2025

Advanced PCB Design: Air quality monitor report

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Table of Contents

1. Introduction

This report outlines the research and processes involved in designing a PCB for air quality monitoring.

It provides a comprehensive overview of the project, covering the general description and functional block diagram. It then explains the theories behind the design and documents the methods used in creating the electronic schematics and PCB design. Additionally, it includes a detailed presentation of the results, observations, tests, and measurements conducted throughout the project.

2. Description

The goal is to design a PCB that can detect various gases and alert the user about the air quality in a room using sensors and actuators.

To achieve this, research on harmful gases is key to choosing the appropriate sensors. When poor air quality is detected, a buzzer will alert the user, and a ventilator will activate to help improve the air quality. After selecting the components, their output values and communication requirements are analysed to determine what additional modules, such as ADCs or other interfaces, are needed for proper integration with the microcontroller. Lastly, the circuit's power supply is carefully selected to meet the specific requirements of the various components.

3. Block Theory

In this part of the report, we detail the different blocks and components that make up the circuit.

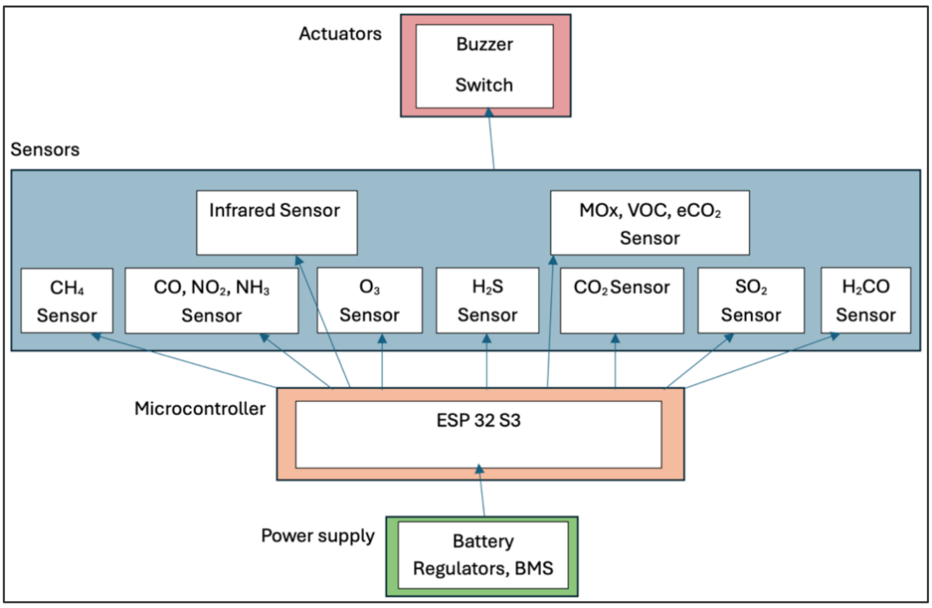

Figure 1 : Bloc Diagram

3.1 Power Supply

First of all, the power supply unit is designed to provide stable and reliable power to all components. It consists of a lithium battery, voltage regulators, and a Battery Management System (BMS) for battery protection and safety.

The BMS is used to protect the battery against overcharging, over-discharging, and overcurrent scenarios by monitoring the battery's voltage and current levels. It regulates the charging and discharging processes, maintaining the battery's health.

The voltage regulation is achieved using an LDO (Low Dropout Regulator) and a boost converter, which step the battery's 3.7V nominal voltage to 3.3V and 5V as required by the system components. This setup ensures that each component receives the appropriate voltage for optimal performance.

3.2 Microcontroller

Next, the ESP32-S3 is used to collect the data supplied by the sensors. It then processes this information to assess whether the air quality is within acceptable limits, by analysing the concentration levels of the various gases. Depending on the results, the ESP32-S3 can activate specific actions, such as triggering the buzzer and switch. The microcontroller uses modules to process the values and signals received. It therefore includes an ADC converter, I^2C communication and a circuit for resetting the microcontroller.

3.3 Sensors

In order to monitor air quality effectively, the next block groups together several sensors used to detect the various noxious gases. These sensors work synchronously with the ESP32-S3 to provide accurate real-time measurements.

Each sensor is connected to the necessary modules so that its values/signals can be processed correctly by the ESP32-S3. The functionality and configuration details of each sensor are explained in the sections below.

- **MICS-6814**

This sensor works on the principle of variations in the electrical resistance of its metal oxide layer (MOx), enabling it to detect the presence and concentration of different gases. The gas concentration in ppm is given in the datasheet in function of the resistance divided by the sensing resistance in air at 23°C.

The sensitive semi-conductive SnO2 layer reacts with the gases (**NO_2, CO, NH_3**). At high temperatures, the resistance of this material changes when exposed to reducing or oxidising gases according to these reactions:

Gas	Type	Reaction	Resistance change
NO_2	Oxidizing	$NO_2+e^- \rightarrow NO_2^-$	R increases
CO	Reducing	$CO+O^- \rightarrow CO_2+e^-$	R decreases
NH_3	Reducing	$4NH_3+3O_2 \rightarrow 2N_2+6H_2O+e^-$	R decreases

- **MQ135**

The MQ135 is a gas sensor used to detect **ammonia (NH3)**, **alcohol**, **benzene**, **carbon dioxide (CO2)**, and **NOx**.

The MQ135 also uses a metal oxide semiconductor sensing layer. When gas molecules come into contact with this layer, they are adsorbed, and the electrical resistance of the sensor changes. The different gases affect the resistance in specific ways, allowing the sensor to detect and measure the gas concentration.

