Mohamed Khider University of Biskra
Faculty of Science and Technology
Department of Electrical Engineering

MASTER'S THESIS

Science and Technology

Automation

Automation and Industrial Computing

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Submitted and defended by:

BENNACER AICHA CHANEZ & ATIG AHMED

On: Tuesday, June 3, 2025

Design and Implementation of a Fire and Gas Leak Detection System Based on the ESP32 Microcontroller with Voice Control.

Jury :

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Academic Year: 2024/2025

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Supervisor's Approval:

Prof. MECHGOUG RAIHANE

Signature - Approval of the Jury President

Stamp and Signatur

Abstract

This work aims to design and build a miniature prototype of a fire and gas (F&G) detection and protection system, inspired by technologies used in sensitive industrial facilities, such as oil production plants and stations, including examples such as Sonatrach's SP3 NK1 and OK1Our prototype, developed with available resources, is based on the ESP32 microcontroller, available sensors (MQ-2, DHT11, flame sensor, ultrasound), and a Wi-Fi interface allowing remote control via voice or digital commands.

Keywords: Fire and Gas System, prototype, ESP32, Wi-Fi, remote control, industrial safety, sensors,

Résumé

Ce travail vise à concevoir et réaliser un prototype miniature d'un système de détection et de protection contre les incendies et les gaz (F&G), inspiré des technologies utilisées dans les installations industrielles sensibles, telles que les usines et stations de production pétrolières, incluant des exemples comme SP3 NK1 et OK1 de Sonatrach.

Notre prototype, développé avec les ressources disponibles, repose sur le microcontrôleur ESP32, des capteurs disponibles (MQ-2, DHT11, capteur de flamme, ultrasons) et une interface Wi-Fi permettant un contrôle à distance via des commandes vocales ou numériques.

Mots-clés : Système Feu et Gaz, prototype, ESP32, Wi-Fi, contrôle à distance, sécurité industrielle, capteurs, automates, interface vocale.

ملخص

يهدف هذا العمل إلى تصميم وإنتاج نموذج أولي مصغر لنظام الكشف عن الحرائق والغازات والحماية منها، مستوحى من التقنيات المستخدمة في المنشآت الصناعية الحساسة، مثل مصانع النفط ومحطات الإنتاج، بما في ذلك أمثلة مثل SP3 NK1 و OK1من شركة سوناطراك .

يعتمد النموذج الأولي لدينا، والذي تم تطويره بالموارد المتاحة، على متحكمESP32 ، وأجهزة الاستشعار المتاحة-MQ) 2، DHT11 مستشعر اللهب، الموجات فوق الصوتية (وواجهة Wi-Fi تسمح بالتحكم عن بعد عبر الصوت أو الأوامر الرقمية .

الكلمات المفتاحية: نظام الحريق والغاز، النموذج الأولي، ESP32، واي فاي، التحكم عن بعد، السلامة الصناعية، أجهزة الاستشعار، الأتمتة، واجهة الصوت.

Dedication

To those who were the guiding light in every step I took, the unwavering support in my weariness, the living heartbeat in my moments of doubt…
Without your presence, this dream would never have come to fruition.
I dedicate this achievement not as an individual conquest, but as the ripe fruit of sincere love, constant support, and invaluable presence in my life.

To my beloved mother,
The primary source of infinite tenderness, embodiment of patience and serenity…
Every word in this thesis echoes your prayers, and every step on this path was illuminated by the clarity of your gaze.
I offer you this success, a shining reflection of the generosity of your heart, a subtle fragrance of your benevolent invocations.

To my dear father,
A solid wall and immutable refuge, a protective shade against the sometimes harsh winds of life…
You taught me that perseverance is an invincible force and that silence carries the greatness of sacrifice.
All I have accomplished springs from your planting, and what I will become is the continuation of your unwavering strength.

To my dear aunts,
Sources of tenderness and endless giving, your presence has always wrapped me in comfort and strength.
Your affection, prayers, and warm support have been a safe haven in my life.

To my dear sisters and brothers, true gifts from God:
Rokia, Zahra, Amina, Hiba, Yasmine, Mohammed Ali, Abdessamad, Ismail and Nizar.
You are more than family, you are my strength, my comfort, and my home.

To my entire family,
You are my roots, my refuge, and the essence of this journey.
This work is devoted to you.

To my loyal friends,
In every hardship, you were my anchor and spark.
This achievement bears your mark as much as mine.

To my esteemed professors, and all who planted the seed of knowledge in my mind or uttered a word of encouragement,
Please accept my utmost gratitude and deep respect: without you, this experience would not have held such unique depth and richness.

This dedication cannot fully express my gratitude, yet within its lines lie infinite love and appreciation…

BennacerAicha Chanez

Dedication

This work is humbly dedicated to those who have left an indelible mark on my life and academic journey.

To my dear mother
Your boundless love, unwavering strength, and countless sacrifices have been the bedrock of every step I've taken. Your faith in me was the light that guided me through the darkest moments. I owe you my deepest gratitude.

To my beloved father
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To my dear uncle, Mostefa Mohamed TOUBA
Thank you for your constant support and wise guidance, which have strengthened and inspired me throughout this journey. I am deeply grateful for your presence in my life.

To my beloved family
Thank you for your unwavering belief in me, your constant encouragement, and for being the solid foundation that sustained me throughout this path.

To my loyal friends
Your kindness, patience, and companionship brightened the journey and filled it with meaning. I am truly fortunate to have shared these moments with you.

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ATIG Ahmed

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List of Abbreviations

F&G : Fire And Gas (Detection And Protection System)

SIS : Safety Instrumented System

ESP32 : Espressif Systems Processor 32

MQ-2 : Methane And Quad-Gas Sensor

DHT11 : Digital Humidity And Temperature Sensor

HC-SR04 : High-Capacity Sonic Ranging 04

Wi-Fi : Wireless Fidelity

IEC : International Electrotechnical Commission

NFPA : National Fire Protection Association

ATEX : Atmosphères Explosibles

EN 54 : European Norm 54 (Fire Detection And Fire Alarm Systems)

API : American Petroleum Institute

SIL : Safety Integrity Level

ESD : Emergency Shutdown

PLC : Programmable Logic Controller

HART : Highway Addressable Remote Transducer

LEL : Lower Explosive Limit

UV/IR : Ultraviolet/Infrared

NDIR : Non-Dispersive Infrared

CH_4 : Methane

C_2H_6 : Ethane

C_4H_{10} : Butane

CO_2 : Carbon Dioxide

H_2S : Hydrogen Sulfide

CO : Carbon Monoxide

NOx : Nitrogen Oxides

DCS : Distributed Control System

Modbus : Modular Bus

Profibus : Process Field Bus

Ethernet/IP : Ethernet Industrial Protocol

VESDA : Very Early Smoke Detection Apparatus

FM-200 : Fire Suppression Medium 200

PWM : Pulse Width Modulation

I2C : Inter-Integrated Circuit

GPIO : General Purpose Input/Output

IDE : Integrated Development Environment

VS Code : Visual Studio Code

EDA : Electronic Design Automation

VSM : Virtual System Modeling

IoT : Internet Of Things

WSN : Wireless Sensor Networks

RFID : Radio Frequency Identification

NFC : Near Field Communication

HTTP : Hypertext Transfer Protocol

JSON : JavaScript Object Notation

PHP : Hypertext Preprocessor

MySQL : My Structured Query Language

XAMPP : Cross-Platform Apache, MySQL, PHP, Perl

LPG : Liquefied Petroleum Gas

AO : Analog Output

DO : Digital Output

Ppm : Parts Per Million

RH : Relative Humidity

NTC : Negative Temperature Coefficient

OTP : One Time Programming

ADC : Analog-To-Digital Converter

NO/NC : Normally Open/Normally Closed

COM : Common

OVP : Overvoltage Protection

SCP : Short Circuit Protection

OTP : Overheating Protection

General Introduction

Every year, many people are victims, directly or indirectly, of fires. Burns are among the most serious injuries, often leaving lasting physical and psychological after-effects. In addition, smoke poisoning represents an equally serious danger for the victims. Beyond bodily injury, fires have serious consequences emotional for those affected, which often require a long process of recovery. In a professional context, a fire or a gas leak can cause losses catastrophic. In some cases, resuming activities becomes impossible due to the loss of market share or a prolonged production shutdown. The environmental impact is not negligible either: fires release toxic substances and disperse polluting residues into nature. Material losses, which can amount to several million euros, constitute a real economic tragedy for the affected companies. Thus, the security of the systems is now a crucial issue, both to guarantee the reliability of their operation only to ensure their economic viability. In Algeria, where the hydrocarbon industry is a fundamental economic pillar, the sensitive facilities, such as factories and production stations, operate in environments where the risks of fires, explosions and toxic gas leaks threaten constantly security. Fire and fire detection and protection systems gas (F&G), as safety instrumented systems (SIS), play a decisive role in disaster prevention, by monitoring anomalies in real time and triggering emergency measures to contain incidents.

This project is part of an innovation approach aimed at strengthening security in high-risk industrial environments, drawing inspiration from technologies deployed in installations such as Sonatrach pumping stations (e.g. SP3 NK1 and OK1).

During our internship in these environments, we analyzed the functioning of systems F&G advanced, such as the SILVANI CS400-R and the Simplex 4100U, and noted their crucial role in the protection of operators and sensitive equipment. However, the limits of conventional systems, including their reliance on risky manual interventions in the event of failure of automatic mechanisms, reveal a critical gap. This work offers an innovative solution by developing a miniature prototype of the F&G system, designed with available resources, which integrates a remote control interface insensitive to extreme conditions.

The central problem of this project lies in the limitations of traditional F&G systems in the face of extreme scenarios, where a failure of automatic or electrical mechanisms requires operators to intervene manually in dangerous conditions, exposing their lives at mortal risk. How to design an F&G system capable of ensuring a safe and efficient management of emergency situations in sensitive installations, while eliminating the need for physical interventions near risk areas? This question guide to an innovative solution based on remote control.

The aim of this project is to: design and develop a miniature prototype of the F&G system, using available resources, with a remote control interface via Wi-Fi, evaluate the prototype's performance in terms of rapid detection and responsiveness in fire and gas leak simulations; offer an economical, secure and adaptable to the requirements of high-risk industries, such as the oil industry. The research questions guiding this work are: How can a F&G system based on the Can remote control via Wi-Fi improve security compared to traditional systems? traditional ones in sensitive industrial environments? How effective are traditional ones? simple components (ESP32, MQ-2 sensors, DHT11, etc.) in real-time detection of fires and gases in simulations? Can remote control reduce significantly reduce response time and human risks in emergency scenarios? The adopted approach is based on an experimental methodology, combining design of a prototype based on the ESP32 microcontroller and available sensors (MQ-2, DHT11, flame sensor, HC-SR04), with a Wi-Fi interface for remote control.

Data is collected through simulations of fire and gas leak scenarios, analyzed using software tools like the Arduino IDE, to assess accuracy and system responsiveness. This thesis is structured in three chapters :

- The first analyzes the F&G systems, their architecture, their components (sensors, automatons, actuators) and safety standards (IEC 61511, IEC 61508), with a study

systems observed in sensitive industrial installations

- The second presents the ESP32 microcontroller, the sensors used, and the technologies communication (Wi-Fi, I2C), as well as programming and simulation tools;

- the third describes the design, development and testing of the prototype, with a analysis of the results to evaluate its performance. A general conclusion summarizes

the project's contributions and offers perspectives for its future development.

- The development of the prototype faced technical challenges, including the integration of simple sensors with a Wi-Fi interface and the optimization of responsiveness

in extreme simulated conditions, due to limited resources. These obstacles

were overcome through rigorous iterations and careful programming, strengthening the robustness of the system.

Chapter I

Fire and Gas (F&G) Detection and Protection System in Industrial Installations.

I.1. Introduction

The Fire & Gas (F&G) detection system provides continuous monitoring of sensitive installations in high-risk industrial environments. It combines sensors (gas, flame, smoke, heat) with a certified safety automation system (SIS) and emergency actuators. Its role is to identify any outbreak of fire or leak of flammable/toxic gas, then immediately trigger appropriate protective measures. The objective is to protect personnel, property, and the environment from the devastating effects of such incidents.

Designed as a Safety Instrumented System (SIS), the F&G must meet very strict functional safety requirements. Its deployment complies with applicable international standards: IEC 61511 (process industry), IEC 61508 (safety functions), NFPA 72/850 (fire detection), ATEX directives, EN 54 (fire), etc. These standards ensure complete coverage of critical areas and consistent coordination with other safety devices (ESD emergency shutdown systems, automatic fire extinguishers, fire compartmentation, etc.). The following chapter details the structure, technologies used and application of F&G systems in different industrial sectors.

I.2.Industrial Safety and Issues in High-Risk Sectors

Industrial safety encompasses all the methods, tools, and systems implemented to ensure the protection of people, property, and the environment in an industrial production setting. It aims to prevent, detect, and control incidents or accidents that may occur at any time in industrial processes.

These issues are of particular importance in sectors handling flammable or toxic materials, such as petrochemicals, chemicals, pharmaceuticals, nuclear power or the Voltage industry, where the risks of fire or gas leaks can have catastrophic consequences [4]. For example, in a refinery or gas installation, the constant presence of vapors and gases requires continuous monitoring using catalytic or infrared sensors to detect hydrocarbons, as well as thermal and smoke detectors placed in sensitive areas such as technical rooms [5].

Fire and gas (F&G) detection systems play a fundamental role: they trigger alarms, automatically isolate affected areas (closing valves, stopping pumps), and prevent the spread of the incident. Their architecture is designed to be extremely reliable, with fail-safe structures, redundant paths and continuous self-monitoring, ensuring their proper operation even in the event of component failure [6].

Safety issues cover personnel protection (rapid detection and evacuation), facility safeguarding (prevention of explosions and fires), production continuity (reduction of unplanned shutdowns) and environmental protection (prevention of pollution by combustion or gas leaks). To meet these requirements, F&G systems must comply with strict standards such as ATEX, IEC 61511, NFPA or API, with high performance requirements, such as flame or gas detection in seconds and an extremely low false alarm rate [2] [7] [8].

I.3. Objectives of F&G systems

The main objective of F&G systems is to detect any dangerous situation relating to fire or gas as early as possible and to automatically initiate actions to control the consequences. In concrete terms, they must [5][6]:

- Detect early any abnormal presence (start of fire, accumulation of flammable gas or toxic gas).
- Immediately trigger audible and visual alarms to alert personnel and local emergency services.
- Automatically or manually activate extinguishing devices (gaseous agents, water, foam, powder) and containment devices (fire breaks, insulation) to limit the spread of the fire.
- Order the emergency shutdown (ESD) of the affected installation: this includes shutting down pumps, process valves, and powering off hazardous equipment.

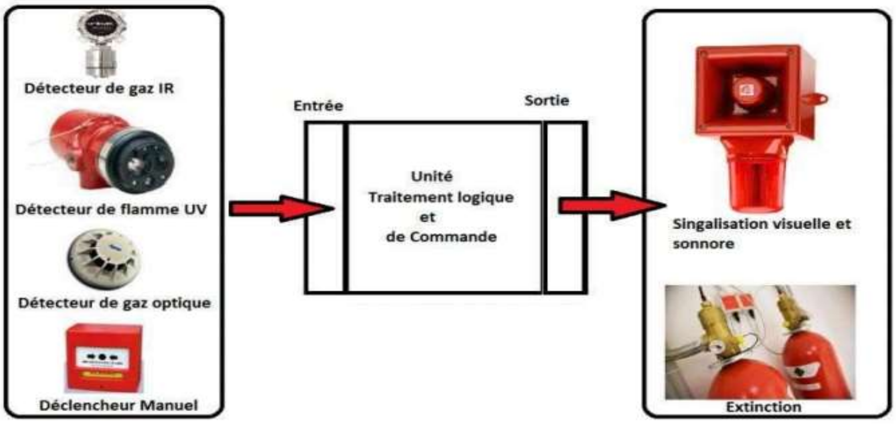

Figure I.1. Fire detection system structure (F&G System).

I.4. Reference standards

F&G systems must comply with a set of international norms and standards that define their technical and safety requirements. The main standards include :

- **IEC 61511 (and IEC 61508)**: these standards specify the requirements for Safety Instrumented Systems (SIS). They impose integrity levels (SIL – Safety Integrity Level) for the design of the controllers and the reliability of the sensors/detectors used. An F&G system must achieve the required SIL depending on the risk level of the process [6].
- **ATEX (European Directive)**: it governs the design, manufacture and installation of equipment in explosive atmospheres. All sensors and actuators deployed in an ATEX zone must be "Ex" certified with the appropriate level of protection (Ex d, Ex ia, etc.) [4].
- **NFPA 72 and EN 54**: These standards cover fire alarm and detection systems. NFPA 72 (fire detection and alarm) and European standard EN 54 (fixed fire detection) describe the minimum performance requirements for smoke detectors, alarm circuits, and sirens. They guide the selection of technologies and the design of maintenance tests.
- **API (American Petroleum Institute)** and NFPA (National Fire Protection Association): In the oil and gas industry, several API (e.g. API RP 14C) and NFPA (NFPA 72, NFPA 75/76) recommendations supplement the requirements, particularly for the monitoring of refineries and offshore platforms.
- **Nuclear standards (e.g. IEC 61513, KTA guide)**: in the nuclear sector, specific standards govern fire and gas safety automation systems (radiation robustness, high redundancy, etc.).

Compliance with these standards ensures that the F&G system meets industry best practices for functional safety. For example, adopting IEC 61511 requires risk analysis, defining SIL levels for each safety loop, and maintaining rigorous documentation. [6]. Therefore, F&G projects must combine normative requirements with local constraints (e.g. national ATEX regulations) to develop a reliable and certifiable solution.

I.5. Architecture and functions of the F&G system

I.5.1. Detection function

The detection function includes all the sensors responsible for measuring the physical parameters of the environment and signaling any anomalies. Each type of sensor is chosen according to the hazard to be covered: flammable gases, toxic gases, flames, smoke, abnormal temperatures, etc. Concretely, a detector converts a physical quantity (for a gas detector: concentration, for a flame detector: UV/IR radiation, for a smoke detector: particle rate, for a heat detector: temperature rise) into an electrical signal. This signal (often 4–20 mA or HART) is sent continuously to the safety controller.

The sensors are strategically located according to the site risk analysis. For example, detectors for light combustible gases (CH_4, C_2H_6) are mounted high up, while heavy gases (C_4H_{10}, CO_2) are detected close to the ground. [4]. Recommendations such as the SAES Aramco regulation define the installation height and protection of probes (anti-splash grids, shelters) [4]. The wiring is shielded to prevent interference, and the connections comply with the ATEX classification of the premises. Each sensor generally has a unique tag and is connected to a separate input channel in the system.

The sensitivity of the detectors is calibrated for the relevant thresholds: for example, for combustible gases, an alarm can be programmed as early as 10–20% of the lower explosive limit (LEL) to ensure detection before the mixture reaches a hazardous area[11]In addition, specific electrochemical gas sensors measure the concentrations of toxic gases (H_2S, CO, NOx, etc.) in processes requiring special vigilance.[12]This plurality of sensors ensures multi-criteria coverage: a complete system thus combines UV/IR flame detectors, catalytic or IR detectors for combustible gases, electrochemical sensors for toxic substances, optical smoke detectors and thermal probes (fixed or linear) to detect abnormal heat.

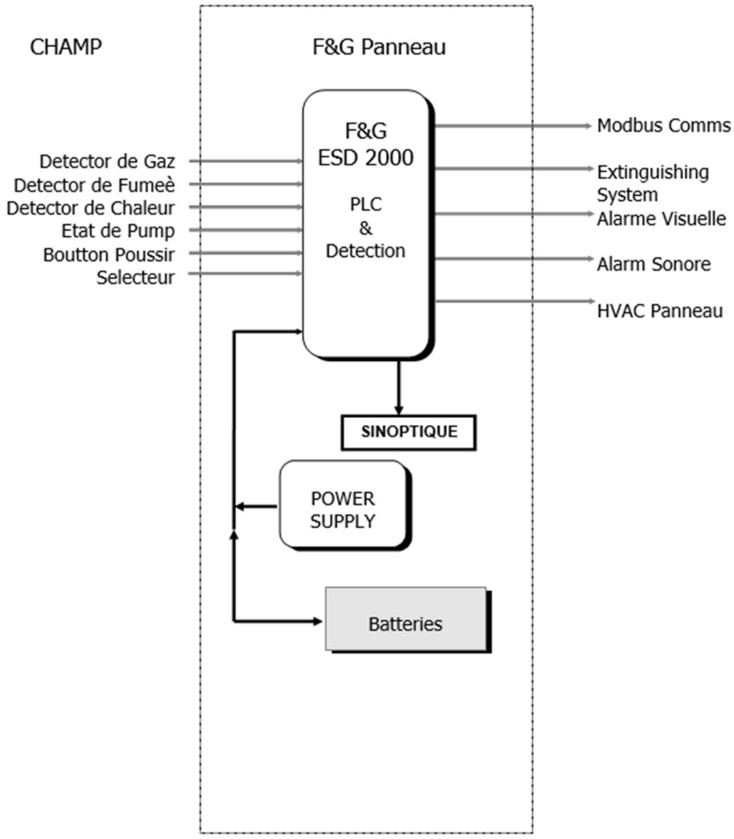

Figure I.2. Typical architecture of a Fire & Gas system.

I.5.2. Control function (safety logic)

The control function is performed by a dedicated safety PLC (e.g. a SIS-certified PLC or an F&G system from specialist manufacturers). This PLC continuously receives signals from the detectors and executes predefined safety logic to validate any alarm. The logic typically includes voting algorithms (1 out of 2, 2 out of 3, etc.), time delays and filtering to reduce false alarms [1][2].

The safety PLC is generally redundant: it has at least two mirrored computing channels (CPU), two independent power supplies and duplicated Input/Output modules [2] [10]. Each channel continuously monitors the other (mutual scanning) and ensures that any anomaly on one channel results in safe neutralization (fail-safe) without interrupting the protection. State changes (switching from one channel to another) are transparent to the operator. This redundant architecture (duplicated controller, redundant inputs/outputs) ensures the high availability required in critical sites, while maintaining the required SIL classification [1].

The safety PLC also exchanges information with other control systems in the plant. It can communicate with the DCS (Distributed Control System) or ESD loops via standard industrial protocols (Modbus, Profibus, Ethernet/IP, etc.), allowing centralized supervision and coordinated triggering of emergency stop loops [10]. In parallel, the PLC has internal diagnostics: it performs permanent self-tests on the sensors (self-monitoring of the flow signal, sensor diagnostics) and on its own hardware (memory, power supplies, redundancy) to detect any drift or internal failure. Fault information is then displayed as an alarm even before it affects operation, to allow rapid maintenance intervention [2].

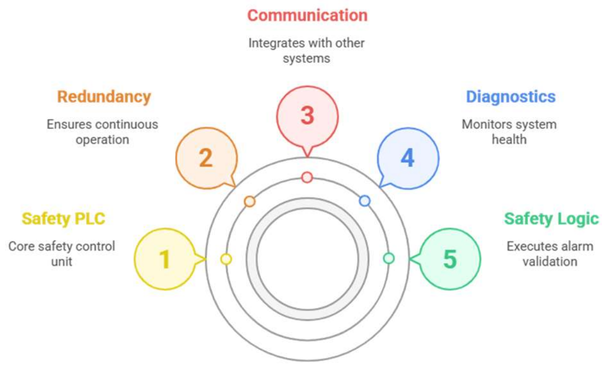

Figure I.3.. Security Alarm Validation Process

I.5.3 Action function

The action function groups together all the actuators controlled by the F&G system to control the detected incident. It mainly comprises two components : alarm and extinction/containment.

