Team: AIR WEAR

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Statement of Disclaimer

Since this project is a result of a class assignment, it has been graded and accepted as fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is done at the risk of the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.

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Executive Summary

Since the outbreak of COVID-19 pandemic, hospitals have experienced an overwhelming increase in patients needing respiratory assistance. Our client identified the need for a sustainable, affordable, and portable outpatient device that will provide supplemental oxygen and assisted breathing to speed up the patient recovery process. Our team accomplished to design a device that contains a more sustainable oxygen supply method, has a longer functional duration, is safer and ergonomic, as well as compact.

Introduction

Air Wear is a team of three Cal Poly engineering students, undertaking an interdisciplinary senior project. The mission of Air Wear is to improve/redesign an existing prototype of a portable oxygen assisting breathing device. Potential improvements include implementing a more sustainable oxygen delivery method with a universally accessible design. The purpose of this device is to provide supplemental oxygen to patients with respiratory problems for use while at rest or under exertion.

The main stakeholder of this project is Rich Murray (also known as Client M), who is an electrical engineering professor at California Polytechnic State University, SLO. If the project succeeds, Client M will patent it and will take actions to put the product in the market. With this in mind, all intellectual property generated by this project belongs to Client M. The money received from the Hannah Forbes grant and the Baker-Koobs grant will be used to purchase the necessary materials needed for the project. The health industry is also a potential stakeholder in this project as the end goal for this device is to supply patients with oxygen aid either through medical companies and/or hospitals. There are no health industry clients to report to, however this may change with further progression and development of the project. Only Client M and the engineering department will be updated on the progress of the oxygen aiding device.

Background

In the past year and a half, hospitals have experienced an overwhelming increase in patients needing respiratory assistance due to the COVID-19 pandemic. In the week of August 31 to September 7, hospitals in Washington reported a 34% increase in the number of patients needing ventilation (Miller, 2021). While COVID is not the only disease that causes symptoms with these requirements, it currently is the most prevalent one.

Client M identified the need for an affordable, sustainable, and portable oxygen assisting device that can be used as an outpatient product. In the previous year, Cal Poly students completing their capstone/senior project took on the challenge and investigated ways to address this unmet need. Their team was titled O2+. Team O2+ designed a portable oxygen aid device that resembles a ventilator. This project's documentation and lab prototype has since been obtained by team Air Wear (Figure 1).

Figure 1. Team O2+ Oxygen Aid Device

Prior to coming up with a solution, our team researched previous work and literature to develop our understanding of the conditions prevalent in patients needing oxygen assisted breathing devices. Respiratory illnesses can affect the oxygen saturation in a patient when the symptoms of these illnesses make it difficult to breathe. Medical professionals typically prescribe oxygen assistance when a patient's blood oxygen saturation (SpO2) drops below 90%. *Respiratory Support for Adult Patients with COVID-19,* an article published in the Journal of the American College of Emergency Medicine, states that the "goal of treatment should be maintenance of oxygen saturation >90% … [or] 92%–95% for pregnant women." (Atwood et al., 2020) The study investigated non-invasive options to avert mechanical ventilation and ICU admission.

Our team looked at two possible treatments that align with our project concept: Low Flow oxygen therapy and High Flow oxygen therapy, both delivered through a nasal cannula. Low flow oxygen therapy is usually prescribed when a patient has an SpO2 < 90% with mild-to-moderately increased work of breathing. Humidified oxygen flows through a nasal cannula at a rate of up to 5 liters per minute (Lpm) or 6Lpm (Atwood et al., 2020). Most outpatient oxygen concentrators, such as the Inogen One G4, pictured as Figure 3 below.

If a patient does not improve with low flow oxygen therapy or displays increasing work of breathing, doctors can prescribe high flow oxygen therapy. Humidified oxygen flows through a nasal cannula at a rate of up to 60 Lpm. This treatment is done in a negative pressure room when possible. Because of the increase in oxygen rate, the authors of the article referenced above suggest frequent monitoring of the patient (every 30 minutes for the first hour of treatment and hourly after). The following image pictures a high flow nasal oxygen delivery system. A high flow nasal oxygen system is pictured as Figure 2 below.

Specifications taken into consideration from the design of team O2+ included functions such as having a high flow rate. With the flow rate and the nasal cannula, the device functions as a high flow nasal cannula (HFNC) oxygen therapy. The basic components of HFNC used in hospitals are shown below (Figure 2). The humidifier and the heated circuit are used to make the patient more comfortable and safer due to the high flow rate. The setback in the device created by team O2+ is that it is not portable for a significantly long period of time due the use of an oxygen tank as its primary source of oxygen. More information on the HFNC oxygen therapy is discussed in the article, *Respiratory Support for Adult Patients with COVID-19* as cited above.

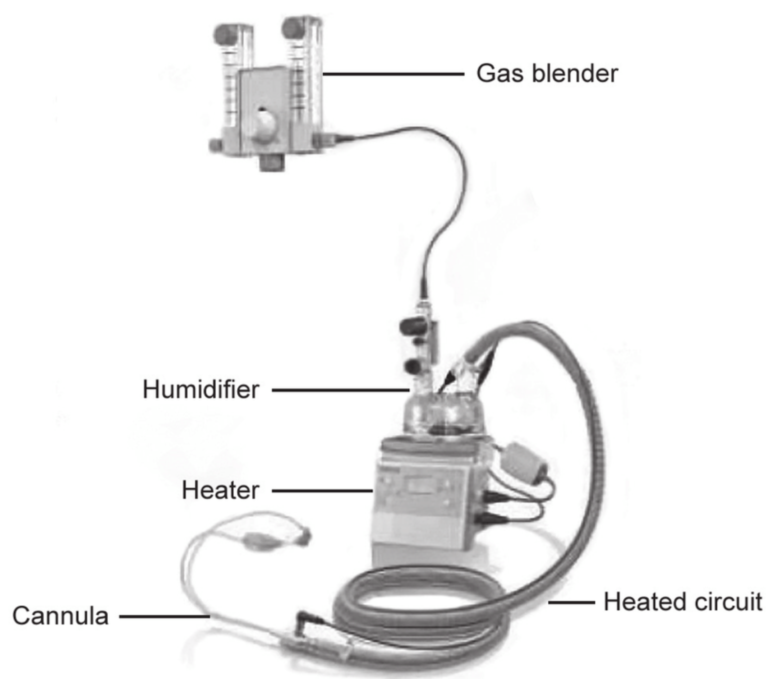


Figure 2. Basic Elements of a HFNC Oxygen Aid Device

There are few portable oxygen concentrators in the market, however they incorporate a low flow nasal cannula (LFNC) oxygen aiding system in their device. A popular oxygen concentrator is the Inogen One G4, shown below (Figure 3). This concentrator has a weight of 3.3 lbs and a battery life of up to 5 hours, so it is portable and travel friendly as long as it can be plugged in at low charge. It has three flow settings, with the lowest at 0.210Lpm and the highest at 0.630Lpm. The device works by taking in air, compressing it, and sending it through an absorption system which filters out oxygen rich air. Oxygen depleted air is pressurized back to atmospheric pressure and oxygen rich air is sent through a nasal cannula to the patient (Labuda, M. J. et al., 2004).

Figure 3. Inogen One G4 (Portable Oxygen Concentrator)

The oxygen aid device for outpatient care with the highest oxygen flow rate of 10 LPM is called the Drive DeVilbiss 10L Oxygen Concentrator and is shown (Figure 4). A disadvantage of this device is that it needs to be plugged into the wall in order to remain operational. This device does not satisfy the need for portability. Details of the product can be found on the Drive DeVilbiss website.

Figure 4. Drive DeVilbiss 10L Oxygen Concentrator

The existing prototype was created by team O2+ and is shown (Figure 1 above). More information can be found in the team's final report, *Portable Ventilator*.

The specifications of O2+ team's device are:

- Weighs less than 10 pounds
- Can be worn as a bag,
- Has an oxygen flow rate of 40 LPM
- Can supply oxygenated air with 21%-100% concentration
- The air is warm (31-37°C) and humidified (up to 100%)
- Portable for 3 minutes (on low settings)
- Can communicate with an apple watch to display the oxygen settings

The product is functional but there are several drawbacks such as:

- The oxygen is supplied from an oxygen tank
    - The oxygen tank is hazardous because it's pressurized oxygen that can explode if not handled with care
    - The tank needs to be replaced often due to its size, so it's not exactly portable (it's only portable for 3 minutes on low settings)
- All the hardware is exposed, which is intimidating to the user and can easily be damaged
- The device is incredibly uncomfortable to wear, with exposed zip ties and a rigid frame
- The device does not look aesthetically pleasing

The main problem of this device is the oxygen tank, because it is hazardous , heavy, needs to be replaced often, and easily runs out of oxygen. Due to the size of the oxygen tank and the high flow rate specified, the oxygen runs out very quickly, which is why it's only portable for 3 minutes. Replacing the oxygen tank with a more sustainable (for long term use, say several hours) solution is one of the main goals of this project and will be discussed in the Objectives section.

Objectives

For this project the sponsor and the end user are different and this distinction is important. Rich Murray wants this device to help both COVID-19 patients and patients with temporary respiratory illnesses. His requirements for the project are listed below and recorded in Table 1:

- Oxygen flow rate of 5-10 LPM
- High oxygen concentration (21% -100%)
- Weighs less than 10 lbs
- Wearable/portable for at least 1 hour
- Redesign the oxygen generation system into something more sustainable, so it doesn't need to be replaced often
- Modify the hardware to be compact

Our end user is:

- An adult (based on the medical definition)
- A patient with a temporary respiratory illness
- A patient who does not require mechanized breathing or constant monitoring
- A person who understands (or is cared for by someone who understands) how to use a basic smartphone
- (We need to decide or at least mention a range for their oxygen needs here)

Specifications for this project were influenced by Client M's requirements, the end user requirements, and the literary research conducted by the Air Wear team. The biggest aid in navigating through the list of requirements was the research conducted by the previous senior project team. According to their reports, the end users of the oxygen-aid device are patients with mild to severe respiratory illness, which means they need a HFNC oxygen therapy to breathe. Patients with severe respiratory illness use the HFNC oxygen therapy because there aren't any ventilators available for them to use. However, a HFNC would not be feasible within the project scope or requirements. This will be further explored during the solutions stage of the project. Ultimately, the team decided to meet the requirements for a LFNC with higher oxygen flow rates than the standard portable oxygen concentrators found in the market.

The oxygen concentration on the existing prototype can be adjusted from 21% to 100%. Air Wear plans to implement this feature of the design into the new prototype.

The oxygen aid device needs to be light enough for the user to comfortably wear it around while performing their daily routines. Competing portable oxygen concentrators are less than 10 pounds, which is why the sponsor and Air Wear team agreed that the weight of this device should be less than 10 pounds. The battery life of market portable concentrators are 4-5 hours in their lowest settings ($\lesssim$ 1 LPM). With this in mind and knowing that the existing prototype is portable for only 3 minutes, the target battery duration for the new prototype was set at 1 hour.

Portable oxygen concentrators currently in the market are priced at around $1500 to $3000. To make the oxygen aid device more accessible to people in need, the team decided to lower the sale cost to $1000. After better understanding the materials, test equipment and electrical components of the manufacturing process, we are unable to optimize the manufacturing cost at this point in time. This price range was chosen by the previous senior project group and it was met. Our team faces a high risk of failing this requirement if our solution for creating sustainable oxygen is too expensive.

The rest of the requirements came from the existing prototype of the customer requirements which are discussed in the House of Quality (Appendix A). The following table of requirements was constructed based on the sponsor requirements, customer requirements and the literature review:

Table 1: Engineering Requirements

Spec. #	**Parameter Description**	**Requirement or Target (units)**	**Tolerance**	**Risk**	**Compliance**
1	Weight	10 lb	Max	M	S, T

2	Battery Life	1 hr	Max	H	A, T
3	Noise Level	60 dB measured at wearer's ear	Max	L	T, I
4	Volume	26 L	Max	L	S, T, I
5	Exposed Hardware	2	Max	M	S, I
6b	Oxygen Flow Capacity	5-10 LPM	Max	M	S, T
7	Oxygen Concentration	100%	Max	L	A, T
8	Humidification	100%	Max	L	A, T
9	Cost (sale cost))	$1000	Avg	H	A, T
10	Number of Replaceable Parts (between users for sanitation purposes)	1	Min	L	S

Management Plan

As a team, the group members will spend time in class and outside of class to work on the product and complete any analysis and testing to meet the deadlines. The duration of the meetings outside of class would be determined by the workload that needs to be completed, but in general each member is willing to spend four to six hours per week outside of class.. These hours will not include the weekly meeting with the sponsor for updates on the project. All the members will try to equally contribute to the designing and building the oxygen aid device, but the members will take the lead responsibility on different tasks, as listed below:

Ada Tadeo:

- Biomedical aspects of the project to ensure optimal quality of life

- Ensuring the team's adherence to governmental regulation and bioethics in all aspects of the design and testing.
- Experimental design, testing procedures, and statistical analysis
- Acquiring grants, materials, etc. Evaluation of costs and benefits.

Ani Svadjian:

- Single point of contact for the sponsor in order to avoid any confusion regarding communication to/from the sponsor. The sponsor contact must communicate in a timely and professional manner with the sponsor. With this role comes the responsibility to keep everyone's schedules in mind and arrange meetings accordingly.
- CAD designs using SolidWorks.
- Mobile control of the device during testing and concept design.

Deepthi Ravuru:

- Hardware and software parts of the oxygen aid device. Such tasks include coding the microcontroller, building the circuits, etc.

Note. The members who are taking the leads on certain aspects of the project are not solely responsible for completing the task. Instead they take a higher responsibility than the rest of the members due to their experiences in that task.

A preliminary timeline of the project is shown below (Table 2). The dates on the timeline are an estimate of when the team plans on completing the tasks, alterations to the timeline may occur due to any obstacles faced during project progression.

Table 2: Project Timeline

Click here to see a Gantt Chart with our revised timeline and completion percentages.

Checkpoint	**Approximate Completion Date**
Current Prototype	Nov 3, 2021
Initial Design Concepts	Nov 16, 2021
Final Design Concept	Nov 25, 2021
Design Concept Report	Dec 5, 2021
Reverse Engineering	Feb 17, 2022

Detailed Design	Feb 20, 2022
Final Design Report	Feb 27, 2022
Order Materials	Mar 3-10, 2022
Manufacturing Plan; Begin Manufacturing	Feb 10, 2022
Plan Testing	Mar 6, 2022
Complete First Original Prototype	April 12, 2022
Perform tests and Improve the Design	May 26, 2022
Final Project Report	Jun 3, 2022

Design Development

The sponsor of this project prefers that the oxygen tank of the original prototype be replaced by an oxygen concentrator. With thorough research, the team agreed to do so, seeing that it is a sustainable and effective method of oxygen generation. Therefore, the main focus of the design development process was on the housing of the oxygen aid device. Using the requirements and specifications, the following design concepts for the casing of the device were made. Note that these concepts are possible solutions for the problem and one design was chosen as the final solution.

<u>The Backpack Concept:</u>

The backpack concept consists of two separate halves, functionality and utility (Figure 5). The oxygen aid device is located in the lower half of the backpack, and unlike a typical backpack, the fabric surfaces surrounding the device will be open/permeable to let sufficient air flow enter the device. The upper half of the backpack is used for personal storage.

The backpack's top surface contains a small port opening for the tubing of the nasal cannula to go through. This allows for the majority of the tubing to be stored out of the patient and the environment's way. The backpack weighs almost the same as the O2+ prototype, but presents a more comfortable, ergonomic, and discrete look and fit. It is also more size inclusive and can be worn in all weather conditions.

Figure 5. The Backpack as a Casing for the Device

<u>The “Stormtrooper” Mask Concept:</u>

The oxygen aid device is incorporated into a helmet that fully encapsulates the patients head, face, and chin (Figure 6). The mask features two inhale airways and an exhale airway. The mask also has a removable component to eat food while using the device. Compared to the O2+ prototype, the helmet is lighter in weight and can be worn in all weather conditions. However, this design is not discrete, may be uncomfortable for patients, and is not size inclusive.

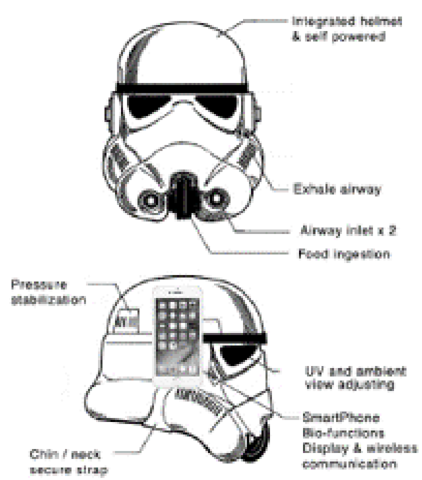


Figure 6. The “Storm Trooper” Mask as a Casing for the Device

<u>The Vest Concept:</u>

The oxygen aid device is incorporated into/throughout the vest (Figure 7). It has a nasal cannula coming from one of the many pockets near the neck region to reduce the length of free dangling tubing. The vest would have more mesh material for the air to filter through the oxygen concentrator. This design presents the opportunity for the weight to be distributed more evenly across the anterior and posterior regions of the body, more ergonomic compared to the O2+ prototype. It's also more discrete and comfortable than the O2+ prototype. But, this design is not size inclusive nor can it be worn in all types of weather.

Figure 7. The Vest as a Casing for the Device

<u>The "Beer" Hat Concept:</u>

The oxygen aid device will be located on both sides of the hat, where beer cans are held (Figure 8). The nasal cannula will come down just as it would like the straw for a beer hat. This design is not at all discrete and may be uncomfortable/harmful for the patient's neck from balancing the device on top of the head. Good qualities of the design include its availability to be worn in all seasons and it is size inclusive.

Figure 8. The "Beer Hat" as a Casing for the Device

The Utility Belt Concept:

The oxygen aid device would be designed to fit the small compartments in a utility belt (Figure 9). This allows for the weight to be evenly distributed around the waist of the patient. A nasal cannula would be coming out of one of the utility pockets. This design would be available for use at any location and season, is discrete, and size inclusive. This design also has the potential to be ergonomic; however, oxygen aid device technology has not yet been reduced to fit the size required for this design.

Figure 9. The Utility Belt as a Casing for the Device

The Elipta Bike Concept:

This elliptical bike includes the storage of the oxygen aid device in/around the frame (Figure 10). Because this is a dynamic transporting device, it includes the ability to produce energy for the oxygen aid device (self-powered). Despite its potential in sustainability, this device has some negative qualities. It is not discrete, would be difficult to bring into an indoor setting, and is not accessible for patients unable to exercise to the extent necessary for power production.

Figure 10. The Elipta Bike as a Casing for the Device

Decision Making Process

A Pugh Matrix was utilized to determine the best design for the casing (Table 3). The O2+ prototype was used as the Datum for the matrix, and other designs were compared against it.
The O2+ prototype weighs between 10-15 lbs, it's not comfortable, ergonomic, or discrete because the whole device is strapped onto the back of a chair with zip ties and has very thin and small straps to wear as a backpack. The prototype can not be worn in all weather conditions because the hardware is exposed to the outside environment. This prototype is also not size inclusive due to the small, thin straps connected to the back of the frame. The matrix compares the designs with the prototype in these criteria, so that "+" means that the design is better than the prototype and "-" means that it is worse than the prototype. The "s" means that it matches the prototype in that criteria.

