SpoilSense

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Abstract

Food waste and the subsequent loss of quality and nutrition continue to pose a major challenge in many households, as produce often spoils unnoticed until it is too late. Frequent manual checks can be inconvenient and time-consuming, while existing monitoring solutions are frequently unreliable, expensive, or overly complex to integrate. This paper details the development of SpoilSense, a system designed to address this gap by providing households with a cost-effective and automated method of identifying produce spoilage.

Contents

1 Introduction

The fundamental engineering challenge lies in detecting the early stages of food spoilage. Specifically, identifying when fruits and vegetables begin releasing certain gases, such as ammonia and methane, as a result of natural enzymatic processes. By accurately sensing these gases and relaying that information to users, the problem of undetected produce decay can be mitigated. The usefulness of this system lies in its ability to reduce food waste, maintain better produce quality, and help users make more informed consumption decisions, ultimately contributing to cost savings and more sustainable household practices.

1.1 Problem and Solution

Food spoilage imposes substantial costs across economic, environmental, health, and social dimensions worldwide. From a monetary standpoint, wasted produce contributes to significant financial losses for producers, retailers, and consumers, while simultaneously straining the global food supply chain. In the U.S. alone, an estimated 133 billion pounds of edible food—worth over $161 billion—goes to waste every year [1]. Environmentally, discarded fruits and vegetables exacerbate landfill overloading, greenhouse gas emissions, and resource depletion. On a health level, consuming food past its prime can lead to nutrient loss, potential foodborne illness, and weakened consumer trust in the overall food system. Socially, frequent spoilage undermines food security and heightens inequality, as vulnerable populations struggle to access fresh, affordable produce. To put this into perspective, 13.5 percent (18.0 million) of U.S. households were food insecure at some time during 2023 [8]. This emphasizes the vast effects that food spoilage can have on society. At the core of these challenges are the natural enzymatic processes inherent to fruits and vegetables. Over time, these enzymes break down complex molecules, resulting in simpler compounds and associated gases such as ammonia and methane. Moreover, the gases released by one item can induce accelerated spoilage in surrounding produce, compounding the effects and further contributing to these broad-ranging implications.

The proposed solution is to implement SpoilSense, a monitoring device that utilizes gas sensors to detect ammonia and methane emissions, a clear indicator of produce spoilage, inside the fridge. When these gases are detected, SpoilSense wirelessly communicates the information via Bluetooth Low Energy (BLE) to an external LED indicator attached to the refrigerator's exterior, providing a clear and immediate alert. By automating the freshness monitoring process, SpoilSense enables households to take timely preventive action, thereby reducing food waste, maintaining the quality of stored produce, and ultimately saving costs. While many modern refrigerators feature "smart" capabilities, such as Wi-Fi connectivity or app integration, the majority of households still rely on conventional refrigerators lacking such advanced features. SpoilSense offers a practical and cost-effective solution to bridge this gap by enhancing traditional fridges with the ability to monitor and detect produce spoilage. This innovation provides functionality similar to that of a "smart" refrigerator without necessitating a complete appliance upgrade. By leveraging gas sensors and BLE communication, SpoilSense transforms an ordinary refrigerator into a smart system capable of preserving food quality and reducing waste. Its external LED alert system ensures ease of use and accessibility, making it a universally adaptable and user-friendly solution.

1.2 Visual Aid

The visualization provides a quick and intuitive overview of the SpoilSense project, showcasing its two primary modules. The first module, housed inside the refrigerator, is responsible for sensing spoilage gases using advanced sensors. The second module, magnetically attached to the exterior of the refrigerator, serves as the alert system. It communicates wirelessly with the sensing module and uses an LED indicator to notify the user when spoilage is detected, ensuring timely action to reduce food waste.