- **Alert and evacuation**: Alarm actuators are intended to immediately warn personnel. These include audible sirens, flashing lights, warning panels and manual push buttons. In the event of an alarm being detected, the F&G system simultaneously triggers the sirens and strobe lights located at critical points (corridors, workshops, points of gathering) [4]. Manual push buttons (EN 54-11, ATEX Ex ia) also allow any operator to trigger a fire/gas alarm. Activation of the alarms triggers organized evacuation procedures and notifies internal security services [5].

- **Control of fire extinguishers and action on the process**: When a hazard is confirmed, the system commands the opening of the valves of the distributed extinguishing systems (sprinklers, CO_2/inert gas networks, water mist, foam). For example, solenoid valves controlled by the F&G PLC release CO_2 or FM200 into confined compartments. In open enclosures (platforms, storage areas), the sprinkler networks can be pressurized or the hydraulic deluges can be manually triggered [2]. At the same time, the process actuators intervene: the PLC instantly closes the isolation valves or seismic valves on critical lines to cut off the hydrocarbon supply. It can also order the shutdown of pumps and compressors to reduce the quantity of combustible fluid introduced onto the site [10].

- **Confinement**: Ventilation and compartmentalization actuators protect against the spread of fire or gas. In ventilation systems, fire dampers or sectional dampers are installed that close automatically to isolate the affected area [5]. Similarly, fire doors retract to compartmentalize the building in the event of a fire. For example, in nuclear power plants, the heating, ventilation and air conditioning circuits are shut off to prevent the spread of fire or gas [5][11]These containment actions are crucial to limit the impact to the initial area of the accident.

All of these actuators are controlled by the logic of the PLC as soon as a threat is detected. Coordination between the alarms, the ESD and the extinguishing devices follows pre-programmed secure sequences.

The activation of fire extinguishers and fire breakers is logically preceded by a lifting of the nozzles (if present) or a pressurization of a short delay (a few seconds) to ensure that the personnel begin the evacuation, then generally takes place without human intervention to save time [2].

I.6. Sensors and detection technologies

F&G systems rely on various sensor technologies, each tailored to a specific hazard. Their combination provides comprehensive risk coverage.

I.6.1. Gas detectors

Gas detectors measure the concentration of combustible or toxic gases in the air. For combustible gases (methane CH_4, propane C_3H_8, light hydrocarbons, organic vapors), two main technologies are used [1][4]:

- **Catalytic pellistors**: they contain a resistive bead (often ceramic) coated with a catalyst. In the presence of combustible gas, the exothermic reaction raises the temperature of the bead, modifying its resistance. This variation in resistance, detected by a Wheatstone bridge, reflects the gas concentration.

Catalytic sensors (e.g. type RG3-LCD) are reliable but require oxygen in the air and are sensitive to chemical poisons, hence their use in well-ventilated conditions [6].

Figure I.4. Catalytic Pellistor Gas Detector

- **Infrared detectors (NDIR)**: they measure the absorption of infrared rays by the gas in a certain spectral band (C–H, C=O bonds, etc.). An NDIR detector contains an IR source and two filters (gas and standard). The Beer–Lambert law translates the absorbed intensity into gas concentration. NDIRs are particularly useful for hydrocarbons and CO_2, and offer high immunity to contamination [6].

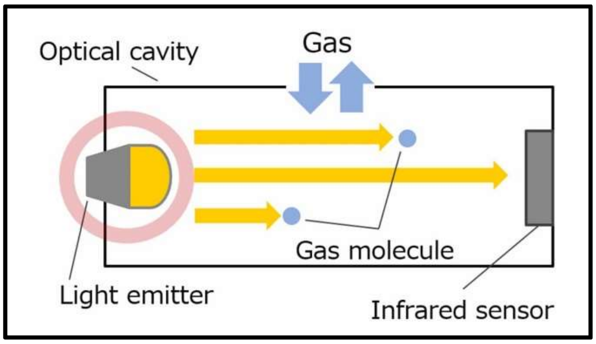

Figure I.5. How an NDIR detector works

Toxic gas sensors (H_2S, CO, NO_2, O_2, etc.) are generally of two types:

- **Electrochemical sensors**: they generate a current proportional to the chemical reaction of the gas on their electrode. For example, electrodes sensitive to H_2S (toxic and corrosive) are often installed near natural gas processing units [12]. Similarly, electrochemical CO probes monitor gases resulting from incomplete combustion.

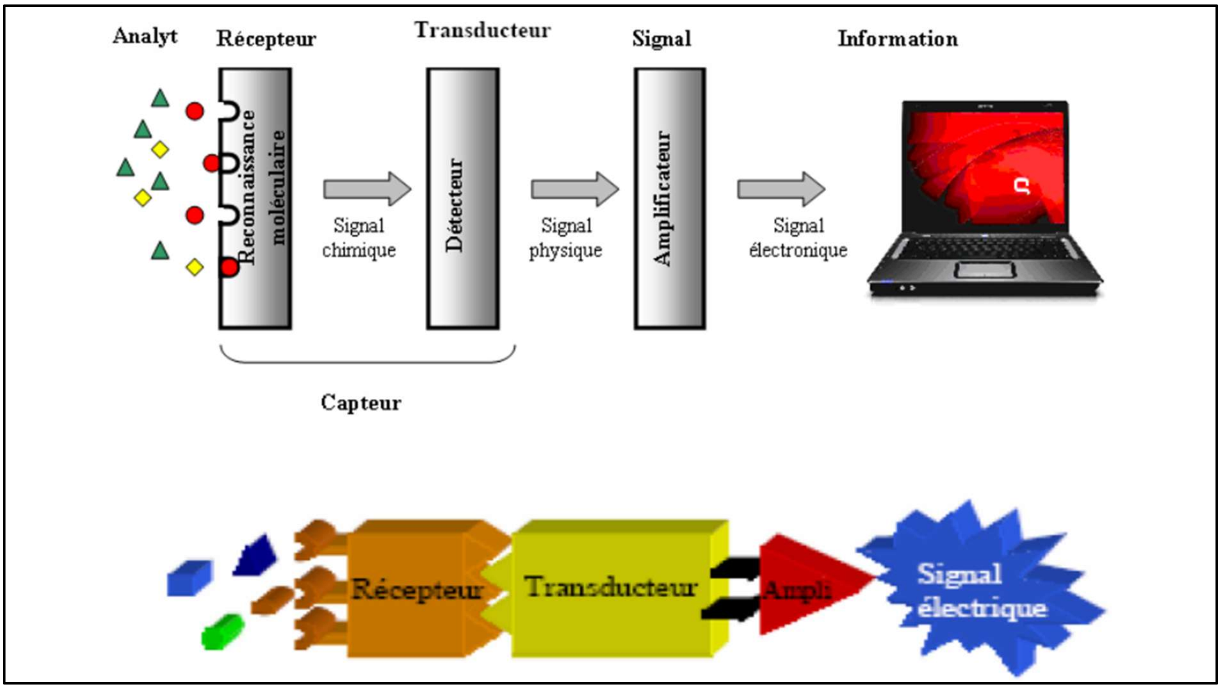

Figure I.6. Operating principle of a bio (chemical) sensor

- **Semiconductor sensors**: these sensors react to gases by variation in the conductivity of the active material. They are more economical, but sensitive to humidity and interference.

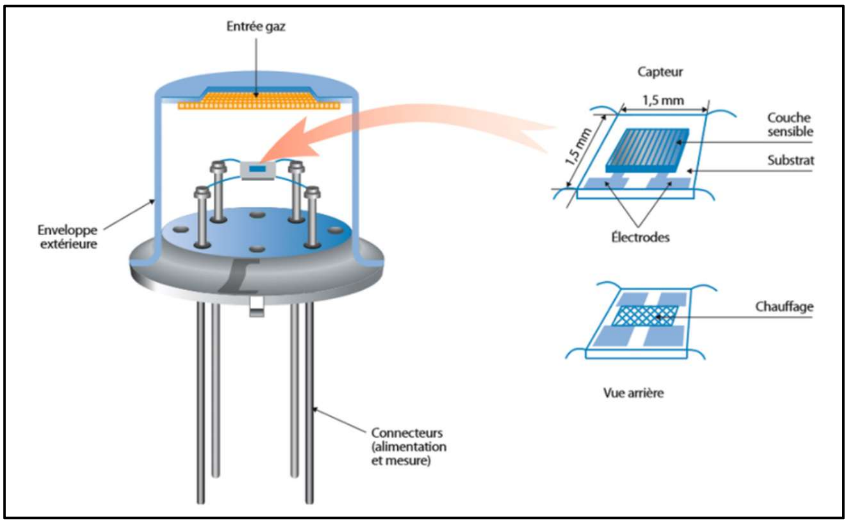

Figure I.7. Structure of a semiconductor gas sensor

I.6.2 Flame detectors

Flame detectors respond to electromagnetic radiation emitted by a burning fire. They are essential in environments where gas or smoke may not be detected quickly, such as large industrial enclosures or outdoor installations [4].

Commonly used technologies are :

- **Dual spectrum UV/IR detectors**: These sensors combine an ultraviolet (UV) detection cell and an infrared (IR) cell. The alarm is only triggered if both signals are detected simultaneously, which makes it possible to distinguish a real flame from a simple light source or parasitic radiation (metallic reflections, lamps, electric arcs). These detectors have a very rapid reaction time, with a detection time often less than one second, particularly effective for hydrocarbon fires [6].

Figure I.8. Dual spectrum UV/IR detectors

- **Multi-zone infrared detectors**: Certain sensitive areas (pipes, technical rooms, explosive zones) can be equipped with thermal cameras or multi-IR detectors analyzing the infrared spectrum over several wavelengths. This multi-band analysis allows reliable remote detection, even in difficult conditions (dust, humidity, vibrations) [6] [10].

Figure I.9. Multi-zone infrared detectors

- **Flame detection cameras**: In large industrial spaces, specialized cameras are used that continuously scan the field of vision for the appearance of flames, using infrared or UV image processing. They offer the advantage of wide spatial coverage and also allow video recording of detected events, useful for post-incident analysis [6].

Figure I.10. Flame detection cameras

I.6.3 Smoke and heat detectors

Smoke and heat detectors complement fire sensors, especially in enclosed or inaccessible areas.

- **Optical (photoelectric) smoke detectors**: They detect soot particles in the air by scattering or obscuring a light beam. Used in civil buildings, offices and control rooms, they react as soon as a fire starts (presence of visible smoke). For example, photoelectric detectors are installed in control rooms or electrical rooms to alert at the slightest internal combustion

[4][6]. Suction systems (VESDA type) exist for very sensitive sites: they continuously sample the air from the room via tubes and detect very low concentrations of particles.

Figure I.11. Optical (photoelectric) smoke detectors

- **Ionic smoke detectors:** These detectors work by ionizing the air inside a chamber containing a radioactive source (usually Americium-241). When smoke particles enter the chamber, they disrupt the ion flow, causing a change in the electrical current that is detected as an alarm. They are particularly effective at detecting the beginnings of fires that burn quickly and without visible smoke (e.g., fires involving flammable liquids or thin papers). They are found in areas such as raised floors, computer rooms, or enclosed offices where early and discreet detection is essential [4][6].

Figure I.12. Ionic smoke detectors

- **Heat detectors**: They are triggered when a critical temperature is reached or when a sudden rise in temperature is observed. Fixed thermostatic detectors (e.g. 68°C) or thermo velocimetric detectors (reacting to the speed of the temperature rise) are commonly used in technical rooms (boiler rooms, transformers, compressors) [4].

  Linear detectors (heat-sensitive cables) can be run along pipes or ducts to detect overheating along their entire length [6]. These sensors are generally used as secondary protection in areas where smoke or flame might not be detected quickly enough.

Figure I.13. Heat detector

The installation of these detectors follows specific recommendations (positioning on the ceiling for smoke, at mid-height or ceiling for heat) and takes into account propagation modes (early detection in corridors, etc.). Their calibration is also periodically checked (aerosol tests for smoke, threshold verification for heat) according to the manufacturer's guidelines.

I.6.4. Specific detectors

In addition to standard sensors, specific detectors can be deployed depending on the site risk:

- **Toxic and special gases**: In chemical or processing units, specialized sensors are installed for very dangerous gases (NH_3, Cl_2, H_2S, etc.). For example, electrochemical probes dedicated to H_2S are used in amine units of refineries for acid gases [12]. Similarly, CO detectors are placed in rooms of incomplete combustion or near diesel engines (deadly carbon monoxide). The sensors are chosen for their appropriate sensitivity and environmental compatibility (temperature, humidity, chemical exposure).

Figure I.14. Toxic and Special Gas Detector

- **Hydrogen in a nuclear environment**: In reactor rooms or nuclear battery areas, radiation-resistant hydrogen detectors monitor the generation of this gas (produced by radiolysis) to prevent a hydrogen explosion [4].

Figure I.15. Hydrogen detector in nuclear environment

- **Oxygen detectors**: In some chemical processes, O_2 detectors monitor the risk of asphyxiation in the event of overpressure of inert gases or CO_2 leaks.

Figure I.16. Oxygen detectors

- **Suction systems**: These highly sensitive systems are used where ultra-early detection is critical (control rooms, nuclear laboratories).
- **Linear detectors:** Linear smoke or CO detectors can be installed in ventilation ducts (offshore sites, machine rooms) to detect a fire in the ducts [4].

Figure I.17. Linear detector

Each specific detector is certified for the intended environment (ATEX, CENELEC, nuclear grade) and selected based on criteria such as detection range and response speed.

I.7. Action and extinguishing devices

F&G-controlled actuators and suppression systems put the facility into a safe state. They are divided into several categories:

I.7.1 Isolation valves

These valves are installed on gas or fuel lines to cut off the supply as soon as a danger is detected. They are generally motorized (pneumatic or electric) valves of the "seismic" or "fire safety" type, capable of closing instantly.

For example, on a gas pipeline, the isolation valve closes as soon as a gas peak is detected, preventing the leak from spreading. In refineries, fast valves on hydrocarbon pipelines are placed at strategic points (ship arrival, key pipes) to limit flows in the event of a fire [4]. The F&G actuators therefore control these valves according to the programmed emergency sequence.

Figure I.18. Isolation valves

I.7.2 Fire extinguishing systems

The control of extinguishing agents is the core of the action function in the event of a confirmed fire. Typical systems are :

- **CO_2 and inert gas tanks (FM-200, Argon, N_2)**: In sensitive confined spaces (electrical rooms, engine rooms), fire extinguisher cylinders are connected to electro-piloted valves. When the alarm is triggered, the F&G controller opens these valves to flood the enclosure with inert gas, thus cutting off the oxygen supply to the fire [4][6].
- **Sprinklers and water networks**: In more open areas (platforms, oil storage areas, cooling circuits), pre-action or deluge sprinkler systems can be triggered. The F&G controller

controls the main solenoid valve which releases pressurized water or foam spray onto hazardous areas [6]. Temperature-sensitive sprinkler heads can also supplement protection by triggering locally.

- **Foam and chemical powder**: For flammable liquid fuels (class B), foam systems (water/foam proportioners) are controlled. Powders (class A, B, C) can be injected to extinguish electrical fires or live equipment. The actuators release the extinguishing agent locally.

Extinguishing systems can be triggered automatically by the F&G alarm or manually by operators. The advantage of automatic triggering is the speed of intervention: even in the absence of an operator, the fire is attacked in a few seconds. The F&G PLC can control a graduated (progressive) or total extinguishing scheme depending on the severity. Extinguishing actuators are tested regularly (flow rate and leak tests) to ensure their effectiveness at the required time.

I.7.3 Ventilation and containment

In addition to extinguishing, containment plays a vital role. Special actuators cut off airflow to prevent the spread of fire or gases:

- **Fire shutters and air intake shutters**: Motorized dampers (ATEX certified) in the ventilation ducts close to isolate the area. This prevents the spread of smoke and fire through the ducts. For example, an F&G extinguishing command can include the simultaneous closing of all fire dampers on a floor within seconds.

Figure I.19. Fire shutters and air intake shutters

- **Fire doors**: Stairwell or airlock doors can close automatically on command from the F&G system to compartmentalize the fire. Their triggering is either associated with the F&G logic or with independent thermal elements.

Figure I.20. Fire doors

- **Circuit breakers and electrical disconnection**: Some actuators cut off the power supply to hazardous equipment (motors, pumps, fans) to eliminate sources of electrical ignition or to prevent the spread of fire by sparks.

Figure I.21. Circuit breakers and electrical disconnection

These ventilation devices are typically operated by a set of controls connected to the F&G PLC outputs. In emergency procedures, shutting off the ventilation (and sometimes creating positive pressure in another area) directs smoke to a programmed outlet, thus protecting escape routes and helping fire crews locate the source.

I.7.4 Audible and visual alarms

Finally, the F&G systems control the on-board warning devices:

- **Sirens and horns**: Sirens (often multi-tone, IP66) broadcast a loud audible alarm in work areas and assembly points.

Figure I.22. Warning siren

- **Flashing lights**: Red strobe lights are triggered simultaneously to signal mandatory evacuation.

Figure I.23. Flashing lights

Voice alert panels: In critical environments, voice messages or pre-recorded alerts can be broadcast to give specific instructions ("evacuate immediately").

- **Manual emergency buttons**: In addition to the automatic detectors, Ex push-button boxes are provided to allow any operator to trigger a general alarm in the event of early human detection or doubt.

Figure I.24. Manual emergency buttons

These multimedia signals guide the evacuation of workers to emergency exits. The activation of local alarms is also often relayed to control centers and external emergency services. The synchronization of sounds and lights is controlled by the F&G API: even in the event of a power outage, backup batteries or an isolated power supply ensure the operation of the sirens for a given period, in accordance with safety requirements [4].

I.8. Safety automatons, redundancy and communication

Certification and reliability matters :

- **SIL and ATEX certification**: The PLC (housing and modules) must be certified Safety Integrity Level compatible with risk calculations (often SIL 2 or SIL 3 in the oil industry) [1] The PLC cabinet is ATEX classified for its installation in zone 2 or 22.[4].
- **Internal redundancy**: In practice, the F&G API is duplicated (two redundant CPUs) with continuous binary synchronization. Each channel has its own power supply, and in the event of a fault on one channel, the other takes over instantly. [3][5]. The I/O modules are self-monitored: a board or sensor fault is reported as a fault (bit fault) and isolated internally. This "fail-safe" architecture means that any hardware failure leads the system to a safe state (for example, closing the valves by default if the PLC shuts down) [1].
- Communication and integration: The F&G PLC exchanges information with the global control system (DCS) or control station via industrial protocols (Modbus RTU, Profibus DP, Ethernet). This interconnection allows F&G alarms to be sent to operators and the necessary process information (pump pressure, valve status) to be received to refine the safety logic. For example, in the event of an alert, the F&G can request the DCS to shut down certain key installations (burners, compressors) or to activate an emergency shutdown scenario (ESD). This interfacability ensures a coordinated response throughout the site [8].
- **Diagnostics and monitoring**: The PLC continuously monitors its own status (program checksums, redundancy, real-time clock, power supplies). Consistency tests of the input signals (detectors) are performed to verify that each sensor is powered and responding. For example, an internal bump test can be triggered periodically to ensure that each gas detector returns to its resting value in the absence of gas. The outputs (valves, extinguishers, sirens) are also supervised: a self-test signals any loss of voltage or open circuit as a fault. Most F&G PLCs provide event logs and operating time counters for each detection/extinguishing loop, in order to trace all interventions [3][5].

- **Fail-safe design**: The system is programmed so that, in the absence of an explicit command (communication bus failure or power off), the default state of the actuators is the safest (typically valves closed, alarms inactive). In addition, voting strategies (e.g. 2 out of 3 detectors must alarm to trigger the action) avoid unwanted alarms. The controllers thus comply with the principle of preventive safety: any uncertainty or fault automatically takes the most protective configuration [1][2].

Thanks to this architecture, the F&G system offers very high overall reliability. For example, in the oil sector, availability of around 99.9% is generally achieved thanks to redundancy and permanent diagnostics. [5]. In addition, standards (IEC 61511, NFPA, API) require regular testing campaigns (functional tests, calibration) to ensure that the desired performance is maintained over time. [1][8] In conclusion, a well-sized and certified safety PLC ensures that the F&G system will always react correctly and quickly when an incident occurs, without unforeseen interruption due to an internal failure.

I.9. Implementation and maintenance

I.9.1 Implementation

The physical layout of sensors and actuators is crucial to the system's effectiveness. It follows the following principles :

- **Risk mapping**: Each risk zone (according to ATEX classes) is identified on the installation plan. The arrangement of the detectors takes into account the prevailing air flows and possible sources of interference. For example, avoid placing a gas detector near a ventilation fan or behind an obstacle.
- **Minimum coverage**: Standards recommend covering at least 95% of critical areas with at least one suitable detector [2] In large spaces, sensor density increases to avoid blind spots. Density maps (based on ATEX 0/1/2) guide the maximum sensor spacing.
- **Mounting height**: Gas detectors are mounted at a height related to the density of the gas (30 cm from the floor for heavy gases, near the ceiling for light gases)[4]Flame detectors are oriented towards potentially flammable areas (surface or hot spots), while smoke and heat detectors generally follow the ceiling of the premises.

- Protection and wiring: Depending on the environment, the sensor housings are made of IP66 stainless steel (resistant to corrosion and water jets) [4]The cables are shielded and routed in fire-resistant or anti-vibration cable trays. In seismic or offshore sites, mechanical reinforcements (stainless steel clamps, anti-vibration mounts) are added.

- System connection: Each sensor is connected to the F&G PLC via safety barriers (for Ex ia loops) or signal amplifiers. Wiring distances can be long (hundreds of meters) without loss thanks to 4–20 mA links and redundant digital protocols.

These implementation principles are verified on site by simulation and testing (air flow study, spot detection tests) before commissioning. Implementation plans are often based on industry standards (e.g. FM Global or IEC 60079-29 for gas detection) [11]

I.9.2 Maintenance and testing

Rigorous maintenance is essential to maintain the reliability of the F&G system. The typical program includes :

- **Sensor calibration**: Gas detectors are calibrated quarterly with standard gases (e.g. methane at 50% LEL for hydrocarbons) [2] This ensures that their response remains linear over the entire measuring range. Electrochemical detectors (H_2S, CO, etc.) are also regularly recalibrated.
- **Functional tests of detectors**: Smoke detectors are tested monthly with a standardized aerosol to check their response time (<30 s) and their detection threshold. [2]. Flame detectors can be tested by specific UV/IR source. Heat detectors are often checked simply by observing temperature variations or by thermal simulation devices.
- Actuator inspection: Isolation valves and extinguishing solenoid valves are checked biannually: they are checked to ensure they open and close correctly (by manual test or internal self-test) and that the extinguisher cylinders are charged to nominal pressure. [1]. Sirens and lights are tested monthly or quarterly to confirm that they activate when the logic is manually overridden.
- End-to-end testing: A complete test of the fire/gas scenario is carried out annually: the sensors are subjected to a stimulus (gas, aerosol, simulated flame), and the complete alarm chain is checked, up to the activation of the alarms and safety valves. The two PLC channels are tested (by disconnecting one then the other) to ensure that they each operate independently.
- Records and instructions: Each maintenance intervention is recorded in a log (schedule, calibration history, detected defects). Checklists (drafted in accordance with NFPA 72 or NFPA 25 standards) ensure that nothing is forgotten. For example, NFPA 72 imposes a

standard schedule: quarterly calibration of gas detectors, semi-annual functionality tests, and monthly visual inspections [2].

Finally, integrity tests are performed periodically to validate the entire system. Database consistency is checked: each physical sensor must correspond to an I/O point in the system, each actuator to an output. Evacuation drills and fire simulations may be organized to prepare personnel and test the overall system response. These maintenances and testing procedures ensure that the performance specified at the outset (fast detection, zero faults, high availability) remains effective over time.

