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Modular Internet of Things system for monitoring, control and alerting in refrigeration systems using ESP32 and Raspberry Pi 4

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Abstract

With the rapid development of Internet of Things (IoT) systems and the increasing need for smart monitoring and control, this paper presents a fully functional platform for collecting, analyzing and controlling data from an experimental setup based on a refrigeration system.
The main goal is the development of a modular architecture that gathers data from multiple sensors in real time, processes it, and displays it through a web interface. The system detects when key parameters deviate from nominal parameters and automatically sends email alerts to prevent failures and reduce system downtime.
The system uses embedded programming on the ESP32-S3 microcontroller to collect data from temperature and pressure sensors. Simultaneously, a Single Board Computer (SBC) Raspberry Pi 4 runs Python scripts that process the data and collect electrical parameters via a dedicated module. Communication between the microcontroller and the SBC is conducted through a Universal Asynchronous Receiver-Transmitter (UART) serial interface. The ESP32-S3 microcontroller handles data acquisition and sends it to the Raspberry Pi 4, which processes and stores the information in a local Stuctrured Query Language Lite (SQLite) database. The platform supports dynamic thermodynamics calculations using the CoolProp library and visualizes results through the web interface. The experimental setup includes a refrigeration system with R404A refrigerant, featuring a square coil evaporator and an air-cooled condenser.
The implemented platform gathers real-time data from sensors and the electrical energy measurement module, processes it, and displays it on the web interface. The system enables dynamic monitoring and component control by running a logic-based algorithm that continuously checks values and automatically triggers corrective actions, including email notifications, based on system status.
The ESP32-S3 microcontroller includes Pulse Width Modulation (PWM) pins reserved for future connection of frequency converters, designed to regulate the speeds of the compressor and condenser fan. This setup provides a solid basis for developing a smart control system capable not only of passive monitoring but also active intervention on operating parameters, aiming to optimize performance depending on different operating conditions.
This method demonstrates not only the modularity of the proposed IoT platform, but also its ability to perform real-time applied thermodynamic analysis and enable direct regulation of the refrigeration installation, bridging the gap between conventional monitoring and intelligent adaptive control, where existing industrial solutions typically lack such thermodynamical calculation-based control.

Keywords: Iot system, Refrigeration system, Real-time data acquisition, Alerting and notification, Industrial automation.

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1. Introduction

In recent years, the rapid development of smart embedded technologies and open-source platforms has led to more affordable solutions for monitoring and controlling systems. IoT combined with Big Data and AI has already proven its effectiveness in agriculture, where integrated sensing and real-time analytics support sustainability goals and emission monitoring [1, 2]. Similar system architectures are now being adopted in industrial environments as well, where they enable real-time monitoring and adaptive control of energy-intensive processes [3].
Commercial data acquisition systems are often expensive, hard to customize, and limited in how well they can integrate with other equipment or other platforms. In this context, using the ESP32-S3 microcontroller along with compact Single Board Computers (SBCs), like the Raspberry Pi 4, offers a practical alternative for developing flexible and cost-effective technical solutions. This issue has also been highlighted by Lawrence et al., who developed an open-source IoT-based SCADA solution using ESP32 and Raspberry Pi as cost-effective alternative [4]. These platforms support a wide range of sensors and control devices, enabling real-time communication through protocols such as Universal Asynchronous Receiver-Transmitter (UART) and Inter-Integrated Circuit (I^2C) for serial data transfer between electronic components, Universal Serial Bus (USB) for connecting external modules, and Wireless Fidelity (Wi-Fi) and Message Queuing Telemetry Transport (MQTT) for data transmission over local or remote networks [5]. Moreover, layered IoT-based architectures allow implementing control strategies locally, close to the physical equipment, or remotely, through cloud-based services, thus adapting to the diverse requirements of the developed applications [6].
From the authors knowledge, despite significant advances in IoT-based monitoring platforms, most existing industrial solutions remain focused on passive data acquisition and visualization, relying primarily on predefined threshold alerts, without natively enabling real-time adaptive control of refrigeration processes based on thermodynamic calculations. This limitation reduces their ability to optimize performance and prevent failures under variable operating conditions [7].
The main objective of this research is to design, implement and experimentally validate a modular IoT platform capable of real-time monitoring, thermodynamic analysis and direct regulation of refrigeration processes based on calculation. The present work is innovative because it combines low-cost open-source hardware with data processing tools, the study aims to bridge the gap between conventional monitoring systems and intelligent adaptive control solutions applicable to educational and industrial environments. Implementing such as system could lead to lower energy consumption of refrigeration systems and thus lower CO_2 emissions, higher reliability and lower maintenance costs.

This work proposes the development and validation of a complete monitoring and control platform for refrigeration systems that integrate:

- Collecting data from temperature and pressure sensors, as well as from the electrical energy measurement module.
- Communication between components using UART, I^2C, USB, and Wi-Fi interfaces.
- Storing and processing data in a local database based on Structured Query Language Lite (SQLite) [8].
- Showing interactive, real-time data through a dedicated web interface.
- Performing dynamic calculations specific for refrigeration systems using the CoolProp library [9, 10].
- Automatically generating alerts and email notifications based on the system status and any deviations from normal parameters.