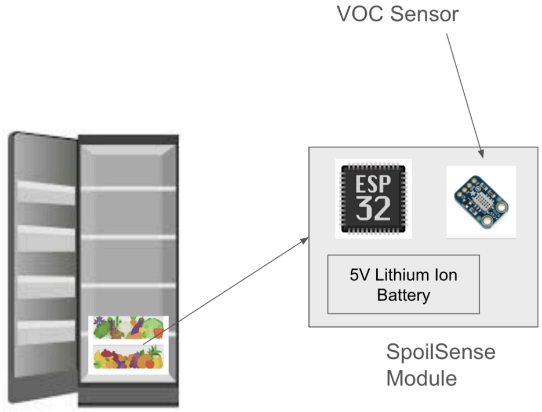

Figure 1: A visual representation of the internal SpoilSense Module

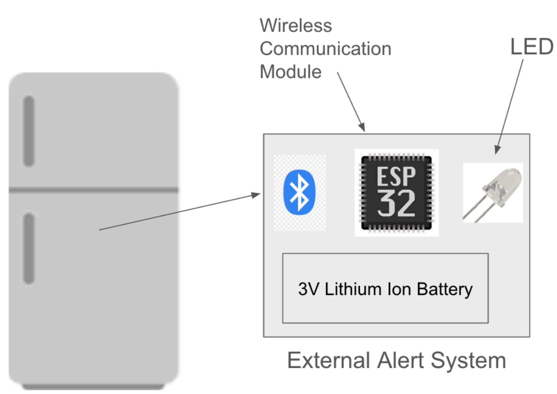

Figure 2: A visual representation of the External Spoilsense Module

1.3 High Level Requirements

These requirements are intended to ensure that SpoilSense performs its core functions effectively and reliably. In other words, by setting clear numerical targets for the device's detection capabilities, response times, and durability these requirements guide the design and development of a system that can reliably identify spoiling produce and inform users in time for them to take meaningful action.

1. The module should be accurate in detecting the presence of volatile organic compounds (VOCs) up to a threshold of 3000 PPM for Methane (CH_4) and 50 PPM for Ammonia (NH_3) in order to trigger an alert.
2. The design should be capable of withstanding standard refrigerator temperatures (3-5 ° C) and should maintain a form factor that is at most dimensions of 5 in x 4 in x 2 in.
3. The system must respond to detected gas concentration changes and trigger an alert within 30 seconds of the threshold being met to ensure timely responses.

2 Design

The SpoilSense project detects food spoilage utilizing two modules: SpoilSense Module (Internal) and Alert Module (External). The SpoilSense module utilizes an ESP32 microcontroller for wireless communication with the Alert module and a MICS-5524 VOC sensor to detect for the presence of methane and ammonia gasses. Similarly, the Alert module utilizes the ESP32 microcontroller for wireless communication with the SpoilSense module and an LED to alert the user that spoilage has been detected. The general design alternatives and details of each design are discussed below.

2.1 Block Diagram

The block diagram is intended to visually represent the main functional components and their relationships within SpoilSense. By outlining subsystems such as the gas sensing module, the microcontroller unit, the wireless communication module, and the external LED indicator, the diagram shows how data and signals flow through the device. This high-level overview clarifies how each subsystem connects and influences the others—illustrating, for example, how sensor readings are processed by the microcontroller, how alert signals are transmitted via BLE, and how the LED responds.

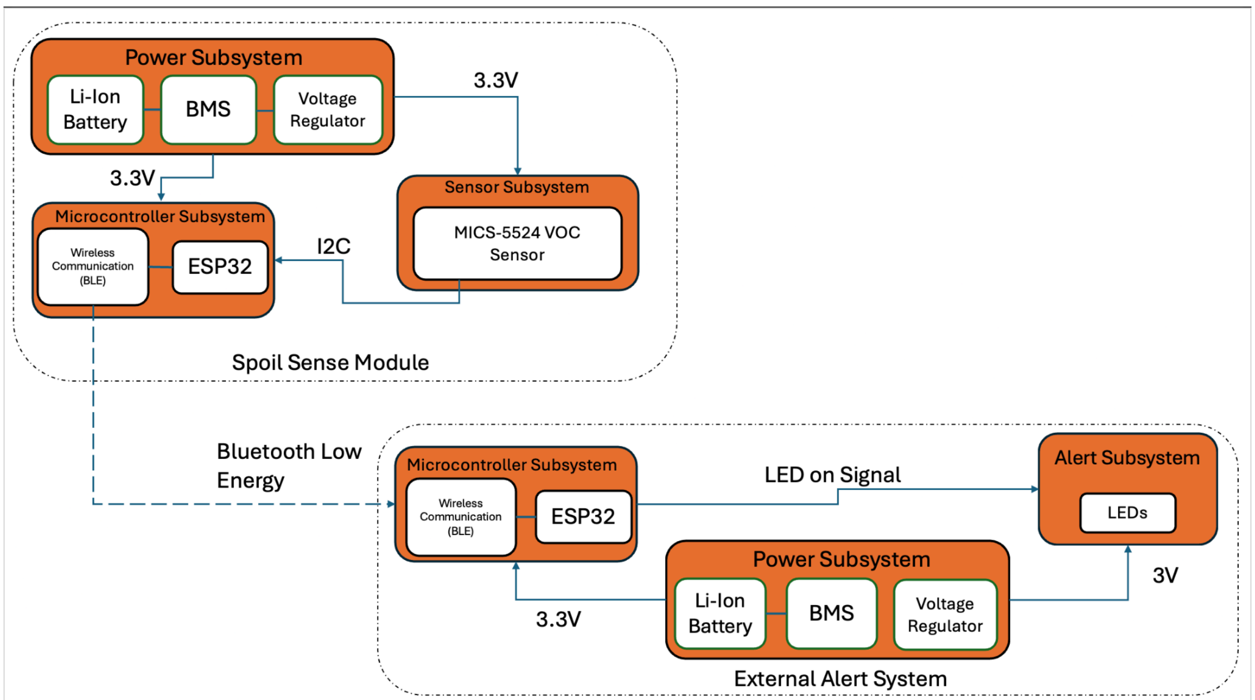

Figure 3: Block Diagram which provides a high level overview of SpoilSense and its subsystems

