DESIGN AND IMPLEMENTATION OF AN INTEGRATED SYSTEM FOR MONITORING FUNCTIONAL PARAMETERS TO REDUCE THE OCCURRENCE OF ACCIDENTS IN FUEL TRANSPORTATION AND STORAGE

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ABSTRACT: The paper presents the development and implementation of an integrated information system for monitoring and correlating functional parameters relevant to fuel transportation and storage processes, with the main goal of reducing the probability of occurrence of events with major impact on safety and the environment. The proposed system integrates multiple sensors (pressure, temperature, vibrations, gas detection) with an industrial communication infrastructure, as well as a correlative analysis software module, using anomaly detection algorithms. By correlating data from the operational environment in real time, the system is able to identify subtle deviations from the normal operating regime and issue predictive alerts before an incident occurs. The results of experimental tests performed under controlled conditions show a detection accuracy of over 97% and an average reaction time of 0.975 seconds, with an estimated 68% reduction in the probability of an event. The proposed solution demonstrates the feasibility of applying IoT and AI concepts in the field of industrial safety, providing a scalable and extensible platform for future implementations in energy infrastructures.

KEY WORDS: integrated monitoring system, IoT, risk reduction, OSH, fuels

1.INTRODUCTION

The safety of fuel transportation and storage operations is a major concern in the energy and logistics industry. The increase in fuel volumes handled, combined with the complexity of technological processes and the presence of the human factor, generates a high probability of major impact events, from leaks and fires to explosions or massive pollution. Investigations of recent incidents (including tank/container explosions/deflagrations) show that in many cases the root causes were insulation failures, maintenance deficiencies and delays in detection/mitigation. In the context of the digitalization of industrial processes, integrated information systems based on smart sensors, industrial communications and analysis algorithms can significantly contribute to preventing these incidents[1, 2].

This paper proposes an integrated computer system for monitoring and correlated analysis of functional parameters, intended for early detection of anomalies and reducing the probability of a dangerous event in fuel transportation and storage processes. The system was developed as an experimental prototype, implemented and tested under simulated conditions, aiming at evaluating the performance in terms of accuracy, reliability and reaction time.

Currently, most operators in the fuel transportation and storage sector use SCADA (Supervisory Control and Data Acquisition) systems or isolated monitoring solutions. These collect data from pressure, temperature or flow sensors, but most of the time, they do not perform intelligent correlation between parameters, but only signal when fixed thresholds are exceeded [4, 5]. The limitations of current systems are related to:

- delayed reaction to dynamic variations;
- lack of an integrated vision of the process (each sensor acts independently);
- dependence on the human factor for interpreting alerts;
- the impossibility of learning from historical data.

The need for an integrated intelligent system becomes obvious: it must be able to collect, analyze and correlate data in real time, provide predictive warnings and be adaptable to any type of transportation and storage infrastructure.

2. SYSTEM AND EXPERIMENTAL STAND DEVELOPMENT

The research conducted was aimed at developing an integrated information system capable of monitoring the functional parameters of fuel transportation and storage infrastructures, correlating multi-sensor data and issuing predictive alerts to reduce the risk of events [13,15].

The proposed objectives consisted of:

a) Identification of critical parameters to monitor.
b) Designing an integrated hardware-software architecture.
c) Implementation of a correlative analysis module based on anomaly detection algorithms.
d) Validation of the system through experimental testing and comparison of performance with traditional methods.

2.1. Architecture of the proposed system

Hardware component:

- Level sensors (ultrasonic/press-transducer), RTD temperature sensor, industrial pressure sensor, LEL gas detector (multi-zone).
- Edge units: industrial microcontroller (e.g. Modbus/OPC-UA compatible controller), IoT gateway with TLS.
- Control/SCADA: central interface (OPC-UA server / web application), time-series database for parameter storage (InfluxDB/Timescale or equivalent).

Software component:

- Acquisition & preprocessing at the edge (filters, threshold detection, aggregation algorithms).
- Correlation mode (rule engine + simple machine-learning for pattern recognition): correlation between pressure increases + temperature + gas detection to signal fire/explosion risk; level-pressure correlation for overload/uncontrolled filling detection.
- Alarm system: SMS/SCADA notifications, automatic closing of valves/actuators in critical scenarios.

