



Electrical Engineering Department  
California Polytechnic State University

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## Senior Project Final Report

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### Portable Ventilator

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## **Abstract**

The current COVID-19 pandemic has heavily impacted the healthcare system in the United States and elsewhere. The need for patients to have access to a hospital with a ventilator along with a shortage of ventilators for recovery and at-home care as a result of minimal hospital vacancy for patients has been greatly stressed. The presented problem is both an unmet demand and supply of portable and effective ventilators. Existing ventilators have many shortcomings that should be addressed: size, weight, cost, and complexity of current ventilators confines users to stay in a medical facility whilst being monitored by professionals. This both increases the risk the user has of contracting other diseases and increases the cost to operate a ventilator. Therefore, there is a need to create a ventilator that is both smaller and more accessible than what is currently available.

The solution is to design a ventilator which can meet the symptoms and strains which COVID-19 can put on various individuals, should they not have access to a commercial ventilator as an economic constraint, or have restricted access to a medical facility attributed to the influx of patients. This means that a portable ventilator targeted for lower risks patients to be the ideal ventilator design. This ventilator would allow for short term out-patient care of low risk patients, thus allowing hospitals to focus on high risk patients. The lower risk patients would then be allowed to be at home and away from hospitals where both the expenses and risks of catching diseases would be higher. This would also mean that there would be greater access to care and less people denied care. While the focus is currently on COVID-19 patients, the use of the ventilator will extend to other patients who also need help breathing. The ventilator would include wireless communication, smartphone integration, and a portable power system which would allow consumers to relocate the ventilator as needed and have back-up power in the event of a power outage.

## Background

A ventilator is a machine that uses mechanical ventilation to help patients breathe and provide oxygen when their own body is not able to do this correctly.[1] The first widely used ventilators were during the polio epidemics, 1920s and 1930s, and called iron lungs. These were large noninvasive devices that required most of the patient's body to be in a box. Then it used negative pressure to expand/contract the patient's chest and thus also the lungs, drawing air in/out. [2]

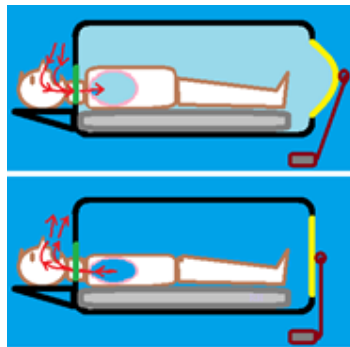


Figure 1 Iron Lung [3]

Following the polio epidemics, the use of mechanical ventilation continued as its benefits were now more widely known, especially in sedated patients. This led to innovation and a focus in minimizing the side effects. The following ventilators, East Radcliffe and Beaver models, used electric motors, but this created a hazard when used around flammable anesthetics. To remove this risk the Roger Manley model was created, 1952, which was gas-driven, thus removing the explosion hazard, and introduced to the mainstream positive pressure ventilation. This model remained the popular choice for anesthetic purposes for decades. Three years later in the US, the Bird model was created which was pneumatic, or pressurized air driven. This allowed the device to be operated without an electric source. Thus it became popular in the US army and, soon after, in US hospitals.

In the following years, the ventilators were constantly improved to function better, minimize maintenance, and increase reliability. However, the next big revolution in ventilator design did not occur until the introduction of microprocessors. This third generation of ventilators started with the Drager EV-A and finally allowed for monitoring of patients on a

screen. Immediately following, were the Puritan Bennett 7200, the Bear 1000, the Servo 300, and the Hamilton Veolar models. These allowed for customized air delivery, improved monitoring, and quick responsive action to patient changes.[4]



Figure 2 Hamilton Veolar Model[5]

Modern ventilators, fourth generation ventilators, did not have a clearly defining innovation as previous generation but are different nonetheless. Current ventilators are controlled by an embedded system that performs all the necessary controls and responses needed. There are also many different alarms and failsafes in place to protect patients from any device malfunctions. These ventilators are also mostly designed for specific needs, such as adult ventilation, transport, and neonatal. They also require to be plugged into a power source, thus limiting patients movement. Due to the complexity of the ventilators, professional monitoring and hospitalization is needed further increasing the price and constraints on patients. This leaves a need for a ventilator that can be operated outside the hospital and gives back freedom and comfort to the patient.



Figure 3. Current ICU Ventilator Setup[6]

## Product/Project Description

The Portable Ventilator is a mechanical ventilation device designed to tackle one of the biggest problems with current ventilators, their restrictiveness. Currently patients are required to either be hospitalized and occupy an ICU room risking contracting disease or forgoing care. This leaves many patients with milder symptoms to have two bad options. Along with this, hospitals are also at a loss. Every patient with milder symptoms that is hospitalized is one less ICU room available for other patients with more severe symptoms. This also puts a strain on the limited resources hospitals have, such as nurses, since the ventilator must be constantly monitored and adjusted.



Figure 4[18]: The first FDA approved portable Unified respiratory system.



Figure 5 [13]: Current portable Ventilator by Philips Respironics

The Portable Ventilator seeks to solve these problems by providing a third option to patients and hospitals. This is the ability to provide out-patient care for mild cases that require help breathing and oxygen intake. This would be done by designing the Portable Ventilator to be lighter, smartphone compatible, automatic monitoring and adjustment, and a simpler interface for controlling the device. This would allow the ventilator to be used at the patients home with no need for professional monitoring. This would meet both the patient's need to be provided care without hospitalization and the hospital's need to keep available rooms and staff.

## **Product Research**

Today most of the ventilators in the market and in use are designed for hospital use and to address specific medical needs. This means that an ICU ventilator may not be able to be used for neonatal ventilation. Having a many different types of ventilators allows most patients to be treated for whatever condition they may get. Modern ventilators include many health safety features to ensure that the patient remains safe even when there is an error.[4] This includes alarms for dangerous changes in patients' biometrics. Another safety feature is the monitoring and displaying of both patient and device conditions. One of the most important features of current ventilators is the ability to change the settings and provide precise control of the device. However, this means that to operate a ventilator not only requires accurate ventilator knowledge but also accurate medical knowledge. This causes ventilators to require professional monitoring and administering.

The current portable ventilators in the market are mostly transport ventilators. These are used to provide short ventilation to patients when they are being transported from one facility or room to another. The remaining portable ventilators are meant for use outside a hospital. However, both of these types of portable ventilators are still complicated and require a medical professional to operate them. This leaves open a market for a portable ventilator that can be operated and monitored by a non-professional, such as the patient or a family member.

## **Technology Research**

Ventilators are controlled by microprocessors. These microprocessors are responsible for controlling and communicating with various components. These components include the sensors, compressors, pumps, displays, and etc. For the Portable Ventilator design we would need a microprocessor that can perform those same duties using I2C communication protocol along with having wireless capability. A Raspberry Pi 4 microprocessor is capable of this[8]. The sensors needed are many, with flow rate, temperature, humidity, and O2 being a few. There are many available sensors that could be used which are both small and require little power.

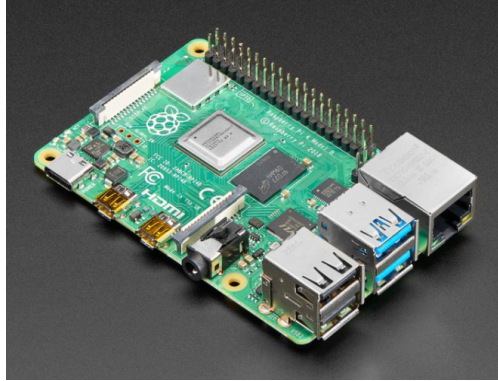


Figure 6 [8]: Raspberry Pi 4 Model B microprocessor.

Focusing on mild symptom/low risk patients could allow the Portable Ventilator to be designed without an air compressor and reduce the cost and complexity of it. Due to the widespread use of advanced smartphones, the Portable Ventilator can use an app to easily communicate with the user and allow the user to easily adjust the ventilator.

The most important feature of modern ventilators are the alarms and failsafe features to protect the patient. This is done through the monitoring of the patient's biometrics and ventilator conditions. Any problem encountered by the ventilators would cause the alarms to set off and failsafe features to activate, if needed, until a nurse can attend to the patient[9]. With the use of an app, the portable ventilator can guide the patient or family member on the steps needed when there is a problem and automatically call for medical attention.

## **Market Research**

The ventilator market is a growing market due to both an increase in the geriatric population and the COVID-19 pandemic.[10] The COVID-19 pandemic rapidly increased the demand for ventilators and companies responded by increasing production of ventilators. However, this increase in production was for ICU ventilators. This led to a saturation in the market as the number of ventilators that can be used is limited by the number of ICU rooms available. Therefore, the largest reason for patients not receiving the necessary ventilation they need is not caused by a lack of ventilators but a lack of hospital space and medical staff. This leaves a need for hospitals to alleviate their in-patient care and increase out-patient care. The Portable Ventilator is designed to meet that need and fill that market.



Along with opening up hospital space, the Portable Ventilator will also fulfill the need for patients to remain active and comfortable. Presenting this new option should cause many current patients to opt into using the Portable Ventilator over the current one they are using.

While the current demand is being driven mainly by the current pandemic, the demand will continue to increase for years due to the geriatric population. The limitations for this increase are due to high cost and operating requirements [15]. The Portable Ventilator would address these issues by presenting a cheaper, lighter, and accessible alternative for out-patient care in both nursing and private homes.

## **Customer Archetype**

\*The customer archetype was adapted from our CPE team

In order to create a customer archetype, one must fully understand the needs that the portable ventilator must satisfy. To meet the needs of a customer, the device must be completely reliable. In many cases, the user's life will depend on the functionality of this device. Any patient using the device will require the following:

- Constant monitoring of blood oxygen level
- Constant supply of oxygenated air (21%-100%)
- Adjustable flow rate of incoming air (0-40 L/min)
- War, (31-37°C) and humidified air (up to 100% humidity)
- Portability for at least 3 minutes

To meet these needs, the device needs an internal power supply, portable oxygen supply (likely an oxygen tank), and needs to be lightweight (ideally less than 25 pounds).

Through research and advice from advisors, we have found two main customer archetypes: high risk and low risk patients. The high risk archetype is a COVID-19 patient who only intends to use our device temporarily during recovery. There is a great risk that their condition may worsen rapidly, resulting in their return to the hospital. The other archetype, the low risk patient, intends to use our device long-term and suffers from milder symptoms without much risk of their condition worsening. Details of these two customer archetypes are explained below.

### *High Risk*

These patients have an active family member nearby who can assist them if needed in an emergency. These patients also have a professional healthcare clerk checking in with them as needed (to be determined by healthcare personnel).

Users in the high risk archetype have a hands-off approach to their ventilator, as they may rely on others to actively monitor their physical state and adjust oxygen flow accordingly. A member of this archetype must complete an initial health survey with a medical professional who will provide the parameters for various ventilator modes. The user will then wear the ventilator as often as the medical professional dictates.




The user or user's caretaker will be responsible for monitoring their health status. If a healthcare professional monitoring them (remotely) inquires about specific reading, the user can provide the indicated data by observing their smartphone application or inspecting the app's history setting. Additionally, the user must monitor health status in the case of an emergency. Should the ventilator fail, the user must seek medical assistance immediately. The patient should also have an emergency bag-valve-mask (BVM) in case of a power outage.

### *Low Risk*

For this product, low risk patients are those adult patients with chronic breathing ailments who intend to use this device indefinitely. They may already be using an at-home ventilator due to preexisting health conditions, such as chronic lung disease, spinal injuries, muscular dystrophy, or other ailments that prevent effective breathing. These patients regularly visit their doctor but otherwise have complete control over their daily oxygen supply/delivery level that they change depending on how they feel or what activities they are doing.

These patients are not sick enough to be placed on an ICU ventilator for more than 14 days. Beyond mild breathing ailments, these patients are physically fit and may desire to return to an active lifestyle. They would greatly benefit from a return to a "normal" lifestyle by returning home with a similar oxygen delivery device. They may live independently or in a group home setting. Helping these patients would free up ER and hospital space.

The low risk patient would begin by completing the initial health history survey by themselves or with the guidance of a medical professional to create their ventilator presets. They will then wear the ventilator whenever they feel that they need breathing assistance. This user is responsible for monitoring their own health and hardware status. The ventilator may automatically adjust mode based on biometrics, but this will be limited by user presets. For finer control, the user must manually change their mode/inputs depending on what they feel is needed. The patient should also have an emergency bag-valve-mask (BVM) in case of a power outage.

Currently Available Devices	Manufacturers/Descriptions
 <p data-bbox="370 695 540 730">Figure 7 [11]</p>	<p data-bbox="735 331 1419 621">Allied Healthcare Products Inc. [11]: Sells the EPV200 which is a portable , lightweight, and robust ventilator system for \$700. It is designed to provide effective ventilation for intubated or non-intubated patients to maximize medical surge response during initial stages of a mass casualty event. It can run up to 48 hours on two D cell batteries. It does not include an oxygen tank.</p>
 <p data-bbox="370 1213 540 1249">Figure 8 [12]</p>	<p data-bbox="735 762 1409 1052">Invacare [12]: Sells the Invacar Perfecto2 V Oxygen Concentrator which is a two feet tall home oxygen machine. It weighs 39 pounds and costs around \$677. It uses less power that most O2 concentrators while maintaining the same oxygen output. It offers quiet operation which is ideal for use while sleeping. It offers up to 5 liters of continuous oxygen per minute.</p>
 <p data-bbox="370 1753 540 1789">Figure 9 [14]</p>	<p data-bbox="735 1360 1409 1612">Philips Respironics [14]: Sells the SimplyGo portable oxygen concentrator for \$2500. This device is extremely compact and lightweight at only 10 pounds. This device comes with multiple different oxygen delivery modes for the patient to configure. While this device is more expensive, it makes up for it with more portability and easier functionality.</p>

**Table 1: Market Leaders/Industry Competitors**

For our product, we are expecting hospitals to purchase the devices and lease them out to the patients described by our high risk customer archetype. These costs could be covered by insurance agencies for the patients. For our low risk archetype customers which may require more permanent use, we would expect them to purchase their own ventilator.

According to ReportLinker [13], “The Global Portable Ventilator Medical Ventilators Market is expected to grow from USD 368 Million in 2019 to USD 846 Million by the end of 2025.” This is due to the high demand caused by COVID-19 related issues. Due to the size of this market with the relatively low supply of manufacturers, our product could possibly break into the market. Our product can bring functionality, portability, and price to an ideal spot which can appeal to a large amount of customers.

## Market Description

The portable ventilator aims to create an avenue for hospitals to provide out-patient care so that they may increase the amount of rooms available for patients with more severe respiratory symptoms while still administering adequate out-patient care for those with less-severe symptoms. The ventilator will be driven with a desire to make sure all patients with respiratory symptoms may receive the care they need appropriate to their symptom severity. This is much inspired by the 2019 outbreak of COVID-19 and its impact on hospitals with a focus on the United States.

## Developmental Challenges and Limitations

Software	Our team includes members who are proficient in firmware/embedded systems development, but limited high-level software development experience. There is a separate team which deals with external communication to other devices (i.e. Smartphone, smartwatch), but communication between the two groups may be challenging.
Specialized Parts	A fair portion of the parts included in the materials required for construction of this

	<p>system are quite foreign to this Electrical Engineering team. Such parts include pneumatic pumps, air filters, and valves. This limited knowledge will have to be compensated for by accelerated research so that parts which fit together nicely in the rest of the system will be able to meet the system specifications and are able to be actuated accordingly if necessary.</p>
<p>FDA Regulatory Process</p>	<p>In order for this product to be legally sold/used/prescribed for use in the United States, the Food and Drug Administration requires that the device to conform to a list of regulations that make it suitable for different applications: Declarations of Conformity, Device Specifications and Instructions for Ventilators and Accessories, Reprocessing and Shelf-life Information, Facility Requirements, and Labeling Requirements for Conditions of Use. These standards will need to be heavily researched and verified before, while, and after construction for this product to be legally market-viable. Additionally, the FCC's Electronic Code for Federal Regulation 47 FCC Ia. 15b §109a specifies that for Class B devices, the field strength of field strength of radiated emissions from a Class B digital device, as determined at a distance of 3 meters, shall not exceed 500 microvolts per meter when operating above 960 MHz. In this case because bluetooth operates within the ISM band (2.45 GHz), this device falls within this region and is subject to §15.109(a) regulation. For reference, see Appendices A and B for Ventilators on the FDA's website [7], and see [19] to view table (a) of §15.109 on the FCC's website to view acceptable emi emission limits.</p>
<p>Manufacturing</p>	<p>This system is not meant to replace ventilators found in emergency rooms and ICUs, it is an outpatient compliment to such systems. Therefore the components and parts found within hospitals will be far too expensive and perhaps exclusive to obtain. Therefore, it will</p>

	<p>be necessary to source adequate parts in order to have them assembled and tested together. We can design and print circuit board assemblies externally, but some of the mechanical pieces such as the O2 tank may have to be sourced pre-manufactured.</p>
Time Limitations	<p>We are constrained by the strict deadline of the CPE team who is working on the software and connectivity of the ventilator to other devices. This deadline requires a (working) alpha prototype to be completed by the end of the quarter, therefore it is necessary to develop our component list early on and order parts as soon as possible.</p>
Proprietary Information	<p>Along with an FDA approval, other biomedical device companies hold I.P. on many products which makes it a difficult realm to enter, checking parts to make sure they do not require licensing for use or looking into paying royalties for a part of the system may be a heavily limiting factor.</p>

**Table 2. Limitations**

Our product offers a solution over other ventilators in that it provides a solution to hospitals and patients: hospitals will have more room to treat patients with more serious symptoms (left to the in-house ventilators), and patients with minor symptoms will be able to receive remote treatment from the comfort of their own homes, which is advantageous for recovery of minor symptoms [16]. The portability of this device will also allow it to be advantageous over those located within hospital premises. It allows the user to move the device from room to room without the need to fear for their respirator well-being as it will be able to run on a battery for a short amount of time before it will need to be charged again.