The sensor provides both an analog and digital outputs. The analog pin measures precisely the gas concentration but will need an ADC for the microcontroller to process the data. As for the digital pin, it simply indicates whether the gas concentration has crossed a threshold predefined via a potentiometer.

- **CMJCU8118**

This module integrates 2 sensors: CCS811 and HDC1080

The CCS811 gas sensor uses semiconductor technology, similar to the previous sensors. Its metal oxide (MOX) material changes conductivity when it interacts with **volatile organic compounds (VOCs)** and **equivalent carbon dioxide (eCO2)**, which are reducing gases.

Moreover, the CCS811 sensor incorporates a microcontroller and an ADC for signal processing. The microcontroller applies algorithms to estimate gas levels in ppm (parts per million) and ppb (parts per billion). By using temperature and humidity data (measured by the HDC1080 sensor), the CCS811 compensates for drift and improves the accuracy of its measurements.

The HDC1080 sensor uses capacitive technology to measure **temperature** and **humidity**. For humidity, it detects changes in the dielectric constant of a material inside the sensor, and these variations are converted into an electrical signal. To measure temperature, the sensor uses a thermistor.

These sensors both use an I2C communication.

- **PS1-SO2-50 and PS1-O3-5**

The PS1-03-5 and PS1-SO2-50 are **ozone** and **SO2** sensors respectively, which operate on the catalytic reaction principle. Here is a detailed explanation of how these sensors work and of the catalytic reaction principle:

1. Catalytic reaction of gases:

The gas first passes through a porous membrane (PEM) to the operating electrode, which will measure the concentration of the gas.

Ozone is an oxidising gas. When it meets a catalytic electrode, it undergoes a chemical reduction reaction at the electrode surface. The electrode is designed to enhance the conversion of ozone into oxygen by a redox process. Ozone is reduced to oxygen, releasing electrons.

SO_2 on the other hand is a reducing gas which, when it meets a catalytic electrode, undergoes a redox reaction. On the sensing electrode, an oxidation reaction of SO_2 takes place.

The reaction is as follows for ozone and sulphur dioxide:

$O_3 + 2e- + 2H^+ \rightarrow O_2 + H_2O$
$SO_2 + 2H_2O \rightarrow SO_4^{2-} + 4H^+ + 2e-$

Water is captured by a water retention layer.

2. Generation of an electric current:

The electrons released during these reactions create a very small electric current of a few nA proportional to the concentration of gas in the environment. By converting this current in a voltage using a transimpedance converter and testing it with different gas concentrations we can measure the concentration of ozone and sulphur dioxide in the air. Unlike other sensors, this small current does not need an external power supply to be generated, as it comes directly from the electrochemical reaction.

Role of the three electrodes:

Operating (or sensing) electrode: This is where the gas reacts. It has a surface area made of precious metal and other materials, which facilitates the chemical reaction.

Reference electrode: This electrode maintains a constant potential in relation to the measuring electrode, ensuring that the reaction takes place under stable conditions. It helps to measure current variations without interference.

Counter electrode: This completes the electrical circuit by allowing the electrons generated during the reaction to return to the sensor. It ensures that the electric current flows correctly.

- **MLX90614**

This sensor operates based on the principle of thermal radiation: any object emits infrared radiation proportional to its temperature. It will be used to detect **fires** by measuring **temperature** from a distance.

A thermopile converts the infrared radiation into an electrical signal (a voltage difference), which is then used to measure the temperature.

An integrated microcontroller processes the thermopile's signal. It compensates for variations in ambient temperature and applies calibration algorithms to ensure accurate temperature measurements. The sensor outputs the measured object's temperature, as well as the ambient temperature, in digital form.

This sensor uses an I2C communication.

Unfortunately during a lab session this component was lost. It was later reordered but since there was delay in the order our group was not able to test it.

3.4 Analog to digital converter (ADC)

In order to choose wisely an analog to digital converter, several criteria are taken into account: resolution, noise, number of channels, etc.

To begin with, four sensors need an ADC in our case: MICS-6814, MQ135, PS1-SO2-50 and PS1-O3-5. So only four channels are needed on our converter.

To detect a gas concentration, the analog sensors deliver a small current or make small variations to their resistance. High resolution is needed to display these small measurements. The smallest variations needed to be measured is for the PS1 sensors. With a sensitivity of 20nA/ppm and a range of 0 to 50ppm and by calculating the quantization level with a 24-bit ADC, the sensor offers a resolution of 3µppm. This is a very small resolution that can be affected by the noise. Overall, we found the ADS131M04IRUKR to be suitable.

3.5 Actuators

Finally, the last block consists of components that act as actuators. The function of this block is to indicate poor air quality based on the data collected by the ESP32-S3. The buzzer emits a sound when the concentration of a gas exceeds a threshold, while the switch, a MOSFET, activates to turn on a fan when needed.

4. Design Specifications

In this section, the design methodologies and considerations used in the design of the schematic will be aborded.

4.1 Test Points

In designing a new PCB, it is important to be able to measure and test out the prototype to find any problems that can arise. To facilitate testing and measurements, test points should be acknowledged in the PCB layout. Placing the test points with its labels on the outside of the circuit is ideal.

4.2 Power Circuit Design

To properly design the power circuits, decoupling capacitors are used to stabilize the power supply in the LDO and boost converter circuits by filtering out high-frequency noise. To improve efficiency, the decoupling capacitors are positioned near the components.

Additionally, the power tracks are wider than signal tracks to allow high-current to flow.