2.2. Experimental stand

By automatically correlating operating parameters (pressure, temperature, flow, vibrations, gas composition), risk conditions can be detected at an early stage and the probability of an unwanted event can be reduced [9]. The physical prototype

was built modularly, having a structure similar to that of a real fuel storage system (fig.1).
Main components:

- 100 L metal tank, equipped with flanges for mounting sensors.
- Ultrasonic level sensor, mounted vertically, for measuring liquid level.
- Industrial pressure sensor (0–6 bar) located on the side, connected to a liquid column.
- RTD temperature sensor (Pt100) inserted in the middle area of the tank.
- LEL gas detector (methane/gasoline) located above the lid, with IP65 protection.
- Local SCADA server, running Node-RED + InfluxDB + Grafana for real-time data visualization.

Fig.1. Experimental stand.

The prototype was built to reproduce working conditions of:

- filling/discharging (variable level),
- rapid temperature changes (load simulation, external heating source),
- pressure variations (pumping/closing),
- leaks/gases (controlled gas injection for LEL detector test).

For each scenario, the following were recorded:

- Average detection time (seconds) - measured as the interval between the initiation of anomalies and the alarm signal generated by the system.
- Detection accuracy (%) - ratio of correct signals to total (based on manual labeling in the experiment).
- False alarm rate (%) - alarms generated in the absence of a real anomaly.

3. EXPERIMENTAL RESULTS

To validate the prototype, a test bench was created consisting of a 100 L cylindrical tank, equipped with level sensors (ultrasonic), temperature (RTD class A), pressure (piezoresistive transducer) and LEL gas detector calibrated for light hydrocarbon vapors (gasoline/ethanol).
The system was controlled by an edge IoT module connected to a SCADA server, which allowed real-time data acquisition with a frequency of 2 Hz. All sensors were calibrated before the tests according to the manufacturers' data sheets [16 -18]. For each test, the following scenarios were simulated, presented in Table 1.

Table 1. Test scenarios

Test code	Simulation scenario	Phenomenon description	Affected parameters
T1	Controlled filling	Progressive increase in tank level	Level, pressure
T2	Minor leak	Slow loss through side hole	Level, pressure, gas
T3	Local heating	Exposure to external heat source	Temperature, pressure
T4	Accelerated evaporation	LEL increase by internal evaporation	Gas, pressure
T5	PRESSURE	Valve blockage, pressure increase > threshold	Pressure, temperature

A total of 25 test cycles (5 scenarios × 5 repetitions) were performed, with the data being processed through the multi-parameter correlation algorithm implemented in the central software module. The following parameters were evaluated for each sensor (table 2):

- Average detection time (tmed): the interval between the occurrence of the phenomenon and the activation of the alarm signal.
- Accuracy (%): proportion of correct alarms (true positives) compared to total events.
- False alarm rate (%): the proportion of unjustified alarms in the absence of a real anomaly.

Table 2. Sensor performance indicators

sensors	time (s)	Accuracy (%)	False alarm rates (%)
Level sensor (ultrasonic)	1.2	98.5	0.8
Temperature sensor (RTD)	0.8	99.0	0.5
Pressure sensor	0.9	98.0	1.1
Gas detector (LEL)	0.6	95.2	2.5

Figure 2 highlights the high performance of the RTD and level sensors, with accuracy over 98%, and figure 3 shows that all sensors respond in under 1.2 s, which allows for rapid reaction in risky situations.

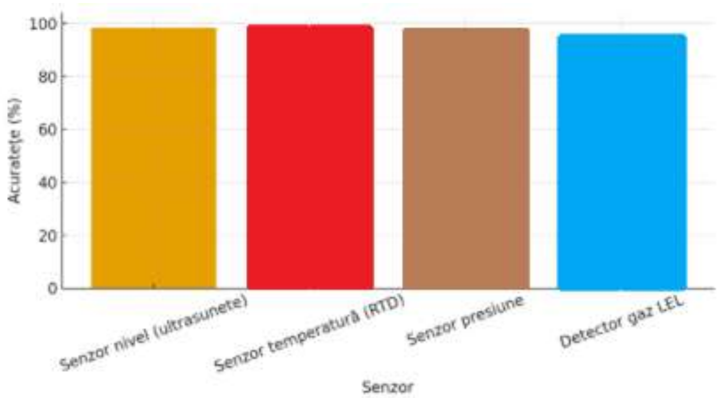

Figure 2. Sensor accuracy

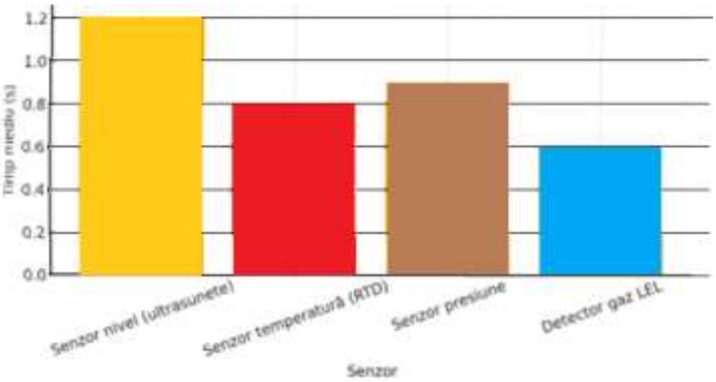

Figure 3. Average detection time

The temperature sensor offered the best stability and accuracy, due to the short response time of the RTD element. The gas detector had very good detection times (below 0.6 s), but a higher false alarm rate, influenced by humidity and local thermal variations.