An area of this market we are not competitive in is the high-performance ventilators, this is not the goal of this device and that market is extremely competitive. This segment is

dominated by professional biomedical, electrical, and mechanical engineers to be error-averse and log highly accurate and sensitive data. This product aims to provide a sufficient level of care for symptoms which require attention but not serious medical intervention.

The window of opportunity for our product is people who require medical attention for their respiratory symptoms, but are not prioritized due to the lack of hospital vacancy and the potential severity of other patients.

To penetrate the market, serious capital would have to be invested into getting this device FDA approved, patent the device, visit trade shows and hospitals to talk with hospital business administrators, and designing and building a working prototype. This will require a minimum of \$25,000 of funding to provide for the materials to produce a ventilator unit, for the labor of the team, for the applications towards patents and FDA approval, and for travel to trade shows and hospitals. The time investment would be large for the team involved. Due to the small team, it could take around 20 hours per person in order to get a unit functional. It also may take two years to get all of the approvals and begin to enter the market.

<b>Advantages</b>	<b>Disadvantages</b>
More patients have access to medical care	Not all patients will receive the same level of care- rather receiving care that meets their symptom severity.
Cost-Efficiency: Doctors and nurses are only seeing the most symptomatic patients in person, which means more hospital rooms available and time being spent more effectively.	Response to more serious symptoms may be delayed compared to the time care would be administered in a hospital.
Outpatient Care	Augments hospitalization access and acute cases

**Table 3: Advantages and Disadvantages**

# Business Model Canvas Graphic

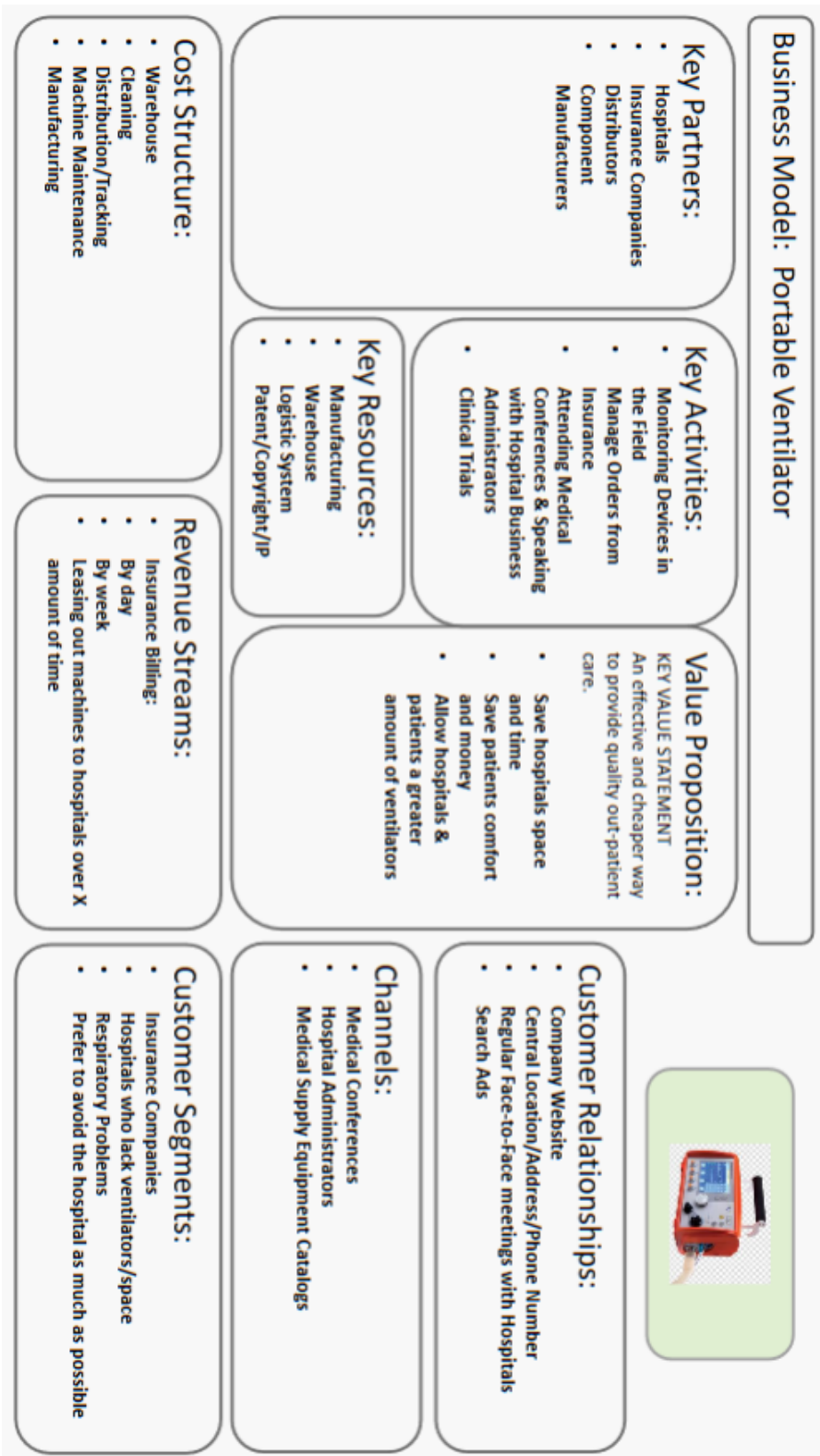


Figure 10: Business Model Canvas



## Marketing Requirements

Marketing Requirements	Reasons
Affordable (Priced below \$1000)	This provides a cheaper ventilator alternative than the expensive ones in the market currently.
Biometric Monitoring	Allows the user to easily access the biometrics of the patient without need for additional hardware.
Smartphone Integration	Allows the user to use the ventilator without needing to ensure the ventilator is visible(can be carried in a backpack).
Portable Battery	This lets the ventilator not have to always be plugged in and will let the user move around with the ventilator.
Lightweight	Carrying the device is doable with one person without need of help.
Humidifier	Prevents mouth and throat dryness due to the ventilation. Keeps the use comfortable during ventilation.
Portable Oxygen Supply	This will let the ventilator and user be mobile without worrying about not getting necessary oxygen.
Simple UI	A simple UI will allow the device to be operated by both medical professionals and non professionals. Prevents information overflow and ease of use.

**Table 4: Marketing Requirements and Reasoning**

The Portable Ventilator will be designed to include features that will solve the current problem with available ventilators. Similar to current ventilators, the Portable Ventilator will provide breathing and oxygen intake assistance to low risk patients. The differentiator between current ventilators and the Portable Ventilator will be the greater accessibility, mobility, and

comfort the Portable Ventilator will provide to patients. This will be done by designing the ventilator to be light, run on a battery, and be easy to use.

Importance	Design Feature
High	Portable power capabilities to last at least 10 minutes
High	Wi-Fi/LTE
High	Bluetooth Communication
High	Smartphone integration
High	Small, lightweight design
Medium	Affordable Cost
Medium	Simple User Interface
Low	Visually Pleasing

**Table 5: Importance and Design Feature**

The Portable Ventilator places higher importance on features that add to the functionality of the device. If there is a choice between a higher cost or a lower functionality of a smartphone integration, the ventilator will have to receive the higher cost in order to provide the extra service to the customer. This is necessary to stand out versus other portable ventilators on the market. Without many of these beneficial design features, this device would not be able to break through the market.

# Marketing Data Sheet

**Product/Project Name:** Portable Ventilator

**Unmet Customer Need:**

Current ventilators are prohibitive because they require 24/7 expert monitoring and are costly. As a result, patients with less-severe needs are being cared for in the most-expensive mode.

**Unique Value Proposition:**

The product operates without the need for constant medical operation and attention. It is also portable and inexpensive enough to be deployed in an out-patient care system.

**Target Customer:**

Primary: Hospitals and clinics with the capability of providing an out-patient respiratory monitoring program  
Secondary: Clinics and Physicians who lack trained personnel to operate ventilators

**Positioning:** Patient-operated ventilator for less-severe and out-patient respiratory treatment

**Customer Benefits:**

- More affordable
- More hospital space
- Allows for ventilator treatment in unconventional places

**Sustainable Differentiation:**

- Out-Patient Care
- Affordability
- Patented Technology (IP)
- FDA Approval



**Pricing and Availability:**

- \$1000 (Direct Price)
- S.P. Expo
- Spring 2020

**Product Objectives:**

Satisfy supply needs for ventilators in the healthcare system  
Increase out-patient care options

**Disruptive Go-to-Market:**

- FDA Regulatory Approval
- Hospitals prescribing ventilator to patients
- Insurance reimburses the leasing and operating cost of using the ventilator

Figure 11: Marketing Data Sheet

## Block Diagram

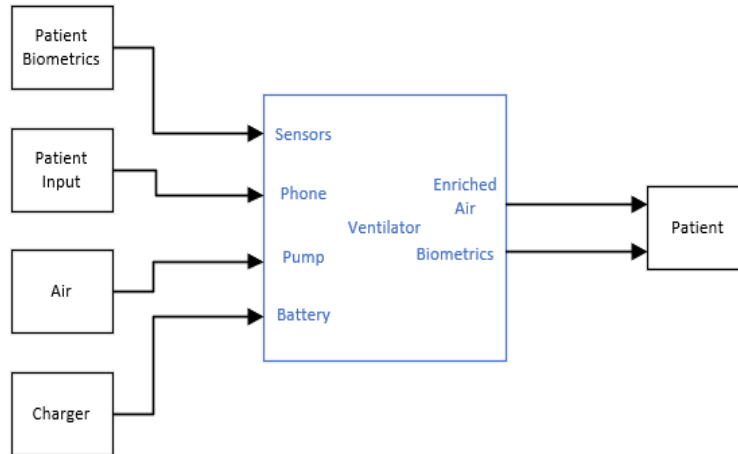


Figure 12: 0th Level Block Diagram

The high(0th) level block diagram for the ventilator displays the necessary inputs and outputs for the system. The inputs for the system are the patient's biometrics, patient input, air, and a charger. The patient's biometrics must be accurately measured to provide feedback to the ventilator so it can adjust to provide the needed enriched air. The patient input sets and changes the settings for the ventilator and defines how the ventilator will be used(e.g. high flow rate). The air input is used by the system to provide the air flow rate and is enriched with oxygen to create the enriched air for the patient. The charger input is necessary to charge the ventilator's battery and allow the ventilator to be portable. The outputs for the system are the enriched air and the measured biometrics. The enriched air is humid, pressurized, oxygen-enriched air that is supplied to the patient. The enriched air's conditions must be carefully and accurately met to provide the patients needs. The measured biometrics must be clearly and readily available to the patient.

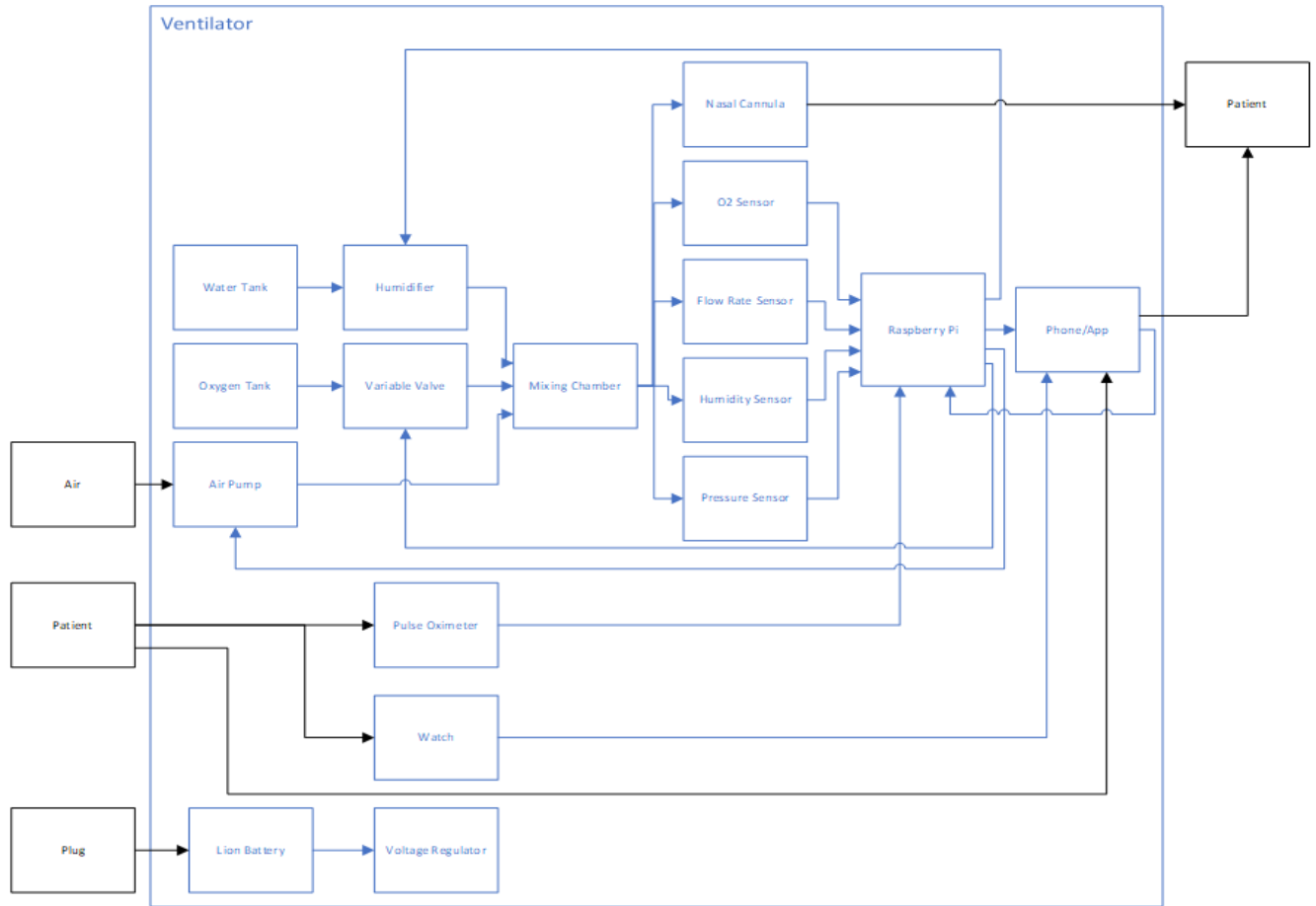


Figure 13: 1st Level Block Diagram

The 1st level block diagram shows the subsystems and connections between them in the working ventilator system. A notable thing about the block diagram is that the Lion Battery and Voltage regulator will connect and provide the power to the various components. The feedback for the system is provided through the combination of the sensors and the Raspberry Pi. The pulse oximeter and watch both measure the patient's biometrics with the pulse oximeter being the back up.

## Engineering Requirements

The engineering requirements for this project were determined using the marketing requirements established earlier. These engineering requirements are all necessary to meet the goals of the project.

<b>Engineering Requirement</b>	<b>Implementation</b>
Chargeable Power System	A rechargeable Li-ion battery with voltage regulators
Measure Patient's Biometrics	An Apple watch with biometric capabilities, and back-up pulse oximeter
Measurements of air output conditions (oxygen, humidity, air flow)	Sensors right before the air is breathed by the patient
Automatic control of systems to meet wanted air conditions	A Raspberry Pi reading sensors and controlling pump, oxygen tank, and humidifier
Controllable Oxygen Content	Oxygen tank with variable valve controlled by servo.
Controllable Air Humidity	Ultrasonic Atomizer
Controllable Air Flow	Air fan
Patient and Ventilator Communication	An app that communicates the input from phone, and displays information on the phone

**Table 6: Engineering Requirements**

## **Testing and Verification**

### **Chargeable Power System**

The power system will need to be tested for functionality. This will be done by measuring the voltage of the battery and the output voltage of the voltage regulator along with keeping the voltages steady while powering the components. The second test will be on how long the battery lasts from full charge. This will need to be performed under two conditions. The first will be with the ventilator operating at the lowest performance setting and the second with the ventilator operating at the highest performance setting. The test will be done by powering the ventilator and measuring how long it operates before stopping.

### **Measure Patient's Biometrics**

This will require two tests, a functional test and accuracy test. The functional portion will be done by reading and displaying what the watch is measuring and checking that the output is reasonable. The accuracy test will be done by once again measuring with the watch and also the pulse oximeter. The measurements will be compared to one another to check if they match.