4.3 Electromagnetic Interference (EMI) Considerations

As for the PCB layout, electromagnetic interference (EMI) should be considered in designing a PCB. Unfortunately, this criterion has not been respected in the design of this PCB. An antenna, for example, should be either placed on the outside of the circuit or placed on the PCB with a cut-out underneath it.

4.4 Ground Plane Design

A ground plane was incorporated into the PCB to provide a low impedance return path for signals and avoid ground loops thus minimizing noise. This way, electromagnetic interferences are reduced.

5. Implementation

When the concentration value of a certain gas crosses the toxicity limit, the process enters in alarm state. Instantly, a buzzer will notify the person in the room that the air is polluted. In the meantime, the fan connection is triggered to allow an HVAC system to renew the air inside the room.

Finally, the owner of the house will be notified via Bluetooth that a problem has occurred and can see which gas concentration is exceeded.

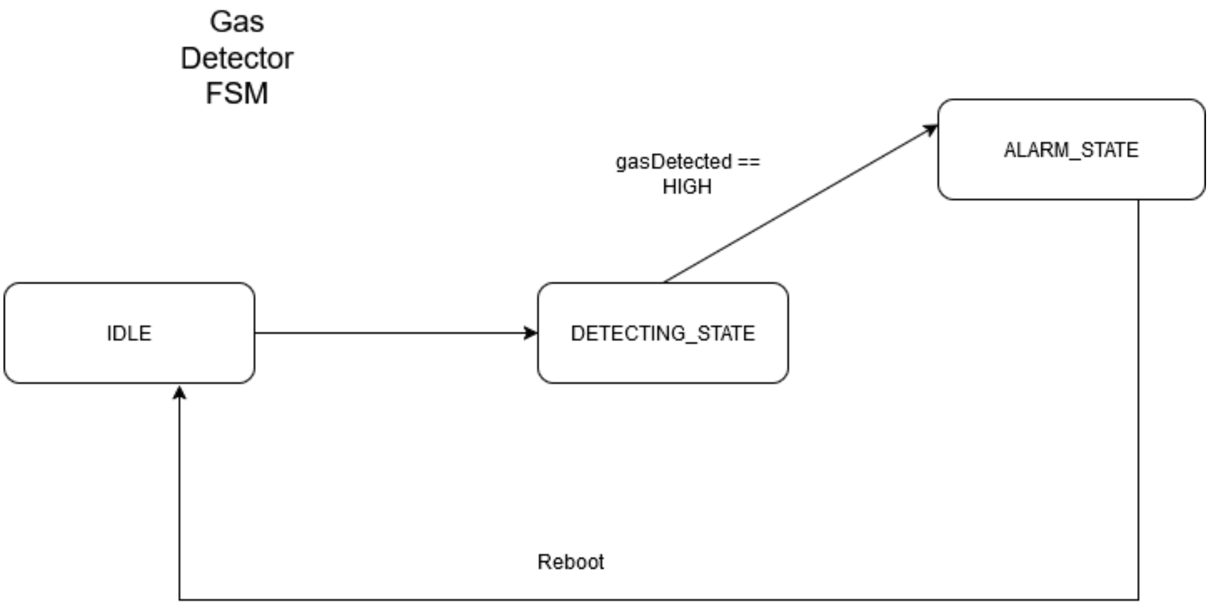

Figure 2: State diagram

Our implementation of this project is basic. Three states are basically implemented:

- The idle state which initialises the process
- The Detecting State where a refresh of the values of our sensors is performed each defined time interval to check if they exceeded a certain threshold
- The Alarm State which sends a message via Bluetooth and activates the fan as well as the passive buzzer in the case of critic air pollution values.

5.1 Idle state :

The Idle state calls a function idleState() which prints the initialization message before changing the currentState variable to DETECTING_STATE.

5.2 Detecting state :

In this state the detectingState() function is called. The constant delay is introduced in order to minimize the power consumption should a sleep mode be later implemented. The different methods used for sensing the gas concentration are used, whether they are only an analogRead() or call more complex methods from external modules.

5.3 Alarm state :

This state calls the alarmstate() function which sets the gate of the MOS to high and therefore supplies the fan and the buzzer. A message should also be sent via Bluetooth to the user using the internal Bluetooth module of the ESP32.

Here is the github link to our project repository:
https://github.com/Jardilou/PCB_Project_4MEO/tree/main

6. PCB Design

This section focuses on the design and development of the circuit schematic.

6.1 Power Supply

- Battery and BMS

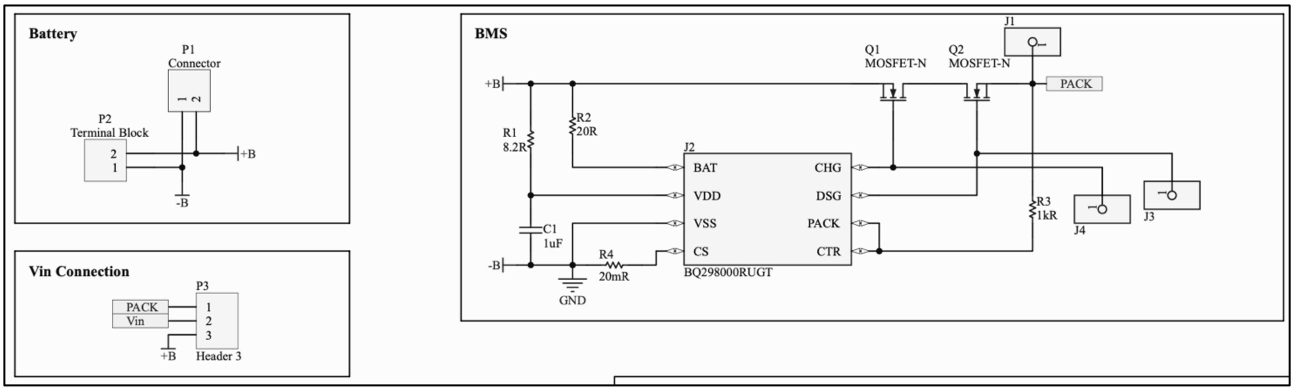

Figure 3: Battery and BMS

The key components of the BMS are:

- The control circuitry (pin CTR): monitors and manages the battery's operation
- Protection FETs: Q1, Q2 MOSFETs to control the flow of current in and out of the battery to the load (*PACK*).