2.2 Subsystems

2.2.1 Microcontroller Subsystem

The microcontroller subsystem consists of the ESP32 microcontroller and serves as the central processing unit of both modules. The microcontroller processes sensor data and enables BLE communication. The ESP32 was specifically chosen due to its wireless communication capability and efficient handling of sensor data. Communication between the internal and external modules follows a client-server architecture where the internal module is the server and the external module is the client. The internal module's ESP32 continuously reads data from the VOC sensor, compares it to the defined thresholds for spoilage. If thresholds are exceeded, the internal module will send an alert notification to the external module's ESP32. BLE was used to ensure reliable and timely communication through refrigerator doors. The microcontroller subsystem did not undergo any significant changes throughout development, so the original plan remained consistent with the goals of the project.

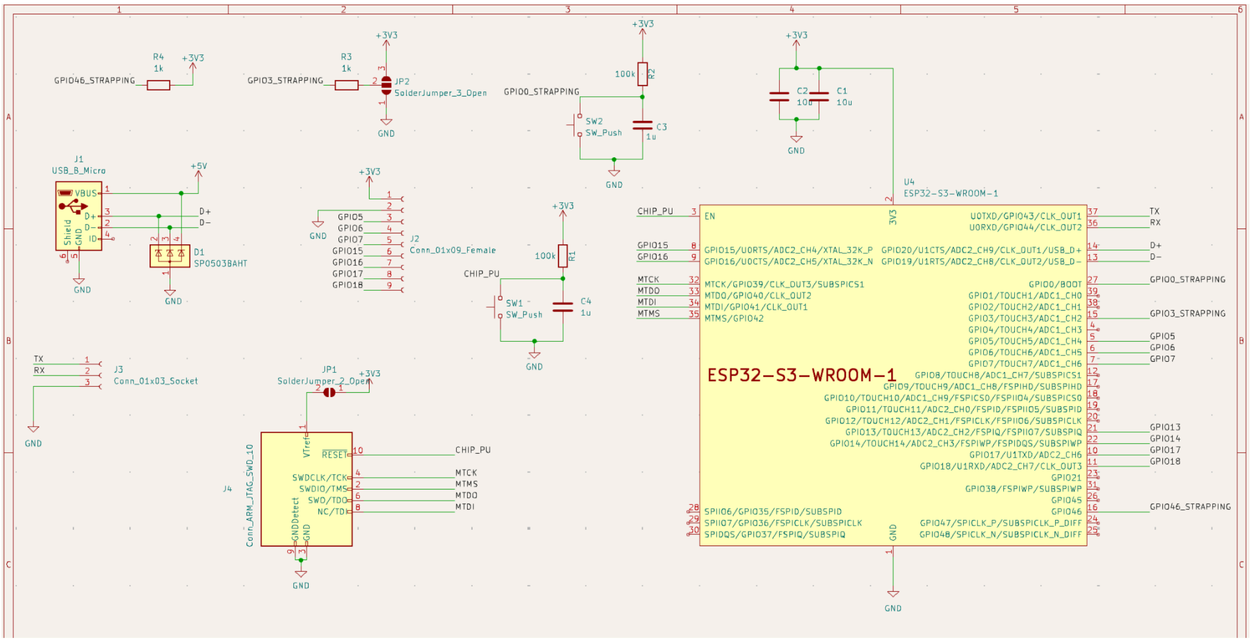

Figure 4: Circuit schematic of the microcontroller implementation

2.2.2 Sensor Subsystem

The sensor subsystem is responsible for detecting volatile organic compounds (VOCs), specifically methane (CH_4) and ammonia (NH_3), which are byproducts of food spoilage. The MICS-5524 VOC sensor was selected due to its ability to detect CH_4 and NH_3 with high sensitivity. The sensor measures changes in resistance due to the presence of certain gas concentrations, which will provide a signal that is then processed by the microcontroller. The sensor subsystem went through a few iterations, as initial attempts to use ethylene (C_2H_4) and carbon dioxide (CO_2) sensors were abandoned due to accuracy and logistical issues. The MICS-5524 was calibrated to detect spoilage thresholds up to 3000 ppm for methane and 50 ppm for ammonia based on controlled experiments.