Table 3: Pugh Matrix

Options → Criteria ↓	Backpack	Storm Trooper Mask	Vest	"Beer" Hat	Utility Belt	Elliptical Bike	O2+ Prototype (Datum)
Lightweight	s	+	+	-	+	-	s
Comfortable	+	s	+	s	s	+	s
Discrete	+	-	+	-	+	-	s
All-Weather	+	+	-	+	+	+	s
Ergonomic	+	s	+	-	s	+	s
Size Inclusive	+	s	-	+	+	+	s
Room for Personal Items	+	s	+	s	s	s	s
Sum of +	6	2	5	2	4	4	s
Sume of -	0	1	2	3	0	2	s
Sum of s	1	4	0	2	3	1	6

The last three rows of the table sum up the results, and were used to pick the final design concept.

Top Concept

The final design concept that resulted with the most positive criteria score, is the oxygen aid device integrated into the backpack. The details of the design are shown below (Figure 11).

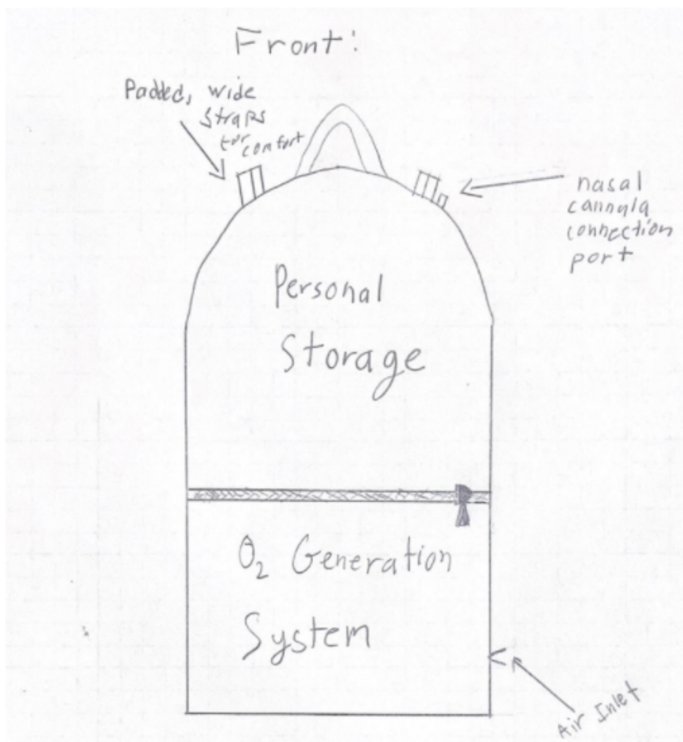


Figure 11. Front View of the Backpack Design

The sides of the backpack will have an open face or mesh material for the oxygen concentrator to take in air and dissipate heat (Figure 12). There will also be a charging port to charge the battery of the system in order to reduce contact with the hardware. Figure 13 demonstrates the superior position in which the nasal cannula port will be placed. With the majority of the tubing running the length within the backpack this results in efficient storage of otherwise loose tubing.

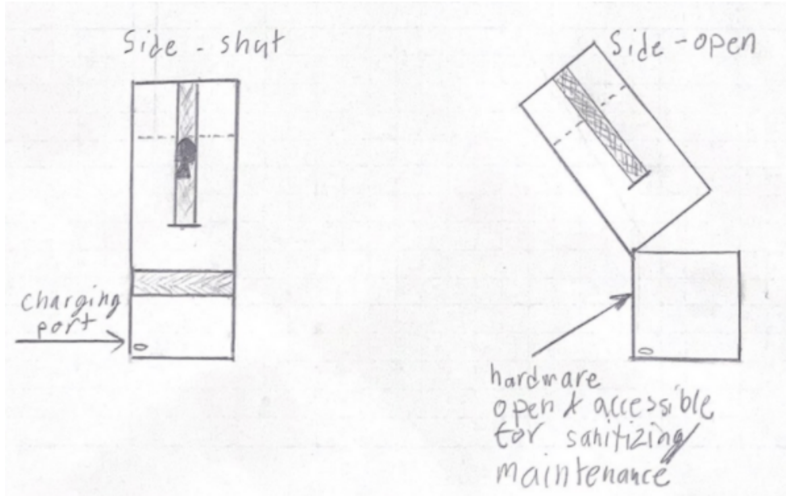


Figure 12. Side View of the Backpack Design

Figure 13. Nasal Cannula Implementation

A challenge the team faced for the oxygen generation part of the device was the risk in producing a dysfunctional system if it were to be created from scratch. The main objective for the team is to create a fully functioning device that connects and functions with the existing hardware and software of the 02+ prototype so that it may be controlled via smartphone or Apple Watch. Therefore the team plans to take a reverse engineering approach to solve the problem.

In order to get a better understanding of the mechanisms and components of the oxygen generation system within a concentrator, we decided to purchase an existing portable oxygen concentrator on the market. We plan on reverse engineering the oxygen concentrator by opening it and examining it to create a detailed design of the oxygen delivery system. In this process, we hope to reuse the concentrator's parts and integrate it into our design. The oxygen concentrator we will be purchasing is the VARON Portable Oxygen Concentrator With 5LPM (Figure 14). This device was chosen because of its rated voltage, price, and flow rate. More details about VARON are found in the references.

Figure 14. VARON Portable Oxygen Concentrator With 5LPM

Note. The image was taken from an e-commerce website caller Oxygencollection

More information about how the oxygen concentrator is incorporated into the O2+ hardware is shown in the flowchart below (Figure 15).

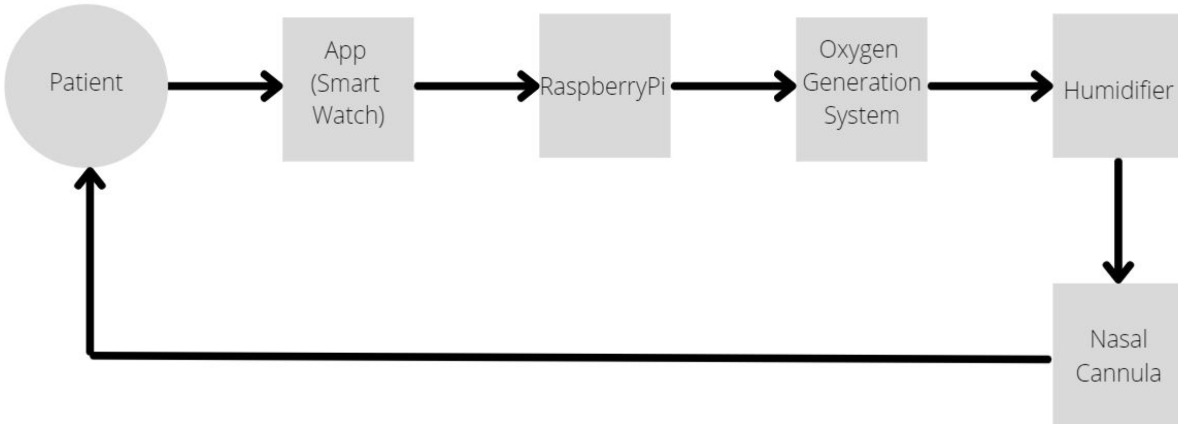


Figure 15. Level 1 Flow Chart of the Oxygen Aid Device System

Figure 15 shows the process of getting oxygen assistance. The patient will communicate to the device through their phone or smart watch using the Oxygen Plus app designed by the O2+ team last year. The app will send that information to a Raspberry-Pi board (microcontroller), which will then send a signal to the oxygen concentrator. Once the oxygen enriched air is generated, it will flow through a humidifier and a nasal cannula back to the patient.

Our conceptual design satisfies the customer requirements because the housing of the device is comfortable, wearable, and ergonomic due to the padding and wide straps of the backpack. It has room for personal items as shown in figure 11. The design is discrete because all the hardware is tucked inside the bottom compartment as shown in figure 11. Since people of all sizes wear backpacks, the design is size inclusive and can be worn in all seasons like a regular backpack. Since the oxygen concentrator is produced from integrating the components of a market oxygen concentrator, it has the potential to satisfy the minimum requirements for the oxygen flow rate and the oxygen concentration. The oxygen concentrator is a device that can be considered quiet because it makes less than 60dB noise.

The existing hardware that is incorporated with the oxygen concentrator satisfies the rest of the requirements. It has a humidifier that can go up to 100% humidity. The entire design satisfies the customer requirements as well because it's lightweight (less than 10lbs), easy to sanitize and inexpensive compared to other devices on the market.

Safety Concerns

Our team has been mindful of safety during the development process of our prototype. Because our process involved taking apart an existing oxygen concentrator, we were aware of the risk of electric shock and release of pure oxygen when performing our analysis. We as a team committed to a) performing the disassembly in a well ventilated area, b) using appropriate electrical grounding techniques, and c) eliminating anything from the environment that could cause a fire. We also performed the disassembly as a group in case any job requires multiple hands to ensure safety. The team also sought out information on lab safety and first aid training, which we kept on hand during the dissection.

As for patient safety, we are aware that oxygen and electrical components can be dangerous if exposed to the patient and environment. This knowledge is reflected in our safety checklist, which can be found in Appendix B. We intend to foster safe design by keeping the oxygen generation system in its own compartment with a protective housing that can be removed for cleaning and maintenance. We also intend to inform the patient and patient care providers of the risks associated with the device and methods of using the device safely.

Maintenance of the device is one of the most important aspects of the design as it impacts the safety of the patient and the entire goal of this project is to support patient recovery. The idea our team has for this device is that it would undergo a thorough sterilization process after being returned from one patient and before it is handed off to the next. In cases where patients will be using this device for a long period of time, we would want them to properly maintain it with ease. Features of the device that may increase the risk of infection if not maintained properly include the humidifier, nasal cannula, oxygen tubing, and the oxygen concentration filter. Distilled water is commonly used as the source for moisture in oxygen aid devices, however without proper maintenance or the presence of a preservative, the water can become a source for bacteria and mold. The sterility of a nasal cannula can be compromised between uses when a patient leaves it resting on a contaminated surface, such as the floor, furniture, or bedding, and can transfer pathogens directly to the mucous membranes in the nasal cavity. The oxygen tubing can become stained or clogged with respiratory secretions or moisturizers placed on the nostril if not replaced often. Lastly, the device filter may be backed up from dust or other external particles it filters out from the environment and needs to be properly cleaned. In order to assist patient self maintenance, the team suggests the development of an informational guide to hand out to patients with instructions on how to properly maintain the oxygen aid device.

Reverse Engineering

Because it is unsafe and outside of our project scope for us to build our own oxygen concentrator from scratch, we took on the reverse engineering approach to build our prototype. To reiterate, we acquired a functioning oxygen concentrator that is currently on the market, taking apart important components, and integrating it with our existing hardware and software. In doing so, we are taking the best mechanisms of each device and consolidating it into one optimized, fully-functioning prototype that fits our engineering specifications.

We started by purchasing a VARON 5 Lpm oxygen concentrator thanks to the generosity of the Hannah Forbes grant. As soon as the concentrator arrived, we made sure that everything was functioning as intended before performing some exterior tests on the device. From these tests, we learned valuable traits of this oxygen concentrator. The first thing we noticed was that the VARON oxygen concentrator did not output a constant airflow. Rather, the device mimics a natural breathing pattern. After some more testing, we discovered that the device does not output a significant “breath” unless the device can detect back pressure by way of a pressure sensor located near the nasal cannula’s connection port. A picture of this sensor, along with other images and quantitative data from our reverse engineering process can be found in Appendix F. After figuring out how to mimic human breathing, we timed how long it took to fill a quart size Ziploc bag (0.95 L) on various flow settings. We also ran the device continuously (while simulating breathing) on the highest setting to see how long it took to completely discharge the battery. We then timed approximately how long it took to fully recharge the battery. We also used an iPhone’s decibel meter to measure the noise level that the device emits. We later ran tests on the device’s oxygen purity, verifying that it outputs oxygen at about 90% purity.

After our exterior tests, we continued to tear down the VARON device. We had it laid out in such a way that it was still fully functional, but we could see each component as the device worked. During this process we were able to label the air compressors, the DC brushless servo motor between them, the filter cylinders, the flow sensor, and the various control boards and shock absorption systems. Once we were able to watch the device work, we connected the air compressors to an oscilloscope that allowed us to view the pulse-width modulation (PWM) signal that drives the motor. Once we calculated each level's duty cycle, we replaced the PCB that drove the motor and used a function generator to simulate our own PWM signals. We also partially disassembled the filter cylinders which we determined use a Pressure Swing Absorption (PSA) system to filter oxygen in one cylinder and clear nitrogen buildup in the other. This way, there is always one cylinder delivering oxygen while the other cylinder is cleaned. This flow is directed by solenoids, but we aren't entirely sure about the timing of them. We were able to guess that the solenoids switch about every 3 seconds, although we suggest that further testing and optimization be done by another project team.

Final Design

The final design of the oxygen concentrator used in the backpack design is shown below (Figure 16). Note that the apple watch system isn't added to the level 2 diagram because the AirWear team will not be modifying the apple watch system to accommodate the new oxygen aid device. According to our sponsor, the apple watch code will be undertaken by a future senior project group. As mentioned before, the Air Wear team will replace the oxygen tank from the O2+ team prototype with a new oxygen generation system as identified in the reverse engineering section. The air compressor and the absorbers will be replacing the oxygen tank for the oxygen generation part of the device. The rest of the systems will be reused from the O2+ prototype, such as, the Fan, the humidifier, the sensors, and the raspberry-pi. To visually display the airflow through the concentrator, the image in Figure 17 was created.

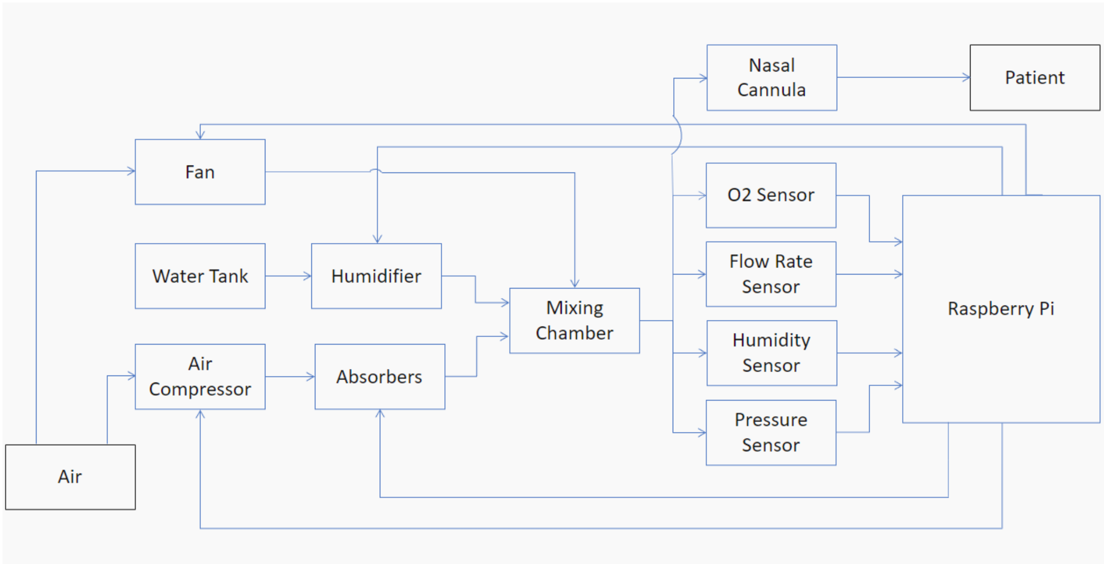


Figure 16. Level 2 Flow Chart of the Oxygen Concentrator

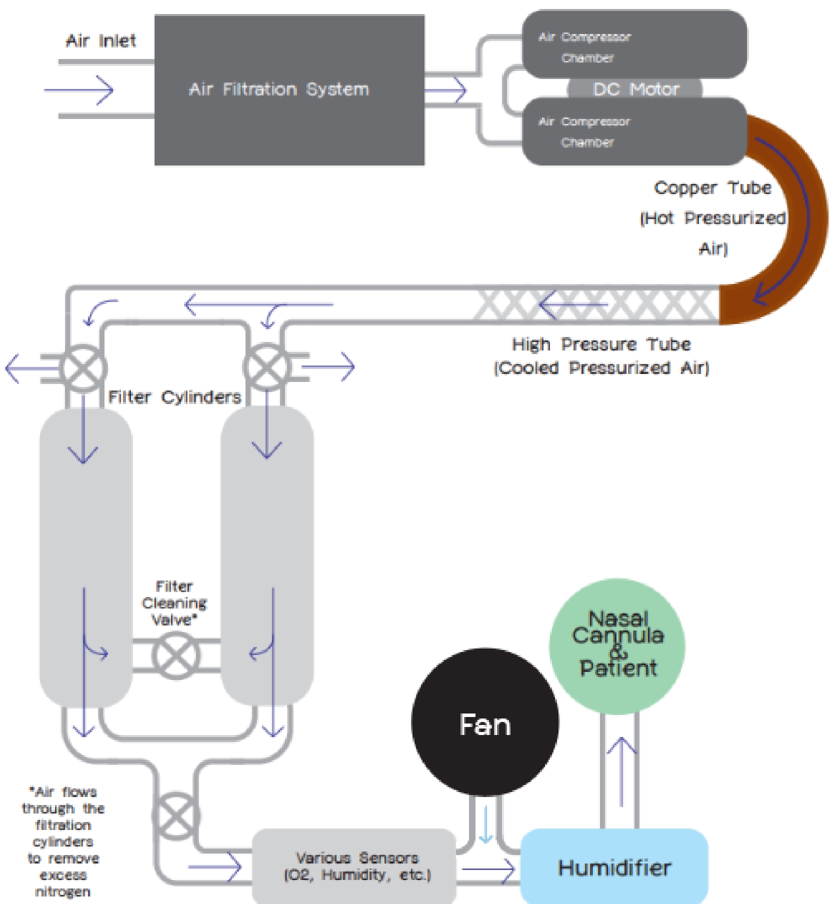


Figure 17. The Airflow Through the Oxygen Concentrator

The description and purpose of each component is described below:

<u>Air Compressor:</u>

The air compressor takes filtered air from the atmosphere and pressurizes it and outputs the high pressure air (Figure 18). The air compressor also controls the oxygen flow rate because the speed of the DC motor inside the compressor controls how fast the air is compressed and flows through the rest of the system. The speed of the DC motor is controlled by a PWM signal, so a high duty cycle results in a high flow rate and vice versa. The air compressor needs 15V to operate, which is the same as the battery voltage. The raspberry-pi will control the air compressor in order to have six flow settings. Note that this component is reused from the Varon 5LPM oxygen concentrator.

