The WorkSafe Monitor: A Comprehensive Wearable Personal Safety Monitor for Manufacturing and Construction Workers

A Technical Report submitted to the Department of Electrical and Computer Engineering

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science, School of Engineering

Spring, 2024
Technical Project Team Members

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Adam Barnes, Department of Electrical and Computer Engineering

Statement of Work

Cambria

Cambria investigated the WiFi capabilities of the NI myRIO and set up the microcontroller as a WiFi access point and a general WiFi connection to determine the usability for the project needs in the beginning. She configured both myRIOs used for testing to connect to the UVA broadcasted 'wahoo' wifi network and created a virtual instrument (VI) in the LabView software that was used for all the wireless communication needs throughout the term. During the project definition period, Cambria researched the best sensors for the project use cases and helped decide what sensors to order based on communication protocol, project needs, and budget.

During the development phase of the project, Cambria mainly focused on the embedded work that needs to be done in Labview for deployment to the NI myRIO. She created the VI for the accelerometer to take all three axis acceleration measurements, the VI for the hazardous gas sensor to take data in via analog input while being powered by the myRIO, the VI for the particulate matter sensor to communicate via UART protocol, and a python script to convert the UART-read hex character particulate matter data into useable particulate mass concentration readings. After testing the particulate matter and hazardous gas sensors, Cambria met with the UVA Environmental Health and Safety Department to discuss how to safely calibrate a hazardous gas sensor. Cambria, with the rest of the team, calibrated the hazardous gas sensor outside of Thornton Hall.

Toward the testing and integration phases of the project, Cambria helped with fall detection testing and physical assembly. Cambria sliced and 3D printed all of the casings and helped determine a way to latch the lid on and 3D printed pieces for that as well.

Vicky

Vicky primarily worked on the PCB design, integration, and assembly. She also worked on a few LabView VIs and testing different sensors and the PCB.

Vicky worked on the design of the microphone, amplifier, and peak detector with Sierra and the integration and powering of the other external sensors and devices. Vicky also tested the final design of the amplifier and peak detector with a breadboard and Waveforms before ordering the final product. She soldered and tested the functionality of the PCB when it arrived. She also did the calculations for the battery life of our product at maximum power consumption by the myRio. Additionally, Vicky created a LabView VI for the microphone in order to test the design and have data sent to the website along with a timestamp for use during calibration. She calibrated the microphone and went through several iterations of trendline equations until deciding on the final calibration equation to match microphone voltage to decibel levels. She also wrote the VI for the buzzer to be turned on at a certain hazardous gas threshold so the user can be alerted of dangerous conditions. Vicky took a major role in the final assembly of the product, assembling the PCB, battery, and external sensors inside the casing.

Additionally, Vicky collaborated with the group to calibrate hazardous gas and fall detection. She also assisted with planning the dimensions and design of the final casing that was 3-D printed by Sierra.

Kamil

Kamil's role in the project primarily focused on website development, database management, and creating the fall detection algorithm. He also conducted tests on data transmission and storage using the myRIO, alongside some embedded development in LabView.

In terms of website development, Kamil handled both frontend and backend programming, using languages like JavaScript, HTML, Python, CSS, and SQL. He designed the main dashboard which featured real-time data and visualizations for fall detection, hazardous gas, particulate matter, and noise levels. At first, Kamil worked on developing a machine learning-based fall detection algorithm, but he eventually shifted to a simpler, yet effective solution for better speed and usability. He also developed an alert system essential to the website's core functionality, which included task schedulers to regularly check database information for signs of potential hazards. These alerts were designed to be then stored in a history database for auditing and review purposes.

Additionally, Kamil collaborated with team members Vicky and Cambria to refine several LabView VIs, ensuring they correctly formatted and consistently sent HTTP posts.

Sierra

Sierra primarily worked on the PCB design, casing design, harness design, assembly and testing. She designed the pre-amplifier and peak detector alongside Vicky and chose the operational amplifiers and microphone for the design. Sierra did the final PCB routing and design and worked with Vicky to test the designed components before the PCB was ordered. When the PCB arrived, she assisted with soldering components to the board. Sierra also worked on choosing the battery concerning the specific needs of the NI MyRio. She worked with Vicky to calibrate the sound level sensor and create a test plan for the calibration.

After the PCB was determined to be functional, Sierra undertook the casing and harness design. She produced all of the CAD designs, cycling through multiple iterations (10 in total). The harness design required multiple iterations as well. She assisted Cambria with some of the 3d printing.

Additionally, Sierra worked to provide the team with calibration gas and a functional gas sensor to calibrate the Hazardous Gas sensor. She emailed and met with AH Environmental and was able to secure 60 ppm CO calibration gas as well as the ALTAIR® 4XR Multigas Detector. She calibrated the ALTAIR® 4XR Multigas Detector. Alongside the rest of her team, she worked on calibrating the Hazardous Gas sensor.

In terms of the final assembly, Sierra worked on the adhering of the sensors to the top and bottom of the casing, adding mesh to the sensors, putting the harness together, and putting the inside components together inside the casing.

Table of Contents

Table of Figures

Abstract

The Occupational Health and Safety Administration (OSHA) reports that approximately 20% of all fatal work injuries occur in the construction sector, with falls being the leading cause [10]. Additionally, exposure to chemicals results in 190,000 illnesses and 50,000 deaths annually, not to mention potential long-term health effects [4]. While not a solution to prevent all fatalities, our wearable safety monitoring device is designed to significantly enhance construction site safety by detecting falls, monitoring sound levels, and identifying hazardous gases and particulate matter. The technology provides major benefits to both workers and employers by sending real-time safety data to an online dashboard for exhaustive oversight and issuing immediate alerts to improve employer responsiveness. This allows for rapid emergency responses, in-depth analysis, and auditing, facilitating a proactive approach to construction safety management. The device comprises three subsystems: a printed circuit board (PCB) equipped with various sensors, the myRIO microcontroller for data processing and transmission, and a dynamic website. The design is cost-effective, priced under $200, and was fully assembled and tested within two months and two weeks.

Background

The idea for a piece of wearable embedded technology is appealing due to its all-encompassing use of knowledge from a variety of UVA ECE classes and its applicability in the modern world as an IoT device. Through research, the team found that many wearable technology pieces for workers in the field aim to monitor their internal conditions or have one specific thing to track. The WorkSafe Monitor aims to sense and track the external conditions in the area where a worker is at any given time. This data is sent to a website wirelessly to track and view the results of the sensors over time, making it applicable and reliable in the modern landscape of wireless devices. Therefore, working with this technology is crucial, and ensuring its security and real-world applicability is a primary goal for our team.

Similar projects have been done in utilizing an advanced microcontroller to interface with sensors for the sensing of plant conditions, for instance, the Plant Whisperer's Fall 2023 Capstone Project [32]. The WorkSafe Monitor is different from past projects as it incorporates a wireless aspect, in terms of power supply and data transfer. To bring an embedded device into the modern world, it must be capable of connecting via WiFi and securely and efficiently managing data. Making the device entirely wireless, particularly with a mounted power supply, facilitates easy deployment in the field.

The development of the WorkSafe Monitor employs electrical engineering skills in signal processing, PCB design, and embedded systems. The team plans to apply their knowledge of embedded system design to learn LabView and create a functioning embedded project that connects external sensors with the microcontroller. Using principles learned in the ECE Fundamentals of Electronics classes, the PCB is designed, simulated, and constructed to support power management, sensor integration, and digital signal processing. Beyond the scope of their previous coursework at UVA, the team ventured into configuring WiFi, setting up a web server, and familiarizing themselves with a new microcontroller within the semester. Skills in software development were also necessary for website creation.

Wearable technology, in general, encompasses a broad range of devices that are typically attached to the body or worn on clothing. These devices rely on advanced sensor technology and complex algorithms to inform users about their health status, surrounding environment, and physical activity levels. This technology has applications across many different industries, including fitness, healthcare, and construction. Although the use of technology in construction is still emerging, the adoption of wearables has seen rapid growth in recent years according to the Chamber of Commerce, with companies increasingly depending on these devices [2].

Construction site hazards can be broadly classified into safety hazards, including slips, trips, and falls from heights, and health hazards, such as stress, exposure to heat, noise, cold, radiation, or chemical exposure. This contrast highlights the necessity for wearable technology in construction to incorporate physiological monitoring, environmental sensing, proximity detection, and location tracking capabilities to address the majority of potential hazards [30].

Several device proposals similar to the team's have been developed, with a notable example presented at a 2019 academic conference [26]. This system uses IoT technology, incorporating smart bands and a helmet that connects with a cellphone through a communication module (to send out SMS notifications). It employs heartbeat and temperature sensors for health monitoring and a tri-axis accelerometer for safety monitoring. Another more recent proposal encompasses solely a smart helmet that prioritizes fall detection (using a barometer and accelerometer) and pulse rate monitoring. Similarly to the WorkSafe Monitor, the helmet relays data to a cloud server for processing and website display. It also tracks employee attendance and the number of hours worked [25]. However, these devices still differ from the WorkSafe Monitor, which focuses on a combination of safety and environmental monitoring. Fall detection, hazardous gas and particulate matter detection, and noise level analysis offer a more comprehensive approach to workplace safety. Additionally, the WorkSafe Monitor is made up of one primary unit that can be relocated around the body.

Societal Impact Constraints

The main stakeholders for the WorkSafe Monitor are construction firms aiming to improve safety oversight at their sites. These are companies looking to take advantage of advanced wearable technology to reduce workplace accidents and emphasize a work culture of safe practices and hazard prevention. Nonetheless, the most directly impacted stakeholders are the construction workers themselves, since the device is ultimately designed to ensure their safety and well-being. By providing near real-time data on a variety of environmental conditions, the WorkSafe Monitor provides employers and by responsibility the workers the information they need to avoid dangerous situations. Moreover, this technology could influence regulatory agencies and third party safety inspectors, who are the stakeholders interested in compliance and the execution of safety measures. These groups could use the data collected by the device to either assess past risks or improve existing policies. Insurance companies could also feel the impact of the wearable, as a decrease in accident claims might lead to shifts in their profits and force changes to business models.

The primary aim of the WorkSafe Monitor is to enhance the safety and health of construction workers. By combining real-time monitoring systems like fall detection, noise level measurement, and hazardous gas and particulate matter detection, the device aims to not only reduce the frequency of workplace injuries but also promote long-term health by tracking environmental conditions that could cause chronic diseases. Through these features, the device supports public health initiatives targeted at mitigating occupational hazards, which are especially important in physically demanding sectors like construction.

The environmental footprint of the WorkSafe Monitor is also important to consider. The main environmental impacts come from the materials used, energy consumption, and disposal at the end of its life. The device currently uses a plastic casing and a lithium-ion battery, which both have long decomposition times. These materials were chosen to keep costs down, but future versions of the device should aim to use sustainable materials that are easier to recycle. Additionally, the device's ability to monitor environmental hazards like hazardous gasses ensures these dangers are identified quickly and contained on worksite premises, helping with environmental protection.

From an economic perspective, using the WorkSafe Monitor could lead to significant cost savings for construction companies. This comes from fewer work-related injuries, lower data collection costs for audits, and potentially downsized legal and medical fees. Additionally, having a good safety record could attract new employees and encourage third parties to choose the company for more projects. Also, when workers feel watched over and protected, their efficiency and job satisfaction are likely to increase.

The global and cultural impacts of the WorkSafe Monitor are complicated. Although it was designed and built in the United States with Western biases and adherence to U.S. regulatory standards, the product has the potential to greatly benefit all parts of the globe, especially countries where worker safety may be overlooked or where similar devices are unavailable. Still, introducing the WorkSafe Monitor into different international markets would require compliance with each country's local health and safety regulations, which the current design doesn't guarantee. Furthermore, the device involves a certain level of workplace surveillance, which may be looked at differently across cultures. These elements of privacy and surveillance were not entirely considered in the initial design, presenting a degree of social constraint.

Finally, the ethical and legal considerations around the technology have to be addressed. Legally, the device must adhere to safety and manufacturing standards and comply with privacy and surveillance laws. This requires thorough future testing to ensure the device's effectiveness and detailed research into the manufacturing of each component to ensure compliance. Meeting these legal standards is necessary to protect companies from potential lawsuits. Ethically, data security is key; it's important that the data collected is secure and inaccessible to potential attackers, and that only authorized users can access the databases. The design currently doesn't account for workers with disabilities who could find it challenging to wear the device on areas like the chest or arms. Future versions should offer multiple wearing options to protect all workers, regardless of physical ability. In addition, training on how to properly use the device would be beneficial, especially for those with limited experience using wearables.

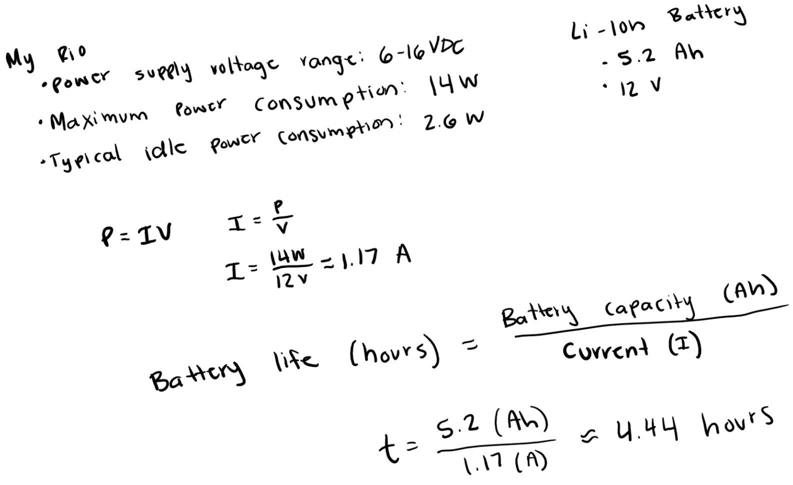
Physical Constraints

Although our final costs were well within our budget, some of our initial purchases were products that were less expensive, in order to allow for variation in our budget. For example, our hazardous gas sensor, although within our budget, was not rated for medical use and it was intended for hobby usage instead. The sensors that would have been rated for actual use were much more expensive and making such extreme purchases in the beginning of our semester did not seem like the best financial choice. If another iteration of this project were to be done, getting safety-rated sensors would allow the project to be used by consumers, and vetted in terms of safety regulations. The other air sensor, the SPS30, is a widely used particulate matter sensor and was quite available for purchasing, as well as its cost-effectiveness. Additionally, the national instruments myRIO microcontroller cost was not taken into consideration, as it was provided by the UVA Electrical and Computer Engineering department as a part of the capstone class. Nominally, the cost of this microcontroller for this project is a bit extreme, and in further research, a more cost-effective and tailored microcontroller would be created or purchased.

One main design and manufacturing constraint that we faced was the timeline regarding our PCB. Because we had to order several parts before our PCB could be ordered to test the functionality of our design, we waited a couple of weeks to order our final PCB. Because of this we only had one iteration of the PCB which is functional and capable of performing all the necessary tasks. However, if we had more time another iteration would have been useful to allow for design choices that would allow the PCB to be smaller to cater more towards the wearable aspect of the device. The PCB components were very accessible and only took a week or so after ordering for things to arrive

Later in the semester, it was brought to our attention that although by OSHA standards and almost all company standards workers should wear hearing protection in any loud environment, the “macho” culture at a construction site would interfere with an individual's willingness to proactively wear hearing protection. Because we had not considered this earlier on in the semester, we did not end up creating a notification system for the user to know when it is absolutely imperative to wear hearing protection, but the logging and notification still are active for the company to view. The rationalization behind this decision was that the employers are held responsible for the safety of the workers so they have all the necessary information and sound logging to mandate their workers to wear hearing protection.

One major constraint we encountered was how often to send HTTP requests, in relation to the battery consumption of the myRIO. There was a big tradeoff between the amount of data being sent to the server, how often it was sent, and the battery life of the myRio. The more HTTP post requests that were sent the more the myRio would have to be woken up to send data to the server, increasing power consumption. Although with maximum power consumption we calculated our battery should last 4.44 hours, as shown below in Figure 1, which was accounted for in our project as we built a removable cap to change the battery during longer shifts, we wanted to avoid reaching this threshold. Because of this aspect, we send data to the server more sparingly. Additionally, we did not want to fill up the database with data that would not have great value to the final customer.



My Rio
- Power supply voltage range: 6-16VDC
- Maximum Power Consumption: 14W
- Typical idle Power consumption: 2.6 W

Li-Ion Battery
- 5.2 Ah
- 12 V

$P = IV \qquad I = \frac{P}{V}$

$I = \frac{14W}{12V} = 1.17\ A$

$$\text{Battery life (hours)} = \frac{\text{Battery capacity (Ah)}}{\text{Current (I)}}$$

$$t = \frac{5.2\ (Ah)}{1.17\ (A)} \approx 4.44\ \text{hours}$$

Figure 1. Li–Ion Battery Life Maximum Power Consumption Calculation

The main tool used for this project was LabView, as this allowed us to interface with our microcontroller and send the data from our sensors to the website. Everyone on the team had to learn LabView, but for the most part, this was a smooth process because of LabView's easy-to-learn graphical interface and tons of online support. The one caveat to Labview is the sheer amount of disk space to download the software onto the teams' computers and would be such for any LabView Developer. It is not as straightforward as downloading a single package to extract an IDE, so some time and lots of computer memory is needed. Additionally, the PCB team used Multisim and Ultiboard to design the schematic and PCB itself. Although these software were used in previous classes, there was still a bit of learning to do to use these tools from scratch. We used Waveforms to test our PCB and schematic on a breadboard. Because we were highly familiar with this technology, it did not pose a problem. The website was constructed with a multitude of coding languages including Python, CSS, and JavaScript. A crucial tool was the Python application of ‘Flask” which allowed a website to be created and broadcast through an IP address native to the computer it is hosted on. In order to host the data, an in-memory database was created using a software called SQLite. Although the web development team members knew these languages in a workable sense, a lot of consideration went into how to use them in conjunction to develop the dynamic website that worked so well with the myRIO.

External Standards

In developing the WorkSafe Monitor, following established industry standards was essential to ensure the wearable device’s safety and effectiveness. This section lists the external standards that were central to the project's compliance specifications.