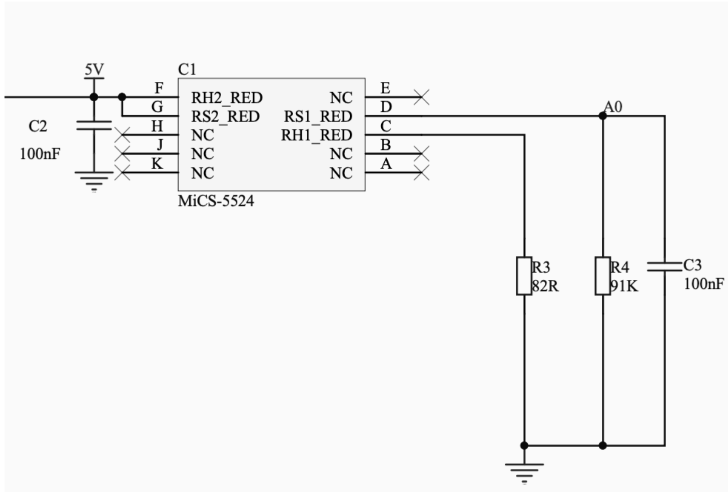

Figure 5: Circuit schematic of the MICS-5524 VOC sensor

2.2.3 Power Subsystem

The power subsystem ensures reliable operation with minimal maintenance. The system utilizes a 6V battery paired with a linear voltage regulator to supply 3.3V to the ESP32 microcontroller and 5V to the MICS-5524 VOC sensor. The initial design utilized a 9V battery, however it was abandoned to address overheating issues observed with a 9V battery design and challenges implementing with a linear voltage regulator.

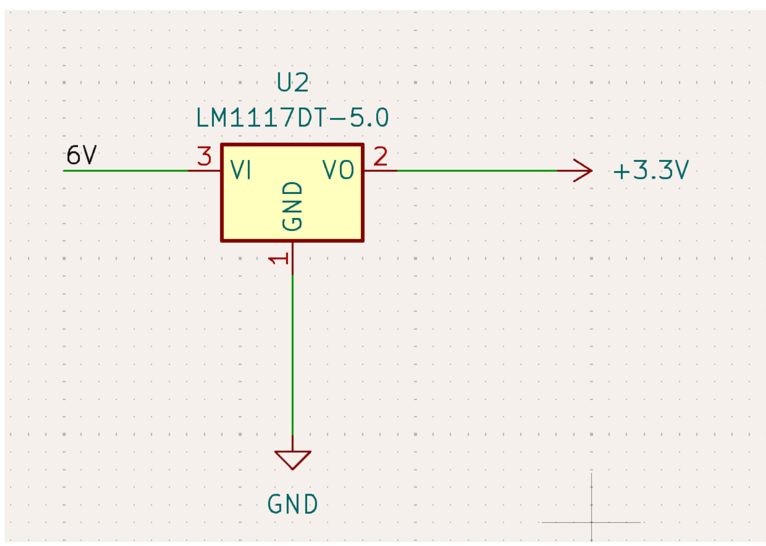

Figure 6: Circuit schematic of the power supply of the module

2.2.4 Alert Subsystem

The alert subsystem provides a user-friendly visual notification system. A single LED was implemented, controlled by the external ESP32 microcontroller. The LED lights up red when spoilage thresholds are exceeded, otherwise it remains off. The initial design implemented 3 LEDs to represent varying levels of spoilage, however due to fluctuating sensor readings this design was simplified to the single LED approach highlighted earlier. The final design offers a more consistent and reliable alert system, whereas future iterations may incorporate RGB LEDs for more nuanced notifications.

2.3 PCB Design

The system integrates all of the components into two PCBs: one for the internal SpoilSense module and one for the external Alert module. The internal PCB hosts the ESP32, MICS-5524 VOC sensor and power distribution components. Similarly, the external PCB houses the ESP32, LED, and power distribution.. The PCBs were designed to optimize space and minimize signal interference. Future modifications may refine the PCB layout for mass production and further enhance the system's functionality. Collectively, these subsystems form a reliable and efficient solution for detecting and notifying users of food spoilage, making SpoilSense a valuable addition to both residential and commercial refrigeration systems.