### **Measurements of Air Output Conditions**

The enriched will be measured through the use of multiple sensors. As such, each of the sensors will have to undergo both a functional test and accuracy test. The test specifics for each will vary but will follow a general structure. This structure is first performing the functional test by reading the output of a sensor and checking that the sensor is measuring and outputting the measurement. Next the accuracy test will be performed. To do this the sensor will be used in known conditions and the output of it will be checked to match the known quantity.

### **Automatic Control of System**

This will be a functional test that will be performed on the microcontroller and the complete system. The functional test on the Raspberry Pi can be done by providing data that simulates the sensor outputs and then checking that the Raspberry Pi's outputs to the pump, humidifier, and variable valve are correct. The data will then be changed to simulate a change in air conditions and the Raspberry Pi outputs are checked to change accordingly to restore the air conditions. The functional test on the completed system will be similar to the Raspberry Pi's test with the data now being provided from the sensors and the outputs of the pump, humidifier, and variable valve being measured.

### **Controllable Oxygen Content**

This functional test will be done through use of the Raspberry Pi connected to the servo for the variable valve. To test this the Raspberry Pi will be told the wanted oxygen content and the variable valve will be observed to open and close as needed.

### **Controllable Air Humidity**

This functional test will be done through use of the Raspberry Pi connected to the humidifier. To test this the Raspberry Pi will be told the wanted humidity and the humidifier will be measured to check the provided water vapour is correct.

### **Controllable Air Flow**

This functional test will be done through use of the Raspberry Pi connected to the pump. To test this the Raspberry Pi will be told what the air flow should be and the pump will be measured to provide the correct air flow.

## **Patient and Ventilator Communication**

This will require both a functional and usability test. The functional test will be a check that the phone/app is correctly communicating to the Raspberry Pi and the phone/app is correctly displaying information. The usability test is to ensure that the ventilator's setting can be easily set and managed. This test will be done by having people outside the project use the app to set the ventilator's setting according to what they are told they should be.

## **Team Project Roles**

### **Power System and Hardware Integration - Jack Brewer**

This role's responsibility is to integrate the voltage regulator and power supply into the overall system. They need to design a safe and reliable system that supplies power to various parts of the ventilator. This role also helps test and integrate other hardware devices to the overall ventilator system.

### **Controller System and Hardware Integration - Sanders Sanabria**

This role's responsibility is to integrate the Raspberry Pi microcontroller into the overall system. They need to be familiar with the various facets of the microcontroller and understand how to properly design a system that incorporates the microcontroller into the ventilator. This role also helps test and integrate other hardware devices to the overall ventilator system.

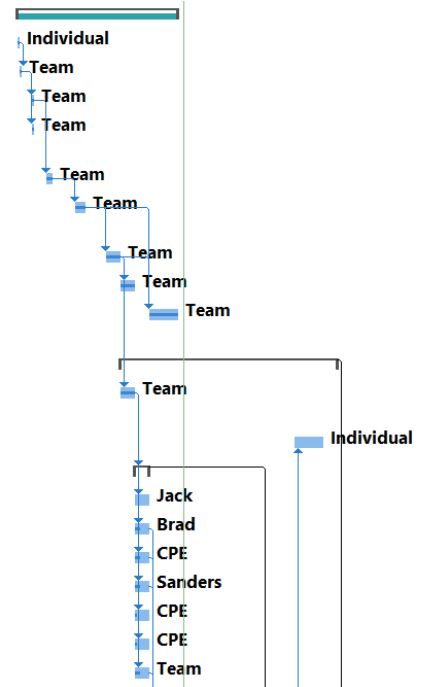
### **Firmware and Hardware Integration - Brad Weeks**

This role's responsibility is to communicate with the CPE team and incorporate firmware that controls the various devices of the ventilator system. They need to produce code that reads from many sensors and controls various components of the system. This role also helps test and integrate other hardware devices to the overall ventilator system.

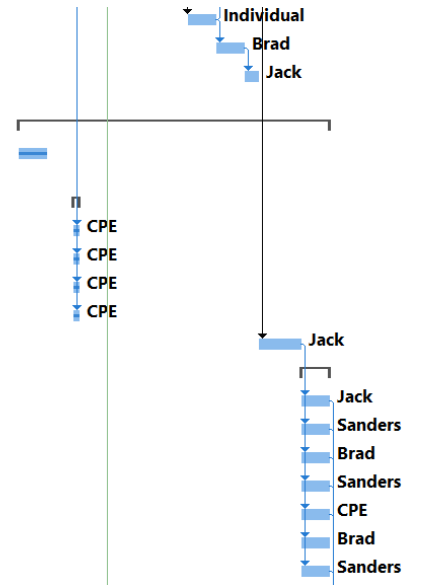


# Schedule

1	🚀	Define	56 days	Mon 9/14/20	Mon 11/30/20	
2	🚀	Choose Project	1 day	Mon 9/14/20	Mon 9/14/20	Individual
3	🚀	Project Abstract	1 day	Tue 9/15/20	Tue 9/15/20	2 Team
4	🚀	Marketing Template	1 day	Mon 9/21/20	Mon 9/21/20	3 Team
5	🚀	Business Model Template	1 day	Mon 9/21/20	Mon 9/21/20	3 Team
6	🚀	Intital Gantt Chart	3 days	Mon 9/28/20	Wed 9/30/20	4 Team
7	🚀	1st Pass Senior Project Report	1 wk	Mon 10/12/20	Fri 10/16/20	6 Team
8	🚀	Ethics Analysis	1 wk	Tue 10/27/20	Mon 11/2/20	7 Team
9	🚀	Project Presentation	5 days	Tue 11/3/20	Mon 11/9/20	8 Team
10	🚀	Final Pass Senior Project Report	2 wks	Tue 11/17/20	Mon 11/30/20	8,7 Team
11	🚀	Design	75 days	Tue 11/3/20	Mon 2/15/21	
12	🚀	Engineering Requirements	1 wk	Tue 11/3/20	Mon 11/9/20	8 Team
13	🚀	Simulations	2 wks	Tue 1/26/21	Mon 2/8/21	22 Individual
14	🚀	Block diagram	5 days	Tue 11/10/20	Mon 11/16/20	12
15	🚀	Power	1 wk	Tue 11/10/20	Mon 11/16/20	12 Jack
16	🚀	Controller	1 wk	Tue 11/10/20	Mon 11/16/20	12 Brad
17	🚀	Display	1 wk	Tue 11/10/20	Mon 11/16/20	12 CPE
18	🚀	Humidifier	1 wk	Tue 11/10/20	Mon 11/16/20	12 Sanders
19	🚀	Air Pump	1 wk	Tue 11/10/20	Mon 11/16/20	12 CPE
20	🚀	Oxygen	1 wk	Tue 11/10/20	Mon 11/16/20	12 CPE
21	🚀	Sensors	1 wk	Tue 11/10/20	Mon 11/16/20	12 Team



22	🚀	Part Design	2 wks	Tue 1/12/21	Mon 1/25/21	14 Individual
23	🚀	Mechanical Casing	2 wks	Tue 1/26/21	Mon 2/8/21	22 Brad
24	🚀	Create Materials Listing	1 wk	Tue 2/9/21	Mon 2/15/21	23 Jack
25	🚀	Build	109 days	Wed 10/21/20	Mon 3/22/21	
26	🚀	Order Prototype Materials	2 wks	Wed 10/21/20	Tue 11/3/20	
27	🚀	Prototype Assembly	3 days	Tue 11/17/20	Thu 11/19/20	
28	🚀	Sensors	3 days	Tue 11/17/20	Thu 11/19/20	21 CPE
29	🚀	Display	3 days	Tue 11/17/20	Thu 11/19/20	17 CPE
30	🚀	Humidifier	3 days	Tue 11/17/20	Thu 11/19/20	18 CPE
31	🚀	Controller	3 days	Tue 11/17/20	Thu 11/19/20	16 CPE
32	🚀	Order Materials	3 wks	Tue 2/16/21	Mon 3/8/21	11 Jack
33	🚀	Assembly	10 days	Tue 3/9/21	Mon 3/22/21	
34	🚀	Power System	2 wks	Tue 3/9/21	Mon 3/22/21	32 Jack
35	🚀	Display	2 wks	Tue 3/9/21	Mon 3/22/21	32 Sanders
36	🚀	Control System	2 wks	Tue 3/9/21	Mon 3/22/21	32 Brad
37	🚀	Humidifier	2 wks	Tue 3/9/21	Mon 3/22/21	32 Sanders
38	🚀	Air Pump	2 wks	Tue 3/9/21	Mon 3/22/21	32 CPE
39	🚀	Casing	2 wks	Tue 3/9/21	Mon 3/22/21	32 Brad
40	🚀	Sensors	2 wks	Tue 3/9/21	Mon 3/22/21	32 Sanders



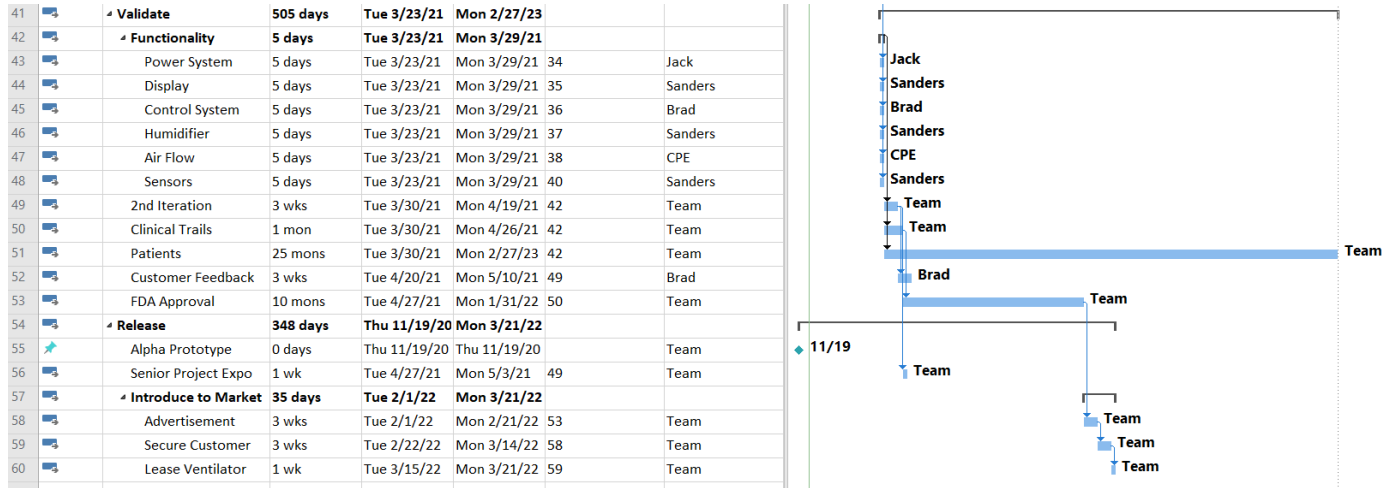


Figure 14: Gantt Chart through June 2021

# Product Cost Estimation

Senior **Portable Ventilator**  
 TEAM: **Jack Brewer, Sanders Sanabria, Brad Weeks**  
 DATE/REV: **DEC 4, 2020 VERSION V1.0**

										USA			
Sub	Sub	Sub	Sub	Description	Qty	P/N	Document	MFG	MFG P/N	LT - Weeks	1 pc Price (USD)		
Box Build - Model 1 - Retail Configuration					1	0		Custom		6			
1	Final Assy - Unit Portable Ventilator				1	1	Instr	Custom		1			
	1	Main Assembly				1	2	Instr	Custom				
		1	PCBA Assy, Assembled and tested				1	2.1	Custom	Custom	6		
			1	Double Sided Protoboard		2.1.1	---	UKRAGRAH	BSKC-003	1	1.4		
			2	Single channel A-D Converter		2.1.2	Spec	Microchip Te	MCP4901	2	0.80		
			3	Resistor, 1k 5%		2.1.3	Spec			2	0.04		
			4	Capacitor, 10nF Ceramic 50V		2.1.4	Spec			2	0.06		
			5	Connector, 4pin 5mm		2.1.5	Spec			4	0.22		
			6	Motor Controller		2.1.6	Spec	TI	L293NE	12	3.30		
			7	Switch, 5x5mm hybrid SMT		2.1.7	Spec			6	0.32		
			8	Capacitor, 10uF Electrolytic 50V		2.1.8	Spec			2	0.15		
		2	Raspberry Pi 4 Model B+				1	2.2	Spec	Rasp. Pi	2	30.0000	
		3	Raspberry Pi Housing Case				1	2.3	Spec	Rasp. Pi	4301	2	6.0000
		4	Label, ID				1	2.4	Custom	3M		4	0.0900
		5	5V Voltage Regulator Unit				1	2.5	Spec	TI	MZ21701EV	4	20.0000
		6	Labor, test, overhead, profit (all in) of Sub assem				1	---			---	N/A	
2	Ultrasonic Atomization Disk				1	3	Spec	WHDTS		4	19.0000		
3	Humidity Sensor				1	4		AOSONG	DHT11	4	5.0000		
4	Servo Motor				1	5	Spec	Bilda		3	32		
5	Pressure Transducer				1	6	Spec	GEMS		4	36.28		
6	Pulse Oximeter				1	7	Spec	iHealth		4	60.01		
7	Oxygen Sensor				1	8	Spec	analytic. Ind	SR-11-917-f	4	95.0000		
8	Mass Air Flow Sensor				1	9	Spec	Seeed	AFM3000	4	99.1000		
9	Air Pump				1	10	Spec	Noctua	NF-A4x20	4	14.9500		
10	O-Rings w/ Cylinder Wrench				1	11	Spec	R. R.		2	6.9900		
11	Nasal Cannula				1	12	Spec	Fisher			29.9900		
12	O2 Tank				1	13	Spec	Meret	K870M9	4	46.9500		
13	O2 Tank Variable Valve				1	14	Spec	W.T. Farley	CGA870	4	99.9900		
14	Labor, test, overhead & profit of Final Assy				1	---				---			
4	Anti-theft device				1	15		stock		4	0.0345		
5	Guide, Quick start				1	16	Y	Custom		4	0.2500		
6	Box, Top & Bottom				1	17	Y	Custom		6	2.5000		
7	Box, packaging insert - egg crate style				1	18	Y	Custom		4	0.3750		
8	Box, Sleeve				1	19	Y	Custom		4	0.8500		
9	Shrink Wrap plastic				1	20		stock		4	0.0100		
10	Bar Code Sku Sticker				1	21		stock		2	0.0100		
											<b>Material Total</b>	<b>605.3795</b>	

If made in USA lhrs x \$40/h	Labor+	40.00
If made in Foreign l.5hrs x \$5/h	OH	
Product Shipping leadtime	Weeks	1

<b>Total</b>	<b>646.38</b>
--------------	---------------

Order Lead time to Fulfill - Wee 7

Figure 15: Bill of Materials

The BOM shown in Figure 15 above yields a Product Cost Estimation of around \$650 for the Portable Ventilator. This project will require financing by Cal Poly's Electrical Engineering Department. However, in order to finance this product for a company, the team could go two

routes. The first route would be to obtain a business line of credit from a bank or lender. The business line of credit would allow the team to draw from a credit line up to a maximum amount and the team only needs to pay back the amount that was actually used. The second route would be to turn to crowdfunding and raise money from individuals. These investors would receive early access to the product and perhaps other special treatment. Both of these routes would be viable for this project.

## **Analysis of Senior Report**

**Project Title:** Oxygen+

**Student's Names:** Jack Brewer, Sanders Sanabria, Brad Weeks

**Advisor's Name:** Prof. Rich Murray

### **Summary of Functional Requirements:**

Oxygen+ is a portable ventilator which aims to provide a solution to mild respiratory symptoms by providing an avenue for outpatient care to offset cost and vacancy thresholds for patients and hospitals in the United States, allowing patients to recover while they are in the comfort of their own residences. The system will consist of a smartphone-compatible and operable high-pressure oxygen system that allows the patient some opportunity for cord-free mobility.

In addition to manual adjustment, the system will be able to actively monitor and adjust oxygen flow rate and pressure based on the patient's blood oxygen content (SPO<sub>2</sub>). The system will also be able to alert the patient if the system is unable to return their SPO<sub>2</sub> to a healthy level and recommend professional healthcare intervention. The final product will be an application that interfaces with a high-pressure oxygen rich and humidified system that will utilize existing components where necessary (due to time constraints).

### **Primary Constraints:**

The primary constraints of the system are as follows: constant monitoring of blood oxygen level, constant supply of oxygenated air (21%-100%), adjustable flow rate of incoming air (0-40 L/min), water, (31-37°C) and humidified air (up to 100% humidity), and lastly, portability for at least 3 minutes.