I.10. Examples of Security SystemF&G in the industrial sector (Sonatrach)

I.10.1. SILVANI CS400-R System with Win400 -Station NK1

The SILVANI CS400-R system is an advanced industrial solution dedicated to fire and gas detection, designed specifically for critical installations in the oil and gas sector. It is developed by Central SILVANI, one of the world leaders in industrial protection [2]. This system is installed at the SP3 NK1 pumping station, operated by the national company SONATRACH (National Company for the Research, Production, Transport, Transformation and Marketing of Hydrocarbons). This station is located in the Selga region, on the route of the NK1 (30") oil pipeline which transfers condensate from Haoud El Hamra (HEH) to the coastal terminal of Skikda. The SP3 station is part of a network comprising two pumping stations (SP1 and SP3) with two intermediate pig stations, stations SP2 and SP4 (future stations if necessary), all designed to operate at the same flow rate and without intermediate inlet or outlet points. SP3 has complete dispatch pumps and auxiliary systems, including the Fire & Gas safety system based on the SILVANI CS400-R PLC, which protects sensitive areas such as the electrical room, turbopump shelters, turbogenerator shelters, technical buildings, the expansion tank, the slop tank and the generator set.

I.10.1.1. Hardware Architecture :

The CS400-R system consists of a modular assembly mounted on 19" rack cabinets, including:

Table I. 1 Hardware components of the CS400-R system and their main functions.

Module	Main function
M401	Analog/digital inputs (gas, smoke, flame, temperature sensors)

M402	TOR outputs for actuator control (CO_2, sirens, flashes, valves)
M404	Inter-system communication (link with ESD / DCS)
Redundant CPU	Secure logic processing with non-volatile memory
Internal bus (RS485)	Fast signal transmission between modules
WIN400™ / PS2400™ Operator Interface	Logical configuration, monitoring, event logging

The system allows easy maintenance thanks to hot-swap modularity and automatic detection of module or sensor line failures.

I.10.1.2. Operating Principle

Stages of the cycle:

1. **Detection**: a sensor detects an anomaly (gas, flame, heat, smoke).
2. **Signal**: electrical transmission (4-20 mA or TOR) to the M401 module.
3. **Logical analysis**: processing in the API according to the WIN400™ configuration.
4. **Reaction** :
   - CO_2 extinguishing valve opening control (M402).
   - Activation of visual and audible alarms.
   - Sending signal to ESD system for emergency stop (USD or PSD).
   - Transmission to the DCS system for operator viewing.

5. **Automatic recording**of the incident with timestamp.

The system ensures complete redundancy on critical modules, guaranteeing continuity of operation even in the event of a partial failure.

I.10.1. 3. Software Operation:

The system is programmed via SILVANI's WIN400 platform, which allows:

- Configuration of trigger thresholds (gas, smoke, temperature).
- Establishment of security logic (activation sequences, time delays).
- Defining alarm priorities.

- Automatic assignment of emergency responses (closing valves, automatic extinguishing).

Communication between modules follows the Modbus RTU protocol, ensuring reliability and speed of transmissions [2].

I.10.1. 4. Sensors and actuators used on SP3 BIS with SILVANI CS400-R

Table I. 2 Sensors and actuators used on the SP3 BIS site with the SILVANI CS400-R system

Component	Kind	TAG	Function
CH_4 gas detector	Catalytic	GAS-FG-001	Combustible gas leak
Flame detector	UV/IR	DFT-UVIR-002	Rapid flame detection
Smoke detector	Optical	SD-OPT-003	Fire in electrical room
Heat sensor	Thermostat	HT-TC-004	Overheating in turbine cabin
Thermal cable	Linear	CBL-TH-005	Temperature along the pipes
Manual button	Ex	BTN-MAN-006	Local emergency triggering
Siren and flash	IP65	ALM-007	Audible/visual signaling
Electropneumatic valve	ATEX	PCV-CO2-008	Opening CO_2 bottles

I.10.1. 5. Role of the CS400-R PLC in Security

- The Silvani API is the logical heart of the system. It allows :
- Redundant processing of alarm signals.
- Programming complex logic sequences (e.g: time delay before triggering).
- The direct link with the ESD system, in particular for:
  - Turbine shutdown.
  - Combustible gas isolation.
  - Automatic closing of main valves.

I.10.1. 6. Integration into the Turbine Cabin (Nuovo Pignone PGT10)

In the PGT10 gas turbine, the F&G CS400-R ensures:

- **Rapid flame detection**via UV/IR detectors directed towards the combustion chamber.
- **Temperature monitoring**in the exhaust circuit (J/K type thermocouples).

- **CH_4 leak control**in the gas skid and the distribution box.
- **Direct control of CO_2 extinguishing**in the closed cabin: the solenoid valves open and flood the enclosure.
- **Automatic reaction**: turbine stop➔gas supply shutdown➔extinction.

The closed space design requires a reaction speed of < 3s, which is made possible by the UV/IR combination coupled with Silvani logic.

I.10.1.7. Hardware Architecture :

Table I. 3 Main technical advantages of the CS400-R system

Asset	**Description**
Modularity	Scalable architecture to cover multiple critical areas
Total redundancy	Dual CPU and power supply for uninterrupted operation
Interoperability	Modbus RTU / TOR relay compatible with DCS, ESD
Ease of supervision	Local synoptic, log export to SCADA
Quick maintenance	Automatic fault detection and on-screen diagnostics

I.10.2. Simplex 4100U System + ASA PLC – OK1 Station (SP3BIS)

The Fire & Gas (F&G) system at the SP3BIS pumping station is an industrial safety solution designed for the early detection of fires and gas leaks, with automatic activation of protective devices (CO_2, alarms, HVAC). It is based on a redundant architecture, compliant with industrial safety standards. The F&G system is installed in its sensitive areas: electrical rooms, technical rooms, gas skids, and turbine cabins.

I.10.2.1. System architecture Simplex 4100U System:

The system is based on the Simplex 4100U, mounted in an 8U – 19" rack, integrating specific cards for logic processing and communication. Two redundant CPUs ensure continuity of operation: one active, the other on standby ready to take over in the event of a fault. The program is stored on a FlashPROM memory.

External communication is via redundant Modbus RTU, ensuring secure exchange with DCS, ESD or other PLC systems. This system is supervised by an ASA PLC, which provides the additional layer of security and interoperability, integrated into the F&G modules.

I.10.2.2. Operating Principle of the F&G System (SP3BIS):

The system is based on a redundant architecture comprising:

- Sensors (gas, flame, heat, smoke detectors)
- Industrial programmable logic controllers (standard or safety type PLCs)
- Control modules integrated into the SES (Extinguishing and Security System) cabinet
- Actuators (CO_2 bottle opening valves, sirens, light beacons)

I.10.2.3. Detectors and Actuators:

Detection equipment is installed in critical areas: control buildings, electrical buildings, turbo-alternator rooms, transformers, gas units, etc. Here are the actual devices used on site:

Table I. 4 Detectors and actuators used in OK1 station (SP3BIS)

Element / Equipment	**Type / Tag**	**Location**	**Operating principle**
Gas detector	RG3-LCD	Battery room, HVAC, turbines	Electrochemical and catalytic sensor
Optical smoke detector	2351E	Control room, technical room, turbo-alternator	Optical scattering
Ionic smoke detector	1151E	Underfloor, offices	Ionization
Heat detector	5351E, 27121 (EExd)	Electrical premises, turbines	Thermovelocimetric / Thermostatic
UV/IR Flame Detector - CCTV	FLAME UV/IR	Turbine area, exhaust area	Spectral analysis of UV + IR radiation
Thermosensitive cable	TS-xxx	Expansion tank, gas skid, transformers	Variation of thermal resistance
Alarm push buttons	EFDC / 2470	Indoor and outdoor areas	TOR (All or Nothing) manual trigger
Audible alarm	ET 20MD/4W	All buildings	Multi-tone electronic siren

Visual alarm	MOD. 4481 / 4481	All buildings	Xenon / strobe lamp
Solenoid valves (CO_2 triggers)	PCV-XXX	–	Opening CO_2 bottles

I.10.2.4. Role of ASA Automation and System Integration

The ASA system is referred to in technical documents as "SES-ASA Protection – Fire & Gas Safety Automation System", providing advanced safety control. The ASA PLC manages :

- CO_2 on/off logic
- Signaling to DCS and ESD
- HVAC controls on detection
- Double detection loop with confirmation, ensuring the avoidance of false alarms

I.10.2.5. Typical Operating Scenario (Detection/Reaction Principle)

1. **Detection**: When a detector (optical, thermal or gas) detects an anomaly (smoke, flame, gas), the signal is transmitted to the F&G panel (Simplex 4100U).
2. **Treatment**: The ASA automaton processes the information (double confirmation loop) and triggers:
    - Audible/Visual Alarms
    - HVAC blockage
    - Preparation for CO_2 discharge
3. **Action**: If a second loop confirms, the system sends:
    - Stop signal to ESD/DCS
    - Fire extinguishing gas release control (if required)
    - Notifications on HMI interface and DCS synoptic

I.10.2.6. Application in Turbines

The system is connected directly to the turbopumps (PGT10). Each turbine is protected by:

- **UV/IR flame detectors**in the exhausts;
- **Exd temperature sensors**in the engine rooms;
- **Gas sensors (CH_4 and H_2)** in HVAC and battery areas

- **Thermosensitive cables**around power transformers.

These devices allow for rapid reaction in the event of non-visible combustion, thanks to the spectral response speed of UV/IR detectors.

I.10.2.7. Why the choice of the system and specific detectors (OK1)

The choice of the Fire & Gas system for the SP3BIS – OK1 station is based on rigorous criteria in terms of reliability, responsiveness, compatibility with explosive environments (ATEX) and integration with existing systems (DCS/ESD).

Reasons for choosing the Simplex 4100U system with ASA PLC:

Built-in redundancy ensuring continuity of service.

Multi-phenomenon detection capability (smoke, heat, gas, flame).

High interoperability via Modbus RTU with DCS and ESD.

Programming flexibility via ASA logic modules.

Compliance with international standards NFPA, IEC61508, SIL3.

Justification for the choice of installed detectors:

Table I. 5 Justification for the choice of installed detectors

Detector type	**Technical and functional justification**
Optical Smoke Detectors (2351E)	Insensitive to dust, suitable for ventilated technical rooms.
Exd thermal detectors (5351E)	Resistant to hot environments, installation in ATEX zones.
Thermosensitive cables	Long distance linear detection, ideal for transformers, skids.
UV/IR detectors	Ultra-fast reaction in < 3s, eliminates false alerts related to vibrations or intermittent flames.
CH_4/H_2 gas detectors (RG3-LCD)	High sensitivity, monitoring of critical enclosed areas (HVAC, battery, turbine).
Ex manual alarm buttons	Regulatory requirement in ATEX zones for human intervention.

Thus, each detector was chosen based on:

- The nature of the risk (gas, fire, heat).
- The characteristics of the area (closed, ATEX, transformer, etc.).
- The required response speed.
- Compatibility with the global F&G system.

I.11. Maintenance and Reliability of Systems

The effectiveness of a Fire & Gas (F&G) system depends not only on the technology installed, but also on the rigor of its preventive maintenance, the traceability of periodic tests, and the use of advanced diagnostic tools. This section details best practices for reliability, recommended testing frequencies, and modern monitoring tools.

I.11.1. Good maintenance practices

Unlike other industrial systems, an F&G system must be operational 24 hours a day, even if it is rarely used. Its proper operation therefore relies on a strict maintenance strategy, in accordance with manufacturers' recommendations and international standards such as IEC 61511, NFPA 72, EN 54 or API RP 14C. [4][6].

The main recommended practices are:

- Planned Preventive Maintenance: Regular inspections of detectors (gas, flame, smoke, heat), checking connections, checking battery status, cleaning optical sensors and testing visual/audible alarms.
- Periodic functional tests: Each sensor must be tested using a simulator or standard gas, to verify its response time, accuracy and proper triggering.
- **Software update and security logic verification**: F&G PLCs (APIs) must be inspected to ensure that they have not undergone any unvalidated modifications, and that the programmed logic is still in line with the risk analyses.
- Actuator Inspection: Response devices (valves, solenoid valves, extinguishing systems, alarms) must be triggered periodically, either manually or automatically, to ensure their proper operation under real conditions.
- **Environmental monitoring**: It is necessary to ensure that the detectors are not obstructed, moved or subjected to abnormal conditions (dust, corrosion, vibrations, water jets, electrical interference, etc.).

Lack of maintenance can lead to false positives (harmful) or, more seriously, failure to trigger during a real incident.

I.12. Conclusion

Throughout this chapter, we have examined in detail the structure, operation and requirements of Fire & Gas (F&G) detection and protection systems in high-risk industrial environments. This analysis shows that these systems are based on an instrumented safety logic requiring highly reliable, certified, redundant components suitable for harsh environments (ATEX, humidity, vibrations, extreme temperatures).

Modern detection technologies—whether gas sensors (catalytic, infrared, electrochemical), flame sensors (UV/IR), smoke sensors (optical, aspirating), or heat sensors—enable comprehensive coverage of fire and explosion threats. These sensors, combined with SIL2 or SIL3-certified safety controllers, form the basis of the decision-making chain.

Rapid and coordinated action is ensured by actuators: isolation valves, extinguishing solenoid valves, sirens, fire shutters, etc. Everything is controlled by redundant safety logic, whose “fail-safe” philosophy guarantees an appropriate response even in the event of a system fault.

The real cases studied (OK1 and NK1 Stations, major industrial accidents) confirm the need for careful deployment and rigorous risk analysis to guarantee the operational reliability of F&G systems

Chapter II

The ESP32 Microcontroller and the hardware used.

II.1. Introduction

Modern embedded systems rely on a synergy between electronics, computing, and telecommunications. They integrate hardware and software technologies to monitor and control various parameters and equipment. At the heart of these systems is a key component: the microcontroller.

The choice of sensors, programming languages and hardware platforms is mainly determined by functional needs, technical compatibility, as well as economic criteria (price-performance ratio and market availability).

A fire and gas detection system relies on a network of sensors and hardware components that meet user requirements, all controlled by a microcontroller programmed to provide the required functionality.

In this chapter we will present the ESP8266 microcontroller and the materials used to carry out this end-of-study project.

II.2. Microcontrollers

With the rise of embedded systems, a variety of microcontrollers (microcontrollers) have emerged on the market. Among the most popular are the Arduino, NodeMCU, and Raspberry Pi. Each has distinct features, and the choice depends on the following criteria:

- **Number of analog and digital inputs/outputs**
- **Computing power** (for real-time processing)
- **Program memory** (firmware storage)
- **RAM memory** (temporary calculations)
- **EEPROM memory** (data backup in case of power outage)
- **Price and availability**
- **Connectivity** (Internet access for data transmission)

Microcontrollers fall into three main categories:

1. **4 bits**: dedicated to simple tasks (household appliances).
2. **8 bits**: used for controlling peripherals (joysticks, simple robots, data acquisition).
3. **16/32 bits**: suitable for real-time, process control and multimedia applications.

Below we detail the most popular microcontrollers, appreciated for their flexibility, development tools and extensive documentation.

II.2.1. Arduino

Launched in 2005 as an educational tool, Arduino is an open-source platform that has revolutionized embedded electronics. Easy to use, it is suitable for both beginners and experts [15].

Benefits

- **Affordable cost** (from $3 for clones).
- **Multiplatform** (Windows, macOS, Linux).
- **Intuitive IDE**and C++ based language.
- **Open-source ecosystem** (extended libraries, modifiable material).
- **Robustness** (wiring error tolerance).

Disadvantages

- **Basic Features** (no built-in WiFi, Bluetooth or Ethernet).
- **Limited power** (16 MHz ATMEGA processor).
- **Limited memory** (2 KB RAM, 32 KB ROM).

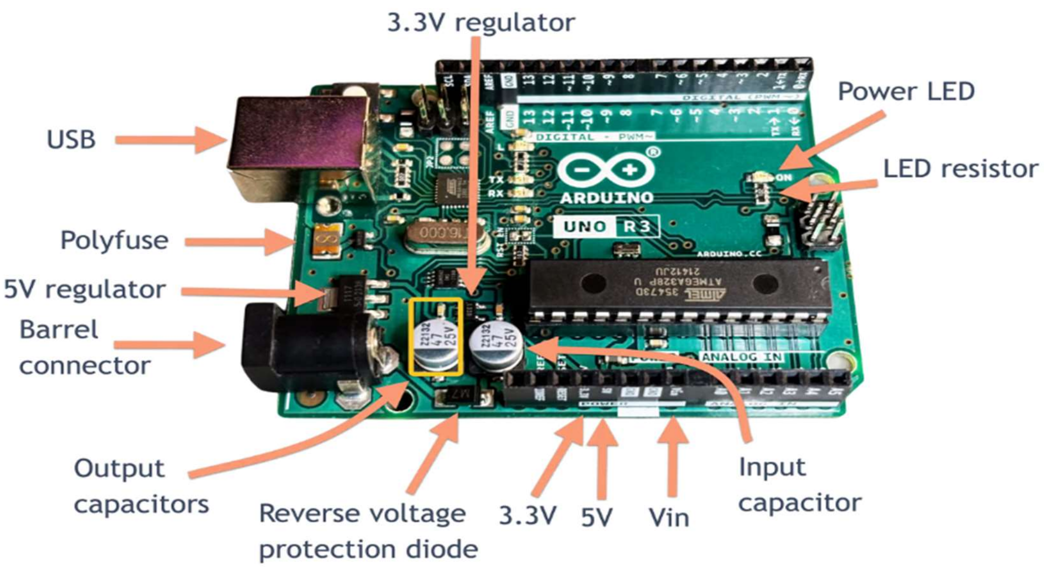

Figure II.1. Arduino Uno

II.2.2. Raspberry Pi

A single-board computer, the Raspberry Pi excels in projects requiring high computing power (e.g., servers, graphical interfaces).

Benefits

- **Complete operating system** (Linux, Windows IoT).
- **Advanced connectivity** (WiFi, Bluetooth, extended GPIO).
- **Multilingual** (Python, C++, etc.).

Disadvantages

- **High cost** (12,000 DA).
- **Complexity** (oversized for simple applications).

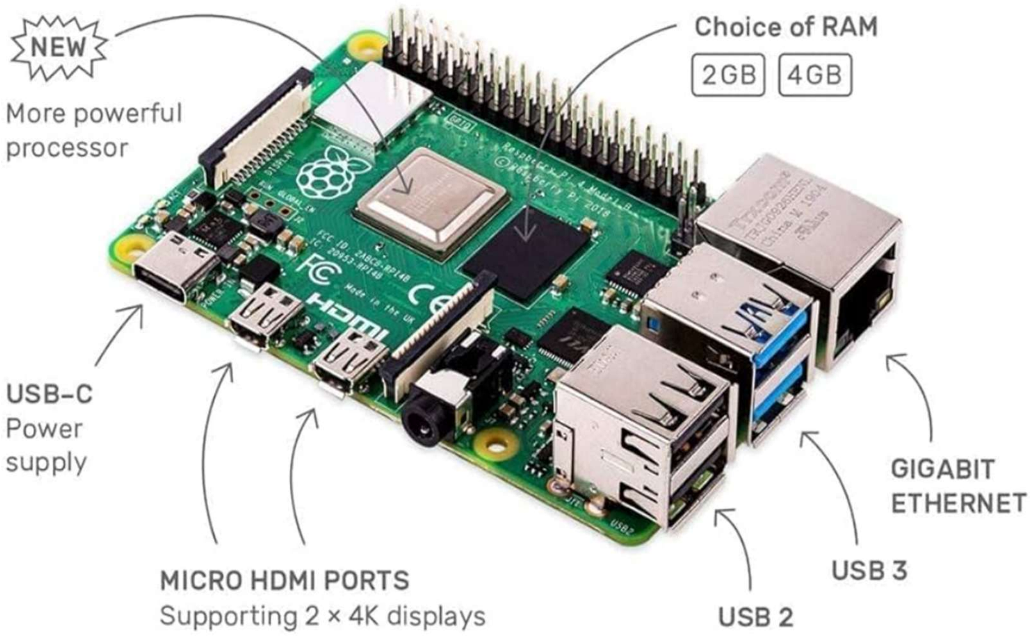

Figure II.2. Raspberry Pi 4

II.2.3. NodeMCU ESP32

The ESP32-based NodeMCU is a powerful, integrated Wi-Fi/Bluetooth development board that is ideal for IoT projects. It is a good replacement for the ESP8266 by offering dual wireless connectivity, more memory, and improved performance [14].

Benefits :

- Dual-core processor up to 240 MHz
- 520 KB of SRAM and up to 16 MB of external Flash
- Connectivity Wi-Fi 802.11 b/g/n + Bluetooth v4.2 BLE
- Multiple GPIOs, integrated ADC/DAC converters
- Optimized energy consumption (Deep Sleep < 10 µA)
- Compatible with Arduino IDE and MicroPython [14][15]

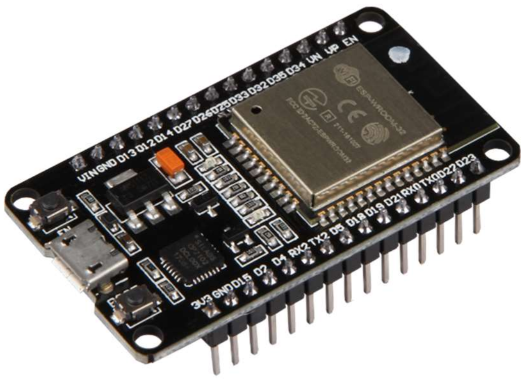

Figure II.3. NodeMCU ESP32

II.3. Selection Criteria for the Optimal Microcontroller

The choice of microcontroller is based on a multi-criteria evaluation:

1. Determining factors :

- Level of expertise required
- Network connectivity
- Number of available I/Os

- Processing power
- Budget

Table II. 1 Technical comparison of microcontrollers

Setting	Arduino UNO	NodeMCU ESP32	Raspberry Pi 4
Price (DA)	2400	2000	12000
Architecture	8-bit	32-bit dual-core	64-bit quad-core
Frequency (MHz)	16	Up to 240	Up to 1500
RAM	2 KB	520 KB	1 to 8 GB
Flash memory	32 KB	4 to 16 MB	microSD
Wi-Fi	No	Yes (integrated)	Yes
Bluetooth	No	Yes (BLE)	Yes
Digital GPIOs	14	Up to 34	40
Analog inputs	6	Up to 18	0

2. Final Technical Decision

Our selection fell on the NodeMCU ESP32 after a rigorous multi-criteria evaluation, taking into account the requirements of the fire and gas detection project.

Decisive Advantages of ESP32 **:**

- **Wi-Fi + Bluetooth connectivity**integrated, essential for remote alerts and hybrid wireless networks [14].
- **Optimal performance/price ratio**: Around 2,000 DA for a powerful and flexible platform.
- **Low energy consumption**, especially in deep sleep mode (<10 µA), crucial for continuous operation on battery [14].
- High processing capacity with its dual core, suitable for the simultaneous management of multiple sensors (MQ2, DHT11, flame, etc.).
- Compatibility with Arduino IDE, ESP-IDF and MicroPython, facilitating prototyping and deployment.

- Built-in security: secure boot, AES/RSA encryption, random number generator [14].

- **Suitability for the Project :**

  - Ability to simultaneously manage multiple sensors (gas, smoke, temperature)
  - Native support for IoT protocols (HTTP, MQTT, WebSocket) for transmitting alerts
  - Compact size of the ESP32 DevKitC module for discreet integration into enclosures
  - High number of GPIOs to connect various sensors and actuators
  - I²C and SPI bus compatibility for easy expansion
  - Ultra-low-power Deep Sleep mode suitable for autonomous systems
  - Flexible programming (C++, MicroPython) according to development needs

This solution represents a reliable, economical and scalable platform for embedded hazard detection systems, while enabling real-time communication with the user, locally or remotely via Wi-Fi/Bluetooth.