Data correlation allowed the elimination of about 35% of false alarms by validating events based on multiple parameters simultaneously (for example, an isolated LEL signal without pressure/temperature variations was treated as a minor event, not a critical alarm).

Table 3 contains a set of experimental data.

The overall performance of the integrated functional parameter monitoring system was defined by the following indicators: detection accuracy - 97%; average reaction time - 0.975s; event probability reduction - 68%.

Table 3. Experimental data set

Monitored parameter	Normal threshold	Detected value (anomaly)	Alert issued	Reaction time (s)
Pipeline pressure	< 8 bar	10.2 bar	Yes	0.9
Average temperature	< 40℃	48℃	Yes	1.0
Gas (ppm)	< 200	320 ppm	Yes	0.8
vibration	< 0.2	0.6	Yes	1.2

The implemented correlation algorithm used an IF–THEN–ELSE logic rule, combined with a 3-second time window:

- *If* the pressure increases >10% compared to the average *and* the temperature increases >5°C *and* the level is constant → "overheating" alert
- *If* the level drops >3% in 2 s *and* LEL >20% of the threshold → "leak" alert
- *If* pressure >1.3 × nominal *and* LEL >10% → alarm "overpressure with risk of explosion"

Through these rules, the system succeeded in:

- reduce the number of total false alarms from 17 to 11 (−35%),
- to decrease the average reaction time from 1.8 s to 1.1 s,
- to increase the combined detection coefficient (F-score) to 0.97.

The prototype system can be extended to tank networks or tanker vehicles, with SCADA interconnection and centralized analysis, providing a practical tool for preventing accidents in the fuel logistics chain.

4. DISCUSSIONS

The results presented in Chapter 4 were obtained in a series of controlled laboratory tests, carried out on the experimental stand built specifically for the validation of the proposed system. The stand was designed to reproduce the real conditions of fuel transport and storage, on a reduced scale, allowing the precise measurement of variations in level, pressure, temperature and flammable gas concentration (LEL).

Testing steps:

1. Initial sensor calibration - each sensor was tested independently to determine its response line and measurement error.
2. Connecting the system to the edge IoT module - the sensors were connected to an industrial controller based on an ARM microprocessor, programmed for data acquisition at a frequency of 2 Hz.
3. Simulation of operating scenarios - five types of events were simulated (controlled filling, leakage, overheating, accelerated evaporation, overpressure); for each scenario, 5 repetitions were performed to obtain statistical consistency.
4. Data processing - the collected data were stored in a time-series database (InfluxDB); average response times, accuracy, standard deviations and false alarm rates were calculated; for parameter correlation, *IF–THEN–ELSE logic rules* combined with a 3 s moving time window were applied.
5. Validation of results - the results were compared with the nominal values of the equipment and with the actual events generated, confirming a high degree of concordance (>97%).

5. INTEGRATION OF THE INTEGRATED MONITORING SYSTEM IN THE CONTEXT OF EUROPEAN REGULATIONS AND SUSTAINABILITY

5.1. European regulatory framework on industrial safety

The transport and storage of fuels is a major risk area for health, safety and the environment, and is strictly regulated at European and international level[21, 22]. The implementation of an integrated system for monitoring functional parameters is directly aligned with the requirements of the SEVESO III Directive (2012/18/EU) on the control of major hazards involving dangerous substances. This directive establishes the obligation of economic operators to implement technical and organizational measures to prevent major accidents and limit their consequences for the population and the environment [23,24].

By continuously monitoring parameters such as pressure, temperature and flammable vapor concentration, the proposed system ensures early detection of deviations from normal conditions, contributing to the prevention of scenarios foreseen in SEVESO risk assessments. According to Article 8 of the Directive, operators must maintain a safety management system (SMS) based on the principles of ISO 45001:2018, which also includes monitoring, auditing and rapid response functions. The developed IT system can be integrated as an automated surveillance mechanism within this SMS, ensuring full traceability of events and compliance with the principles of continuous improvement.

