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BEng Electrical and Electronic Engineering

ELE3001: Final Year Project Interim Report

IoT-based system for indoor monitoring of greenhouse gasses and pollutants

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Contents

1. Project Specification

1.1 Project Motivation

The project specification outlines the necessity of indoor air quality sensors in modern society due to the rising threat of air pollution on the long-term health of people. It highlights common and hazardous pollutants, such as particulate matter (**PM**), volatile organic substances (**VOCs**), e.g. methane (**CH_4**), and Carbon Monoxide (**CO**). These warnings are then consolidated with statistics from the UK's Department of Health and Social Care, such as how their Committee on the Medical Effects of Air Pollutants (**COMEAP**) calculated that the long-term impacts of PM exposure in the UK equates to about 340,000 years of life lost.

1.2 Project requirements

The project specification then goes on to list the objectives of the project: to perform a literature review of the shortcomings of current indoor air sensors, to interface PM, CO, temperature, humidity, CH_4 and Carbon Dioxide (**CO_2**) sensors to an Arduino microcontroller, to develop a PCB with noise-reducing circuitry, and to develop an IoT dashboard of sorts, such as on MATLAB (full project specification in **Appendix 1**).

2. Project Objectives

2.1 Refining Project Objective

Through the undertaking of the first requirement of *1.2*, it became apparent that to maximise the efficiency of an air quality monitor, a clear target working environment had to be established. For example, the most popular sensors on the market, like the *PurpleAir Zen* or the *IQAir AirVisual Pro*, are clearly for home use; they monitor only temperature, humidity, CO_2 and PM, the most common indicators of air quality within a home. They do not waste any resources on improbable pollutants, like VOCs. In that capacity, carrying on the project with a home in mind would be counterintuitive, given the second requirement in *1.2* necessitates the inclusion of both CH_4 and CO sensors.

Through further research into areas which would benefit from improved air quality, an article by Fragkou et al **[1]** explained that *"Many agricultural activities rely on energy consumption of relevant machinery and equipment, resulting to significant emissions of greenhouse gases and air pollutants, including carbon dioxide, nitrogen oxides, and particulate matter"*. As such, it is clear that an agricultural setting would be an optimal location to meet the criteria of

1.2, as the target gasses are not only likely, some, such as PM, CO_2 and CH_4, may even be abundant. An article by hortisensors.com **[2]** consolidates this point, declaring that "*managing air quality in agriculture is crucial to ensuring optimal plant growth and animal health*", this statement makes it clear that good quality air is paramount when it comes to the operation of a farm. On top of simple operation, the long-term health of the farm workers heavily rests on good air quality as noted in *1.1*. Long-term exposure to PM, CO_2, CH_4 and CO have all been documented to be dangerous, which can quickly become lethal if left to get worse. Therefore, not only profit but lives are dependent on an accurate, fast and reliable air quality sensor on a farm.

Secondly, the ever-growing concern of climate change also necessitates a good air quality sensor on a farm. Douglas **[3]** writes that the agricultural industry generates "*21% of all the world's carbon dioxide, 53% of all methane and 78% of all nitrous oxide emissions globally*." These are alarming statistics which can be alleviated with the aid of an air quality sensor. The data from such a sensor could help guide farmers in avoiding negative practices with high greenhouse gas emissions, lowering their overall contribution to climate change.

2.2 Tailoring Project Criteria

With the goal of the sensor performing on a farm in mind, certain criterion for the project were amended to better align with the goal. These amendments were devised and agreed upon by both the student and the project supervisor. Firstly, a Hydrogen Sulphide (**H_2S**) gas sensor was incorporated into the list of sensors for the project. This addition was implemented with the thought of the tragic loss of professional rugby player Nevin Spence and his father and brother. The BBC **[4]** reported that the men were "*overcome by the slurry fumes*" and thus fell unconscious. Tasker **[5]** explains in an article he wrote to warn people of the dangers of slurry fumes that: "*at higher levels it* (H_2S) *can't be smelt, shutting down the nervous system, causing collapse, unconsciousness and ultimately death*." These two sources make it abundantly clear that a H_2S sensor is an imperative addition to the project.

Technical considerations also had to be made because of the planned environment of operation. The main one being point four of *1.2*, an online dashboard. This is an unfit way to present data to the planned user, i.e. farmers and agricultural workers, as they do not tend to be technologically inclined. For example, the United States Department of Agriculture published a report in 2021 **[6]** informing that only "*67 percent of farms* (in the USA) *had a desktop or laptop computer*." Considering that such a large proportion of farmers do not own a computer at all, it can be extrapolated to assume that a large number of those that do are not digitally adept. Hence, it was concluded by the student and supervisor that the best way to display the readings would be by way of a physical screen on the device itself, which the farmer or agricultural worker can read easily.