II.4. Technical Details of the ESP32 Microcontroller

The ESP32 is a highly integrated microcontroller developed by Espressif Systems, designed to provide an all-in-one solution for connected Internet of Things (IoT) applications. It integrates into a single chip: a powerful processor, dual wireless connectivity (Wi-Fi and Bluetooth) and a rich set of digital and analog peripherals [14].

II.4.1. Technological and historical innovation

Launched in 2016, the ESP32 succeeds the ESP8266 by correcting its limitations while bringing many improvements:

- Dual-core architecture up to 240 MHz
- Added Bluetooth v4.2 (BR/EDR + BLE)
- Multiplication of communication interfaces (ADC, DAC, I²C, SPI, UART...)
- Native security support (encryption, Secure Boot, RNG)

Developed by Espressif Systems, a Chinese semiconductor company, the ESP32 quickly gained popularity due to its versatility, low cost, and strong open source community [14].

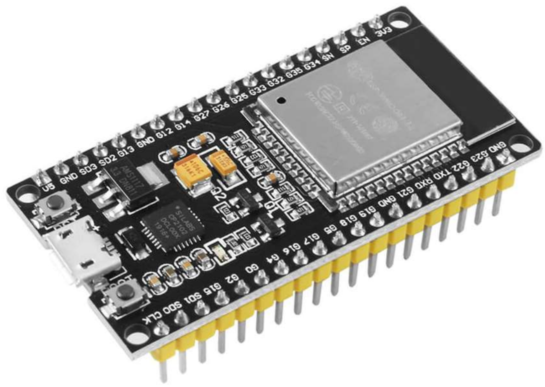

Figure II.3.. NodeMCU ESP32 DevKit V1 Module

II.4.2. Detailed technical architecture

The ESP32 is based on a 32-bit dual-core Xtensa LX6 processor, with an architecture suitable for real-time systems and advanced IoT applications. Each core can be controlled independently, supporting the FreeRTOS operating system for efficient multitasking. The chip includes 520 KB of SRAM, 4 MB of SPI Flash memory (expandable), and hardware blocks dedicated to cryptography (AES, SHA, RSA). This architecture allows us to simultaneously manage Wi-Fi communication, sensor data processing, and remote command execution in our F&G system.

II.4.3. Constraints and Limitations of Pins

Some ESP32 pins have significant constraints that influenced the design of our prototype. GPIO6 to GPIO11 pins are reserved for SPI Flash memory and cannot be used for other functions. ADC2 channels (GPIO0, GPIO2, GPIO4, etc.) are incompatible with Wi-Fi functionality, which is essential for remote control of our F&G system. Therefore, ADC1 channels (GPIO32 to GPIO39) were prioritized to ensure optimal sensor integration. The strapping pins (GPIO0, GPIO2, GPIO12, GPIO15) must be handled carefully to avoid malfunctions at startup, especially when using external pull-up/pull-down resistors. Each GPIO pin can supply a maximum current of 40 mA, which requires careful design to avoid damage. The following diagram illustrates these constraints [14].

II.4.4 ESP32 NodeMCU Pinout

The NodeMCU ESP32 board has a 38-pin connector, offering a wide range of configurable features according to the project's needs:

- Digital and analog GPIOs
- PWM on all pins
- Software I²C bus on any GPIO
- UART0, UART1, UART2
- Hardware SPI (up to 4 lines)
- Analog inputs (ADC): up to 18 channels
- Integrated DAC: 2 channels
- Capacitive detection (touch sensors) [14]

Important note: Some pins (GPIO6 to GPIO11) are used for SPI Flash memory and should not be assigned to other functions. In addition, the ADC2 pins cannot be used simultaneously with Wi-Fi, and the strapping pins require special attention. These features were taken into account to ensure compatibility with our F&G system requirements. The following figure illustrates the ESP32 pin functions, distinguishing between safe pins and those to avoid.

Figure. II.4. Pinout diagram of the ESP32 NodeMCU

II.4.5. Available Power Supply Modes for the ESP32

1. **Power supply via USB port (recommended for development)**
    - **Use**: ideal for programming and testing phases.
    - **Input voltage**: 5V (converted to 3.3V by a regulator integrated into the card).
    - **Benefits**: ease of connection, no additional configuration required [15].
    - **Boundaries**: dependency on a computer or USB source.
2. **Power supply via 3.3V pin**
    - **Use**: suitable for autonomous deployments when a perfectly regulated voltage source is available.
    - **Prerequisites** :
        - A stable external power supply at 3.3V.
        - A precision voltage regulator if the source exceeds this value.
    - **Main advantage**: allows complete isolation from the PC or any USB device.
    - **Attention**: any overvoltage can irreversibly damage the card [15].
3. **Power supply via the VIN pin (or "V5" depending on the card)**
    - **Features** :
        - Recommended input voltage: between 7V and 12V.
        - Maximum current: up to 800mA depending on the on-board regulator.
        - Internal regulation to 3.3V provided by the integrated circuit.
    - **Restrictions** :
        - Do not directly connect 3.3V devices to the VIN pin.
        - Absolute maximum voltage not to be exceeded: 12V, at the risk of damaging the voltage regulator [42].

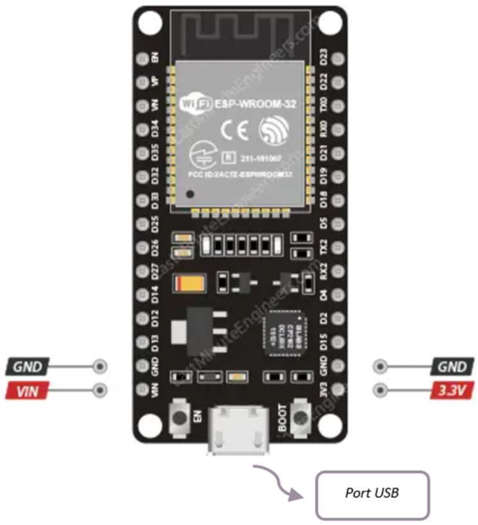

Figure II.1. ESP32 Power Pin Diagram

II.4.6. Technical Characteristics of the Module

The NodeMCU ESP32 DevKitC module is based on the ESP32-WROOM-32 or ESP32-WROVER depending on the version. It combines the following features :

1. **Dual-core architecture**
    - Real-time multitasking
    - Built-in FreeRTOS support
2. **Extended memory**
    - 520 KB SRAM
    - 4 MB SPI Flash (expandable)
3. **Connectivity**
    - Wi-Fi 802.11 b/g/n
    - Bluetooth v4.2 + BLE
4. **Development and programming**
    - Arduino IDE, ESP-IDF, MicroPython compatible
    - Programming via USB (built-in USB-UART converter)
5. **Diagnostic LEDs**
    - LED connected to GPIO2 (often used for code testing)

II.5. Communication Protocols

II.5.1. Presentation and role in intelligent systems

Communication protocols are sets of rules and conventions that govern the exchange of information between different electronic or digital devices. They ensure the consistency, reliability, and synchronization of transmitted data, thus enabling efficient interaction between heterogeneous components in complex systems. These protocols are essential in many fields, including embedded systems, the Internet of Things (IoT), computer networks, and industrial applications, where communication between sensors, microcontrollers, actuators, and servers must be perfectly orchestrated. A communication protocol defines the syntax, semantics, and timing of data exchanges. It specifies how data is formatted, how errors are detected and corrected, how devices identify each other, and how transmission is initiated and terminated. These rules ensure that information sent by a transmitter is correctly received and interpreted by a receiver. [27].

II.5.2. Types of protocols:

Protocols can be classified according to their transmission mode [27] [28]:

- **Series: UART**, SPI, I2C — used in embedded systems for point-to-point or multi-device communication.
- **Parallel:** Simultaneous transfer of multiple bits, fast but complex wiring.
- **Wireless:** Wi-Fi, Bluetooth, Zigbee — essential in IoT.
- **Network: TCP**/IP, HTTP — communication over the Internet.
- **Industrialists:** Modbus, CAN — robust for industrial environments.

II.5.3. The I2C Protocol:

The I2C (Inter-Integrated Circuit) protocol is a synchronous serial communication bus developed by Philips (now NXP). It uses only two wires: SDA (Serial Data Line) for data and SCL (Serial Clock Line) for the clock. This simplicity reduces wiring and facilitates integration into embedded systems [27] [44].

I2C is based on a master-slave architecture. Each slave device has a unique 7- or 10-bit address. The master initiates communications, generates the clock, and controls sending or receiving. The bus supports multiple masters and up to 127 slaves (in 7 bits).

Benefits :

- Only two threads, reducing complexity.
- Shared bus with multiple addressable devices.
- Multiple speeds available: 100 kbit/s (standard), 400 kbit/s (fast), up to 3.4 Mbps (high speed).
- Supported by most modern microcontrollers and sensors.

Disadvantages :

- Speed lower than SPI.
- Limited bus capacitance (approximately 400 pF).
- Complex conflict management with multiple masters.

Justification for choice: For a NodeMCU ESP8266/ESP32-based fire and gas detection project, using I2C allows connecting multiple sensors and modules (such as PCA9685 and ADS1015) while freeing up GPIO space. This protocol allows for easy expansion, minimal wiring, and seamless integration into modular systems, while maintaining low power consumption—a crucial criterion for standalone systems [28].

Table II. 2 comparison of UART, SPI, I2C protocols

Criteria	**I2C**	**SPI**	**UART**
Number of threads	2 (SDA, SCL)	4+ (MOSI, MISO, SCLK, SS)	2 (TX, RX)
Type of communication	Synchronous, multi-master/slave	Synchronous, master/slave	Asynchronous, point-to-point
Maximum speed	Up to 3.4 Mbps	Up to 10+ Mbps	Up to 115 kbit/s typical
Material complexity	Low (pull-up resistors required)	Higher (more lines, SS management)	Very weak
Number of devices	Up to 127 (7-bit) or 1024 (10-bit)	Limited by the number of SS lines	Usually 2 (point to point)
Robustness	More robust	More robust	Simple but error-prone
Energy consumption	Moderate	Higher (continuous clock)	Weak

Typical applications	Sensors, EEPROM, RTC, LCD	Flash memory, ADC, displays	GPS modules, Bluetooth, serial consoles

II.6. Programming Environment

II.6.1. The Arduino IDE

The Arduino IDE (Integrated Development Environment) is an essential tool for programming IoT devices using the ESP8266 module. This open-source software provides a comprehensive platform for writing, compiling, and transferring code to ESP8266 modules, while ensuring seamless integration with the Arduino ecosystem.

II.6.1.1. General presentation

The Arduino IDE provides a simplified programming environment based on the C/C++ language, compatible with ESP8266 modules thanks to the addition of boards via third-party packages. Its compatibility with several operating systems (Windows, macOS, Linux) as well as the richness of its libraries make it a relevant choice for the development of IoT applications [15].

II.6.1.2. Key features

- **Code editor**: Supports syntax highlighting and basic autocompletion.
- **Integrated compiler**: Converts code into instructions that microcontrollers can understand.
- **Library Manager**: Facilitates the integration of external libraries (e.g., for sensors or communication modules) [16].
- **Serial monitor**: Allows real-time debugging and data visualization [20].

The IDE's compatibility extends to other platforms like the ESP8266, making it versatile for IoT projects [20].

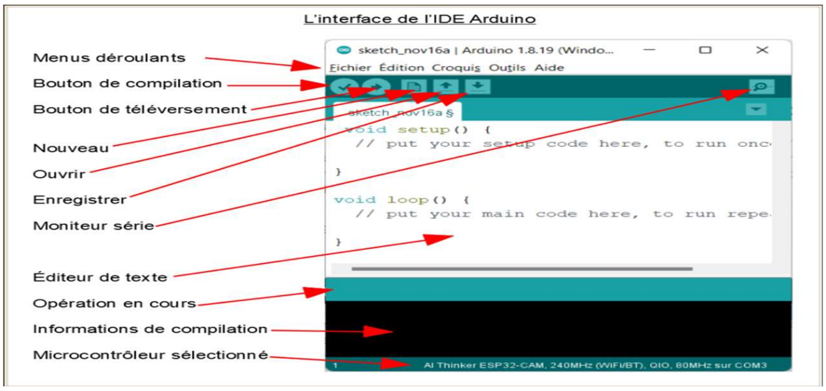

Figure. II.6. General interface of the Arduino IDE

II.6.2. Visual Studio Code (VS Code)

Visual Studio Code (VS Code) is a lightweight, open-source integrated development environment (IDE) developed by Microsoft, designed for efficient code editing, debugging, and version control. It features a rich extensibility model, allowing customization via plugins, and includes native support for IntelliSense (code completion), Git integration, and a terminal emulator. VS Code uses a modular architecture based on Electron, enabling cross-platform compatibility while maintaining high performance [17]. Its Language Server Protocol (LSP) facilitates real-time code analysis and diagnostics, making this tool a versatile solution for multiple programming languages [18].

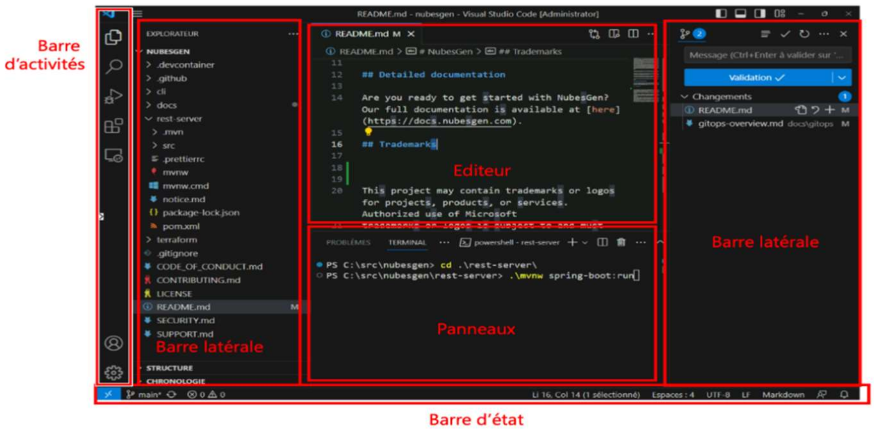

Figure II.7. VS code interface

II.7. Simulation and Design Tool

II.7.1. Proteus software: simulation of embedded systems

The Proteus Design Suite, developed by Labcenter Electronics, is an Electronic Design Automation (EDA) tool widely used by engineers and students to simulate electronic circuits before their physical implementation. It allows both the design of electronic schematics and the creation of printed circuit boards (PCBs). One of its most notable features is Virtual System Modeling (VSM), which allows simultaneous simulation of microcontroller-based systems with real-time debugging [19] [20].

When paired with the ESP8266, a low-cost Wi-Fi microcontroller developed by Espressif Systems, Proteus, becomes capable of simulating IoT (Internet of Things) applications. [21] Although the software does not natively support the ESP8266, it can be integrated using custom libraries or by loading hex files, allowing the simulation and testing of ESP8266-based projects in a virtual environment [21] [45]

II.7.1.1. Main features

- **Schema capture:** Allows users to create and edit electronic circuit diagrams.
- **PCB Design:** Generates PCBs directly from schematics.
- **VSM Simulation:** Allows simultaneous simulation of microcontrollers and their connected peripherals.
- **Microcontroller emulation:** Offers simulation for platforms such as Arduino, PIC, AVR, and ARM**,** with expansion possibilities for the ESP8266 [22].
- **Embedded code debugging:** Provides tools for debugging code integrated into the simulated environment.
- **Device simulation:** Capable of emulating components such **as**LCD displays**,** sensors**,** enginesAndWi-Fi modules [23].

II.7.2. Fritzing software: prototyping and diagramming

Fritzing is an open-source software program developed by the Interaction Design Lab at the Potsdam University of Applied Sciences. It aims to facilitate the transition from breadboard prototyping to printed circuit board (PCB) design by offering an intuitive interface suitable for both beginners and professionals.

II.7.2.1. Main features

- **Breadboard view:** Visual representation of the assembly on a breadboard, ideal for beginners.
- **Schema capture:** Creation and modification of electronic circuit diagrams with standardized symbols.

- **PCB Design:** Generation of printed circuit boards from schematics, with customization of tracks, pads, copper areas, etc.
- **Component Library:** Access to a vast collection of electronic components, with the ability to add custom parts.
- **Export:** Supports exporting designs in various formats for manufacturing, simulation, or documentation purposes.

II.7.2.2. Typical applications

- **Rapid prototyping:** Smooth transition from concept to physical realization of the circuit.
- **Education: Educational** tool for teaching electronics and circuit design.
- **Documentation:** Creation of clear diagrams for presenting and sharing projects.
- **PCB manufacturing:** Preparation of files for the production of professional printed circuit boards.

II.8. Web Technologies Used

II.8.1. React

React is a JavaScript library developed by Facebook, used to build dynamic and reactive user interfaces based on reusable components. It allows for efficient application state management and automatic updating of interface elements based on received data [32]

II.8.2. TypeScript

TypeScript is an open-source language developed by Microsoft. It is a superset of JavaScript that introduces static typing, which improves the reliability, maintainability, and robustness of code in complex projects [33].

II.8.3. Tailwind CSS

Tailwind CSS is a utility CSS framework based on pre-designed classes. It allows rapid development of aesthetically pleasing, responsive, and consistent interfaces, without the need to redefine styles for each element. It is particularly suitable for monitoring interfaces [34].

II.8.4. Quickly

Vite is a rapid build and development tool for front-end projects. It is optimized for React and TypeScript, and allows instant reloading during development, significantly speeding up the production cycle [35].

II.8.5. PHP & MySQL

The backend is based on PHP, a lightweight server-side language for receiving data from the ESP32 microcontroller via HTTP requests. The data is then stored in a MySQL database, which facilitates the management of history, alerts and logs [36] [37] [48].

II.8.6. XAMPP

XAMPP is a local development platform integrating Apache, PHP and MySQL. It facilitates backend and database testing without requiring online deployment during the prototyping phase [38].

II.8. 7. HTTP (GET/POST)

The HTTP protocol is used for communication between the ESP32 and the server. GET requests are used to read information, while POST requests are used to send data, such as sensor measurements or device activation commands [39].

II.8. 8. WebSocket

WebSocket is a bidirectional communication protocol that enables a persistent connection between the web interface and the ESP32. Unlike HTTP, it allows continuous data transmission without reloading, ensuring real-time monitoring of critical industrial parameters [40].

II.8.9. JSON (JavaScript Object Notation)

JSON is a lightweight data structuring format used to efficiently transmit sensor measurements (e.g., temperature, level, gas) between the ESP32 and the server. It is easily interpreted by the React frontend to automatically update visualizations [41].

II.9. The Internet of Things (IoT)

The Internet of Things (IoT) is a rapidly growing technology that enables the interconnection of smart devices to automate and optimize various processes. The IoT has applications in several fields, including manufacturing, energy management, healthcare, and logistics. This chapter explores the role of the IoT in optimizing connected and intelligent systems.

II .9.1. Definition and concepts of IoT

IoT is defined as a network of physical devices integrating sensors, actuators and communication technologies that allow them to collect and exchange data [27]. These connected objects are managed via centralized platforms that allow the automation of reactions based on the data received.

II.9.2. Technologies used in IoT

Several technologies enable the deployment of IoT systems [28]:

- **Wireless networks (Wi-Fi, ZigBee, LoRaWAN)**: They provide connectivity between devices.
- **Wireless Sensor Networks (WSN)**: They facilitate the collection and transmission of environmental data.
- **RFID and NFC**: Technologies for identifying and tracking connected objects.
- **Cloud computing and Edge computing**: Management and processing of data collected by sensors.

II.9.3. IoT Applications in Industry and Beyond

IoT plays a crucial role in monitoring and optimizing industrial processes, as well as in other areas such as logistics, energy management, and healthcare. The integration of connected sensors enables real-time response to incidents and optimizes resource management.

II.10. Electronic components used in the system

When developing an embedded system using the NodeMCU ESP8266 microcontroller, various electronic components are integrated to perform specific functions related to detection, control, alerting, and physical action. These components include sensors, actuators, and connection modules that allow the system to collect data from the environment and interact with it.

II.10.1. Sensors

II.10.1.1.MQ-2 Gas/Smoke Sensor

The MQ-2 sensor is a gas detection device designed to identify the presence of combustible gases and fumes in the air. It is particularly sensitive to compounds such as propane, methane, butane, LPG, alcohol, hydrogen, and smoke. This sensor operates by energizing an internal heating element that activates the sensitive semiconductor material. It provides two types of outputs: analog (AO) for a reading proportional to the gas concentration, and digital (DO), activated when an adjustable concentration threshold is exceeded via a potentiometer.

- **Supply voltage :**5V DC
- **Exits:**AO (analog), DO (digital)
- **Detection range :**200 to 10000 ppm

- **Role in the system:** Air quality monitoring and leak or fire detection

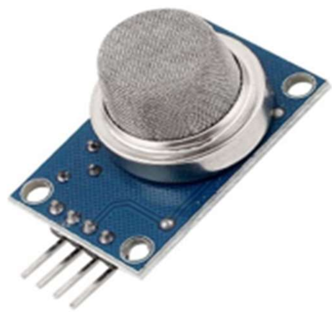

Figure II.2. MQ-2 gas/smoke sensor.

II.10.1.2. DHT11 Temperature and Humidity Sensor:

The DHT11 is a very popular temperature and humidity sensor due to its ease of use and low cost. It only requires a pull-up resistor and a 3V or 5V power supply to operate. It is easy to program using Arduino libraries. This digital module transmits and receives a digital signal via a single serial input/output pin. It uses two analog sensors: a polymer resistor to measure humidity, and an NTC (Negative Temperature Coefficient) thermistor for temperature. The module is factory calibrated, and its parameters are stored in an OTP (One Time Programming) memory, similar to the one seen in PeiP1's tutorial for diodes. Communication between the Arduino and the DHT11 is handled by an 8-bit microcontroller. Data exchange is carried out on 40 bits and typically lasts 4 ms.

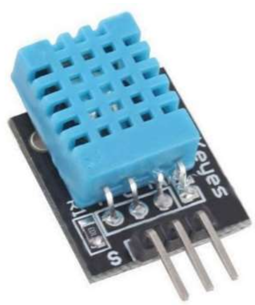

Figure II.3. Flame sensor

The DHT11 has the following features:

- **Voltage :**3-5.5V DC
- **Output signal:** Digital signal via single-bus

- **Sensor :** Polymer resistance
- **Measuring range :**
    - Humidity : 20-90% RH
    - Temperature : 0-50°C
- **Precision :**
    - Humidity : ±4% RH (Max ±5% RH)
    - Temperature : ±2.0°C
- **Resolution :**
    - Humidity : 1% RH
    - Temperature : 0.1°C
- **Hysteresis :** ±1% RH
- **Stability :** ±0.5% RH/year
- **Measurement period :**2 seconds
- **Dimensions :**12 × 15.5 × 5.5 mm

II.10.1.3. Flame sensor KY-026 :

The flame sensor is a module designed to detect flames by capturing infrared radiation (760-1100 nm). It is easy to use, economical, and compatible with Arduino. It requires a 3.3V or 5V power supply and provides an analog (flame intensity) or digital (detection with adjustable threshold via potentiometer) output. The sensor uses an infrared phototransistor to detect the light emitted by the flames. Communication with a microcontroller is via an analog or digital pin. The signal is processed by an integrated circuit, with a fast response time.

Figure II.4. flame sensor KY-026

Features:

- **Voltage** : 3.3-5V DC
- **Output signal**: Analog (proportional voltage) or digital (adjustable threshold)
- **Sensor** : Infrared phototransistor
- **Measuring range** :
  - Wavelength : 760-1100 nm
  - Distance: 20-100 cm (depending on intensity)
- **Precision** : Depends on calibration
- **Resolution**: Analog (~10 bits with Arduino)
- **Detection angle** : ~60°
- **Stability**: Good, but sensitive to light interference
- **Measurement period** : A few milliseconds
- **Dimensions** : 15 × 35 × 10 mm (typical)

II.10.1.4. HC-SR04 ultrasonic sensor:

The HC-SR04 ultrasonic sensor is widely used to measure distance through sound wave propagation. This sensor consists of two modules: a transmitter and a receiver. The transmitter sends out ultrasonic waves, while the receiver picks up the waves reflected by an object or surface. The distance is then calculated by measuring the time elapsed between signal transmission and reception. The HC-SR04 sensor operates on a 5V power supply and uses an input/output pin to communicate with a microcontroller, such as an Arduino. It is very popular due to its simplicity and low cost, and is particularly used in robotics or proximity detection projects.