**Economic:**

- a. Human Capital: Oxygen+ presents job opportunities within engineering, sciences, marketing, health, manufacturing, and sales sectors.
- b. Financial Capital: Our target customers will be able to obtain this device through a doctor and lease the device through insurance, which will cost less than using a ventilator in a hospital, and can be sanitized and reused with a different customer.
- c. Natural Capital: This product will contain many electrical and mechanical components including various sensors, a Raspberry Pi 4B+, an oxygen tank, a Lithium Ion battery, and a variable valve. Many of these parts are not recyclable and therefore
- d. Cost and Timing: The target cost of the Oxygen+ ventilator is under \$1000, this is heavily dependent on components used in the final design, and will increase with the number of sensors and features implemented on the device

**If Manufactured on a Large-Scale Basis:**

Estimated number of devices per year: 1200

Estimated manufacturing cost of each device: \$650

Estimated lease cost for device (billed from insurance): \$150/week

Estimated profit per year (50 % Usage, device only): \$3,900,000

**Manufacturability:**

Much of the circuitry will be able to be pre-fabricated by a pcb vendor, sensors, servos, and the power supply will have to be attached manually. Mechanically, the casing will have to be manufactured, and the oxygen tank, along with the raspberry pi will have to be installed manually as well. Each device will also have to be rigorously and individually tested to meet FDA and FCC requirements to ensure their compliance and quality is up to standard.

**Environmental Impact:**

One of the important features of this product is its ability to be reused by multiple people after being sent back from the customer for sanitization. When parts break, we should make sure that they are replaced, but the broken parts may not be salvageable/repairable, this negatively affects the carbon footprint of the device as these parts may not be recyclable. This device is also powered by a lithium-ion battery, this will reduce the usage of single-use batteries but ultimately still leaves a carbon-footprint.

**Sustainability:**

In order to keep these devices out of landfills, the decision to reuse and repair is more beneficial both economically and sustainably. When making the decision to reuse available parts or repair a broken segment instead of tossing it into a landfill, this both extends the lifetime of the device and keeps more devices out of landfills. With a longer device lifetime the 'bottom' of the Weibull (bathtub) distribution is extended, and because the current business model is a lease-per-time arrangement, the longer a device is in use the more value it adds to the company, the more people it can help, and the longer it stays out of a landfill.

**Ethical:**

This device deals with the collection and radio transmission of sensitive health data, therefore the discussion of secure transfer of sensitive data arises. This transmission and storage must be encrypted and securely transferred to a secure healthcare server, where the contents will remain unseen except by the specific healthcare professional intended.

**Health and Safety:**

In terms of safety, our plan for testing is to utilize 50psi air from an air pump in place of 50psi oxygen from an oxygen tank wherever possible. In cases where using concentrated oxygen is required, proper cleaning and ventilation of all equipment will be used. Any oxygen tank(s) will be properly constrained to reduce the risk of leaking and/or explosion.

Also, development of the Alpha prototype has led to some minor adjustments of the medical hardware system, namely that the heater has been removed for safety reasons. It may be added on later, time permitting. Additionally, the pump between the mixing chamber and humidifier may not be necessary (further analysis during Winter Quarter will be conducted).

**Social and Political:**

This project is one born out of the current state of the world with COVID-19 ravaging communities and rendering hospitals non-vacant. With such a device in the market the duty to make certain the affordability and access to such a device is paramount. The average cost to rent a ventilator is approximately \$350/week [20]. Our presented cost is \$150/week and the margin is still very positive as far as profit is concerned. This means there is an opportunity to provide healthcare to communities which would otherwise not be able to support it, given the insurance would permit the device's prescription.

## Preliminary Design Analysis

After the engineering specifications and black box diagrams were completed, the team searched for components that would achieve the goals of the portable ventilator's alpha prototype. The alpha design's hardware requirements were to have hardware control of at least two functional elements and have at least one sensor reading a measurement. The team also generated a 3D model of a potential enclosure for the Raspberry Pi microcontroller.

Further design will be completed in the Winter 2021 quarter. A full system integration between watch, phone, controller, and hardware will be completed. All sensors and movers will be implemented and improved within the entire system. The prototype will be further adapted to allow the ability of the controller to send at least four sensor status readings to an iPhone and display at least two of those conditions on an apple watch. The next prototype must also allow a user to initiate at least two ventilator operations via apple watch. The system will generate a "warning" to the user on the watch when a preset bio metric is outside of a safe range. Overall, the design goal of Winter 2021 will be to allow robust breathing capabilities with control and feedback from an apple watch or iPhone.

### Alpha Prototype

The alpha design's hardware requirements were to have hardware control of at least two functional elements and have at least one sensor reading a measurement. To accomplish this, we obtained two ultrasonic atomization disks, a humidity sensor, a mass air flow sensor, an oxygen sensor, and a servo motor. The EE team performed initial testing of the humidifier, humidity sensor, and mass air flow sensor. These results were passed along to the CPE team who constructed the alpha prototype. The air-oxygen mixer alpha prototype and diagram constructed by the CPE team is shown in Figure 16 below.

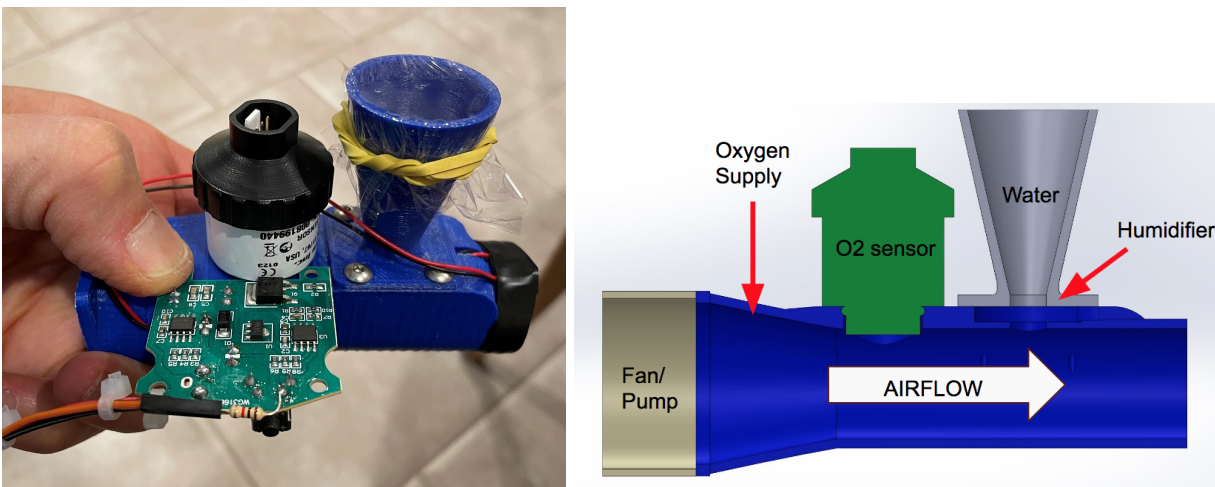


Figure 16: Air-Oxygen Mixer Alpha Prototype and Diagram

## Mechanical Housing Design

This is the mechanical housing for a Raspberry Pi 4B+. It is a rectangular housing to protect the Raspberry Pi microcontroller and allows for external connections to the ethernet, USB, and USB-C (power). The board sits on 10mm spacers to allow space from the board to the bottom of the housing as well as to provide air flow under the board. It has four screw holes to allow screws to fasten the board mechanically to the housing.

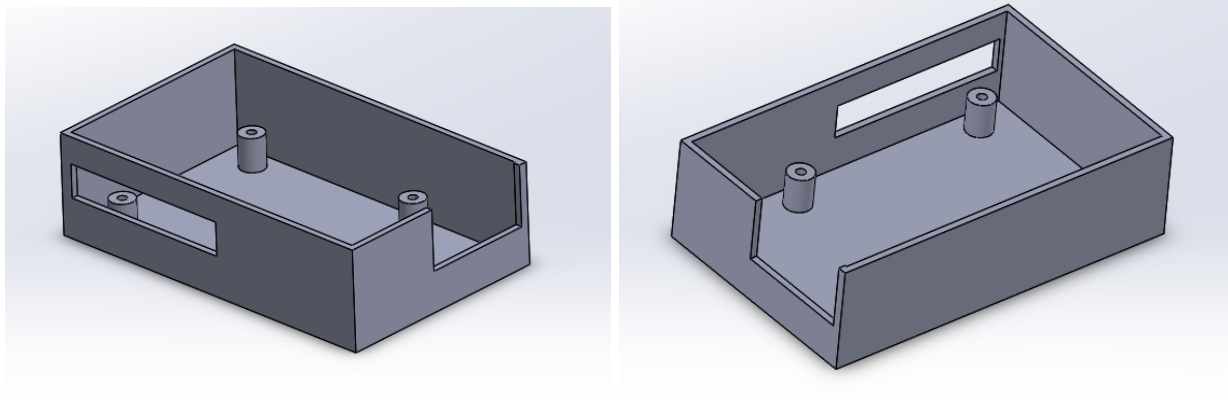


Figure 17: Solidworks model of the mechanical housing

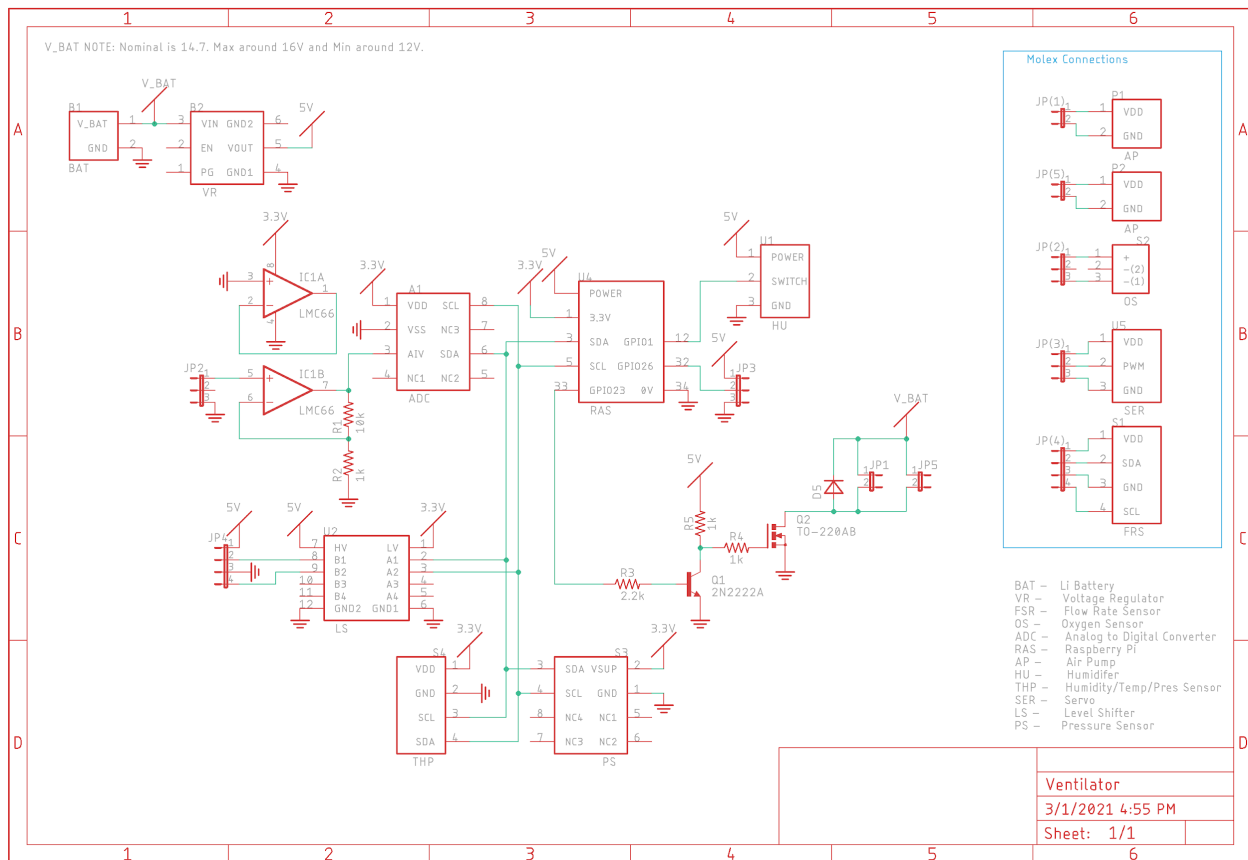


## EE 461 Addendum

The main goal of the EE team over the Winter 2021 quarter was to provide support to the CPE Capstone team. The EE team developed the hardware for the portable ventilator system, which included an in-depth schematic of the system, an oxygen sensor circuit, and a power supply. When issues or questions arose, it was the EE team's responsibility to help the CPE team solve them. The next few pages will describe the actions the EE team took over the quarter in order to support the CPE team.

### Schematic (Sanders)

With more components being added to the ventilator there was a need to create a schematic of the complete system. This schematic would help keep track of the connections between the components and allow an easy way to replicate the system later. The schematic was done using EAGLE, this gives the option to use the schematic for PCB layout. The schematic was an ongoing task, being improved and updated as changes were made to the system and asked for by the client. The schematic is currently on its 4th draft.



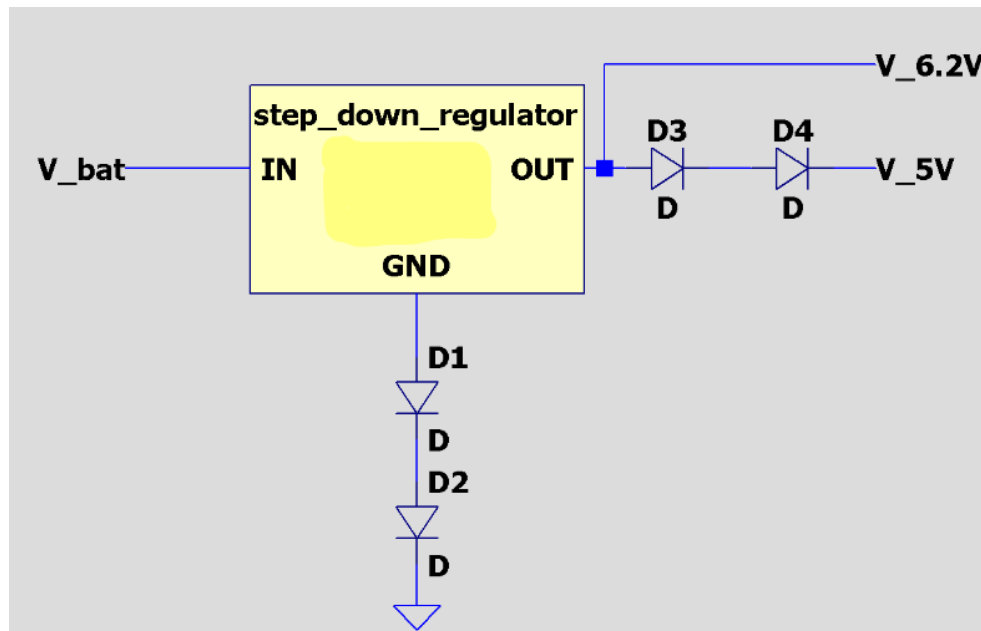
Schematic of Portable Ventilator system

The schematic uses device numbers (top) and component name abbreviations (bottom) to differentiate and identify the components, with an abbreviation to full component name list on the bottom right. Standard symbols were used for common components, such as resistors, op amps, etc. Unique symbols were created for the rest of the components. It should be noted that there are three different positive power rails:  $V_{bat}$ , 5V and 3.3V. The 3.3V is provided by the raspberry pi. It should also be noted that the pins in the schematic were placed with clarity in mind and not the physical placement they will be found in. The schematic must be used in conjunction with component datasheets to ensure correct connections.

The next steps for the schematic will be to continue updating as more changes are made to the system and asked for by the client. The pins should also be rearranged to match their physical placement if a PCB will be created.

### Power Supply (Jack)

The portable ventilator operates from a 14.8 V battery pack. This battery pack can vary from 9 V to 16.5 V depending on charge status. A power supply needed to be developed to supply separate voltages that stay constant during variations in battery voltage. A [21] D24V22F5 5 V, 2.5 A step-down voltage regulator was chosen to supply the power lines for the system.



Initial power supply system design.

By using a high power diode configuration, the voltage regulator could theoretically supply a 6.2 V and a 5 V power line. The 6.2 V line would be optimal for running the servo and the 5 V line would power the microcontroller, sensors, and other electronics in the system. The voltage regulator, a battery connector, and pin headers were soldered onto a protoboard in order

to give easy access to the power lines. However, the power supply did not operate correctly when tested. It was determined that the voltage regulator possibly utilized feedback current through its ground port and the diodes interfered with its operation. Due to this, the diode configuration was scrapped and the power supply was used for only a single 5 V line. The servo was adapted to use a 5 V supply instead of a 6.2 V supply, so no new designs had to be made to create a 6.2 V power line. The finished product was handed off to the CPE team which used it in their system. There were no issues with the operation of the power supply.

### **Ultrasonic Atomizer (Jack)**

A WG3166A ultrasonic atomizer was used to humidify the ventilator system. The humidifier board works well and has had no issues. However, it is a goal of the EE team to have our own dedicated board layout by the end of this senior project. To do this, the current humidifier board needs to be reverse engineered so that the team can integrate it into our overall design. In addition, some components of the board may be unnecessary for our purposes so the team could possibly simplify our system.

