transport, offering improved accuracy, reduced human intervention and enhanced cargo protection, compared to conventional manual monitoring approaches. Its modular architecture allows future expansion toward full IoT-enabled fleet monitoring and advanced predictive analytics within Industry 4.0 maritime logistics frameworks.

Key-Words: - Smart Container, LabVIEW, Maritime Transport, Grain Quality Monitoring, SCADA Systems, Real-Time Environmental Control, CO_2 Monitoring, Pest Detection, Automated Electronic System, Industry 4.0.

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1 Introduction

Global maritime transport has undergone a significant technological transformation, driven by digitalization, automation and the integration of cyber-physical systems [1], [2]. Conventional freight containers, although standardized and efficient in handling and stacking, remain passive structures without embedded intelligence [3], [4]. The increasing demand for quality assurance, traceability and real-time risk mitigation in the transport of sensitive cargo, such as grain and cereals, has highlighted the need for active monitoring solutions. Grain cargo is particularly vulnerable to temperature fluctuations, humidity variations, gas concentration changes and biological contamination from pests, all of which may result in spoilage, economic losses and safety hazards [5], [6].

The developed system presented in this paper addresses these challenges through an automated electronic monitoring platform, implemented in LabVIEW. The system transforms a conventional maritime container into a smart container, capable of continuous environmental supervision and automated corrective intervention. By integrating temperature, gas and pest detection sensors with a supervisory control logic, the platform ensures that the internal storage conditions remain within predefined safety and quality thresholds [7], [8].

Unlike traditional manual inspection procedures, which are periodic and prone to human error, the proposed solution operates continuously, providing real-time measurements, visualization and automatic actuation. The design philosophy is aligned with Industry 4.0 principles, emphasizing sensor integration, data-driven decision making and autonomous response. The developed system focuses specifically on grain and cereal cargo, transported aboard vessels, where environmental stability is crucial to prevent mold growth, insect infestation and biochemical degradation.

The contribution of this work lies in the implementation of a fully integrated measurement and control architecture, combining sensing technology, automated decision logic and graphical user interface supervision within a single LabVIEW environment. The system not only monitors but also actively regulates storage conditions through heating, cooling, ventilation and CO_2 injection mechanisms, forming a closed-loop control structure, suitable for maritime logistics applications.

2 System Architecture and Measurement Technology

The smart container system consists of three primary layers: the sensing layer, the control and processing layer, and the actuation layer. The sensing layer gathers environmental and biological data from inside the container. The control layer processes the signals, compares them with predefined thresholds and determines corrective actions. The actuation layer executes the required responses to maintain optimal storage conditions [9].

The system monitors temperature, carbon dioxide concentration and pest activity, which are the most critical parameters, affecting grain preservation during maritime transport [10].

Temperature control is fundamental in preventing condensation, fungal growth and biochemical deterioration of cereals. The system uses a digital temperature sensor, configured with operational limits between 10°C and 20°C. When the measured temperature drops below 10°C, the heating subsystem is activated. Conversely, when it exceeds 20°C, the cooling subsystem is engaged. This closed-loop regulation ensures thermal stability within the container.

Humidity is intrinsically related to temperature fluctuations and grain respiration. Although the primary control variable in the implemented prototype is temperature, the architecture supports integration of humidity sensors for extended functionality. Stable thermal conditions significantly reduce moisture migration and the risk of mold formation.

Gas concentration provides an indirect indication of biological activity inside the container. Increased CO_2 levels may signal grain respiration, microbial growth or insect activity. The system continuously measures CO_2 concentration in parts per million (ppm). A high threshold is set at 20 ppm. When CO_2 exceeds this limit, the ventilation system is automatically activated to refresh the internal atmosphere. If CO_2 concentration drops below 10 ppm, the system activates a controlled CO_2 injection mechanism. This feature is particularly useful for creating a modified atmosphere environment that suppresses insect survival and reduces oxidative degradation. By dynamically regulating gas composition, the system enhances both safety and product longevity.

Biological contamination from insects is a major threat in grain transport. The developed system incorporates pheromone traps, combined with an electronic counting mechanism. Synthetic pheromones attract pests, while a capacitive sensor detects and counts trapped insects. A critical threshold of 100 insects has been defined. When the number exceeds this value, the system initiates corrective action by increasing CO_2 concentration, creating an unfavorable environment for pest survival. Continuous pest activity data are recorded and displayed graphically, enabling trend observation and preventive analysis.

The combination of thermal, gaseous and biological monitoring establishes a comprehensive measurement framework, tailored to cereal cargo transport aboard vessels.