A 3-pin header is used to choose from connecting the voltage regulators to either the battery directly or the BMS.

- Voltage Regulators

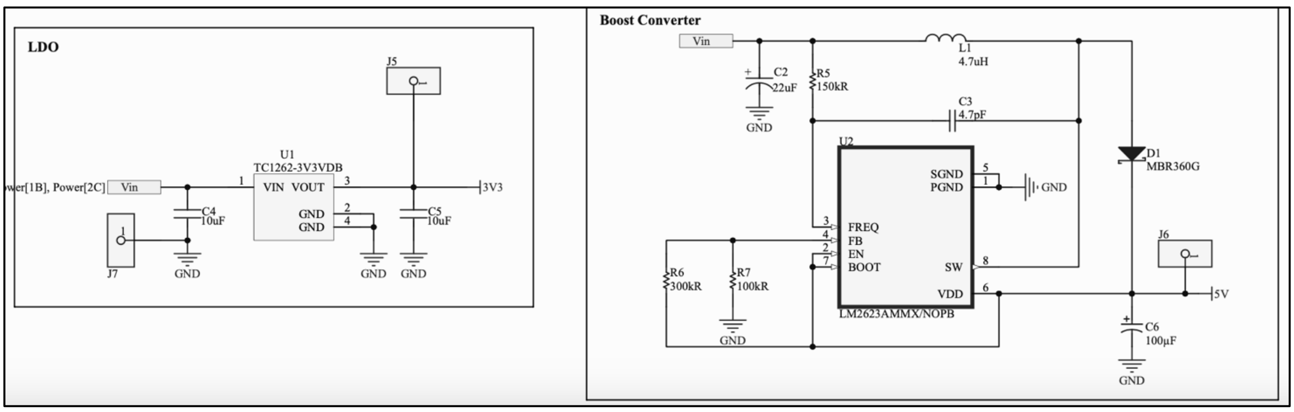

Figure 4: LDO and Boost Converter

6.2 Microcontroller Modules

- I^2C Module

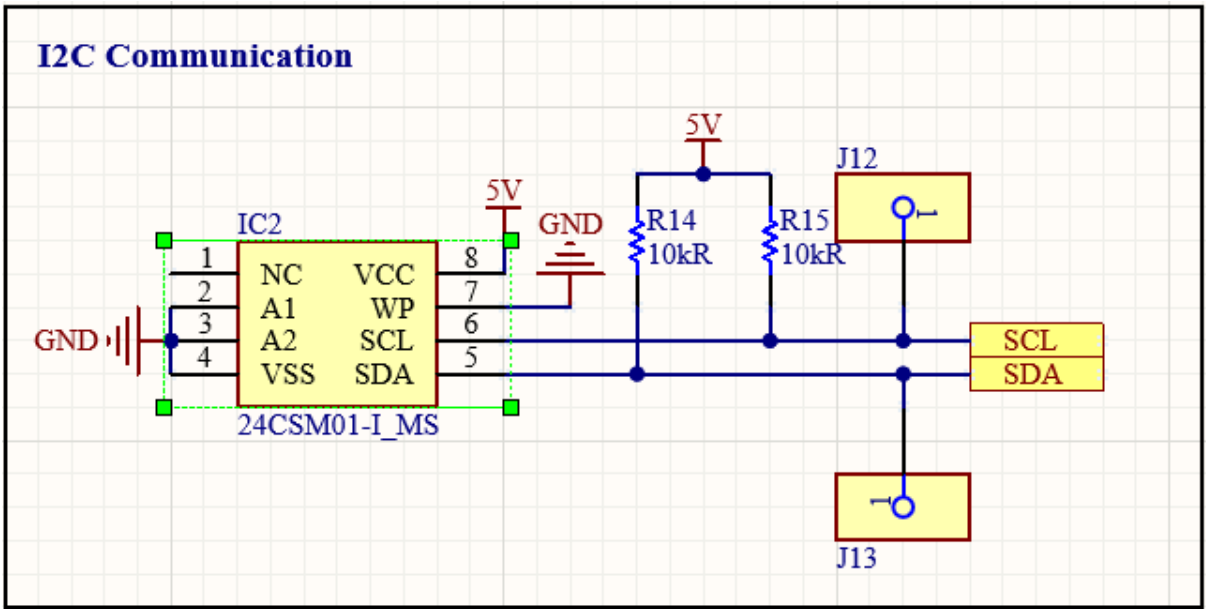

Figure 5: I2C Module

Here, 2 standard pullup resistors are needed in order to bring back the SDA and SCL to a 5V state when the devices do not pull the line to earth. Without these resistors, SCL and SDA lines could float, causing indeterminate states or interference, disrupting communication.