1. OSHA Standards for Personal Protective Equipment (PPE) [9]
    - OSHA 1910.132(a): This standard requires that personal protective equipment, such as the WorkSafe Monitor, be kept clean and in good working condition. The team designed the device to withstand the tough conditions typically found on construction sites, ensuring it remains functional and continues to protect users. The device features a sturdy casing to protect the electronics and anti-static foam inside to cushion the components. Due to time constraints, the initial prototypes were 3D-printed with regular plastic instead of the stronger nylon carbon fiber that was initially planned. For future versions intended for commercial sale to construction firms, the team plans to upgrade to nylon carbon fiber to enhance the device's durability.
    - OSHA 1910.132(c): This standard states that all personal protective equipment must be designed safely and not get in the way during construction work. The WorkSafe Monitor was designed to be lightweight and non-intrusive, which means it won’t stop someone wearing it from moving freely and staying safe while on the job. Because of this, the team decided to place the device on the chest area. This location helps make sure that it doesn’t restrict movement, allowing workers to freely use their hands and legs. The edges of the casing were smoothed to eliminate any sharpness, reducing the risk of irritation or injury in case of a fall. On top of that, the team went through five different designs for the casing to make it as small and easy to wear as possible. The final design includes lightweight straps that wrap comfortably around the shoulders and waist to keep the device securely in place.
2. NFPA 70: National Electrical Code (NEC) [12]
    - The NEC lists electrical safety standards for residential, commercial, and industrial settings. To meet these standards, the WorkSafe Monitor ensures that all electrical components, including wiring and batteries, follow safety requirements, thereby preventing common electrical hazards like shorts and overheating. These safety codes directly influenced the team's PCB design. The layout was planned to optimize spacing and reduce the risk of electrical interference, which can cause malfunctions. Careful attention was also given to selecting materials and determining trace widths in the PCB design software to manage the expected currents and voltages.
3. IPC 2221A: Generic Standard on Printed Board Design [15]
    - The IPC 2221A standard is also important for designing and assembling the PCB in the WorkSafe Monitor. It guided decisions on layout, component placement, and spacing to ensure the hardware performs reliably, even under the chaotic environmental conditions found at construction sites.
4. IEEE P1912: Standard for Privacy and Security Framework for Consumer Wireless Devices [16]

- Given the sensitive nature of the data collected, the team referenced the IEEE P1912 standard to guide the privacy and security measures for worker data. While full adherence to this standard is planned for future iterations of the device and not the prototype, it helped begin plans for a secure website with a login interface for employers. However, due to constraints such as time, limited website hosting capabilities, and the myRIO's HTTP data transmission protocol, the project couldn't fully meet the privacy standards set by this guideline. Future improvements will focus on including login features and comprehensive database security features. Hosting the website on a cloud computing platform, rather than a single laptop, would also help a lot in implementing these improvements.

Each of these standards was integrated into the design process to ensure that the WorkSafe Monitor met the current demands of wearable technology in construction while also prioritizing safety and reliability.

Intellectual Property Issues

Although there are several patents pertaining to wearable safety technology, most other devices on the market focus on one specific feature rather than sensing multiple safety factors. The Smart safety apparatus, system and method is the patent that is most similar to our device [28]. The description specifically states "the device may comprise a digital personal protective equipment/"internet of things" wearable." It also mentions "a plurality of sensors" and a "full-body harness" could be under the protection of the patent. The smart safety apparatus is a patent protecting the device, system, and method of wearable technology designed for digital personal protective equipment with data transmission and communication features. Although this device is similar to ours, the patent is very broad, and does not mention hazardous gas, particulate matter, or sound levels. This patent, despite being marketed as a wearable safety device, actually is more related to communicating with other individual workers or supervisors. Although ours does notify the employer when some kind of event occurs, it is mainly intended for longer term data tracking. Therefore, even though part of their patent includes a safety harness with sensors, data transmission, and WIFI connection, the usage of their device and the specific data it tracks differs from ours.

The next patent that is similar to ours is the Wearable Computing Device for monitoring hazards [29]. This patent covers wearable computing devices designed to monitor occupational hazards, including sensors that detect user aspects or environmental conditions and generate alerts when certain thresholds are exceeded. The patent specifically describes that in some embodiments the device could have a CO2 sensor, accelerometers, and detect harmful chemical agents. Some similarities that this patent has with ours is the use of a CO2 detector and attaching the device with a harness. The patent centers around monitoring human safety and well-being. It also uses accelerometer and microphone data. Some differences between our project and this patent is that the patent does not use accelerometer data for fall detection or microphone data specifically for high noise level detection.

Lastly, the third similar patent we found was the Safety harness motion detector systems and methods for use [31].This patent protects the systems and methods for monitoring lifeline attachment to a harness using a motion detector module (MDM) with motion sensing, timing, and communication capabilities to detect worker movement, relay data to a nearby device or a centralized system, and issue alerts for noncompliance. This device is also intended to be used on job sites and its main purpose is to protect against worker falls. The device is attached to a harness and monitors fall detection while sending events over a WIFI module. Although this device does use a WIFI module and perform fall detection, it does not sense other safety factors, which is the main capability of our device and it is structured differently as it is an attachment to a harness rather than a device held up by a harness.

Although multiple of these patents have the same intent as our device, to monitor the safety of construction workers, and monitor similar data, we believe our project is still patentable in light of these claims as we have the benefit of novelty. None of the patents mention all the sensing capabilities that our device offers or have a focus solely on sensing and tracking environmental data from the users perspective.

Project Description

Performance Objectives & Specifications

The WorkSafe Monitor was created to be geared towards companies that advocate for their workers' safety. Although the end-user of the device would be a construction or manufacturing worker, the customer is the company purchasing and deploying the devices in the field. The Worksafe Monitor has many features geared towards the customer, including alerts on employee incidents, easy-to-view graphs and charts of history, and a management console with all employees and their data. In the management console on the website, the company can view the history of alerts for employees and also see any alerts that would come in real-time via a desktop notification. The website contains subpages for data on each type of sensor for each worker. There are four subpages, which house the data for particulate matter, hazardous gas, fall detection, and noise levels.

The workers that will be wearing the device also have the features of real-time alerts on hazardous gas detection, wireless power, and portability. The real-time alert is a buzzer that alerts the worker that they are in the presence of a dangerous level of hazardous gas to humans. The device is also battery-powered to allow for portability so the worker can have it with them during working hours to monitor their surroundings, with a removable rechargeable battery. When the device is not being powered, the data is not sampled or sent to the website hub. The device comes with a strap/harness that allows the workers to wear the device for maximum safety detection.

Initially, the website was going to be developed with both the company and the worker in mind, with the option to have separate logins where workers could view their own past data and the company could view all employees' data. Instead, the console was created with only the company in mind. This is because the company is the consumer of the product that will be purchasing and distributing it to their workers, so we decided to gear the main features towards the company. However, we did not sacrifice the real-time alert for hazardous gas detections, as the overarching goal of the device is still to keep the worker's safety at the forefront.

How It Works

The project is based on four primary sensing capabilities: hazardous gas detection, airborne particulate matter monitoring, sound level measurement, and fall detection. It is designed for a construction worker to wear the device on their body in a way that does not interfere with their work, facilitated by an adjustable strap. Once powered on, the device continuously senses and detects these key parameters. The data collected from the sensing activities is transmitted over a Wi-Fi network to a website, where it is stored and made accessible for the company to view and monitor.

The entire system can be divided into three main components: the PCB, the NI myRIO microcontroller, and the website. The PCB board hosts the two external sensors soldered directly to the board via wires and connected to the 3D-printed casing exterior where they can take more accurate data. It also incorporates the electronic components and routing necessary for supplying power to the sensors, powering the microcontroller, and a custom sound level meter. The PCB connects directly to the myRIO Expansion Ports(MXP) B-side connectors via a 2x17 pin ribbon cable from the PCB. The following figure shows how the ports are laid out on the myRIO MXP connectors.

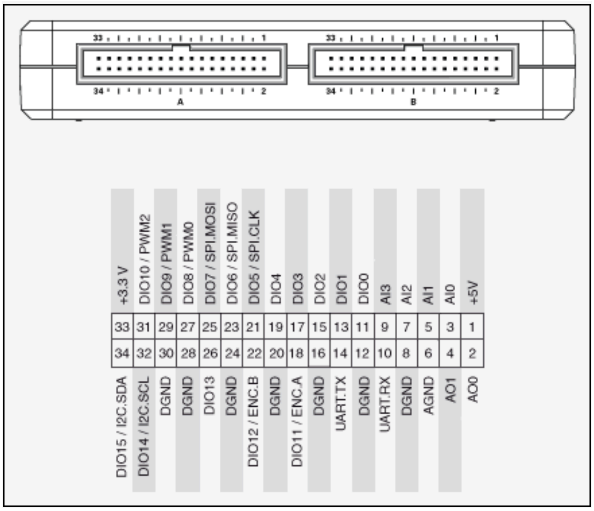


Figure 2. NI myRIO MXP Connections

The myRIO runs a LabView project that receives all the sensor data, processes it into JSON packets, and then sends these packets to the website using HTTP POST requests. The website, set up with a Flask Python web server on the backend, manages the reception and processing of the POST requests from the myRIO to insert the sensor data into a relational SQLite database as appropriate. Furthermore, the web server continuously updates all web pages to display the relevant sensor data and history through graphs and other user interface elements. The homepage alerts are checked every ten seconds. Fall detection data is analyzed every two seconds, and the hazardous gas scatter plot is updated every five seconds. Additionally, the particulate matter line plot refreshes every two seconds, while noise level readings are updated every second. The connectedness of these three main project components is outlined in the figure below.

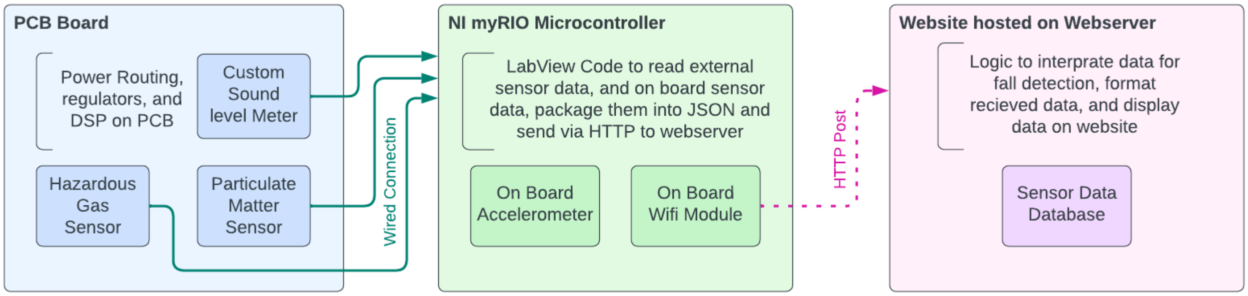


Figure 3. Block Diagram of WorkSafe Monitor Components

A single-line diagram was sketched out for the electrical connections between the physical hardware of the project. The electrical connections shown are the power and data lines between devices. This diagram is shown in Figure 4 below.

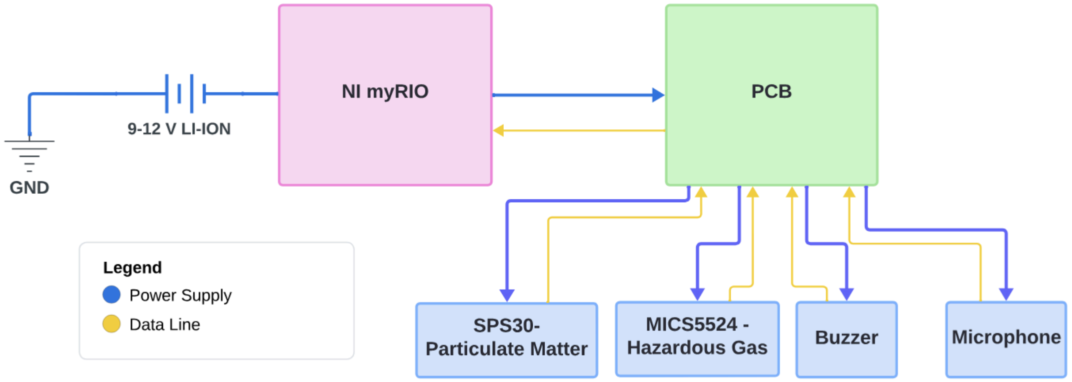


Figure 4. Single Line Diagram Showing the Power Supplies and Data

PCB Details

The PCB design started with designing the audio amplifier. The amplifier was imperative for the sound level sensor to work properly, and the only sensor to rely fully on the PCB. From start to finish the sound level sensor works as so: sound is captured by the microphone, amplified through the pre-amplifier, peaks are detected through the peak detector, and then the voltage data is sent to the microcontroller and web server. The microphone was an important factor and considerations such as the sizing, input voltage, and impedance level had to be taken into account when determining which one to use. Ultimately, the POM3535P-3-R was chosen [8]. Then, the pre-amplifier had to be designed. A trans-impedance amplifier was chosen to create gain without a large output offset. When choosing the components for the amplifier, several values were calculated. This included the gain of the pre-amplifier, which relied on the sensitivity of the microphone, the V_{out} which relied on the line level voltage of the microphone, and the I_{out} which relied on what the max sound level input of the microphone would be (which corresponds to a specific pressure). Capacitors were chosen to compensate for the parasitic capacitance of the system, as well as filter noise from voltage supplies. Resistors were chosen to control the bias of the microphone, to create the operational amplifier bias network, and to limit current. In the amplifier design, there are two high-pass filters (formed by R_1 & C_3 and R_6 & C_5) and one low-pass filter (formed by R_3 & R_5 & C_6). Lastly, an operational amplifier had to be selected for the pre-amplifier design. The base specifications for the amplifier were that the max supply voltage had to be greater than 5V and the supply current had to be less than 2.5 mA. Ultimately the OPA172 was chosen for its size, fast slew rate, and low offset [11]. The full calculations for the pre-amplifier design can be found in the Appendix Section D. The next step for the sound level sensor was to design the peak detector. The peak detector is simple in design, including only an operational amplifier, a diode, and a capacitor. The largest consideration in the peak detector design was the capacitor, which affected how long the peak was held. Appendix Section J. shows the initial testing of the peak detector. Figure 5 below shows the overall Multisim Schematic for the PCB design.

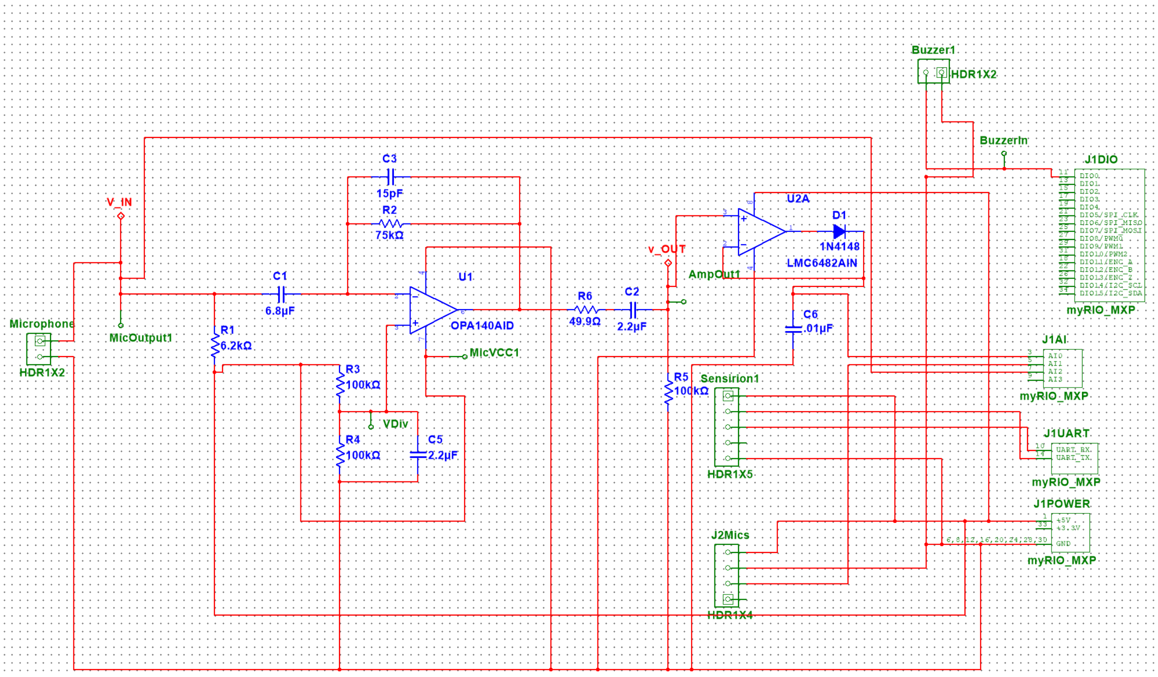


Figure 5. PCB Multisim Design

Other components on the PCB included the Hazardous Gas Sensor, the Particulate Matter Sensor, and the buzzer. These components were pre-fabricated and did not require any additional parts to be functional, just the power and data routing. Each component was connected to the board via soldered wires. In addition to the sensors, test points were added to the board. These included: in between the voltage divider, the output of the amplifier, the output of the microphone, and the input of the buzzer. These test points were determined essential to test the PCB and would help us diagnose if there was an error somewhere on the board. We determined that the other components could be tested by connecting the board to a breadboard and utilizing the header that connects to the NI MyRio.

The next step in designing the PCB was routing all of the power and data. The power supply was not directly connected to the board but to the NI MyRio, all of the data was routed to the NI MyRio as well. One of the main considerations in routing the power and data was the choice to utilize just one of the MXP sections of the NI MyRio. This choice enabled us to reduce the space the PCB took up, however this complicated the routing on the physical board. Furthermore, we decided to connect multiple components to the same nodes of ground and power supply to reduce the amount of connections to the NI MyRio, this decision marginally reduced the difficulty of the routing. To reduce the amount of space taken up by the power and data lines, we chose to utilize both the copper top and copper bottom. Figure 6 below shows the Ultiboard layout for the PCB.