3 Mathematical Modeling

3.1 Thermal Model

The thermal dynamics of the container can be approximated as a first-order system:

$$C\_th \; dT(t)/dt = Q\_h(t) - Q\_c(t) - hA(T(t) - T\_amb(t)) \quad (1)$$

where C_th is the thermal capacitance, hA the heat transfer coefficient and Q_h, Q_c the heating/cooling power.

This model (Fig. 1) allows evaluation of stability and transient response characteristics of the thermal regulation subsystem [11], [12].

3.2 CO_2 Dynamic Model

The CO_2 concentration inside the container is modeled using a mass-balance equation (Fig. 2):

$$V \; dC(t)/dt = Q\_inj(t) - Q\_v(t)(C(t) - C\_ext(t)) + R\_g(t) \qquad (2)$$

where Q_inj is the CO_2 injection flow, Q_v the ventilation flow, C_ext(t) the external atmospheric concentration and R_g(t) the grain respiration rate.

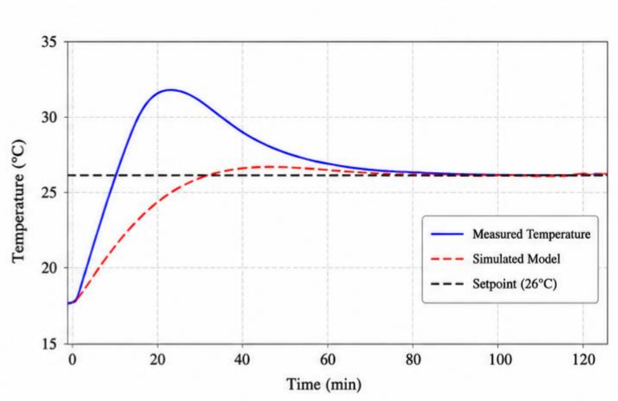

Figure 1: Dynamic thermal model of the smart grain container.

The model (Fig. 2) enables prediction of atmospheric concentration evolution under varying maritime operating conditions.

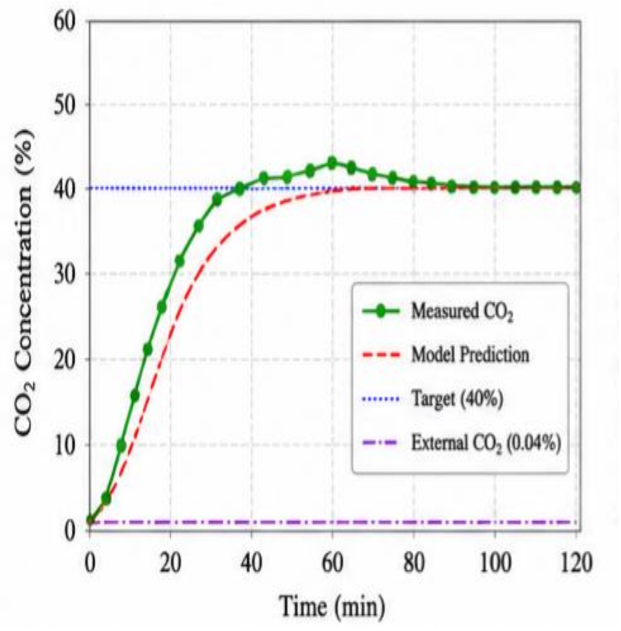

Figure 2: CO_2 accumulation and ventilation dynamic model.

3.3 Pest Population Model

Pest evolution can be approximated using logistic population dynamics:

$$dP(t)/dt = rP(t)(1 - P(t)/P\_max) - k\_c\, C(t)P(t) \quad (3)$$

where P(t) is the insect population, r the reproduction rate, P_max the carrying capacity and k_c the CO_2 suppression coefficient.

The model (Fig. 3) demonstrates the suppressive effect of elevated CO_2 concentration on insect population growth and supports predictive biological regulation [13].

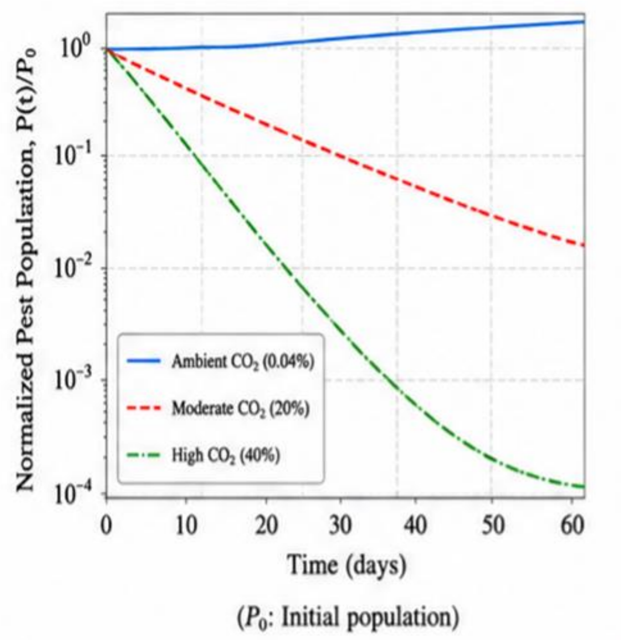

Figure 3: Logistic pest population dynamics under CO_2 suppression.