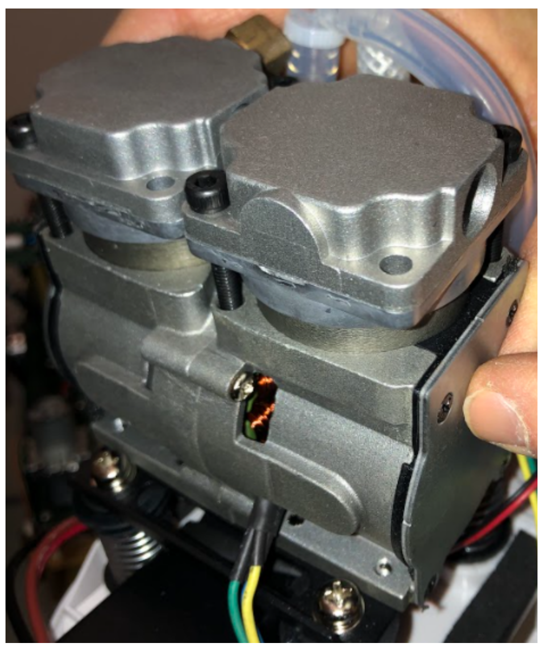


Figure 18. Air Compressor

<u>Absorbers:</u>

The air needs to be at a high pressure in order to filter oxygen through the Absorbers (Figure 19). The absorbers have multiple layers of zeolite beads and other materials to filter oxygen. The absorbers follow the PSA model to constantly supply oxygen. This means that one absorber will filter the high pressured air while a small portion of the filtered air will clean the other oxygen concentrator by flowing in the opposite direction, so that the output of the second absorber is waste that will leave the concentrator. When the first absorber starts getting saturated with nitrogen that it's filtering out, the air flow switches, so that the secondon absorber is now filtering air, while the first absorber outputs the waste materials. The air flow through the two absorbers are controlled by solenoids that will be controlled by the raspberry-pi. Note that this component is reused from the Varon 5LPM oxygen concentrator.

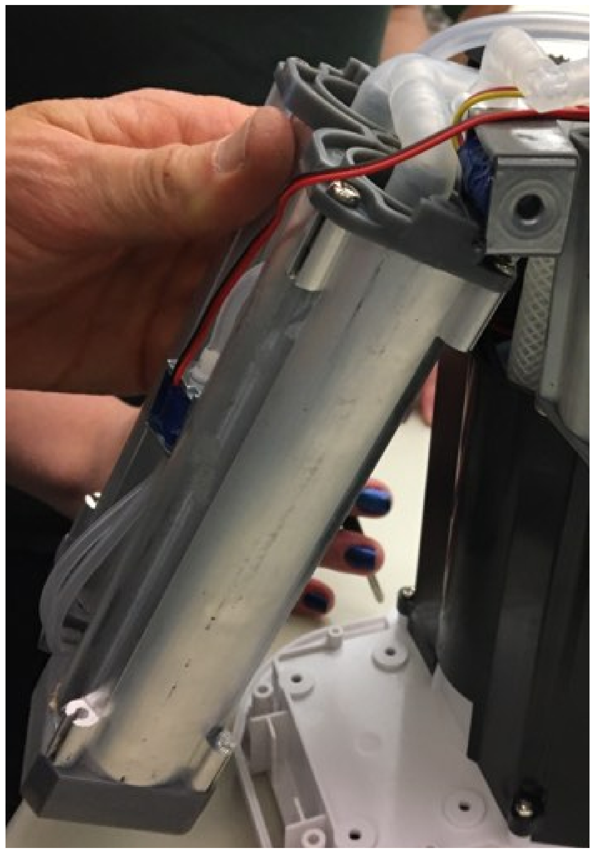


Figure 19. Absorbers

<u>Fan:</u>

The purpose of the fan circuit is to provide a higher flow rate so that patients who have a hard time breathing can use the fan settings to breathe in more air (Figure 20). The fan also uses a PWM signal that comes from the raspberry-pi, and it has four flow settings. The air from the fan will be mixed with oxygen from the absorbers in the mixing chamber.

Figure 20: Fan

<u>Water Tank, Humidifier, and Mixing Chamber:</u>

The humidifier is an electrode that turns the water in the water tank (the green part in Figure 21) into water vapor that is mixed with the air coming from the absorbers (middle hole in Figure 21) and the Fan (the big hole on the right in Figure 21). The humidifier is controlled by the raspberry-pi and the user can control if they want humidified air or not through the raspberry-pi. The mixing chamber is just a tube where all air from the humidifier, the fan, and the absorbers meet.

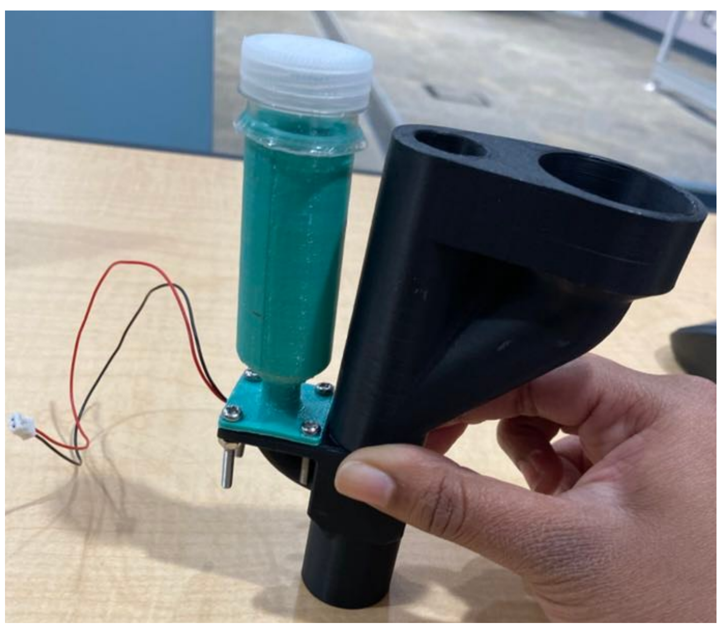


Figure 21. The Water Tank, Humidifier, and Mixing Chamber

Sensors and Their Circuits:

There are four sensors that send data to the raspberry-pi, which then send data to the apple watch that allows the user to control the device. The oxygen sensor reports the oxygen concentration to the pi, so the user can increase or decrease the flow settings for the oxygen generation system by controlling the air compressor. The flow rate sensor measures the flow rate of the air outputting out of the device, so the user can increase or decrease it by either controlling the fan (to increase the airflow) or the air compressor (to increase the oxygen flow rate). The humidity sensor reports the humidity of the air outputting out of the device, so the user can choose to have humidified air or not by controlling the humidity of the air. The pressure sensor reports the air pressure of the air outputting by the device and it's the only sensor that is used for regulating the system and not for user control purposes. Unfortunately, the code for the sensors isn't complete. Since building and running the code for them is out of our project scope, we will not have any working sensors in our final prototype. This decision was both recommended and approved by our sponsor. While looking at the sensor circuit, an issue with the oxygen sensor circuit was identified and can be fixed as discussed below.

The oxygen sensor outputs a signal between 13mV to 16mV, which is supposed to be amplified by the op-amp circuit designed by the O2+ team. The circuit will not function as designed (Figure 22) because the supply voltage is rail to rail and the O2 sensor voltage is close enough to ground that the op amp doesn't amplify the signal enough for the ADC (which converts the signal from analog to digital) to recognize the voltage. As an example, a square pulse signal with a peak voltage of 16mV was used as an input for the op-amp circuit and the resulting output signal is shown below. The output signal has a peak voltage of about 210mV and the ADC requires a minimum input voltage of 2.7V (Figure 23). With the current design, the ADC will interpret the input voltage as ground all the time, regardless of what the op-amp is outputting.

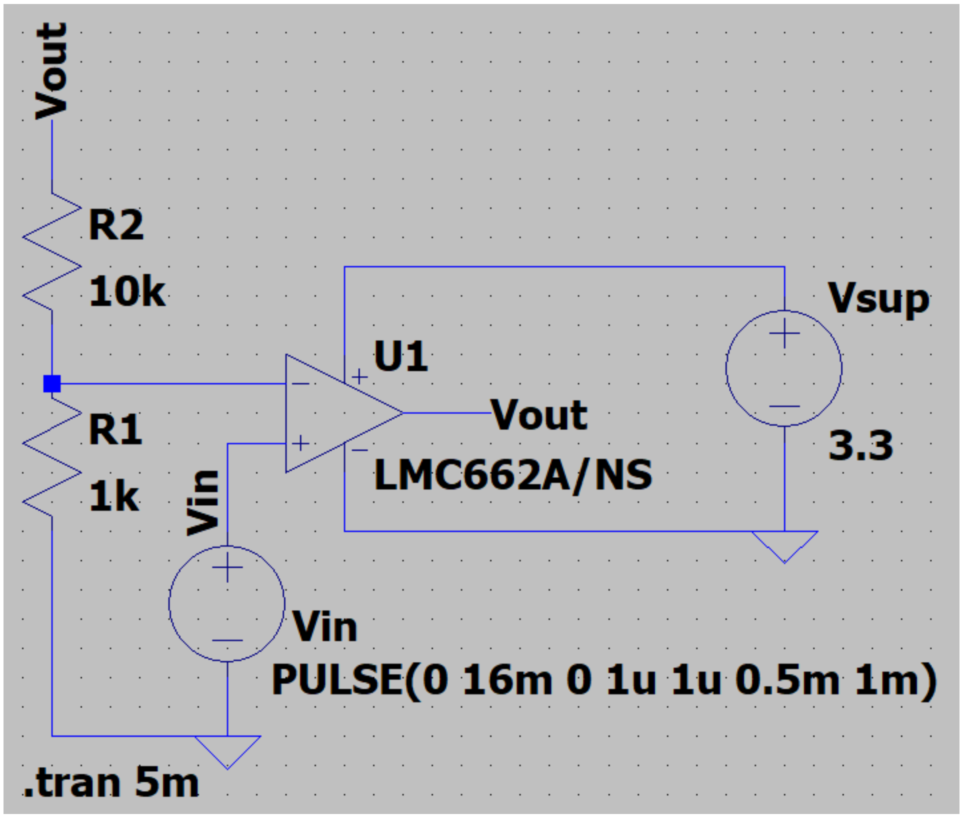


Figure 22. O2+ Team's Oxygen Sensor Circuit

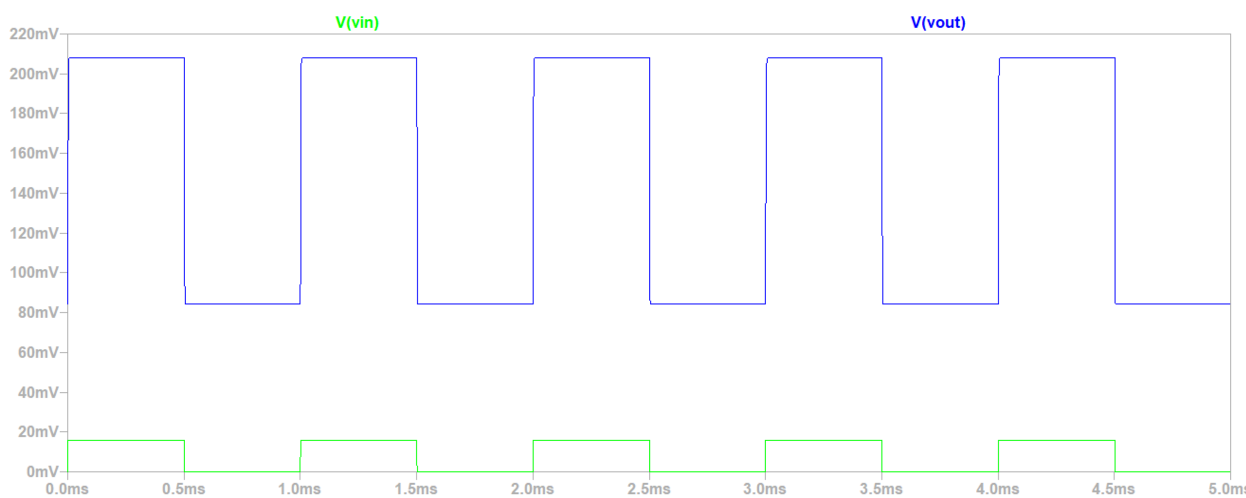


Figure 23. O2+ Team's Oxygen Sensor Circuit Input and Output Voltage Waveforms

The design shown below (Figure 24) outputs a 3.3V signal instead of a 210mV signal for the same example input voltage. As shown below (Figure 25), the output voltage waveform has a peak voltage of about 3.3V and the min voltage is 0V, which means the

ADC will be able to read the waveform coming from the op-amp circuit, and output a readable digital signal. The O2 sensor circuit wasn't built and tested because it is outside the scope of this project, instead it was redesigned so another senior project group can implement it in their design in the future.

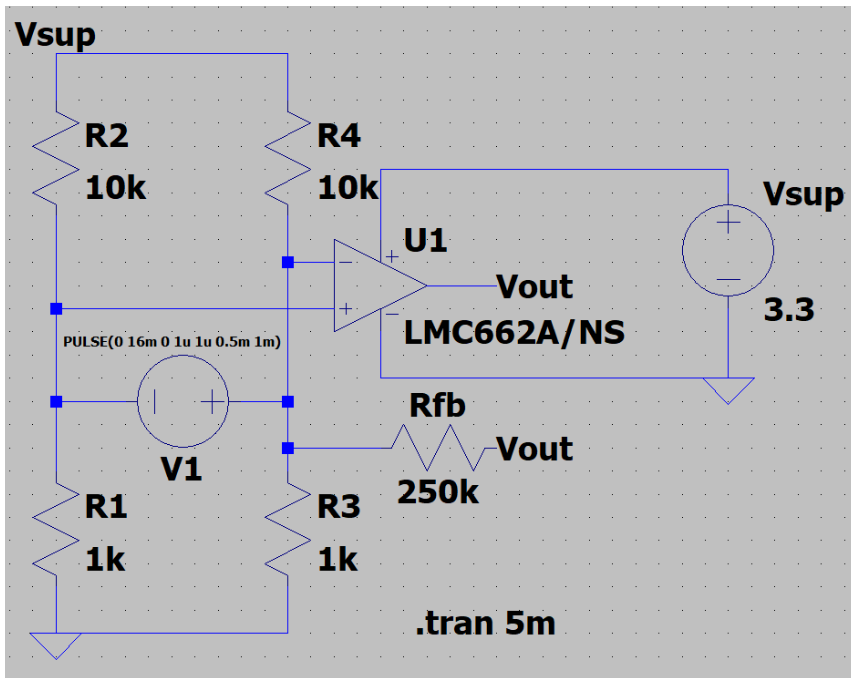


Figure 24. Air Wear Team's Oxygen Sensor Circuit

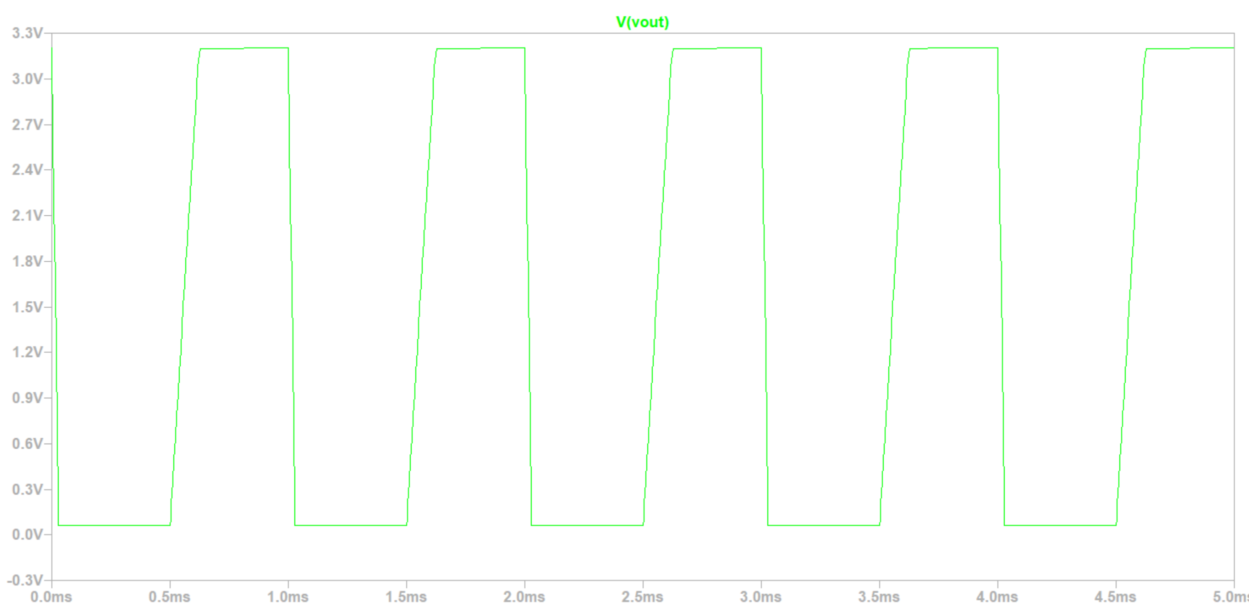


Figure 25. Air Wear Team's Oxygen Sensor Circuit Output Voltage Waveforms

Software Development Plan

The O2+ team's code will be reused and modified to control the hardware and the firmware of our device. The new code that will be added is to control the air compressors and the absorbers. The basic logic to control the air compressors is shown below (Figure 26). The chosen duty cycles were random and should be tested in the future to find the optimum duty cycles values that result in a high flow rate and oxygen concentration.

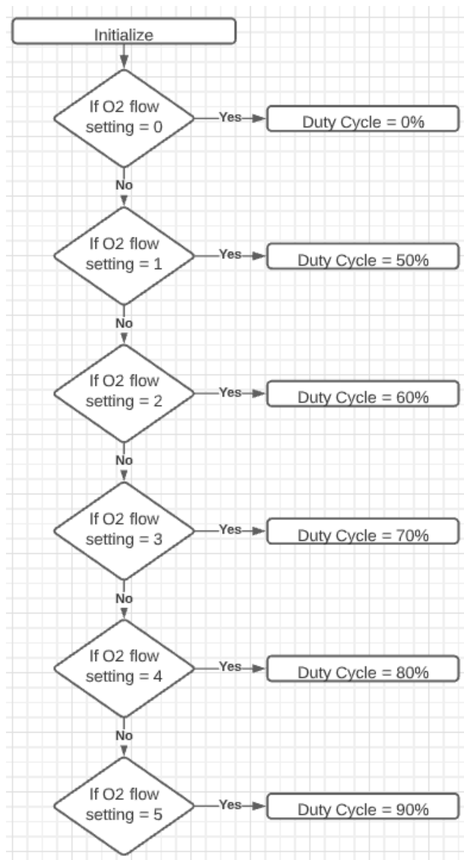


Figure 26. The Logic to Control the Air Compressors

The code to control the air flow through the solenoids is the hardest part of this project and tests will be conducted to identify the timing of when the solenoids should be open and closed. This will be done by using an oxygen analyzer to measure the oxygen concentration at the output of the absorbers. When the oxygen concentration starts dropping, we know that the absorber that is filtering the oxygen is saturated, so it's ready to be cleaned. We will use these times to open and close the three solenoids attached to the absorber, where two of them are used to control the air flow from the air compressors, while the third is used during the switch from using one absorber to another. The following diagram (Figure 27) demonstrates the solenoid logic used, where the saturation and transition times are values we will identify during the testing process.