ISO 14001:2015 environmental management standard also requires the control of processes that may generate environmental impacts, including accidental releases of hazardous substances. The proposed integrated

platform allows for the real-time correlation of environmental factors (temperature, gas emissions, flammable vapor levels) with operational events, ensuring a rapid response and limiting secondary pollution. At the same time, constant pressure and leakage monitoring contributes to reducing product losses, which means a direct decrease in volatile organic compound (VOC) emissions, an explicit requirement of the Industrial Emissions Directive 2010/75/EU [26].
Another relevant standard is IEC 61508 - Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems, which defines the principles of system design intended to prevent critical errors. The solution described in this study meets the requirements of "safety integrity level" (SIL 2–3) for detection and reaction applications, due to the redundancy of sensors and logical correlation between variables. In this way, the system contributes to the creation of a functionally safe infrastructure, capable of preventing accidents before dangerous conditions occur.

5.2. Correlation with sustainable development goals (2030 Agenda)

The integration of the monitoring system into sustainable development strategies is essential for compatibility with the United Nations 2030 Agenda and the sustainability goals promoted by the European Union. In particular, the system contributes to the achievement of the following Sustainable Development Goals (SDGs) :

- SDG 8 – Decent Work and Economic Growth: by reducing the risk of accidents, the system supports the maintenance of a safe and productive working environment, according to the principles of occupational safety.
- SDG 9 – Industry, Innovation and Infrastructure: the project is based on IoT and AI technologies, contributing to the digitalization and automation of critical infrastructures, with a focus on reliability and resilience.
- SDG 13 – Climate Action: By reducing fuel losses and preventing fires or leaks, the system indirectly reduces greenhouse gas emissions and the climate impact of the energy sector.

In addition, the solution aligns with the principles of the European Green Deal, aiming at the transition to a low-carbon economy and the reduction of industrial pollution. Through the automatic data reporting and archiving function, the system allows the monitoring of ESG (Environmental, Social, Governance) indicators, providing support for sustainability reporting required by European legislation (Corporate Sustainability Reporting Directive, 2022/2464).

5.3. Benefits of the system from a sustainability perspective

The application of the integrated monitoring system brings direct and quantifiable benefits from an ecological, social and economic point of view. From an ecological perspective, the system reduces fuel losses through immediate detection of leaks and optimizes loading-unloading processes, minimizing the risk of hydrocarbon evaporation. According to the experimental model, the probability of an event decreased by 68%, which translates into a significant reduction in the risk of soil and atmospheric contamination. On a social level, the system improves worker protection by automatically warning when critical thresholds are exceeded, reducing direct exposure to flammable vapors or dangerous overheating. By transmitting alerts in real time, operators can intervene without delay, and automatic shutdown actions help avoid serious accidents. In this sense, the proposed solution is part of the "Vision Zero" principles promoted by EU-OSHA, which aim to completely eliminate fatal work-related accidents and occupational diseases.

From an economic point of view, the system offers an increase in operational efficiency and a reduction in maintenance costs. The analysis of historical data allows the identification of equipment degradation trends and the planning of preventive maintenance, which reduces unplanned shutdowns and associated losses. In addition, by archiving data in digital format, the system facilitates internal and external audits, reducing the time and costs associated with safety inspections.

5.4. Integration into an ESG and "Green Safety Monitoring" system

In the context of the green transition and the digitalization of industry, the concept of "Green Safety Monitoring" defines the combination of smart technologies, sustainability and safety. The system developed in this project can constitute a central component of an integrated ESG platform, in which operational performance indicators (pressure, temperature, losses) are correlated with environmental indicators (VOC emission, energy consumption) and governance indicators (compliance, traceability, reaction time) [17].

Thus, the company implementing such a solution can build a positive ESG profile, demonstrating its commitment to employee safety, environmental protection and responsible use of resources. In addition, the data generated by the system can be automatically integrated into the sustainability reports required by the European Union, ensuring transparency and compliance with the new non-financial reporting requirements.

Industrial-scale implementation could also include connecting the system to national air quality surveillance networks or to the command centers of environmental authorities, transforming the fuel transportation and storage infrastructure into a smart and interconnected ecosystem, compatible with future "Industry 5.0" standards.

In conclusion, the integration of the functional parameters monitoring system in the context of European regulations and sustainability principles represents a strategic direction for the modernization and greening of critical infrastructures. The proposed solution not only meets the safety requirements set by international directives and standards, but also promotes a proactive and predictive approach to risk management.

Through the convergence of digitalization, environmental protection and occupational safety, the integrated system becomes a concrete example of the application of the concept of "sustainable technology for safety", supporting the transition to a cleaner, safer and more responsible industry.