The platform allows users to set up automatic rules that trigger control actions, such as turning the refrigeration system's relays on or off. Thanks to its modular design, the platform can be expanded to include smart control of components like the compressor and condenser fan, using Pulse Width Modulation (PWM) signals available on the control board. There is also potential to add frequency converters in the future to optimize the system's operating modes [11] .
This work presents the development and testing of a modular, scalable IoT system designed for real-time monitoring and control of the functional parameters of the experimental refrigeration setup. The platform proves to be useful both for teaching purposes and applied research or prototype development. It includes advanced features for notifications, alarms, and adaptive interventions, with the possibility to extend it to industrial applications. The system architecture for IoT system is presented in Figure 1.

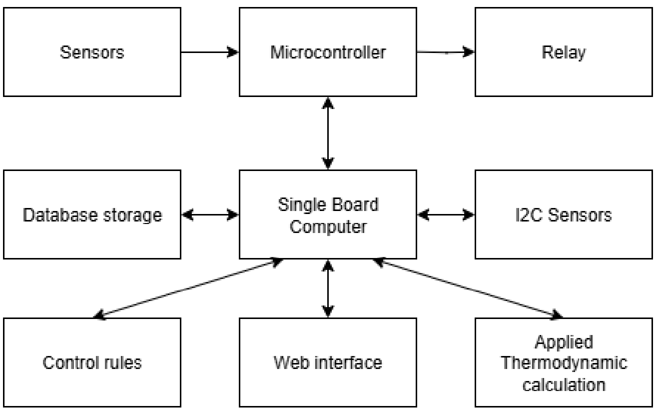

Figure 1. System Architecture for IoT System

2. Experimental setup, objectives and methods

This work proposes the design, implementation, and experimental validation of an intelligent data acquisition and

control platform aimed at monitoring refrigeration systems. The platform focuses on integrating modern hardware and software components within a modular, open, and extensible architecture.
This architecture is mainly designed for monitoring and controlling refrigeration systems that use vapor compression. In these types of systems, the monitored points correspond to critical spots that directly affect the system's performance and durability [12] .

Some of these key parameters include:

- Discharge temperature
- Condenser outlet temperature
- Evaporator outlet temperature
- Temperature inside the electrical panel
- Evaporating temperature
- Condensing temperature
- Electrical voltage
- Compressor current
- Electrical frequency
- Compressor outlet pressure
- Evaporator outlet pressure
- Condenser outlet pressure
- Expansion valve outlet pressure

The experimental setup used in this work is presented in Figure 2. Basically, it is a water chiller that uses a refrigeration system configured to work with R404A refrigerant. The system includes a square copper coil evaporator immersed in a 55-liter water tank (maximum capacity 100 liters) responsible for cooling the water, and an air-cooled condenser mounted at the top of the setup.
At the top of the setup, there is a condensing unit (CML90TB3N) consisting of a compressor, condenser, and liquid receiver that stores the refrigerant after condensation. At the bottom, the expansion valve controls the flow of refrigerant entering the evaporator, where it transfers heat to the water in the tank [13] .
The refrigeration circuit connects these components following the classic vapor compression cycle steps: (1) compression, (2) condensation, (3) expansion, and (4) evaporation [14]. The refrigerant is compressed, sent to the condenser to release heat to the surrounding air, expanded through the valve, and then evaporated in the evaporator [15].
The mechanical design of the stand includes optimized refrigerant pathways to ensure smooth flow and minimize pressure losses. The suction line is oriented to improve the degree of superheating and reduce the risk of liquid refrigerant flooding the compressor. The thermal load on the evaporator can be adjusted by filling the tank with large amounts of water, allowing simulation of high thermal demand conditions. The entire assembly is mounted on a metal frame with multiple levels and equipped with wheels for easy movement. This makes the setup suitable both for teaching and applied research, where it can be adapted to different experimental scenarios.
The refrigeration system is set up to maintain stable working conditions for a predetermined time, with the condensing pressure around 16 bar and the evaporating pressure near 4.60 bar. The main constraint is keeping the superheat (the temperature difference between the refrigerant vapor at the compressor inlet and saturation temperature of fluid at working pressure at evaporator) at a minimum of 8 kelvin (K) to prevent liquid refrigerant from flooding the compressor, protecting internal components and ensuring efficient compression [16].