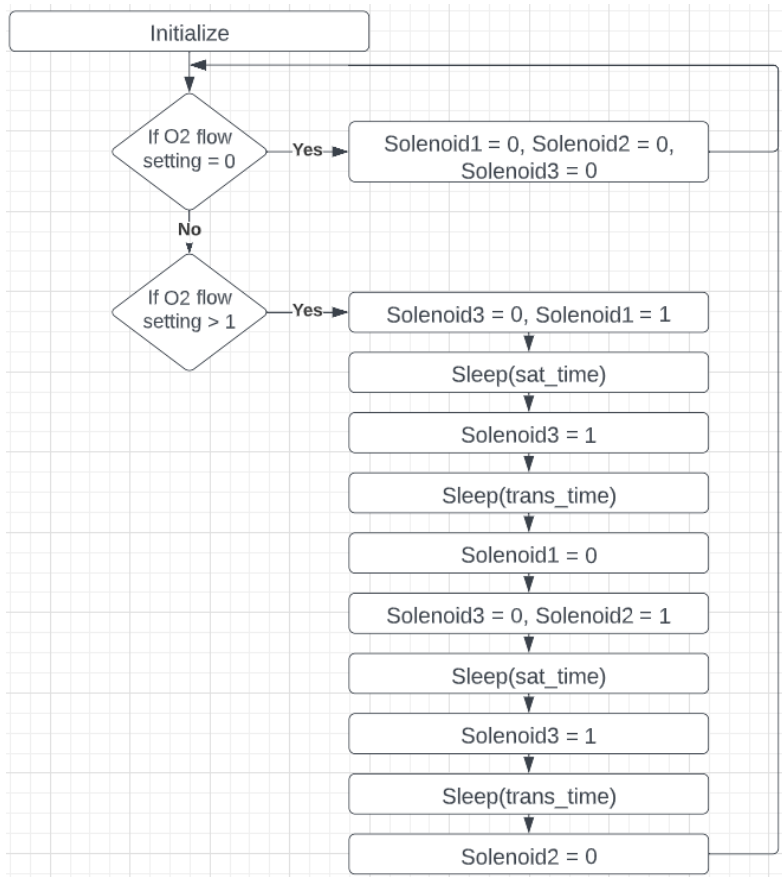


Figure 27. The Logic to Control the Airflow Through the Absorbers

Product Manufacturing

Our product was manufactured in the following pieces: circuits on the breadboard, system integration, optimization, and circuits on perfboard.

Circuits on the Breadboard:

During this phase in development, Ada and Ani assembled the circuits required for power regulation, sensors (we discovered later that these circuits were ineffective), solenoid control, and air compressor control. Deepthi worked on firmware during this time. The images below (Figure 28) show part of the circuit-building process and the completed circuit on the breadboard.

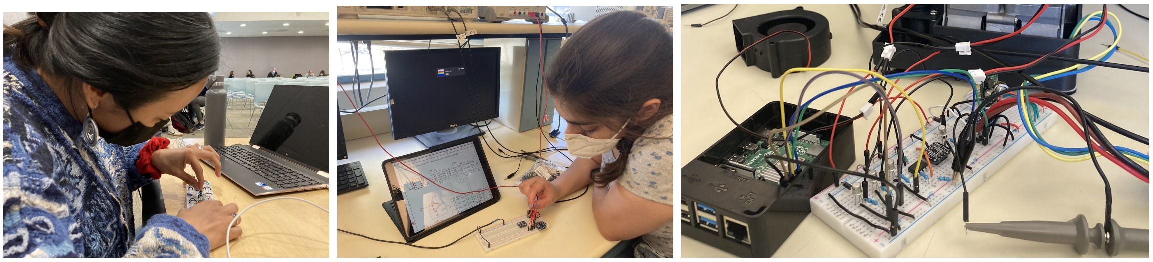


Figure 28. Assembling Circuits on the Breadboard

<ins>System Integration:</ins>

The first phase of our system integration involved connecting and controlling our air compressor to and by the raspberry-pi (Figure 29). During this phase we focused solely on getting the compressor to run at different pwm signals as dictated by Deepthi's firmware.

The second phase of our system integration involved connecting and controlling the solenoids on our filter cylinders to and by the raspberry-pi. During this phase we focused solely on controlling the solenoids individually and dialing in the solenoid logic. The third phase of our system integration involved connecting the air compressor to the filter cylinders and outputting some amount of oxygen. We did not focus on the quality of the oxygen output at this time. Figure 29 below shows the system after this process, so the air compressor and filters are connected to each other at this point.

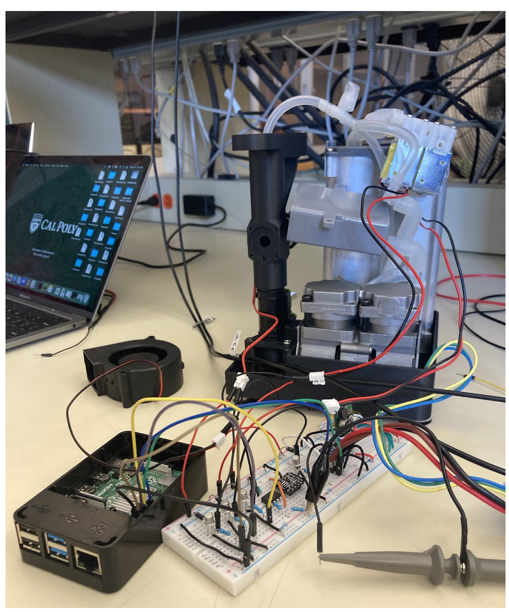


Figure 29. Compressor and Filter Integration

Optimization:

During this phase, we ran tests on our completed system to determine the best timing for the solenoid logic. We ran our system while it was connected to an external oxygen concentration sensor. We tracked peak oxygen concentrations across different periods for the solenoids, agreeing that 3-3.5 seconds per filter yielded us the highest oxygen output we could produce. Figure 30 below shows the iterations of firmware code that we refined during this process.

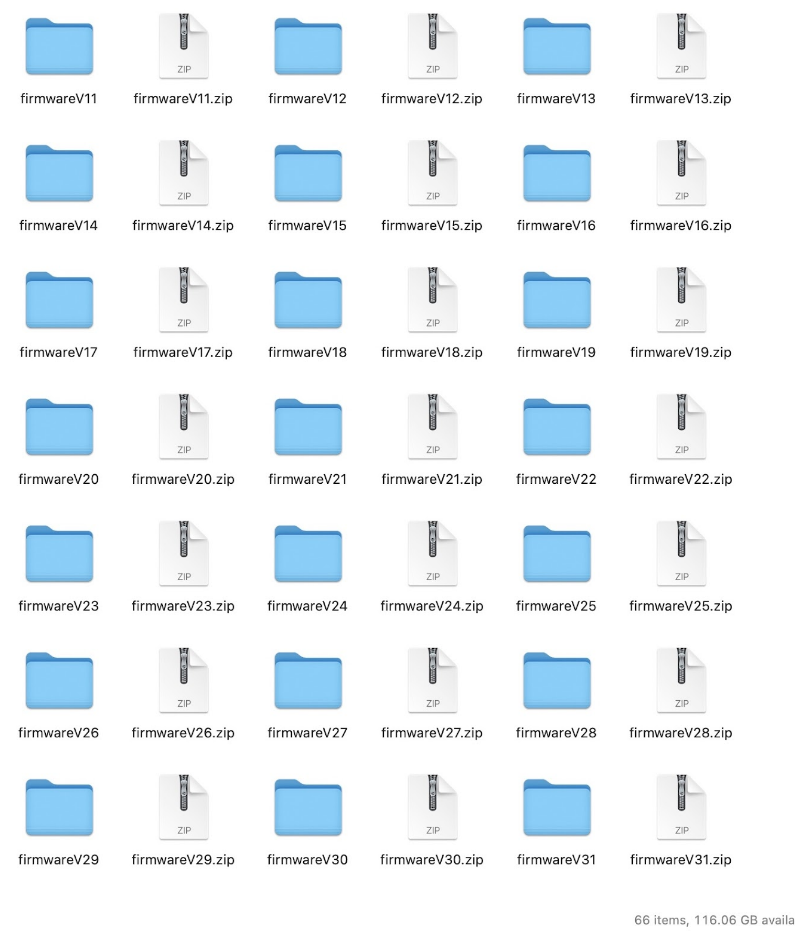


Figure 30. Optimizing Firmware Iterations

Circuits on Perfboards:

After receiving wise feedback that a breadboard is hardly safe in a backpack, we began to work on creating a solution that would hold together better if jostled. Although we tried to repurpose some PCBs from the previous group, we quickly discovered that the printed circuits did not match our revised circuits. Some changes in the code were made to match the PCB connections such as switching around certain pinouts of the raspberry-pi. Furthermore, the only devices soldered on to the PCB were the 5V regulator, the level shifter, and the fan circuit. The rest of the circuits weren't soldered onto the board because they weren't being used since their code wasn't complete. The circuitry to control the solenoids was transferred from the breadboard to a perfboard because there wasn't enough time to create the PCB layout and to get it printed. The images below (Figure 31) showcase the final hardware, for our portable oxygen aid device, that is directly plugged onto the raspberry-pi. The schematic for the hardware implemented by the Air Wear team is shown in Appendix G.

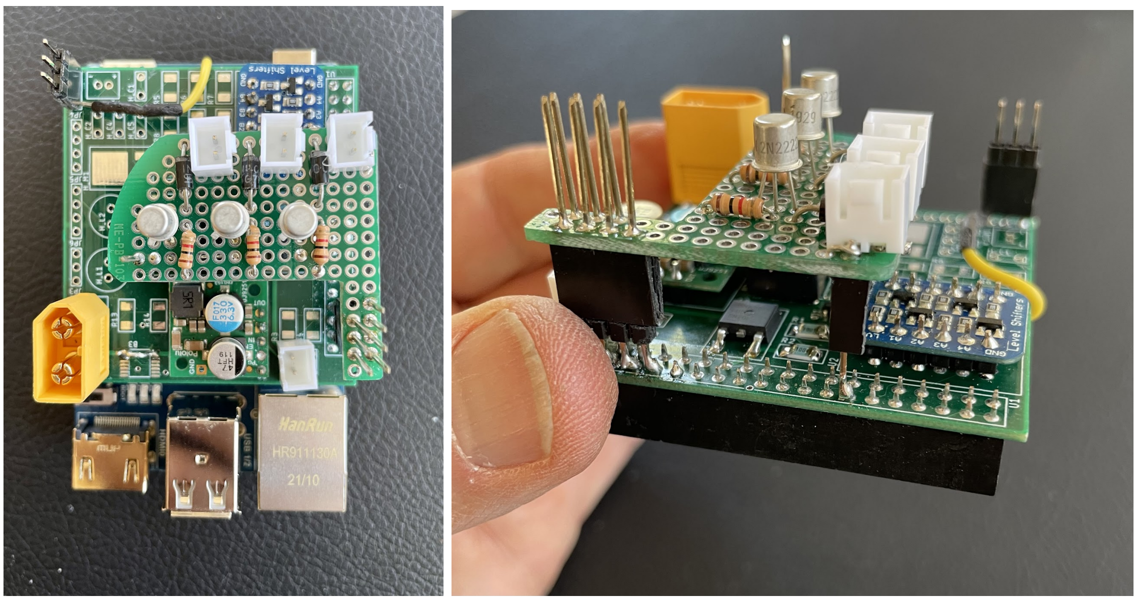


Figure 31. Finalized Circuit Boards

Maintenance and Safety

Maintenance of the device is one of the most important aspects of the design as it impacts the safety of the patient. Features including the humidification, the nasal cannula, oxygen tubing, the oxygen concentration filter, and basic hand hygiene all require special attention to reduce the risk of infection. Our plan for maintenance includes subjecting the device to a sterilization process after being returned from one patient and before it is handed off to the next. In cases where patients will be using this device for a long period of time, we plan to provide a maintenance manual with clear and simple instructions on how to properly maintain the device.

Sustainability

Out of all seven Design for the Environment Criteria, our project focuses most heavily on three: design for **minimizing hazardous materials**, design for **energy efficiency**, and design for **disassembly/refurbishment**.

One of the most hazardous materials in the original wearable ventilator was a 16-inch-tall tank of pressurized oxygen. Pressurized gasses risk rapid decompression, which can cause fire, explosion, suffocation, and other injuries according to the Occupational Safety and Health Administration (OSHA). By replacing this tank with an oxygen generation system, we are cutting down on the amount of pressurized gas in the system at one time. We can assert this because our generation system sends out oxygen as it generates it, meaning that the amount of pressurized oxygen sitting around at any given moment is much smaller.

Also on the topic of pressurized oxygen, it takes a lot of energy to pressurize oxygen to the point where it condenses. This process, known as cryogenic oxygen production, can take up to about 200 kWh to produce 1 ton of liquid oxygen. While our oxygen generation system does not produce near that amount of oxygen, it produces enough oxygen for a patient at home while running off of a 14.8 V lithium-ion battery and runs on up to 75 W power, meaning energy consumption of 4.5 kWh maximum. This makes our design more energy efficient than the previous iteration.

Finally, our design is created with maintenance and disassembly in mind. Since the device will need to be cleaned and maintained between users, our design includes an easy to access zippered compartment, in which a magnetic lid can be removed to access the entirety of the oxygen generation system. This will facilitate repairing and replacing parts as long as the device lasts and quick disassembly once the device ceases functioning.

Cost Breakdown

A breakdown of all expenses shown in Table 4. Items are categorized as “Given” or “Purchased.” Given items include materials that were received from the sponsor or taken from the original O2+ prototype. Purchased materials were bought by the Air Wear team. Overall costs totaled to $2026.70.

The team acquired funding from two grants: Hannah Forbes and Baker Koob. The award totaled to $1800.00 ($500.00 and $1,300.00 respectively). The Hanna Forbes Grant went towards purchasing the VARON 5LPM machine which includes the air compressor and DC motor unit, air filters, absorbers, buffer chamber, 14.8V li-ion battery, tubing, and solenoids, all of which are components we will be integrating into our design. The Baker Koob Grant has been utilized for all remaining items in our table. The team spent a total of $1,309.16 of the Baker Koob fund, leaving $9.16 remaining which will be covered by the sponsor. A more detailed bill of materials of all electrical and hardware components will be included in the Appendix.

Table 4: Cost Estimate

ITEM	PRICE/UNIT	QUANTITY	PRICE
Given			
MicroSDXC EVO Select Memor Card 256GB	$ 49.99	1	$ 49.99
Raspberry-Pi Model 4B	$ 150.00	1	$ 150.00
Bread Board	$ 12.49	1	$ 12.49
Nasal Cannula	$ 33.00	1	$ 33.00
Purchased			
VARON 5LPM Pulse Flow Portable Oxygen Concentrator	$ 494.10	1	$ 494.10
Waterproof Laptop Travel Backpack	$ 21.44	1	$ 21.44
Flow Sensor	$ 175.13	1	$ 175.13
Oxygen Analyzer, Measures O2	$ 281.52	1	$ 281.52
Spacer Mesh	$ 13.10	1	$ 13.10
Magnets 250pcs	$ 14.99	1	$ 14.99
SunMed Test Lung	$ 26.41	1	$ 26.41
Pololu Step Down Voltage Regulator	$ 26.76	2	$ 53.52
IC Station Humidifier	$ 8.73	2	$ 17.46
DigiKey Electronics		1	$ 65.42
AdaFruit Power Sensor	$ 12.82	2	$ 25.64
Mouser Electronics 12bit ADC	$ 10.06	1	$ 10.06
DigiKey Back Up Parts	$ 33.43	1	$ 33.43
VARON 5LPM Pulse Flow Portable Oxygen Concentrator	$ 549.00	1	$549.00
		Total Price	**$2,026.70**

Testing and Results

The testing criteria reflects the engineering specifications mentioned earlier with our final design. We divided the testing variables into two categories, functionality and ergonomics. Functionality of device components will be measured to ensure the device is operating correctly and providing sufficient oxygen aid to the patient. Test variables in this category include flow rate, air pressure, humidity, and oxygen concentration percentage. Ergonomics of the device as a whole will be measured to satisfy the sponsors requirements and make this device easy to use and comfortable to wear in the dynamic working environment it will be used in. Test variables in this category include battery life, weight, portability, and ease of maintenance. The test plan details are shown in Figure 32.

DVP&R									
	Report Date	4/19/2022							
TEST PLAN									
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED		TIMING	
						Quantity	Type	Start date	Finish date
1	High Oxygen Concentration	measure output air oxygen concentration with oxygen flow sensor	90% O2	Deepthi R.	PV	25	Numerical	4/22/2022	5/19/2022
2	High Oxygen Capacity	measure flow rate of output oxygenated air	5 LPM	Ada T.	PV	25	Numerical	4/22/2022	5/19/2022
3	Humidification	measure output air humidity level with sensor	100%	Ani S.	DV	25	Numerical	4/26/2022	5/19/2022
4	Air Pressure	measure output air pressure with pressure sensor	~1kPa	Ada T.	PV	25	Numerical	4/26/2022	5/19/2022
5	Portable	measure battery life in hours using a stopwatch	1 hr	Deepthi R.	CV	5	Numerical	4/26/2022	5/19/2022
6	Lightweight	measure weight of backpack with oxygen concentration using a scale	< 10 lbs	Ada T.	DV	1	Numerical	5/3/2022	5/19/2022
7	Ergonomics	assess backpack fit	Comfortable	Ani S.	CV	1	Categorical	5/3/2022	5/19/2022
8	Cost	sum budget items	<= $1500	Ada T.	CV	1	Numerical	5/3/2022	5/19/2022
9	Visually Discrete	assess backpack look	typical backpack	Deepthi R.	CV	1	Categorical	5/3/2022	5/19/2022
10	Audio	asses noise level of device using a decibel reader	< 70dB	Ani S.	DV	25	Numerical	4/26/2022	5/19/2022

Figure 32. Design Verification Plan

Testing of our device was limited to utilizing an artificial lung, as we were not allowed to test on human volunteers. The testing was a similar set up as shown in Figure 33. All testing was completed on Cal Poly campus in a safe lab, the Bonderson High Bay, or an outdoor setting.

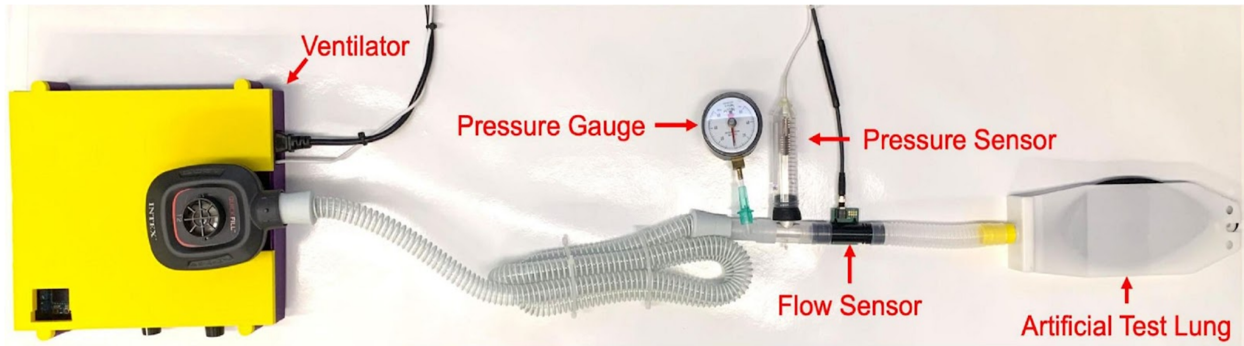


Figure 33. Device Testing Layout Example

Measuring the Saturation Time of Absorbers:

Further testing was completed during the construction of the prototype which is not reported above in the DVP&R. These tests include measuring the time the solenoids need to be open or closed for having the most efficient supply of oxygen (Table 5).