3. Schedule/Timeline

3.1 System Design and Integration

With the project's purpose and operation in mind, the design and engineering to realise that vision could commence. **Figure 1** models the engineering process of how the system was put together, it was repeated for each step of the project until the air quality sensor was complete. The first step of identifying the challenge to take on would be worked out in the student's weekly meeting with the supervisor, where they would discuss the state of the project, and the supervisor would guide the student on the appropriate next step to keep the project advancing. With the goal in mind, the student would then go through supplier websites such as RS, Farnell and Digikey to find the most suitable component to fulfil that requirement. The component would then be ordered through the EEECS support team and while waiting for it to arrive, the student would prepare by reading the component data sheet and watching tutorial videos of its operation on Youtube.com. With that preparation in place, it is then simple to complete step 3: testing the component. With the component functional, the final task is to integrate the component to the rest of the system by wiring it up to the main breadboard of connections to the Arduino Mega 2560 microcontroller and adding the component's operating code to the main project code programmed into the Arduino.

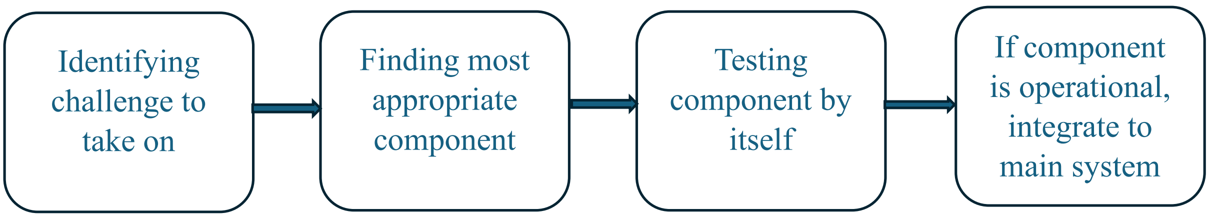

Figure 1 – Design and engineering process

3.2 Recording Progress

Initially, a document recording the main points of the meeting, the planned work for the week and the achieved work that week was updated to keep track of progress, an example of which can be found in **Appendix 2**. This document allowed for the accurate tracking of progress and work needing to be undertaken but as time went on and the workload increased, it became inconvenient to continuously have to type in each new update. This inefficiency was addressed in a meeting with the supervisor, where he suggested using a Gantt chart to keep track of the project. As can be seen in **Figure 2**, the Gantt chart makes it much simpler to track the status of each task and to plan ahead and be able to complete tasks in parallel.

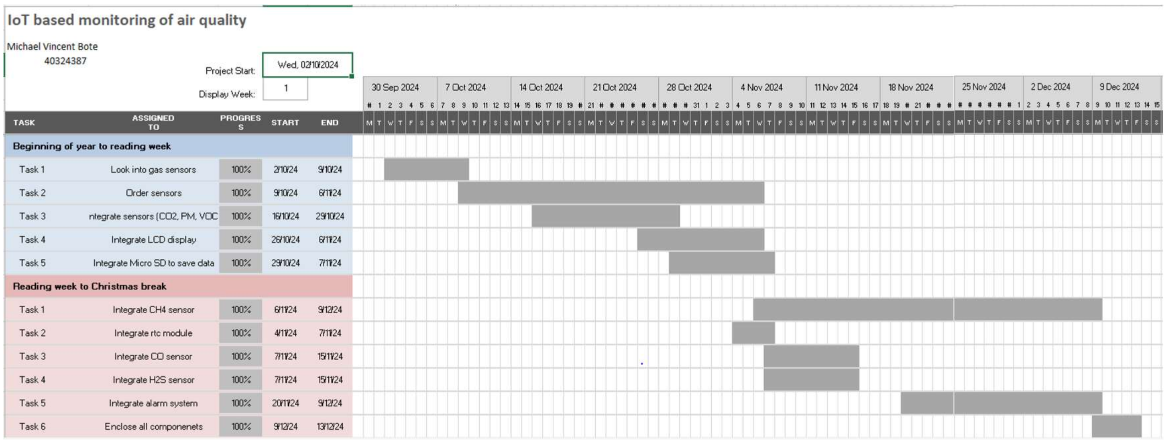

Figure 2 – Gantt chart of project progress

3.3 Current Status

As can be viewed in **Figure 2**, the design and building phase of the project is completed as of the end of semester 1. All components have been successfully operated individually as well as simultaneously in a bare-board system (**Figure 3**). With all components working well, the process of enclosing all the parts into the single, plastic enclosure was started and completed in the week 9-13/12/24; the completed, enclosed system can be viewed in **Figure 4**. The planned work to be completed in the second semester can be found in **Section 5**.