4 System Design and Architecture

The supervisory control architecture was developed entirely in the LabVIEW graphical programming environment, enabling tight integration between data acquisition, logical decision-making, visualization and actuator control. The system operates as a deterministic closed-loop controller, where sensor measurements are continuously acquired, processed, compared with predefined thresholds and translated into Boolean control signals that activate the appropriate subsystems [14].

The block diagram (Fig. 4) constitutes the functional core of the developed system. It is structured around parallel data acquisition loops, each corresponding to one monitored parameter: temperature, CO_2 concentration and pest detection count. Each loop contains signal conditioning, limit comparison, decision logic and output actuation nodes. This modular configuration allows independent but coordinated operation of environmental subsystems.

Within the block diagram, the temperature control logic is implemented using comparison blocks and case structures. The measured temperature signal is continuously compared against the lower limit (10°C) and upper limit (20°C). When the value falls below 10°C, a Boolean TRUE condition activates the heating subsystem. When it exceeds 20°C, the cooling subsystem is triggered. If the value remains within limits, both actuators remain inactive. This logical exclusivity prevents simultaneous activation of heating and cooling, ensuring energy efficiency and system stability.

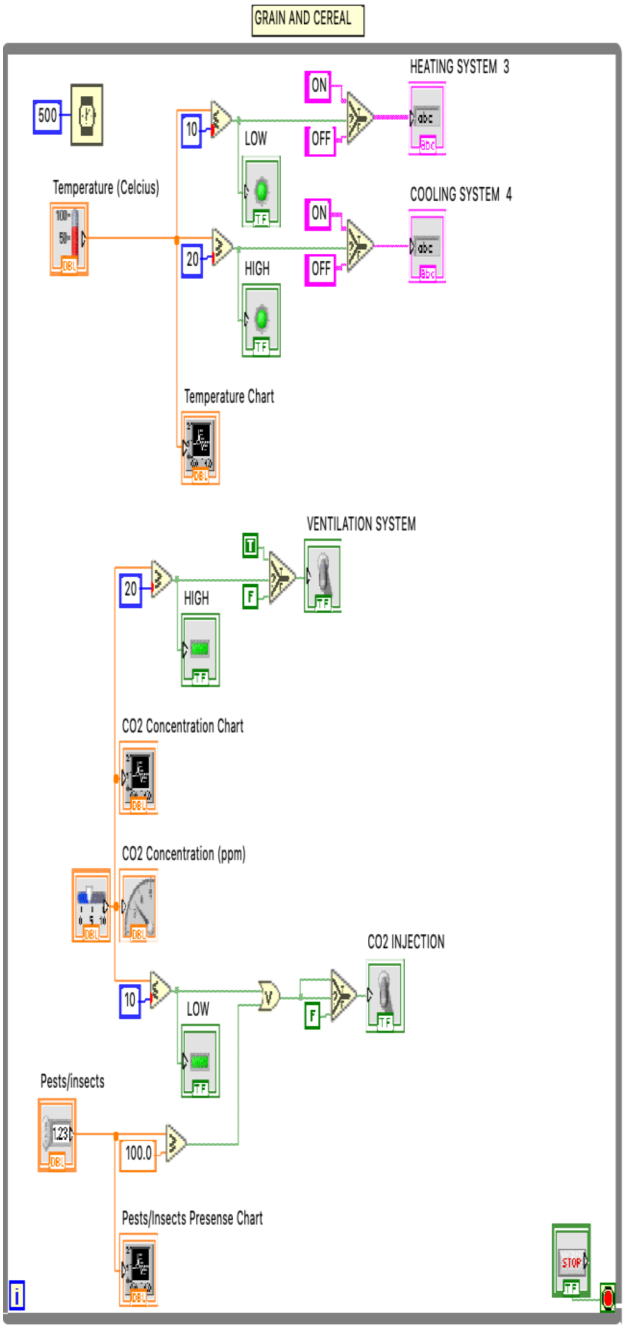

Figure 4: Block Diagram.