To start, a schematic must be made of the system so the team can understand its operation and how to replicate it. All of the components on the humidifier need to be identified to do this. Some components on the board don't have markings to identify them, which makes it difficult to figure out their purpose. However, through testing and analysis, all components on the humidifier have been identified. A detailed schematic is currently being drawn up which will be helpful in analysis and testing of our own design. As of now, the system has been divided into two sections. There is a power supply section, which converts the 5 V supply voltage into a ~20 V drive voltage. This is done through a MC34063A [22] boost switching regulator with an accompanying system. The next section is the transducer driver portion. This section uses a 78L05 5V regulator [23] (which we won't need in our design), a NE555 timer [24] for a 113kHz oscillation, and a FQD2N60C N-channel power mosfet [25] in order to resonate the transducer which atomizes water and creates the humidity. This work is being continued into the next quarter and its goals will be defined in the Spring 2021 Goals section of the addendum.

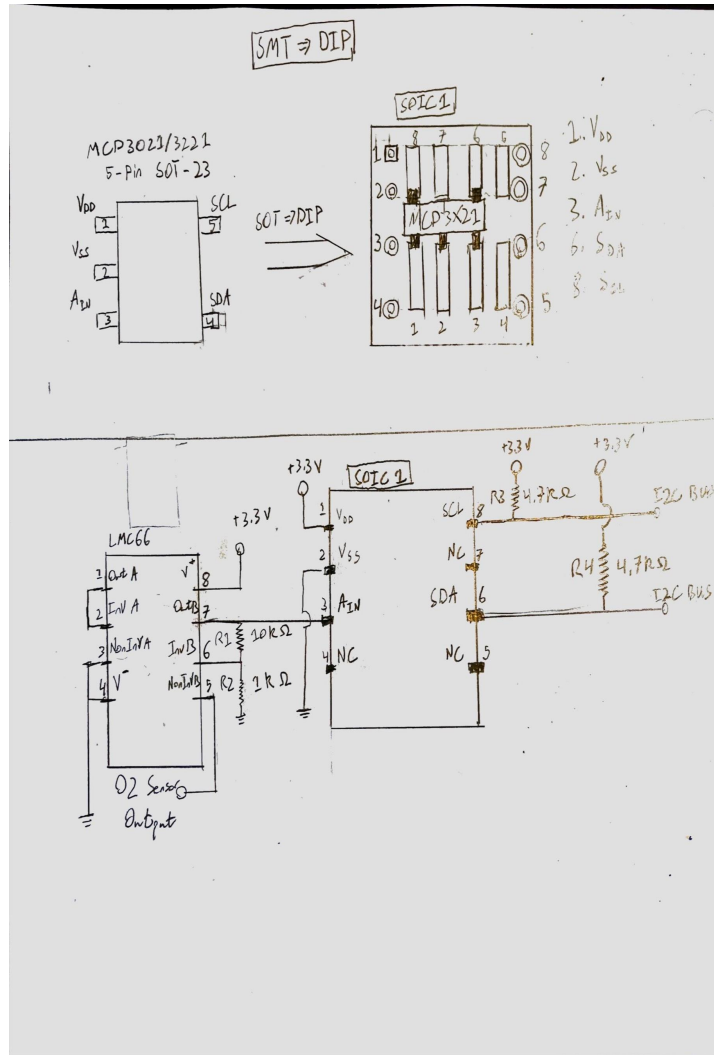
### **Humidity Sensor (Brad)**

Initially, there was the task of identifying and selecting sensors which measured within the specified range and were cost-effective. I happened to own a [DHT11](#) [26] Pressure/Temperature chip, which was not I2C but already had code written for it. Unfortunately, the DHT11 was not reliably giving consistent results when read. So the next step was to acquire and write code for a different sensor, this time with I2C compatibility and much more reliable. The [HTU21D](#) [27] fit all of the same measuring specifications as the original. When the chip was hooked up to the I2C bus however, it shared the same address with the flow rate sensor (0x40).

Lastly, an even better chip was found which has a different I2C address and also included a humidity sensor, the [BME280](#) [28]. This chip has been working reliably within the system, although the humidity collection capabilities are not being utilized.

## **O2 Interface Design (Brad)**

Next, there was the task of creating an interface between the Oxygen Sensor and the ADC. It involves the use of a simple 10x gain non-inverting op-amp from the sensor output to the input of the ADC. The original goal was to prototype the 10-bit, I2C-compatible [MCP3021](#) [29] on a breadboard. Upon the delivery of the ADC, the part was much too small to be breadboarded or even soldered. Therefore a set of SMT to DIP adapters were ordered and used to breadboard and prototype the final design onto. It does not appear that any I2C-compatible chips are manufactured in any form but SMT. Additionally, a handful of 12-bit, I2C-compatible [MCP3221](#) [30] were soldered on some of the SMT to DIP adapters if higher resolution was necessary. The original op-amp used in the design was the [LM741](#) [31], but this does not currently come in an SMT package. As a goal for the next quarter, the entire schematic (currently curated by Sanders) will be laid out onto one PCB. This means most all parts will have to be SMT. Fortunately, the [LMC662 CMOS Dual Dual Op-amp](#) [32] comes in an SMT package, with some better specifications than the LM741. Below is the two schematic drawings, the top is the SMT to DIP translations from the MCP3021/3221:



Top: MCP3021 Mounted on SMT to DIP Chipset with Pin Translation  
 Bottom: Full O2 Interface - O2 Sensor->LMC662 ->MCP3021->I2CBUS/PI

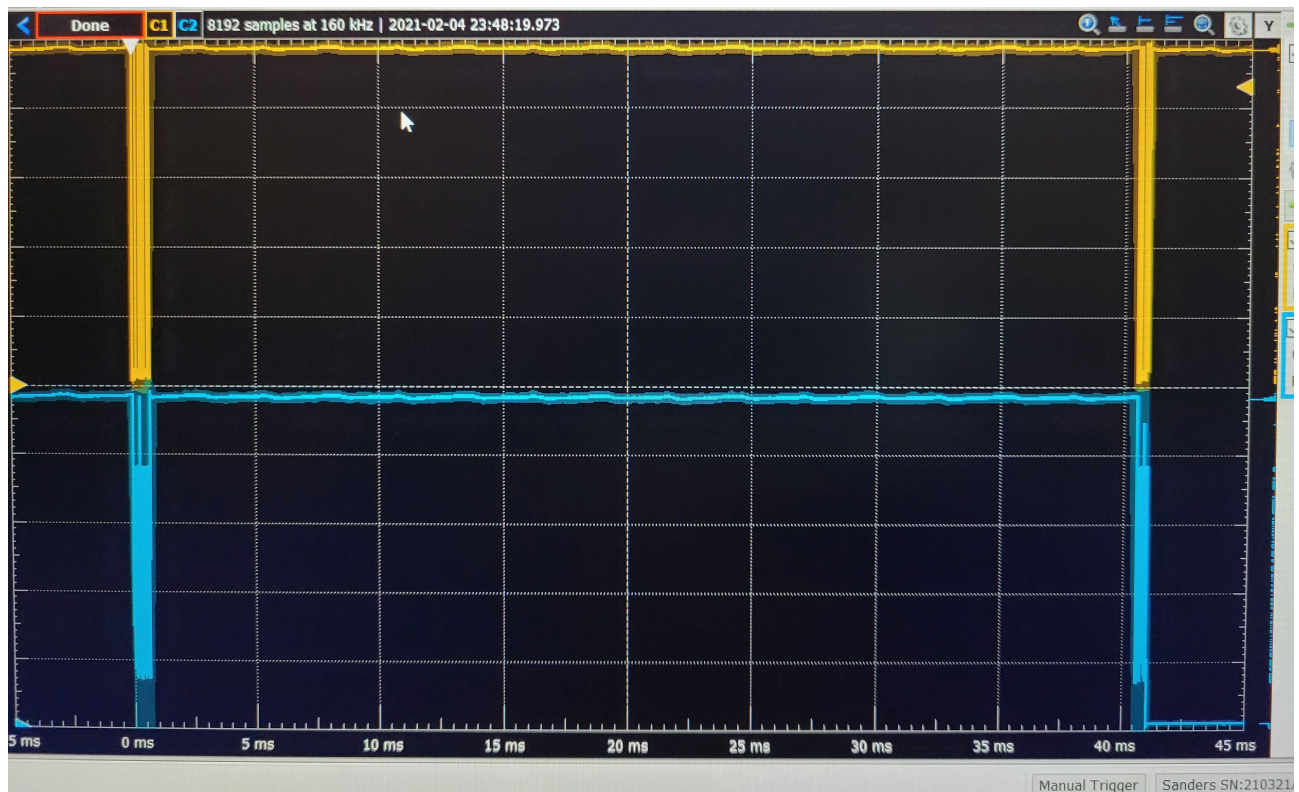
The feedback and gain resistors' value in the actual circuits are both lower than the actual schematic, this is to try and keep the gain as close to possible at 10. Both 4.7k resistors on the SDA and SCL lines are purely representative of the voltage that the resistors should be pulling up to. They have been taken out in the final iteration because the ventilator bus already has pull-up resistors.

When it came to the code, I ended up helping Jared write a lot of the ADC translation functionality, always there to answer questions about LSB and how Vref affects the final calculation. The biggest part was understanding that the oxygen sensor signal output was 9-14mV with an approximate gain of 10 from the op-amp leading into the analog in port of the ADC. This means the values will range from 0.09V to 0.14V for the 10-bit ADC. It was then a simple matter of linearly mapping the range of ADC outputs to a calculation of oxygen percentages.

## Air Flow Rate Sensor (Sanders)

Along with the schematic, I worked with the CPE team, in particular with Jared, to troubleshoot and fix issues with the components. The first major issue was with the Air Flow Rate Sensor. The CPE team was having trouble reading the I2C data. Once I received the sensor I performed tests to identify the problem. Initial tests were done using an Aruduino and then a MSP432 since the Raspberry Pi in my possession stopped working. Initial tests found that the pull up resistors in the sensor did not interact correctly with the pull up resistors in an MCU and prevented the SDA and SCL lines from being pulled to ground. This issue was found to be fixed by using the level shifter.

After fixing this issue, further tests were performed and the I2C data was still a problem. This second round of testing showed that writing to the sensor was able to be done correctly and multiple times. This was not the case when reading data from the sensor. The first time data is read from the sensor there is no problem and the data being read is correct. This was tested by blowing air through the sensor and checking by hand that the data was different than when no air would flow through and corresponds to the correct direction. However, when trying to read data the second time the sensor would break I2C communication.



Yellow: SDA

Blue: SCL

During the transmission of the second read, the sensor would take control of the SCL and hold the line to ground. The reason that the sensor is thought to be responsible for this is that the SCL is not pulled completely to ground. During testing whenever the sensor had control of either SDA or SCL it would always pull the lines close, but not exactly, to ground. The MCU on the other hand would be able to pull the lines exactly to ground. Further tests were done to try to find the root cause, however, these were all unsuccessful. The tests showed that changing the type of data being transmitted or telling the sensor to reset would not stop the SCL being taken over by the sensor during the transmission of the second read.

Due to the nature of the ventilator a working flow rate sensor was needed by the CPE to continue integration and testing. This time constraint meant that it was more important to find some type of solution than it was to find the cause of the problem. Therefore, the focus changed to finding a workaround to the problem. It was found that forcing the sensor to not send the third byte would prevent the sensor from taking control of the SCL line. This was done in the code[33]. The pros of this are that the first two bytes contain all the measurement data, but the main con is that the third byte contains the error checking data (CRC8). This means that other precautions must be taken to minimize possible errors in the data. One such precaution was to add a capacitor between the ground and  $V_{DD}$  pins to minimize crosstalk and errors.

### **Humidity/Temperature/Pressure Sensor (Sanders)**

The second major component issue was conflicting addresses with the air flow rate sensor and the humidity/temperature sensor. The temporary solution used was to use the raspberry pi's second set of I2C lines, pins 27 and 28. This was done by modifying the flow rate sensor code. This was a temporary solution because documentation and other information on the raspberry pi warned against using those pins as they could be unreliable. The permanent solution was decided to then be finding a new humidity sensor with a unique address. The new sensor, BME280 [28], was found by Brad and chosen due to it being a better sensor than the previous with additional capabilities, such as measuring pressure and oversampling.

The next step was to get the sensor to work correctly. Along with the sensor being a better performing and higher quality sensor, it was also a more complex and difficult to understand component. After many iterations of code[34], the sensor was working correctly but could not verify how accurate it is due to lack of equipment. This was left to the CPE team to test and confirm. The most important and difficult part for correct and accurate measurements was the compensation of the data.

## I2C Addresses

To prevent future issues with I2C addresses a table was made that contains all current I2C devices and their address.

Device	Address
Flow Rate Sensor	0x40
Humidity/Temp/Pres Sensor	0x76
ADC	0x4D
Pressure Sensor	0x28

## Component Specifications

This component specifications table contains information about both the operating conditions and maximum/minimum conditions for the components used.

Parameter	Minimum	Typical	Maximum	Units
<b>Battery</b>				
<b>Output Voltage</b>	12	14.7	16	V
<b>Voltage Regulator</b>				
<b>Input Voltage</b>	5.3	-	36	V
<b>Output Voltage</b>	-	5	-	V
<b>Continuous Output Current</b>	1.4	-	2.6	A
<b>Quiescent Input Current</b>	-	1	-	mA
<b>Quiescent Input Current (low-power)</b>	5	-	10	μA/V
<b>Raspberry Pi 4B</b>				
<b>Supply Voltage</b>	-	5	6	V
<b>Supply Current</b>	3	-	-	A
<b>GPIO Voltage</b>	0	-	3.3	V



<b>GPIO Output Current</b>	0	-	16	mA
<b>Pull-Up Resistors</b>	-	1.8	-	kΩ
<b>Humidifier</b>				
<b>Supply Voltage</b>	3.7	-	12.7	V
<b>Rated Power</b>	-	2.5	-	W
<b>Humidity/Temp Sensor</b>				
<b>Supply Voltage</b>	1.71	-	3.6	V
<b>Startup Time</b>	-	2	-	ms
<b>I2C Voltage</b>	-0.3	-	3.6	V
<b>Pressure Sensor</b>				
<b>Supply Voltage</b>	3	3.3	3.6	V
<b>Supply Current</b>	-	2.1	2.8	mA
<b>Startup Time</b>	-	-	5	Ms
<b>I2C Voltage</b>	-0.3	-	3.6	V
<b>Air Pump</b>				
<b>Rated Voltage</b>	6	-	12	V
<b>Rated Current</b>	-	1	-	A
<b>Rated Power</b>	-	10	-	W
<b>Air Flow</b>	-	16	-	CFM
<b>Oxygen Sensor</b>				
<b>Output Voltage</b>	9	-	14	mV

<b>Flow Rate</b>	0.1	-	10	Lpm
<b>Flow Rate Sensor</b>				
<b>Supply Voltage</b>	4.75	5	5.25	V
<b>Supply Current</b>		7.5	10	mA
<b>I2C Voltage</b>	0	-	5	V
<b>Sampling time</b>	-	10	-	Ms
<b>Flow Rate Range</b>	-200	-	200	slm
<b>Servo</b>				
<b>Supply Voltage</b>	4.8	-	7.4	V
<b>PWM Range</b>	500	-	2500	$\mu$ s
<b>Level Shifter</b>				
<b>High Voltage</b>	-	-	10	V
<b>Low Voltage</b>	1.8	-	-	V
<b>Pull-Up Resistors</b>	-	10	-	k $\Omega$
<b>ADC</b>				
<b>Supply Voltage</b>	2.7	-	5.5	V
<b>Supply Current</b>	-	-	370	$\mu$ A
<b>Input Voltage</b>	-0.6	-	$V_{\text{supply}} + 0.6$	V
<b>I2C Voltage</b>	-0.6	-	$V_{\text{supply}} + 1$	V
<b>Conversion Time</b>	-	8.96	-	$\mu$ s

LMC66 (Op Amp)				
Supply Voltage	4.75	-	15.5	V
Supply Current	-	-	35	mA
Input/Output Voltage	-0.3	-	$V_{\text{supply}} + 0.3$	V
Output Current	-18	-	18	mA

## Spring 2021 Goals

### Brad

Next quarter I am planning on aiding Sanders with the PCB layout of the entire schematic, this does not imply sending schematic files back and forth. Instead, it will be worked on collaboratively so that the best decisions about layout may be made. Also, I'd like to work more with Jared in improving any of the firmware where needed and look into any feedback systems which need analysis. I would also like to apply any signal processing techniques which may improve the readouts, as well as analyze closed loops in the feedback system and apply control theory to check for stability or reduce sensitivity. I wager the firmware improvement will be an ongoing-yet minimal time commitment every week through meetings. Given the PCB turnaround time is shy of 3 weeks, The PCB layout needs to be completed before week 5. This dictates each week a certain subsection of the total schematic must be completed. Any closed loops will have to be analyzed using more modern-control theory, where the feedback is replaced with a MCU. Some additional reading will have to be done on the translation between the two. Lastly, any additional circuitry or problems either project lead Vanessa or continuation-member Jared need my assistance with is also my obligation.