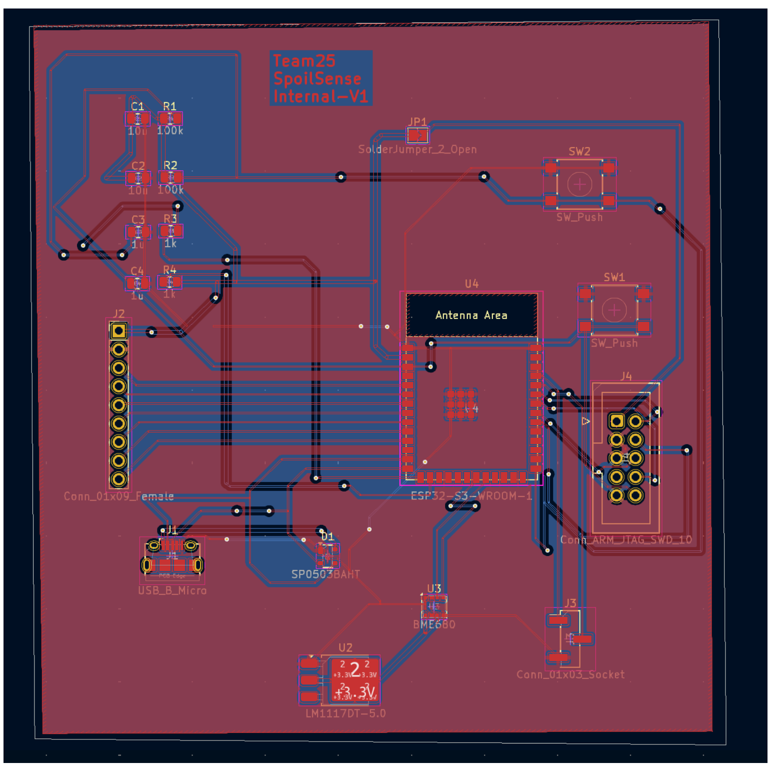

Figure 7: SpoilSense Module PCB Design

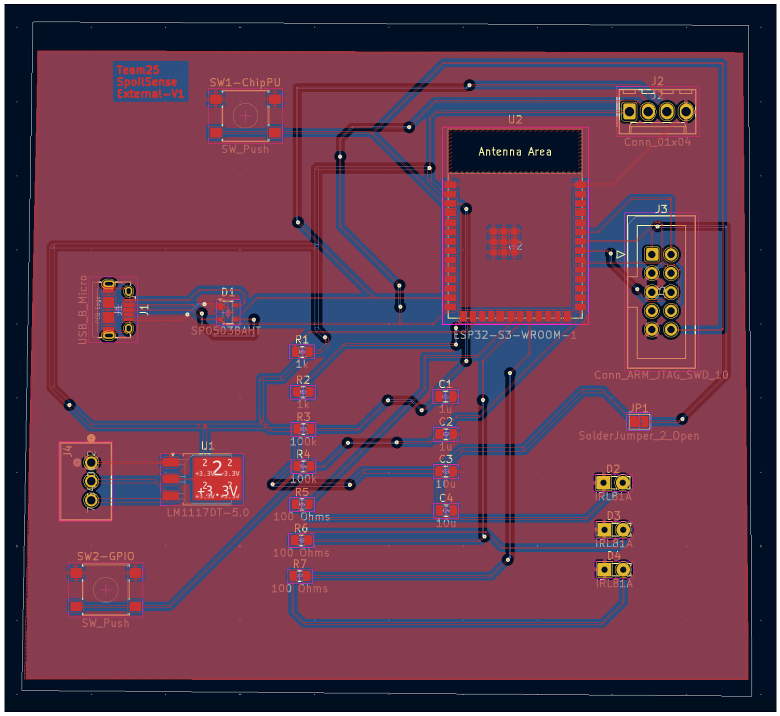

Figure 8: Alert Module PCB Design

3 Design Verification

The SpoilSense system has clearly defined requirements and verification procedures for each subsystem to ensure reliability and functionality across its components. These requirements were validated through controlled testing and real-world simulations. Each subsystem has its own requirements and verification procedures and they will be discussed below.

To conduct testing under realistic conditions, the team utilized a mini-fridge to closely approximate the standard environment of a household refrigerator, which is pictured below. In order to satisfy the requirement of durability, parts were chosen such that they had operating temperatures that fit within the temperature range of refrigerators, which is 3-5 ° C. Additionally, the enclosure was chosen to fit the the size requirement of 5 in x 4 in x 2 in so as not to take up too much space in the produce drawer of refrigerators.

Figure 9: Testing environment used to verify requirements

3.1 Sensor Subsystem Requirements and Verification

The sensor subsystem was required to accurately detect volatile organic compounds (VOCs), methane (CH_4) up to a threshold of 3000 ppm and ammonia (NH_3) up to thresholds of 50 ppm, respectively. This was verified by setting up a controlled environment using samples of spoiled and unspoiled produce to measure sensor outputs. The readings were recorded and analyzed to determine the appropriate spoilage thresholds for the microcontroller. Multiple fruits were tested to confirm consistent detection and reliable threshold identification, ensuring the sensor's accuracy. Due to inaccuracies from the sensor, the readings are a bit inconsistent, but were still able to discern the concentration of CH4 and NH3 spoiling foods.