Table 5: Saturation Time (seconds) of O_2 Concentration

Test Number	**1**	**2**	**3**	**4**	**5**	**6**	**Average**
Level 1	10.7	11.04	10.76	10.43	10.82	10.92	10.78
Level 2	10.65	10.5	10.45	10.77	10.67	9.68	10.45
Level 3	10.09	9.88	10.3	10.48	10.11	10.45	10.22
Level 4	10.23	10.21	9.67	10	9.95	10.11	10.03
Level 5	10.36	9.5	10.53	9.73	9.9	10.3	10.03

Optimizing the Solenoids Timing:

Oxygen concentration was then measured using the generated saturation time from the previous test, as well as other saturation times (Table 6). For reference, the oxygen concentration measured for a normal indoor and outdoor environment averaged at 25.4%.

Table 6: Oxygen Concentration (%) at Various Saturation Times

Test Number	*	**5 sec switch time**	**2.5sec switch time**	**3 sec switch time**	**3 sec & 1.5 sec trans time**	**3.5 sec**	**8 sec**
Level 1	33.8	42.8	37.8	42.3	43	41.7	41.6
Level 2	34.6	44.5	39.6	46	46.6	45.8	40.7
Level 3	34.4	47.3	42.2	49.5	50.7	49.2	40.2
Level 4	34.7	47.5	44.7	52.4	54	51.5	39.8
Level 5	35.4	48	47	54.9	56	54.7	39.8

*using average measurements from previous test

Measuring the Oxygen Flow Rate:

Oxygen flow rate was measured at all 5 levels to determine the rate at which pure oxygen is supplied to the patient (Figure 34). The time to fill a 1 quart size plastic bag (test lung) was initially recorded (seconds) and the flow rate was then calculated from this measurement (Table 7). These tests were conducted with the air compressor and the absorbers in operation only.

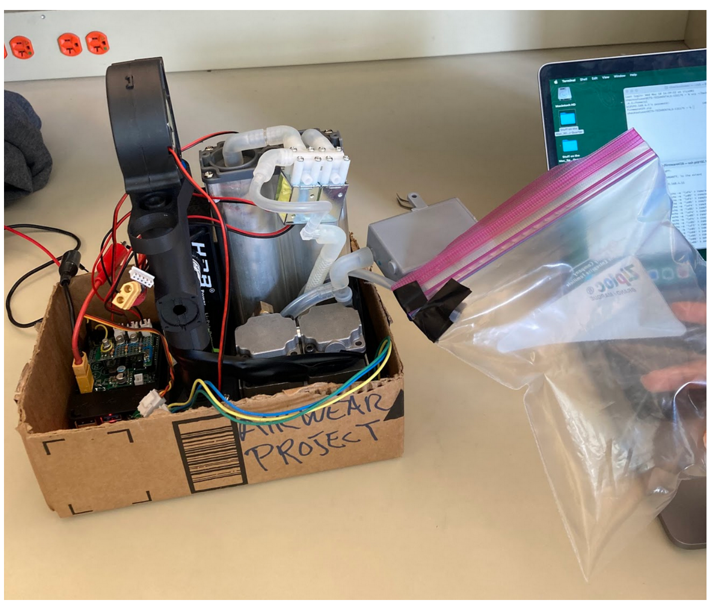


Figure 34: Measuring Oxygen Flow Rate

Table 7: Oxygen Flow Rate (liters/minute)

Time to fill bag (seconds)						
Test Number	**1**	**2**	**3**	**4**	**Average**	**Flow Rate**
Level 1	24.26	25	24.8	23.65	24.4275	2.45624808
Level 2	30	21.8	25.48	24.51	25.4475	2.35779546
Level 3	21.5	21.75	21.8	11.7	19.1875	3.12703583
Level 4	19	21.91	18	19.6	19.6275	3.05693542
Level 5	14.8	15	15.05	15.01	14.965	4.00935516

<u>Measuring the Fan's Flow Rate:</u>

Air flow rate was measured at all 3 levels to determine the rate at which air containing oxygen is supplied to the patient (Figure 35). The time to fill a 1 quart size plastic bag (test lung) was initially recorded (seconds) and the flow rate was then calculated from this measurement (Table 8). These tests were conducted with the fan in operation only.

Figure 35. Measuring Airflow Rate

Table 8: Airflow Rate (liters/minute)

Test Number	**1**	**2**	**3**	**4**	**Averag e**	**Flow Rate**
Level 1	6.83	6.18	5.71	6.43	6.2875	9.542744
Level 2	3.95	3.78	4.00	4.10	3.9575	15.16109
Level 3	2.20	3.23	2.45	2.93	2.7025	22.20167

Testing the Humidifier:

Humidification tests were completed by dripping a water-soaked paper towelette onto the humidifier (Figure 36).

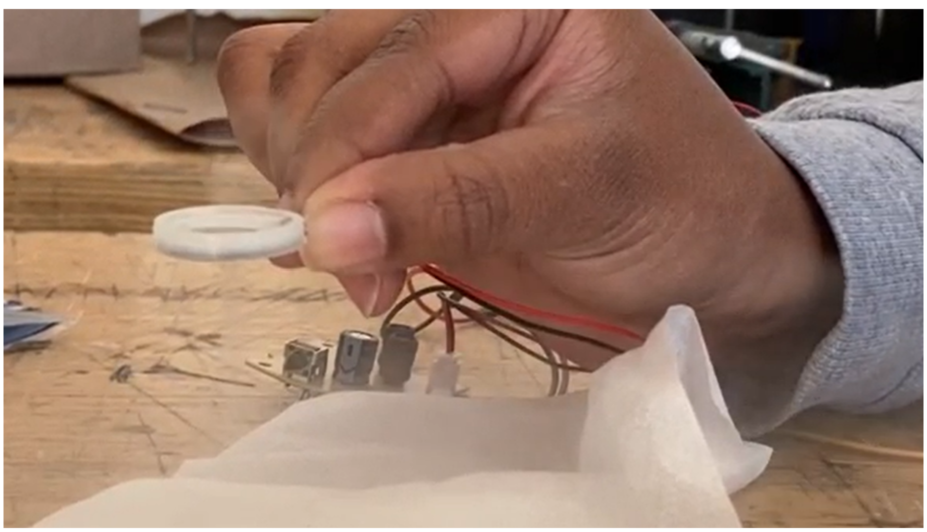


Figure 36. Water Evaporating on the humidifier

Note that the pressure of the air supplied by this device was not measured or recorded due to complications integrating the sensor.

Ergonomic and Other Testing:

Portability was measured by timing the functional duration (hours:minutes) of the device while running on the battery and at the highest oxygen flow rate setting.

The weight of the device (pounds) was measured using a scale (Figure 26).

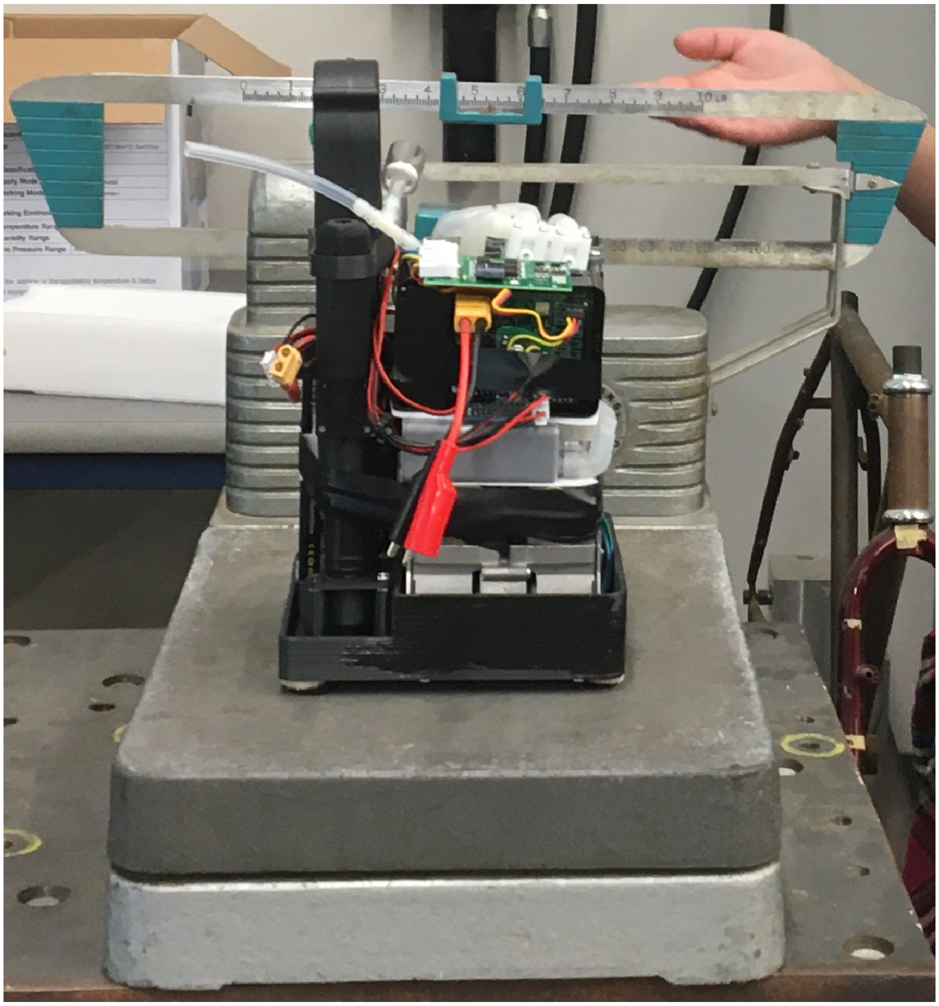


Figure 37. Scale Measuring the Weight (lbs) of the Device

The backpack containing the device was worn and assessed for comfortability to determine ergonomic quality (Figure 37).

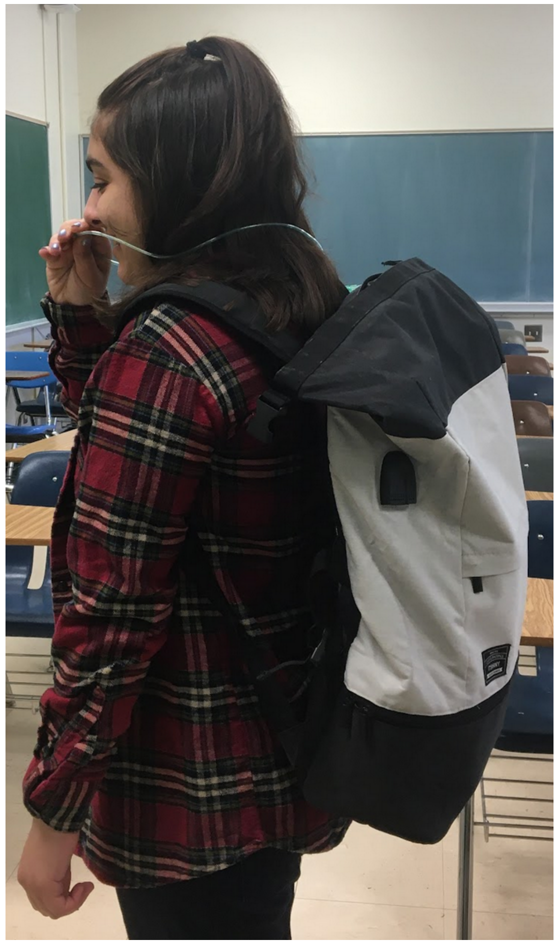


Figure 38. Worn Backpack Containing the Concentrator

The cost of manufacturing the device was measured by summing the budget items. The cost breakdown is explained in the previous section and represented in Table 3.

The aesthetic quality of the device was determined by assessing whether the device was visually discrete. The device was placed inside the backpack and the “look” of the entire product was assessed (Figure 38).

Figure 39. Backpack Containing the Concentrator

Sounds tests were run to determine the noise level of the device on all 5 levels. The device was placed in the backpack while noise level was recorded (Table 9).

Table 9: Noise level (dB)

	Noise level
Baseline environment	52
Level 1	57
Level 2	58
Level 3	61
Level 4	63
Level 5	62

Final Results:

Results of all tests were recorded and are detailed in the Design Verification Report (Figure 40). Seven of the 10 tests successfully passed the engineering specification. Two tests failed to pass the engineering specifications, however the sponsor was still satisfied by the result. One test was not conducted and therefore no conclusion on its result is recorded.

DVP&R							
Report Date		4/19/2022			REPORTING ENGINEER:		Deepthi R., Ani S., Ada T.
TEST PLAN				TEST REPORT			
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	TEST RESULTS			NOTES
				Test Result	Quantity Pass	Quantity Fail	
1	High Oxygen Concentration	measure output air oxygen concentration with oxygen flow sensor	90% O2	60% O2		F	test result still considered satisfactory by sponsor
2	High Oxygen Capacity	measure flow rate of output oxygenated air	5 LPM	4LPM		F	test result still considered satisfactory by sponsor
3	Humidification	measure output air humidity level with sensor	100%	high humidity	P		evaporation of liquid occurred
4	Air Pressure	measure output air pressure with pressure sensor	~1kPa	n/a			not measured
5	Portable	measure battery life in hours using a stopwatch	1 hr	1 hr 39min	P		
6	Lightweight	measure weight of backpack with oxygen concentration using a scale	< 10 lbs	5.4lbs	P		
7	Ergonomics	assess backpack fit	Comfortable	Comfortable	P		
8	Cost	sum budget items	<= $1500	$ 1,254.26	P		
9	Visually Discrete	assess backpack look	typical backpack	Discrete	P		device fit inside designated compartment of the backpack
10	Audio	asses noise level of device using a decibel reader	< 70dB	56-63dB	P		measured while the device was inside the backpack

Figure 40. Design Verification Report

Future Work

While the Air Wear team is finished with their original goal of replacing the oxygen tank in the O2+ team's prototype, there is still plenty of possible future work. In Fall Quarter of 2022, our sponsor plans to dedicate a Capstone team to optimizing the firmware, the sensor circuits, and the oxygen output on our device. Further work to integrate our system more securely and fashionably into a backpack is also possible, and further integration with the Oxygen Plus app is necessary before we can even consider getting this device ready for consumer use. It is also in any manufacturer or commercial owner's interest to make an original air compressor and original filter cylinders before monetizing this product.

Acknowledgements

The Air Wear team would like to thank our professors Dr. Jim Widmann, Dr. Vladimir Prodanov, Karla Carichner, and Dr. Lily Laiho for their mentorship, lectures, and advice on this project. It was an absolute pleasure learning from and with all of you.

We'd also like to thank our sponsor (and professor) Rich Murray for his guidance and direction for this project.

Additionally, we'd like to thank Jenna Chatillon (from CablesandSensors.com) and VARON Support for their help in getting technical information when we needed it.

We received funding from two very generous grants, the Hannah Forbes Fund and the Baker Koob Endowment. We are so grateful for their funding and support of this project; we were able to do (and learn) so much because of their belief in us and our project.

Lastly, to everyone else who got excited when we talked about our project or encouraged us along the way, thank you. We are incredibly touched by your support.

Appendix

Appendix A: House of Quality

This house of quality is a tool used to match specifications with customer requirements related to them. We ranked each specification based on what customer requirements it affects and included at least one specification for each requirement. Information on the Inogen One G4 and the Drive DeVilbiss 10L have been taken from their respective technical manuals.

	Customer (Step #1) Requirements (Whats)		Engineering Requirements (HOWS)										Benchmarks		
		Weighting (1 to 5)	Less than 10lbs	Wireless for 1 hr	35 dB (< 60 dB)	At least 1 replaceable parts between patients	Should fit in a normal bag (< 26L)	1 piece of exposed hardware (nasal cannula)	0-10 LPM capable and renewable	< $1000	Up to100% Oxygen Concentration	Up to100% Humidification	Oxygen+ (prototype)	Inogen One G4	Drive DeVilbiss 10L
Customer Requirements (Step #2)	Light Weight	4	9										5	5	1
	Portability*	4		9									1	5	1
	Quiet	2			9								5	5	3
	Easy to Sanitize	3				9							2	5	5
	Wearable*	4	3				9	3					3	5	1
	Comfortable	1	1					9				3	1	2	1
	High Oxgen Capacity	5		3					9				2	2	5
	Inexpensive	5								9	3		5	1	4
	Oxygen Purity	3	1								9		4	5	5
	Room for personal items	1	1				3						1	1	1
	Ergonomic	3	9										1	5	3
	Discrete	2						9					1	5	3
	Not Seasonal	1						3					1	5	5
	Size Inclusive	1					1						1	5	5
	Units		Lbs	hr	dB	# Parts	L	# Parts	Lpm	$	%O2	%			
	Targets		< 10	1	35	>0	< 26	1	20(HF) 6(LF)	500	100	100			
	Inogen One G4		3.3	5*	40**	1	1.85	0 i	0.630(LF)	3,665	87 - 96	100			
	Drive DeVilbiss 10L		42	0 ii	< 69	1	65	0 i	10 (HF)	1,399	87 - 96	100			
	Importance Scoring		80	51	18	27	40	42	45	45	42	3			
	Importance Rating (%)		100	64	23	34	50	53	56	56	53	4			
9	Strong Correlation														
3	Medium Correlation														
1	Small Correlation														
Blank	No Correlation														
	*on lowest setting														
	** on average														
	i designed for permanent use														
	ii no battery														

Appendix B: Safety Checklist

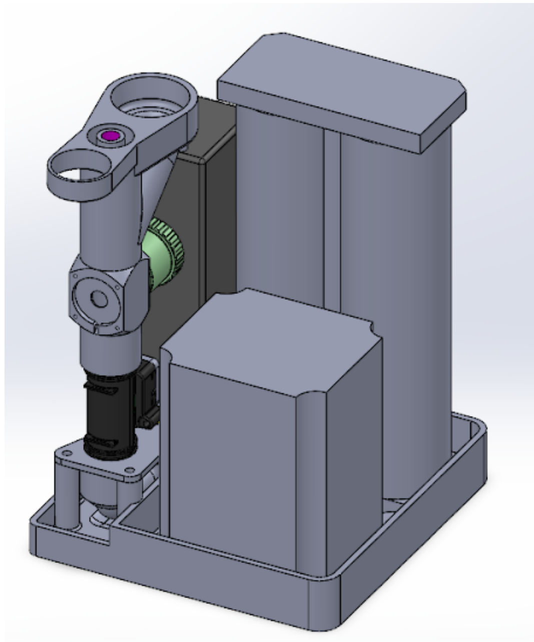
SENIOR PROJECT CONCEPTUAL DESIGN REVIEW HAZARD IDENTIFICATION CHECKLIST

Y	N	
■		Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	■	Can any part of the design undergo high accelerations/decelerations?
	■	Will the system have any large moving masses or large forces?
	■	Will the system produce a projectile?
■		Would it be possible for the system to fall under gravity creating injury?
	■	Will a user be exposed to overhanging weights as part of the design?
	■	Will the system have any sharp edges?
■		Will all the electrical systems be properly grounded?
	■	Will there be any large batteries or electrical voltage in the system above 40 V either AC or DC?
■		Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
■		Will there be any explosive or flammable liquids, gases, dust fuel part of the system?
	■	Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	■	Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	■	Can the system generate high levels of noise?
■		Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures ,etc…?
■		Will the system be easier to use safely than unsafely?