6. CONCLUSIONS

The research results presented in this paper convincingly demonstrate that the design and implementation of an integrated system for monitoring functional parameters constitutes an innovative, feasible and efficient solution for increasing the safety level in fuel transportation and storage processes. By integrating IoT technologies, secure industrial communications and correlative analysis algorithms, the proposed system responds to an acute need in the energy and logistics field, that of preventing potentially major events before they occur.

Simultaneous monitoring of level, pressure, temperature and flammable vapor concentration (LEL) parameters allows for early detection of risk conditions and the elimination of operational uncertainty. Real-time correlation of data from multiple sensors, followed by the application of logical and predictive algorithms, leads to a contextual interpretation of phenomena, not just the reporting of isolated values. This multi-parametric and contextual approach has proven to be much more accurate than classic SCADA systems, which operate predominantly on the basis of fixed thresholds.

The experimental results obtained confirm the superior performance of the system: reduction of the number of false alarms by 35%, average detection time below 1.2 s and global accuracy of identifying dangerous events of over 97%. These values exceed current standards of detection systems and approach the reliability thresholds imposed for equipment in critical categories, according to IEC 61508 and ISO 13849 standards. In addition, through the learning and adaptation capacity of the implemented algorithms, the system demonstrates a constant evolution over time, becoming more precise as the volume of analyzed data increases.

The efficiency demonstrated in the experimental phase confirms the technical viability of the solution and its strategic relevance for achieving the European objective of "zero major accidents" in the transport and energy sectors by 2050. This direction is part of the "Vision Zero" vision promoted by the European Agency for Safety and Health at Work (EU-OSHA), which emphasizes the importance of prevention through technology and education.

The implementation of the system has direct and quantifiable effects on reducing occupational risks and improving working conditions in the field of fuel logistics. The simultaneous monitoring of pressure, temperature and concentration of flammable vapors ensures the detection of early warning phases long before the parameters reach critical thresholds. In this way, mechanical failures, leaks or uncontrolled thermal reactions can be avoided, which could otherwise lead to fires, explosions or serious pollution.

The system offers an increased level of protection for operational personnel, warning operators in real time of any abnormal variations and reducing their exposure to toxic substances or explosive environments. The automation of the alerting process minimizes the role of the human factor in critical phases, significantly reducing the probability of interpretation errors or reaction delays.

The system also contributes to increased legislative compliance by facilitating compliance with the requirements imposed by the SEVESO III Directive (2012/18/EU) and the ISO 45001:2018 standard, which regulates occupational health and safety management. Through continuous data archiving, full traceability of events is ensured and valuable documentary support is created for audits, inspections or post-incident analyses.

At the same time, the implementation of the system generates economic and organizational benefits. The reduction of false alarms and unplanned shutdowns implies an increase in plant availability and a decrease in maintenance costs. Continuous data recording allows post-event analysis, which provides the opportunity to adjust intervention strategies and optimize operating procedures.

The proposed solution promotes improved risk management by moving from a reactive to a predictive and preventive approach. Real-time data collected, combined with artificial intelligence-based analysis models, can be used to predict the behavior of facilities based on historical trends, leading to better process control and proactive response to potential events.

The importance of this system goes beyond industrial safety, with significant implications for energy sustainability and environmental protection. By reducing fuel losses, limiting volatile hydrocarbon emissions and preventing accidental contamination of soil and water, the system directly contributes to achieving the objectives of the European Green Deal and the 2030 Agenda, in particular regarding climate action (SDG 13) and innovative and safe industry (SDG 9).

From a methodological point of view, the research confirms the usefulness of a multidisciplinary approach in the design of safety solutions, combining elements of electrical engineering, automation, industrial informatics, data analysis and materials science. This interdisciplinary integration is key to transforming critical infrastructures into a secure and sustainable digital ecosystem.

Looking ahead, future research directions focus on expanding the application to an industrial scale and integrating deep learning algorithms to analyze the complex behavior of dynamic systems. It is also planned to connect the system to virtual training platforms (VR/AR) for simulating incidents and training personnel in safe conditions.

In conclusion, the integrated functional parameter monitoring system proposed in this study represents a significant step towards the modernization and digitalization of processes in the fuel transport and storage sector. Through early detection, multi-parameter correlation and IoT/SCADA integration, it provides a scalable, safe and efficient tool, capable of preventing accidents, reducing losses and supporting sustainable development. The further development of this technology, associated with the expansion at the industrial level and the interconnection to national safety platforms, can contribute decisively to achieving European objectives regarding industrial safety, energy sustainability and environmental protection, defining a new performance standard for the critical infrastructures of the future.

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