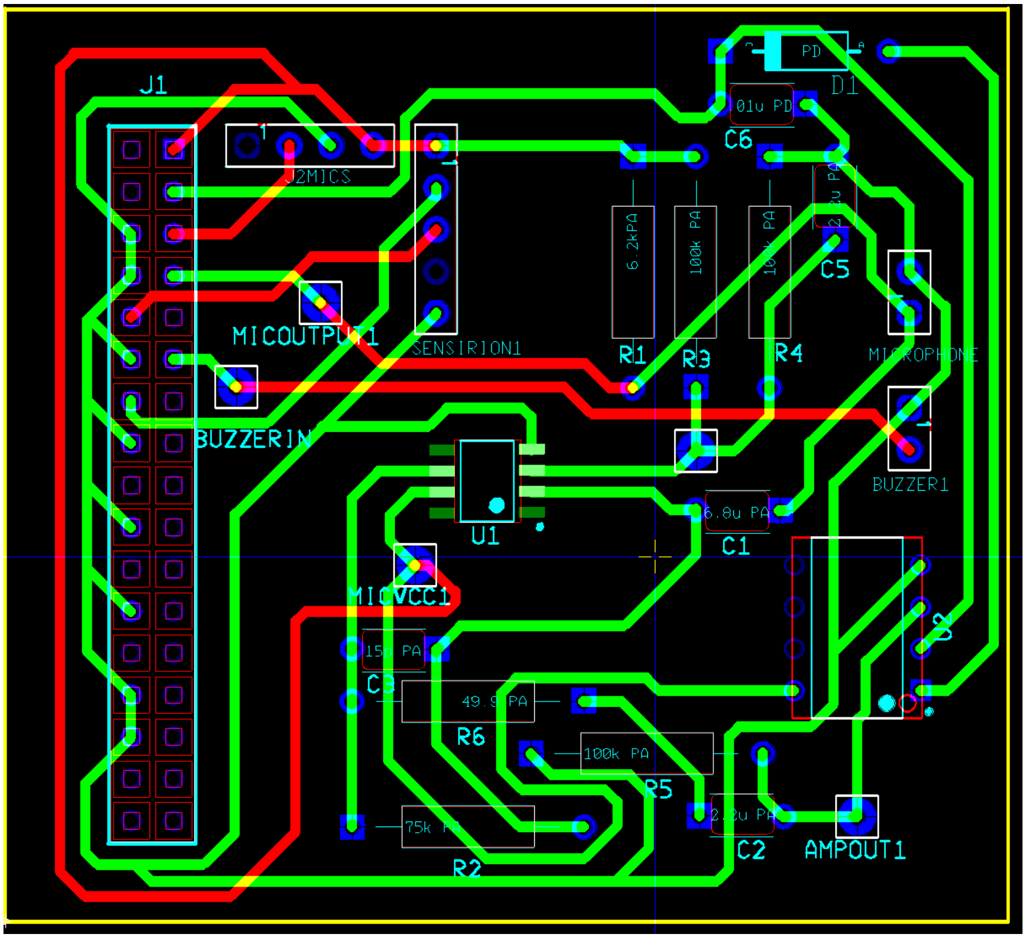


Figure 6. PCB Ultiboard Layout

Finally, the last factor we considered in this design was the size of the PCB. Because the WorkSafe Monitor is a wearable device, the PCB had to be small so as to not further constrain the sizing of the casing. To ensure this, the board components were pushed closely together and routed often when through components. The final board size was 2” x 2”.

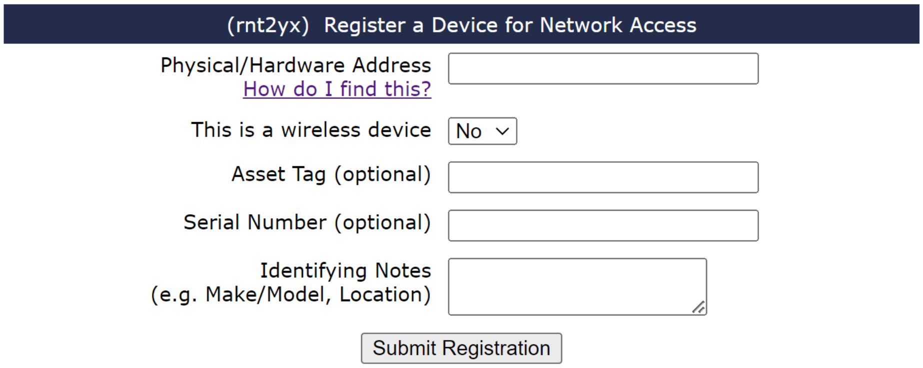
Battery Details

The battery was chosen to fit several specifications. The NI MyRio minutiae to follow for power, including: the power supply voltage range had to be 6 to 16 VDC, the max power consumption had to be 14 W, and the typical idle power consumption, 2.6 W [37]. We also had to consider the power that would be drawn from the sensor. With all of these considerations in mind, we chose a 5200 mAh lithium-ion battery that was rechargeable. This battery had a continuous 5A current output and an output voltage range of 9 to 12.6V. Therefore there would always be 63 to 45 W available. Figure 7 shows the Lithium Ion Battery selected.

Figure 7. Battery that powers the MyRio [38]

Embedded Details

Before expanding the LabView code, the team verified that the NI myRIO had the necessary wireless capabilities. The onboard WiFi module serves as a connection to a WiFi network independently. The UVA unbroadcasted WiFi network 'wahoo' is the intermediary network connection between the computer hosting the web server and the myRIO [18]. To connect to the wahoo network, the MAC address of the device was found on the NI MAX software and registered online through UVA. Figure 8 below shows the UVA online registration page for a device.



(rnt2yx) Register a Device for Network Access

Physical/Hardware Address
How do I find this?

This is a wireless device: No

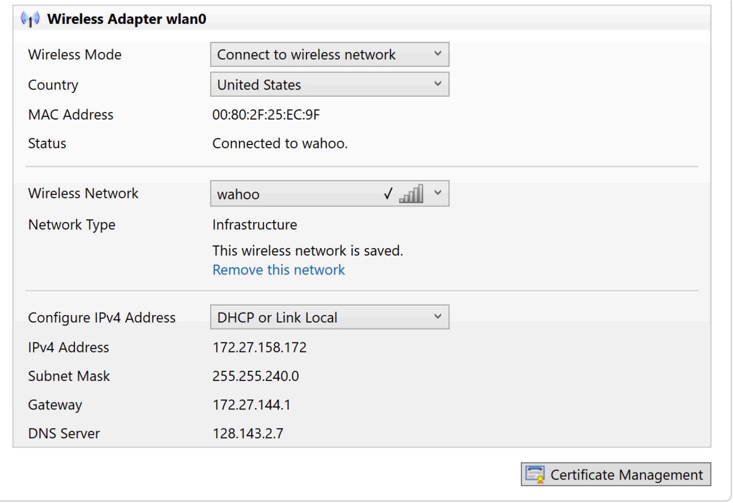
Asset Tag (optional)

Serial Number (optional)

Identifying Notes
(e.g. Make/Model, Location)

Figure 8. Wahoo Network Device Registration

Once the myRIO was configured to be connected to the wahoo network, everytime the microcontroller is powered up, the connection is established. Figure 9 below shows the software setup for initializing the myRIO as a connection and establishing an IP address.



Wireless Adapter wlan0

Wireless Mode: Connect to wireless network

Country: United States

MAC Address: 00:80:2F:25:EC:9F

Status: Connected to wahoo.

Wireless Network: wahoo

Network Type: Infrastructure

This wireless network is saved.

Remove this network

Configure IPv4 Address: DHCP or Link Local

IPv4 Address: 172.27.158.172

Subnet Mask: 255.255.240.0

Gateway: 172.27.144.1

DNS Server: 128.143.2.7

Figure 9. WiFi Setup on myRIO with NI MAX software

The WorkSafe Monitor's four total sensing capabilities are achieved using external sensors and onboard functions. The external sensors, particulate matter, and hazardous gas are soldered on the PCB board to ensure stability and access to outside air. The microphone has some components directly on the PCB and others soldered via wires so that it can reach to the outside of the casing. Figure 10 below shows how the PCB board connects to the myRIO and delegates its power to the various sensing capabilities,

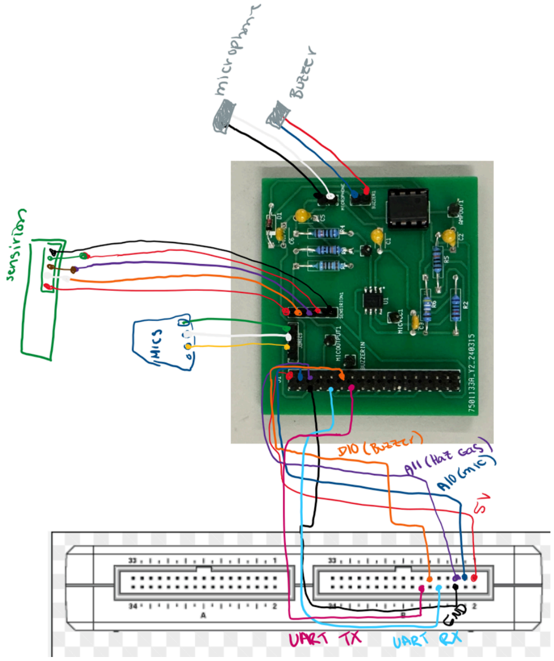


Figure 10. Wired Connection Diagram between PCB and myRIO MXP ports

With the above connections in place, the Labview code can be constructed to interface with all of the PCB components. The following figure shows how the LabView code is structured in a high-level sense. This overview will be discussed in detail for each component in the following paragraphs.

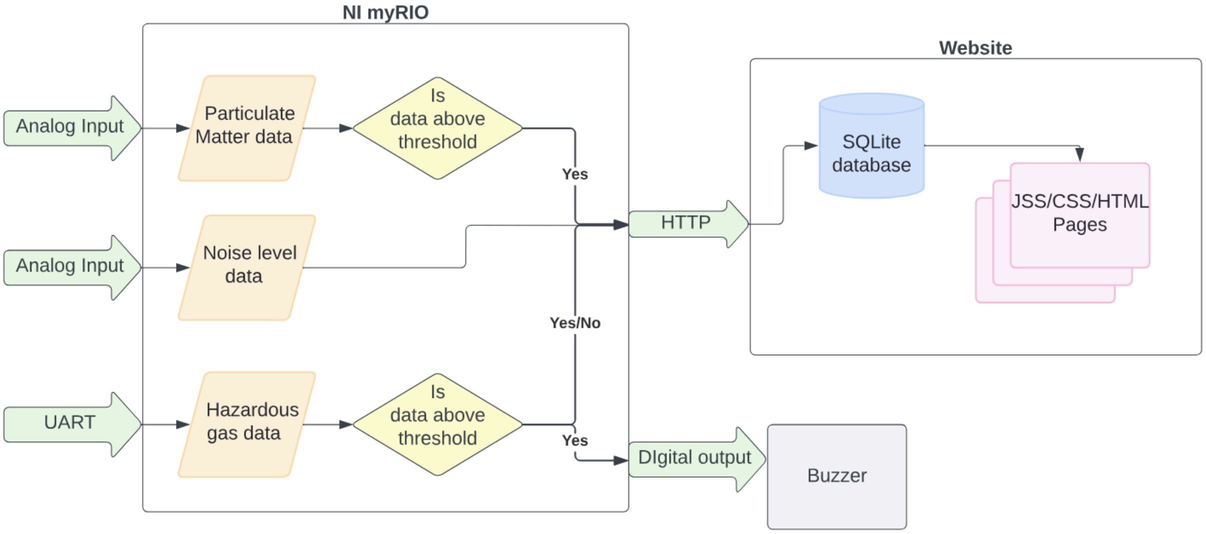


Figure 11. Overview of LabView Code Flow

The Adafruit MiCS5524 hazardous gas sensor, a robust micro-electro-mechanical sensor, detects multiple hazardous gasses including carbon monoxide and ethanol, crucial for monitoring indoor air quality and early fire detection [27]. This sensor is connected to the myRIO via a wired connection and is powered by the myRIO with a five-volt output pin. The following figure shows the pinout of the Adafruit sensor itself.

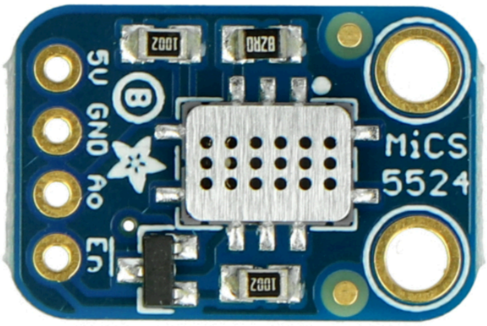


Figure 12. Adafruit MICS5524 Pinout

It transmits voltage through an analog input pin on the microcontroller respective to the concentration of hazardous gas present. In Labview, an 'Analog Input' express VI is used to receive the data by specifying the exact port that the data is coming through [7]. For this project, pin 5 on the B-side of the MXP was used for hazardous gas reading. The value is then changed using the formula node to convert voltage to ppm according to the calibration curve received during testing. The ppm value is checked to see if it is over 9 and/or 150 ppm. If it is over 9 ppm, the value is sent to be packaged in a JSON packet and sent to the web server with an HTTP post request. This value was chosen because after the team did the calibration and produced the calibration curve that they input into Labview, the ranges of ppm output when measuring clean air were more visible. With the hazardous gas sensor sitting inside with no external gasses being applied to the sensor, the voltage output to the myRIO ranged from 0-0.12 volts, which when converted to ppm with the calibration equation resulted in 0-9 ppm. So by only sending the data to the web server when the ppm reads over 9, we are ensuring that carbon monoxide concentrations are wrongfully sent to the web server when in reality it is just the range of error in the voltage output. If the value is over 150 ppm, A digital output pin is set high, with turns on the piezoelectric buzzer to alert the wearer to immediately leave the area [8]. The value of 150 ppm was chosen in congruence with the U.S. Consumer Product Safety Commission guidelines as the concentration of CO that puts workers in immediate danger, thus warranting an immediate alert to the user [22]. The data is sampled from the sensor once a second due to the need to constantly monitor the presence of hazardous gas, particularly carbon monoxide. Figure 13 below shows the Labview code for the hazardous gas sensor.

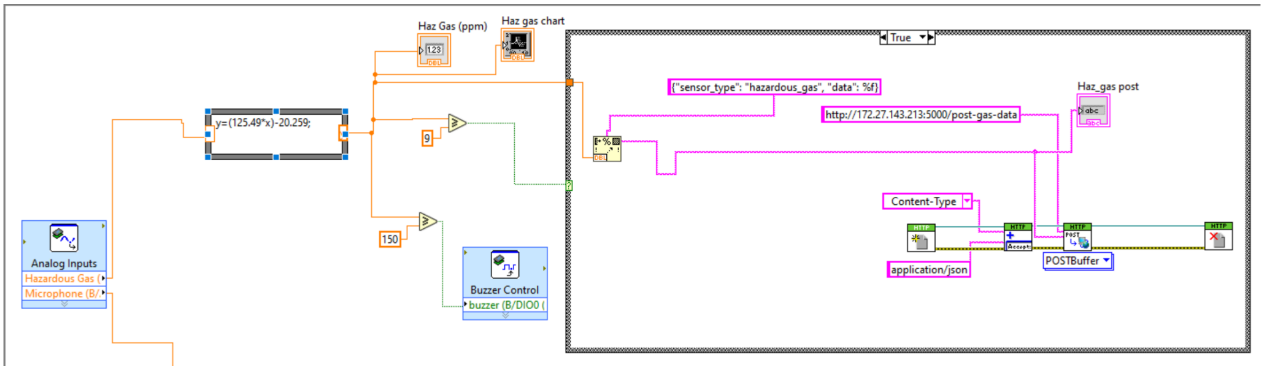
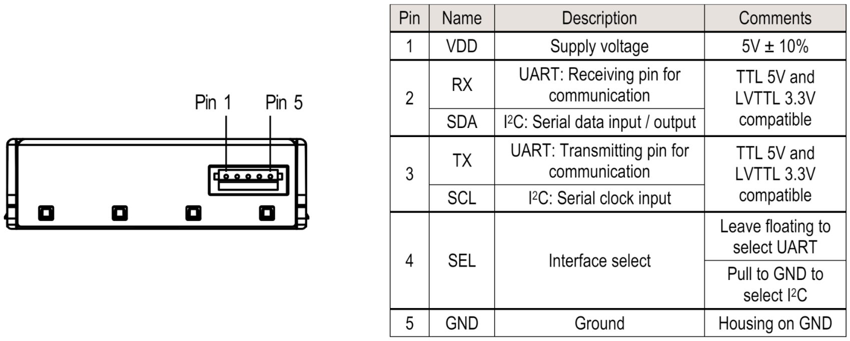


Figure 13. Hazardous Gas LabView Graphical Code

The particulate matter sensor, Sensirion SPS30, is capable of detecting the mass concentration of particles 1, 2.5, 4, and 10 microns in size—particles small enough to enter the lungs and cause serious health issues [6]. It communicates with the microcontroller using the UART communication protocol, in which Labview has native virtual instruments to utilize. The transmit and receive pins of the SPS30 are connected to the respective transmit and receive pins on the myRIO MXP B-side ports. Is it also powered by a pin on the myRIO supplying five volts. The pinout of the SPS30 sensor is shown in Figure 14 below.



Pin	Name	Description	Comments
1	VDD	Supply voltage	5V ± 10%
2	RX	UART: Receiving pin for communication	TTL 5V and LVTTL 3.3V compatible
	SDA	I^{2}C: Serial data input / output	
3	TX	UART: Transmitting pin for communication	TTL 5V and LVTTL 3.3V compatible
	SCL	I^{2}C: Serial clock input	
4	SEL	Interface select	Leave floating to select UART
			Pull to GND to select I^{2}C
5	GND	Ground	Housing on GND

Figure 14. SPS30 Sensor Pinout

Before taking measurements in LabView, the SPS30 must be told to initialize the sensor and then continuously take measurements unless told otherwise. A series of bytes are sent that tells the SPS30 to say ‘Start Measurement’ and then a small wait period of one second for the instructions to be received by the sensor. Then, a series of bytes are sent to say ‘Read Measured Values’ followed by another one-second wait period. A loop of read values and waiting ensues every 15 seconds to get data. The data comes from the UART express Read VI as a byte array of hex characters [3]. These hex characters are converted to a string of letters, which is sent to the web server for deconstruction and value extraction [1]. This data, read every 15 seconds since it is just passively monitored on the web server, is packaged into a JSON packet and sent to the web server with the same logic as other sensors. Figure 15 below shows the Labview code for the particulate matter sensor.

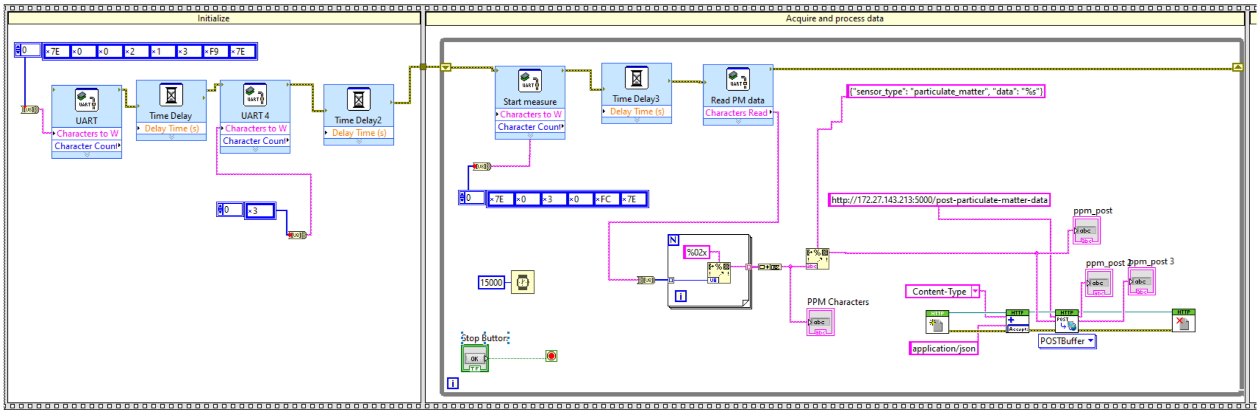


Figure 15. Particulate Matter LabView Graphical Code

The National Instruments myRIO microcontroller is equipped with several onboard functionalities, with the accelerometer and the WiFi module being the most utilized for this project. The accelerometer, which measures changes in direction along the X, Y, and Z axes, is used in conjunction with timestamps to develop code that can detect falls and log the incidents on the website. The LabView code reads the acceleration magnitude in all three directions and formats them into an array of values. Those values are formatted into a JSON packet and sent to the web server similarly to other sensors. The values are sent every 50 ms since the fall detection algorithm on the website needs to be able to average a bunch of data points in quick succession. Figure 16 below shows the Labview code for the on-board accelerometer.