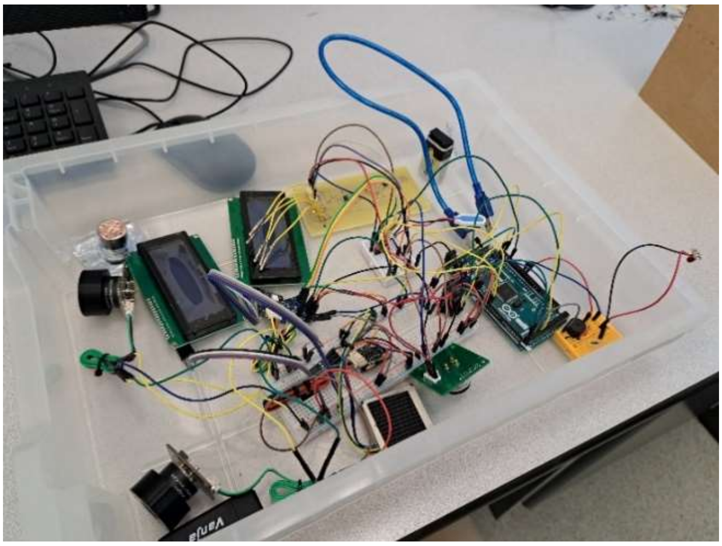

Figure 3 – Air quality sensor, bare-board stage

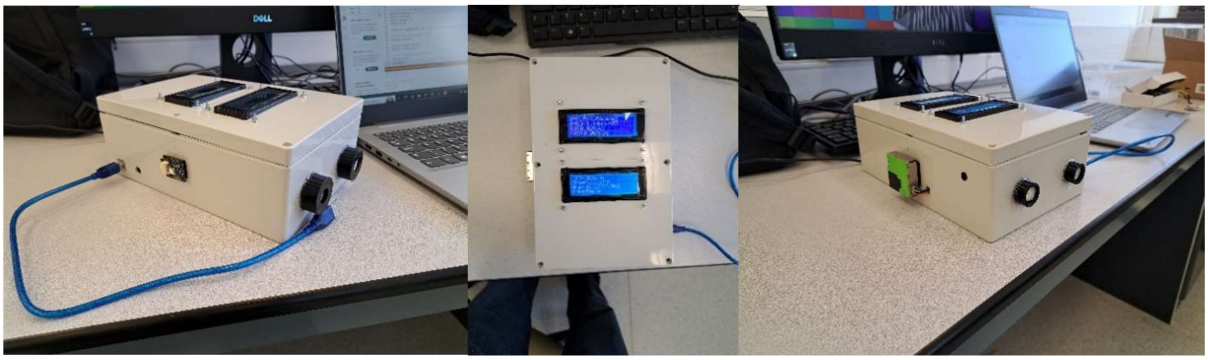

Figure 4 – Air quality sensor, enclosed

4. Completed Work

The first components tested and integrated were two sensors by Sensirion: the SCD41, which senses CO_2, temperature and humidity, and the SPS30, which senses PM. These sensors were inherited from a previous air quality sensing project and were already known to be operational and reliable. These sensors were also an ideal first step as Sensirion had provided github repositories for both the SCD41 **[7]** and the SPS30 **[8]** with instructions on how to properly connect the sensors to an Arduino microcontroller as well as example code to run them. Both sensors also used the I2C communication protocol, simplifying connections as both communicated to the microcontroller via the same two pins: the serial data pin (**SDA**) and the serial clock pin (**SCL**).

After a meeting with the supervisor, the next step was agreed upon to be displaying the data in real-time on a physical display as mentioned in *2.2*. To carry on the simple and effective communication connections, only displays with I2C capabilities were looked at. After testing a few options, such as an OLED display, it was eventually decided upon that an I2C 16-02 LCD by FREENOVE was the best option for its simple code as well as its robustness. Later on, given the number of readings to be displayed (eight in total), the 16-02 LCD proved to be insufficient to display all the data so instead, two 20-04 LCDs by Youmile were incorporated and now all readings could be displayed simultaneously.

Next, a kwnmobile Micro SD card reader was added so the data could not only be displayed but also saved. The SD card reader used the SPI communication interface however, which complicated the wiring as SPI requires four wires to communicate rather than just two. After dealing with a few challenges (as addressed in *6.2*), the reader was operational, but it then became obvious that the readings would be meaningless without a timestamp, as the user would have no way of knowing what actions triggered the readings without knowing when they occurred. To address this issue, the DFRobot DFR0151 real-time-clock (**rtc**), which had I2C communication, was brought in to allow the sensor to keep the time. A tutorial by Tim **[9]** proved to be extremely useful in testing the rtc and integrating it into the main system by providing an in-dept explanation of the component as well as example code to run it. **Table 1** displays an example of the csv file saved by the sensor.