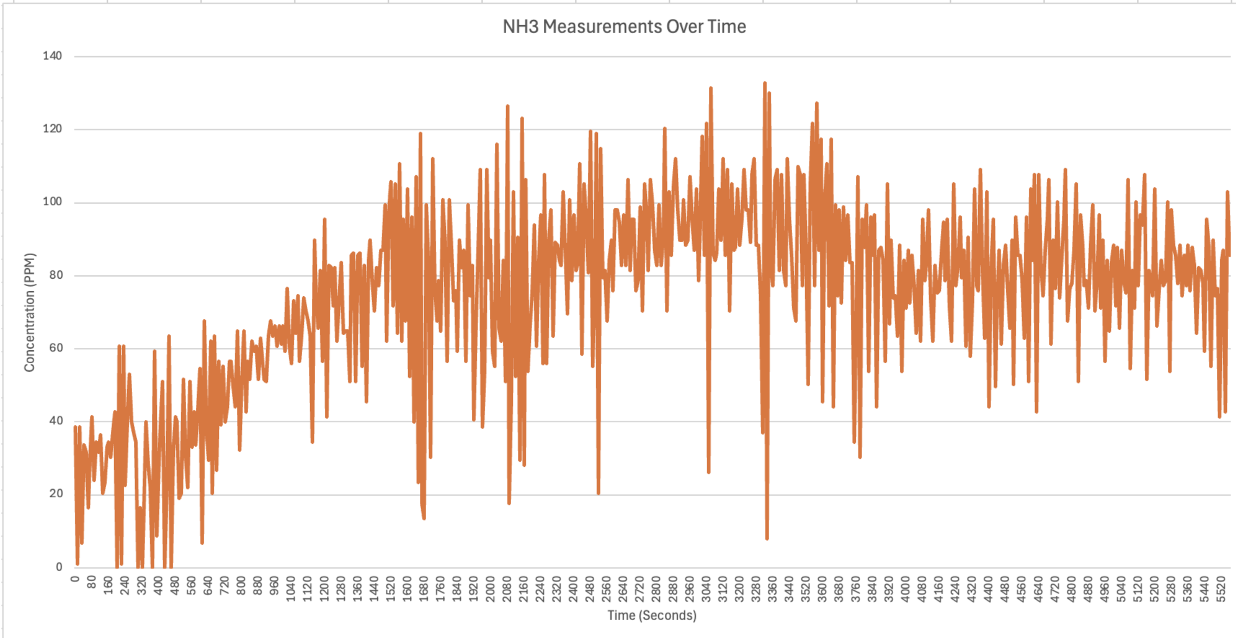

Figure 10: Graph of recorded NH3 concentrations

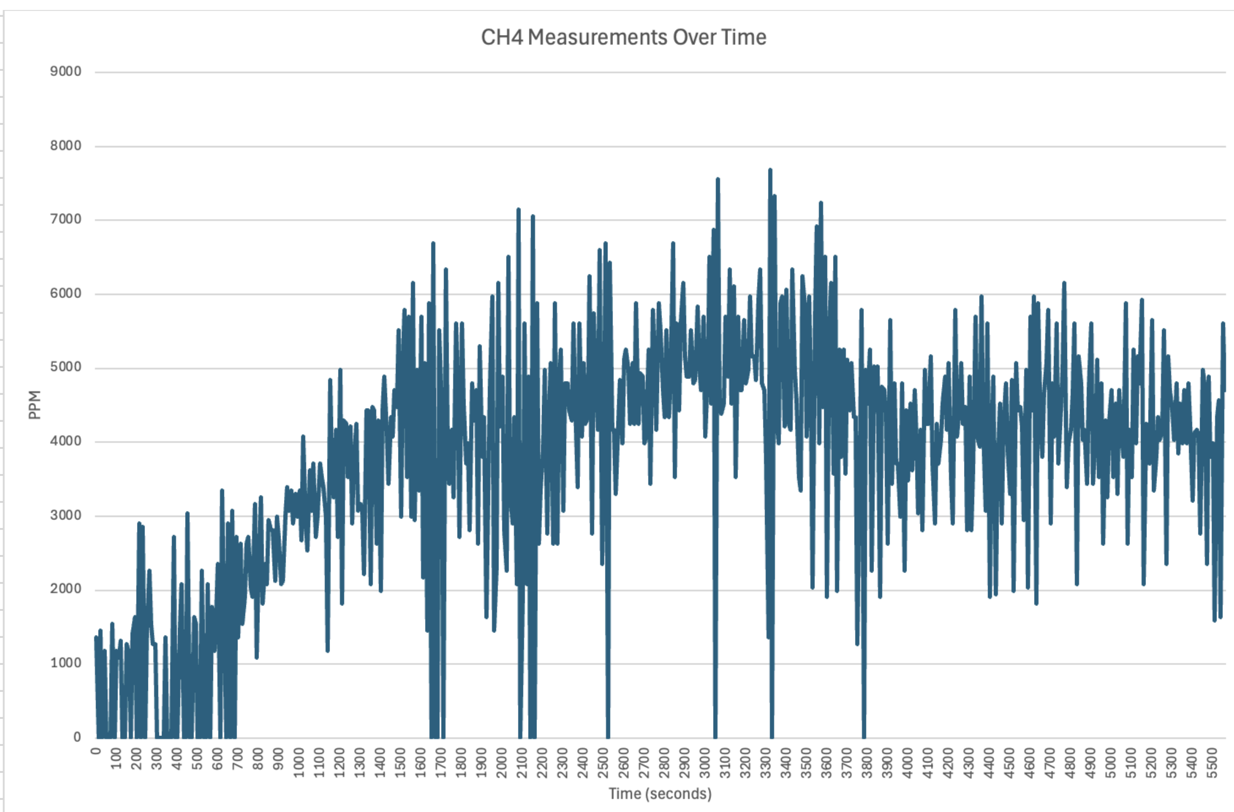

Figure 11: Graph of recorded CH4 concentrations

The above readings are a small sample of the many trials conducted. Taken over a period of roughly 90 mins from a combination of fruits, they give a numerical value that can be associated with a degree of spoilage through visual inspection. While there were inconsistencies in the readings due to the sensor, it was still possible to find an appropriate threshold that certainly indicated spoilage; 3000 PPM for CH4 and 50 PPM for NH3.

