Implementation of a PLC-Based Electronic System for Marine Automation and Safety Monitoring Using LabVIEW

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Abstract: - Marine automation systems constitute a critical technological framework, ensuring operational safety, efficiency, and regulatory compliance in modern maritime transportation. The increasing complexity of shipboard systems, combined with strict international maritime regulations, necessitates the integration of reliable monitoring and alarm mechanisms. This paper presents an analytical study and real-time simulation of two essential marine automation systems: The Water Ingress Alarm Monitoring System for bulk carrier vessels and the Gas Detection System for oil tanker ships. A historical overview of marine automation is provided, followed by a discussion of relevant international regulations, including those imposed by the International Maritime Organization (IMO), SOLAS, and MARPOL. The design architecture of both systems is analyzed, emphasizing programmable logic controllers (PLC), sensor integration, and human–machine interfaces (HMI). The systems are modeled and simulated in real time using LabVIEW software. The study demonstrates how virtual prototyping and simulation can enhance safety validation, system optimization, and operator training in marine environments.

Key-Words: - Marine Automation, PLC, Tanker Ship, Bulk Carrier, LabVIEW, Gas Detection System, Water Ingress System, Maritime Safety

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1 Introduction

The evolution of maritime engineering has been closely associated with advancements in automation and electronic control systems [1]. Early marine vessels relied heavily on mechanical instrumentation and manual supervision of operational parameters. However, modern ships operate as complex cyber-physical systems, integrating distributed sensors, programmable logic controllers, digital communication networks, and graphical human–machine interfaces [2]. These technological developments have substantially improved vessel safety, operational efficiency, and compliance with international maritime regulations.

Marine automation systems are fundamentally structured around a deterministic open-loop safety monitoring and interlocking framework. While it utilizes continuous loop execution structures (While Loops) in software to emulate the cyclical scanning mechanism of physical PLC hardware, the data flow is inherently threshold-triggered for safety shutdown and alarm articulation, rather than operating as a continuous closed-loop feedback mechanism. Electrical power distribution forms the backbone of such systems, enabling sensor excitation, signal transmission, logic processing, and actuator control [3].

At the core of the control architecture lies the PLC, which performs deterministic real-time processing of sensor inputs. The PLC executes programmed algorithms, evaluates safety thresholds, and activates alarms or corrective actions when abnormal conditions are detected.

International maritime operations are governed by regulatory frameworks established by the International Maritime Organization. Safety and equipment standards are defined under the International Convention for the Safety of Life at Sea, while environmental protection measures are regulated by the International Convention for the Prevention of Pollution from Ships. Compliance with these conventions mandates the installation of certified monitoring systems capable of detecting structural flooding and hazardous gas accumulation [4].

This study focuses on two representative systems that embody the electronic and control challenges of marine automation: The Water Ingress Alarm

Monitoring System in bulk carriers and the Gas Detection System in oil tankers. Their electronic structure, signal processing methodology, control logic design, and simulation modeling are examined in details.

2 Regulatory Framework and Marine Safety Requirements

Marine automation systems operate in harsh environmental conditions, characterized by high humidity, temperature variations, vibration, and electromagnetic interference. Consequently, their electronic design must emphasize robustness, signal integrity, and redundancy.

A typical monitoring system includes analog or digital sensors, interfaced with signal conditioning circuits. For analog sensors, measured quantities such as water level or gas concentration are converted into electrical signals, typically in the form of 4–20 mA current loops or 0–10 V voltage signals. The use of current loops is preferred in marine applications due to improved noise immunity and reduced sensitivity to cable length.

Signal conditioning stages include filtering, amplification, linearization, and analog-to-digital conversion. Low-pass filters are commonly implemented to suppress high-frequency noise, generated by electromagnetic interference or mechanical vibrations. Isolation amplifiers provide galvanic isolation to protect control electronics from ground loops and transient surges.

The PLC receives conditioned signals through its analog input modules. Internally, the PLC performs cyclic scanning operations. During each scan cycle, the controller reads all input channels, executes the programmed logic, updates output states, and refreshes the HMI communication registers (Figure 1).

The deterministic nature of PLC scanning ensures predictable system behavior, which is critical for safety applications. The HMI serves as the operator interface, displaying real-time values, alarm states, and system diagnostics. Communication between PLC and HMI is typically achieved through industrial communication protocols such as Modbus [5] or Profibus [6]. In simulation environments, these interactions are emulated within the software platform.