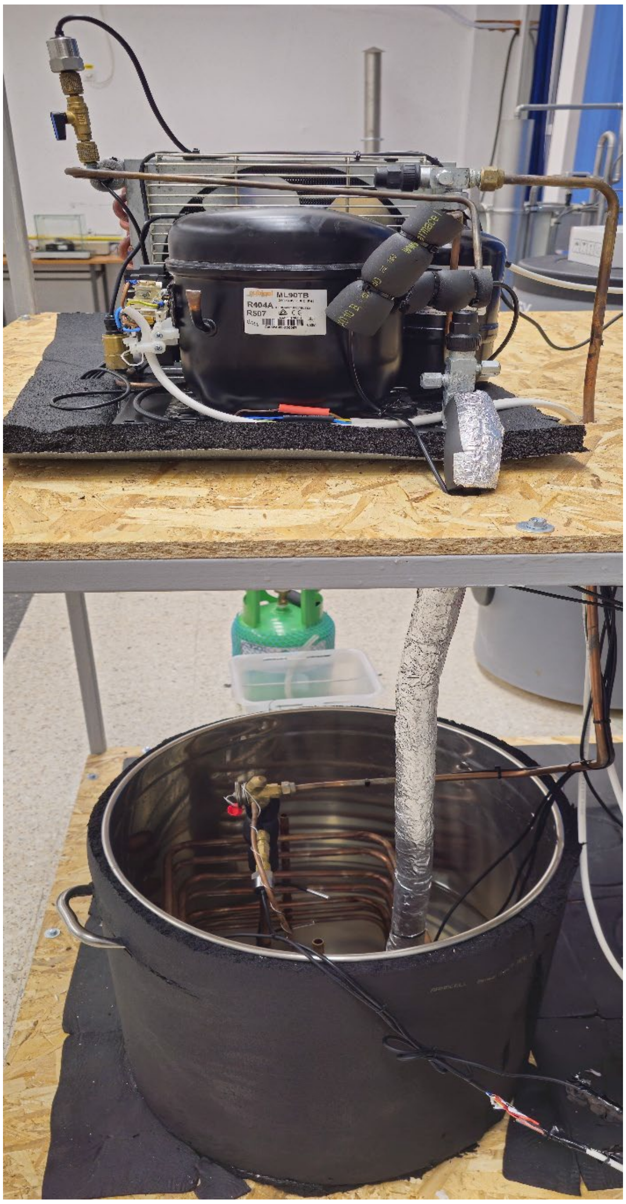

Figure 2. Experimental setup

To achieve the objectives, the study focuses on:

1. Designing an architecture with distributed functions based on the ESP32-S3 microcontroller, used as a data acquisition node, and the SBC unit Raspberry Pi 4, which is responsible for interpreting, recording, and displaying the data [11] .
2. Connecting sensors through different protocols, including:
    a. Digital temperature sensors accessed via a multiplexer,
    b. Analog pressure transducers,
    c. Digital pressure sensors,
    d. The PZEM module for monitoring electrical parameters [17] .
3. Ensuring reliable communication by using the UART asynchronous serial interface between the ESP32-S3 and Raspberry Pi 4. This interface was chosen for its easy implementation and high error tolerance, with clear and simple syntax [18].
4. Implementing a data storage system using a local SQLite database for efficient and flexible operation [19].
5. Automatically calculating essential applied Thermodynamics parameters based on the properties of the R404A refrigerant, using the Python CoolProp library [20].
6. Developing a unified web interface accessible locally, which offers:
    a. Tabular and graphical displays for all monitored variables,
    b. Direct control functionality when the set rules are disabled,
    c. Loading and showing a dynamic p-h diagram with real-time data points overlay.
7. Implementing an automation system based on declarative rules, with periodic evaluation, predefined actions, and safety mechanisms (like a critical lock) to protect the equipment [21].
8. Integrating an electrical protection and control system for the refrigeration equipment using switching relays, contactors, and fuses. This system protects sensitive components like the compressor and condenser from overloads and short circuits, ensuring safe operation. The relays isolate the control circuits from the power circuits, while the contactors handle the control of the power devices, helping maintain efficient and reliable operation [22].

The automation panel shown in Figure 3 combines all the hardware and software (or electronic and electrical) components of the developed platform in a compact setup. It includes the automation board with the ESP32-S3 microcontroller, the SBC Raspberry Pi 4, control relays, and the connection interfaces for temperature, pressure, and electrical parameter sensors.

At the bottom of the panel, one can find the contactors, protection fuses, power distribution block, current measurement module, stabilized power supply for the automation boards, and the main circuit breaker responsible for completely cutting off power in case of failure.

The modular configuration allows easy access for maintenance, modifications, or future expansions. It is optimized for experimental and demonstration purposes but can also be adapted for industrial use and connected to external Supervisory Control and Data Acquisition (SCADA) systems.

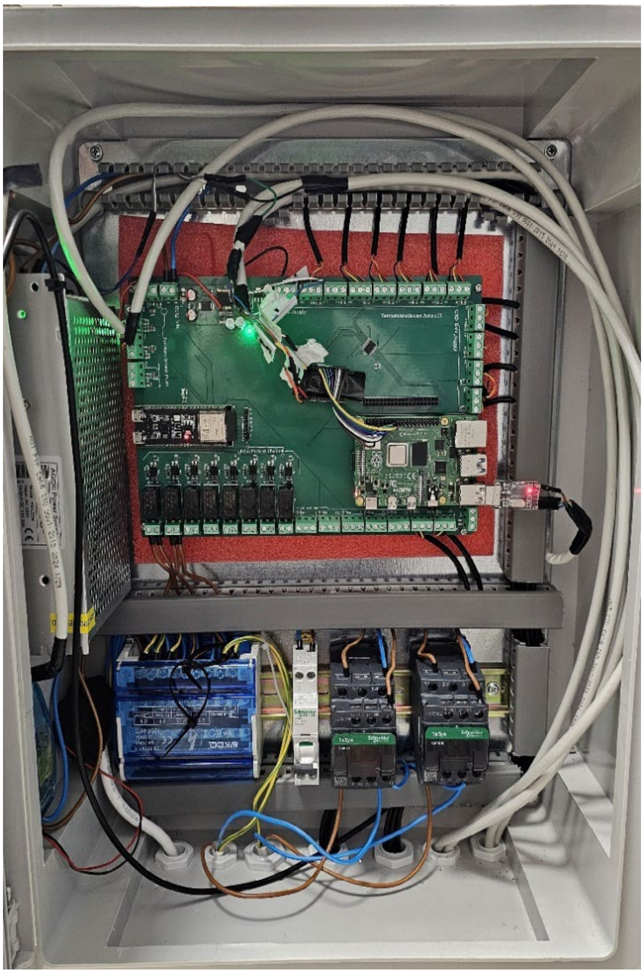

Figure 3. Automation panel

The method used in this work aims to develop a real-time data acquisition and control system based on open-source concepts, capable of monitoring key physical parameters in refrigeration applications. The resulting platform combines hardware and software components, multi-protocol communication, local data processing, applied Thermodynamics analysis, and an intuitive interface that can be easily extended or modified by the end user.