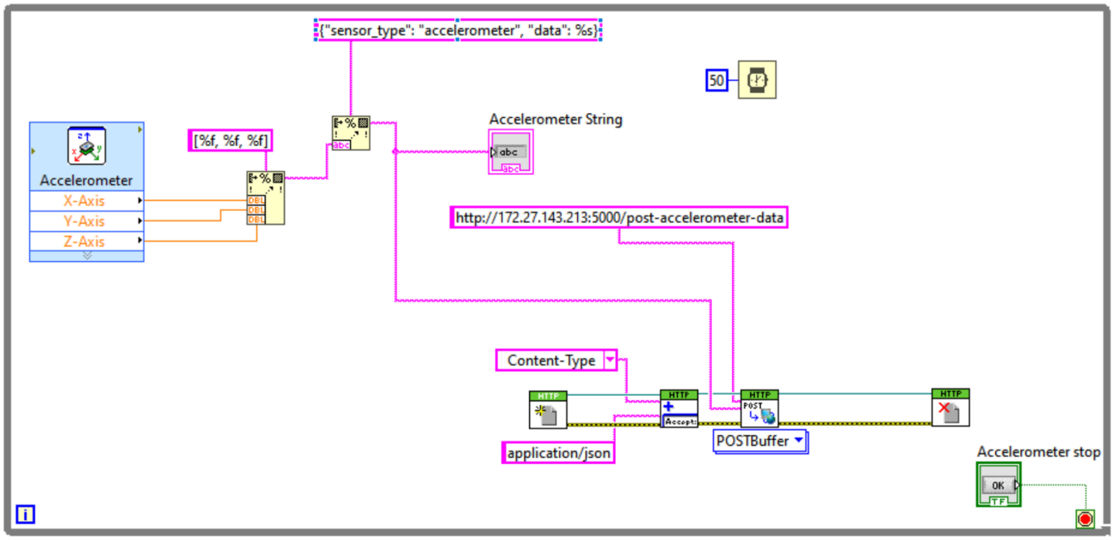


Figure 16. Accelerometer LabView Graphical Code

For sound detection, the team constructed a preamplifier and peak detector that was integrated into a PCB, in addition to procuring a CMA-4544PF-W microphone [20]. This specific microphone was selected because of its compatibility with the myRio/PCB. The microphone required the least amount of connections, only 5V and ground, and was easy to solder wires onto to allow it to extend past the PCB. It was also omnidirectional so it worked best with our device as it could sense sound from multiple directions. The microphone is connected to the ground and the 5V source is from the myRio. The signal that the microphone takes in is sent to the amplifier, and the strength of the signal is increased. Next, the amplified signal is sent to the peak detector, which captures and holds the peak of the input signal. This is then sent to the analog input of the myRio, in which it is sampled every second. The incoming sound level is converted to dB based on an equation determined through calibration testing, shown below in Figure_. The decibel sound level is evaluated to see if it is greater than 80. This value was chosen from research regarding safe sound levels for adults [14]. If the decibel sound level is above 80, the value will be packaged into a JSON packet and sent to the website via HTTP post request. The website will monitor long-term effects given the history of data sent above 80dB. Figure 17 below shows the Labview code for the microphone sensor.

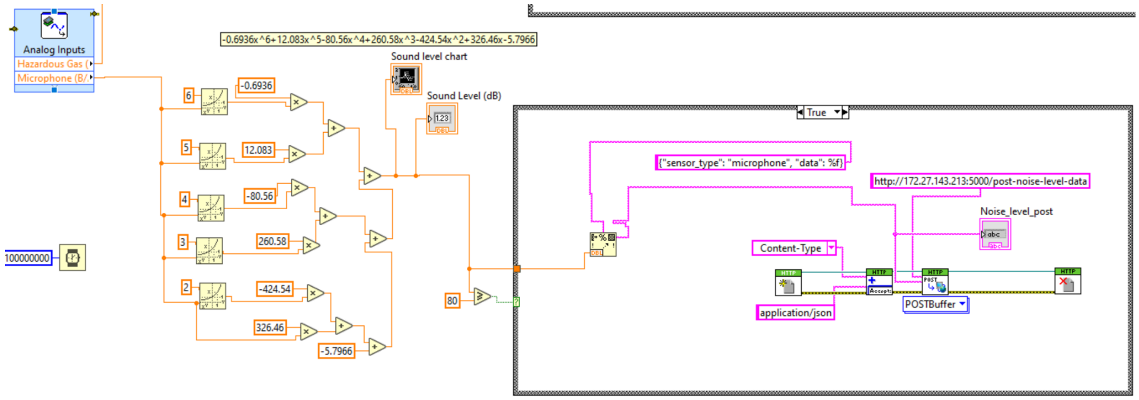
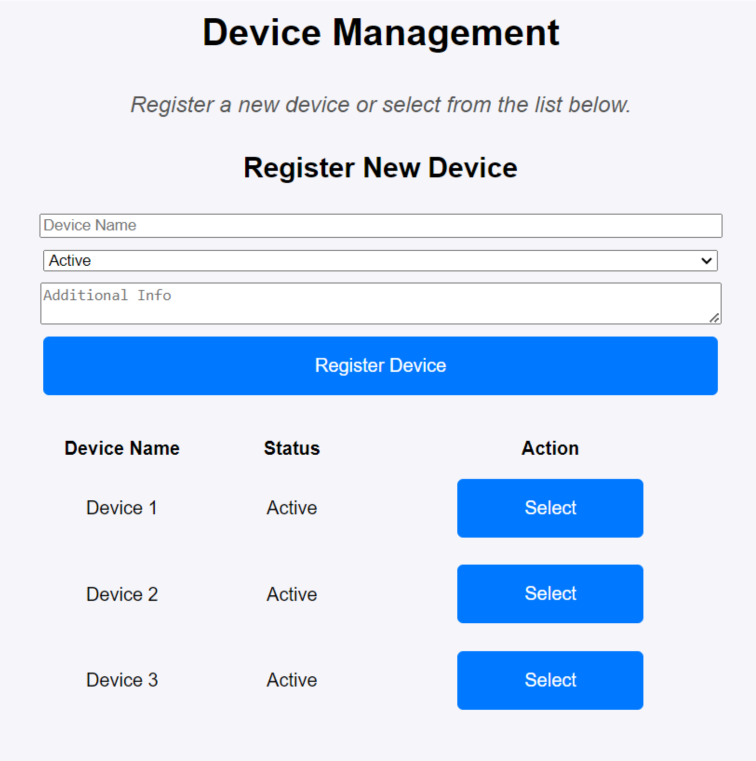


Figure 17. Microphone LabView Graphical Code

Website Details

The website consists of six distinct pages, each serving a different function. The first page is designed for device registration and selection, allowing an employer to add devices or select from those assigned to specific construction workers. This page was developed to enable employers to monitor numerous workers at a construction site simultaneously. It’s important to note that during development, our website was hosted locally on a single laptop, meaning this page primarily served as a placeholder in our proof of concept. For a fully operational system integrating multiple devices, additional processing power and greater database storage would be necessary. Figure 18 shows this below, with multiple registered devices as an example.



Device Management

Register a new device or select from the list below.

Register New Device

Device Name

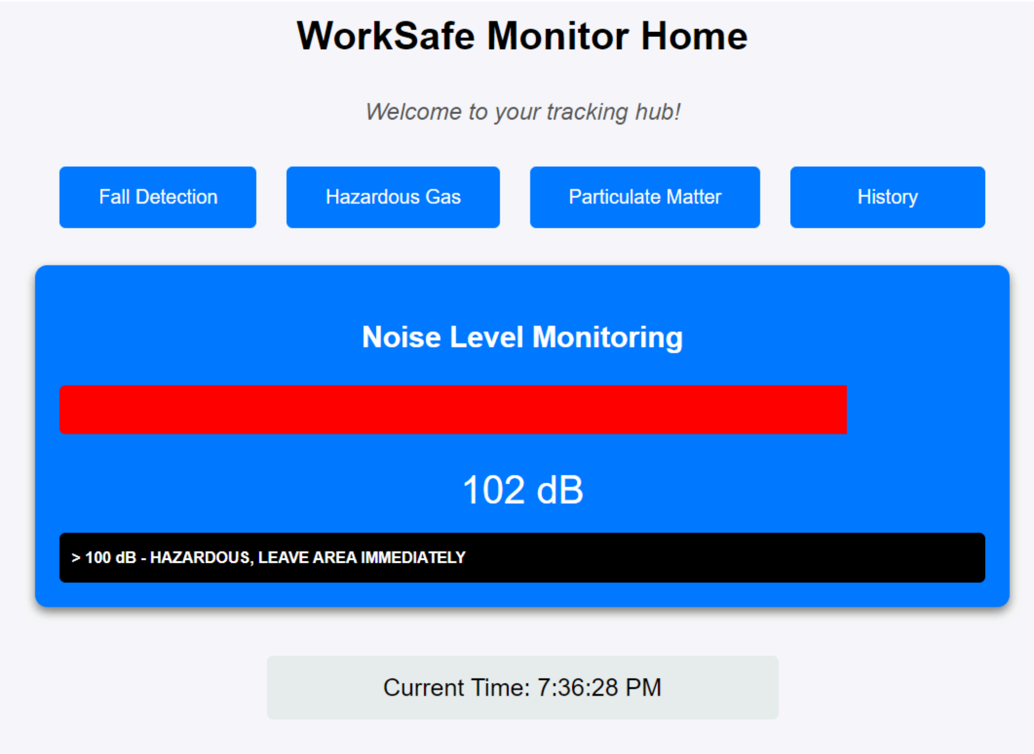
Active

Additional Info

Device Name	Status	Action
Device 1	Active	Select
Device 2	Active	Select
Device 3	Active	Select

Figure 18. Website Device Registration and Selection Page

When an employer selects a device, they are directed to the monitoring hub, which serves as the central interface for our device functions. From this hub, users can navigate to different functionalities like fall detection, hazardous gas monitoring, particulate matter tracking, or review a history of previously recorded events, each of which will be detailed further below. Additionally, the homepage features a noise level monitor that displays live decibel readings and notifies users about the safety status of the most recent measurement. In the top right corner of the monitoring hub, alerts about dangerous events are displayed. These alerts are generated by task schedulers that analyze the stored data to detect potential hazards. The specifics of how these task schedulers work will be discussed later.



WorkSafe Monitor Home

Welcome to your tracking hub!

Noise Level Monitoring

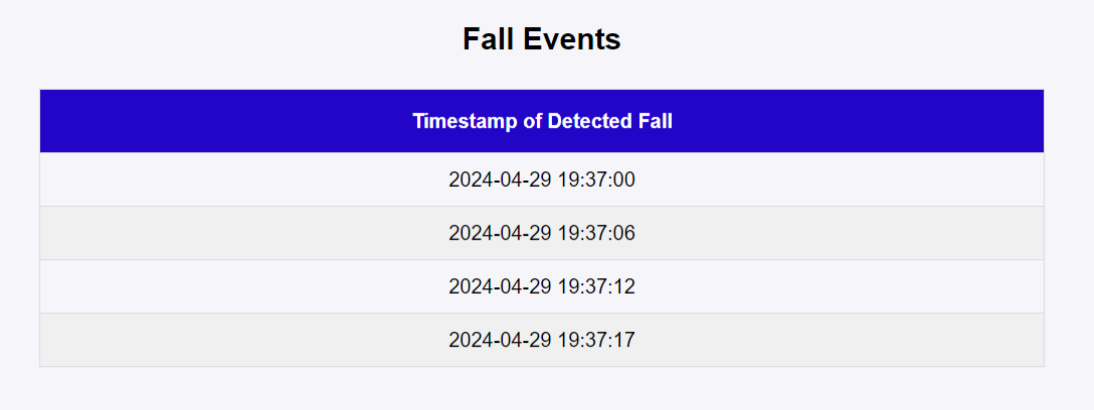
102 dB

> 100 dB - HAZARDOUS, LEAVE AREA IMMEDIATELY

Current Time: 7:36:28 PM

Figure 19. Website Device Monitoring Homepage

The fall detection page includes a simple, dynamically updated table that logs timestamps whenever potential falls are detected. Originally, the plan was to display live accelerometer magnitude data. However, since data is transmitted to the server every 50 milliseconds, the team concluded that presenting too frequent updates would not be exactly useful to the employer. It would also require excessive processing power and memory, resources that are better allocated to running the fall detection algorithm and managing the database. The table format enables employers to quickly identify when a potential fall has occurred, allowing them to quickly implement safety measures for the affected worker.

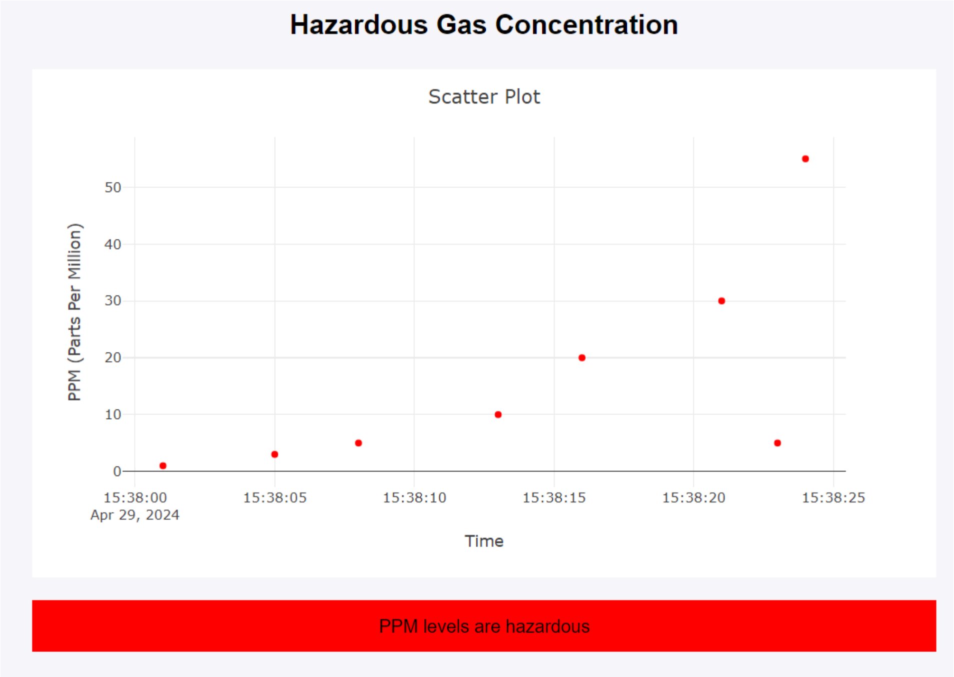


Fall Events

Timestamp of Detected Fall
2024-04-29 19:37:00
2024-04-29 19:37:06
2024-04-29 19:37:12
2024-04-29 19:37:17

Figure 20. Fall Detection Subpage

The hazardous gas monitoring page displays an autoscaled scatterplot that tracks dangerous gas PPM values, with the embedded code configured to send only values greater than 9 to the server. Below the scatterplot, there's an infobar that provides details about the most recent reading; this assesses the current danger level of the gas concentrations and indicates whether any action is required. This setup is designed to give employers detailed insights into the surrounding gas levels in a specific area. While hazardous events trigger separate alerts on the homepage a layer above, this page provides near real-time monitoring and offers more precise information.



PPM levels are hazardous

Figure 21. Hazardous Gas Subpage

The particulate matter level monitoring page is structured similarly to the hazardous gas subpage, but it features a line plot with distinct lines for various particulate matter (PM) values, each identified by a legend. The Sensirion sensor measures all four particulate matter sizes (PM1.0, PM2.5, PM4.0, PM10), making it useful to display these on the website to provide a clearer overview of air quality. While PM2.5 and PM10 are known to be most hazardous, displaying the other PM sizes also helps in assessing the overall health effects. These line plots are continuously updated and autoscaled in real-time. Like the hazardous gas subpage, the particulate matter page includes an infobar that categorizes the safety of the latest PM10 reading from good to hazardous. Although PM2.5 is generally recognized as the most dangerous due to its ability to penetrate deep into the lungs and bloodstream, the focus on PM10 on this subpage is deliberate because these larger particles are also vital indicators of air quality, especially in settings like construction sites. Displaying PM10 helps employers identify the need for immediate safety measures such as respiratory protection. PM2.5 readings, nonetheless, are analyzed by a separate task scheduler on the server-side.