Table 1 – Example sensor output csv file

Timestamp	CO2(PPM)	Temperature(*C)	Humidity(%RH)	PM2.5(ug/m3)	PM10(ug/m3)	CO(%vol)	H2S(%vol)	CH4(ppm)
09/12/2024 12:30	748	24.19	31.48	1.51	1.63	0	0	0
09/12/2024 12:31	737	24.17	31.82	3.26	5.79	0	0	0
09/12/2024 12:31	735	23.97	32.15	3.22	5.64	0	0	0
09/12/2024 12:31	792	23.89	32.6	2.83	4.67	0	0	0
09/12/2024 12:31	822	23.73	33.13	2.73	4.44	0	0	50
09/12/2024 12:31	838	23.63	33.53	2.62	4.35	0	0	88
09/12/2024 12:31	841	23.52	33.8	2.46	3.98	0	0	59

Subsequently added to the system were sensors for CO and H_2S, both of which are from the DFRobot gravity gas sensors range (further reading in **Appendix 3**). These sensors particularly stood out thanks to their accuracy as they had been calibrated by DFRobot in-factory. They also had the benefit of simple operational code, thanks to their custom Arduino library, and convenient wiring requirements, thanks to their I2C communication capabilities.

The next piece decided upon to be added was the CH_4 sensor; it had already been decided that the IRM-AT by alphasense was the most appropriate as, unlike most on the market, it was a non-dispersive infrared (**NDIR**) sensor. This is relevant as in a paper by González et al **[10]**, specifically section 3, figures 16 and 17, which compare the predicted and true responses of sensors for CO_2 and CH_4, it is clear that that the NDIR sensor is more accurate than other sensor types. As by looking only at non-NDIR sensors in figure 16, the observed values show a much larger variance from the predicted perfect response, while in figure 17, which includes the NDIR sensors, the observed responses are almost exactly equal to the predicted perfect response. The IRM-AT had the challenge however, of requiring an integration PCB to allow it to communicate to the microcontroller. This was achieved through the KiCAD PCB design software which allowed for the schematic in **Figure 5** (which is the suggested circuit by alphasense to integrate the IRM-AT to a system) to be turned into the PCB design in **Figure 6**. The PCB was then manufactured by the EEECS support team and then tested. After addressing some problems (as explained in section *6.3*) the IRM-AT was fully operational and was integrated into the main system. To aid with the accuracy of the IRM-AT, another alphasense sensor, the PID-AH VOC sensor, was added as explained in section *5.1*.