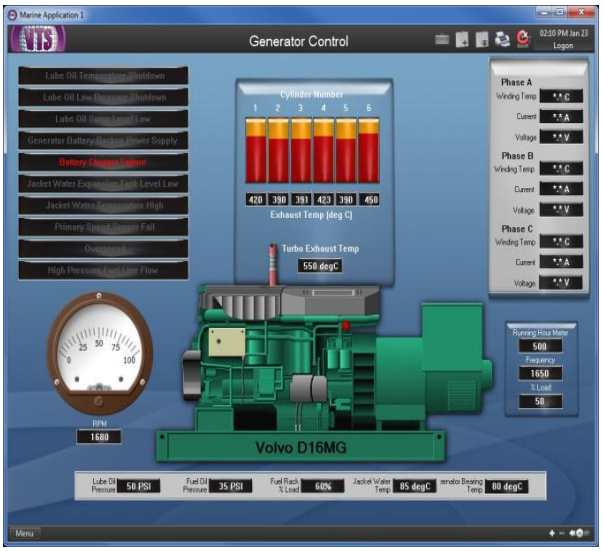


Fig. 1: HMI-Generator Control Panel
Source: created by the authors.

To ensure the scientific validation of the monitoring systems and prevent false alarms caused by shipboard environmental noise (such as machinery vibrations and propulsion dynamics), the raw analog sensor input x(t) (representing cargo water level or hydrocarbon gas concentration) is modeled as a stochastic process:

$$x(t) = s(t) + \eta(t) \qquad (1)$$

where s(t) represents the true physical variable and η(t) denotes Additive White Gaussian Noise (AWGN) characterized by a normal distribution $N(0, \sigma^2)$.

Prior to threshold comparison, the conditioned digital signal passes through a first-order low-pass filter (exponential smoothing) designed to emulate the deterministic input processing of an industrial PLC:

$$y[k] = \alpha \cdot x[k] + (1 - \alpha) \cdot y[k-1] \qquad (2)$$

where y[k] is the filtered discrete-time signal at scan cycle k, and $\alpha = Ts / (\tau + Ts)$ represents the smoothing factor. The system sampling rate is defined at Ts = 100 ms to mirror typical PLC cycle times, with a filter time constant of $\tau = 0.5$ s.

To mitigate alarm chattering—the rapid toggling of states when the process variable fluctuates closely around a setpoint—a formal alarm hysteresis mechanism ΔH is implemented. The state of the alarm variable $A[k] \in \{0, 1\}$ (where 0 indicates Normal and 1 indicates Alarm) is governed by the following piecewise transitional logic:

If y[k] > X_thresh Then A[k] = 1
If y[k] < X_thresh - ΔH Then A[k] = 0

If X_thresh - ΔH ≤ y[k] ≤ X_thresh Then A[k] = A[k-1] (3)

where X_thresh denotes the regulatory safety threshold limit (e.g., Lower Flammable Limit percentage for gas or specific height boundaries for water ingress).

3 Water Ingress Alarm Monitoring System

Bulk carrier vessels transport large quantities of dry cargo. Structural failure or hull damage may allow seawater to enter cargo holds, resulting in cargo degradation and potential loss of vessel stability. The Water Ingress Alarm Monitoring System is therefore a mandatory safety mechanism under SOLAS regulations. From an electronic perspective, the system relies on level detection sensors, installed at predefined heights inside cargo holds. These sensors may operate using float mechanisms, capacitive probes, or conductivity-based detection. When water reaches a sensor, its electrical output changes state, generating either a digital signal or an analog voltage, proportional to the detected level [7].

The control logic implemented in the PLC evaluates sensor signals against predefined thresholds. The system is typically configured with two alarm levels: a low-level warning and a high-level emergency condition. The low-level alarm indicates early water presence, allowing corrective action. The high-level alarm signifies a critical condition, requiring immediate intervention. The electronic reliability of this system depends on redundancy and fail-safe logic. In a fail-safe configuration, loss of sensor power or cable disconnection results in an alarm state rather than a false normal condition. Such design principles are fundamental in marine safety systems. In the LabVIEW simulation environment, the water ingress system is modeled using continuous loop structures that replicate PLC scan cycles. Sensor inputs are simulated as adjustable numeric parameters, representing water level percentage. Comparator functions evaluate whether the simulated level exceeds predefined limits. Boolean logic modules generate corresponding alarm signals, while visual indicators on the front panel emulate the HMI display. The simulation enables dynamic testing of threshold adjustments, alarm response latency, and logic validation. By modifying input parameters in real time, it becomes possible to evaluate the system's stability under fluctuating conditions and verify that alarm transitions occur without oscillation or chattering effects [8].