Figure II.5. HC-SR04

- **Voltage :**5V DC
- **Measuring range :** 2 cm to 4 m
- **Precision :** ±3 mm

- **Detection angle :**15°
- **Measurement time:** about 10 ms per measure
- **Operating frequency :** 40 kHz
- **Communication:** Using a trig pin (to trigger the signal to be emitted) and an echo pin (to capture the reflected signal)
- **Consumption :** Low energy consumption
- **Dimensions :** 45 × 20 × 15 mm

The HC-SR04 sensor is easy to integrate into embedded systems, and its ability to reliably measure distance makes it a popular tool in various applications, such as obstacle detection, level management, or distance mapping.

II.10.2. Actuators

II.10.2.1. Buzzer

The buzzer is an electroacoustic component used to emit audible alert signals. Powered by direct current, it generates a sound when the system detects an abnormal condition. In the context of the project, it is mainly used to notify the user in case of gas, flame or water overflow detection. It is a passive buzzer, requiring an oscillating signal (2–5 kHz) to operate.

- **Operating voltage :**3.5–5.5V
- **Typical current:**< 25 mA
- **Role in the system:** Audible signaling in case of alert

Figure II.6. Buzzer

II.10.2.2.12V fan

This component is a DC fan operating at 12V. It is generally more powerful than 5V models, making it suitable for applications requiring more intense ventilation or covering a larger volume of air. In the system, its operation is triggered automatically depending on the ambient temperature detected by a thermal sensor, thus ensuring optimal cooling of heat-sensitive elements [30].

- **Operating voltage :**12V DC
- **Role in the system:** Efficient cooling and automatic ventilation adapted to the temperature

Figure II.7. 12V Fan

II.10.2.3.LED

Light-emitting diodes (LEDs) are used as visual indicators in the system. Depending on the device state, they can signal power-on, an alert, or an ongoing operation. Their use requires a series resistor to limit the current and prevent component degradation [29].

- **Typical forward voltage :**2V to 3V
- **Role in the system:** Visual status indication (system active, alarm, error)

Figure II.8. LED

II.10.2.4. 5V relay

The 5V electromechanical relay is used to electrically isolate the microcontroller from loads requiring higher voltages or currents. It acts as a switch controlled by a logic signal from the NodeMCU. It is commonly used to control devices such as fans, pumps or other power elements [30].

- **Control voltage:** 5V DC
- **Role in the system:** Control of electrical loads from logic signals

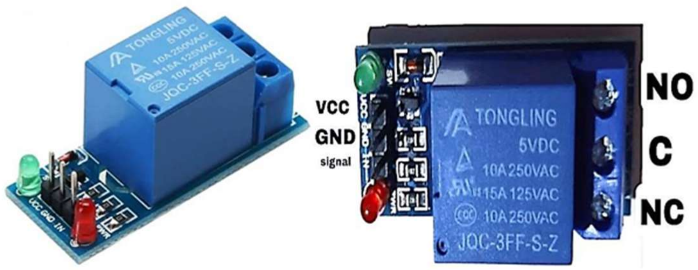

Figure II.9. 5V Relay

II.10.2.5.SG90 Servo Motor

- The SG90 servo motor is a precision micro-servo motor capable of controlled angular movements. Powered by a 5V voltage, it can perform rotations from 0 to 180 degrees. It is controlled by a PWM (pulse width modulation) signal, making it perfectly compatible with the NodeMCU output pins. It is used in this system to perform automated mechanical tasks such as opening or closing a device.
- **Operating voltage :**5V DC
- **Rotation angle :**0–180°
- **Role in the system:** Controlled mechanical action (e.g., access mechanism)

Figure II.10. SG90 Servo Motor

II.10.2.6. Micro-water pump

The micro water pump is a miniature hydraulic actuator used for water transfer. It is controlled via a relay or a transistor depending on the signals generated by the system. Its activation is generally triggered by the reading of a level or humidity sensor. It allows the implementation of a liquid control mechanism (filling, emptying, etc.) [31].

- **Operating voltage :**5V DC
- **Role in the system:** Liquid management (watering, drainage, circulation)

Figure II.11. Micro water pump

II.10.2.7. 12V Water-pump

The 12V Water-pump is an electromechanical actuator intended for transferring or circulating liquids such as water, foam, or chemical agents. It is activated by a relay, a MOSFET transistor, or directly by a microcontroller via an interface circuit. Its activation is generally conditioned by the reading of a gas sensor, a flame detector, or a temperature sensor, thus allowing automatic response actions such as cooling, fire suppression, or hazardous fluid evacuation. This type of pump is widely used in embedded safety systems and smart prototypes due to its compact size, low energy consumption, and reliable operation under industrial conditions.

- **Operating voltage :** 12V DC
- **Role in the system :** Liquid transfer or spraying (e.g., foam or water), automatic activation in case of gas detection, fire, or overheating, enabling cooling, suppression, or drainage functionalities.

Figure II. 12. 12v Water pump

II.10.3. Modules

II.10.3.1. PCA9685 (PWM Controller*):*

The PCA9685 is a widely used PWM controller for driving multiple outputs independently [46]. It is particularly useful for controlling servo motors, DC motors, and LED lights, while freeing up microcontroller resources thanks to its internal oscillator. The module communicates via the I2C bus and can control up to 16 PWM channels with high resolution.

- Control of 16 independent PWM outputs via I2C.
- 12-bit resolution (4096 levels).
- Logic supply voltage between 3.3V and 5V.
- Ability to control servomotors, motors and LEDs.
- Internal oscillator preventing microcontroller overload.

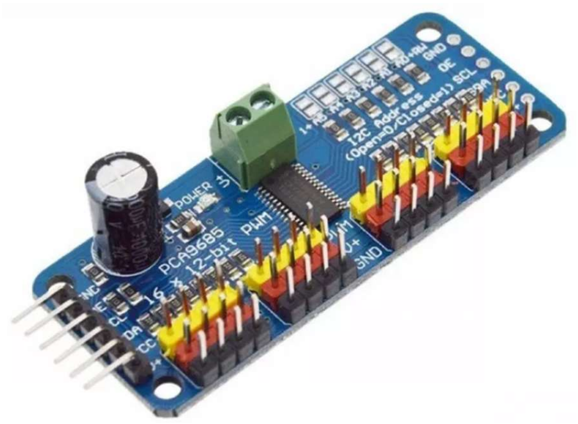

Figure II.13. PCA9685

II.10.3.2. ADS1015 (Analog-to-Digital Converter - ADC)

The ADS1015 module is a high-performance analog-to-digital converter (ADC), ideal for extending the analog readout capabilities of microcontrollers [47]. It offers four analog input channels, operating in either single-ended or differential mode, with communication via the I2C bus. Thanks to its programmable gate array amplifier (PGA), it allows the measurement range to be adapted as required.

- 4 analog channels (single or differential).
- 12-bit resolution.
- Programmable amplifier for adjustment of measurement ranges.
- I2C interface for fast and efficient communication.
- Operates with a power supply between 2V and 5.5V.

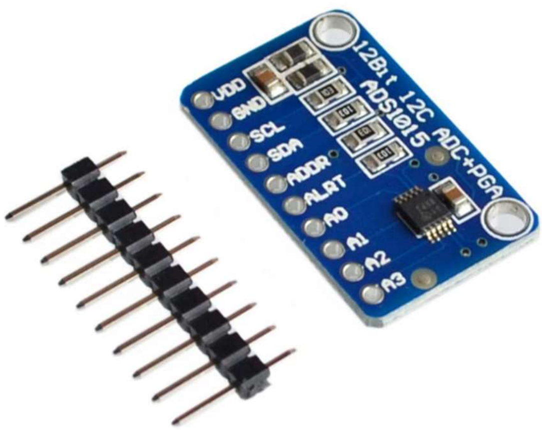

Figure II.14. ADS1015

II.10.3.3. L298N Module (Motor Driver):

The L298N is an integrated circuit designed to drive two direct current (DC) motors or one stepper motor. It uses a dual H-bridge configuration to control the direction and speed of the motors. Each channel can handle up to 2 A of current continuously. This module is widely used in robotics and automation projects.

- Driving two DC motors or one stepper motor.
- Double H-bridge configuration for polarity reversal.
- Output current: up to 2 A per channel.
- Supported motor voltage: from 5 V to 35 V.
- Logic voltage : 5 V.
- Integrated 5V regulator (disableable via jumper).
- Backflow protection diodes.
- Heat sink for better heat dissipation.
- Speed control via PWM signal.

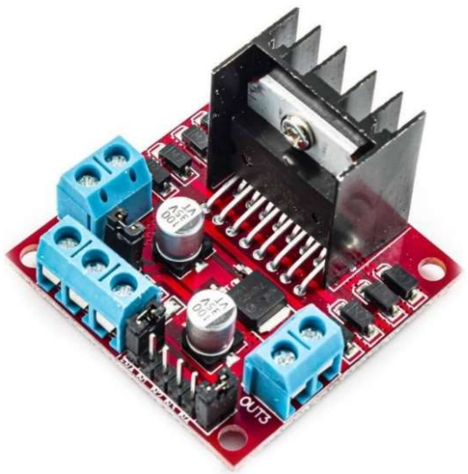

Figure II.15. L298N module

II.10.3.4. 12V DC power supply

A 12V DC power supply is a specialized device designed to convert alternating current (AC) into a stable 12-volt direct voltage, particularly suitable for on-board systems such as fire/gas detectors.

- **Entrance** : 100-240V AC (standard mains)
- **Exit** : 12V DC ±5% regulated
- **Power**: 5W to 60W (depending on model)
- **Yield** : >85% (80 PLUS certified models)
- **Protections** :
  - Overvoltage (OVP)
  - Short circuit (SCP)
  - Overheating (0TP)

II.10.4. Interfaces

II.10.4.1. Breadboard

A breadboard is a support for quickly creating solderless prototypes. It facilitates the assembly, testing and modification of electronic circuits during the development phase [2].

- **Role in the system:** Rapid prototyping and circuit modification

Figure II.16. Test plate

I.10.4.2. Jumper wires

Jumper wires are used to establish electrical connections between the various components and modules of the system. They come in different forms (male-male, male-female, female-female) and provide flexible and reliable connectivity on the breadboard or between modules.

- **Role in the system:** Internal electrical connections to the system

Figure II.17. Connection wires

II.10.4.3. Resistances

Resistors are fundamental electronic components that limit, distribute, or adjust the electric current in a circuit. They play an essential role in protecting sensitive components, adjusting voltage levels, or filtering signals. Their value, expressed in ohms (Ω), determines their capacity to oppose the passage of current [43].

In this project, three types of resistance were used:

- **220 Ω:** used mainly to limit the current flowing through the LEDs, thus preventing their deterioration.

Figure II.18. 220 Ω resistor

- **110 Ω:** used in signal adaptation or protection circuits, in particular to avoid overvoltages or interference on certain microcontroller pins.

Figure II.19. 110 Ω resistor

- **10 kΩ:** Typically used as pull-up or pull-down resistors, to stabilize the logic state of an input pin (e.g. on I2C communication lines or buttons).

Figure II.20. 10 kΩ resistor

II.10.4.4. Push button (NO/NC):

The push button used in this project is a direct replacement for a limit switch, thus providing increased mechanical flexibility. It is a model equipped with three terminals: NO (Normally Open), NC (Normally Closed) and COM (Common). In the rest position, the NO contact is open and NC is closed. When the button is pressed, the NO closes and the NC opens, thus generating a change-of-state signal.

This type of button is used here to detect a position or mechanical event, similar to a limit switch in a machine. It is connected to a digital input of the ESP32 and can be associated with a pull-up resistor (internal or external) to ensure a reliable reading. It can trigger, for example, the stopping of a motor, the activation of an alarm, or any other programmed event.

Figure II.21. Push button

Chapter III

Practical Implementation

From an experimental model

for industry equipped with voice control.

III.1. Introduction

This chapter presents the design and construction of a prototype of an automated fire and gas leak detection system, with a flammable material cooling device, reproducing a small industrial area. The system is based on an ESP32 microcontroller connected to several sensors and actuators (gas, flame, temperature, level sensors; pumps, servomotors, relays, LEDs, buzzer). It detects the start of a fire or a gas leak and responds automatically (extinguishing with water or foam, targeted cooling, ventilation, audible/visual alerts). The programming is carried out under the Arduino IDE with the appropriate libraries (PCA9685, ADS1015, etc.), and the hardware design has been validated by simulation using Proteus ISIS and Fritzing

III.2. Stages of implementation

The implementation of the project followed three major stages, illustrated in Figure III.1:

- ***Programming the ESP32 microcontroller***: Writing and compiling the code in the Arduino IDE, including all necessary libraries (PCA9685, ADS1015, gas sensors, flame sensors, etc.). After verification, the program is uploaded to the ESP32 board.

- ***System simulation:*** Unit testing of the modules, then integration into a global diagram under Proteus ISIS to electrically validate the assembly behavior. The circuits were then represented in the form of clear wiring diagrams using Fritzing software, facilitating understanding and the transition to the physical prototype.

- ***Production of the model:*** All components are assembled on a 50 cm x 50 cm wooden board. Wiring is done with Dupont wires, with the modules arranged according to their function (“fire”, “gas”, “cooling/foam”, “central treatment” zones). After assembly, practical tests validate each scenario (detection, extinguishing, ventilation, etc.)

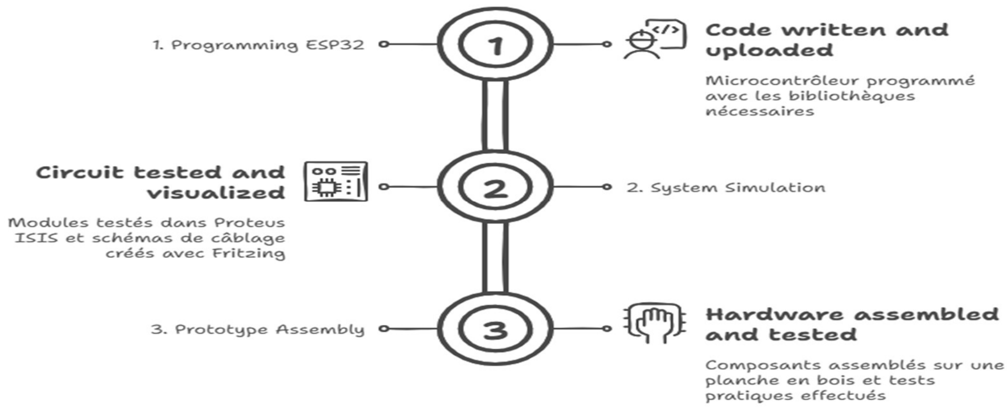

Figure III.1 Stages of the realization

III.3. System design and simulation

III.3.1. Global diagram under Proteus

To validate the electronic design before actual assembly, a global diagram integrating the ESP32 card, all the sensors (MQ-2, flame sensor, DHT11, HC-SR04, limit switch), the ADS1015 and PCA9685 modules, as well as the actuators (pumps, servomotors, relays, LEDs, buzzer) was produced underProteus ISIS.

This simulation allows you to check the electrical connections, in particular the I2C bus (SDA/SCL) between ESP32 and the modules, as well as the logical behavior of the system.

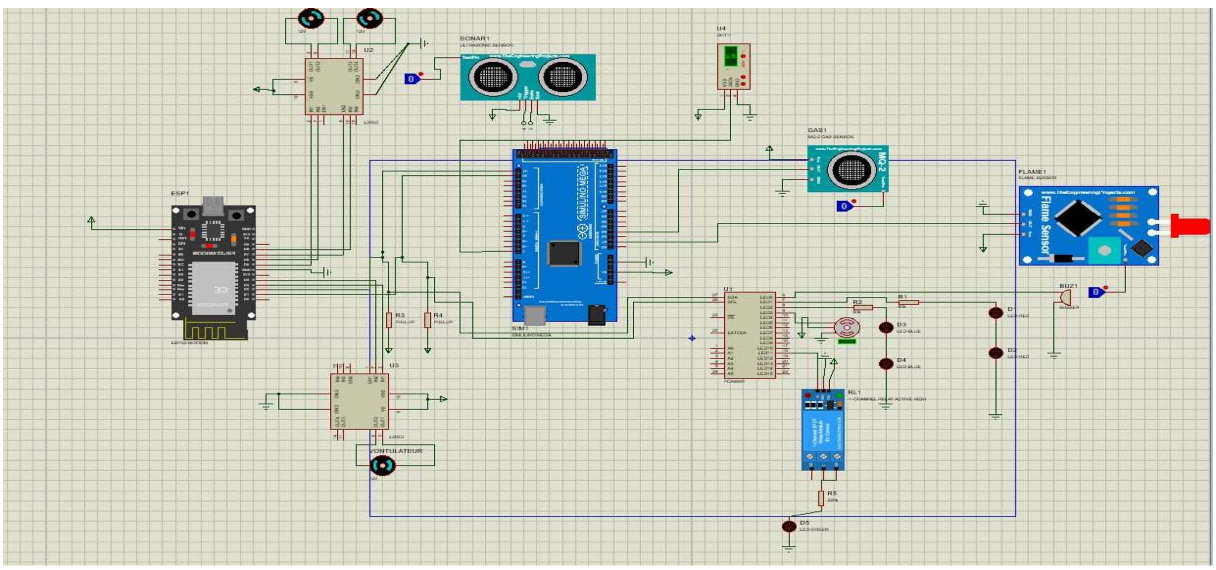

Figure III. 2. Global diagram under Proteus

III.3.2. Modular diagrams under Fritzing

In order to clarify the structure of the system and facilitate its implementation, each subsystem was modeled separately using the softwareFritzingFor each module, two types of diagrams were developed:

- Awiring diagram (Wiring)showing the actual physical connections on breadboard or mockup,
- Aelectrical diagram (Electrical diagram) illustrating the functional representation of the connections.

The modules produced are as follows:

- ***Fire Module**:* flame sensor, water pump, door servomotor, LEDs, buzzer.

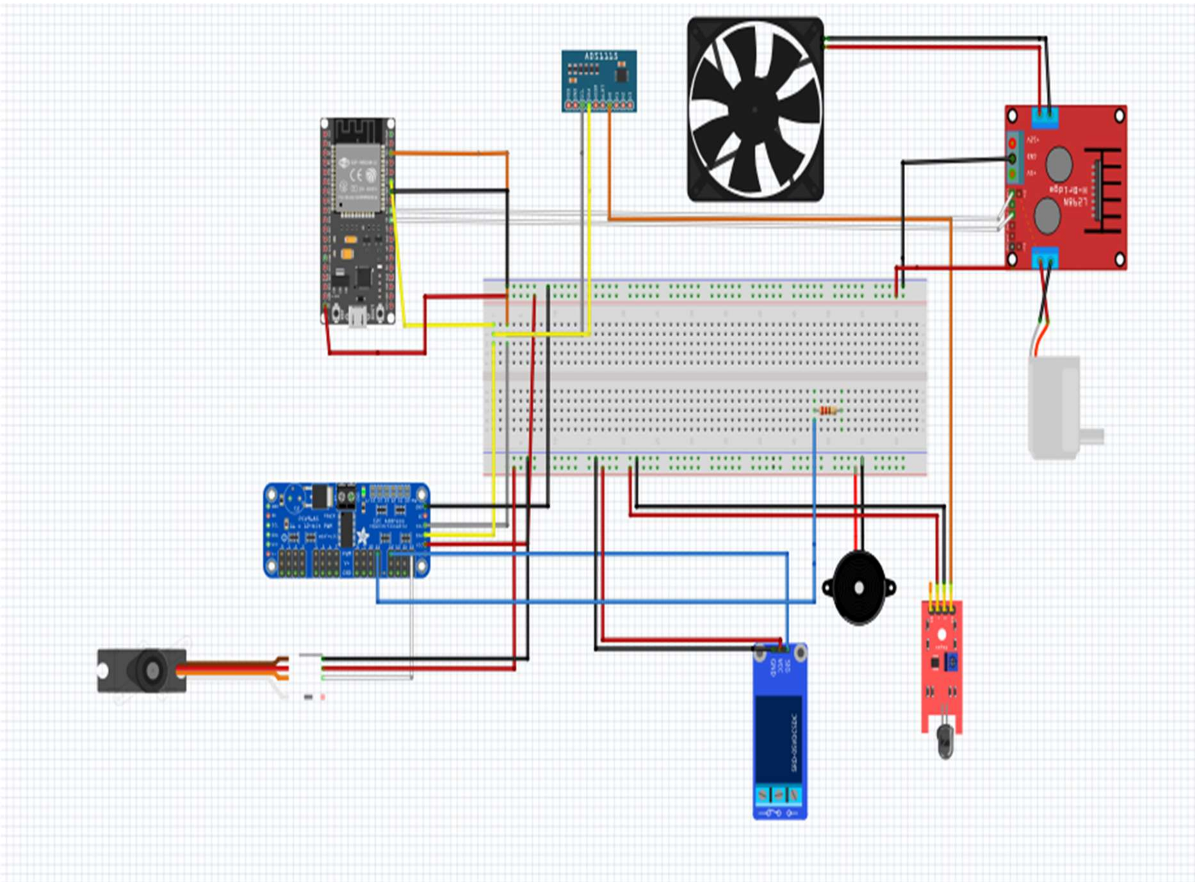

Figure III.3. Fire Control System Wiring under Fritzing

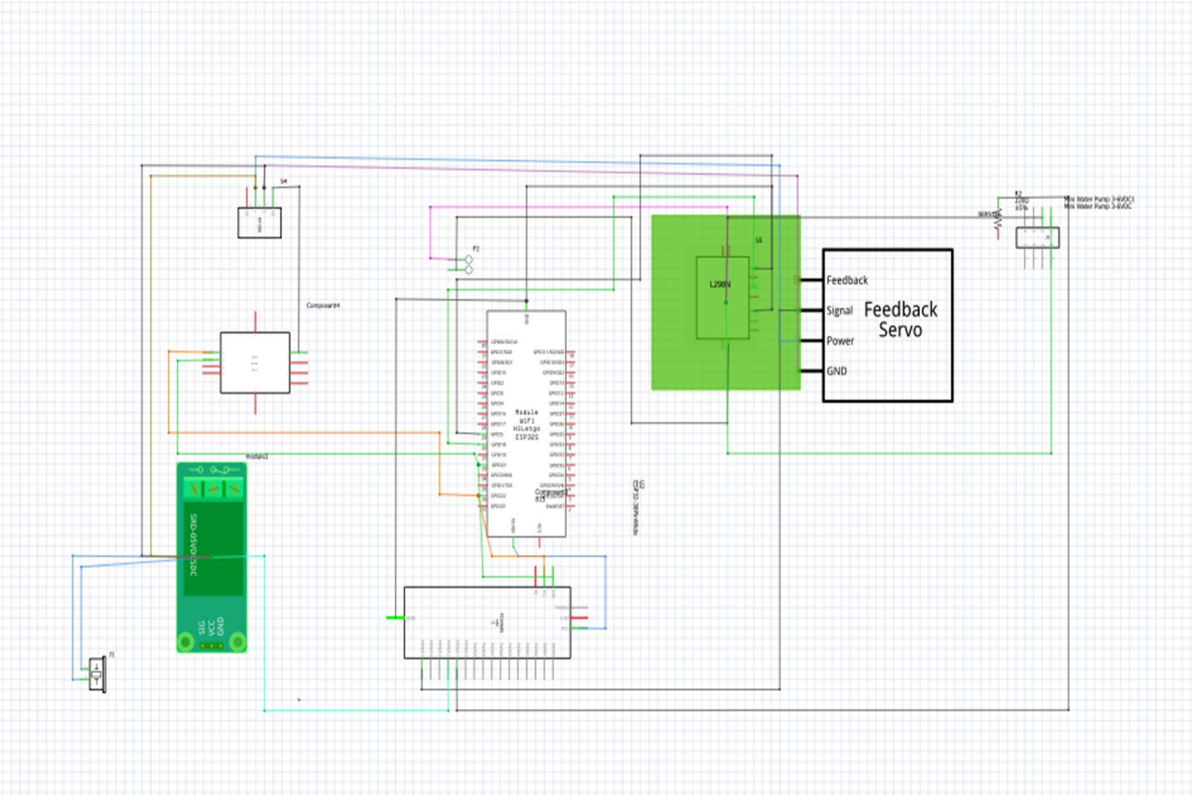

Figure III.4. Electrical diagram of fire control system under Fritzing

2. ***Gas Module***: MQ-2 sensor, 5V relay, door servomotor, fan, LEDs, buzzer.