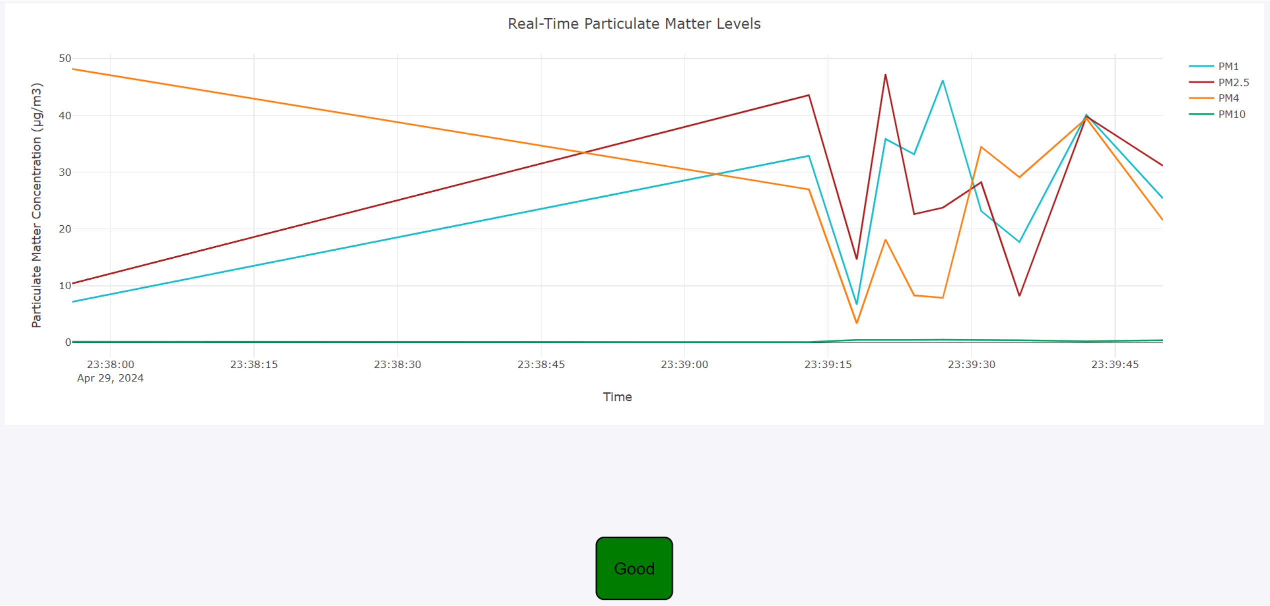
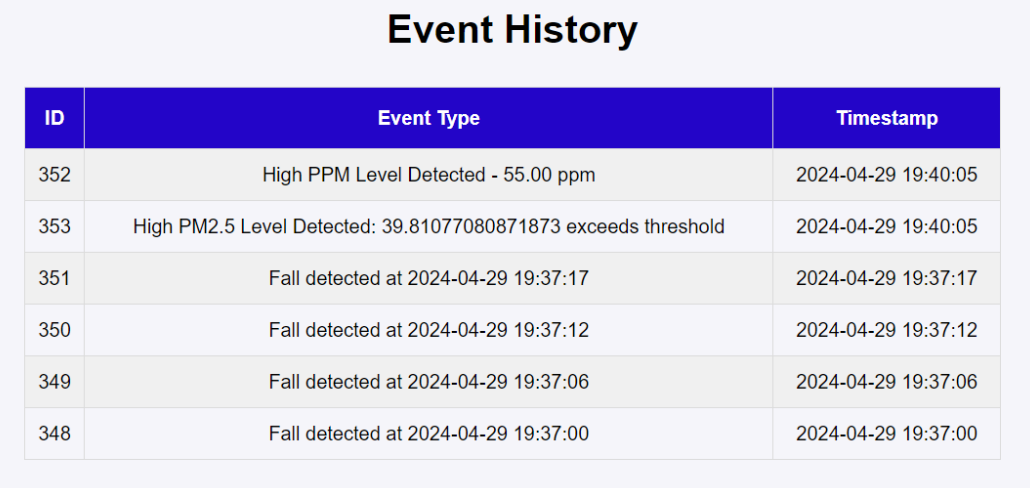


Figure 22. Particulate Matter Subpage

Finally, the last subpage is the event history subpage, which, similar to the fall detection subpage, consists of a table that logs recently recorded hazardous events. The specifics of which events are recorded and the recording process will be described in the next paragraph. It's important to highlight that this page uses a separate database from the one used for sensor data. The main reason for this separation is that event history data is typically retained for some time after a workday and does not consume much space, whereas sensor data is frequently updated and needs regular cleaning. This separation was decided-on as the best approach to ensure system modularity and efficiency.



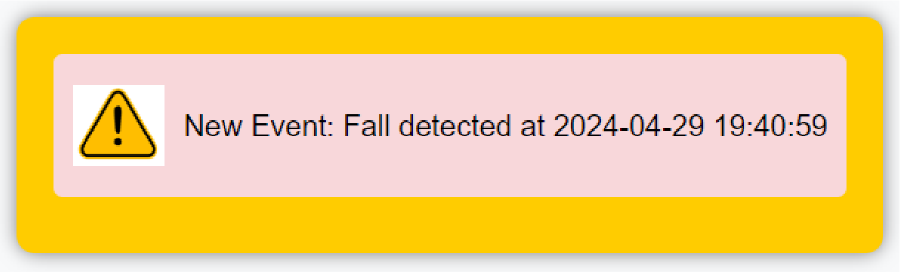
Event History

ID	Event Type	Timestamp
352	High PPM Level Detected - 55.00 ppm	2024-04-29 19:40:05
353	High PM2.5 Level Detected: 39.81077080871873 exceeds threshold	2024-04-29 19:40:05
351	Fall detected at 2024-04-29 19:37:17	2024-04-29 19:37:17
350	Fall detected at 2024-04-29 19:37:12	2024-04-29 19:37:12
349	Fall detected at 2024-04-29 19:37:06	2024-04-29 19:37:06
348	Fall detected at 2024-04-29 19:37:00	2024-04-29 19:37:00

Figure 23. Event History Subpage

The alert system on our website is a key feature designed to enable employers to quickly react to potentially hazardous events. This system is displayed on the device-specific homepage, one hierarchical page below the device selection one. The alerts appear in the top right corner of the page and include a yellow identifier for easy recognition. An important aspect of this system is that the alerts do not disappear automatically; instead, they must be manually clicked by the user to be cleared. This ensures that notifications aren't missed. Additionally, it's worth mentioning that any triggered alert is immediately recorded in the history database along with a timestamp and a description, creating a detailed event log.

Now, it must be described what actually triggers the alerts in the system. First, an alert is generated whenever a fall is detected by the fall detection algorithm; the details of how this algorithm functions will be provided in the following paragraphs. Additionally, a task is scheduled to run every five minutes that scans through newly added hazardous gas data. If this scan identifies a reading exceeding 25 parts per million (PPM), a hazardous gas alert is sent. The reason for setting the threshold at 25 PPM is that exposure to levels above this, such as from carbon monoxide, can lead to symptoms like dizziness after approximately 8 hours. Monitoring the PPM values every five minutes ensures that any higher levels are quickly detected, allowing users to be quickly evacuated. For particulate matter monitoring, the system uses two task schedulers, one analyzing PM2.5 levels and the other PM10 levels. Each scheduler runs every minute, analyzing newly added data. If the micrograms per cubic meter readings for PM2.5 and PM10 exceed 35 and 54 respectively, these concentrations are deemed dangerous according to OSHA standards, and an alert is issued. For noise levels, the approach is slightly more complex. A task scheduler operates every 15 minutes to analyze different durations of noise exposure. The thresholds are set as follows: 115 dB for up to 15 minutes, 110 dB for up to 30 minutes, 105 dB for up to 1 hour, 100 dB for up to 2 hours, and 95 dB for up to 4 hours. Each time the scheduler runs, it reviews all the past intervals; if the average noise exposure for any interval exceeds its limit, an alert is issued. This method allows the system to assess overall noise exposure rather than just temporary spikes detected by the microphone. Together, these algorithms work to continuously analyze data, helping companies effectively monitor the safety of their workers. It must also be noted that a separate task scheduler also takes care of dataset cleaning, removing unnecessary accelerometer and noise level data as needed (ran every hour), given that these sensors take up a majority of database storage. Below is an example of how an alert is displayed on the homepage.



New Event: Fall detected at 2024-04-29 19:40:59

Figure 24. Alert System

The fall detection algorithm initially considered by the group was to use an SVM-based neural network trained on the FallAllD dataset [24]. However, this approach encountered several challenges. Firstly, the dataset used to train the model predominantly comprised data from common everyday falls, which did not accurately represent falls that might occur on construction sites. Moreover, training the network on such a large dataset proved to be highly time-consuming and required significant server-side resources. Additionally, when the algorithm was tested against the FallAllD test set, it showed significant imbalances between precision and recall, further complicating its effectiveness for our application. Therefore, the group decided to switch to a simpler fall detection method that could still accurately and consistently detect falls.

The algorithm that was implemented functions by monitoring and analyzing accelerometer data to detect potential falls. It starts by calculating the magnitude of the acceleration vector from 3D accelerometer inputs using the Euclidean distance. This simplifies the X, Y, and Z data sent from the microcontroller, making detection easier. To reduce noise and random spikes in data, a moving average filter is applied. The filter, which is defined by a tested window size, smooths out the acceleration magnitudes by averaging data points within it. To detect falls, the algorithm uses typical fall patterns, which usually show a sharp increase in acceleration followed by a period of low activity. It flags a potential fall when the acceleration goes above a predefined threshold—initially based on recommendations from the FallAllD dataset but adjusted after further testing. After spotting this increase, the algorithm checks the following magnitudes for a set time to see if activity remains low. If these values stay below a certain threshold, indicating little movement, it triggers a fall alert.

In addition, the algorithm pulls new accelerometer data from the SQLite database using a specific key to prevent duplicating data. It logs the times of detected falls into the history database. This approach is straightforward but effective and performs well in tests. Its settings can be easily tweaked to suit different needs. The algorithm is fast and doesn't require training or a lot of processing power. However, it does rely on getting a steady stream of data from the myRIO device at a frequency of 20 Hz.

Casing Details

The initial casing was designed with adjustability in mind. The device had to fit a wide array of body types, as well as be able to move across and sit on different parts of the body as desired. This factor influenced how the casing had to be connected together as well as how the harnessing connected to the casing. It was decided that the straps should be directly coupled to the casing. This eliminated extra hardware and improved the maneuverability of the strapping, there would be no hardware pressing against the wearer's body. The casing was printed with four locations for strapping, each with two through holes for the straps to loop in and out of the casing. This configuration also allows for the device to be worn on the front of the body, the back, and at the hip if desired. The Figure below shows where the straps are connected to the case as well as the strapping configuration for wearing the device on the front of your body. Alternate strapping and harness design can be seen in Appendix H.

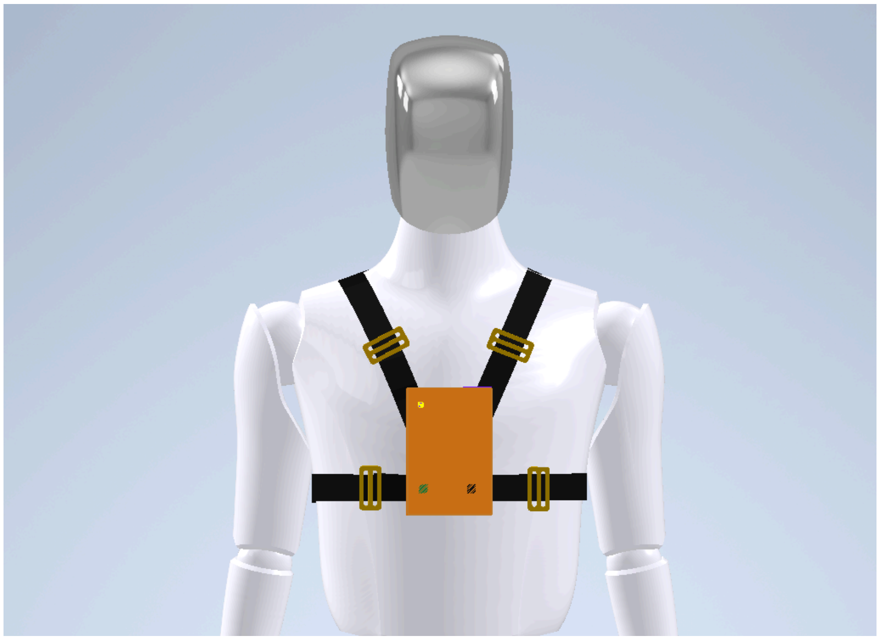


Figure 25. WorkSafe Monitor Harness Design

How the casing opens was a large element considered in the design process. Because we wanted the device to be as maneuverable as possible, we were somewhat limited in the ways that the device could be opened. Initially, we wanted the forward-facing top to come completely off, but because we have sensor components attached to that panel, that was not possible. We then looked into making the sides of the casing removable. Ideally, we wanted to have more than one of the side pieces removable, however, with the way the strapping is connected, this was found to be impossible. If too much stress was placed on the removable side where the strapping was, the siding opened. Therefore we were left with one option, having just the bottom of the casing removable, where there was no strapping. The lid was created by removing the face of the bottom of the casing in CAD and creating a section that was sized to the outer dimensions of the casing on top of a section that was sized to the inner dimensions of the casing. A sliding latch lid was also considered. Figure 26 displays the final casing design with the pull off lid at the bottom.

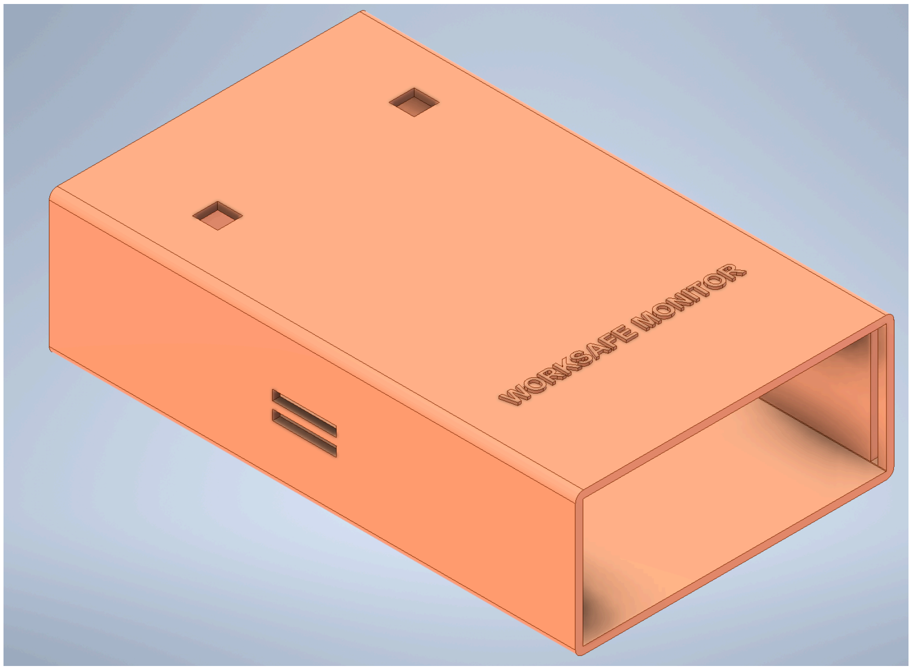


Figure 26. WorkSafe Monitor Casing Design

The final aspect of the design was how the sensors inside would interact with the outside world. Both the Hazardous Gas and Particulate Matter Sensors need to draw in "air" and consequently cannot function properly without airflow. Because the Hazardous Gas sensor is relatively light and small, it was decided to mount it to the top of the casing with a through hole for ventilation. Due to the bulkiness of the Particulate Matter sensor, it was mounted to the top of the NI MyRio, and smaller vent holes were drilled into the casing. The same method of mount for the Hazardous Gas sensor was used for the microphone. This was determined so internal noise from the device would not affect the microphone as well as so the microphone could have the clearest sound quality as possible. The vent holes for the Hazardous Gas sensor and the microphone were covered with a fabric mesh to reduce damage to the components. In addition to those sensors, the buzzer also needed to be fed through the casing, to maximize feeling, we wanted the buzzer to physically touch the wearer of the device. A throughhole that matches the dimension of the buzzer was printed on the back of the casing. Because the buzzer is flush with the casing, no mesh was added.

For ease of our production, we decided that 3d printing the casing would be most efficient. This choice allowed us to easily print and test multiple iterations of the casing. The material chosen for the print was Polylactic Acid or PLA. For future iterations, we would change the material to carbon fiber, this would increase the strength of the casing. The harness straps are made from polyester, with a breaking strength of 900 lbs and a working load limit of 300 lbs [5]. Each strap was equipped with a slide bar buckle. These are to provide adjustability for the strap length as well as keep the ends of strapping from coming loose from the casing. The design also utilized 3 side release buckles. The side release buckles connect the harness together and allow the device to be worn, as well as providing more adjustability in how long the harness can be and how the device can be worn.

Figure 27. Slide Bar Buckle [35] (Left) and Side Release Buckle [34] (Right)

Figure 28. Initial Harness on Casing (Left) and Strapping for Harness [33] (Right))

Engineering Tradeoffs

There were a few different engineering challenges and tradeoffs we had to navigate during the course of the project development, while still adhering to the main goals of the device and the project. One of the first and biggest trade-offs was choosing which microcontroller to pursue as the brain of the device. We cycled through testing with the Texas instruments MSP432 and the STM32 before finally deciding to use the National Instruments' myRIO[13][36]. This was chosen mainly because of the on board accelerometer and Wifi module that was provided by the myRio. This was an essential part of our project and having an accelerometer that was easy to access allowed the group to make great strides in fall detection early on in the process. Additionally, LabView being more of a graphical language allowed all team members to learn the language with more ease than expected. This allowed the WIFI module and post-request set up portion of the project to be developed early on. Although the myRio was the largest of our three options, it was the best choice for our project.

The sizing of the device was a big engineering trade off that had multiple considerations attached. Aside from the microcontroller, the battery was also a limiting factor when it came to size. The battery we chose was relatively bigger and heavier than some other options. However, this battery had the ease of plugging directly into our microcontroller and providing power, avoiding any extra or larger/more complex PCB design that would have to be created to account for surge protection. It also outputs 5.2Ah, which allows for a longer battery lifetime that would only have to be replaced once during a regular work shift. Another consideration to account for battery lifetime was the number of HTTP post requests that were sent. We choose a reduced number of HTTP post requests, which means data is being sent to the website less frequently which classifies our data tracking as near-real-time rather than real-time, in order to preserve the battery life so the myRio is not working at its maximum battery consumption of 14W.

When designing the casing, we went through five different iterations until we settled on the one with the smallest volume that fit everything we needed. Our fourth iteration was the smallest we had made that fit the PCB, sensors, battery, and microcontroller. However, it was still bigger than we anticipated. In order to make the best product possible, we were able to solder a new PCB with fewer loose connections and change the planned orientation of the battery to make a casing with the smallest volume. Although this did increase the length of the casing, the overall volume was the smallest because the height and width were reduced. Furthermore, we had multiple sensors that needed good airflow in order to give the best readings. This was definitely a big tradeoff between making our product weather-resistant and more robust and having the best airflow for our sensors. The conclusion we came to was that the hazardous gas sensor, the microphone, and the buzzer have small holes that allow them to stick out of the casing. The particulate matter sensor, although inside the casing, has access to air coming in from the holes of the device and is uncovered from the padding that surrounds the internal components.

Relating to internal components, the hazardous gas sensor was a large trade-off. Although it works for an educational project and larger manufacturing orders would minimize the price of a different sensor, the specific sensor we chose is not rated for safety purposes. This was due to budget constraints as other sensors that were rated for safety were more expensive and we could not justify spending that portion of our budget so early in the design process. Additionally, because our group finalized our PCB design later in the semester than intended in order to thoroughly test all components and design iterations, we only did one iteration of our PCB. This PCB is fully functional for our needs, but with more time we would have considered a different iteration that could improve the compressibility of the design.