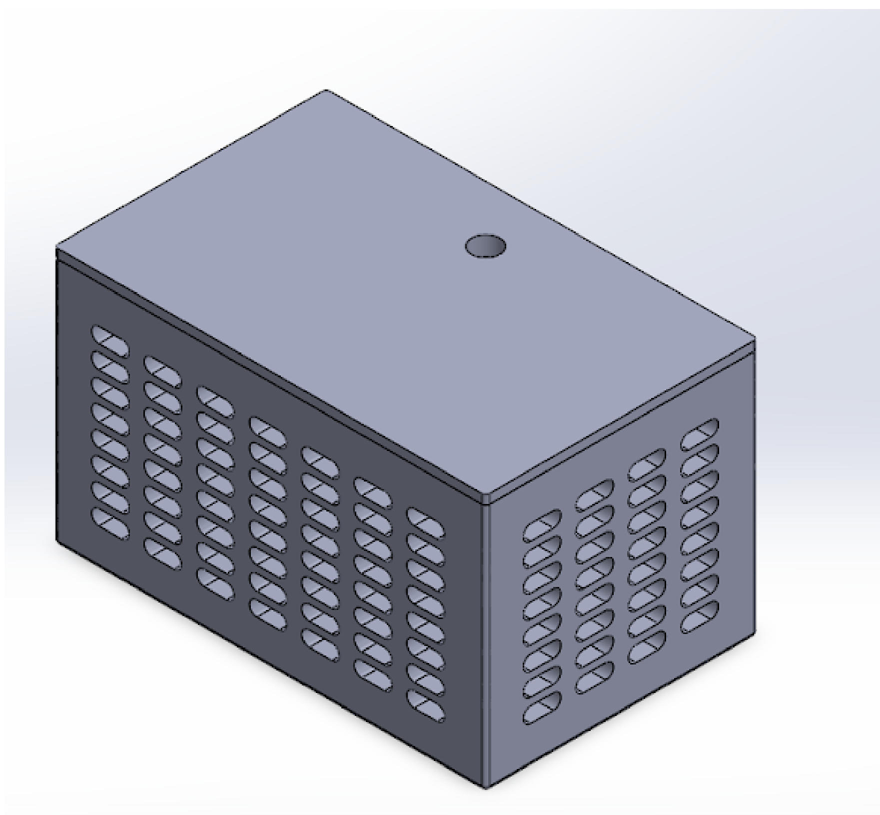
Will there be any other potential hazards not listed above? If yes, please explain below:

➔ Liquid spills near devices could interact with circuitry and mechanical systems.

Appendix C: Final Drawings

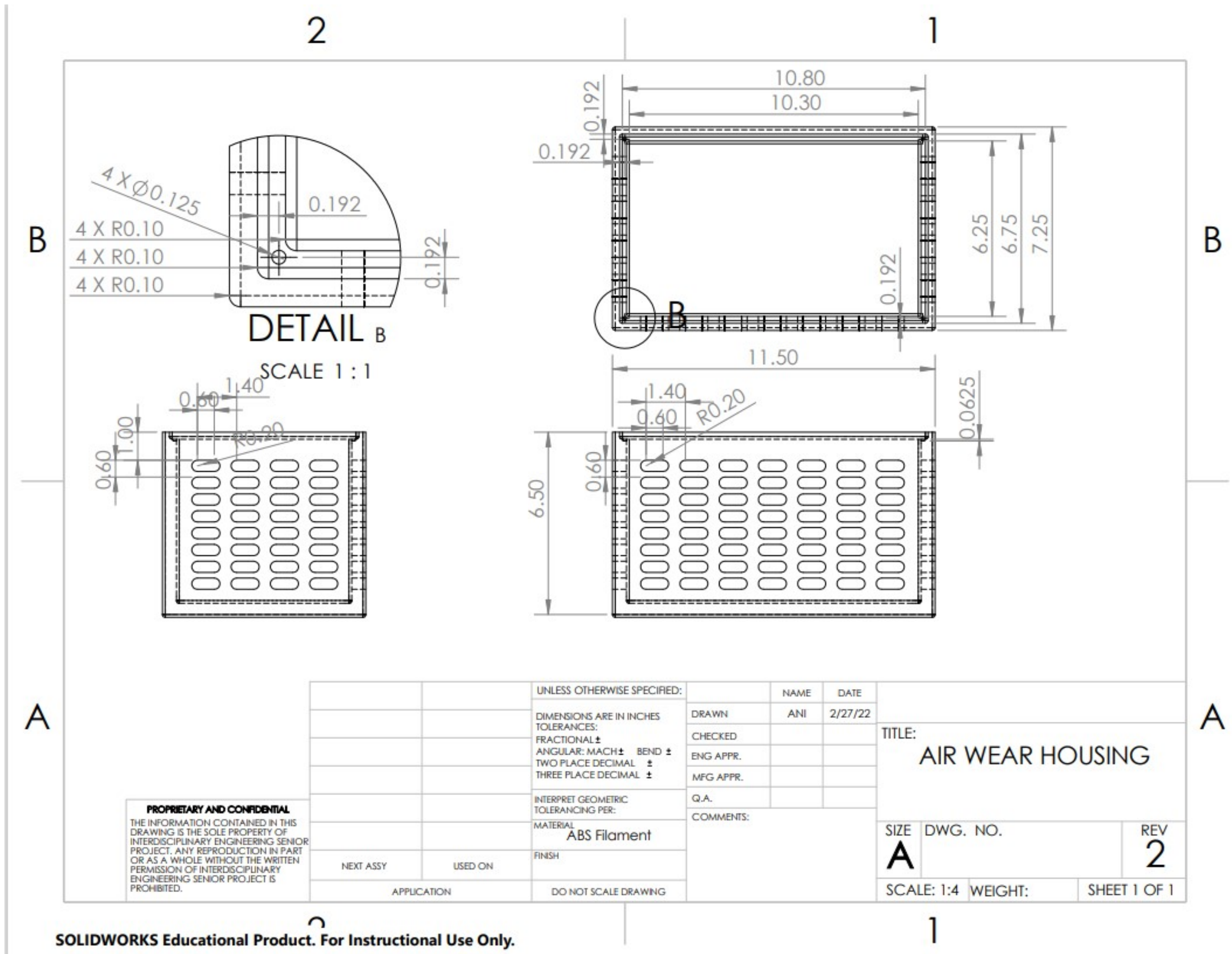


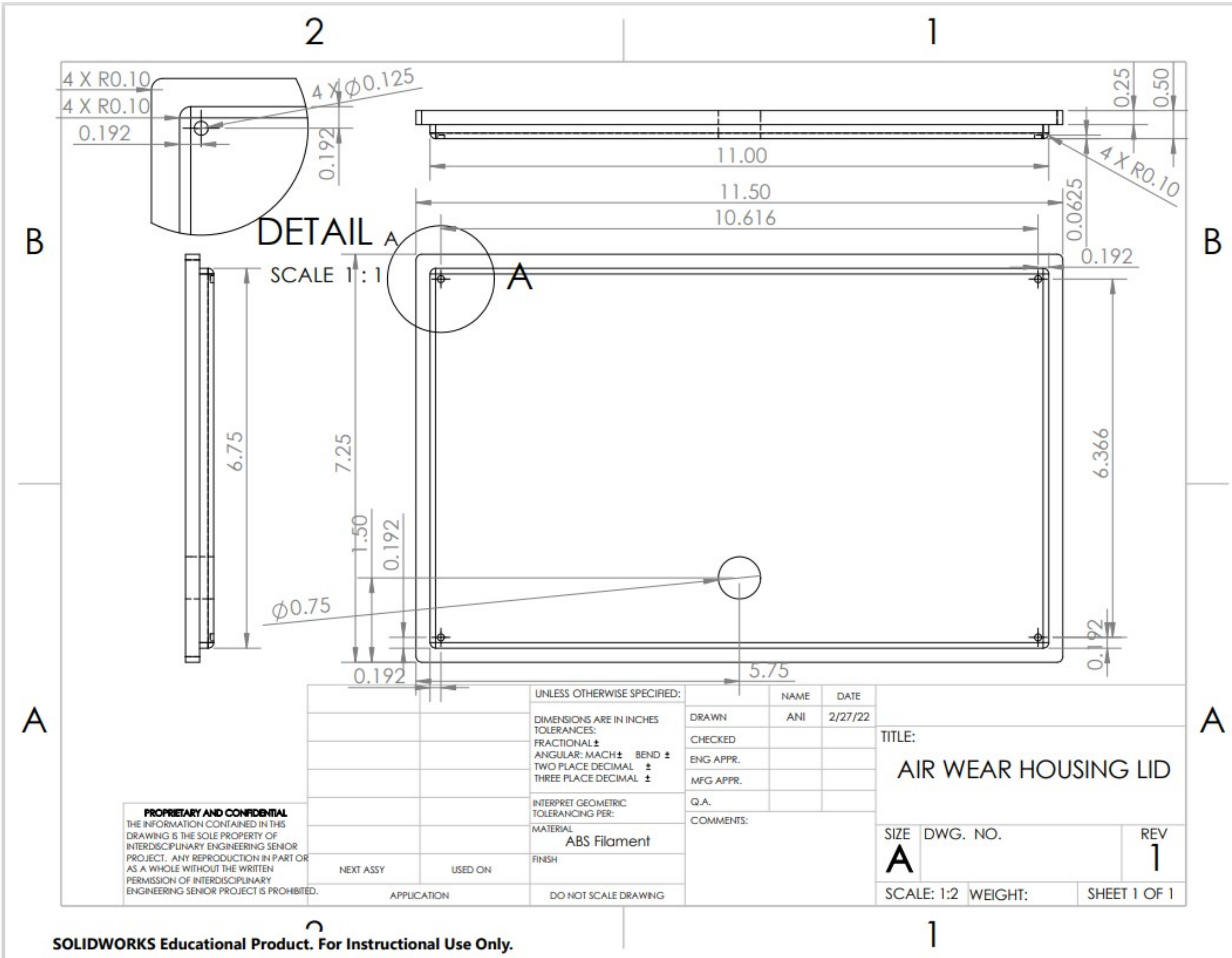
System Frame From Last Year With Rough Estimations of New Hardware



Air Wear External Housing Assembly

The next few images are Engineering Drawings, but they are hard to fit on the page. Because of this, they (along with their respective SolidWorks parts) will be saved on a public Google Drive File which can be accessed here.

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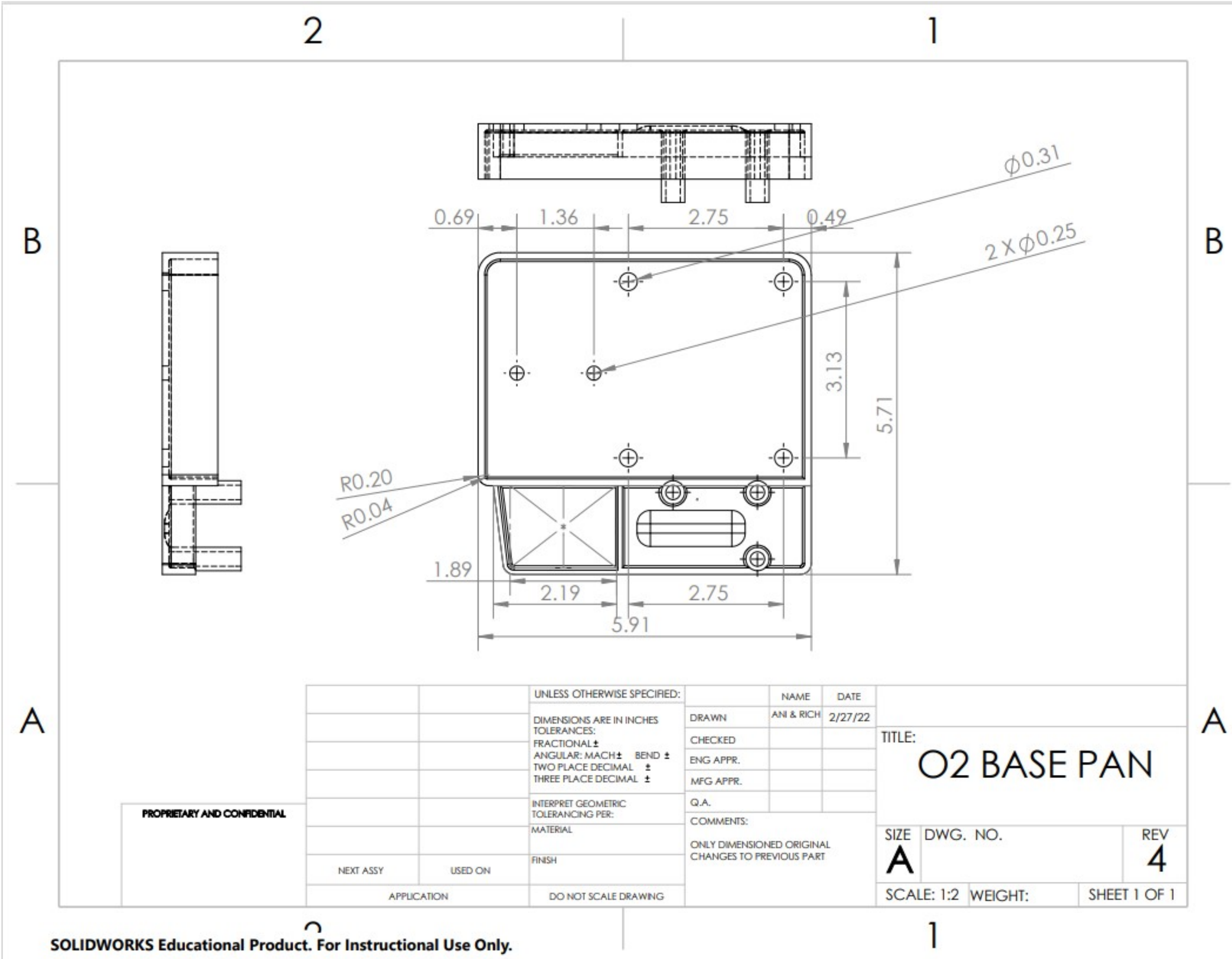
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF INTERDISCIPLINARY ENGINEERING SENIOR PROJECT. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF INTERDISCIPLINARY ENGINEERING SENIOR PROJECT IS PROHIBITED.
SOLIDWORKS Educational Product. For Instructional Use Only.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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
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SOLIDWORKS Educational Product. For Instructional Use Only.

Appendix D: BOM for the Hardware

Item	Part #	Link	Price/Unit	Quantity Needed	Quantity for Purchase	Price	Status
CMOS amplifier	LMC622AIN	link	$2.44	1	2	$4.88	
12-bit ADC	MCP3221	link	$1.75	1	2	$3.50	Given only 1
Bi-directional Level Shifter	757	link	$3.95	1	2	$7.90	
BJT	2N2222A	link	$0.35	1	2	$0.70	
NMOS	IRLB3813PBF	link	$1.86	1	2	$3.72	
Step down voltage regulator	D24V50F5	link	$24.95	1	2	$49.90	
Power sensor	INA260	link	$13.97	1	2	$27.94	
Buck Boost	MC34063A	link	$0.92	1	2	$1.84	
Battery connectors	XT60	link	$1.50	1	2	$3.00	
Power mosfet	AUIRLR3410	link	$2.36	1	2	$4.72	
NMOS	FQD5N20LTM	link	$0.79	5	7	$5.53	
O2 Sensor	PSR11917M	link	$84.00	1	1	$84.00	
Humidifier	WG3166A	link	$6.08	1	3	$18.24	Given only 1
Humidity sensor	DHT11	link	$5.00	1	1	$5.00	
10k ohm Resistor	-	-	-	1	1	-	
1k ohm Resistor	-	-	-	7	7	-	
2.2k ohm Resistor	ROX2SJ2K2	link	$0.41	1	2	$0.82	
330 ohm Resistor	ROX1SJ330R	link	$0.38	1	2	$0.76	
1 ohm Resistor	ROX1SJ1R0	link	$0.38	3	5	$1.90	
180k ohm Resistor	ROX2SJ180K	link	$0.41	1	2	$0.82	
15k ohm Resistor	ROX3SJ15K	link	$0.39	1	2	$0.78	
2.7k ohm Resistor	ROX1SJ2K7	link	$0.38	1	2	$0.76	
180 ohm Resistor	ROX1SJ180R	link	$0.38	1	2	$0.76	
100nF Ceramic 25V, Capacitor	FK18X7R1E104K	link	$0.32	3	5	$1.60	
220uF Electrolytic 25V, Capacitor	-	-	-	1	1	-	
1nF Ceramic 25V, Capacitor	C320C102K3G5TA	link	$0.43	1	1	$0.43	
330uH, 2A, Inductor	-	-	-	1	1	-	
180uH, 2A, Inductor	-	-	-	1	1	-	
Diode (Vrmax = 50V)	IN4001G	link	$0.31	5	5	$1.55	
				Total Price		**$231.05**	