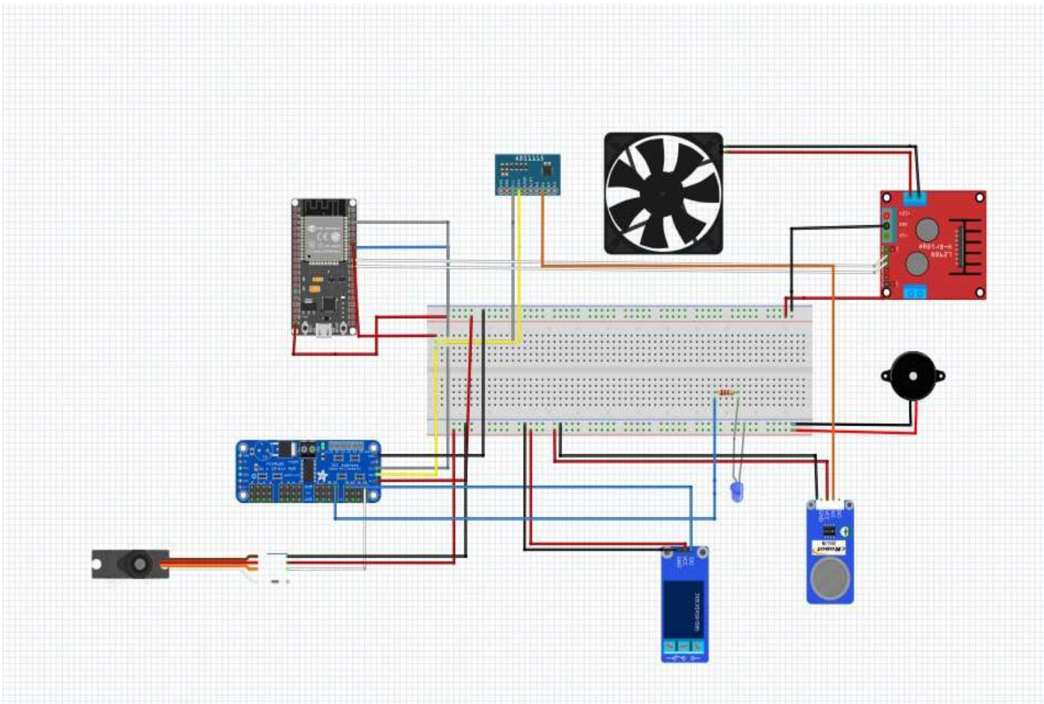

Figure III.5. Gas Control System Wiring Under Fritzing

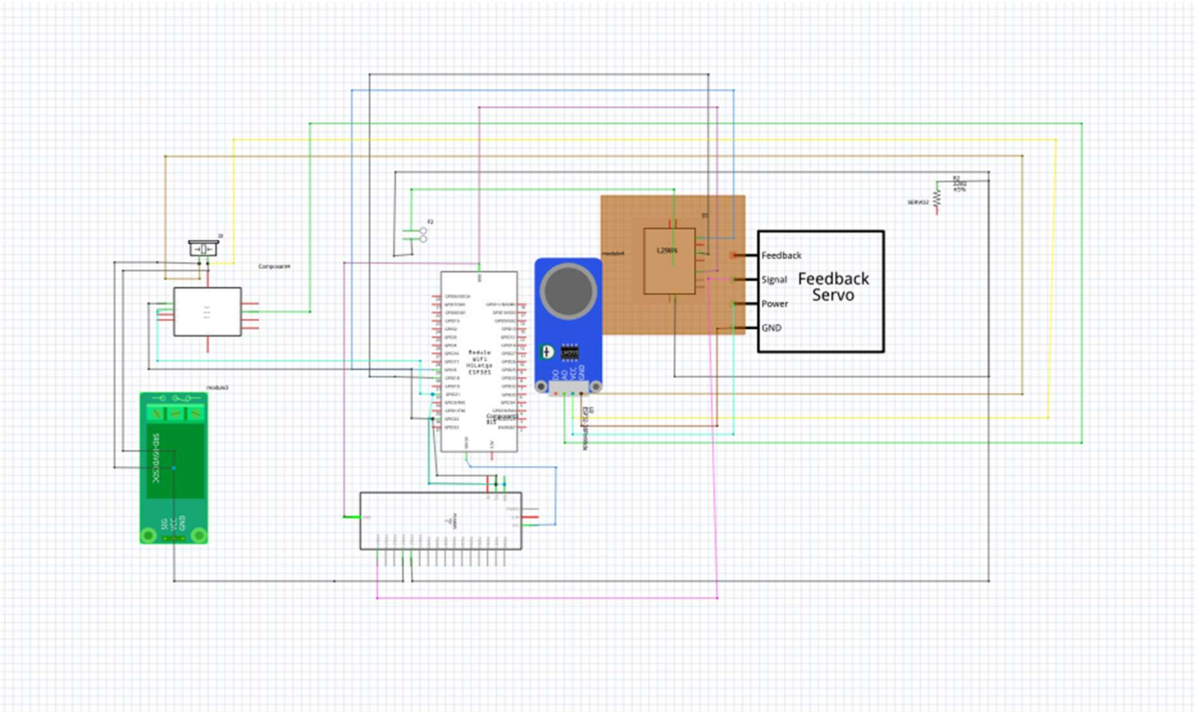

Figure III.6. Electrical diagram of gas control system under Fritzing

3. ***Flammable Tray Module***(cooling/foam): DHT11 temperature sensor, HC-SR04 level sensor, foam pump, LEDs, buzzer.

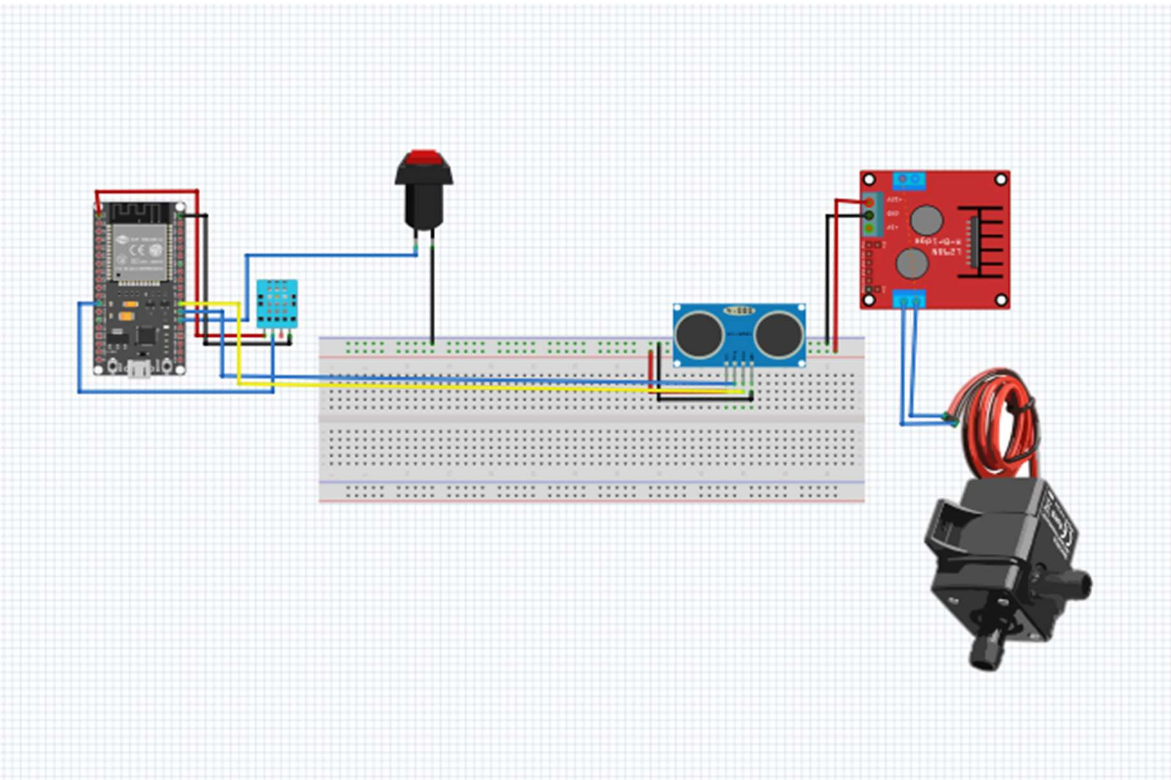

Figure III.7. Wiring of Flammable Bin Control System under Fritzing

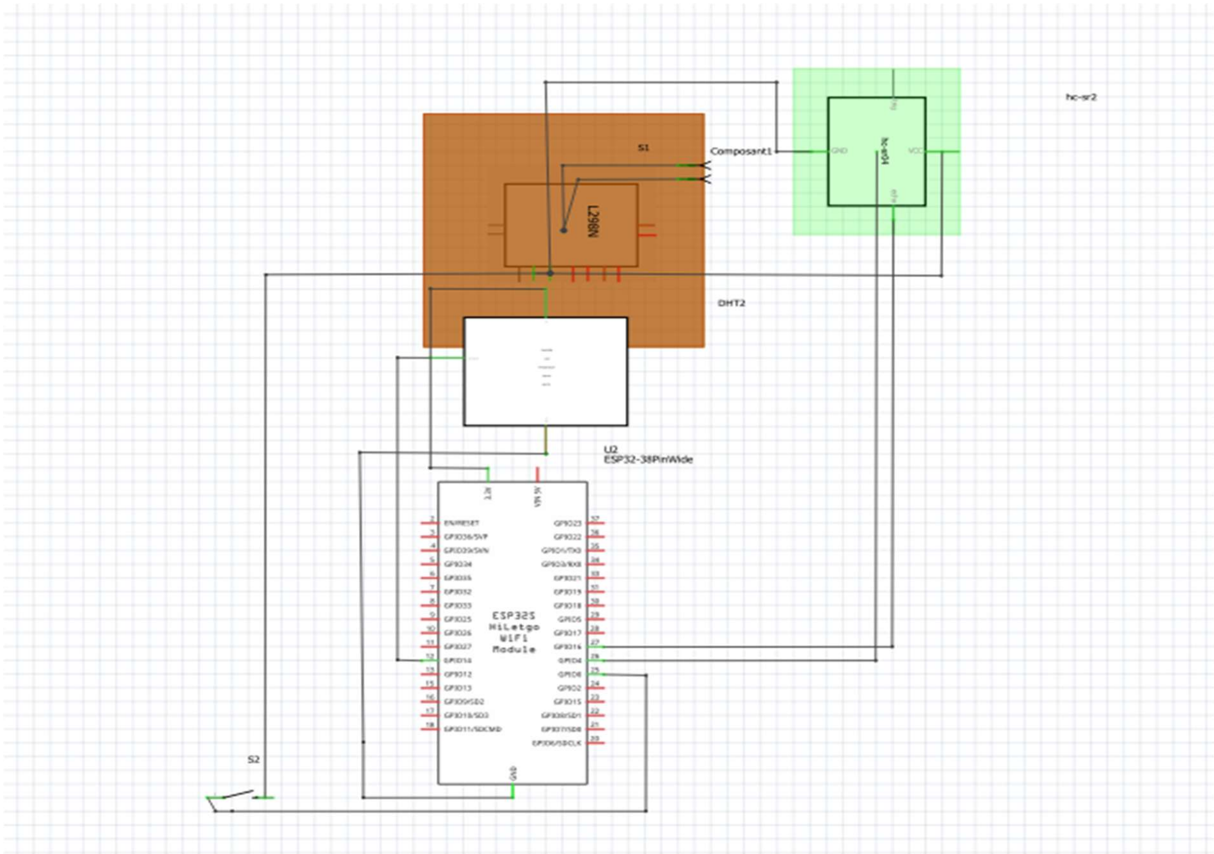

Figure III.8. Electrical diagram of Flammable Bin Control System under Fritzing

These diagrams clearly detail the use of the pinsGPIO, connections to the I2C bus, as well as the physical implementation of the components. This modular approach considerably facilitated the actual assembly phase, as well as the technical documentation of the system.

III.4. System architecture and component interconnections

The architecture of the Fire & Gas system is based on a modular organization, distributed around a central microcontrollerESP32, responsible for reading sensors, processing data, and controlling actuators. The system is designed to reproduce the automatic and intelligent reactions of an industrial environment in the event of a fire, gas leak, or overheating in a flammable container.

The general architectural diagram illustrates how components interact with each other, particularly via interfacesI2CAndGPIO, divided into four functional subsystems: fire detection, gas detection, foam extinguishing, and central processing.

III.4. 1. Central components

- **ESP32**: main processing unit. It ensures the reading of analog sensors via ADS1015, the control of pumps and servomotors viaPCA9685, and the triggering of alerts by the outputsGPIO**.**
- **PCA9685 (I2C)**: used to generate signalsPWM intended for servomotors, pumps, LEDs, and buzzers. It frees up the limited native PWM outputs of the ESP32.
- **ADS1015 (I2C)**: external analog-to-digital converter to accurately read voltages from analog sensors such as the MQ-2 gas sensor.

III.4. 2. Connected sensors

- **Flame sensor (GPIO)**: detects fire outbreaks.
- **MQ-2 gas sensor (ADC via ADS1015)**: measures gas concentration.
- **DHT11 temperature sensor (via I2C or GPIO depending on configuration)**: monitors the temperature at the flammable tank level.
- **Level sensor (HC-SR04 or limit switch)**: detects the amount of liquid or foam available.

III.4. 3. Controlled actuators

- **Pumps (water, foam)**: controlled via PCA9685 or relay.
- **Servomotors**: for the automatic opening of doors or valves.
- **Fans**: activated to dissipate heat or ventilate a gas leak area.
- **Alert LEDs** (red, blue, orange, green): visual signaling of different states.
- **Buzzer**: audible alert in case of danger.

III.4. 4. Communication and interconnection

- **I2C bus**: connects ESP32 to PCA9685 and ADS1015 modules, enabling two-wire communication (SDA, SCL) with multiple addressable peripherals.
- **GPIO Connections**: used for digital sensors, buttons, LEDs and relays.
- **Voltage**: The entire system is powered by an external 5V source. The ESP32 can be powered via USB or a 5V regulator. The motors and fans are electrically isolated to avoid interference.

- This distributed architecture allows ascalability (adding sensors or actuators), awiring clarity, and arobustnessin a simulated industrial context. It also complies with color coding standards (red LED = fire, blue = gas, orange = alert, green = safety).

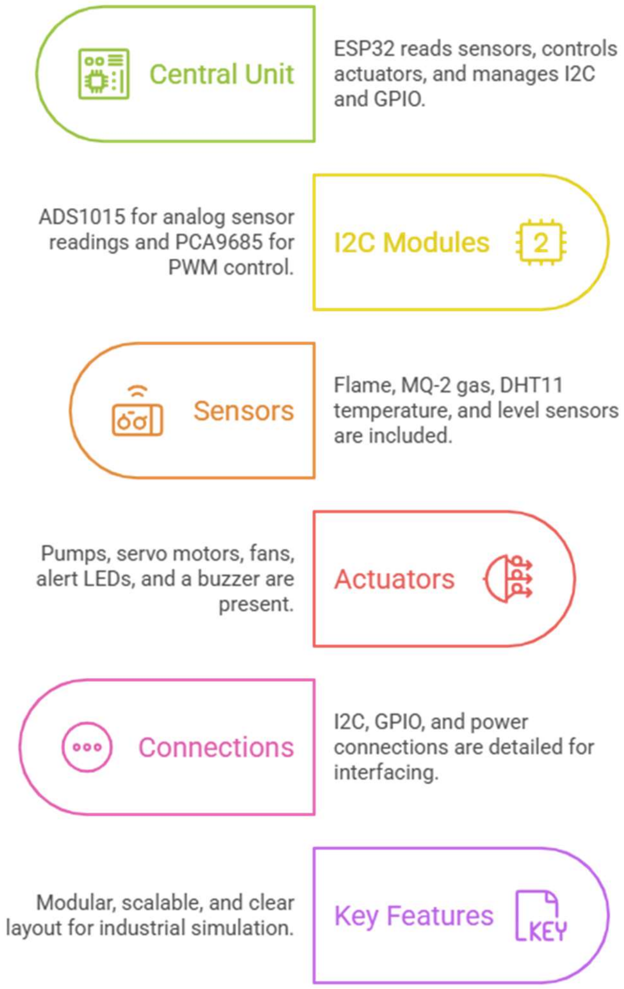

Figure III.9. System architecture and component interconnections

III.5. Production of the model

III.5.1. 2D design of the model

The detailed plan of the model was created in two dimensions (2D) using AutoCAD software, allowing the precise layout of sensors, actuators and other components to be plotted on a flat surface. This 2D design provided a reliable basis for the physical assembly of the system, facilitating the spatial organization and distribution of elements according to the technical and functional constraints of the project.

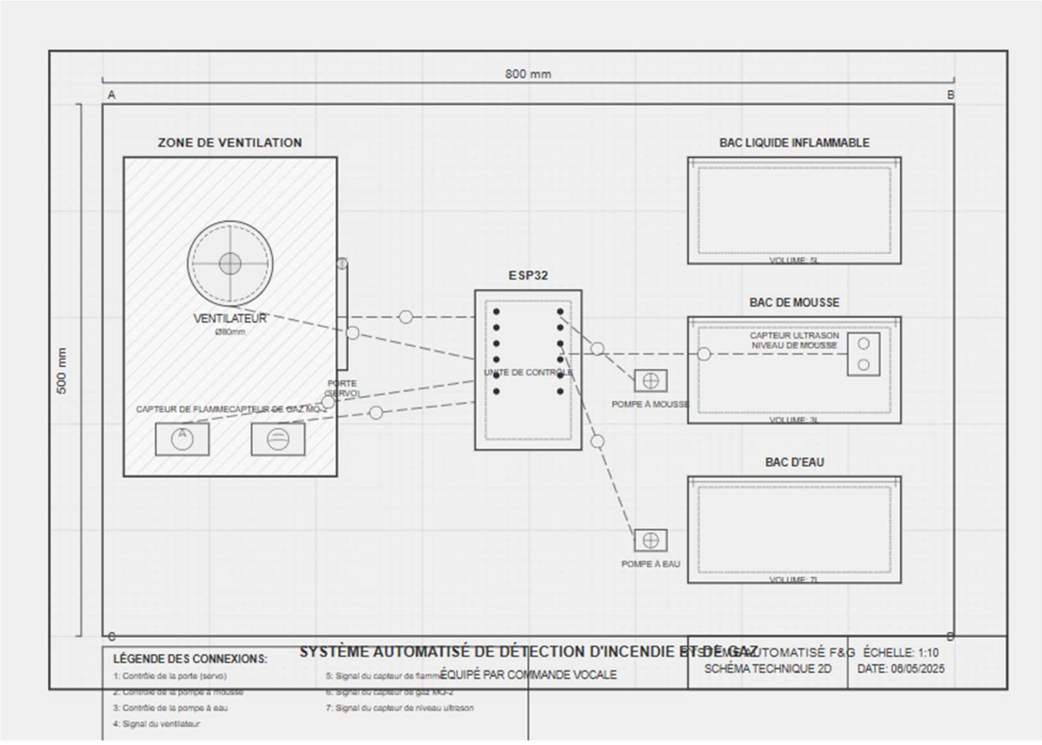

Figure III.10. Two dimensions (2D) model plan

III.5.2. Arrangement of elements on the model

- The model is placed on a wooden board measuring 50 cm × 50 cm, representing a miniature industrial zone.
- The components are grouped into distinct functional areas:

Table III. 1 System areas and their components with associated functions

Area	Included items	Main function
“Fire” Zone	Flammable tank, flame sensor, water pump, red LED, buzzer	Fire detection and extinguishing
“Gas” Zone	MQ-2 sensor, 5V relay, fan, servo motor (door)	Gas leak detection and ventilation
“Flammable Bin” Zone	Flammable tank, foam tank, DHT11 sensor, HC-SR04 sensor, limit switch, foam pump	Foam extinguishing, cooling and level monitoring
“Processing” area	ESP32, PCA9685, ADS1015, breadboard	Electronic heart of the system

III.6. Programming and control logic

III.6.1. General structure of the program

- The program developed underArduino IDEfor the ESP32 card is organized into several modules corresponding to different scenarios: fire detection, gas leak, overheating in the flammable container, etc. The main loop continuously reads the data from the sensors, analyzes the conditions, and controls the actuators according to the results.
- Using the PCA9685 and ADS1015 modules via the I2C bus frees up the ESP32's GPIO pins and provides precise control of servo motors, pumps, and analog measurements.

III.6.2. Scenario flowcharts

1. Overall system organization chart

- This flowchart provides an overview of how the Fire & Gas system works, illustrating the sequence for checking the various sensors and managing alarm and automatic intervention scenarios.