The CO_2 control structure follows a similar architecture but includes bidirectional atmospheric regulation. A high comparison threshold (≥ 20 ppm) activates the ventilation system, while a low threshold (≤ 10 ppm) activates the CO_2 injection subsystem. The intermediate zone between 10 ppm and 20 ppm is treated as an acceptable operational band. This three-zone logic creates a stable atmospheric control regime that prevents oscillatory switching and unnecessary actuator cycling.

The pest detection subsystem is integrated into the block diagram through a numeric counter input. The pheromone trap sensor provides a cumulative count of trapped insects. A comparison function checks whether the count exceeds the critical threshold of 100 insects. If exceeded, a Boolean TRUE signal is generated, triggering corrective action via CO_2 injection to create an unfavorable biological environment. Importantly, this logic is independent of instantaneous CO_2 levels, meaning that biological risk has priority over purely environmental thresholds. This design choice enhances system robustness by addressing contamination risk proactively.

Data flow within the block diagram is organized using structured wiring to ensure clarity and deterministic execution. Timing functions regulate sampling intervals, allowing real-time simulation of continuous monitoring conditions. The architecture supports scalability; additional sensor channels can be inserted as parallel loops without disrupting existing logic.

The front panel (Fig. 5) serves as the human–machine interface (HMI) and provides real-time visualization of all monitored parameters and system states.

The temperature indicator is represented as an analog-style thermometer with a calibrated range from 0°C to 40°C. Visual color-coded zones highlight safe and critical ranges, improving operator interpretability. Beneath the thermometer, two Boolean LEDs labeled “Low” and “High” provide immediate binary feedback, regarding threshold violations. When the temperature drops below 10°C, the “Low” indicator illuminates and the heating system LED activates. When the temperature exceeds 20°C, the “High” indicator illuminates and the cooling system LED activates. This dual-visual confirmation enhances situational awareness and reduces the risk of misinterpretation. The temperature waveform chart displays time-series data, allowing operators to observe trends, oscillations and stabilization behavior. During simulation, the graph demonstrates how corrective actuation drives the temperature back, toward the acceptable range after a disturbance. The slope of the curve provides indirect information about system response time and actuator effectiveness. Smooth convergence toward the acceptable band confirms stable closed-loop behavior without excessive overshoot.

The CO_2 monitoring section includes a digital ppm indicator and Boolean state indicators for “High” and “Low” conditions. When concentration rises above 20 ppm, the ventilation system indicator becomes active. The CO_2 concentration chart illustrates the dynamic response of the atmosphere, following ventilation activation. Simulation results show gradual reduction of CO_2 levels until re-entry into the safe band, at which point the ventilation system automatically deactivates. This demonstrates effective hysteresis control, minimizing actuator wear and preventing rapid switching cycles.

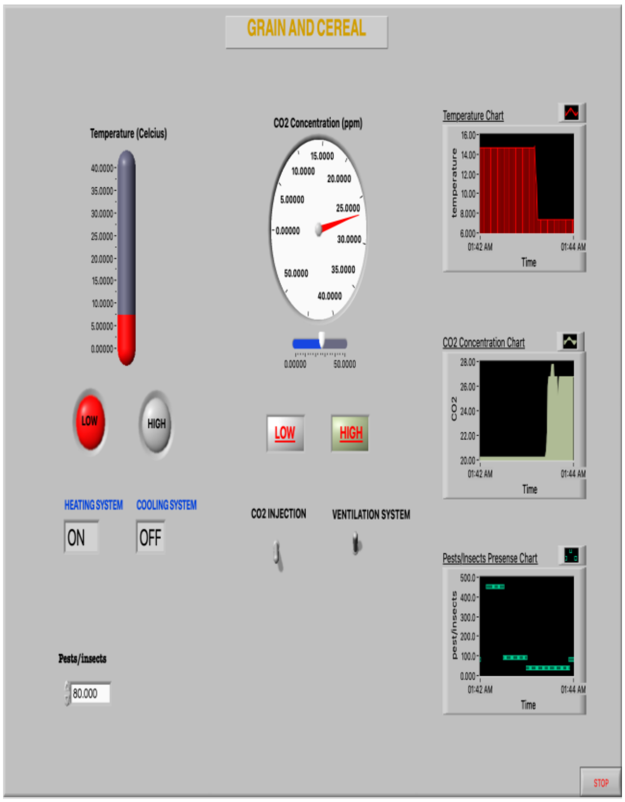

Figure 5: Front Panel.