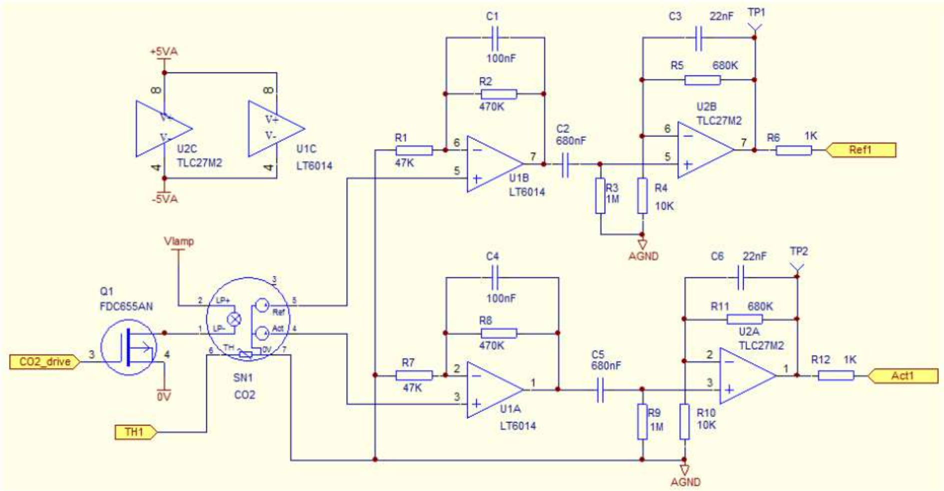

Figure 5 – IRM-AT integration PCB schematic

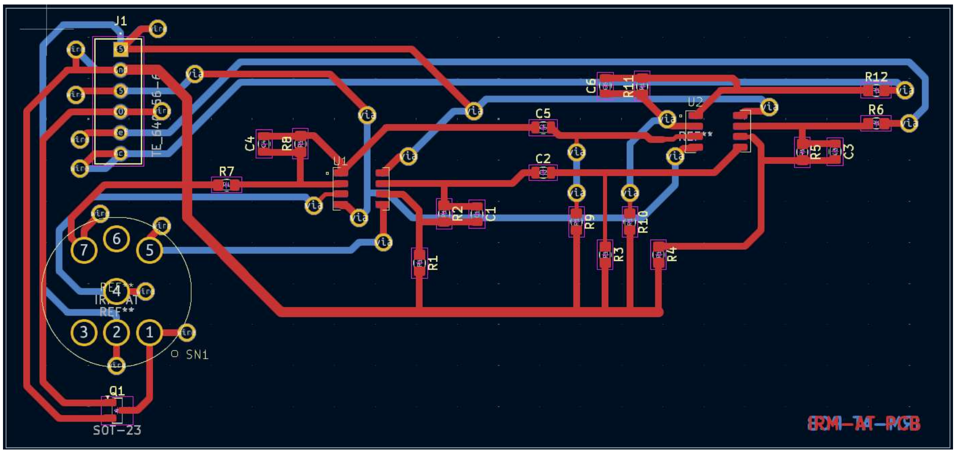

Figure 6 – IRM-AT integration PCB design

The final part of the system to be added was the alarm system. Research was performed to find at which levels the pollutants were considered by experts to be concerning, denoted as a level 1 alarm, and levels which are considered dangerous or lethal, denoted as a level 2 alarm. A flashing red LED is used to display a level 1 alarm, and a buzzer is used along with the LCDs flashing in case of a level 2 alarm. The alarm would be controlled and monitored in software with there being dedicated variables and subroutines to monitor the readings of each pollutant as well as how long alarming readings had been observed. The event of an alarm would also be noted in the saved csv file of data readings. To turn off the alarm the microcontroller must be manually reset, ensuring that the user cannot ignore it, and that appropriate action is taken before it is turned off.

The final piece of work completed in the first semester is to enclose the system within a 16x25x9 cm RSPRO enclosure. Much aid was provided by EEECS support team on the

Ashby Building 9th floor labs through the accurate drilling of the enclosure to allow easy access to the Arduino Mega's USB-B and DC power ports as well as holes to allow the sensors and their wires to go in and out of the enclosure. The final product can be viewed in **Figure 4** and the completed system wiring diagram can be viewed in **Appendix 4**.

5. Planned Work

5.1 CH_4 Sensor Calibration

The IRM-AT and the PID-AH both only give an analogue voltage reading which is proportional to the gas level sensed, not an actual measured value. In order to get an accurate reading, it is planned to test the system in a fume cupboard in the university's chemistry labs with a source of CH_4 with a known concentration. Through this experiment, the analogue voltage value can then be scaled in software so that an accurate measurement of CH_4 in ppm is outputted. The PID-AH sensor is utilised to aid in the IRM-AT's accuracy; it cannot detect CH_4, but it can detect other VOCs; this means the PID-AH can be used to ensure that the IRM-AT is not reacting to VOCs that are not CH_4. By monitoring both sensors in software and comparing their readings, the likelihood of false CH_4 readings decreases.

5.2 Software Improvements

The student has identified multiple shortcomings in the software operation and plans to address such issues before performing full tests. The main issue identified is the data saving feature: all data is currently being stored into the same csv file. While this is fine for testing, which will only see the device active for minutes at a time, during proper operation, where the device could be active for days at a time, this method is simply unusable as the csv file will quickly become too full and crash the system as the data saving feature is integral to its operation. The student plans to be able create a new csv file each day to maintain organised and efficient data collection. Another software challenge is to code a subroutine to monitor the IRM-AT and PID-AH sensors, as specified in *5.1*. To achieve this, a comparator subroutine must be created to keep track of two sensors' readings and if both readings experience a spike simultaneously, then that spike would be noted as a false positive.

5.3 Home Test

With all sensors fully operational, the next test would be an initial operational check in a controlled environment where it can be constantly monitored by the student. It is planned for the student to bring the device home and to place it in environments where the reactivity of the device would be tested; for example, in the kitchen whilst cooking to test the PM sensor, or beside a compost caddy to observe the change in CH_4 levels over time through food decomposition. An extended use test will also be performed with the sensor being operated continuously for several hours up to a full day to ensure it can handle the strain of prolonged operation. During this, the student will repeatedly check the device's output levels to ensure it remains accurate for the full test. After, analysis on the subsequent csv file of the data recorded will be performed to look out for any anomalous data. If any problems with the reading are found, fault-analysis and repairs will be made. This will be repeated until the device can successfully perform accurately and reliably for a full extended test.

5.4 Field Test

When the device passes the home test, the next test planned is a full in-situ field test. The supervisor and the student both agree that the knowledge to be gained from such a test would be invaluable. University connections to local farms would be used to find a willing volunteer to test out the operability of the air quality sensor. The device along with a battery supply or mains cable would be given to the volunteer to place it in its intended environment: an indoor area within a farm. The volunteer would then power up the device and let it run as normal, displaying readings for air quality. At the end of the test period the student will then be able to ask the volunteer for feedback on the device's user interface, accuracy, helpfulness, etc. providing insight into any improvements that can be made. Combing through the subsequent data file would also be useful in checking the device's accuracy and reliability, if anomalous data is found then an investigation into the cause would be performed.

6. Problems Faced

6.1 SPS30 Wiring Issue

The first problem faced was an issue with the SPS30 PM sensor, as stated before it was one of the sensors which were inherited rather than bought new, so when testing it the original wiring was followed (3.3 V supply with I2C communication interface). The issue was it outputting extremely high readings for PM, so high they were not physically possible. At first the student assumed this was a software issue, but after combing through the example software from the creators, no problem was found. Eventually, after examining its data sheet, the student discovered that while technically 3.3 V could turn the SPS30 on, its input voltage ranged from 3.3 – 5 V and experience had taught the student that devices tended to prefer the upper bound value. When the device was powered with 5 V, the issue did not occur.