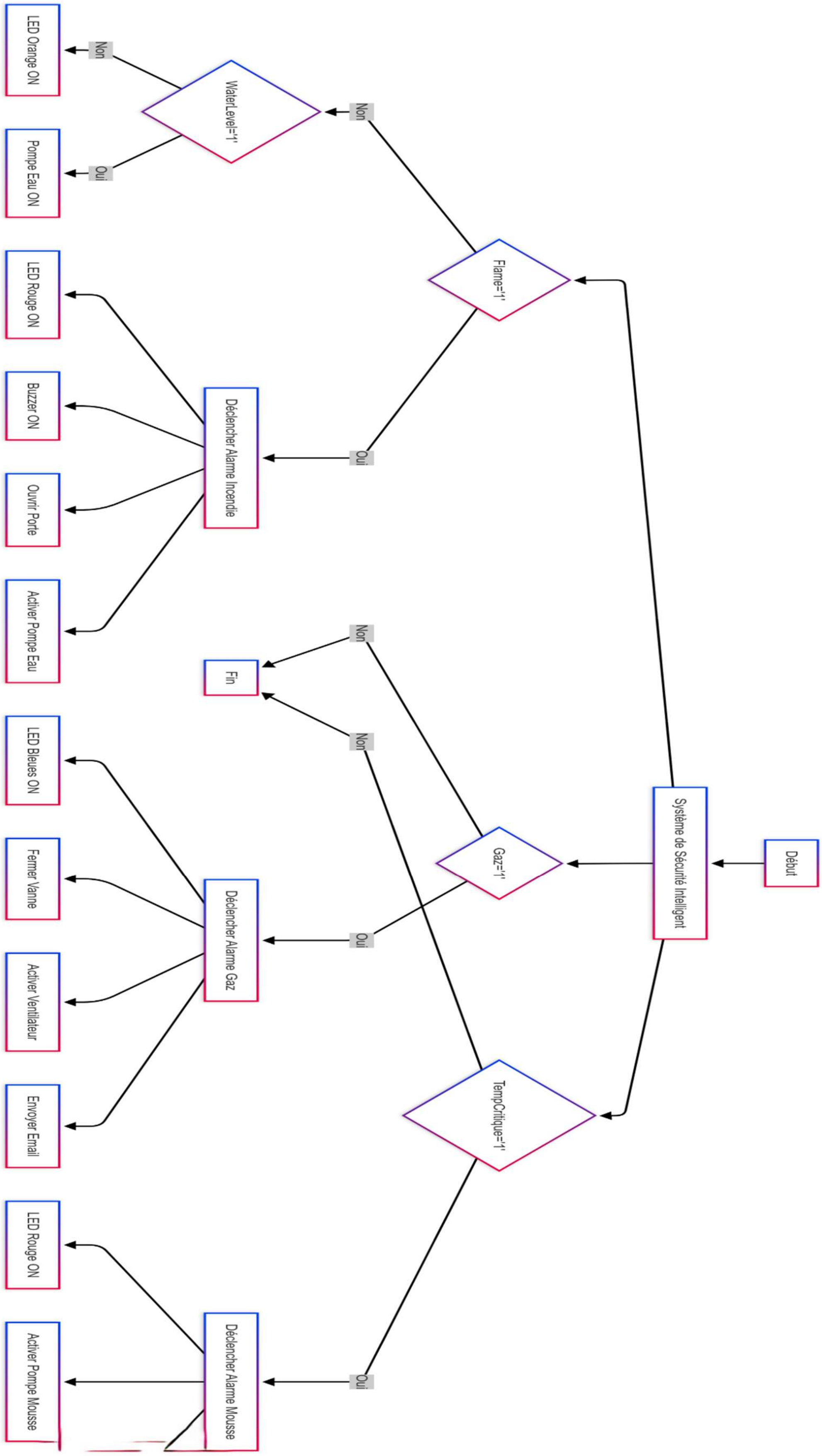

Figure III.11. Overall system organization chart

2. Flowchart of the fire detection and extinguishing system

This diagram details the procedure followed when a fire is detected, from the detection of the flame to the activation of extinguishing devices and visual and audible alerts.

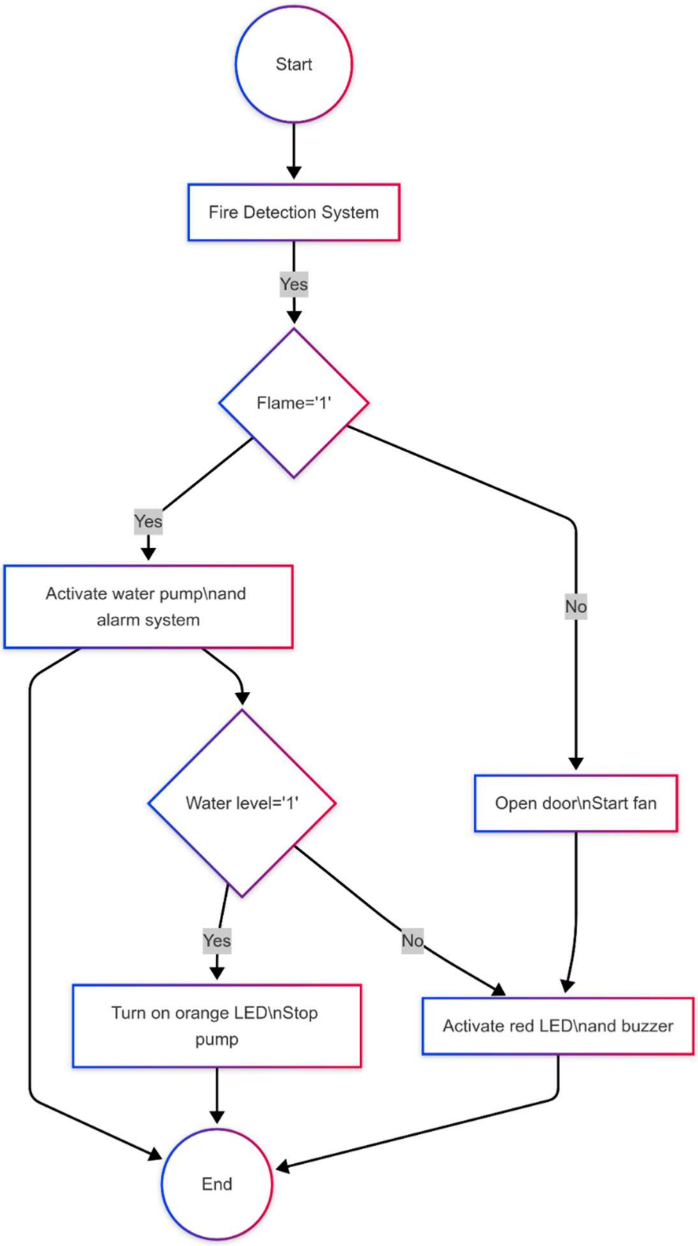

Figure III.12 . Fire Detection and Extinguishing System Flowchart

3. Flowchart of the gas detection system

This diagram highlights the process of detecting a gas leak, shutting off the valve, and triggering the ventilation and alert systems.

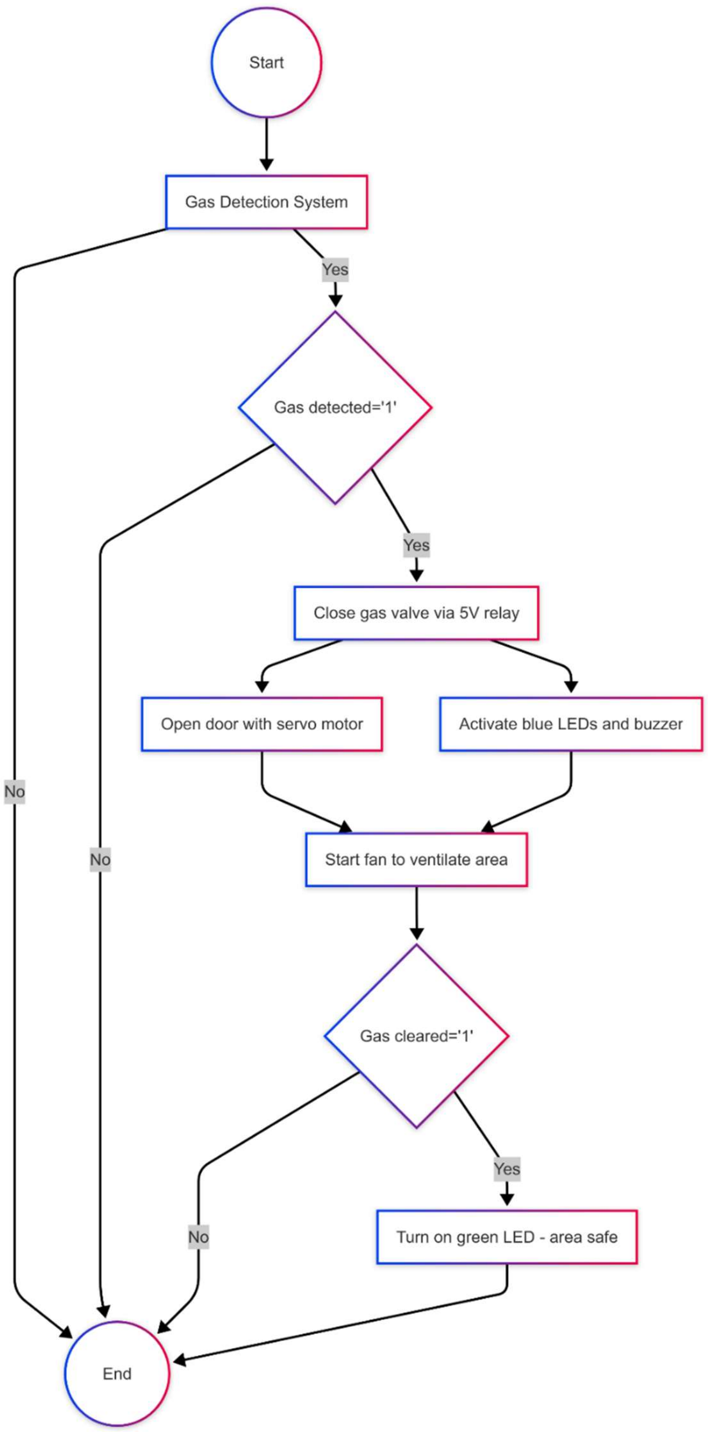

Figure III.13. Gas Detection System Flowchart

4. Flowchart of the flammable tank cooling and extinguishing system

This section explains the steps taken in the event of a temperature rise or flame detection at the flammable tank, including activating the foam pump and monitoring the foam level to ensure an effective response.

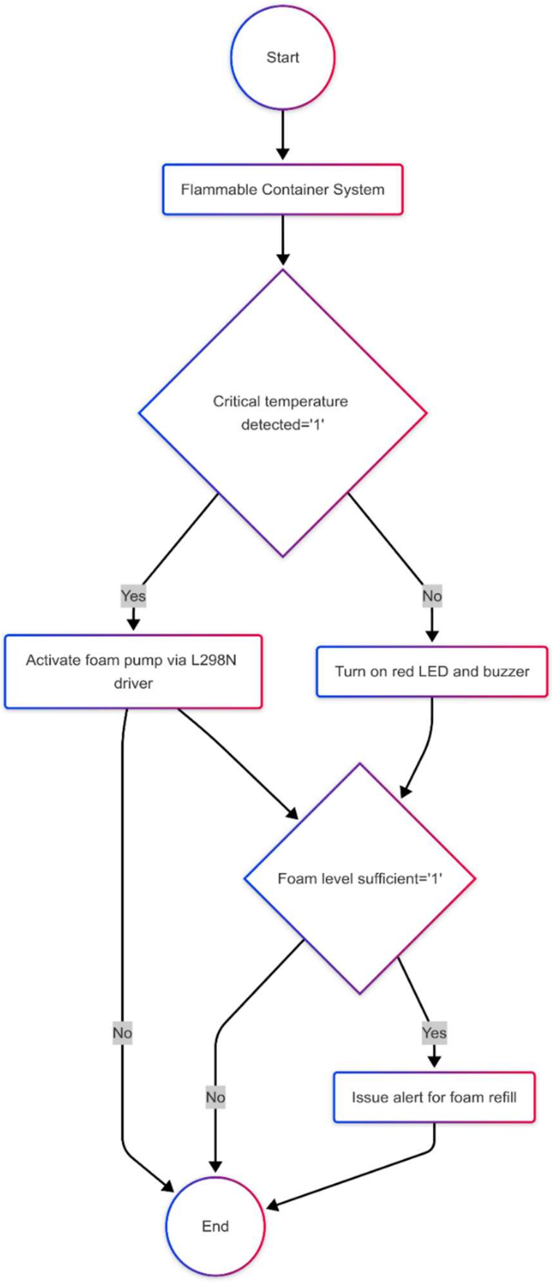

Figure III.14 . Flowchart of the flammable tank cooling and extinguishing system

III.6.3. Libraries used

In this project, several essential libraries were used to manage thedifferent hardware components and facilitate system programming:

Table III. 2 Libraries used and their functions in the Fire & Gas system

Library	Function
Wire.h	Management of I2C communication between ESP8266 and sensors (PCA9685, ADS1015, I2C sensors)
Adafruit_PWMServoDriver.h	Control of PWM outputs via the PCA9685 module to drive LEDs, buzzers, relays and motors
Adafruit_ADS1X15.h	High-precision analog signal reading via ADS1015 analog-to-digital converter (MQ-2 gas sensor)

III.6.4. Security strategies

- Software debounce on buttons to avoid spurious activations.
- Prohibition of pump activation in case of empty level (water or foam).
- Boot tests to check the status of critical modules.
- Secure pooling to prevent foam and water systems from operating simultaneously.

III.7. Detailed operation by subsystem

III.7.1. Fire detection and response system

The main purpose of this subsystem is to detect any presence of flame and initiate a series of automatic actions to quickly control the fire. The KY-026 sensor, connected to channel A1 of the ADS1115 converter, detects the infrared rays emitted by the flame. This information is transmitted to the ESP32 microcontroller via the I2C bus.

As soon as a fire is detected, the PCA9685 module is requested to generate a PWM signal activating:

- A visual alert via a flashing red LED,
- An audible alert via a buzzer,
- A CO_2 pump to extinguish the fire. This non-flammable and non-conductive gas is used for its residue-free extinguishing properties.

Next, a fan is activated to evacuate the CO_2-laden air, and a servomotor automatically opens a door to ensure optimal ventilation of the area. Finally, the PCA9685 controls a relay that cuts off the gas supply to prevent any risk of leaks after the fire has been extinguished. One minute after detection, all elements return to their initial state, ensuring the system is ready for further intervention.

III.7.2. Gas leak detection and response system

The MQ2 sensor, connected to channel A0 of the ADS1115 module, is used to measure gas concentrations in the air. When a critical threshold is exceeded, the ESP32 receives the information via the I2C protocol.

The PCA9685 module is then activated to:

- Turn on two blue LEDs indicating a visual alert,
- Trigger a buzzer for sound signal,
- Close a relay immediately cutting off the gas supply,
- Open a door by servomotor to facilitate air circulation,
- Turn on a fan to ventilate the room.

After the gas has dissipated, a green LED signals the return to normal. The system then automatically returns to its standby state.

III.7.3. Tank overheating or fire response system

The DHT11 sensor, installed at the flammable tank, measures the ambient temperature. If the critical threshold is exceeded or a flame is detected, the ESP32 immediately activates a foam pump connected to channel 2 of the L298N driver.

This foam not only extinguishes the fire but also cools the fire zone. At the same time, a level sensor (ultrasonic or limit switch) monitors the amount of foam remaining in the tank to ensure the process is efficient. Once the temperature returns to normal or the fire is out, the system automatically resets.

III.8. Development of a Web Interface for The LifeSaver System

III.8.1. Presentation of The LifeSaver system

As part of centralized data management and to ensure optimal responsiveness to emergencies (fire, gas leak), we have developed The LifeSaver, a professional, modern web interface accessible from any browser.

The system offers an intuitive and comprehensive user interface that allows you to:

- View in real time the status of the different sensors connected to the ESP32
- Receive alerts classified by severity level
- Manually check the security system components
- Analyze trends and performance through analytical dashboards

Development is based on two main axes:

- **Backend**: communication between the ESP32, a local PHP server (XAMPP) and a MySQL database
- **Frontend**: creation of an advanced web interface using React, TypeScript and Tailwind CSS

III.8.2. Backend: Communication between ESP32, PHP and MySQL

The local backend architecture was implemented to ensure the secure collection, storage, and management of sensor data. The main steps are :

- **Installing XAMPP**: activation of Apache (web server) and MySQL (database) services for reliable local hosting.

- **Creating the database**: a database named lifesaver_db with a sensor_data table containing the fields id, temperature, gas, flame, and timestamp.

- **Development of PHP scripts** :

  - *insert.php*: receives data sent by the ESP32 via HTTP POST and inserts it into the database.
  - *getdata.php*: Retrieves stored data via HTTP GET for display in the user interface.

- **Programming the ESP32** :

  - Connecting to WiFi network using WiFi.h and HTTPClient.h libraries.
  - Periodically sending sensor measurements (DHT11, MQ2, etc.) to insert.php.
  - Validation of server responses to ensure reliability and robustness of communication.

This backend architecture enables continuous, secure and reliable communication between the embedded system and the monitoring platform, thus ensuring efficient data management for real-time control.

III.8.3. Project organization and structure

The LifeSaver project structure is modular to facilitate code maintenance, reuse, and evolution. The main src folder contains all the application source code, structured as follows:

- **Components** : groups reusable components for different user interfaces.
- **context**: manages global states and communication with the ESP32.
- **hooks**: Contains custom logic for data processing and management.
- **Pages**: groups together the different sections and views of the application.
- **types**: Defines TypeScript types for sensor data to ensure strict and reliable typing.
- **utilities**: groups together utility functions for signal processing and other recurring operations.

In addition, several complementary technologies were used to improve the quality and performance of development:

- **Tailwind CSS**: for a modern, responsive and easily customizable design.
- **Quickly**: a fast and efficient build system to accelerate the development cycle.
- **TypeScript**: to ensure robust, maintainable, and statically typed code.

This modular organization combined with modern technologies ensures a high-performance, scalable and easy-to-maintain web interface.

III.8.4. Functional structure of The LifeSaver interface

1. **Sidebar (Navigation)**

The fixed sidebar provides quick and intuitive access to the various main sections of the interface:

- **Dashboard**
- **Live Monitoring**
- **Controls**

- **Alerts**
- **Voice Control**
- **Analytics**

2. Dashboard

The dashboard presents a synthetic view of the general status of the system with:

- Graphs illustrating trends (fire alerts, gas levels, etc.)
- Key indicators such as temperature and CO_2 levels
- Number of active alerts in real time
- Button to export or save data

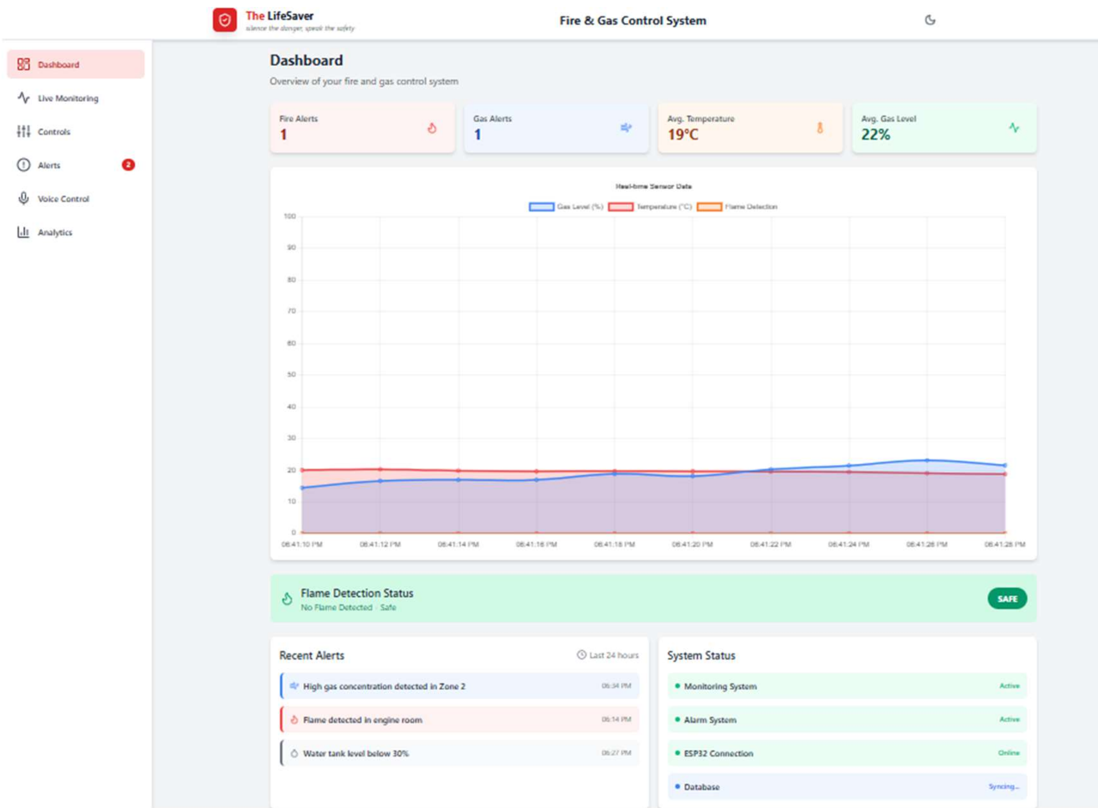

Figure III.15. System Dashboard Interface

3. Live Monitoring

This section allows real-time monitoring of sensors:

- Gas level displayed by a colored gauge
- Flame detection
- Current temperature

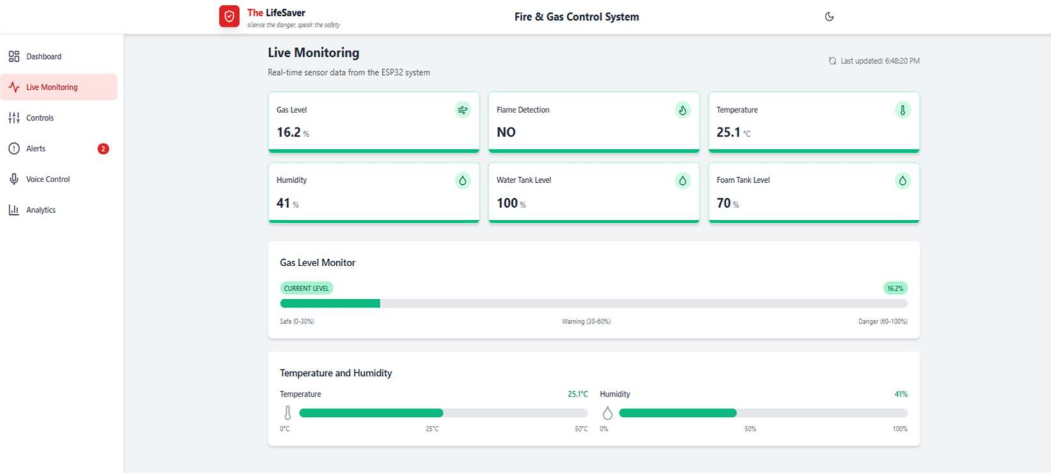

Figure III.16. Real-Time Monitoring Interface

4. Controls

The user can manually control the actuators via this interface:

- Water and foam pumps
- Fan
- Motorized door
- Emergency stop button
- Actuator status monitoring table

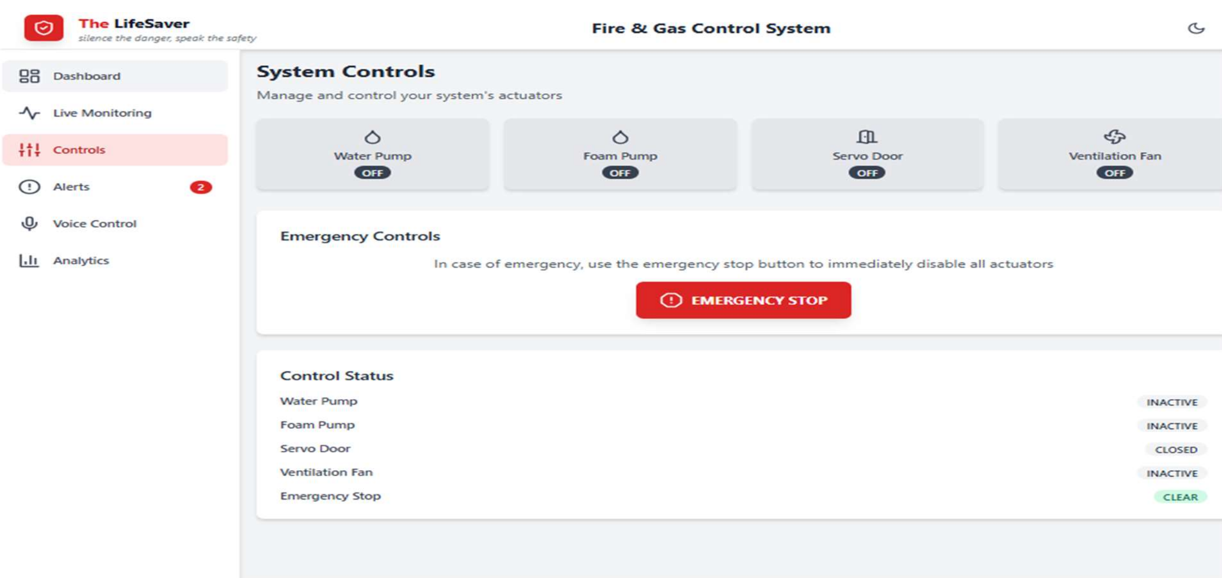

Figure III.17. Actuator Control Interface

5. Alerts

The Incident Management Center includes:

- A time-stamped history of alerts with detailed description
- A pie chart categorizing alerts by type (Fire, Gas, Water, System)
- A summary of alerts in a dedicated section called "Alert Summary"

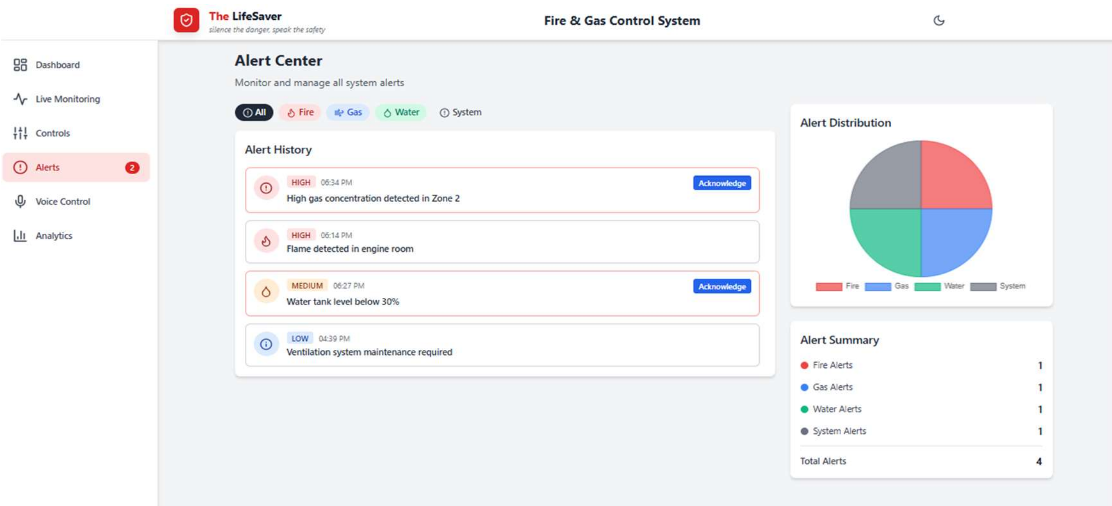

Figure III.18. Alert Management Interface

6. Voice Control

Voice control offers the following features:

- Remote activation or deactivation of devices by voice
- Increased responsiveness in emergency situations without resorting to manual controls
- Improved accessibility and overall system security

7. Analytics

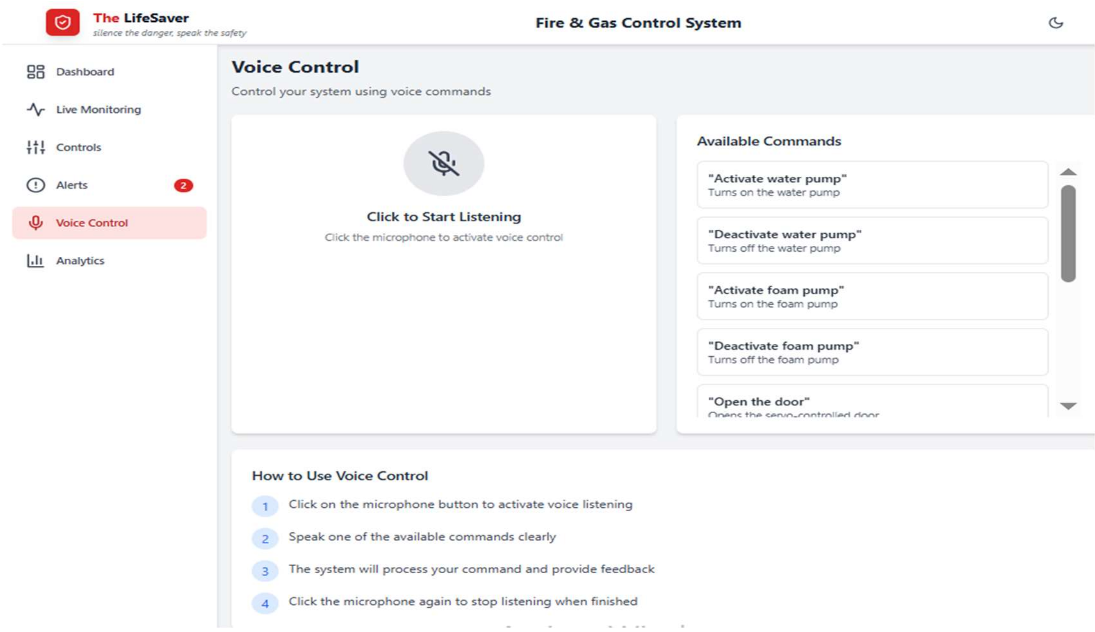

Figure III.19. Voice Command Interface

- Statistical dashboards for system performance analysis
- Averages and trends in gas levels and temperatures over different periods
- Detection rate and overall system effectiveness
- Alert activity graphs for trend identification

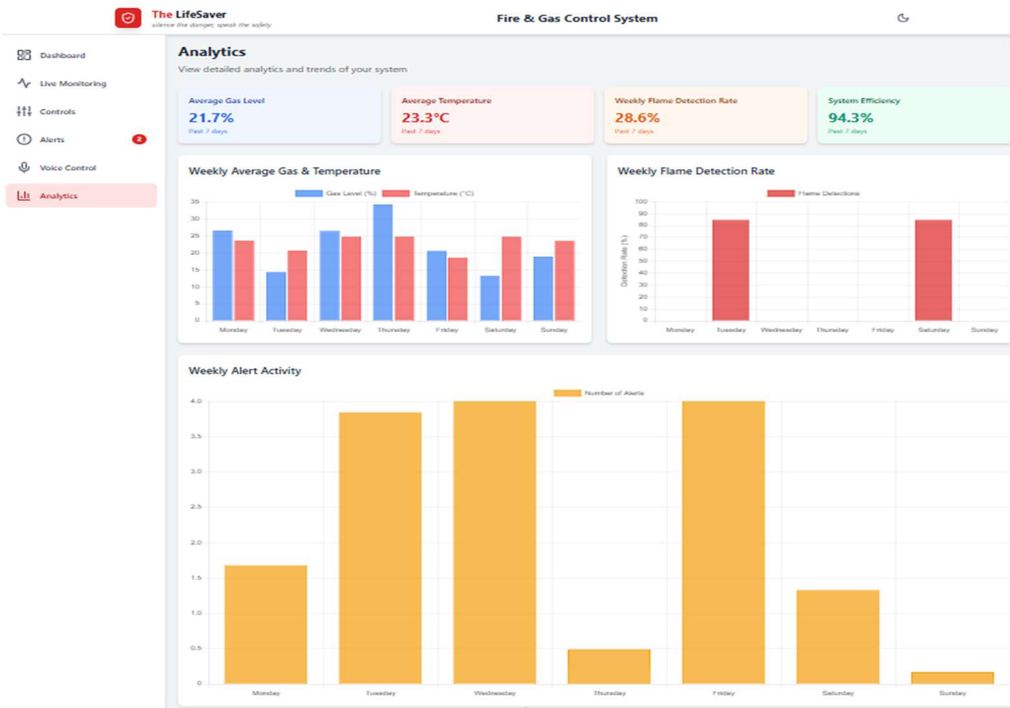

Figure III.20. Statistical System Analysis Interface

III.8.5. Cross-platform compatibility

The LifeSaver interface is designed to ensure optimal accessibility thanks to its compatibility with:

- Computerson Windows, Linux, macOS
- Modern browsers: Chrome, Firefox, Edge, Safari
- Tablets and smartphones

This responsive design allows :

- Real-time mobile monitoring
- Effective remote management
- Great flexibility of use in a demanding industrial environment

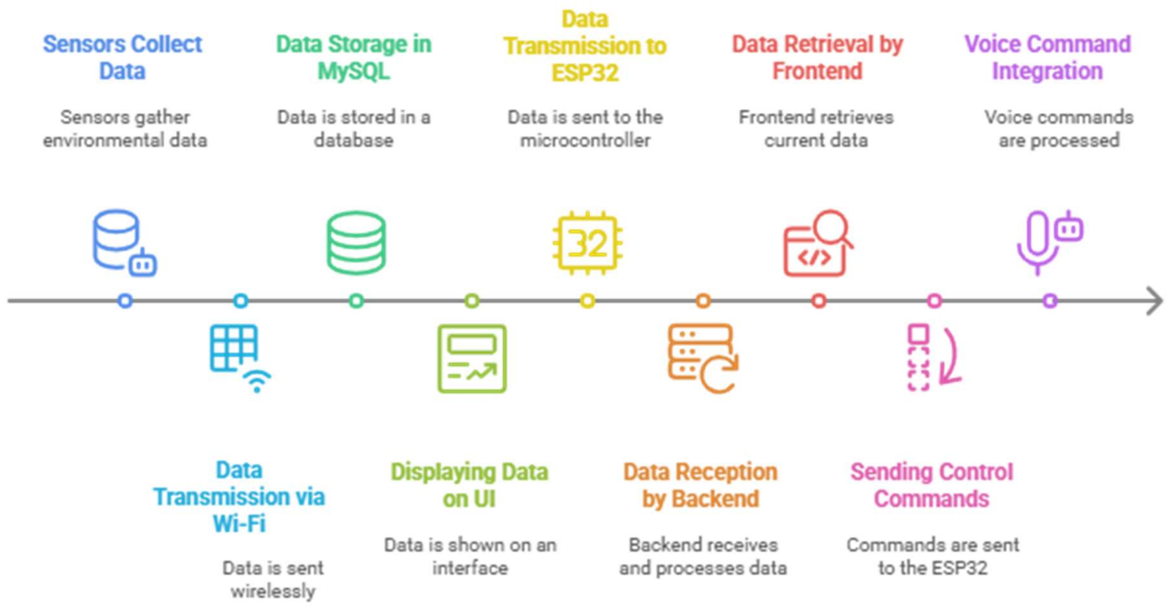

Figure III.21. Data Flow and System CommandsLifeSaver

III.8.6. Advantages compared to a mobile application

- Accessibility from any device with a web browser
- Richer and more detailed data visualization with interactive charts
- A comprehensive dashboard that centralizes all important information
- Smoother navigation between different features
- More advanced data analysis capabilities

- A more scalable and maintainable architecture

III.8.7. Electrical Part

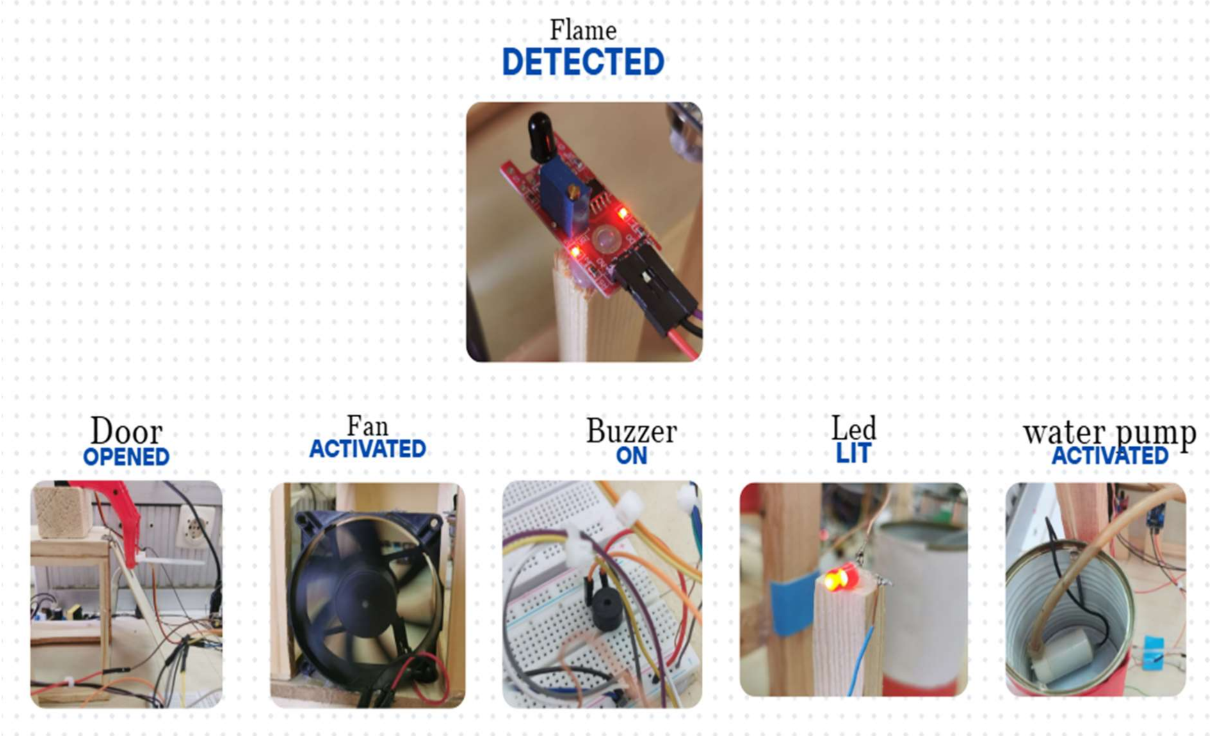

Figure III.22. Fire detection and response system

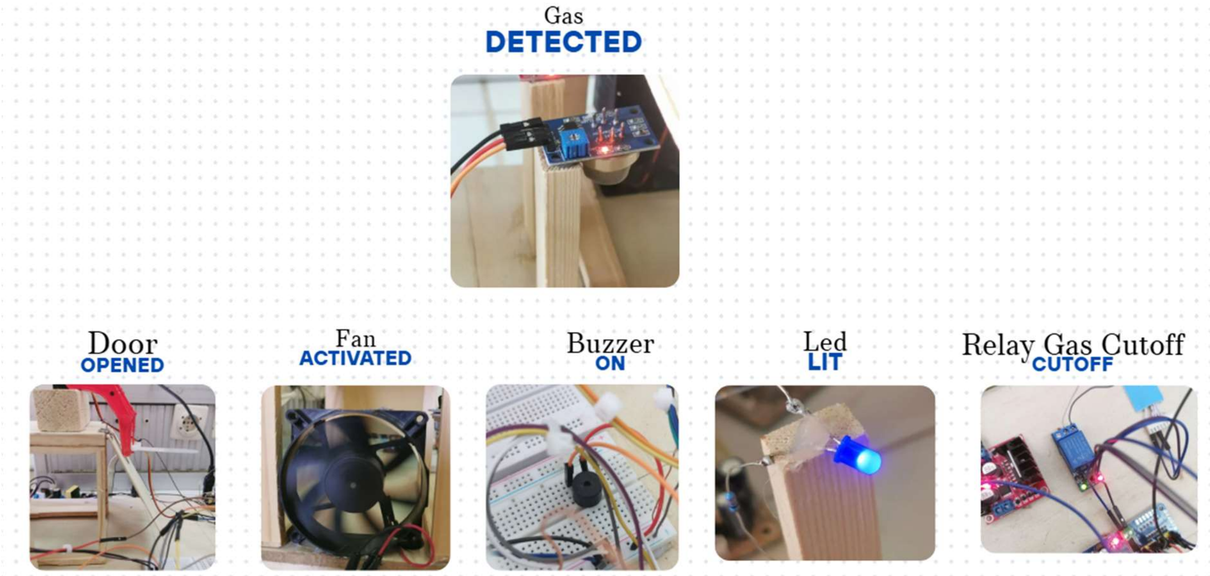

Figure III.23. Gas leak detection and response system

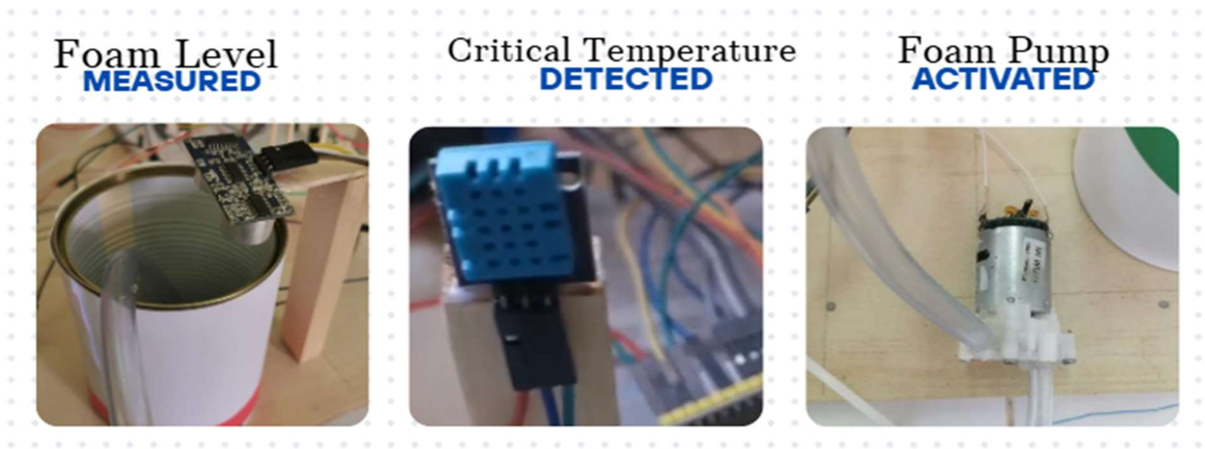

Figure III.24 .Tank overheating or fire response system

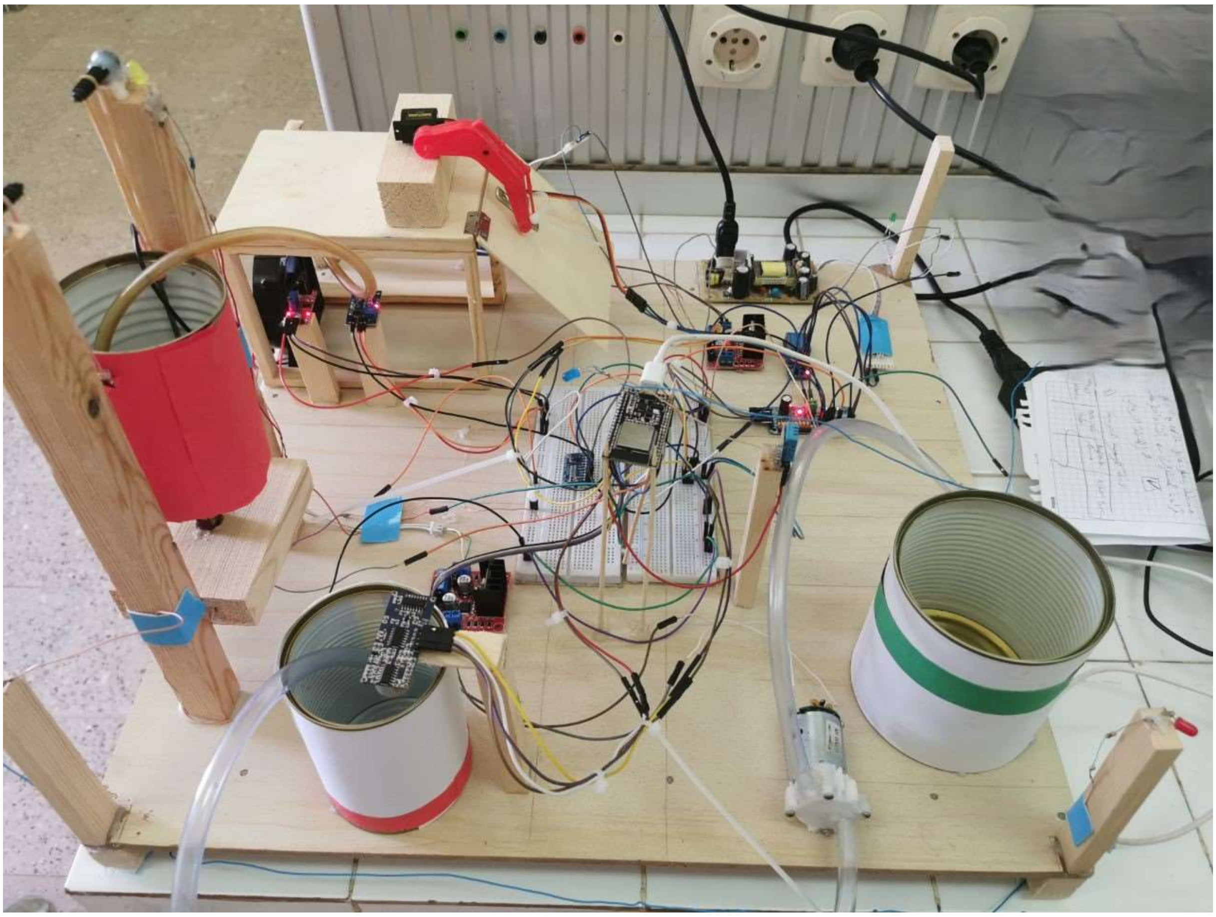

Figure III.25. Overall assembly

III.9. Conclusion

In this chapter, we created a smart model simulating an industrial area, capable of automatically detecting fires, gas leaks, and overheating, and then responding autonomously through various actuators. A dedicated web interface was also developed to ensure real-time monitoring and remote control of the system, thus enhancing its efficiency and flexibility of use.

General conclusion

This work focused on the design and development of a miniature prototype of a fire and gas (F&G) detection and protection system, inspired by industrial systems deployed in critical facilities such as factories and production stations in the oil and gas sector, including stations like SP3 NK1 and OK1 of Sonatrach. The objective was to address the limitations of traditional systems in high-risk environments, where fires and gas leaks pose a major threat to human lives, sensitive equipment, and the environment, potentially leading to catastrophic disasters in the absence of rapid and effective management.

During our practical training in industrial environments, we studied advanced F&G systems such as the SILVANI CS400-R and the Simplex 4100U, and gained an understanding of their crucial role in protecting facilities operating under extreme conditions and housing sensitive equipment. However, the constraints associated with manual intervention in case of failure of automatic systems highlighted the need for innovative solutions.

To meet this challenge, we developed a prototype using available resources, based on the ESP32 microcontroller and equipped with simple and accessible sensors (MQ-2, DHT11, flame sensor, and HC-SR04), along with a remote control interface using Wi-Fi technology. This system enables secure remote operations, using voice or digital commands via smartphones or computers, significantly reducing the risks of exposure to fires or toxic gases in sensitive sites.

The prototype was designed and tested using available software tools, such as the Arduino IDE, with simulations of fire and gas leak scenarios similar to those encountered in factories and production stations. The results demonstrated the prototype’s ability to rapidly detect hazards, send instant alerts, and activate protective measures with high efficiency, despite the use of simple components. The system also proved its stability by maintaining a Wi-Fi connection in simulated harsh environments, making it a promising solution adaptable to the needs of industrial facilities.

The project faced technical challenges, particularly in integrating basic sensors with the Wi-Fi interface and ensuring real-time responsiveness with limited resources. These obstacles were overcome through rigorous testing and software optimization, thereby enhancing system reliability.

This work enriched our skills in embedded systems, wireless communication technologies, and the application of industrial safety standards such as IEC 61508 and IEC 61511.

The following objectives were achieved :

- Design of an efficient F&G system prototype using accessible components and enabling remote control.
- Evaluation of the prototype's performance through simulations of fire and gas leak scenarios similar to industrial environments.
- Proposal of a cost-effective and secure solution adaptable to high-risk industries.

As future perspectives, we propose :

- Improving the prototype with more advanced components to increase reliability under extreme conditions.
- Integrating artificial intelligence technologies to analyze sensor data and accelerate decision-making.
- Expanding the application to more complex simulations of various industrial installations, with comparative studies against commercial systems.
- Developing a cross-platform control interface supporting voice commands in multiple languages for easier use in diverse environments.

In conclusion, this project represents an innovative step toward enhancing safety in sensitive industries facing fire and gas risks. We hope that this prototype serves as a reference for the development of advanced safety systems, contributing to the protection of lives and equipment while preventing disasters in high-risk industrial facilities.

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