The system is made up of two main parts:

- An ESP32-S3-DevKitC-1-N32R8 microcontroller, responsible for collecting data from sensors and controlling actuators.
- A Raspberry Pi 4 Model B Single Board Computer, which acts as the central unit handling data processing, storage, analysis, and managing the web interface. Communication between the two modules happens through a UART serial interface, using General Purpose Input/Output (GPIO) pins in full-duplex mode. About 75% of the temperature sensor ports, meaning 16 DS18B20 sensors, are connected to the microcontroller through a 74HC4067 multiplexer, which maximizes its performance.

At the same time, the system has 4 dedicated ports for analog pressure sensors with a 0–30 bar measurement range and a 0.5–4.5 V output signal. This signal is hardware-adjusted using a resistor network to fit the microcontroller's accepted voltage range of 0–3.3 V.

The Raspberry Pi receives data from the ESP32 and correlates it with values collected from the PZEM–004T electrical parameter measurement module connected via a USB-TTL converter, as well as from digital pressure sensors integrated via the I^2C interface, accessed sequentially through the PCA9548A multiplexer.

The whole system is powered by a primary 12 V DC source, with voltages distributed and stabilized through two dedicated converters. This helps reduce electrical noise and ensure stable operation of the sensitive electronic components.

To clearly show the overall architecture and how the platform works, Figure 4 presents the system's block diagram, including all relevant systems and subsystems, signal paths, information flows, and communication protocols used.

Table 1. Hardware components and main functions

Component	Model/ Specifications	Main function
Microcontroller	ESP-S3-DevKicC1-N32R8, 32 Mb flash, 8 Mb PS Ram	Data acquisition, relay and PWM pin control
SBC central unit	Raspberry Pi 4 Model b	Processing of acquired data, storage in the database, applied thermodynamics calculations, web interface display
Temperature sensors	DS18B20, protocol 1-Wire	Measuring temperatures at different points
Digital pressure sensors	3.3V – interface I^2C, range -1bar to – 40 bar	Measuring working pressures at sensitive points
Analog pressure sensors	0.5V – 4.5V, range 0 bar to 30 bar	Measuring working pressures at sensitive points
PZEM electrical measurement module	PZEM-004T	Measurement of electrical parameters: current, voltage frequency