### Jack

I am currently working on the Ultrasonic Atomizer reverse engineering project. Next quarter, it is my goal to come up with a complete schematic for the system. I will then develop and test my own design. Then after the system works on my own design, we can integrate my design into the team's overall board layout. I estimate that this project will take a few weeks to accomplish because I need to completely figure out the system, order specific components, and then build and test my own circuit. I also plan to help out the rest of the Portable Ventilator team when needed. From the Capstone team, Jared and Vanessa will be continuing the portable ventilator senior project. We will be in contact with them to determine how we can add more

functionality and improve the overall performance of the system. By the end of the quarter, we hope to have a fully independent portable ventilator which operates off our single PCB design.

## **Sanders**

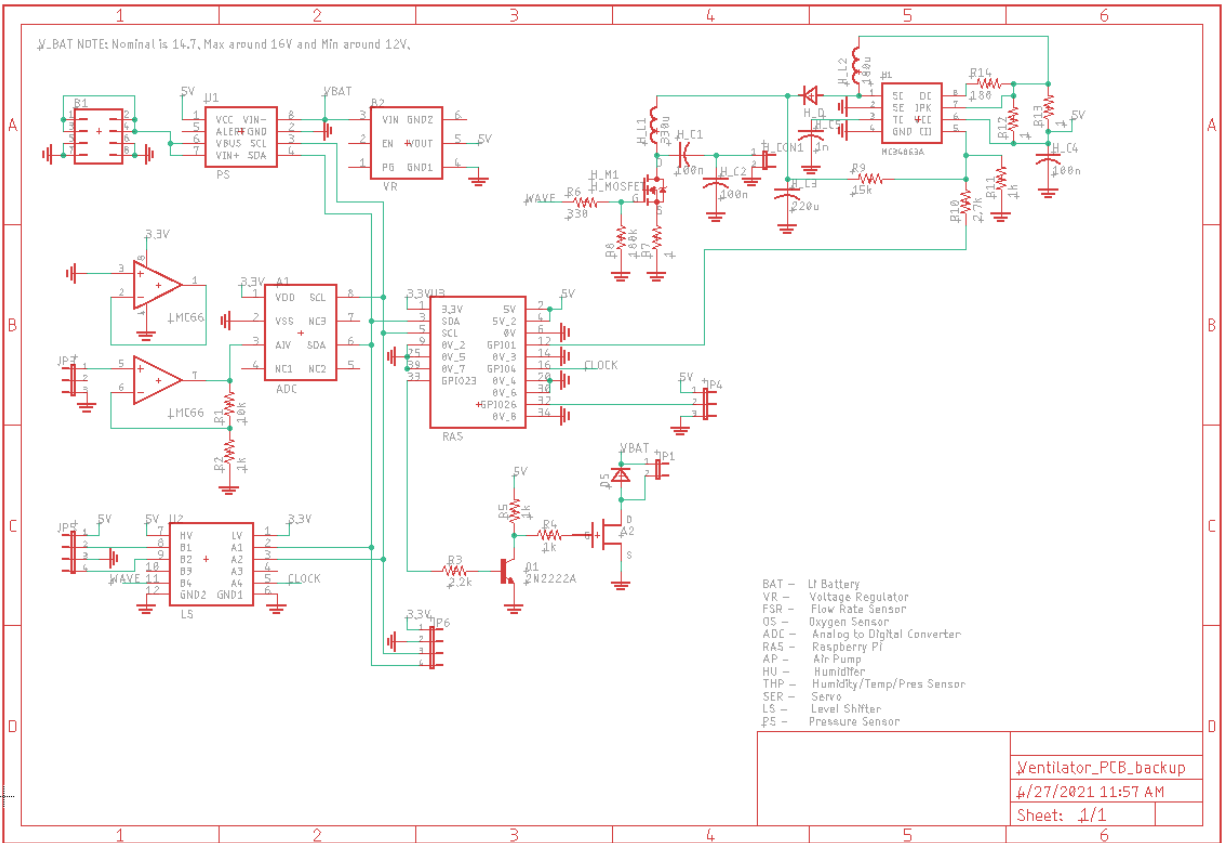
Next quarter, I will continue with the responsibilities of this previous quarter. This will be to update the schematic as needed and provide support in troubleshooting and fixing component issues. Along with this, I will work in collaboration with Brad to create a PCB layout before week 5. This will mean that any updates to the schematic must also be complete before week 5. I would also like to develop and work on safety protocols for the components. This would be for issues such as component malfunctions, error checking, and other possible dangers. To achieve some of this, further research will need to be done into patients' vital needs, such as max length of time without proper air flow, max and min air pressure, and etc. Therefore, I will need to continue working with Jared and, in particular, Vanessa from the capstone team.

## **EE 462 Addendum**

### **PCB (Sanders)**

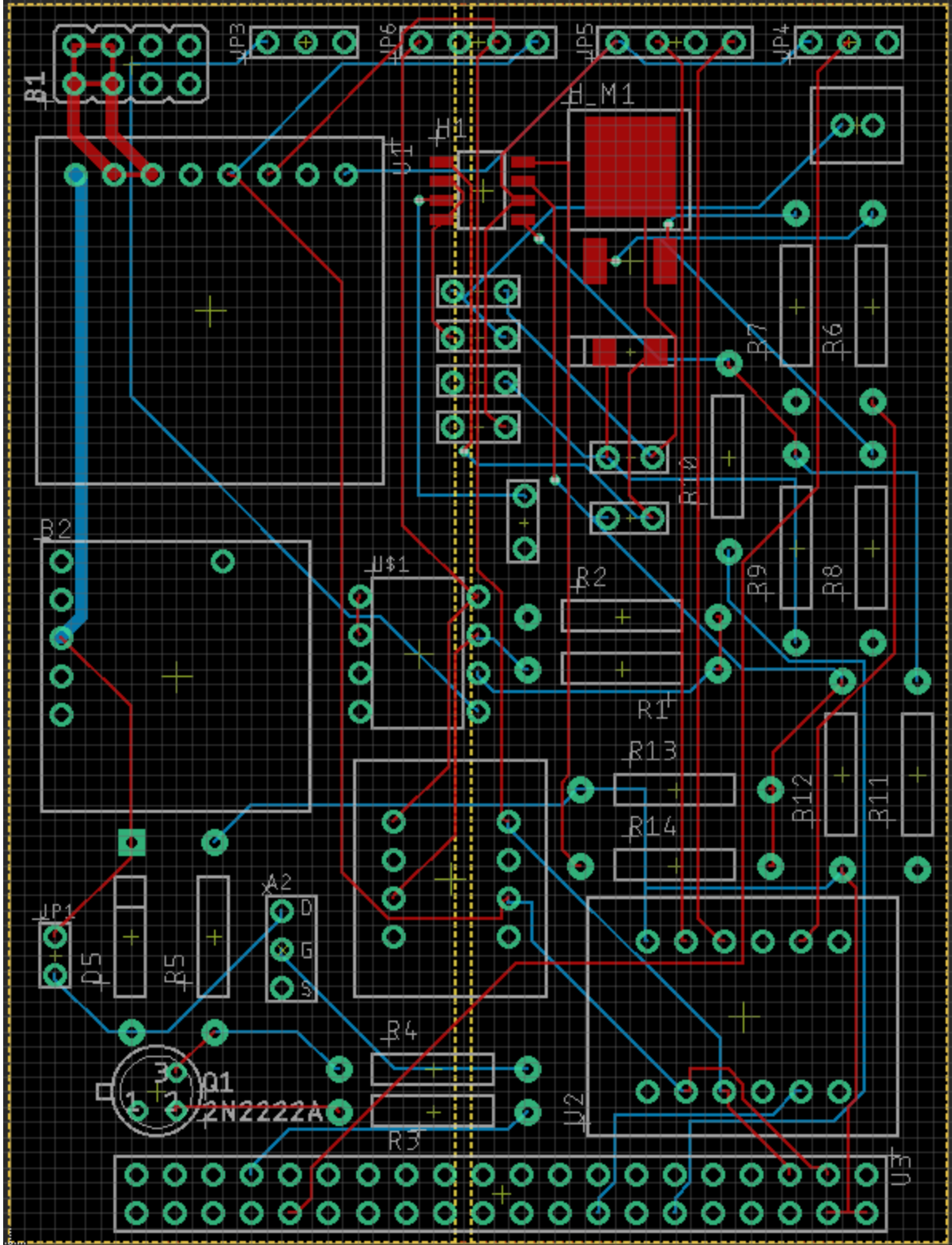
Initially a breadboard and wires were being used to hold and connect the components of the ventilator. While this was acceptable for the initial testing and prototypes, the final design would use a pcb for the electrical components of the system. The pcb would provide more reliable and secure connections between components, and a minimized area.

The first design pass of the pcb included the raspberry pi, voltage regulator, power sensor, oxygen sensor amplifier, a/d soic board, level shifter, air pump/fan system, and the humidifier system. Along with these components, there were connectors for the components that would be off-board. To be able to use Eagle for the layout, a new schematic had to be made that only included the on-board components.



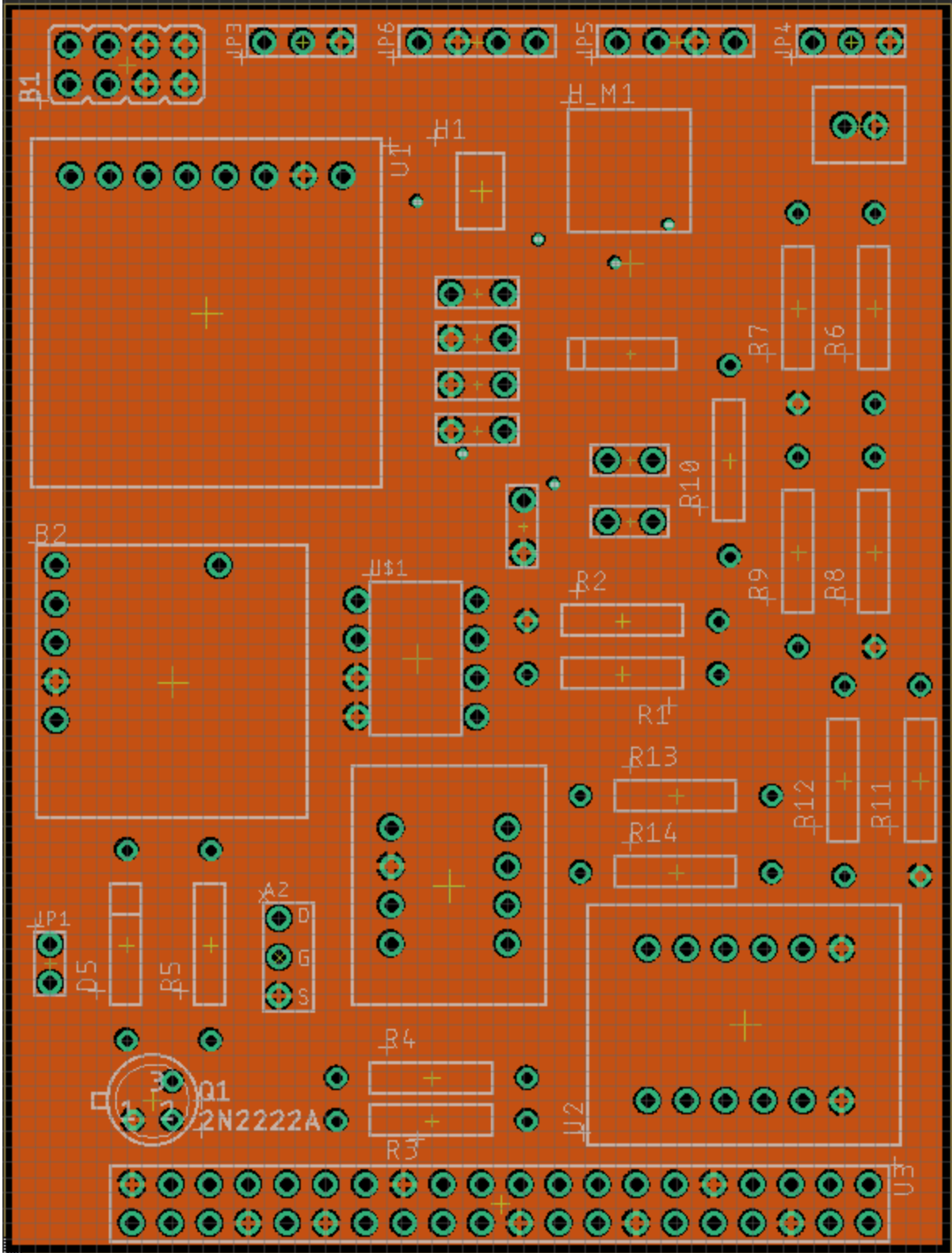
Layout Schematic 1st Pass

To be able to create the pcb layout, footprints were created for every component that would be on-board. This required using the dimensions in the datasheets to create the footprints. However, some components had no datasheet or did not have the dimensions in the datasheet. This meant that those components had to be measured by the CPE team and they then would relay that information to me. The design of the footprints took the longest time. After designing the footprints a layout and route were done and then sent to the advisor for comments. After some changes the layout was done and sent for manufacturing.



Layout 1st Pass Top(red) and Bottom(blue) Layer





Layout 1st Pass 3rd Layer

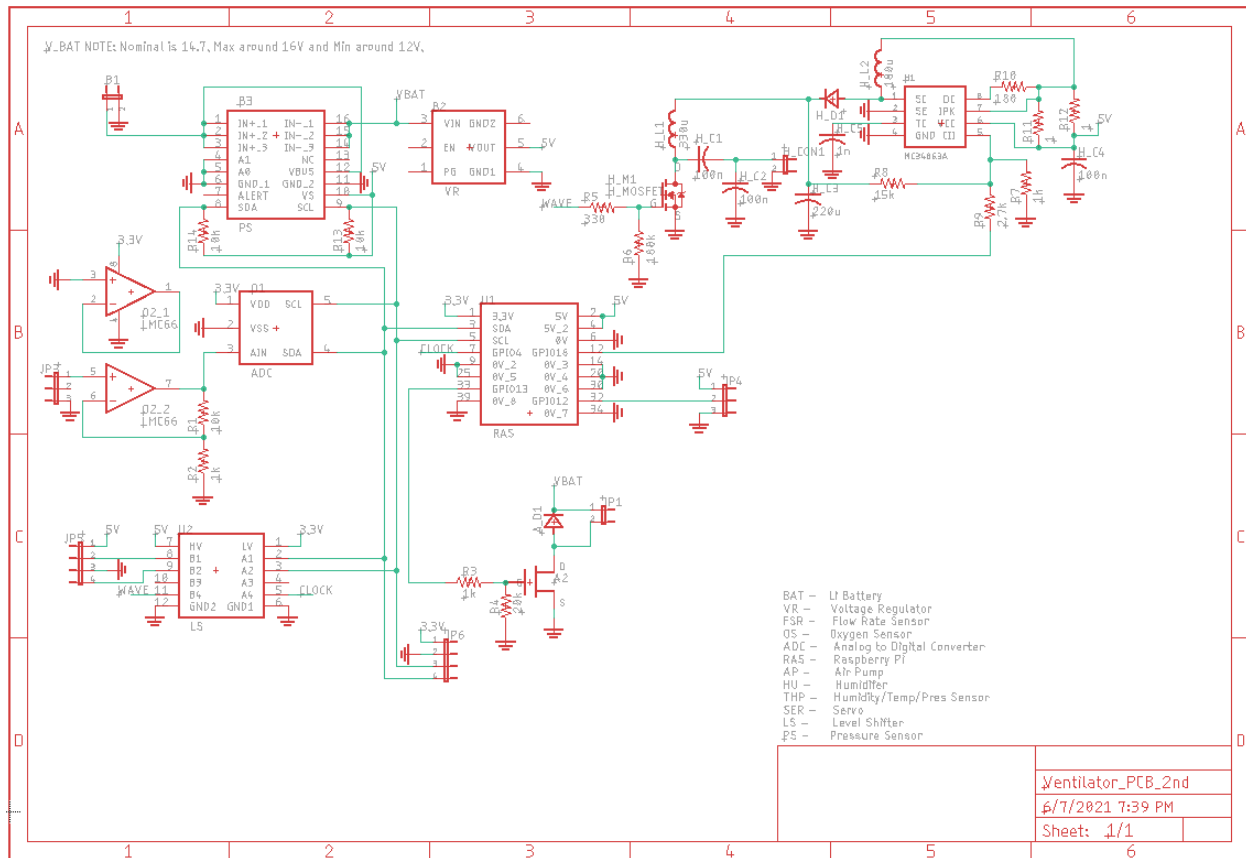
The size of the first iteration was about 62mm x 82mm. It is a 4 layer pcb with the 2nd layer being used for 5V and 3.3V planes. The 3rd layer is used for ground. The top and bottom



layer are used for traces. Due to time constraints the capacitors, inductors, humidifier diode, humidifier connector, a/d, and op-amps were not labeled correctly. The battery traces are wider than the rest of the traces because those traces would have higher current going through them. The mosfet A2 pinout was incorrect, it should be GDS not DGS. This was solved by adjusting the mosfet leads used.