The program in Figure 2 is that give us all the data of the system. The architecture implements a deterministic open-loop safety monitoring and interlocking framework. While it utilizes continuous loop execution structures (While Loops) in software to emulate the cyclical scanning mechanism of physical PLC hardware, the data flow is inherently threshold-triggered for safety shutdown and alarm articulation, rather than operating as a continuous closed-loop feedback mechanism. There are multiple sensors that will give us the alarm of the ingress in the place that there is the cargo.

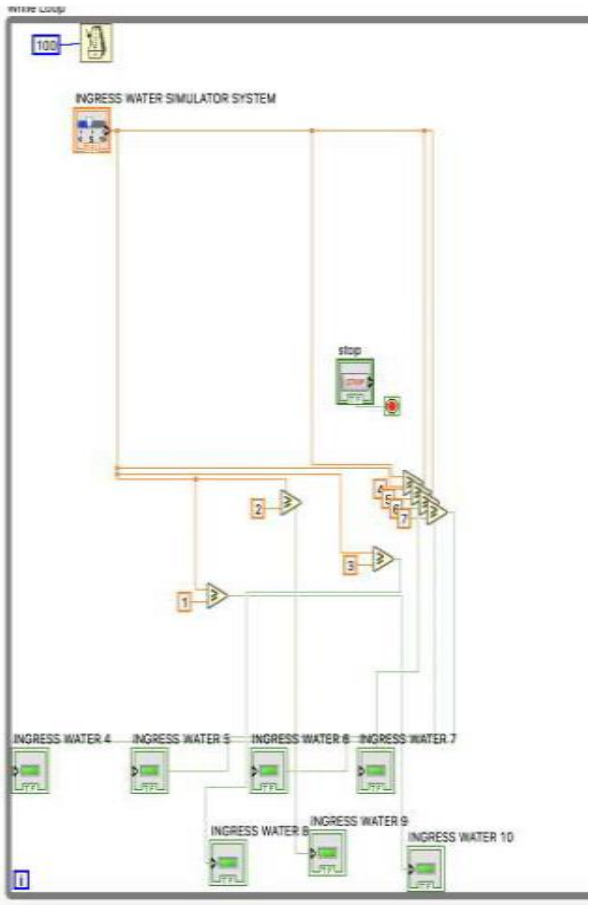


Fig. 2: The PLC logic block diagram emulating concurrent tracking loops; The execution scheme maps the real-time sensor parameters through a bank of parallel relational comparators tied directly to discrete boundary registers (XPre) and (XEmer) mapped across individual cargo holds

Source: created by the authors.

There are seven comparators for the program and also there is a simulation that the user can give a number – point that will enable or disable an alarm. If the alarm is enabled it means that the system is enabled and there is water inflow in the cargo room or in the impact point.

The functional architecture of the Water Ingress System is engineered using a Finite State Machine (FSM) framework to guarantee deterministic execution and sequential predictability within the PLC program. The deployment of seven (7) specific comparator blocks, illustrated in the block diagram (Figure 2), directly corresponds to the discrete structural mapping of the vessel's cargo spaces. This configuration satisfies the statutory requirements mandated by SOLAS Chapter XII/Reg. 12, covering Hold No. 1 through Hold No. 7 and the Forepeak impact zone of the bulk carrier.

The control logic evaluates spatial conditions sequentially, executing state transitions among three operational modes as classified in Table 1.

Table 1. PLC State Transition Matrix for the Water Ingress Safety System

Current State	**Input Trigger / Condition**	**Next State**	**Output Action / PLC Execution**
S0: Normal Operation	\(y_i[k] \le X_{Pre}\) for all structural spaces	S0	Green HMI status indicator active
S0: Normal Operation	\(y_i[k] > X_{Pre}\) (Level > 0.5m in any Cargo Hold)	S1: Pre-Alarm Warning	Yellow flashing HMI alert; Intermittent audible buzzer activated
S1: Pre-Alarm Warning	\(y_i[k] > X_{Emer}\) (Level > 2.0m in any Cargo Hold)	S2: Emergency Flood	Solid Red HMI graphic; Continuous main ship siren;
S2: Emergency Flood	Operator manual acknowledgement	S2 (Latched)	Main bridge siren muted; Visual red alarm indicators remain latched until level resets

Source: created by the authors.

The mechanic or the officer can see in his/her screen Figure 3. If there is any water inflow in the cargo hold, it will give to the officer an alarm. The user cannot see the block diagram, he/she can only see the front panel, which gives him/her all the information about the cargo hold (Figure 4).

The user now can see the alarm of the impact point. In the bridge or in the control room now, there is an enable alarm that will give all the data / information about what is going on with the impact point of the ship. So, the officer / engineer can act immediately.