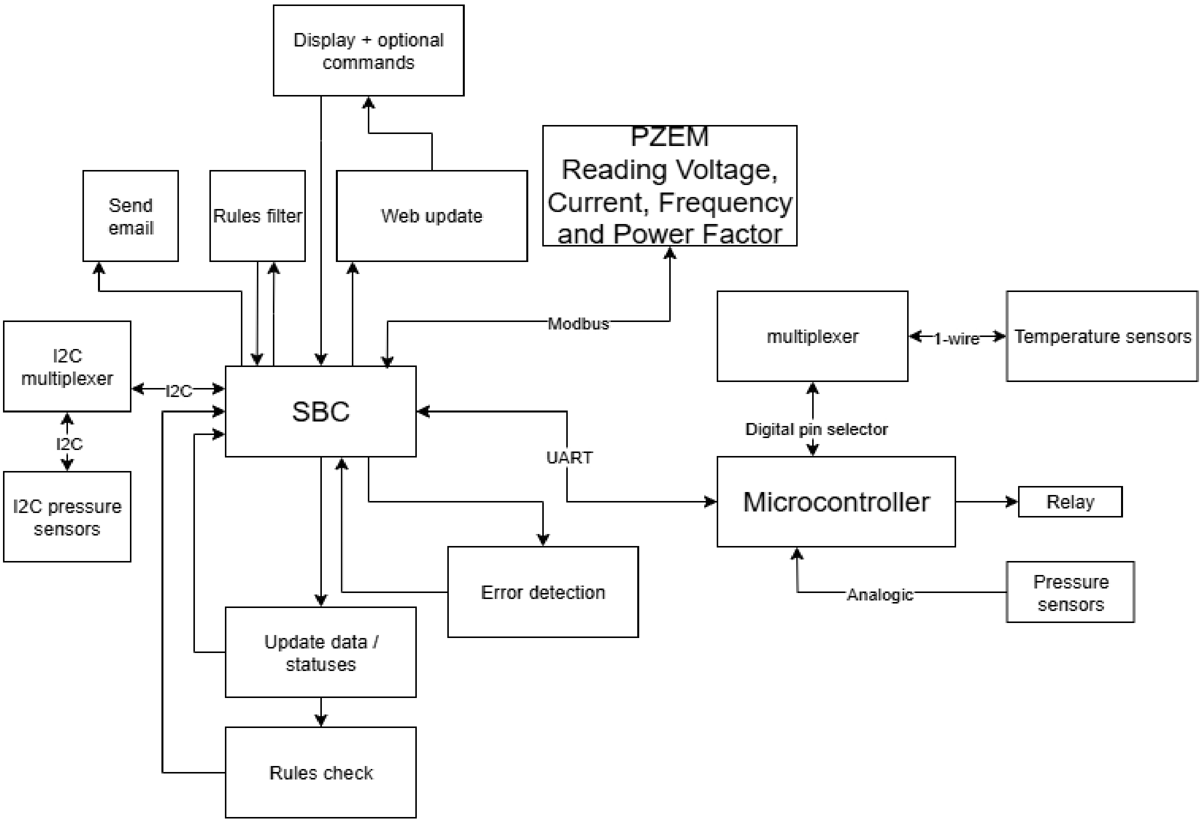

Figure 4. Detailed System Architecture for IoT – Based Refrigeration Monitoring and Smart Control

3. Results

Following the implementation and experimental testing of the developed platform, the feasibility of the proposed architecture has been validated. The IoT system successfully integrates multiple temperature and pressure sensors, along with electrical parameter measurements, using the ESP32-S3 microcontroller for data acquisition and the Raspberry Pi 4 SBC as the central processing node.

The platform allows dynamic data collection, processing, and visualization, confirming the full functionality of both hardware and software architecture (proof of concept). Its modular structure makes it easy to expand with additional subsystems, including integration with external platforms such as SCADA, Home Assistant, or MQTT, through both USB interface and local network protocols.

The web interface implemented on the platform, shown in Figure 5, enables real-time monitoring and control of the refrigeration system. It is designed to be intuitive, giving the user direct access to essential information as well as control and intervention functions.

The current session runtime is dynamically displayed at the top, helping users track how long the system has been operating.

A general status indicator shows the system's current condition, distinguishing between three main states: normal operation, alert level (triggered by temporary crossing of predefined thresholds), and critical level (which activates alarms, switches the system into fault mode, and sends notifications about detected issues).

The interface also includes a module for viewing the history of alerts and notifications, providing detailed records of past events and the system's performance over time.

The control section allows setting reference values for parameters like the tank temperature using dedicated sliders. If critical errors occur, there is a "Reset Critical Errors" button to restore operation within preset parameters without needing a full system restart. Additionally, a button is available to safely shut down the platform, ensuring that data acquisition and communication processes close properly.

At the bottom of the interface, real-time data is displayed for:

- Electrical parameters monitored by the PZEM module.
- Temperatures measured at key points of the system.
- Operating pressures along the refrigeration circuit.

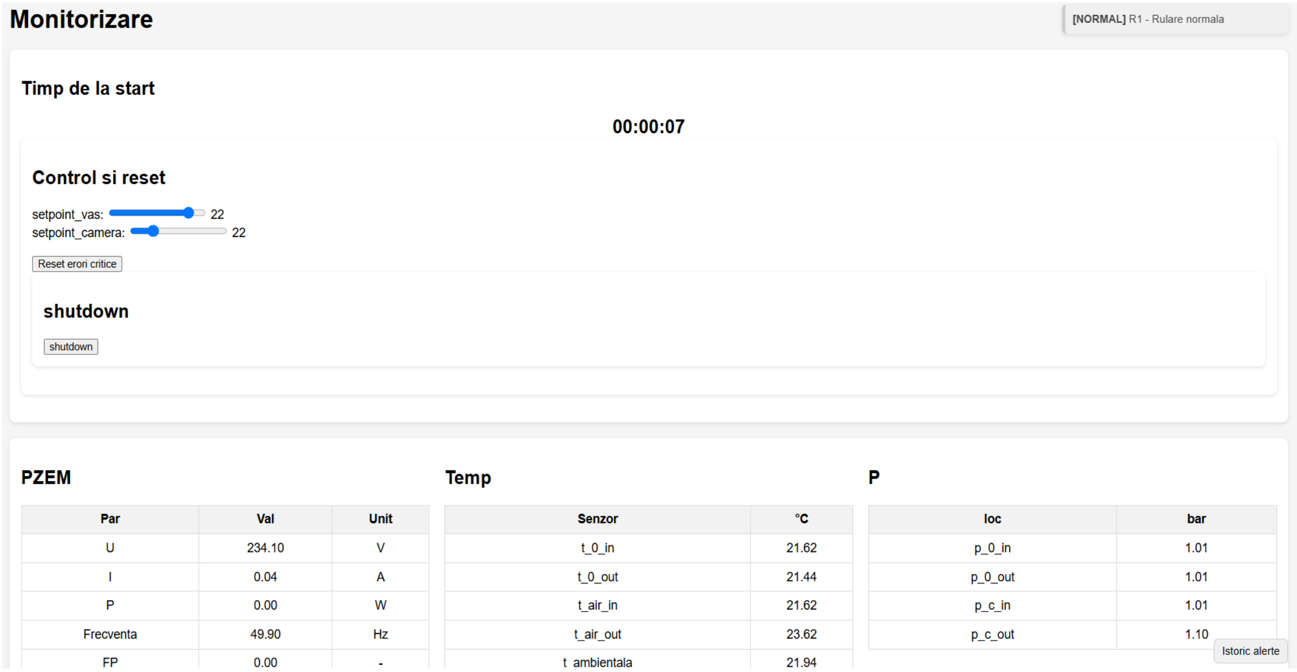

Figure 5. Real-time monitoring and control web interface

This centralized structure provides a clear overview of the system's operation and makes quick intervention easier. Its modular architecture allows for future expansion of features, including adaptive control through PWM pins on the ESP32-S3 microcontroller. These pins are intended for controlling frequency converters later on, to optimize the speed of the compressor and the fan. This capability lays the groundwork for advanced control mechanisms to adjust the superheat level and adapt to changing thermal loads—features that are already planned in the software and anticipated in the interface design.