Test Plans

The main features that required external calibration or testing were particulate matter, sound levels, fall detection, and hazardous gas. For our particulate matter sensor, because we bought a pre-calibrated sensor, the testing was the least intense. The way that the particulate matter sensor was tested was by connecting the sensor to the myRio, creating a LabView program to read the data from the sensor, send it to the website, and on the website end converting the hex byte data to usable data in accordance with the spec sheet. In order to get higher or lower levels of data of particulate matter we used a compressed air can and sprayed its contents within varying distances from the sensor. Through this testing regimen, we were able to get a variety of values that aligned with the calibration curve on the datasheet. We also correlated these values to the levels of danger as specified by OSHA.

Sound level detection was validated and calibrated in a series of steps. First, the raw microphone output was tested on a breadboard to ensure functionality. Then, an amplifier and a peak detector were designed, constructed, and tested on the breadboard using an AD2 and the Waveforms software. Once this design was finalized, the PCB was ordered and tested. In order to calibrate this data, we used two different decibel measuring devices to compare the readings to: one was an iPhone 14 Pro and the other device was an Apple Watch. The testing procedure involved playing a 1000 Hz tone and taking a snapshot of the decibel reading on the iPhone, Watch, and the voltage reading on LabView at the same time (Appendix Section E).This step was then repeated for varying volume levels of the tone. Appendix Section F. shows the data collected during calibration of the sensor. From the data acquired, the average was calculated for the decibel levels of the two measuring devices, and a final graph was created that mapped voltage levels to decibel levels. Figure 29 below shows this graph.

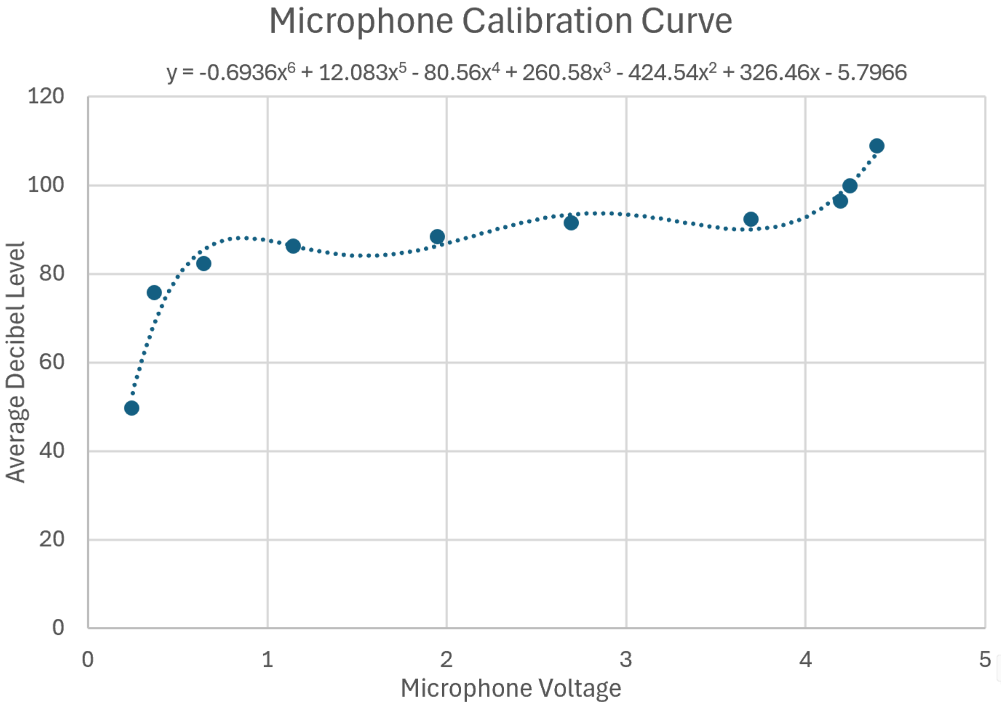


Figure 29. Microphone Calibration Curve

From this graph, a 6th-order polynomial trendline was calculated. This equation was then used to convert voltage levels directly in LabView to decibel levels so that the data could then be sent to the website. There was a bit of trial and error that occurred with different trendline equations, as a line of best fit, logarithmic, exponential, and varying order polynomial equations were tested but the best results aligned with the 6th order polynomial.

Once the best algorithm was integrated into our website from the real-time accelerometer data provided by the myRIO was designed, the fall detection testing plan was created. This involved producing a series of different simulated falls with the myRio and battery tightly packaged together and held at the test user’s chest with the data being sent to the website. The following figure shows the types of tests conducted to determine accuracy of the fall detection algorithm.

Dropping:
- Fall straight down from 5 ft and still after for 5 seconds
- Fall straight down from 5 ft and resume upward motion within 5 seconds

Forward Motion:
- Walking straight with device on chest for 20 ft
- Jogging straight with device on chest for 20 ft
- Walking 20 ft and then fall from 5 ft
- Jogging 20 ft and then fall from 5 ft

Fast Movement:
- Jumping up and down 2 times with device on chest then walk
- Still sitting on ledge then falling off

Figure 30. Fall Detection Tests Conducted

The main simulated falls included dropping, forward motion, and fast movement, with at least three trials for all tests. For dropping, we included tests for falling straight down from five feet and staying still (simulated a real fall) and tests for falling straight down from five feet and resuming upward motion for five seconds (simulating no fall). For forward motion, our tests involved walking forward with the device at chest level for 20 ft (no fall), jogging straight for 20 ft (no fall), walking 20 ft and then falling for 5 ft (simulated fall), and then jogging 20 ft and falling for 5 ft (simulated fall). For fast movement, we included jumping up and down two times with a device on the chest and then walking (no fall), and then sitting still on a ledge and falling down (simulated fall). In total there were 30 trials conducted with an accuracy of 80%. Throughout the testing sequence, some small changes were made on the coding end to alter sensitivity.

Finally, hazardous gas was the most rigorous and plan-intensive testing process. Because the sensor was not pre-calibrated we had to use carbon monoxide to calibrate and test the device as a group. When the sensor was first delivered, in order to validate that it worked we monitored its voltage levels in LabView when compressed air was sprayed on it at varying distances. For the calibration process, we were able to obtain carbon monoxide for bump tests as well as a confined space monitor that specifically read PPM of carbon monoxide. We put the hazardous gas sensor, the confined space monitor, and a plastic tube that connected to the carbon monoxide tank in a sealed plastic bag. We initialized the hazardous gas sensor to begin taking data and slowly released the carbon monoxide into the bag where the confined space monitor and the hazardous gas sensor were. The confined space monitor took the surrounding air and constantly displayed on the screen the level of carbon monoxide present, in PPM. Once we were able to get the carbon monoxide concentration in the bag up to 60 ppm, which was the calibrated amount we had in the tank, we shut off the flow of carbon monoxide and let it dissipate. When doing this, we used a camera with a time stamp to record the carbon monoxide detector readings and saved the hazardous gas readings with a timestamp to the database. This data can be found in Appendix G. The data from both the video and database was then sampled every 5 seconds and mapped to one another. This allowed us to create a calibration curve that was then used to map the voltage levels of the sensor to carbon monoxide PPM. Figure 31 below shows the data for the hazardous gas calibration curve and the line of best fit matched to it.

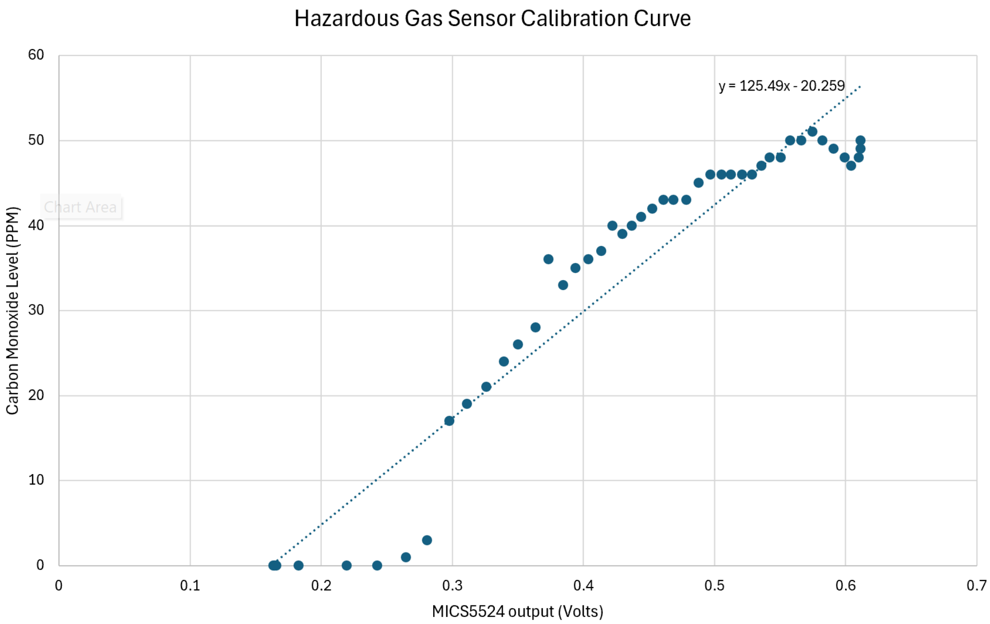


Figure 31. Hazardous Gas Calibration Curve for Carbon Monoxide

One of the issues encountered in calibrating the hazardous gas sensor was that the confined space monitor reading jumped between values every few seconds, which resulted in some choppy data. Initially, the values on the confined space monitor did not change until a concentration of around 17 ppm was reached. In the future, a highly accurate ppm reading would be needed to accomplish a significant calibration curve, and ideally, the data could be automatically exported to a database with timestamps.

After all the sensors were calibrated and tested separately, they were tested on the PCB with the myRio, ensuring that all data was able to be sent at the same time with all sensors running. We also provoked certain events like falling or hazardous gas using compressed air to ensure the hazardous events were logged on the website. We also released enough compressed air toward the hazardous gas sensor to make the buzzer alert the user that dangerous levels are present.

Website testing began with unit tests, where each feature was strictly checked before starting development on the next. After all desired features were implemented, the team proceeded to do integration testing. The main functionalities tested included consistent and accurate data storage in the database, processing, and presentation on the user interface. Alert testing was also important; the system needed to reliably trigger alerts and log data in the history database whenever hazardous event thresholds were met. Testing was closely intertwined with the development process. For each sensor, separate Python functions simulated data transmission when the myRIO was being worked on or sensors were unavailable. These functions generated "fake falls," and fabricated data for hazardous gasses, particulate matter, and noise levels, ensuring the data appeared in near real-time and simulated what would actually be sent by the microcontroller. Any errors were quickly fixed using common debugging methods.

The integration testing of the whole system was completed in three stages. First was the integration of the microcontroller and the website, since WiFi was verified and set up early on. Then the PCB was tested with the microcontroller, once the PCB was ordered and delivered. Finally, all three were tested together. Figure 32 below shows the order and overview of this testing.

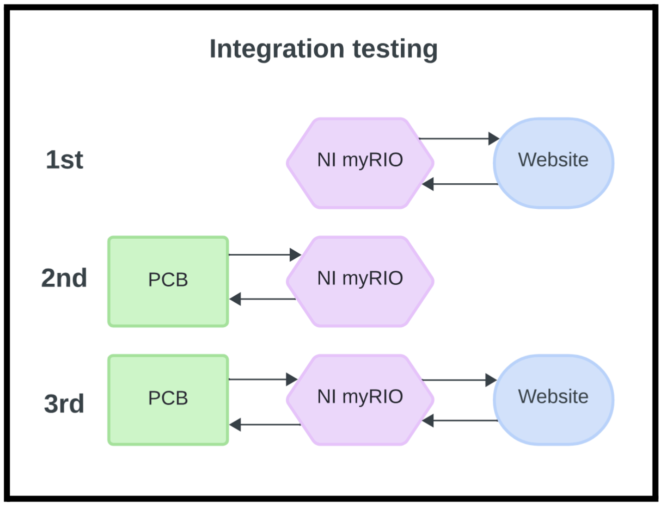


Figure 32. Integration Testing Flowchart

In the final phase of integration testing, the myRIO was connected to all its sensors and the PCB, verifying that data transmission occurred as necessary. Website testing focused on the user interface, with the team checking that plots were correctly generated and appropriate warnings were displayed. In addition, the website was designed to handle user inputs well; all buttons, clicks, and unusual inputs were tested to ensure no unexpected behaviors happened. While unit tests initially revealed several bugs, these were immediately addressed. Integration testing was also successful with no software errors detected at the end.

Timeline

Outlined below are two Gantt charts, the first one is from the project proposal (Figure 33), and the second one (Figure 34) is what timeline actually occurred. For the most part, our general timeline stayed the same. However, there were a few differences. These include: pushing back the PCB testing, lengthening the amount of time to synthesize the sensor-embedded code, and shortening the amount of time used on wireless capability, the final assembly time was pushed back marginally as well. We also added sections for research and the video demo and report. Most of these changes were due to slight setbacks that occurred during the semester. For example, we took longer to design our PCB, which in turn pushed back PCB testing, integration of everything, and final assembly. The sensor-embedded code took longer to write because we were learning how to utilize the program while writing the code. Because we decided to use the NI MyRio, which has an embedded wireless module, the time it took to calibrate it was reduced. Because of the setbacks with the PCB, the sensor-embedded code, and the device casing, the final assembly was pushed back.

Setbacks that lengthed our timeline are listed below:

- Shipping delays for electrical components pushed back the testing of the amplifier and subsequently, the ordering of the PCB
- Learning a new programming language
- Printing the casing multiple times due to mismeasurement and lack of spacing efficiency when putting the inside components together
- Not initially planning for the final report and video demo

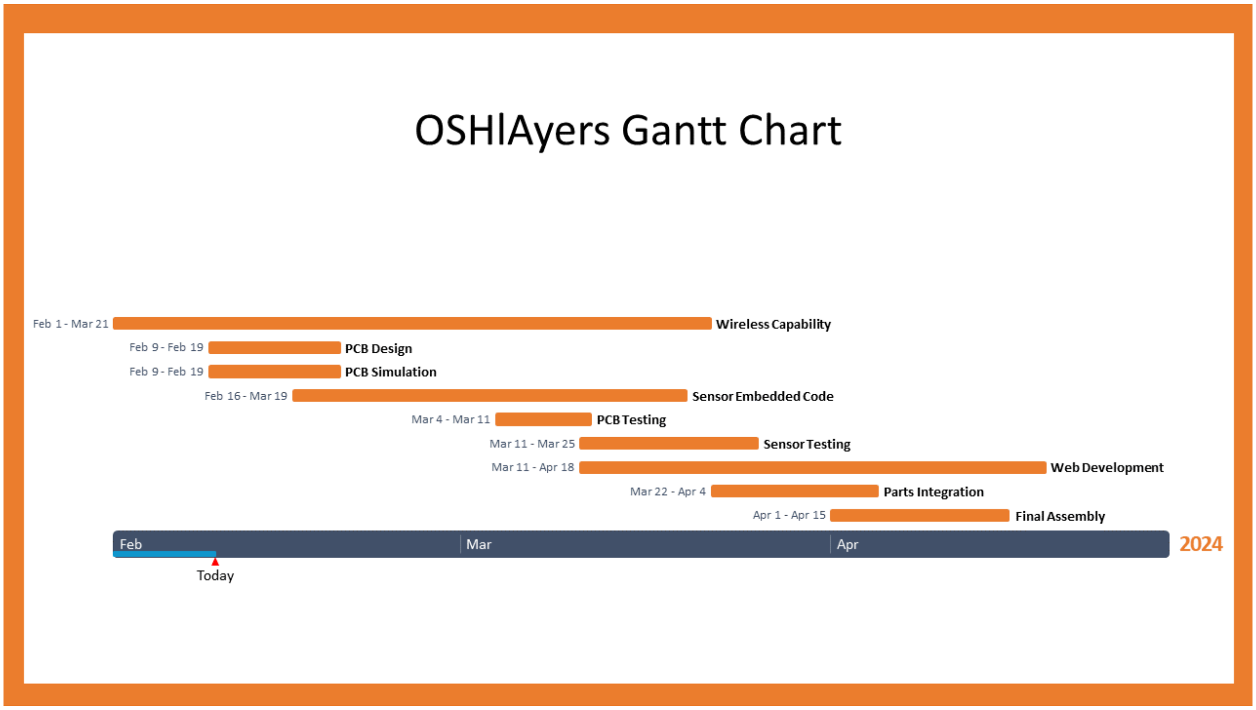
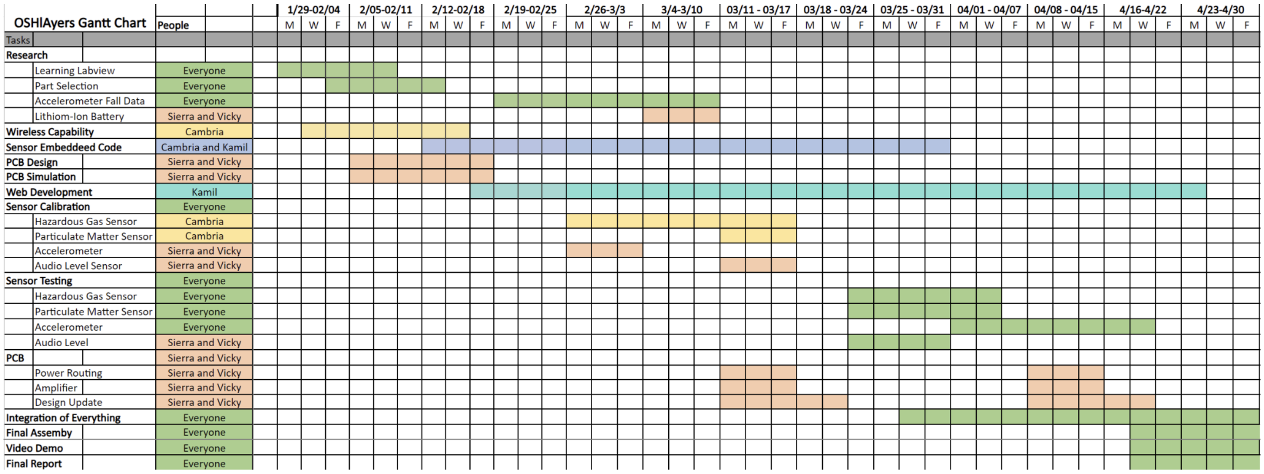