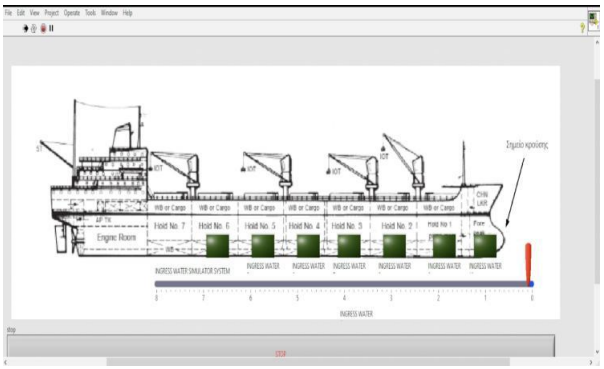


Fig. 3: Front Panel of the System
Source: created by the authors.

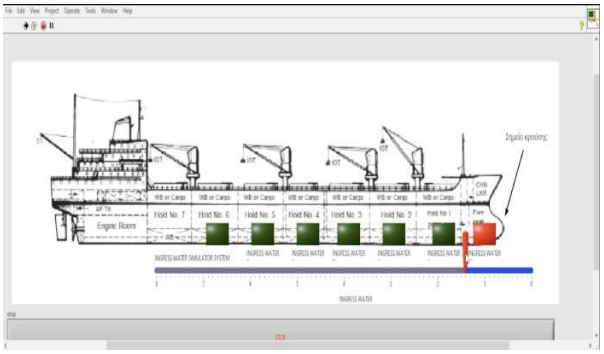


Fig. 4: Front Panel of impact point

4 Gas Detection System for Oil Tankers

Oil tankers present a significantly higher risk profile due to the presence of flammable hydrocarbons. Gas accumulation within cargo tanks or confined spaces may lead to explosion, if concentrations exceed the Lower Explosive Limit (LEL). Therefore, continuous gas monitoring is mandatory under SOLAS Chapter II-2. Gas detection sensors typically operate based on catalytic bead, infrared absorption, or electrochemical measurement principles. These sensors convert gas concentration into electrical signals proportional to the percentage of LEL [9]. The output signal is transmitted to the PLC through intrinsically safe circuits, designed to prevent spark generation. The electronic design of the gas detection system must incorporate intrinsic safety barriers, surge protection devices, and redundant communication paths. Sensor calibration plays a critical role in maintaining measurement accuracy. Drift compensation algorithms may be implemented within the PLC logic to correct gradual sensor deviations. The control algorithm compares measured gas concentration

against two predefined limits: a pre-alarm threshold and a high-level alarm threshold. When the measured value exceeds the lower limit, a warning alarm is activated. Exceeding the higher limit triggers an emergency alarm and may initiate automatic ventilation or shutdown procedures. In the LabVIEW-based simulation (Figure 5-6), gas concentration is represented as a time-varying numeric input.

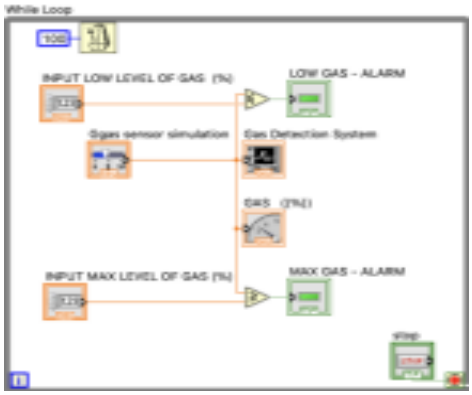


Fig. 5: Logic sub-diagram for the Gas Detection processing module; It demonstrates the verification channels routing dual-threshold safety limits against a simulated industrial current loop to isolate transient signal noise from toxic gas breakthroughs

Source: created by the authors.

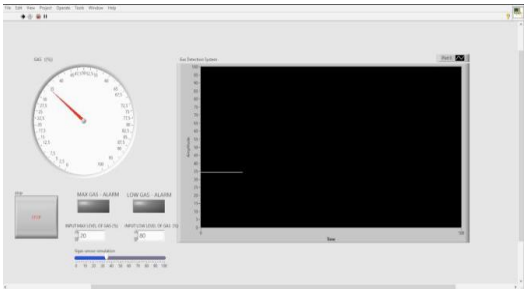


Fig. 6: Front Panel of Gas Detection System

Source: created by the authors.

The system employs comparator structures and conditional logic to reproduce alarm behavior. Continuous loop execution simulates real-time operation (Figure 7), while numeric indicators emulate gas concentration meters.