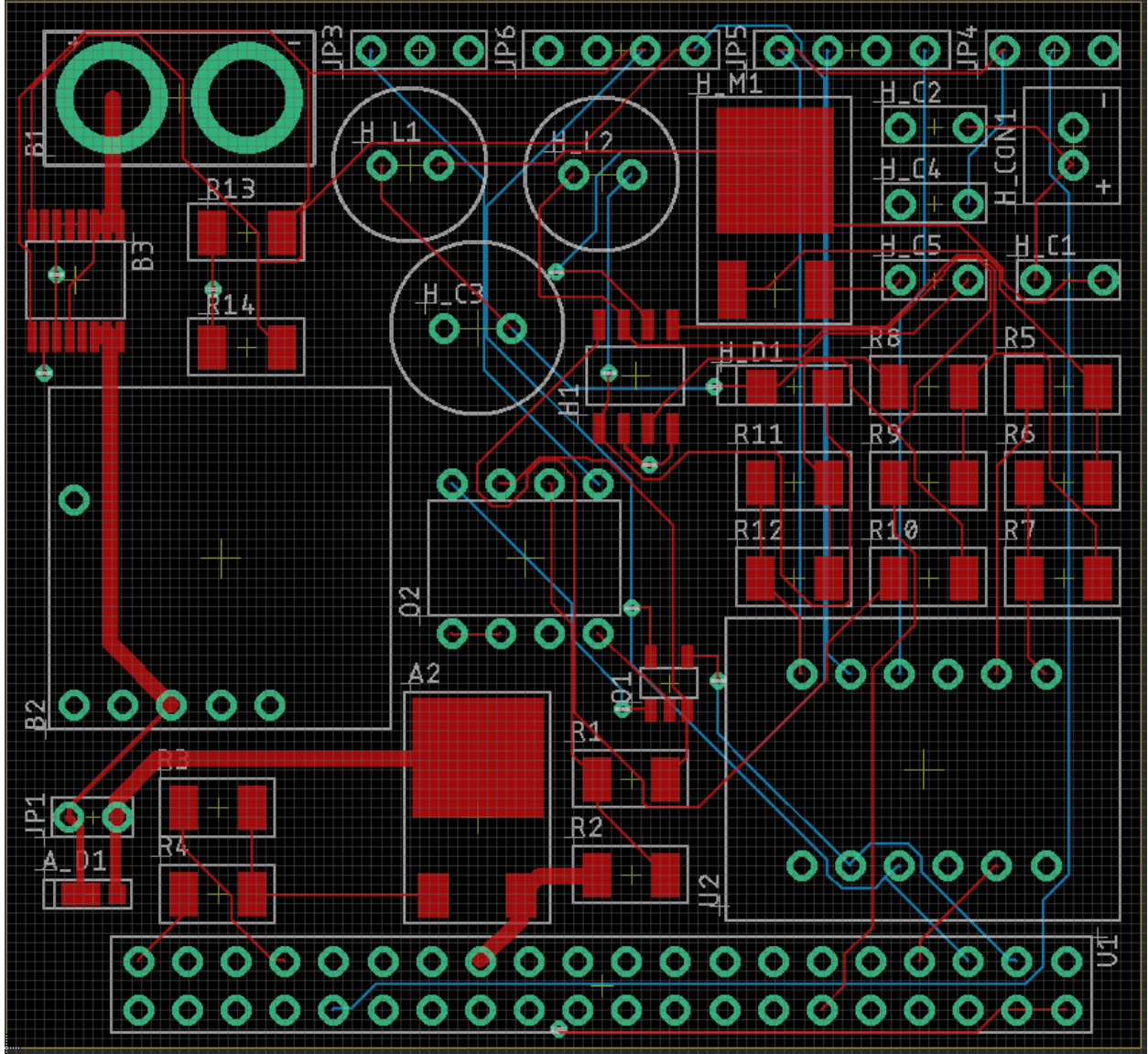
After the pcbs were manufactured and picked up, the board was assembled and tested. A second pinout issue was noticed. In the schematic and layout the clock signal for the humidifier was placed at pin 16, however it is pin 7 that is actually used to provide the clock signal. This was a simple fix with a wire connecting pin 7 to pin 16 fixing the issue. Another issue noticed was about clarity. There was confusion on how things were oriented, in particular U2, U\$1 and the unlabeled a/d.

For the second pass all of these issues were fixed. Along with this many components were changed and a new schematic and layout were created.



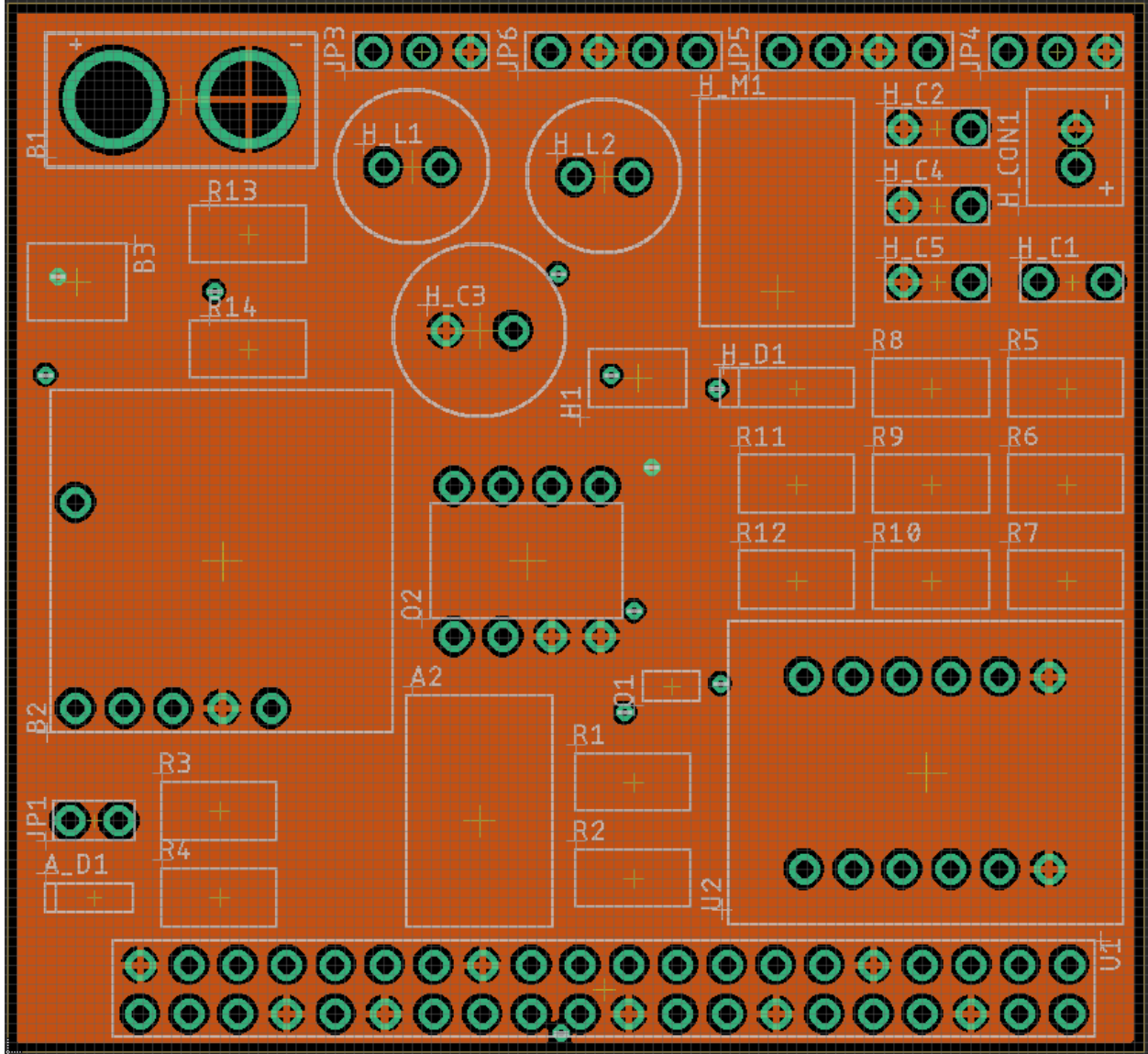
Layout Schematic 2nd Pass

The largest changes for the 2nd pass were the replacement of the power sensing board with the smd chip and the replacement of the a/d soic board with the a/d directly placed on the pcb. Similar to the first pass the layout was submitted to the advisor and then adjusted as asked.



Layout 2nd Pass Top(red) and Bottom(blue) Layer





Layout 2nd Pass 3rd Layer

The size of the second iteration is 59mm x 54mm. The smaller size was achieved by replacing thru-hole components with smd components. The full list of changes made to the board are as followed:

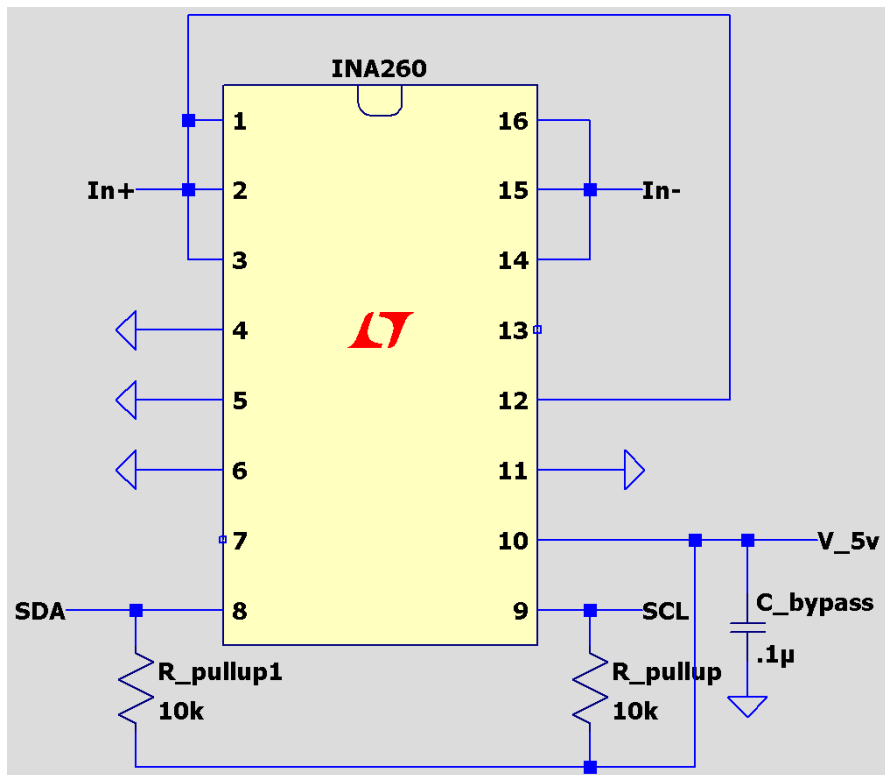
- The resistors, diode, a/d, power mosfet and power sensor are now smd.
- Removed 2n2222 transistor.
- All components are now labeled.
- The battery connector is now direct.
- The pins are fixed on the components that had an error.
- Large capacitor and inductors are now properly marked and spaced.
- Resistors, capacitors, inductors, diodes, and transistors are oriented the same, i.e. their labels are oriented in the same direction.
- ICs, connectors, and boards are oriented the same.

- All component labels are now placed so that pin 1 is always the closest pin to the label. (Pin 1 should be the same in the schematic and the component's datasheet).
- Battery and humidifier connectors have extra labels to help distinguish positive V (+) and GND (-).

### INA260 Voltage Sensing Circuit (Jack)

The portable ventilator will require a basic battery management system. The initial step to accomplish a BMS is to integrate a power sensor. The power sensor will read the voltage and current from the battery and relay the information to the raspberry pi microcontroller. With this information, the microcontroller could potentially enter a low power mode and display “low battery” warnings to the user.

An INA260 Power Sensor Adafruit Board was chosen to provide battery sensing for the ventilator. The INA260 chip can support the ventilator’s battery voltage with currents up to 15A. This board was integrated into the initial PCB design by Sanders. Next, an INA260 circuit needed to be designed in order to remove the adafruit board from the PCB, as a goal of the portable ventilator is to have a self sufficient PCB without the need of external boards. The schematic below shows the simple circuit that was designed to produce correct operation of the INA260 chip.

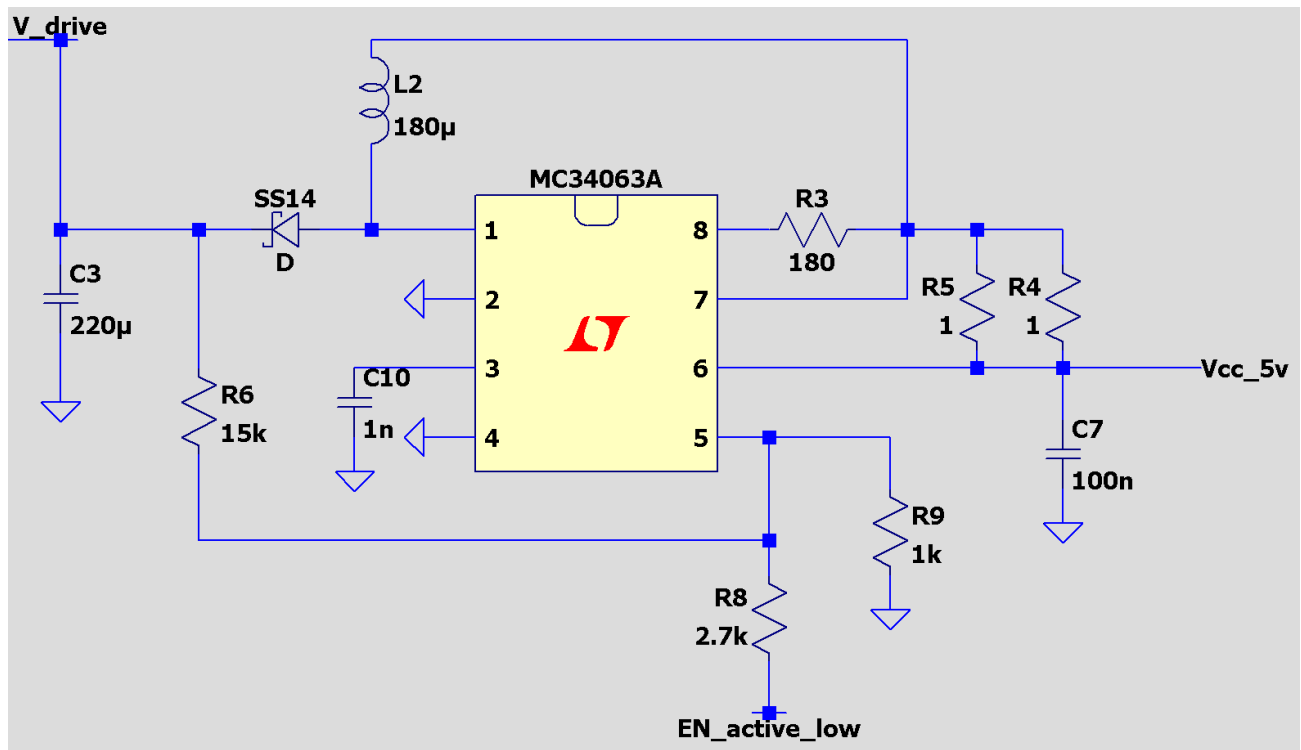


INA260 Power Sensor Schematic

This circuit has been integrated into the second iteration of the PCB design. It will be used to obtain voltage and current measurements from the battery. The INA260 circuit will be the stepping stone for a more complex battery management system in the future for the portable ventilator.

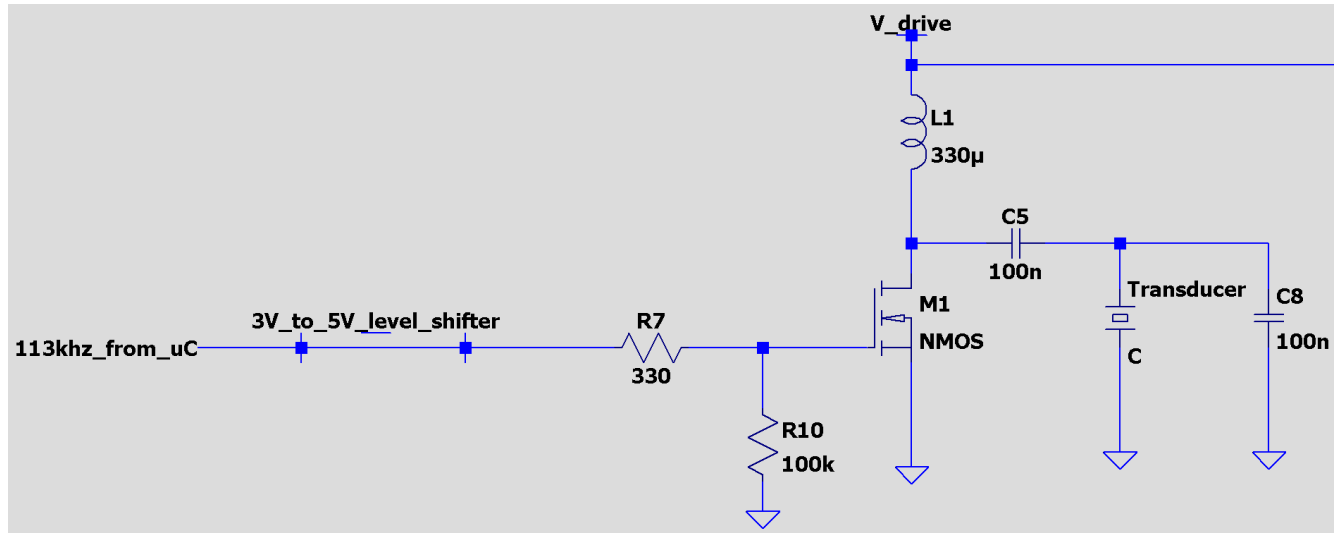
### Ultrasonic Atomizer Design and Testing (Jack)

A large goal of the EE team was to have our own dedicated board layout by the end of the senior project. To do this, we would need to not use premade boards and make our own designs when possible. A WG3166A ultrasonic atomizer was reverse engineered to humidify the ventilator system. In the process of reverse engineering, it was determined that many components on the WG3166A board were unnecessary for our application. The final schematic for the ultrasonic atomizer system is shown in two parts below.