The next section of the web interface includes advanced features for dynamic control, monitoring, and analysis of the experimental setup. It has a dedicated relay control module that allows users to turn the equipment's control circuits on or off individually, directly from the interface. There is also a software-implemented slider for the PWM channel, shown in Figure 6. This PWM channel is part of the platform's architecture for future integration of frequency converters, enabling automatic adjustment of the compressor and fan speeds to optimize system performance. The graphical part of the interface shows real-time trends of monitored parameters, including temperatures, pressures, and electrical values, displayed as dynamic charts. Users can select which variables they want to analyze to observe trends over time or compare them with other relevant parameters. All acquired data is automatically saved in a local SQLite database, organized by separate sessions. This makes it easy to access measurement history and compare different operating conditions.

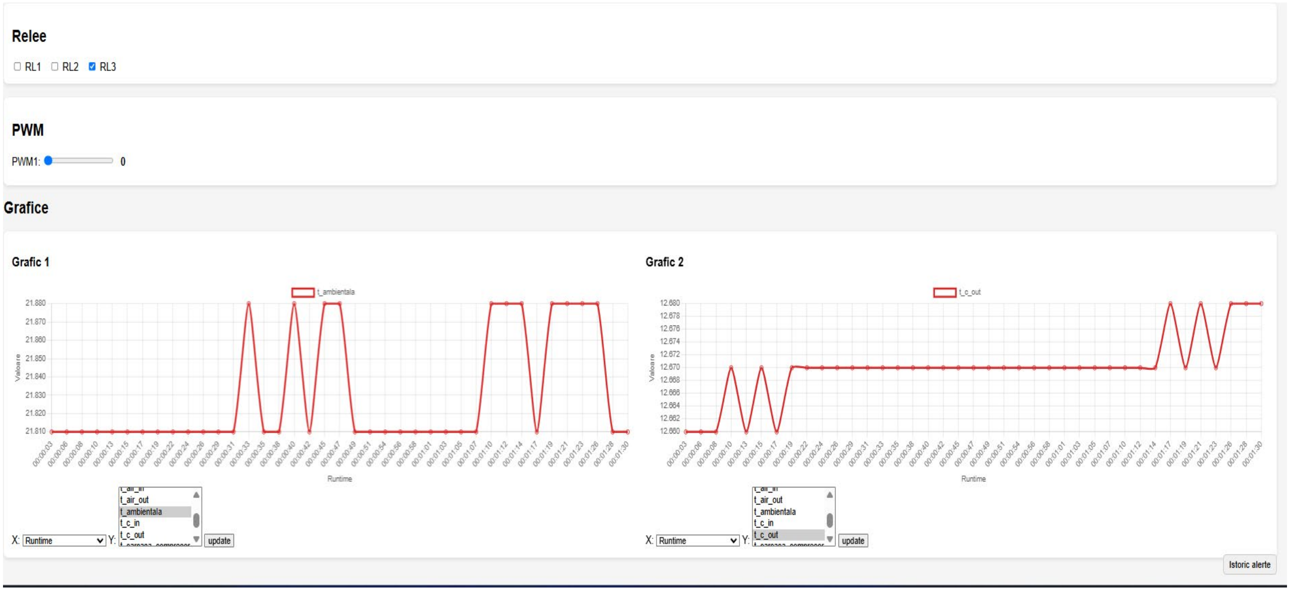

Figure 6. Web interface module for advanced dynamic control, including relay management and PWM

For integrating specialized calculations into the software application, the CoolProp library is used through a Python-compatible wrapper adapted to the Advanced RISC Machine (ARM) architecture. This allows the system to determine the state parameters of the R404A refrigerant, which are needed for performing applied thermodynamics calculations specific to the refrigeration system. The results are automatically processed within the application and used to generate the pressure-enthalpy (p-h) diagram with the measured data points overlaid. This helps with advanced analysis of the processes and is shown in Figure 7. Therefore, the platform provides a comprehensive real-time analysis tool that helps quickly identify deviations from normal operating conditions and supports proactive intervention to optimize system performance.