In our I^2C system, several peripherals are connected to the same SCL and SDA lines. Pull-up resistors thus ensure that the shared lines operate correctly. The 10 kΩ resistor value is a typical value for operating up to 100 kHz. As you will see often, we put connectors in order to test our circuit at different point.

- Ventilator and buzzer circuit

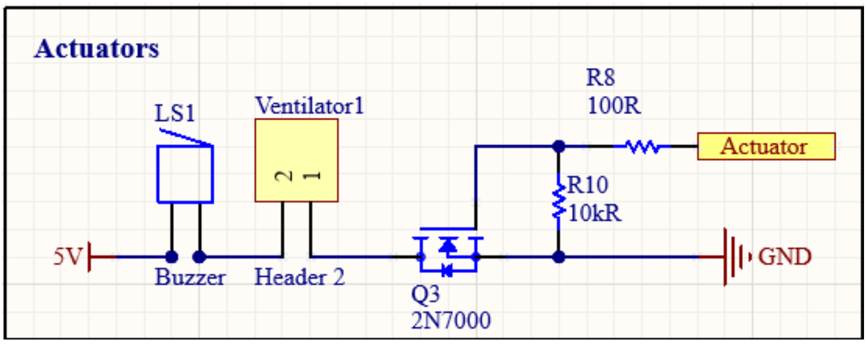

Figure 6: Fan and Buzzer

To control the actuators (ventilator and buzzer), a port from the ESP32 labelled "*Actuator*" is connected to the gate of the MOSFET (Q3). When the "*Actuator*" port sets the gate of the MOSFET to HIGH, the MOSFET is activated, allowing current to flow from the 5V power supply to the ventilator and buzzer, thereby turning them on.

A pull-down resistor (10kΩ) is added to ensure that the gate of the MOSFET stays at 0V (LOW) when the "*Actuator*" port from the ESP32 is not setting the MOSFET to HIGH. This prevents accidental activation of the actuators due to a floating gate.

A small gate resistor (100Ω) is placed between the ESP32 and the gate of the MOSFET. This resistor limits the inrush current to the gate during switching, protecting the microcontroller pin and reducing noise.

- Reset button and Led

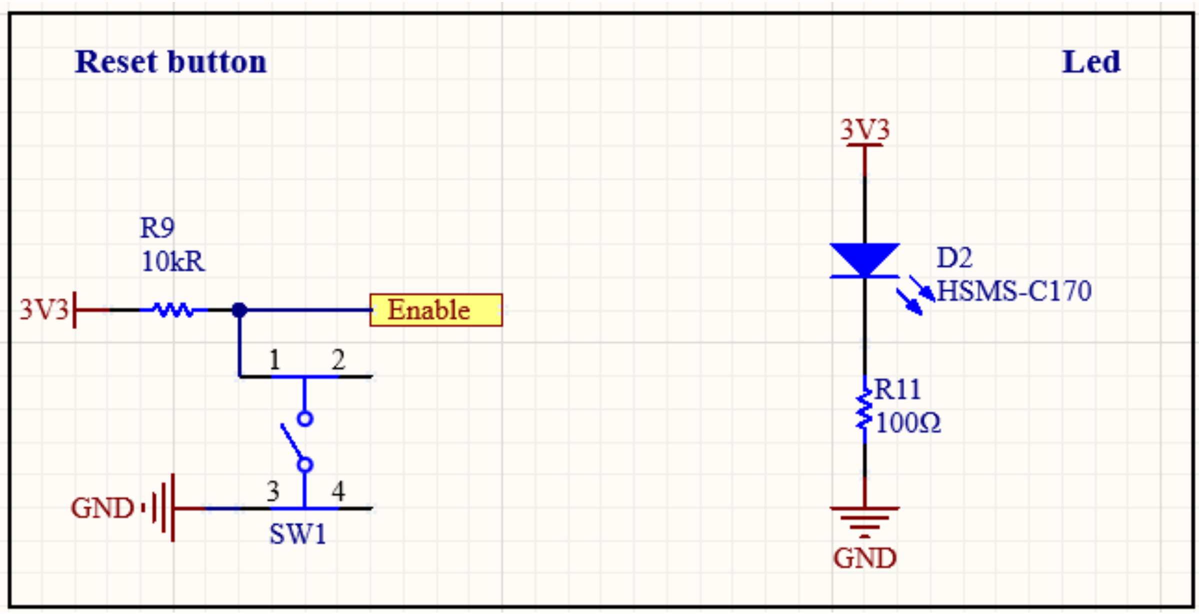

Figure 7: Reset button and Led

For a manual reset of the ESP32, a button (SW1) is added and connected to the pin "*Enable*" of the ESP32 and a pull-up resistor. The latter ensures that the "*Enable*" pin remains connected to the 3.3V power, keeping the microcontroller on. When the button is pressed, the "*Enable*" pin is pulled to GND, resetting the ESP32.

To provide a visual indication that the ESP32 is powered on, an LED (D2) is connected to a 3.3V supply though its appropriate resistor. This LED will light up when the ESP32 is on.