6.2 Micro SD Card Saving Issue

The next large hurdle was with the Micro SD card module. Whilst testing it on its own with example code found online, an error kept occurring, stating that there was no Micro SD card present. To address this issue the wiring was first checked, as stated before this module used an SPI interface, which requires twice as many connections as I2C. The wiring was found to be all correct and the code was also exactly as needed, it also was not a faulty device as the student had tried multiple devices, and all displayed the same issue. The student then went through all available tutorial videos on YouTube.com in an attempt to diagnose the issue; a video by Robojax **[11]** provided the answer by explaining that, in order for the Arduino to be able to communicate to the Micro SD card, the SD card had to be in the correct file format, specifically the FAT32 file format. However, this file format is only available for Micro SD cards which have a storage capacity of 32 GB and below, and the Micro SD card procured by the student was 128 GB, hence, why it could not automatically communicate to the microcontroller. The issue was immediately resolved with a new 32 GB Micro SD card.

6.3 IRM-AT PCB Issue

The most recent challenge was to get the IRM-AT integration PCB working and outputting realistic results as initially, its readings were extremely erratic, swinging from minimum to maximum constantly (an analogue voltage reading from 0 to 1023). To diagnose the issue, the IRM-AT was connected to an Arduino Uno microcontroller along with the PID-AH (to act as a reference as it had a stable output) to form a small system. Code to run the two sensors was the initiated, and their outputs were probed and visualised through an oscilloscope. The PID-AH's output is as in **Figure 7**, a square wave with low amplitude; this waveform displays its stability. Similarly, the IRM-AT's output wave form (**Figure 8**) illustrates its inconsistency, having a far larger range of -0.75 to 3.46 V. This range proved to be the key to solving the issue as its trough was far shallower than its peak, even though the operational amplifiers should have had supply rails of 5 and -5 V. After further investigation with the oscilloscope, the student found that neither of the operational amplifiers were receiving their negative power rail because of an improperly soldered via in the PCB, which was preventing the negative rail from reaching them. The issue was immediately resolved after fixing that issue and the subsequently stable output waveform of the IRM-AT is as seen in **Figure 9**.