3.2 Microcontroller Subsystem Requirements and Verification

The microcontroller subsystem needed to process sensor data and trigger alerts within 30 seconds of spoilage detection. This was verified by creating a controlled environment where spoilage conditions were simulated. Timed alerts were initiated based on sensor data, with timestamps recorded at both the server (internal module) and client (external module) ends. Communication reliability was tested by placing the internal and external modules on opposite sides of a refrigerator door. From testing, it was possible to verify that the BLE signal had no issues going through the refrigerator door.

```
12:36:21.712 -> NH3: 76.6 PPM, 185094
12:36:21.712 -> CH4: 4073.6 PPM, 185094
12:36:21.712 -> Alert sent to client!
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Figure 12: Serial monitor output of server sending alert notification

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12:36:26.722 -> Alert received: CH4/NH3 > threshold
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Figure 13: Serial monitor output of client receiving notification from server

Furthermore, in order to verify that the microcontroller was sending alert notifications in a timely manner, timestamps were utilized to confirm that these alerts were being sent and received within the specified threshold of 30 seconds.

3.3 Power Subsystem Requirements and Verification

The power subsystem was designed to supply a stable voltage to the components. The microcontroller required a voltage range of 3.0V to 3.3V, while the VOC sensor operated within a range of 4.9V to 5.1V. These requirements were verified by measuring output voltages using an oscilloscope to ensure they remained within acceptable ranges. Although the PCB version could not be fully tested, the prototype confirmed the power subsystem's effectiveness.

4 Costs

4.1 Parts

Table 1: Parts Costs

Part	Part Number	Manufacturer	Quantity	Cost
ESP32 Microcontroller	ESP32-S3	Esspressif Systems	2	$3.70
Plastic Casing	VM-24M19VMTT	PolyCase	2	$17.06
Magnetic Sticker	-	Homakover	1	$8.99
6V Lithium Ion Battery	DL-40	Dantona Industries	2	$15.09
LED	SSL-LX5097SISGSYC	Lumex Opto/Components Inc.	1	$4.40
MICS-5524 VOC Sensor	1782-MICS-5524TR-ND - Tape & Reel (TR)	Amphenol SGX Sensortech	1	$7.23
Voltage Regulator	LM1117-5.0	Texas Instruments	2	$5.00
Total				$61.47

4.2 Labor

Table 2: Labor

Category	Azim	Sar	Vikram
Circuit Design (Spoil Sense Module)	8	8	6
Circuit Design (Alert System)	2	9	7
Soldering	12	12	8
Prototyping and Debugging	10	10	10
Documentation	5	5	5
Total Hours	37	44	36

4.3 Labor Cost

All members of this group are Computer Engineering students. According to the Grainger College of Engineering's website on postgraduate success [6], the average starting salary for a Computer Engineering graduate is $118,752 per year , which equates to $57.09 per hour.

4.4 Total Cost

Based on the estimated total hours and the estimated hourly wage, the estimated total cost of labor for the project is $6,679.53. With the cost of all the materials, the estimated total cost of the project is $6756.43.

5. Conclusion

5.1 Accomplishments

Through the development of SpoilSense, A working prototype was successfully created that effectively demonstrated the desired concept. The system reliably detects spoilage gases, such as ammonia and methane, and communicates the information wirelessly to an external alert module. This working version of SpoilSense addresses the core problem of monitoring produce freshness within a refrigerator, proving its feasibility and ability to mitigate food waste. The design met the initial objectives of providing a user-friendly, cost-effective solution that integrates seamlessly into existing refrigerators.

5.2 Uncertainties

While SpoilSense achieved its fundamental goals, there are areas where improvements could enhance its performance and reliability. One such area is the spoilage detection thresholds. Currently, the system uses fixed thresholds, which may lead to inconsistencies in varying environmental conditions. Implementing moving or weighted averages could provide more accurate and adaptive detection. Additionally, the notification system could benefit from multiple alert levels, offering users a more nuanced understanding of the spoilage status, such as early warnings or critical alerts.

Other challenges that were faced during development was the creation of the custom PCB. Initially, the team lacked familiarity with CAD software, leading it to take a longer period of time to design the necessary schematics. Issues with distributing power effectively across the PCB were also dealt with, necessitating design revisions. Additionally, the team underwent multiple iterations of sensor selection and testing before finding the correct one that met the requirements. Compounding these challenges were logistical issues where the PCB was lost in transit and returned to the manufacturer in China. These experiences provided valuable insights into the complexities of developing a project from the ground up and highlighted the importance of perseverance through struggles and failures.

5.3 Ethical considerations