- USBC Port

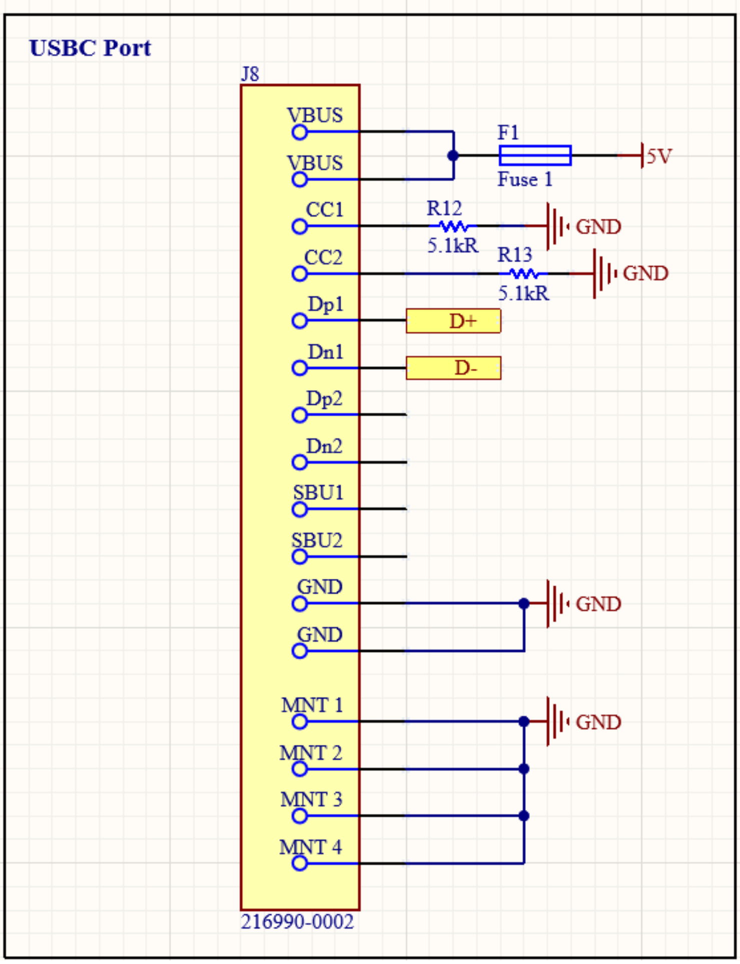

Figure 8: USB-C Port

To safely supply the USB-C port, a polyfused (F1) is placed between the "*VBUS*" of the USB-C port and the 5V power supply. This protects the circuit from overcurrent situations.

To enable the USB-C port to function correctly and indicate that it's acting as a device and not a power provider, the CC1 and CC2 pins (Configuration Channels) are connected to GND through 5.1kΩ pull-down resistors. These resistors indicate to the connected PC or host that the port is a downstream-facing device.

The "D+" and "D-" data lines are directly connected to the corresponding pins on the ESP32, allowing communication between the USB-C port and the microcontroller.

6.3 Sensors

- MICS 6814 sensor

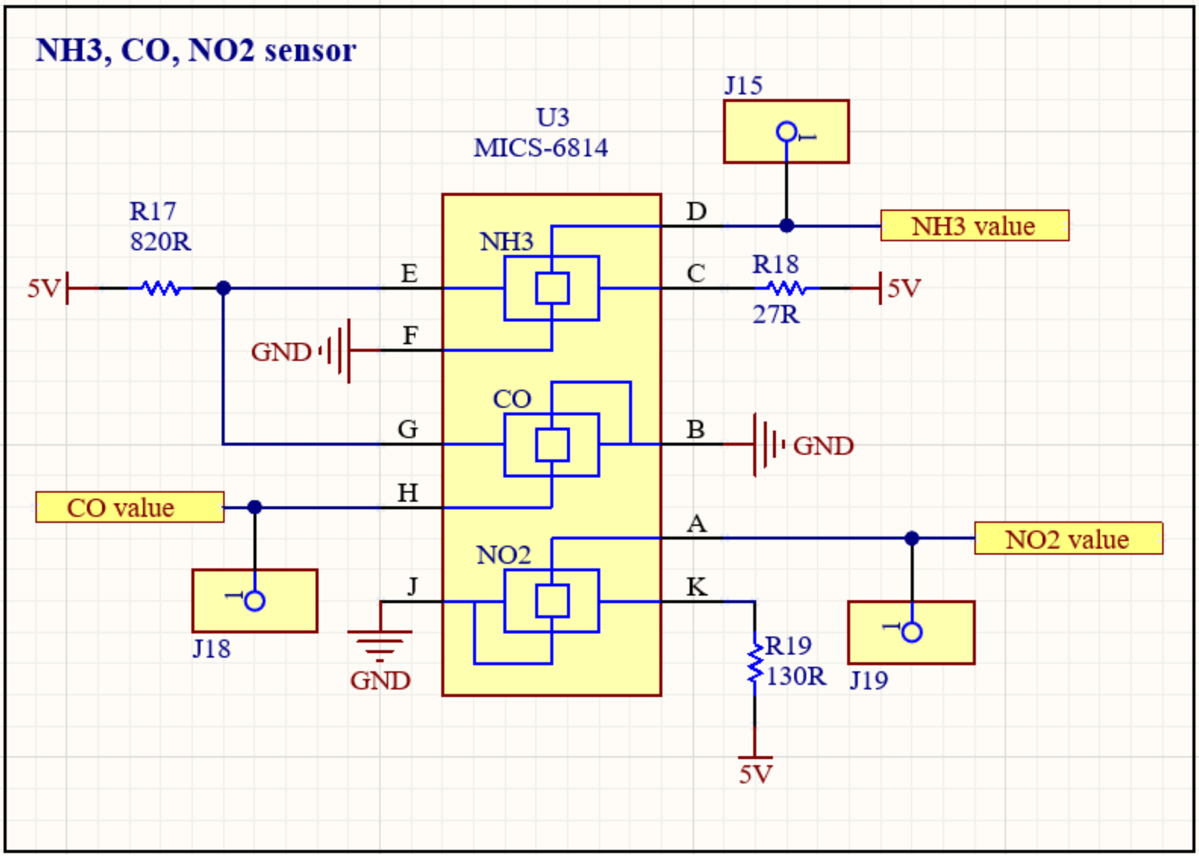

Figure 9: MICS-6814 Sensor

The MICS 6814 sensor is a NH3, CO and NO2 gaz detector. 3 resistors of respectful values 130Ω, 820Ω and 27Ω were necessary to obtain the right temperatures on the three independent heaters while using a single 5 V power supply. The resulting voltages are typically 2.4 V on the CO sensor, 1.7 V on the NO2 sensor and 2.2 V on the NH3 sensor. These gas concentrations are each connected to a pin on the ESP32.