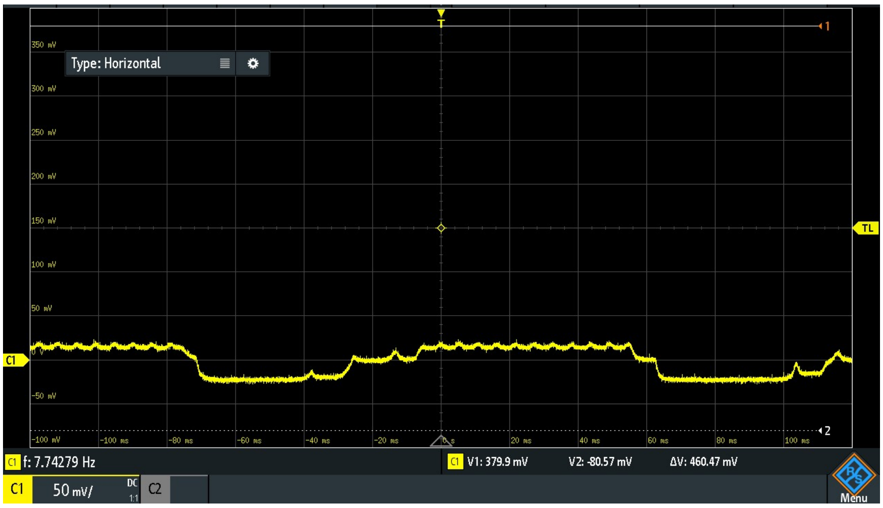

Figure 7 – PID-AH output waveform

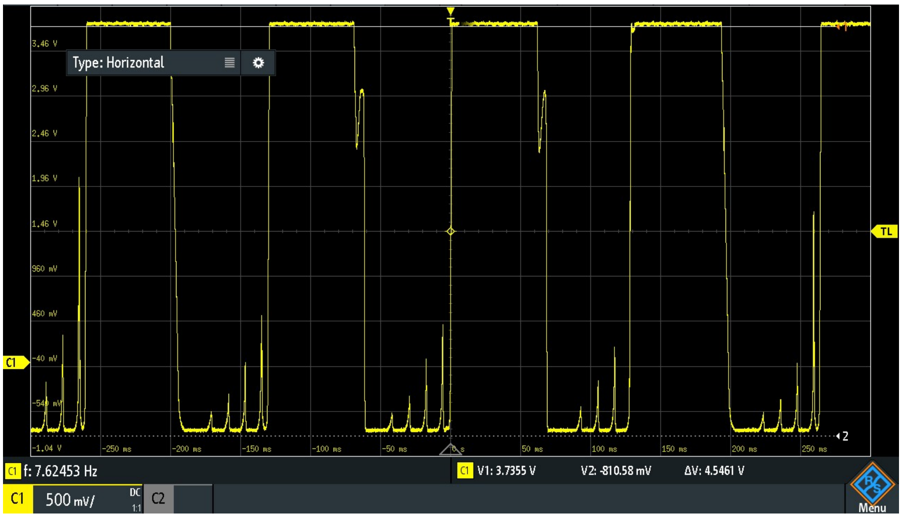

Figure 8 – IRM-AT initial output waveform

Figure 9 – IRM-AT final output waveform

7. Risk Assessment

7.1 Hardware Risks

With regards to hardware, the project is low risk in terms of health and safety; this is due to the components being used having sensitive circuitry which only requires low voltage ($<=$ 5 V) and low current ($<=$ 80 mA). On the other hand, while these operating conditions minimise risk to health and safety, it increases the risk of damage to the devices as their sensitive circuitry makes them vulnerable to damage from electrostatic discharge. This risk was minimised by housing the components in a container made of insulator material to ensure no electrostatic build up. The student would also wear an electrostatic discharging ankle strap whenever working with the hardware to further mitigate this risk. The need for soldering components and drilling the enclosure adds a health and safety risk due to the tools' nature. The risks with the soldering iron were minimised by following safety protocol as instructed by the EEECS support team and by performing all work in a safe environment such as the Ashby 9th floor labs. All drilling was performed by the EEECS support team, greatly minimising risk thanks to their vast experience with such apparatus.

7.2 Software Risks

A large risk with the software occurs if all code and documents are stored locally onto a single machine. Van den Eynden et al **[12]** list: hardware failure, software or media faults, virus infection of malicious hacking, power failure and human errors as reasons as to why *"making back-ups of files is an essential element of data management."* As such to minimise this risk, all the data files for this project were backed up in two areas: firstly, on the student's personal Google drive storage and also on the student's github online account (this repository can be accessed via the URL in **Appendix 5**).

7.3 Calibration Risks

A moderate risk identified was the calibration of the CH_4 sensor. This is because even in volumes as low as 1%vol, CH_4 can be explosive. This risk is minimised by planning to perform the calibration in the university chemistry labs, under appropriate supervision, to ensure that the experiment is performed as safely as possible. This risk may not be faced at all however, as the supervisor has suggested the alternative method of calibrating the sensor against the safe levels of CH_4 naturally produced by compost along with the device data sheet which gives a rough measurement of the sensor output values to various levels of CH_4 in mV.

8. References

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9. Appendix

Appendix 1 – Full project specification

Electrical & Electronic Engineering, Software & Electronic Systems Engineering
Final Year Projects 2024-2025

IoT based system for indoor monitoring of greenhouse gases and pollutants

Supervisor: Dr Hamza Shakeel

	Control		Embedded Systems		High Frequency Electronics		Microelectronics
	Electric Power		Software		Connected Health		MEMS
	Cyber-Security		Wireless Communications		Signal/Image Processing		Intelligent Systems
	Digital Design	x	Sensor Networks	x	Data Analytics	x	Electronics

Air pollution is the world's leading environmental health risk and pervasive threat to healthy living. It is the cause of over one-third of deaths from strokes, lung disease and chronic obstructive pulmonary disease and one quarter of deaths from ischaemic heart disease (WHO, 2016). Particulate Matter (PM) causes at least 40,000 deaths/year in the UK, reducing average life expectancy by around 6 months and costs the national economy £16Bn/year. The principal constituents of urban air pollution are oxides of nitrogen (NOx), PM10, Volatile Organic Compounds (VOC) including methane, and CO. PM tiny toxic particles get into the lungs and bloodstream by inhalation. PM can cause short-term health impacts over a single day with elevated concentrations and long-term impacts from lower-level exposure over the years. The UK's Department of Health and Social Care's independent Committee on the Medical Effects of Air Pollutants (COMEAP) quantified the long-term impacts of UK PM exposure in terms of mortality as equivalent to 340,000 life years lost. NO2 content in urban areas is associated with increased mortality and hospital admissions for a range of respiratory and cardiovascular endpoints.

In recent years, the widespread use of low-cost sensors has become a reality. The cost-effectiveness of the sensor increases the opportunity to obtain information about different chemicals, providing real-time and high-resolution data. The main objective of the project is to develop a portable system (PM, methane, CO/CO2, temperature, and humidity) for indoor monitoring of emissions.

Objectives
1. Literature review to understand shortcomings of state-of-the-art low-cost sensor networks
2. Interface PM, CO, methane, and temperature sensors with an appropriate Arduino board
3. Develop a PCB board and work on different routing schemes to reduce electro-magnetic noise in circuit
4. Develop an IoT dashboard (MATLAB) to monitor indoor pollution level.