Figure 33. OSHlAyers Original Gantt Chart from Project Proposal



OSHlAyers Gantt Chart	People		1/29-02/04			2/05-02/11			2/12-02/18			2/19-02/25			2/26-3/3			3/4-3/10			03/11 - 03/17			03/18 - 03/24			03/25 - 03/31			04/01 - 04/07			04/08 - 04/15			4/16-4/22			4/23-4/30		
			M	W	F	M	W	F	M	W	F	M	W	F	M	W	F	M	W	F	M	W	F	M	W	F	M	W	F	M	W	F	M	W	F	M	W	F	M	W	F
Tasks																																									
Research																																									
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Lithiom-Ion Battery	Sierra and Vicky																	🟧	🟧	🟧																					
Wireless Capability	Cambria			🟨	🟨	🟨	🟨	🟨	🟨	🟨																															
Sensor Embeddeed Code	Cambria and Kamil								🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦												
PCB Design	Sierra and Vicky					🟧	🟧	🟧	🟧	🟧	🟧																														
PCB Simulation	Sierra and Vicky					🟧	🟧	🟧	🟧	🟧	🟧																														
Web Development	Kamil										🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦		
Sensor Calibration	Everyone																																								
Hazardous Gas Sensor	Cambria														🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨																		
Particulate Matter Sensor	Cambria																				🟨	🟨	🟨																		
Accelerometer	Sierra and Vicky														🟧	🟧	🟧																								
Audio Level Sensor	Sierra and Vicky																				🟧	🟧	🟧																		
Sensor Testing	Everyone																																								
Hazardous Gas Sensor	Everyone																									🟩	🟩	🟩	🟩	🟩	🟩										
Particulate Matter Sensor	Everyone																									🟩	🟩	🟩	🟩	🟩	🟩										
Accelerometer	Everyone																													🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩				
Audio Level	Sierra and Vicky																									🟩	🟩	🟩	🟩												
PCB	Sierra and Vicky																																								
Power Routing	Sierra and Vicky																				🟧	🟧	🟧										🟧	🟧	🟧						
Amplifier	Sierra and Vicky																				🟧	🟧	🟧										🟧	🟧	🟧						
Design Update	Sierra and Vicky																				🟧	🟧	🟧	🟧	🟧								🟧	🟧	🟧	🟧	🟧				
Integration of Everything	Everyone																											🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Final Assemby	Everyone																																				🟩	🟩	🟩	🟩	🟩
Video Demo	Everyone																																				🟩	🟩	🟩	🟩	🟩
Final Report	Everyone																																				🟩	🟩	🟩	🟩	🟩

Figure 34. OSHlAyers Final Gantt Chart for Final Report

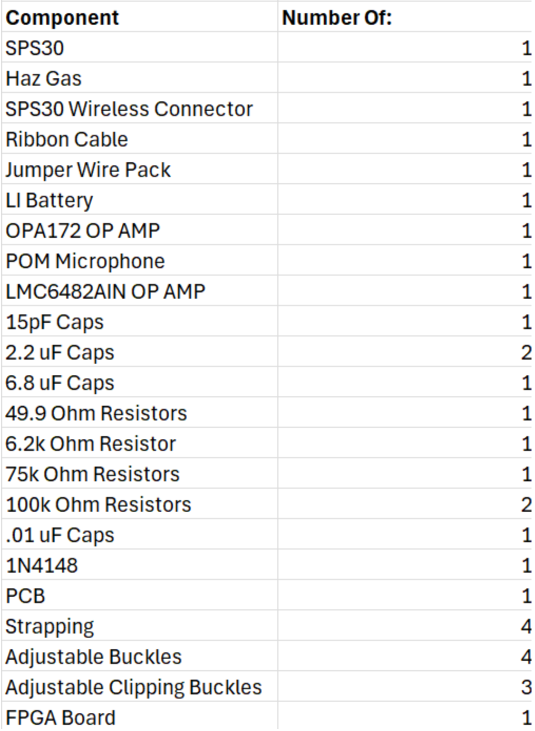
The left side column describes tasks to be completed, as well as subtasks, and who was responsible for completing those tasks. Each grouping of people are assigned a specific color code (i.e. everyone is green). The timeline is divided into the weeks of the semester, three blocks for each week.

Costs

Out of the $500.00 dollars provided to us, we utilized $177.50. A cost breakdown is listed below, and a more detailed one can be found in Appendix Section B:

Sensors	$56.12
Connectors	$24.22
Battery	$32.99
Electrical Components	$23.87
PCB	$10.32
Hardware	$29.98

Although we utilized that amount of our budget, the consumer's price would most likely reflect differently. We didn't use all of the components we purchased and the microcontroller was never considered in our project costs. A list of all of the components utilized in the final product is shown in the figure below. Using bulk prices from Digikey and Mouser, as well as an estimation for a specialized microcontroller, a high volume unit cost was determined. In total, the cost to produce 10,000 units would be $2,104,811.85 at $210.48 per unit. A cost breakdown of the high-volume production can be found in Appendix Section C. If we were to produce the WorkSafe Monitor in bulk, the PCB would more than likely not be assembled by hand, it would most likely be wave-soldered during the manufacturing process, increasing the price.



Component	Number Of:
SPS30	1
Haz Gas	1
SPS30 Wireless Connector	1
Ribbon Cable	1
Jumper Wire Pack	1
LI Battery	1
OPA172 OP AMP	1
POM Microphone	1
LMC6482AIN OP AMP	1
15pF Caps	1
2.2 uF Caps	2
6.8 uF Caps	1
49.9 Ohm Resistors	1
6.2k Ohm Resistor	1
75k Ohm Resistors	1
100k Ohm Resistors	2
.01 uF Caps	1
1N4148	1
PCB	1
Strapping	4
Adjustable Buckles	4
Adjustable Clipping Buckles	3
FPGA Board	1

Figure 35. List of Components Used in Final Device

Final Results

At the completion of the project term of 2 months and 2 weeks, the WorkSafe Monitor met all main objectives and performed to the initial expectations of the project proposal. The WorkSafe monitor successfully interfaces the NI myRIO microcontroller with a PCB and website. The microcontroller connects with the four intended sensing types of particulate matter, hazardous gas, noise levels, and fall detention via an accelerometer. All external sensors are powered by the myRIO port, which in turn the entire microcontroller is powered wirelessly with a rechargeable battery. The myRIO MXP ports connect directly via a ribbon cable to the PCB when the power routing, connections, and microphone are dealt with on-board. The entire system functions wirelessly in terms of power and data, as the sampled sensors' data is sent to the website via Wifi. Having the device remain wireless in both of these aspects was a major pillar of the initial proposal and goals of the device.

The device can remain wireless as long as the battery is charged and plugged into the myRIO in the casing of the device. A metric for battery life was not set in the initial proposal, but the goal was to have it be able to power the device for the period of a typical work shift in the construction or manufacturing sector, which could range from 10-12 hours. Unfortunately, the battery life of our prototype is not expected to last this long. This is due to the power consumption of the myRIO microcontroller. Given the choice, a more tailored microcontroller would consume less battery power.

The data transmission pipeline occurs between the myRIO and the website, which can be hosted on any computer or moved to a server for future project iterations. The LabView project deployed on the myRIO handles the initialization of the wireless connection to the website and sends data in JSON wirelessly. The website handles all data analysis and graphing/notifications. This is on par with the initial standard proposed of wireless data transmission for all sensors in near real-time. The website hosted an in-memory database where all relevant data is stored, which was the goal for data storage for this project. The website initially was going to be aimed towards both the worker wearing the device and the company purchasing them. The final product shifted slightly to mainly be aimed towards the needs of the customer, which is the company purchasing the device. Because of this, the website does not have separate logins for the company and the users, but just the pages that the company would be viewing. Regardless, the website was developed more in-depth than the initial proposal with constant tracking of data and history of alerts as well as real-time alerts for the company. These aspects support the goal of visibility and monitoring for the overall project.

The PCB was developed and resized before ordering the first iteration, so when the first order time came, the team was fairly confident with the design decisions and calculations. The PCB was ordered for 5 copies. After thorough testing of the PCB, it was decided that a second iteration was not needed. The PCB was as small as it could get with the necessary components and header for the myRIO MXP connections. After developing one of the PCB copies with all the necessary components but without the functioning ribbon cable, the team decided to solder another whole PCB with the remaining components to utilize the ribbon cable. Once this worked successfully, all PCB goals were accomplished with power routing, microphone components soldered, and utilization of the ribbon cable.

The casing and harnessing was one of the last components to be developed, as we wanted to be sure of the smallest size casing that could be printed given the size of the microcontroller and PCB with parts. Before the PCB with the ribbon cable was able to be used, a version of the casing was designed and 3D printed to be quite large. The device was pretty large at this point to be considered a wearable device. However, after the PCB was developed with the usage of the ribbon cable, the casing was redesigned to be as small as possible and helped with the team's goal of designing a wearable device. The harnessing mechanism proposed at the beginning of the project term was realized almost exactly as intended with adjustable, strong straps that connected to the bottom and sides of the casing that holds all the device components. The device was intended to be able to be worn in multiple locations around the body, but the team settled with the ideal location being on the chest, as the strap supports the device most in this location and it is protected against extra movements of the arms.

All in all, the final WorkSafe Monitor meets all of the expectations of the initial project proposal and satisfies the deliverables presented. Broadly, the device incorporates the microcontroller, designed PCB, and website into a fully functioning system physically encased in a custom, wearable 3D printed cover.

Future Work

One area for improvement includes upgrading the design to a more permanent assembly with higher-quality materials and additional PCB iterations. Considering the use of the FPGA on the myRIO, which was initially not chosen, could also improve integration with the WiFi module, resulting in increased organization.

To improve long-term capabilities, the website can be made compatible with multiple devices, with separate databases built for each device type. Upgrading the website to handle larger data streaming loads, improving security for logins and data access, and introducing a machine-learning-based fall detection algorithm (potentially using neural networks or non-linear classification) would be extremely beneficial as well. Hosting the website on a cloud computing platform like AWS or Microsoft Azure would finally assist with maintaining the software and making it more customizable.

The code could benefit from better organization. At the moment, many of the data processing functions and endpoints are merged into a single app.py file, which has become a lot to deal with towards the end of the semester. Using cleaner coding practices from the start would simplify debugging a lot. Additionally, taking advantage of a web development framework such as Django or Angular would help manage the complexity as the website scales, especially with additional pages and subpages.

The project also has major potential for growth in the number of detectable variables. Given the modular design of our system, adding more sensors to expand the device's functionality would make it more useful to employers. This expansion would require more extensive research, upgrades to the PCB, improvements to both LabView and the website, and a potentially larger casing for any additional components.

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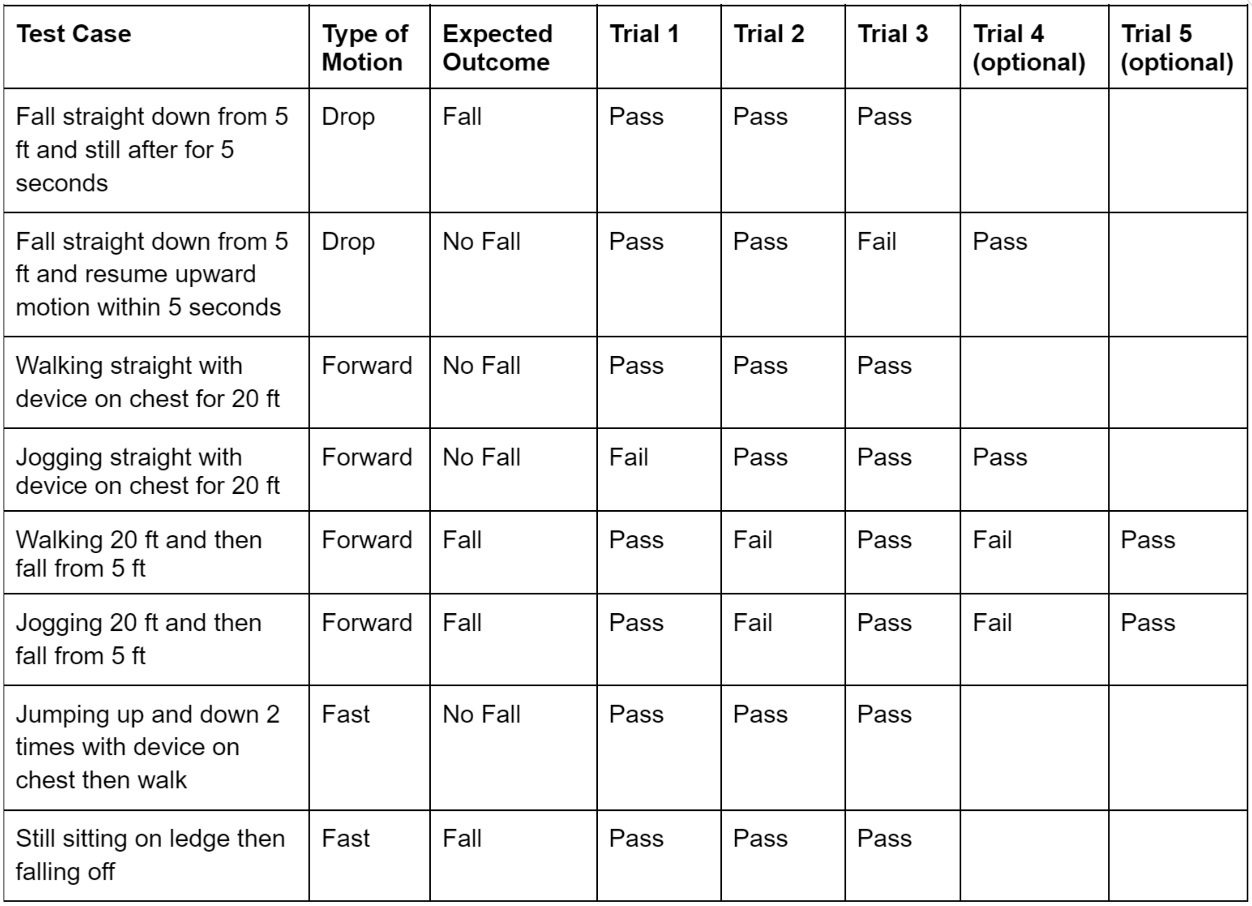
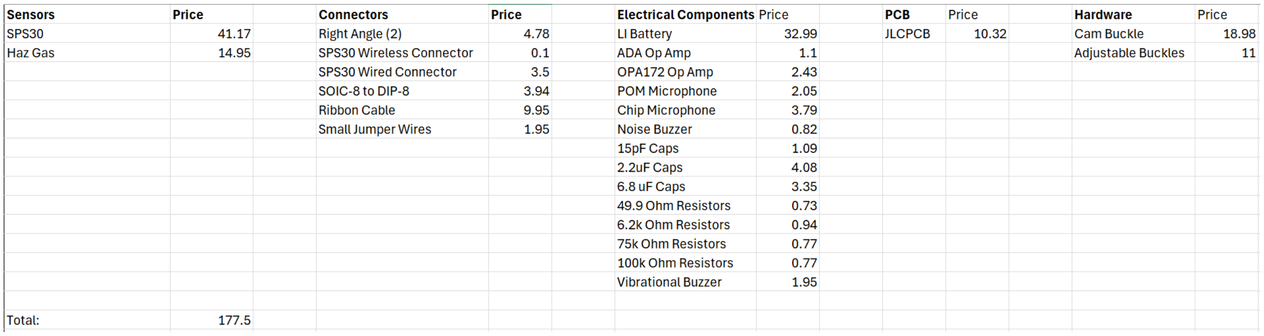
Appendix

A. Fall Detection Testing Results



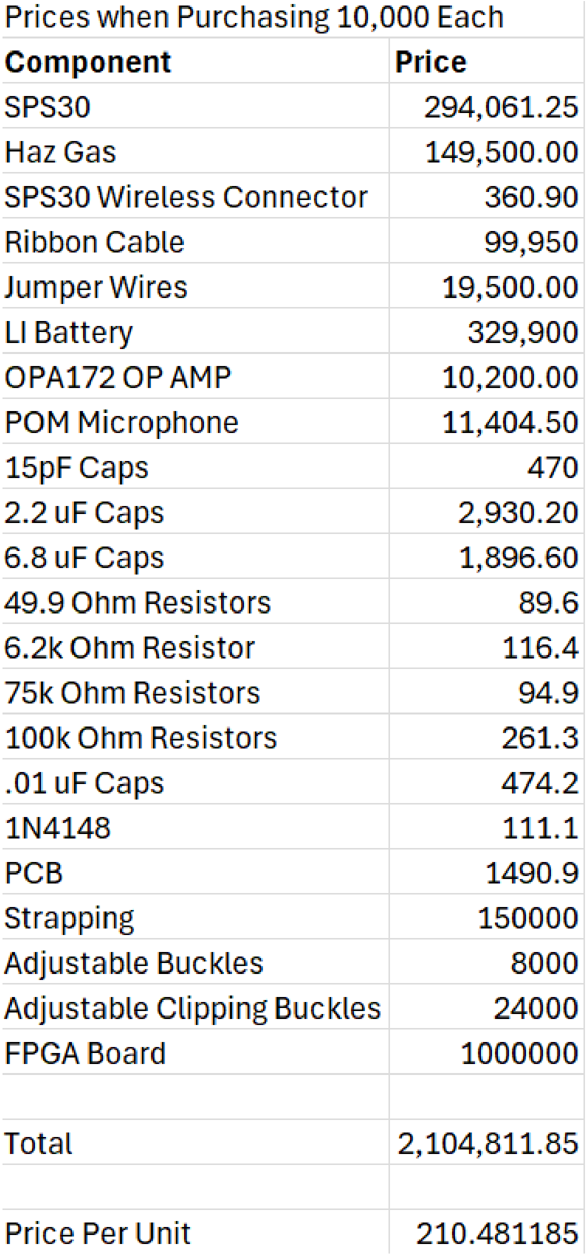
Test Case	Type of Motion	Expected Outcome	Trial 1	Trial 2	Trial 3	Trial 4 (optional)	Trial 5 (optional)
Fall straight down from 5 ft and still after for 5 seconds	Drop	Fall	Pass	Pass	Pass		
Fall straight down from 5 ft and resume upward motion within 5 seconds	Drop	No Fall	Pass	Pass	Fail	Pass	
Walking straight with device on chest for 20 ft	Forward	No Fall	Pass	Pass	Pass		
Jogging straight with device on chest for 20 ft	Forward	No Fall	Fail	Pass	Pass	Pass	
Walking 20 ft and then fall from 5 ft	Forward	Fall	Pass	Fail	Pass	Fail	Pass
Jogging 20 ft and then fall from 5 ft	Forward	Fall	Pass	Fail	Pass	Fail	Pass
Jumping up and down 2 times with device on chest then walk	Fast	No Fall	Pass	Pass	Pass		
Still sitting on ledge then falling off	Fast	Fall	Pass	Pass	Pass		