- PS1-O3-5 and PS1-SO2-50 sensors

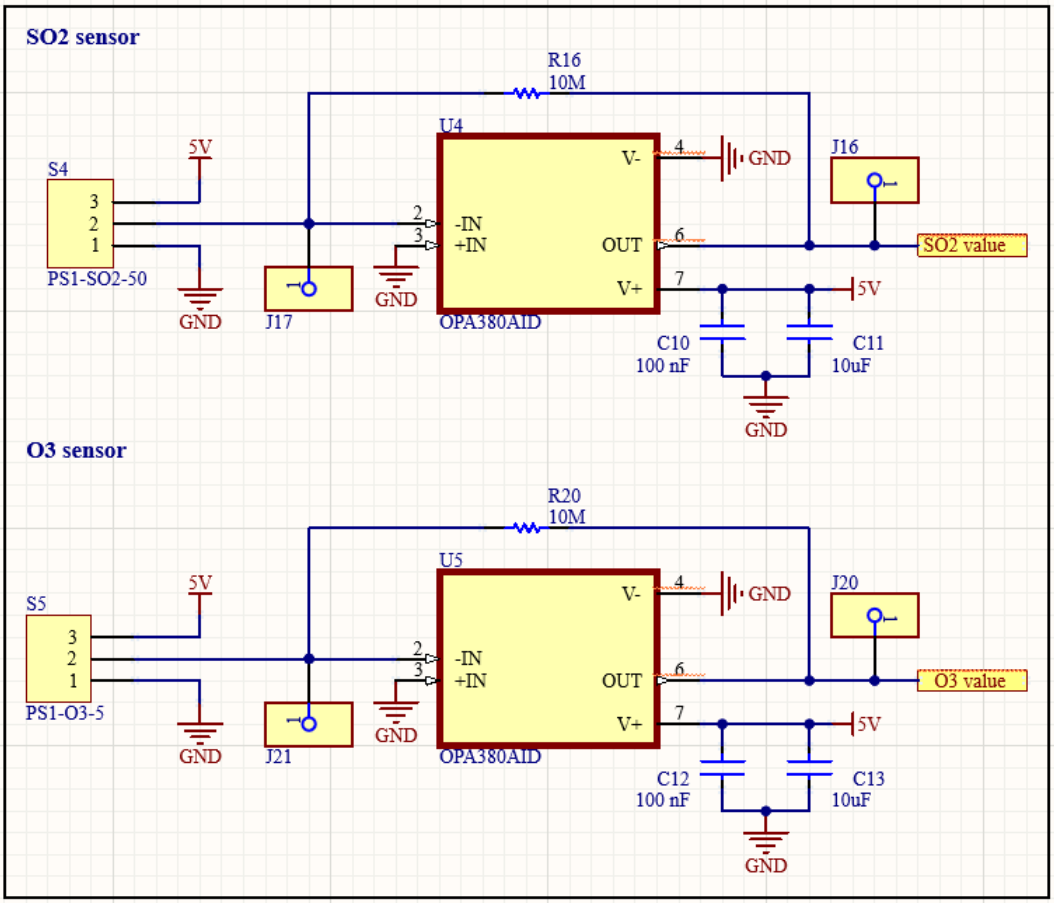

Figure 10: PS1 Sensors for SO2 and O3 detection

These 2 sensors work in the same way in theory.

A very low current will be measured on pin 2 of the sensors, which is the sensing pin. This current is then amplified by a transimpedance amplifier (OPA380AID) in parallel with a 1MΩ resistor required for a voltage gain of 120dB.

Pin 1 of the sensors corresponds to the reference pin thus has to be connected to the ground.

Pin 3 of the sensors corresponds to the counter pin thus has to be connected to the 5V power supply in order to counter the reaction inside the sensing pin, which depletes the voltage.

Again, connectors [Jxx] were placed in various places in order to collect voltage information for testing. Additionally, 2 decoupling capacitors (100nF and 10uF) were also placed near the amplifier to stabilize the power supply and filter out noise.

- The MQ135 sensor

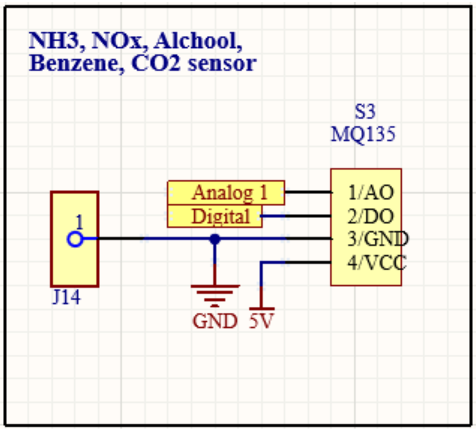

Figure 11: MQ135 Sensor

This sensor is connected to a digital and an analog pin on the esp32 in order to receive both digital and analog input from the sensor.