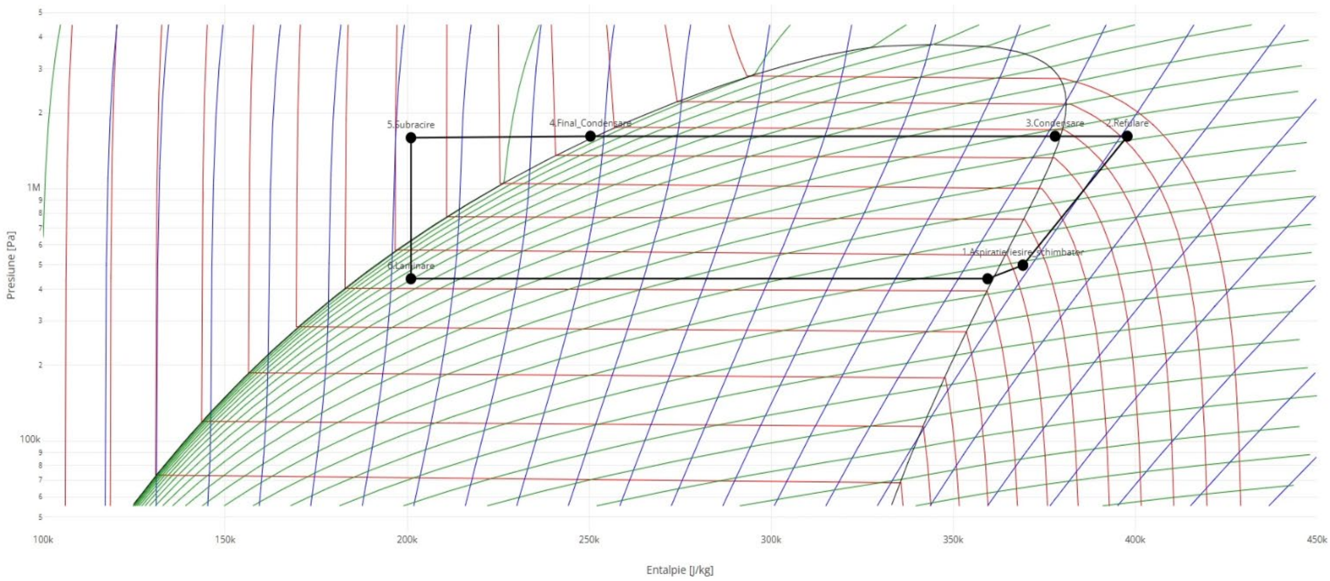

Figure 7. Pressure-enthalpy(p-h) diagram with overlay of measured data points

The platform's automation system features an advanced monitoring model based on configurable logical rules. It continuously evaluates the measured values in real time and automatically triggers corrective actions depending on the level of deviation from nominal parameters. Each rule can be defined individually or as a combination of multiple logical expressions, tailored to the specific operating scenarios of the refrigeration system.

Notifications are managed through a modular alert system capable of sending messages via email (as shown in Figure 9), dedicated apps, or push notifications, configurable based on the user's setup. The alert history is saved and can be accessed directly through the web interface, providing details about recent events such as triggering parameters, exceeded thresholds, and measured values at the time of the alert, as presented in Figure 8.

To protect equipment and reduce response times, each alert can include automatic suggestions for fixing the issue, displayed in the interface and sent through the configured notification channels. In critical situations, the platform automatically acts on the control relays, shuts down the system, and blocks restart until a manual reset is performed via the control interface.

The alert system has a hierarchical structure with three severity levels:

- “Normal” level is the optimal operating state, continuously monitored without generating notifications.
- “Alert” level triggers interactive notifications in the web interface and sends alerts to predefined channels.
- “Critical” level automatically activates safety mechanisms, disables control circuits, blocks system restart, and sends detailed notifications to the user about the problem, along with suggestions for fixing it to allow manual reset and system recovery.

This architecture enables remote monitoring and proactive intervention, supporting safe operation of the refrigeration system and continuous performance optimization under varying operating conditions.