In alignment with the IEEE Code of Ethics, SpoilSense was developed with a focus on improving quality of life by addressing food waste and enhancing food security. By reducing spoilage, the device indirectly supports global efforts to alleviate hunger and minimize environmental impact. Throughout the project, the team ensured transparency in the design process, prioritized user safety, and adhered to principles of sustainability. Ethical considerations also included using environmentally friendly materials and designing a system that is accessible and cost-effective for a broad range of users.

Food spoilage can also lead to foodborne illnesses, which pose significant risks to public health. Consuming spoiled or contaminated food can result in severe health consequences, including outbreaks of diseases such as salmonella or E. coli. These illnesses not only affect individuals but also place a strain on healthcare systems and economies globally. By mitigating spoilage through timely detection and intervention, SpoilSense contributes to reducing the prevalence of such illnesses, fostering a healthier society and promoting global well-being.

5.4 Future work

SpoilSense has the potential for broader applications beyond household refrigerators. In transportation vehicles, it could monitor produce freshness during transit from farms to homes, ensuring quality along the supply chain. Similarly, grocery stores could utilize the system to monitor large quantities of produce, reducing waste and enhancing inventory management. Future iterations of the device could also include sensors tailored to detect spoilage in specific types of food, allowing for a more customized monitoring experience. Additionally, the system could be adapted for use in different parts of the refrigerator, accommodating diverse storage needs and ensuring optimal freshness across all food types.

Overall, SpoilSense represents a promising step toward smarter food storage solutions, with plenty of opportunities for refinement and expansion to maximize its impact in reducing food waste globally.

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Appendix A: Requirement and Verification Table

Table 3: Internal SpoilSense Module Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
The microcontroller must process sensor data and trigger alerts within 30 seconds of spoilage detection.	- Created a controlled test environment where spoilage conditions are simulated and detected by the sensors. - Initiated the spoilage event and utilized alert sent/received timestamps on the respective server and client side in order to ensure timely communication between modules.	Y
The microcontroller must maintain a wireless communication through the door of the fridge with the external alert system, using BLE	- Set up an environment where the device and the alert system are placed at varying positions on either side of the metal barrier. - At each position, conduct communication tests to assess successful pairing, data transmission reliability, signal strength, and latency, while recording any instances of dropped connections or errors.	Y
The VOC sensor should be able to accurately detect the presence of volatile compounds up to thresholds mentioned in requirements	- To verify the VOC sensor accuracy up to necessary thresholds, the team set up a controlled test environment with some sort of spoiled food. - Conducted tests with various fruits, recording the sensor readings to a serial console. Once a common value was found that indicates spoilage, that value will be the threshold for the microcontroller.	Y
The power system must supply voltage to microcontroller within operating range of 3V - 3.3V	- Measured voltage reading across terminals via oscilloscope, to verify it is within range	N
Supply voltage to VOC sensor should range between 4.9 V - 5.1 V	- Operating bias voltage range is 4.9 V - 5.1 V, so measured voltage readings across terminals via oscilloscope	N

Table 4: External SpoilSense Module Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
The alert must be able to accurately light the LED based on detecting a certain amount of VOCs (based on the threshold) LED off: no spoilage detected LED on: spoilage detected	- Conducted controlled tests by introducing known spoiled food and paid special attention to the transition thresholds to confirm that the LED changes precisely at the specified points without delay.	Y
The microcontroller must maintain a wireless communication through the door of the fridge with the external alert system, using BLE	- Set up an environment where the device and the alert system are placed at varying positions on either side of the metal barrier. - At each position, conduct communication tests to assess successful pairing, data transmission reliability, signal strength, and latency, while recording any instances of dropped connections or errors.	Y
The microcontroller must process sensor data and trigger alerts within 30 seconds of spoilage detection.	- Created a controlled test environment where spoilage conditions are simulated and detected by the sensors. - Initiated the spoilage event and utilized alert sent/received timestamps on the respective server and client side in order to ensure timely communication between modules.	Y