7. Measurement :

The only working measure we got from the PCB was when we plugged the battery and tested the output tension between the battery ground and the BMS. We can see that the voltage is lowered to 3.64 V which is not far off the 3.7 V lithium battery voltage.

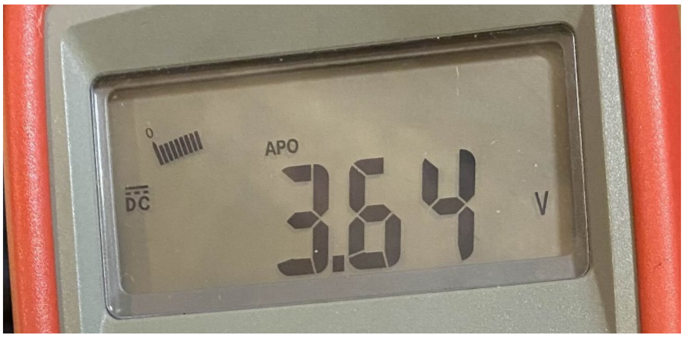

Figure 12: Measurement between Battery and BMS

The measurements done on the regulated voltage test pins were incoherent with what we were aiming for (3.3V, 5V). Therefore, we did not proceed with the measurements of the value of the sensors.

It is of note that additional measurements may appear in the presentation since the due date for this report is 19/01 but the presentation is due on the 21/01. This is unfortunately due to a lack of circumstances for measurement in the lab (the school was closed, an exam was performed in the local at the desired moment, etc).

8. Errors :

8.1. Missing components :

Several components are missing from the original order :

- Two sensors : PS1-SO2 and PS1-O3
- The Resistance R4 placed into the BMS circuit
- Two coupling capacitors of 10µF (SMD)
- The resistance for the Led indicator

These parts of the printed circuit board could thus not be effectively tested.

8.2. Burned components :

During our tests we realized the I2C module of one of our sensors, the CJMCU8118, was burned as the board didn't recognize it but recognized the I2C modules of other sensors. This sensor was thus not suitable for proper use nor testing.

8.3. Missing layer :

During the PCB design phase, a ground plane had to be included for good wiring of our components. Since there are around 200 connections, some couldn't be made with the top and bottom layers only. Unfortunately, our assumption is that this request wasn't respected during the manufacturing process since the only ground measurable when connecting the source, whether it is the battery or the esp32 module, is the ground of the source.

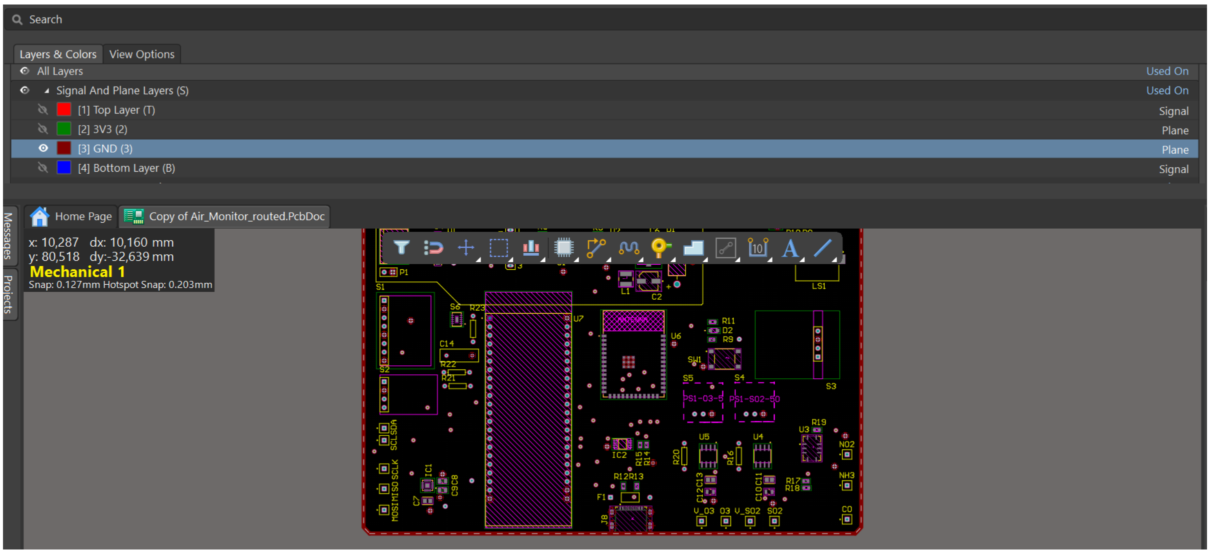

Figure 13 : GND Plane

8.4. Wrong footprint :

The USB-C connection was assured through a separate USB-C connector. Regrettably, the wrong footprint was downloaded and without this connection we cannot be sure that the ESP32 chip could properly work (should the errors listed above not exist).

9. Conclusion :

In conclusion, for multiple unfortunate reasons, the PCB is not working at all. The ground plane missing layer preventing us of getting the right output tensions to supply all the components is the main issue.

With that in mind, we must admit that we learned and improved a lot of skills : from dimensioning previously unknown components to getting familiar with advanced design techniques. Whether it concerns components such as the LDO, the BMS or the many different sensors with various working principles, the routing of a circuit board with a previously unmatched amount of components and the problematics that go along, the most important hazardous gases present in our atmosphere and their critical levels as well as how to solder small scale SMD components and test I^2C connections, etc...

Even though the final circuit board didn't yield expected results, our team still feels like it gained a lot from this project.

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