Not ordering them due to various reasons

Given but still need to order more

Given and don't need to order more

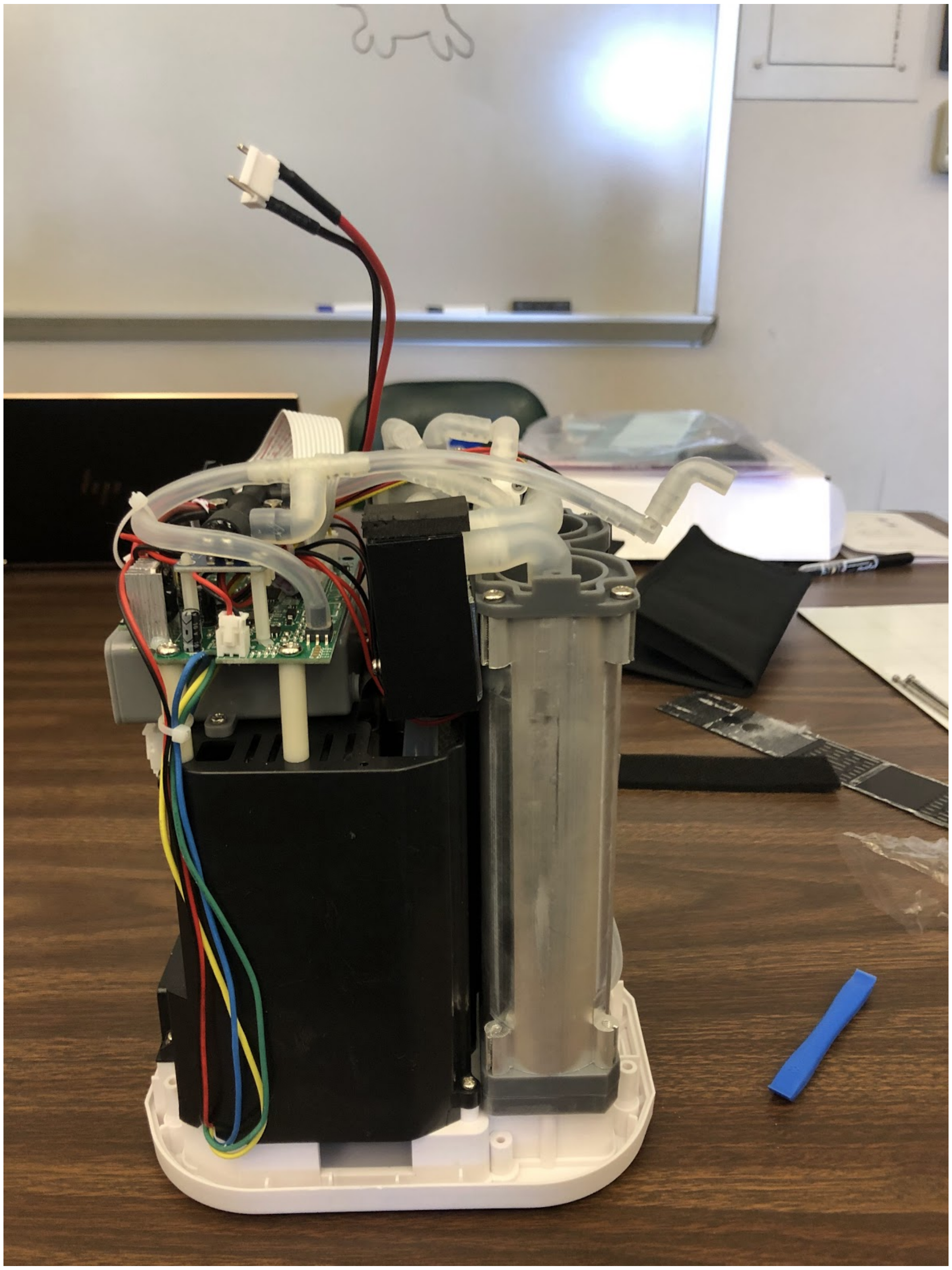
Purchased

Appendix E: Analysis and Reverse Engineering Information

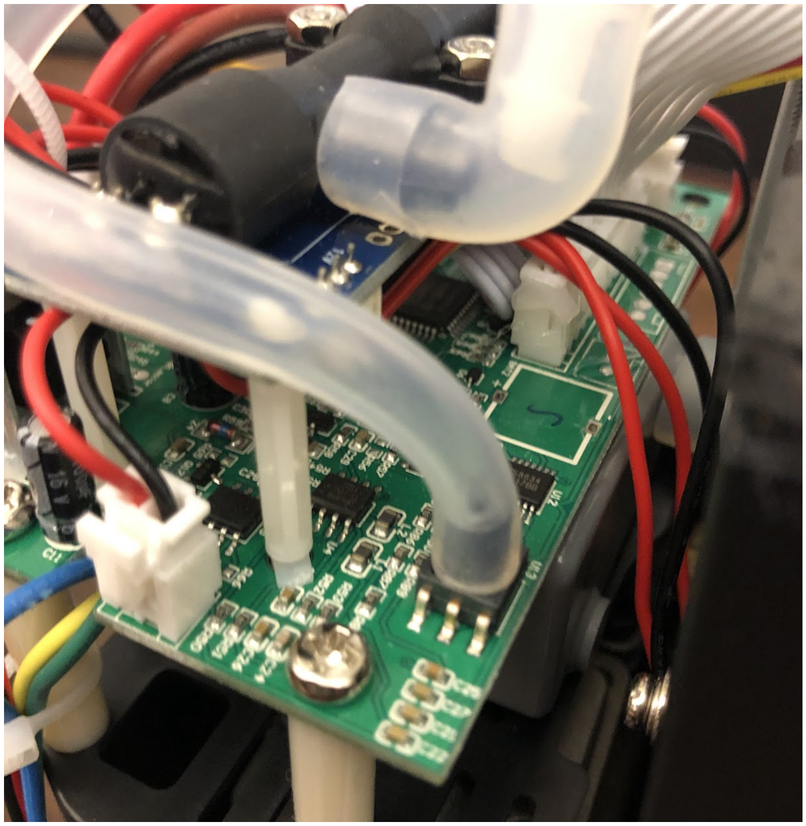
Initial Condition and Exterior Testing:

VARON 5 LPM Oxygen Concentrator

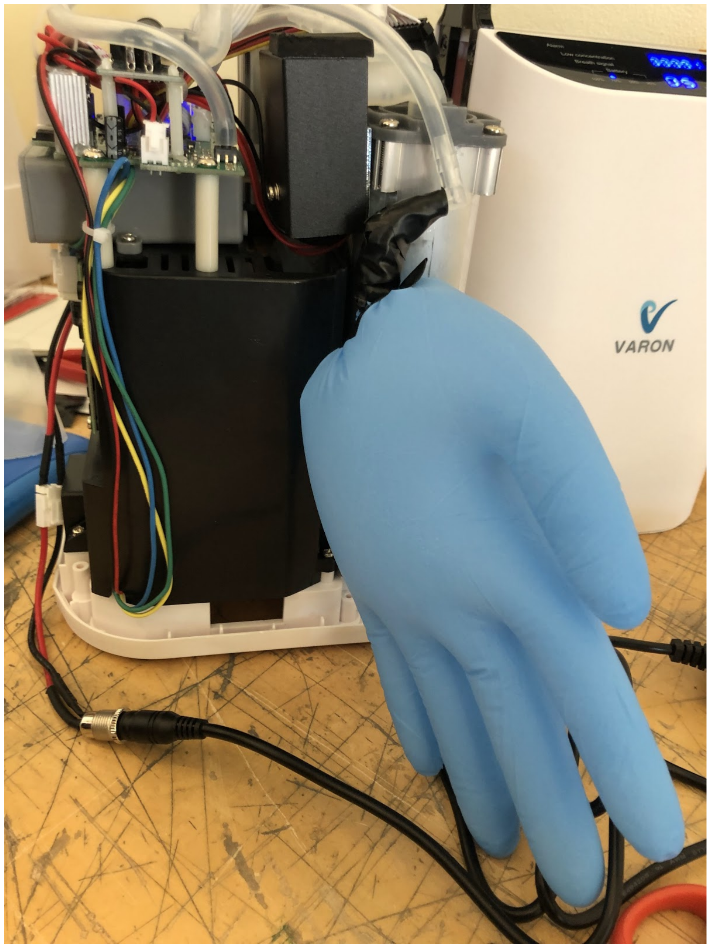
VARON Oxygen Concentrator Worn in Provided Backpack



VARON Oxygen Concentrator Without Casing



Back Pressure Sensor



Initial Test for Airflow (the glove was easier to make airtight)
The purpose of this test was mainly to figure out how to measure the flow rate. Once we got the breathing rhythm correct we moved to a known volume.

Known Volume Flow Rate Testing Setup

Flow Rate Testing Results:

Concentrator Flow Rate Settings										
Level 5	1.27	1.07	0.55	1.05	1.05	0.59	1.10	1.24	1.26	1.02

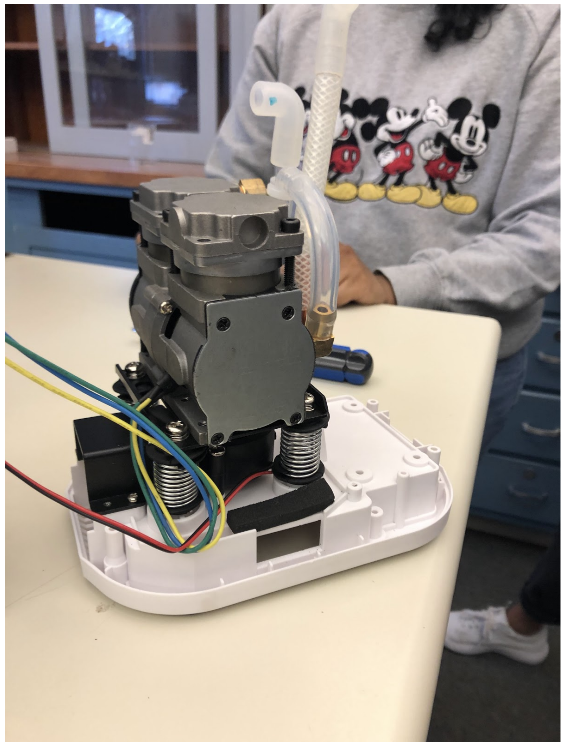
Battery Life Testing Results:

Since we wanted to find the minimum battery life, we only calculated how long the battery lasted on its highest setting, level 5. The battery lasted **1:36.56** until it died. It then took about 3 hours to recharge completely.

Noise Level Test:

Again, we wanted to check the maximum noise created so we tested level 5. The iPhone's decibel meter picked up a range of **69 - 79 dB**, which tells us that we have to factor noise reduction into our design in order for it to meet specifications.

Further Teardown and Component Testing:



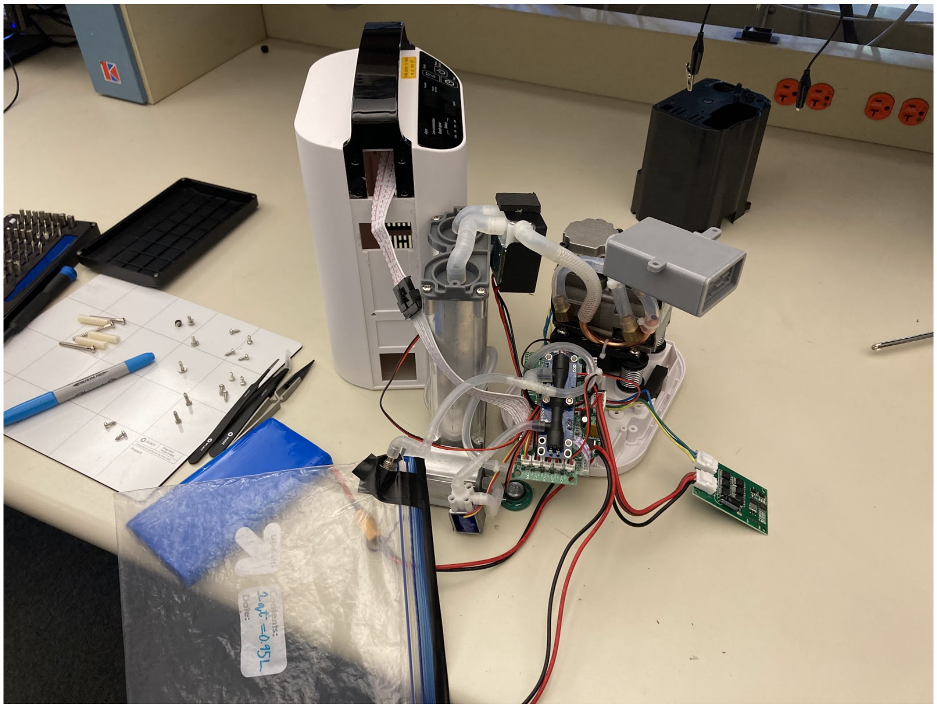
Air Compressor and Shock Absorption System

Air Compressor's Motor's PWM Signals

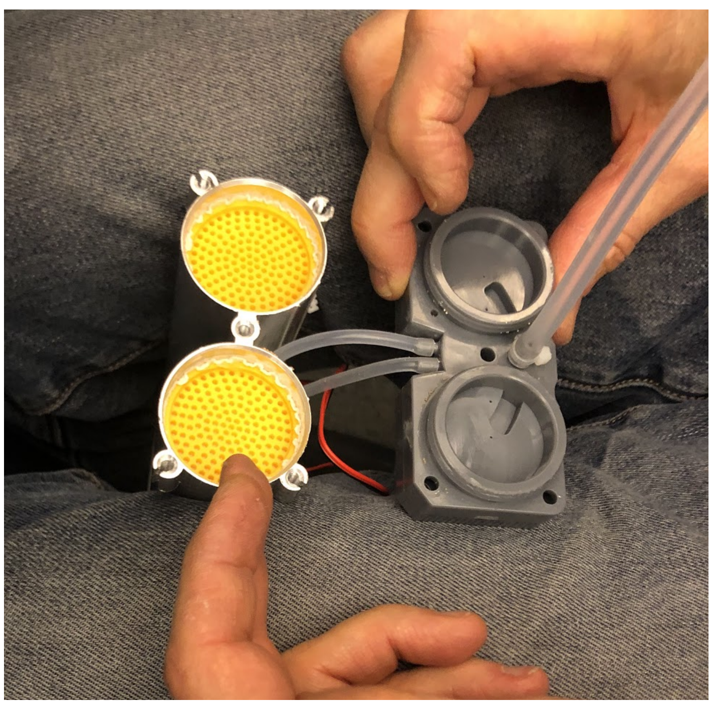
VARON Level Duty Cycles:

Level	Duty Cycle
1	68.3
2	73.5
3	78.2
4	88.1

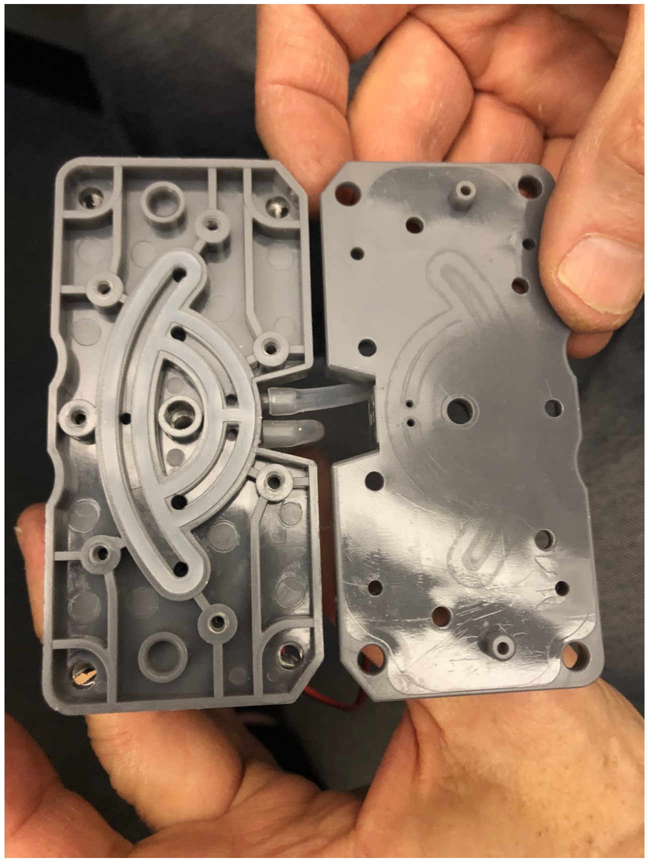
5	93.0



Still Functional Exposed System (While Testing Duty Cycles)



Filter Cylinders: Filter Medium Exposed

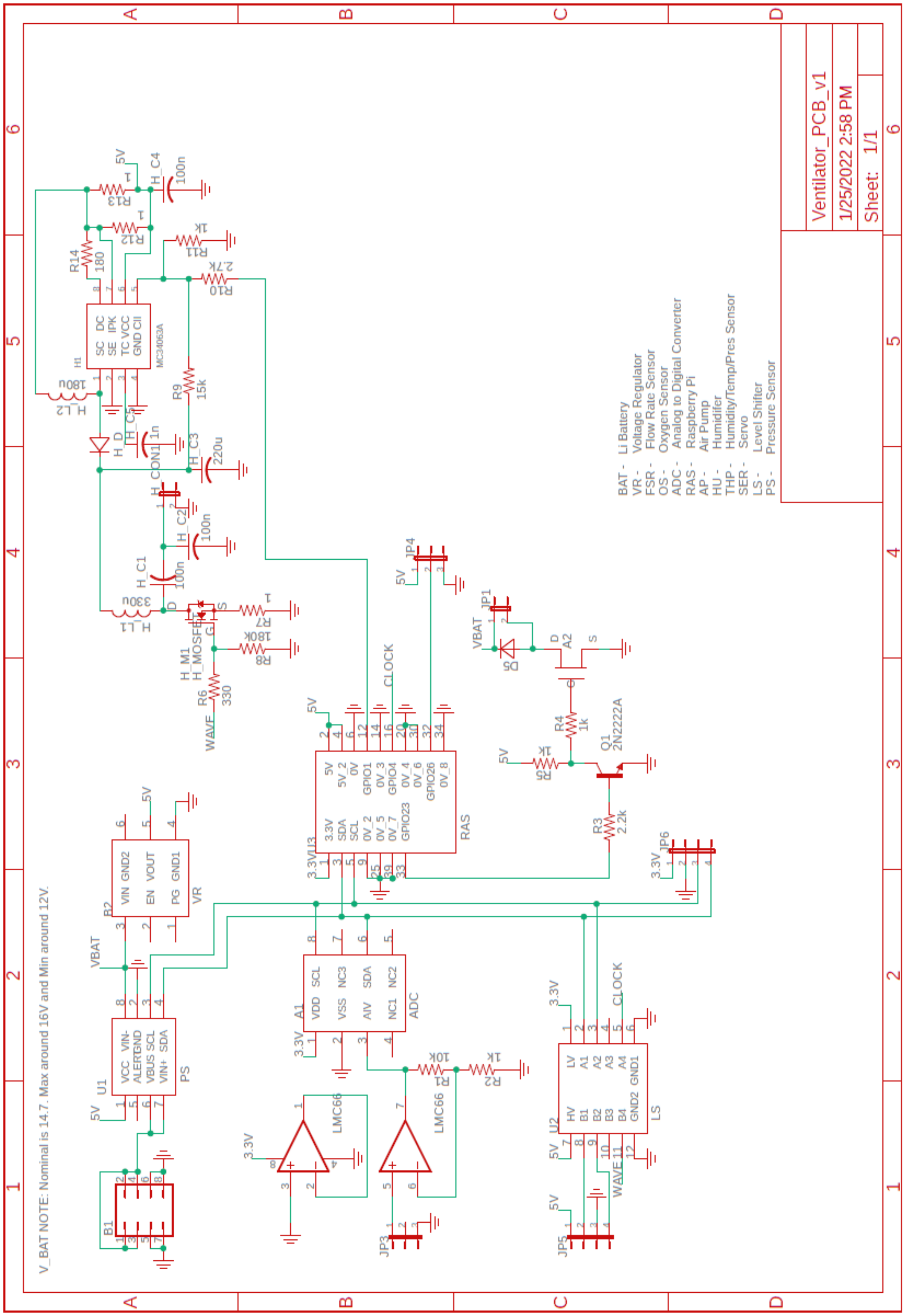


Filter Cylinders: Top Plate Removed

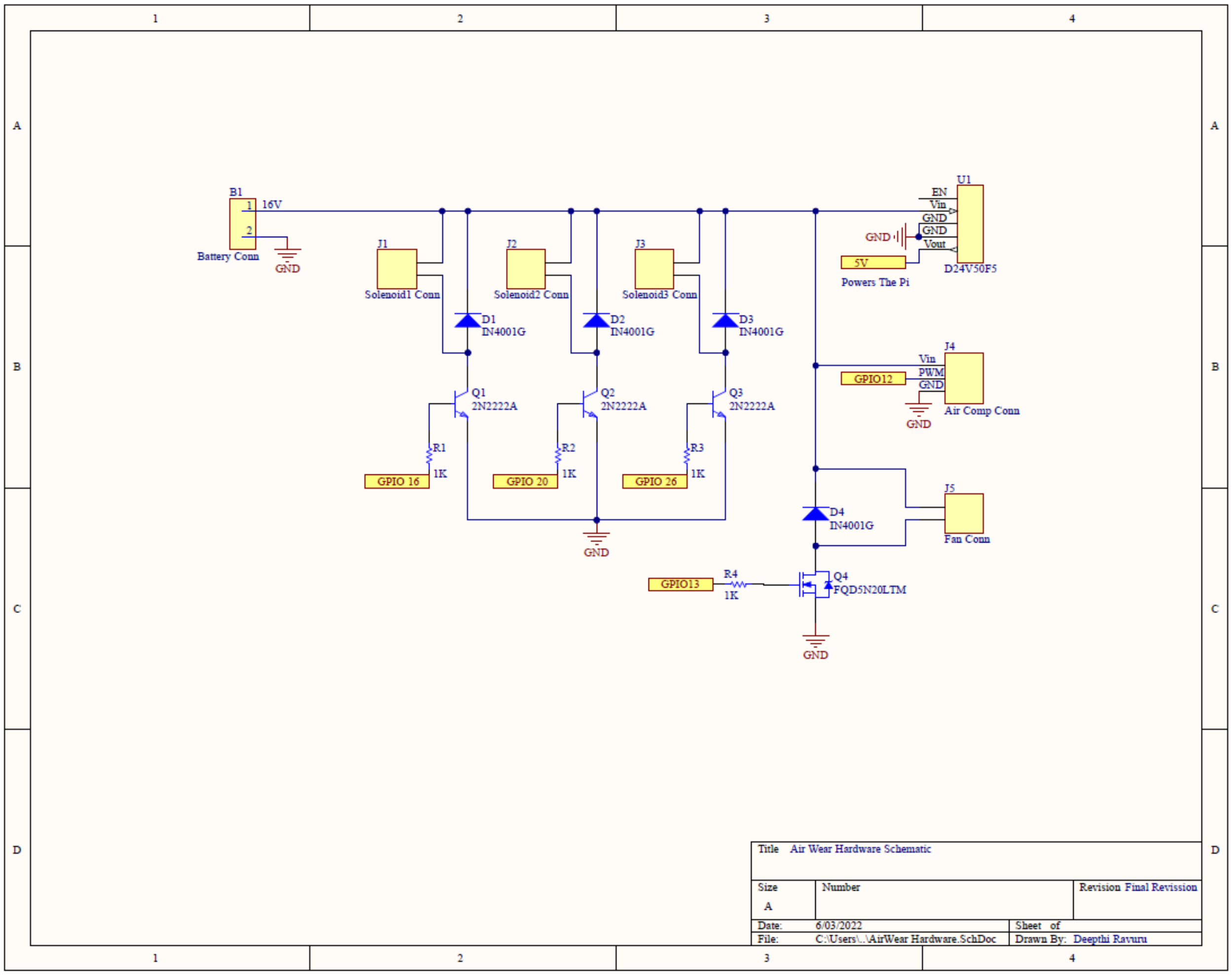
Analysis Still Needed:

- Oxygen Concentration Outputted
- Oxygen Purity Timing (For Solenoids Driving PSA)
- Further Analog Control

Appendix F: Sensors Circuit by The O2+ Team



Appendix G: Hardware Schematic of Air Wear Team



Appendix H: Code

*Note: The code added in this section is only code the Air Wear team has modified and added on. There is more code that isn't added in this section, such as the code for the sensors.

pins.h

```c
#ifndef PIN_H
#define PIN_H

// PINS ARE GIVEN IN PWM
// PWM PINS
#define AIR_PUMP_PWM 13
#define OXYGEN_VALVE_PWM 12

// PINS FOR THE SOLENOIDS CONTROLLING THE ABSORBERS
#define SOLENOID1 16
#define SOLENOID2 20
#define SOLENOID3 26


#endif
```

init.c

```c
#include <pigpio.h>
#include <unistd.h>
#include <stdint.h>
#include <stdlib.h>
#include <stdio.h>
#include "system.h"
#include "remote.h"
#include "pins.h"
#include "drivers/afm3000.h"
#include "drivers/bma150.h"
#include "drivers/mcp3021.h"

void init_hardware(){
    // initialize pigpio
    gpioInitialise();

    // --- FAN PWM --- //
    // configure fan pwm
    gpioSetPWMrange(AIR_PUMP_PWM, AIR_PUMP_RANGE); // range of acceptable values is 0 to 1000
    gpioSetPWMfrequency(AIR_PUMP_PWM, AIR_PUMP_FREQ); // frequency of 2 KHz

    // default to 0% duty cycle
    gpioPWM(AIR_PUMP_PWM, 0);

    // --- AIR COMPRESSOR CONTROL (controls the oxygen flow) --- //

    gpioSetPWMrange(OXYGEN_VALVE_PWM, OXYGEN_RANGE);
    gpioSetPWMfrequency(OXYGEN_VALVE_PWM, OXYGEN_FREQ);

```

```c
    // default to 0% duty cycle (OFF)
    gpioPWM(OXYGEN_VALVE_PWM, 0);

    // --- HUMIDIFIER CONTROL --- //
    //gpioSetMode(HUMIDIFIER_CONTROL_PIN, PI_OUTPUT);

    // --- SOLENOIDS CONTROL FOR THE ABSORBERS --- //
    gpioSetMode(SOLENOID1, PI_OUTPUT);
    gpioSetMode(SOLENOID2, PI_OUTPUT);
    gpioSetMode(SOLENOID3, PI_OUTPUT);

    //printf("SOLENOIDS are set as output pins\n");


    printf("[INIT] Finished hardware initialization\n");
}

void init_system(){
    //setAirFlowLevel(0);
    setOxygenLevel(OXY_LEVEL0);
    setHumidifierLevel(HUM_OFF);
}

int main(){
    int32_t temp, pressure, humidity;
    int count = 0;
    long sum = 0;
    double avg = 0;
```

```c

    // ------------ Code for solenoids ------------ //
    int sat_time = 3;        // 3 sec
    int trans_time = 1.5;    // 1.5 sec
    // -------------------------------------------- //

    int16_t o2_buf[10];
    o2_buf[0] = 0;
    o2_buf[1] = 0;
    o2_buf[2] = 0;
    o2_buf[3] = 0;
    o2_buf[4] = 0;
    o2_buf[5] = 0;
    o2_buf[6] = 0;
    o2_buf[7] = 0;
    o2_buf[8] = 0;
    o2_buf[0] = 0;

    // 'POST'
    init_hardware();
    init_remote();
    init_system();

    // scan
    while(1){
        //count++;
        sys_read_airflow();
        sys_read_tph();
        sys_read_o2();
```

```
sys_read_spo2();

o2_buf[0] = o2_buf[1];
o2_buf[1] = o2_buf[2];
o2_buf[2] = o2_buf[3];
o2_buf[3] = o2_buf[4];
o2_buf[4] = o2_buf[5];
o2_buf[5] = o2_buf[6];
o2_buf[6] = o2_buf[7];
o2_buf[7] = o2_buf[8];
o2_buf[8] = o2_buf[9];
o2_buf[9] = sys_o2;

avg = (o2_buf[0] + o2_buf[1] + o2_buf[2] + o2_buf[3] + o2_buf[4] + o2_buf[5] + o2_buf[6] + o2_buf[7] + o2_buf[8] + o2_buf[9]) / 10;

```

```
        // ---------------- CODE FOR THE SOLENOID LOGIC -------------------//

        if (sys_oxygen_level == OXY_LEVEL0){
            gpioWrite(SOLENOID1, 0);
            gpioWrite(SOLENOID2, 0);
            gpioWrite(SOLENOID3, 0);
        }
        else {
            gpioWrite(SOLENOID3, 0);
            gpioWrite(SOLENOID1, 1);
            sleep(sat_time);

            gpioWrite(SOLENOID3, 1);
            sleep(trans_time);
            gpioWrite(SOLENOID1, 0);

            gpioWrite(SOLENOID3, 0);
            gpioWrite(SOLENOID2, 1);
            sleep(sat_time);

            gpioWrite(SOLENOID3, 1);
            sleep(trans_time);
            gpioWrite(SOLENOID2, 0);
        }
        update_remote();
        usleep(100000); // 100 ms
    }
}
```

system.h

```c
#ifndef SYSTEM_H
#define SYSTEM_H

#include <stdint.h>

// Contains available humidifier software states
typedef enum {HUM_OFF, HUM_ON} HumidifierLevel;

// humidifier controls
int toggleHumidifier();
int setHumidifierLevel(HumidifierLevel);

HumidifierLevel getHumidifierLevel();

#define HUMIDIFIER_CLOCK_PIN 4
#define HUMIDIFIER_CLOCK_FREQ 113500

// air compressor controls
#define NUM_OXYGEN_LEVELS 6
typedef enum {OXY_LEVEL0, OXY_LEVEL1, OXY_LEVEL2, OXY_LEVEL3, OXY_LEVEL4, OXY_LEVEL5} OxygenLevel;
#define OXYGEN_RANGE 1000
#define OXYGEN_FREQ 400

extern OxygenLevel sys_oxygen_level;

int increaseOxygenLevel();
int decreaseOxygenLevel();
int setOxygenLevel(OxygenLevel);
OxygenLevel getOxygenLevel();

// fan controls
#define AIR_PUMP_RANGE 1000 // range of acceptable values is 0 to 1000
#define AIR_PUMP_FREQ 2500 // default frequency 2 KHz (val should be 2000)

// Contains the available software states of the air intake fan
// duty cycles: {90, 60, 30, 0}
#define NUM_AIR_FLOW_LEVELS 4
typedef enum {IF_OFF, IF_LOW, IF_MED, IF_HIGH} AirFlowLevel;

// air pump controls
int increaseAirFlowLevel();
int decreaseAirFlowLevel();
int setAirFlowLevel(AirFlowLevel);
```

system.c

```c
#include <pigpio.h>
#include <stdio.h>
#include <stdint.h>
#include <unistd.h>
#include "system.h"
#include "pins.h"
#include "remote.h"
#include "drivers/afm3000.h"
#include "drivers/hw_pressure.h"
#include "drivers/htu21d.h"
#include "drivers/bma150.h"
#include "drivers/mcp3021.h"

```

```
// ------------------ HUMIDIFIER ------------------------ //

HumidifierLevel humidifierLevel;

// simulates a button press for the water atomizer
int toggleHumidifier(){
    if (humidifierLevel == 0){
        gpioHardwareClock(HUMIDIFIER_CLOCK_PIN, HUMIDIFIER_CLOCK_FREQ);
    }
    else{
        gpioHardwareClock(HUMIDIFIER_CLOCK_PIN, HUMIDIFIER_CLOCK_FREQ);
    }
    humidifierLevel ^= 1; // toggle humidifier level
}
// toggle the humidifier if current state is different from the requested state
int setHumidifierLevel(HumidifierLevel level){
    if (!(humidifierLevel == level)){ // this works because HumidifierLevel is boolean
        toggleHumidifier();
    }
}
HumidifierLevel getHumidifierLevel(){
    return humidifierLevel;
}

// ------------------ AIR PUMP --------------------------- //

AirFlowLevel airFlowLevel;

```

```
// private helper
int updateAirFlowLevel(){
    // airFlowLevel = 0 -> 100% duty cycle (full speed)
    // airFlowLevel = 1 -> 60% duty cycle  (med speed)
    // airFlowLevel = 2 -> 30% duty cycle  (low speed)
    // airFlowLevel = 3 -> 0% duty cycle   (off)
    printf("Updating airflow!\n");
    gpioPWM(AIR_PUMP_PWM, (int)(AIR_PUMP_RANGE * (1.0 - (airFlowLevel * 0.33))));
}
int increaseAirFlowLevel(){
    if (airFlowLevel < NUM_AIR_FLOW_LEVELS - 1){ // ensure we stay in range
        airFlowLevel++;
        updateAirFlowLevel();
    }
}
int decreaseAirFlowLevel(){
    if (airFlowLevel > 0){ // ensure we stay in range
        airFlowLevel--;
        updateAirFlowLevel();
    }
}
```

```
int setAirFlowLevel(AirFlowLevel newLevel){
    if (newLevel == airFlowLevel){
        return 0;
    }
    if (newLevel >= 0 && newLevel < NUM_AIR_FLOW_LEVELS){
        airFlowLevel = newLevel;
        updateAirFlowLevel();
    }
}

AirFlowLevel getAirFlowLevel(){
    return airFlowLevel;
}

```

```
// --------------- OXYGEN VALVE ---------------------------- //

OxygenLevel sys_oxygen_level;

// private helper
int updateOxygenLevel(){
    // OXY_LEVEL1 -> 0% duty cycle (OFF)
    // OXY_LEVEL2 -> 50% duty cycle (low speed)
    // OXY_LEVEL3 -> 60% duty cycle (mid-low speed)
    // OXY_LEVEL4 -> 70% duty cycle (mid speed)
    // OXY_LEVEL5 -> 80% duty cycle (mid-high speed)
    // OXY_LEVEL6 -> 90% duty cycle (high speed)

    if (sys_oxygen_level == OXY_LEVEL0){
        gpioPWM(OXYGEN_VALVE_PWM, 0);
    }
    if (sys_oxygen_level == OXY_LEVEL1){
        gpioPWM(OXYGEN_VALVE_PWM, (int)(OXYGEN_RANGE*0.5));
    }
    if (sys_oxygen_level == OXY_LEVEL2){
        gpioPWM(OXYGEN_VALVE_PWM, (int)(OXYGEN_RANGE*0.6));
    }
    if (sys_oxygen_level == OXY_LEVEL3){
        gpioPWM(OXYGEN_VALVE_PWM, (int)(OXYGEN_RANGE*0.7));
    }
    if (sys_oxygen_level == OXY_LEVEL4){
        gpioPWM(OXYGEN_VALVE_PWM, (int)(OXYGEN_RANGE*0.8));
    }
    if (sys_oxygen_level == OXY_LEVEL5){
        gpioPWM(OXYGEN_VALVE_PWM, (int)(OXYGEN_RANGE*0.9));
    }
```

```
}

int increaseOxygenLevel(){
    if (sys_oxygen_level < NUM_OXYGEN_LEVELS - 1){ // ensure we stay in range
        sys_oxygen_level++;
        updateOxygenLevel();
    }
}
int decreaseOxygenLevel(){
    if (sys_oxygen_level > 0){ // ensure we stay in range
        sys_oxygen_level--;
        updateOxygenLevel();
    }
}
int setOxygenLevel(OxygenLevel newLevel){
    if (newLevel == sys_oxygen_level){
        return 0;
    }
    if (newLevel >= 0 && newLevel < NUM_OXYGEN_LEVELS){
        sys_oxygen_level = newLevel;
        updateOxygenLevel();
    }
}
OxygenLevel getOxygenLevel(){
    return sys_oxygen_level;
}
```

remote.c

```c
#include <unistd.h>
#include <stdio.h>
#include <stdlib.h>
#include <stdint.h>
#include <fcntl.h>
#include <pthread.h>
#include <semaphore.h>
#include <sys/wait.h>
#include <pthread.h>
#include "remote.h"
#include "system.h"
#include <string.h>

// TX
int o2_fd;
int temp_fd;
int hum_fd;
int pres_fd;
int airflow_fd;

int read_fd;

// RX
char remote_rx_data;
pthread_t remote_listener_thread; // thread that listens for data

uint8_t remote_status;
pid_t remote_pid; // pid of remote server

```

```c
void process_request(unsigned char command){
    switch (command){
        // cases to control the fan
        case 0x01:
            setAirFlowLevel(0);
            break;
        case 0x02:
            setAirFlowLevel(1);
            break;
        case 0x03:
            setAirFlowLevel(2);
            break;
        case 0x04:
            setAirFlowLevel(3);
            break;

        // cases to control the air compressor
        case 0x05:
            setOxygenLevel(OXY_LEVEL0);
            break;
        case 0x06:
            setOxygenLevel(OXY_LEVEL1);
            break;
        case 0x07:
            setOxygenLevel(OXY_LEVEL2);
            break;
        case 0x08:
            setOxygenLevel(OXY_LEVEL3);
            break;
```

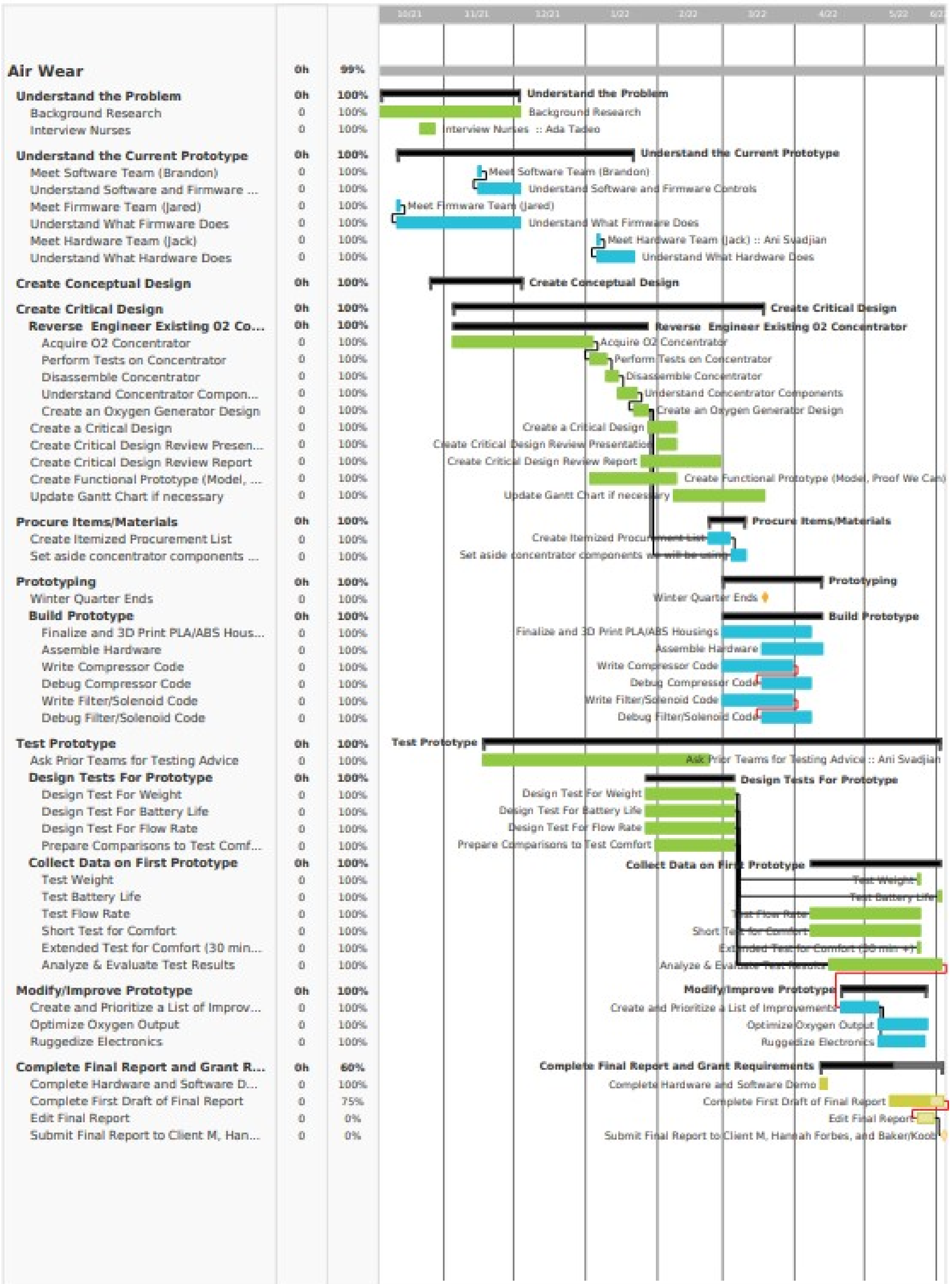
```
        case 0x09:
            setOxygenLevel(OXY_LEVEL4);
            break;
        case 0x0A:
            setOxygenLevel(OXY_LEVEL5);
            break;

        // cases to control the humidifier
        case 0x0B:
            setHumidifierLevel(HUM_ON);
            break;
        case 0x0C:
            setHumidifierLevel(HUM_OFF);
            break;

        default:
            break;
    }
}
```

Appendix I: Gantt Chart

Click here to see a Gantt Chart with our revised timeline and completion percentages.



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