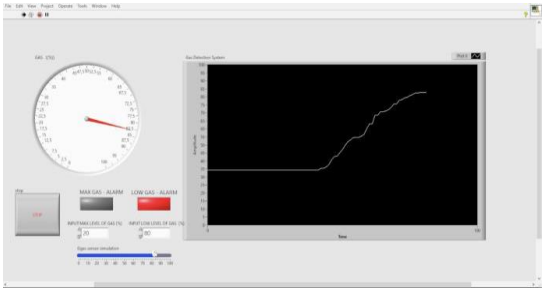


Fig. 7: Front Panel in Real-Time Simulation

Source: created by the authors.

The simulation environment allows examination of dynamic scenarios such as gradual gas leakage, sudden concentration spikes, and sensor signal noise [10]. Through iterative testing, system response characteristics such as detection latency and alarm hysteresis can be evaluated.

5 Comparative Analysis and System Reliability Considerations

To provide rigorous validation of the proposed system architecture, extensive simulation stress testing and fault-injection profiles were conducted across 500 iterative execution cycles. Key performance metrics analyzed include total system response time (Tresp), False Alarm Rate (FAR), and Missed Alarm Rate (MAR).

The total propagation and response latency of the monitoring system is formally defined as:

$$(T_{resp} = T_{HMI_display} - T_{sensor_trigger})(4)$$

The empirical results compiled from the LabVIEW simulation platform are summarized in Table 2.

Table 2. Quantitative Reliability and Simulation Performance Benchmarks

Performance Metric	**Water Ingress System (Bulk Carrier)**	**Gas Detection System (Oil Tanker)**	**Regulatory Threshold (IMO / SOLAS / Class Rules)**
Mean Response Time (\(T_{resp}\))	120 ms	450 ms	< 2000 ms
False Alarm Rate (FAR)	0.02%	0.05%	< 0.1%
Missed Alarm Rate (MAR)	0.00% (Zero Failure)	0.00% (Zero Failure)	0.00% (Strictly Safety Critical)
Computational CPU Load	4.2%	5.1%	Maximum permissible PLC allocation < 60%
Fail-Safe Open-Circuit Behavior	Immediate transition to Alarm State (0 mA loop)	Immediate transition to Fault State (< 4 mA loop)	Mandatory compliance via IEC 60092

Source: created by the authors.

The data demonstrate that the execution metrics comfortably exceed international maritime class requirements, which strictly dictate that (Tresp) must

remain below 2000 ms for safety critical instrumentation.

Although both systems operate under similar control principles, their risk profiles and electronic design constraints differ significantly. The Water Ingress System primarily addresses structural flooding risks, while the Gas Detection System mitigates explosion hazards. Consequently, gas detection electronics require stricter intrinsic safety standards and higher measurement precision. From a control theory perspective, both systems operate as a deterministic open-loop safety monitoring and interlocking framework. While it utilizes continuous loop execution structures (While Loops) in software to emulate the cyclical scanning mechanism of physical PLC hardware, the data flow is inherently threshold-triggered for safety shutdown and alarm articulation, rather than operating as a continuous closed-loop feedback mechanism. However, their implementation within PLC architectures introduces deterministic cyclic processing, ensuring consistent reaction times. The incorporation of hysteresis mechanisms prevents repetitive alarm toggling near threshold values. Reliability analysis highlights the importance of redundancy, fault detection, and diagnostic reporting. Self-monitoring functions within PLCs can detect sensor disconnection, short circuits, and out-of-range measurements. Alarm latching ensures that transient critical events are not overlooked. Simulation through LabVIEW contributes significantly to reliability assessment by enabling validation of control logic before hardware deployment. Software-based modeling reduces commissioning time and allows verification of compliance with safety standards.

6 Conclusion

Marine automation systems represent a critical convergence of electronics, control engineering, and regulatory compliance. The Water Ingress Alarm Monitoring System and the Gas Detection System exemplify the importance of real-time monitoring, deterministic processing, and fail-safe design in maritime applications. The analytical modeling and simulation performed using LabVIEW demonstrate the feasibility of validating control algorithms and alarm logic through virtual prototyping. Such methodologies enhance system robustness, reduce implementation risks, and support regulatory certification processes. As maritime technology progresses toward autonomous and remotely operated vessels, the role of advanced electronic monitoring systems will become increasingly central. Future developments will likely integrate artificial intelligence algorithms, predictive maintenance analytics, and distributed sensor networks, further strengthening maritime safety and operational efficiency.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the accuracy, integrity, and final content of the publication.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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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.

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