MEng Extension
1. Understand the working principle of statistical data fitting
2. Estimating errors in measurements from different types of sensors and develop algorithms to reduce these errors
3. Develop pollution exposure metric based on statistical analysis of data
4. Perform testing of the system in actual settings (e.g. farms)

This project is best suited to a student with an interest in hardware and software. However, a high proportion of Arduino board programming is expected thus the student should be very confident in the use of python/MATLAB. Moreover, MEng project extension would also require extensive data analysis, and the student should be comfortable with using MATLAB.

Learning Outcomes
Upon completion of the project, you will expect to have:
1. Knowledge of interfacing different types of sensors with Arduino board
2. Skills to reduce electro-magnetic noise level in circuit
3. Ability to develop an IoT dashboard for real time data monitoring
4. Demonstrate enhanced data analysis skills
5. Understand statistical analysis techniques and analysis of long-term sensor stability

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Appendix 2 – Project weekly update document example

09-15/10/2024

Meeting conclusion: Sensirion SEN5x sensor for PM, temperature, relative humidity, VOC and NOx as well as Sensirion SCD4x sensor for CO_2 already ordered by university, can begin testing when it arrives (hopefully tested before next meeting). NH_3 sensor already present at university though it requires a relatively high voltage supply and a long (8 to 12 hours) power up time. Need to request Quote from AlphaSense for their IRM-AT CH_4 sensor with projected lead time. Look at supplier websites (e.g. RS components, Farnell, etc.) to find any other suitable gas sensors for selected gasses.

Work planned: Get quote from AlphaSense and see practicality of IRM-AT. Find potential replacement sensors on supplier websites which may be more suitable than current choices or are more practical to source and utilise. Do research on shortcomings of current air quality sensors and benefits of having one in a farm.

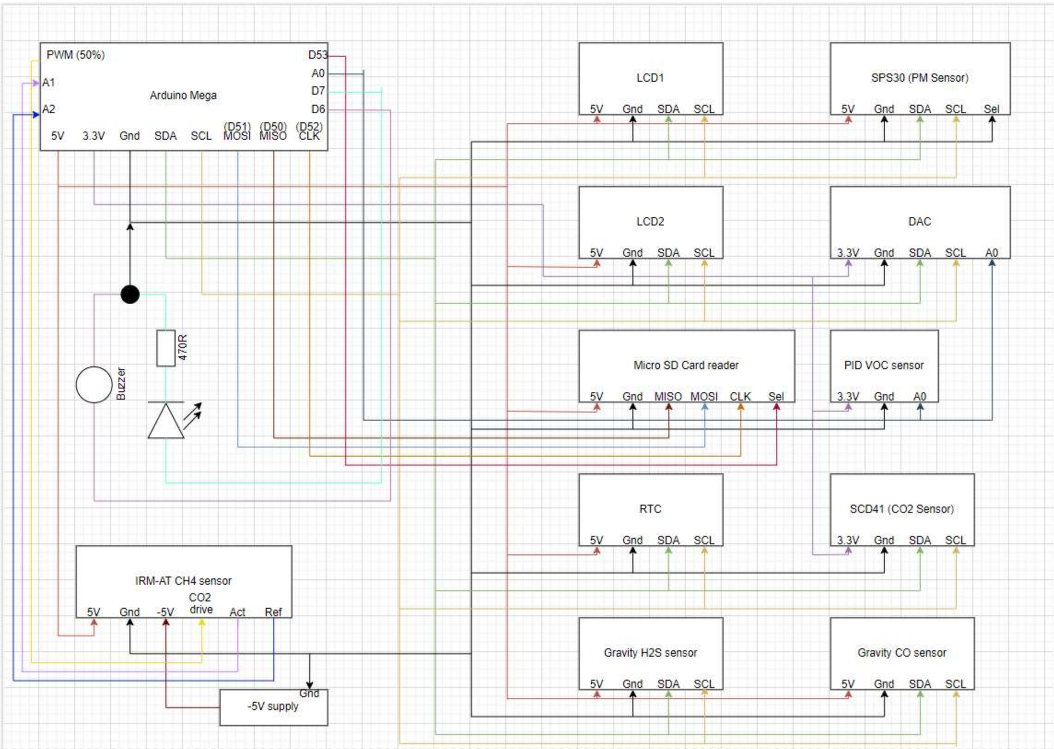
Work achieved: Planned structure of interim and final reports. Researched how to connect Sensirion PM and CO_2 sensors to Arduino development board. Downloaded Arduino libraries for Sensirion detectors. Ordered AlphaSense IRM-AT CH_4 sensor. Analysis of AlphaSense's recommended amplifying and filtering circuit for IRM-AT sensor. Analysis of why NDIR sensors are more suitable for farm case.

Appendix 3 – CO and H_2S sensors Tutorial

Resources for further reading:

https://wiki.dfrobot.com/SKU_SEN0465toSEN0476_Gravity_Gas_Sensor_Calibrated_I2C_UART

Appendix 4 – Completed System Wiring Schematic



Appendix 5 – github back-up data repository URL:

https://github.com/mvincentbote/ELE3001-40324387.git