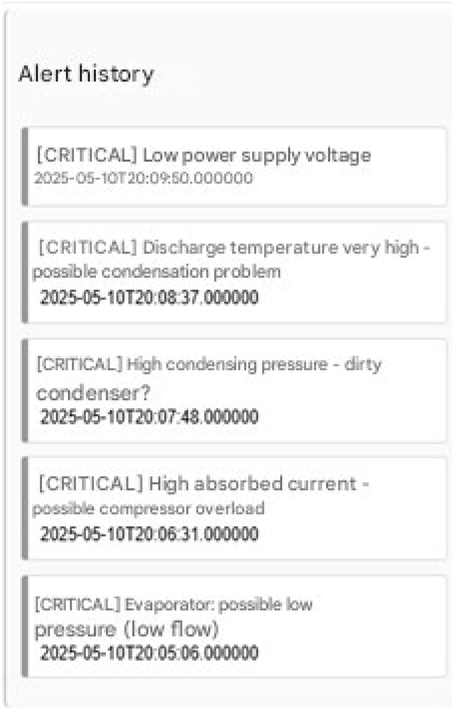

Figure 8. System alert history window

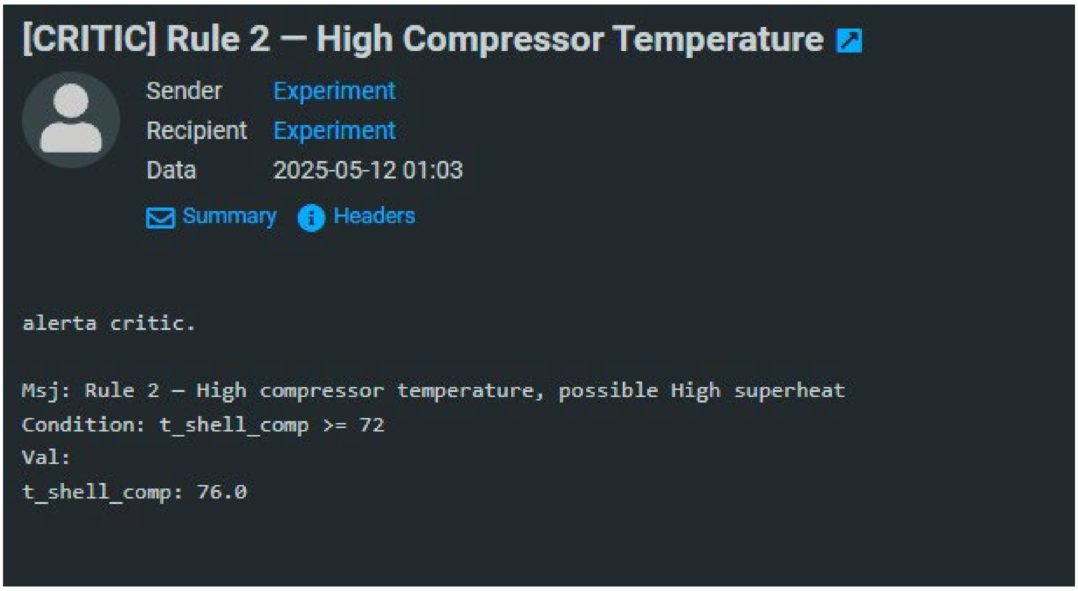

Figure 9. Email notification sent under critical system conditions

4. Conclusions and Future Development

The project presented demonstrates the feasibility of developing a modular Internet of Things (IoT) platform designed for real-time monitoring, analysis, and control of refrigeration system operation. The integration of the ESP32-S3 microcontroller alongside the Raspberry Pi 4 Model B Single Board Computer (SBC) ensures multi-protocol data acquisition from digital sensors (1-Wire, I^2C), analog, and via the Modbus Transistor-Transistor Logic (Modbus TTL) protocol, with local data storage and visualization through an intuitive web interface.

The functionality of the hardware and software architecture is experimentally validated, confirming its adaptability to the specific requirements of modern refrigeration systems. The integration of applied thermodynamics calculations in dynamic mode through the CoolProp library, along with the implementation of an automatic warning and control mechanism, strengthens the platform's applicability not only for educational or research purposes but also in real-world industrial applications. Due to its open and extensible architecture, the developed system addresses current needs in the refrigeration industry, enabling the transition from passive offline monitoring to active, intelligent online control of systems. The approach ensures performance optimization, equipment failure prevention, and a significant reduction in downtime. The proposed platform offers significant technical and functional advantages. Its modular architecture allows the sameless extension of components without affecting overall performance. Furthermore, its high scalability facilitates the integration of additional sensors, actuators, and communication protocols such as MQTT and Modbus TCP, ensuring adaptability to complex industrial applications. The web interface provides fast access to measured data, customized graphs, and real-time control commands directly from the browser, without requiring additional software. The integration of the CoolProp library enables the calculation of specific applied thermodynamic parameters and the analysis of the system's performance coefficient based on acquired data. Stable communication between the ESP32-S3 and Raspberry Pi 4 is ensured through the UART protocol, characterized by low latency and continuous data exchange with error tolerance. In addition to the advantages, the platform presents specific limitations. The limited hardware resources of the ESP32-S3 require sequential reading of digital sensors, generating a minor delay in full data acquisition. The UART protocol does not include advanced mechanism for data integrity verification or complex communication synchronization. Furthermore, local storage through the SQLite database is suitable for testing and experimental use but is suboptimal for distributed access or direct integration with data streams intended for developing machine learning algorithms. To extend the platform's functionalities, various development directions may be considered, such as implementing additional communication protocols, including Modbus TCP and MQTT, and connecting to cloud services such as Amazon Web Services (AWS), thereby facilitating integration within existing industrial systems. The optimization and implementation of a dedicated Application Programming Interface (API) enables multi-platform integration and connection with external applications. Developing a predictive diagnostic system based on historical data and applying Artificial Intelligence/Machine Learning (AI/ML) algorithms allows the anticipation of potential system failures. Additionally, the system architecture allows the integration of advanced security and authentication mechanisms directly at the level of the Raspberry Pi 4 unit. These mechanisms may include multi-factor authentication for user access, role-based access control for different operational levels and the use of encrypted communication protocols (e.g. SSH, HTTPS, VPN tunnels) to secure data exchanges. Currently, the system uses the VPN tunnel. Protection against unauthorized modifications can be ensured through measures such as secure boot, filesystem encryption and integrity verification of critical services, many of which are natively supported within Linux-base operating system running on the Raspberry PI. Furthermore, the implementation of secure Over-The-Air (OTA) update procedures on the Raspberry Pi 4 enables remote maintenance, where firmware or software updates are digitally signed and verified before installation, thus guaranteeing authenticity and preventing malicious alterations. Through this approach, the platform can be remotely managed in a safe and efficient manner, without compromising the integrity and reliability of the overall system. Therefore, the replicability of the proposed solution is evaluated at a high level, as the prototype can be reliably reproduced under comparable laboratory conditions by relying on the provided technical documentation and bill of materials. This reinforces the transferability of the platform beyond the experimental setup, enabling other laboratories and research groups to replicate and further extend the system with minimal integration effort.

In conclusion, the proposed platform validates the feasibility of achieving an integrated monitoring, control and warning system for the refrigeration industry, base entirely on accessible open-source components, including the ESP32-S3 microcontroller and the Raspberry Pi 4. Through its modular architecture and the integration of advanced applied thermodynamics analysis functions, the system fulfills more than the role of a simple data acquisition interface, becoming an active tool for decision support and performance optimization in refrigeration processes.

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