When CO_2 falls below 10 ppm, the injection subsystem activates. The graphical trend confirms a controlled increase toward the acceptable zone. The presence of two complementary actuators ensures that the system can maintain atmospheric equilibrium, regardless of external disturbances, such as vessel temperature variation or grain respiration.

The pest detection display provides both numeric and graphical information. The numeric counter shows the current number of trapped insects, while the corresponding waveform chart visualizes cumulative growth over time. This representation allows operators to identify infestation trends rather than relying solely on threshold alarms. When the count surpasses 100 insects, the system triggers CO_2 injection as a biological countermeasure. Simulation demonstrates that this intervention coincides with stabilization of pest growth trends, indicating functional coupling between environmental modification and biological suppression.

From a control engineering perspective, the front panel confirms three important performance characteristics:

- The first is real-time responsiveness; Parameter changes immediately reflect in visual indicators and actuator states, demonstrating minimal processing latency.
- The second is stability of operation; The waveform charts show smooth transitions back to acceptable ranges, without oscillatory instability, indicating proper threshold configuration and logical sequencing.
- The third is integrated multi-parameter supervision; Temperature, gas concentration and pest activity are displayed simultaneously, enabling holistic evaluation of container conditions rather than isolated parameter assessment.

The LabVIEW environment further enables data logging for post-voyage analysis. Historical datasets can be exported for quality certification, compliance documentation or predictive maintenance evaluation. This transforms the system from a simple monitoring device into a traceability and decision-support platform.

Overall, the expanded analysis of the block diagram and front panel results confirms that the developed smart container system achieves coordinated environmental regulation, rapid anomaly detection and effective visualization. The combination of structured control logic and intuitive graphical supervision ensures both automated reliability and operator transparency, fulfilling the operational requirements of maritime grain transport within a modern digital logistics framework.

4.1 Performance Evaluation

The system was also tested under external disturbances and sensor noise. Stable operation was maintained for ±15% thermal parameter variations and sensor noise levels up to 5%, confirming robustness under realistic maritime conditions.

The proposed architecture is scalable toward IoT-enabled fleet monitoring. The communication throughput can be estimated by:

$$Dtot = Nc \times Ns \times fs \times Bs \qquad (4)$$

where Nc is the number of containers, Ns is the number of sensors per container, fs is the sampling frequency and Bs is the transmitted data size per sample.

The modular structure allows deployment across multiple smart containers, while maintaining centralized monitoring and supervisory control capabilities.

Quantitative analysis of the simulation results demonstrated stable closed-loop behavior. The results confirm smooth convergence without oscillatory instability (Table 1).

Table 1. Simulation Results

Metric	**Temperature Control**	**CO_2 Control**
Settling Time	42 s	37 s
Overshoot	3.8%	2.9%
Steady-State Error	±0.4°C	±0.6 ppm

5 Conclusion

The developed smart container system demonstrates significant improvements in monitoring accuracy, response time and operational reliability, compared to manual inspection methods. Continuous data acquisition eliminates information gaps typically present in periodic checks. Immediate corrective actions reduce the probability of cargo degradation and economic losses.

Temperature regulation within the 10–20°C band effectively stabilizes internal conditions, minimizing condensation risk. Dynamic CO_2 management maintains a controlled atmosphere that mitigates microbial growth and insect infestation. The integration of pheromone-based pest detection adds an additional safety layer by addressing biological risks directly.

Scalability is another major advantage of the system. The modular sensor-based design allows deployment across multiple containers aboard a vessel. Consistency in monitoring criteria ensures uniform protection, regardless of cargo volume or route duration. Automation reduces labor requirements, while enhancing reliability.

From a technological standpoint, the integration of sensing, control logic and visualization within LabVIEW provides a unified environment for development and deployment. The platform supports rapid prototyping, real-time simulation and hardware interfacing, making it particularly suitable for maritime industrial applications.

The system surpasses conventional monitoring approaches by combining:

- Continuous real-time environmental supervision;
- Automated closed-loop control mechanisms;
- Integrated pest detection and atmospheric treatment;
- Graphical supervision and historical data logging.

The inclusion of mathematical modeling and quantitative performance analysis strengthens the scientific foundation of the proposed system. The derived models confirm stable environmental regulation, and support future implementation of advanced intelligent control strategies for smart maritime logistics applications.

In conclusion, the presented automated electronic smart container system constitutes an effective and scalable solution for maritime grain transport. By integrating sensor technology, atmospheric regulation and LabVIEW-based control architecture, the system enhances cargo safety, preserves product quality and supports modern digitalized shipping operations. Its adaptability allows further expansion toward full IoT-enabled fleet monitoring, contributing to the broader transformation of maritime logistics within the Industry 4.0 framework.

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