B. Cost Breakdown



Sensors	**Price**		**Connectors**	**Price**		**Electrical Components**	Price		**PCB**	Price		**Hardware**	Price
SPS30	41.17		Right Angle (2)	4.78		LI Battery	32.99		JLCPCB	10.32		Cam Buckle	18.98
Haz Gas	14.95		SPS30 Wireless Connector	0.1		ADA Op Amp	1.1					Adjustable Buckles	11
			SPS30 Wired Connector	3.5		OPA172 Op Amp	2.43						
			SOIC-8 to DIP-8	3.94		POM Microphone	2.05						
			Ribbon Cable	9.95		Chip Microphone	3.79						
			Small Jumper Wires	1.95		Noise Buzzer	0.82						
						15pF Caps	1.09						
						2.2uF Caps	4.08						
						6.8 uF Caps	3.35						
						49.9 Ohm Resistors	0.73						
						6.2k Ohm Resistors	0.94						
						75k Ohm Resistors	0.77						
						100k Ohm Resistors	0.77						
						Vibrational Buzzer	1.95						
Total:	177.5												

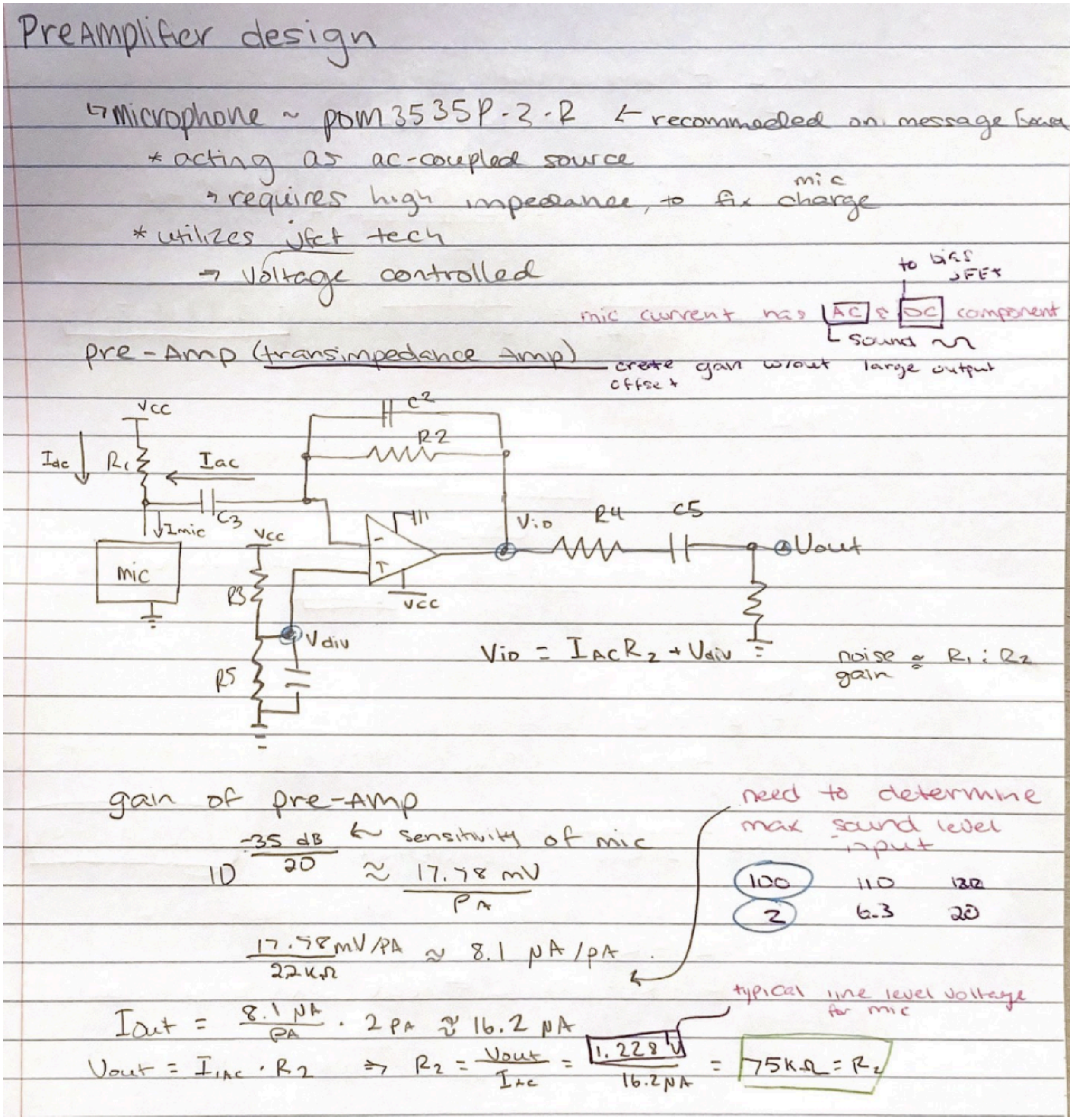
C. Mass Production Cost Breakdown



Prices when Purchasing 10,000 Each

Component	Price
SPS30	294,061.25
Haz Gas	149,500.00
SPS30 Wireless Connector	360.90
Ribbon Cable	99,950
Jumper Wires	19,500.00
LI Battery	329,900
OPA172 OP AMP	10,200.00
POM Microphone	11,404.50
15pF Caps	470
2.2 uF Caps	2,930.20
6.8 uF Caps	1,896.60
49.9 Ohm Resistors	89.6
6.2k Ohm Resistor	116.4
75k Ohm Resistors	94.9
100k Ohm Resistors	261.3
.01 uF Caps	474.2
1N4148	111.1
PCB	1490.9
Strapping	150000
Adjustable Buckles	8000
Adjustable Clipping Buckles	24000
FPGA Board	1000000
Total	2,104,811.85
Price Per Unit	210.481185

D. Full Calculations for the Pre-Amplifier Design



Preamplifier design

↳ Microphone ~ pom3535P-3-R ← recommended on message

* acting as ac-coupled source

→ requires high impedance, to fix mic charge

* utilizes jfet tech

→ voltage controlled

mic current has AC & DC component

└ sound ∿ (AC) · to bias JFET (DC)

pre-Amp (transimpedance amp) — create gain w/out large output offset

$V_{IO} = I_{AC}R_2 + V_{div}$

noise ≈ gain ≈ R1 : R2

gain of pre-Amp

$10^{\frac{-35\text{ dB}}{20}} \approx \frac{17.78\text{ mV}}{PA}$ ← sensitivity of mic

$\frac{17.78\text{mV}/PA}{22\text{k}\Omega} \approx 8.1\ \mu A/pA$

need to determine max sound level input

100	110	120
2	6.3	20

$I_{out} = \frac{8.1\ \mu A}{PA} \cdot 2\ PA \approx 16.2\ \mu A$

$V_{out} = I_{AC} \cdot R_2 \Rightarrow R_2 = \frac{V_{out}}{I_{AC}} = \frac{\boxed{1.228\text{ V}}}{16.2\ \mu A} = \boxed{75\text{k}\Omega = R_2}$

typical line level voltage for mic

~ C_2 t compensates for parasitic capacitance

→ forms a pole w/ R_2

→ use relative gain of 20 kHz

$$f_p = \frac{f}{\sqrt{\left(\frac{G_{10}}{G_{1f}}\right) - 1}} = \frac{20\,\text{kHz}}{\sqrt{\left(\frac{1}{.989}\right)^2 - 1}} = 133725\ \text{Hz}$$

$$C_2 = \frac{1}{2\pi f_p R_2} = \frac{1}{2\pi(133725)(75\,\text{k}\Omega)} \boxed{= 15.87\,\text{pF} = C_2}$$

~ R_1 t controls bias of mic

$$R_1 = \frac{\boxed{V_{cc}} - \boxed{V_{Mic}}}{\boxed{I_s}}$$

desired supply

operating voltage

current consumption of mic

$$R_1 = \frac{9\text{v} - 2\text{v}}{.5\,\text{mA}} = \boxed{14\,\text{k}\Omega}$$

– might need to account for supply var.

~ C_3

→ R_1 & C_3 form High pass filter

→ cutoff (5 Hz?) don't want to attenuate low frequency sound waves

$$C_3 = \frac{1}{2\pi R_1 f_c} = \frac{1}{2\pi(13.7\,\text{k}\Omega)(5\,\text{Hz})} = \boxed{2.32\,\mu\text{F} = C_3}$$

~ R_3 & R_5 ~ Op Amp Bias Network

$R_3 = R_5$ & $V_{div} = V_{cc}/2$

$R_3 = R_5 = 100\,\text{k}\Omega$ ← need limit power supply current

$$I_{div} = \frac{V_{cc}}{R_3 + R_5} = \frac{9\text{V}}{200\,\text{k}\Omega} = 45\,\mu\text{A}$$

C_6 ~ filter noise from supplies

$C_6 = 2.2\ \mu F$ ← not ness

~ low pass filter formed by R_3, R_5, C_6

$$f_c = \frac{1}{2\pi (R_3 || R_5) C_6} = 1.447\ Hz$$

R_4 ~ limiting current capacitor

$R_4 = 50\ \Omega$ ← arbitrary number

C_5 ~ R_6 & C_5 form High pass filter

$$f_c = f\sqrt{\left(\frac{G_0}{G_F}\right)^2 - 1} = 20\sqrt{\left(\frac{1}{.944}\right)^2 - 1} = 6.986\ Hz$$

$$C_5 = \frac{1}{2\pi f_c (R_6 || R_{in})} = \frac{1}{2\pi (6.9\ Hz)(10\ k\Omega)} \boxed{= 2.278\ \mu F = C_5}$$

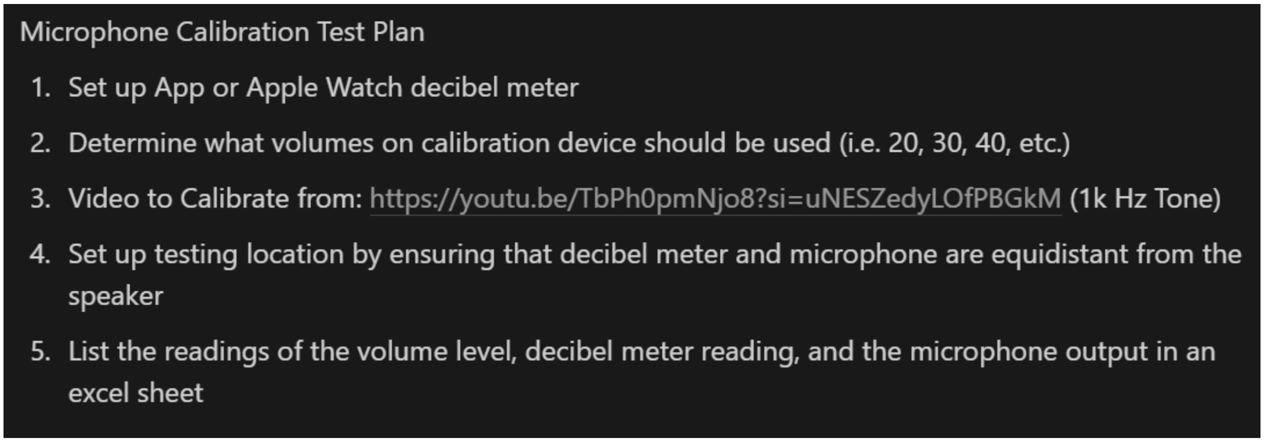
Op Amp ?

max supply Voltage > 9V

supply current < 2.5 mA

OPA 140 [✓ OPA 172] OPA170

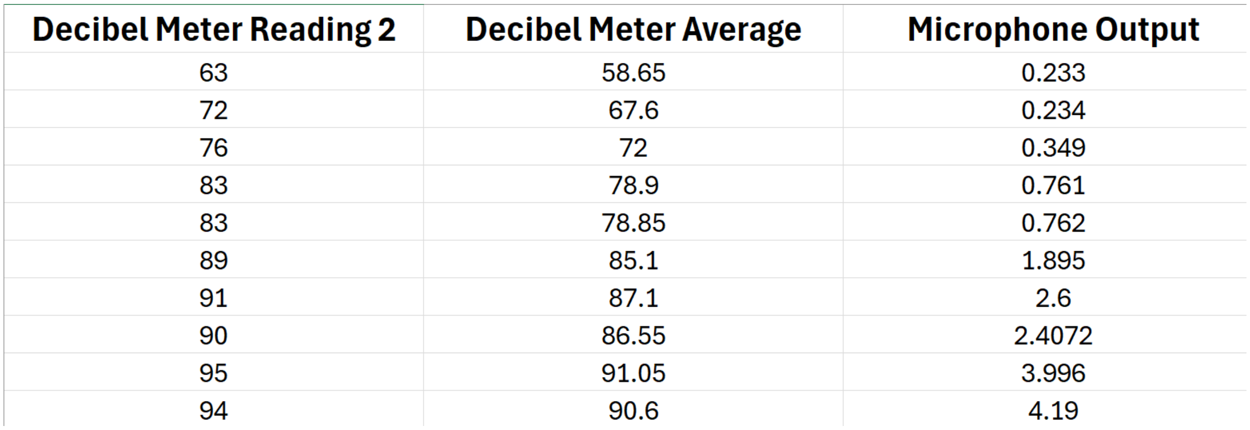
E. Microphone Calibration Test Plan



Microphone Calibration Test Plan

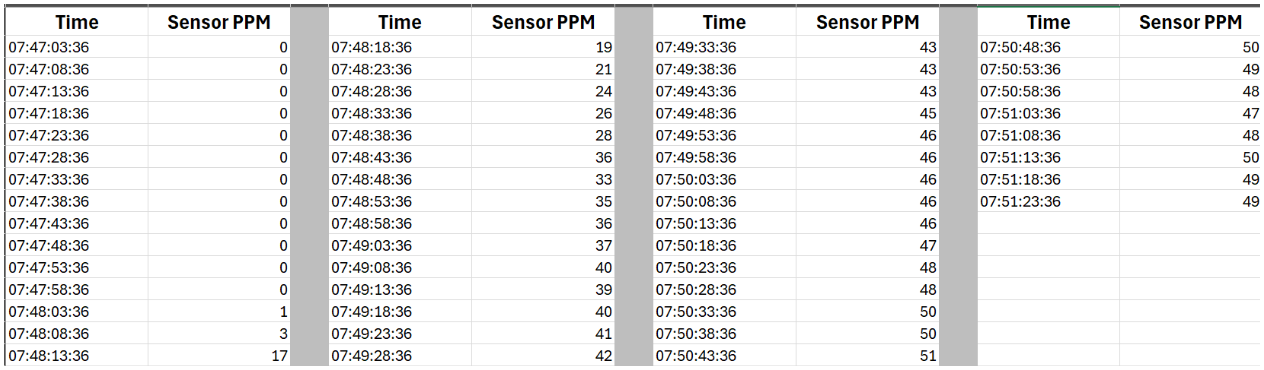
1. Set up App or Apple Watch decibel meter
2. Determine what volumes on calibration device should be used (i.e. 20, 30, 40, etc.)
3. Video to Calibrate from: https://youtu.be/TbPh0pmNjo8?si=uNESZedyLOfPBGkM (1k Hz Tone)
4. Set up testing location by ensuring that decibel meter and microphone are equidistant from the speaker
5. List the readings of the volume level, decibel meter reading, and the microphone output in an excel sheet

F. Decibel Level and Voltage Output Data Collected During Microphone Calibration



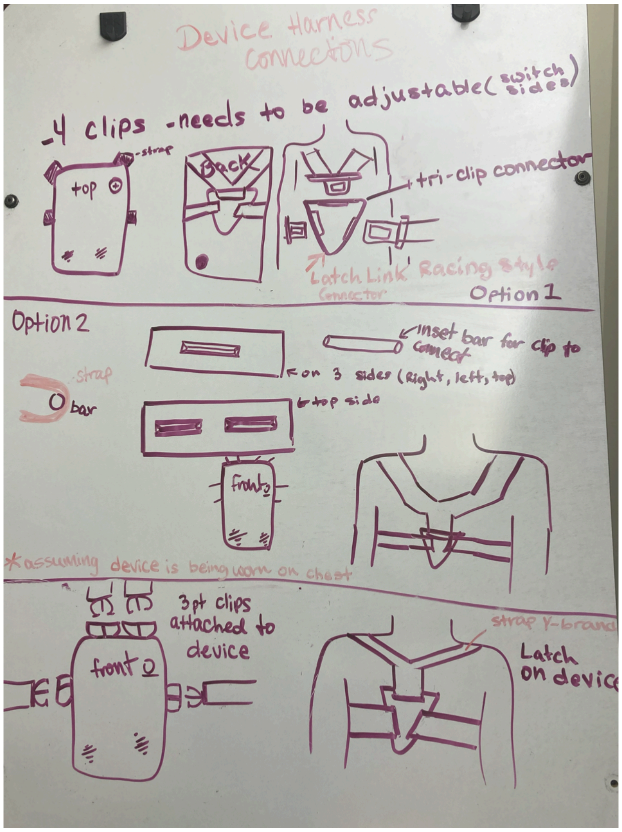
Decibel Meter Reading 2	Decibel Meter Average	Microphone Output
63	58.65	0.233
72	67.6	0.234
76	72	0.349
83	78.9	0.761
83	78.85	0.762
89	85.1	1.895
91	87.1	2.6
90	86.55	2.4072
95	91.05	3.996
94	90.6	4.19

G. Gas Concentration Data Collected from the Altair 4RX during the Hazardous Gas Calibration



Time	Sensor PPM	Time	Sensor PPM	Time	Sensor PPM	Time	Sensor PPM
07:47:03:36	0	07:48:18:36	19	07:49:33:36	43	07:50:48:36	50
07:47:08:36	0	07:48:23:36	21	07:49:38:36	43	07:50:53:36	49
07:47:13:36	0	07:48:28:36	24	07:49:43:36	43	07:50:58:36	48
07:47:18:36	0	07:48:33:36	26	07:49:48:36	45	07:51:03:36	47
07:47:23:36	0	07:48:38:36	28	07:49:53:36	46	07:51:08:36	48
07:47:28:36	0	07:48:43:36	36	07:49:58:36	46	07:51:13:36	50
07:47:33:36	0	07:48:48:36	33	07:50:03:36	46	07:51:18:36	49
07:47:38:36	0	07:48:53:36	35	07:50:08:36	46	07:51:23:36	49
07:47:43:36	0	07:48:58:36	36	07:50:13:36	46		
07:47:48:36	0	07:49:03:36	37	07:50:18:36	47		
07:47:53:36	0	07:49:08:36	40	07:50:23:36	48		
07:47:58:36	0	07:49:13:36	39	07:50:28:36	48		
07:48:03:36	1	07:49:18:36	40	07:50:33:36	50		
07:48:08:36	3	07:49:23:36	41	07:50:38:36	50		
07:48:13:36	17	07:49:28:36	42	07:50:43:36	51		

H. Alternative Harness and Strapping



I. Initial testing of the Peak Detector