Power Driver Circuit

The power driver circuit above utilizes a boost converter to produce a 26V drive signal for the ultrasonic transducer drive shown below. This power driver features an “EN\_active\_low” node that can be used to effectively turn off the buck converter circuit when not in use which will reduce passive current draw. This feature would be used during a “low power” mode in which the portable ventilator is low on battery life.



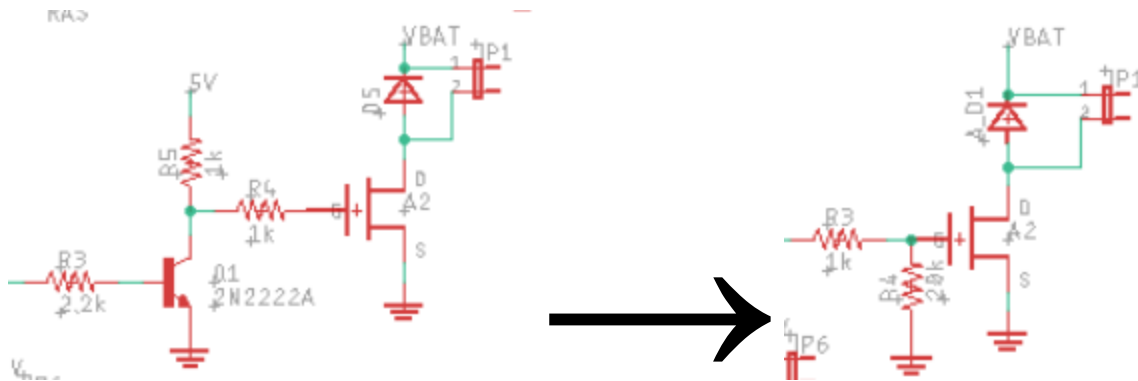
Ultrasonic Transducer Driver Circuit

The ultrasonic transducer driver circuit above uses a power MOSFET to switch an ultrasonic transducer at high voltages. The microcontroller provides the circuit with a 113kHz square wave, which will resonate the ultrasonic transducer. This resonance along with the high voltage supplied from the power driver circuit will cause water to atomize rapidly at the surface of the ultrasonic transducer. This will be used to provide the humidity for the portable ventilator system.

The first PCB iteration was populated with the various systems of the ventilator. After initial testing from the CPE team, it was found that the ultrasonic atomizer system was not operational. The board was then sent back to the EE team. Through testing, it was found that an incorrect resistor had been soldered into the system, which saturated the power MOSFET and restricted the transducer from resonating. It was then determined that some of the pinout locations between the raspberry pi microcontroller and the PCB did not match up. The incorrect pinout connections were corrected manually and the humidifier system became fully operational. The second PCB iteration has changed the incorrect pinout locations which will fix these issues in the future.

### Fan Driver Circuit Improvement (Jack)

The advisor proposed an improvement to the fan driver circuit. This improvement would eliminate the need for a switching BJT and one resistor. He proposed that the fan driver's power MOSFET could be driven directly from the microcontroller's GPIO pin. This would reduce the complexity of the circuit and the number of components on the PCB without degrading performance or power consumption.



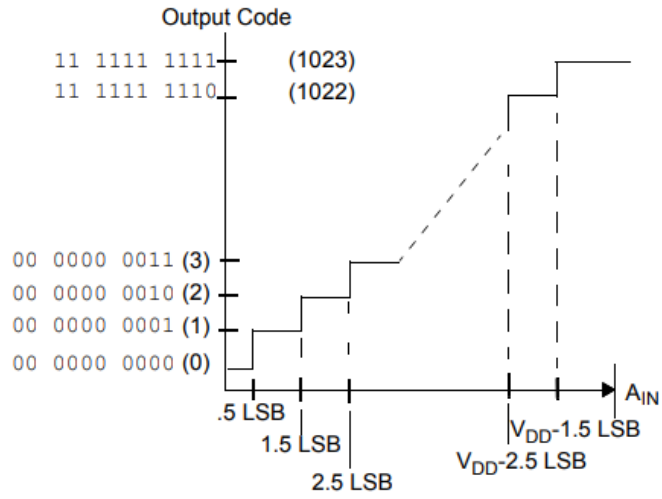
Old design on the left. Improved design on the right.

The new design was constructed and tested using various resistive loads and a muffin fan. The design was proven to work in scenarios requiring current up to 500 mA, which showed the effectiveness of the circuit to reliably drive the fan for the portable ventilator. With this new implementation tested, Sanders integrated the circuit improvement into the second iteration of the PCB.

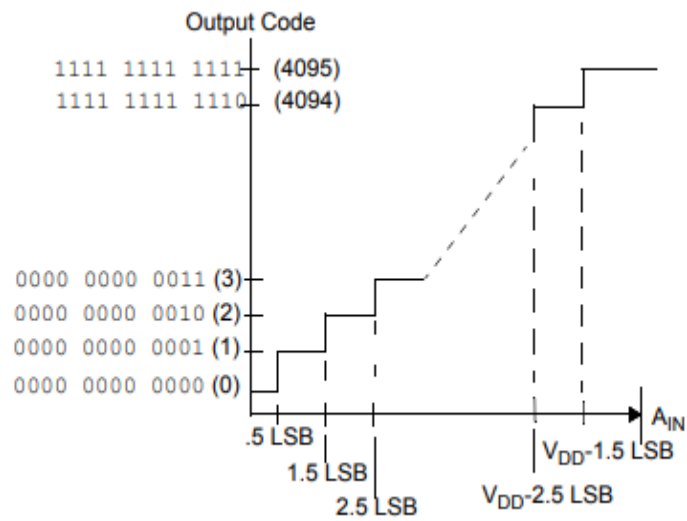
## O2 Sensing Circuit Improvements (Brad)

Two issues arose with the original O2 sensing circuit. The first of which was the lack of range the initial operational amplifier configuration yielded. The 10k feedback resistor with the 1k shunt resistor gives a 10x amplification for an amplified O2 range of 90-140 mV. Unfortunately for the 10-bit ADC, this range is not ideal for precise oxygen percentage measurements. Therefore, to offer more range for the ADC to sample is to increase the feedback resistance to the LMC66, preferably above the hundred-thousand but below the mega ohm range. A 100k feedback resistor augments the range to 0.9-1.4V, a 500 percent output range increase. The second problem was the limited resolution of the ADC. While the original 10-bit MCP3021 was competent at detecting the required ranges, it still offered a limited range given the original input signal range and the reference voltage. In order to increase this range, there is a 12-bit ADC which operates similarly to MCP3021, the MCP3221. In the PCB, the area where this ADC is mounted is occupied by an 8-pin DIP so that either the 10-bit or 12-bit may be placed modularly, as the SMT ADCs sit on a smaller board which makes SMT devices mount onto a DIP set.





MCP3021 Range (10-Bit)



MCP3221 Range (12-Bit)

## Bill of Materials & Assembly (Brad)

All the non-SMT components are all sourced from the same distributor, making the turnaround for ordering parts approximately 2 weeks. The SMT components as well as the hybrid SMT/DIP materials are sourced from a variety of distributors. It was unfortunate that many components do not come in a SMT package, as it would have dramatically reduced the amount of space used on the board. The through-hole resistors from the first iteration of the PCB fit oddly and took up approximately a quarter of the board space. Additionally the height as well as the radius of the capacitors (specifically C1, 2, and 3) were the cause of spacing issues. Instead of having all of the capacitors on one side of the board, the proximity and size of the capacitors meant soldering one of the capacitors on the underside of the PCB, meaning the fitting of the PCB on top of the PI was not as snug due to the protruding underside capacitor.

Resistors	Ohms	Caps	F	Induct	H	ICs		Transistors		Diodes	Header	
R1	10k	C1	100n	L1	330u	IC1	LMC66	Q1	2N2222A	D1	JP1	2x1
R2	1k	C2	100n	L2	180u	IC2	MCP3021	Q2	T0-220AB	D2	JP2	2x1
R3	2.2k	C3	220u					Q3	T0-220AB		JP3	3x1
R4	1k	C4	100n								JP4	3x1
R5	1k	C5	1n								JP5	4x1
R6	330										JP6	4x1
R7	100k										JP7	2x1
R8	1											
R9	15k											
R10	2.7k											
R11	1k											
R12	180											
R13	1											
R14	180											

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Explains the need for and operation of ventilators.

[2] History of Mechanical Ventilation. From Vesalius to Ventilator-induced Lung Injury. American Journal of Respiratory and Critical Care Medicine 2015: Volume 191, Issue 10

Explains the function of negative pressure ventilation in the past.

[3] Penlite, CC BY-SA 4.0 <<https://creativecommons.org/licenses/by-sa/4.0/>>, via Wikimedia Commons

Source for Figure 1

[4] The Mechanical Ventilator: Past, Present, and Future. Robert M Kacmarek. Respiratory Care August 2011, 56 (8) 1170-1180

Provides the history of ventilators.

[5]

[https://lh3.googleusercontent.com/proxy/gt3Vdia8HJczQA-5640ZWbEATwoSsDgvsCMF2j11vpWUIFfm9BgzqbClinmO8IWzZzdgizJh8EWOpdqhzzIelfp4JH-HPfOIBF4g3zr62byOcDQfS2y6S9jvVQoRtsIf39boFAfNUARAGMQWpPozBGIguoBbF4ge6I9CKN5mhVA5yx7qHd7dpMlj0-MNqhEdyDQVoZCNIRQ0v3dNSU\\_pSylj7Q](https://lh3.googleusercontent.com/proxy/gt3Vdia8HJczQA-5640ZWbEATwoSsDgvsCMF2j11vpWUIFfm9BgzqbClinmO8IWzZzdgizJh8EWOpdqhzzIelfp4JH-HPfOIBF4g3zr62byOcDQfS2y6S9jvVQoRtsIf39boFAfNUARAGMQWpPozBGIguoBbF4ge6I9CKN5mhVA5yx7qHd7dpMlj0-MNqhEdyDQVoZCNIRQ0v3dNSU_pSylj7Q)

Source for Figure 2

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Source for Figure 3

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Provide FDA regulatory process.

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CPAP marketplace, includes pricing and quantity

[15] Mechanical Ventilator Market by Components (Devices and Services) Product Type, (Intensive Care Unit/Critical Care, Transport/Portable/Ambulatory, and Neonatal Care Ventilator), Mode (Non-invasive Ventilation and Invasive Ventilation), Age Group (Pediatric & Neonatal, Adult, and Geriatric), and End User (Hospital and Clinic, Home Care, Ambulatory Surgical Center, and Others): Global Opportunity Analysis and Industry Forecast, 2020-2027.

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[33] Air Flow Rate Sensor Code

/\* Flow Rate Sensor Code

Make sure i2c is turned on in raspi-config.

Also pigpio daemon should be off.

Uses sda1 and scl1.

stdio.h is only included for printf() and can

```

    be removed if not using printf().
*/
#include <stdint.h>
#include <stdio.h>
#include <pigpio.h>
#define FRSensor_ADDRESS 0x40

int main(void)
{
    uint16_t value, flow=0;
    uint8_t direction;
    int handle;
    unsigned char data[2];
    unsigned char command[2];

    if (gpioInitialise(<0) return 1; //Initialize pigpio and check for error

    handle = i2cOpen(1, FRSensor_ADDRESS, 0); //Get handle(id) for sensor

    command[0] = 0x10; //Set flow collection command,0x1000
    command[1] = 0x00;

    while(1)
    {
        i2cWriteDevice(handle, &command, 2); //Tell sensor to prepare data
        i2cReadDevice(handle, &data, 2); //Read bytes into value array

        //Get flow rate
        value = (data[0] << 8) | (data[1] && 0xFF);

        if(value > 0x7D00) //check direction of flow

```

```

    {
        flow = ((value - 32000)/140);
        direction = 1; //Forward direction
    }
    else if(value < 0x7D00)
    {
        flow = ((32000-value)/140);
        direction = 0; //Reverse direction
    }
    else
    {
        flow = 0;
        direction =1;
    }

    printf("%d and %d \n", flow, direction);
    for(int i=2850; i>0; i--); //Delay before next read
}

i2cClose(handle);
gpioTerminate();
}

```

#### [34] BME280 Sensor Code

/\* Temp/Humid/Pressure Sensor Code

Make sure i2c is turned on in raspi-config.

Also pigpio daemon should be off.

Uses sda1 and scl1.

stdio.h is only included for printf() and can be removed if not using printf().



Setting:

-Normal Mode (Continuous Measurements)

-Oversampling = 1 (All)

-No IIR Filter

-Standby time = 0.5ms

Max measure time = 9.3ms

Standby time = 0.5ms

Reading Rate =  $1000/(9.3 + 0.5) = 102\text{Hz}$

Chose rate of 50Hz

\*/

```
#include <stdint.h>
```

```
#include <stdio.h>
```

```
#include <pigpio.h>
```

```
#define Sensor_ADDR 0x76
```

```
#define DATA_ADDR 0xF7
```

```
#define COMP1_ADDR 0x88
```

```
#define COMP2_ADDR 0xE1
```

```
int32_t Temp_Compens(int32_t adc_T);
```

```
uint32_t Pres_Compens(int32_t adc_P);
```

```
uint32_t Humi_Compens(int32_t adc_H);
```

```
void org_compens(unsigned char comp1[25], unsigned char comp2[7]);
```

```
int32_t t_fine;
```

```
unsigned char dig_H1, dig_H3;
```

```
uint16_t dig_T1, dig_P1;
```

```
int16_t dig_T2, dig_T3, dig_P2, dig_P3, dig_P4, dig_P5,
```

```
dig_P6, dig_P7, dig_P8, dig_P9, dig_H2, dig_H4=0, dig_H5=0;
signed char dig_H6;
```

```
int main(void)
```

```
{
```

```
    int32_t un_temp, un_pres, un_humi, temp;
```

```
    uint32_t pres, humi;
```

```
    int32_t handle;
```

```
    unsigned char data[8], compens1[25], compens2[7], reg_addr, set[2];
```

```
    if (gpioInitialise(<0) return 1;    //Initialize pigpio and check for error
```

```
    handle = i2cOpen(1, Sensor_ADDR, 0); //Get handle(id) for sensor
```

```
    for(uint32_t i=3000000; i>0; i--);    //start up delay (2ms)
```

```
    //Set Sensor Settings
```

```
    set[0] = 0xF5; //standby time register
```

```
    set[1] = 0;    //standby time = 0.5ms, filter off, spi disabled
```

```
    i2cWriteDevice(handle, &set, 2);
```

```
    set[0] = 0xF2; //humidity sampling register
```

```
    set[1] = 1;    //oversampling = 1
```

```
    i2cWriteDevice(handle, &set, 2);
```

```
    set[0] = 0xF4;    //Temp and Pres sampling, and mode register
```

```
    set[1] = 0b00100111; //oversampling = 1, normal mode
```

```
    i2cWriteDevice(handle, &set, 2);
```

```
    //Get compensation parameters
```

```
    reg_addr = COMP1_ADDR;
```

```

i2cWriteDevice(handle, &reg_addr, 1); //Prepare comp first part
i2cReadDevice(handle, &compens1, 25); //Read bytes into compens1 array
reg_addr = COMP2_ADDR;
i2cWriteDevice(handle, &reg_addr, 1); //Prepare comp second part
i2cReadDevice(handle, &compens2, 7); //Read bytes into compens2 array
org_compens(compens1, compens2); //Organize compensation parameters

```

```

while(1)

```

```

{
    //Get uncompensated measurements
    reg_addr = DATA_ADDR;
    i2cWriteDevice(handle, &reg_addr, 1); //Prepare correct register
    i2cReadDevice(handle, &data, 8); //Read bytes into data array

    //Organize received data
    un_pres = (data[0] << 12) | (data[1] << 4) | ((data[2] && 0xF0) >> 4);
    un_temp = (data[3] << 12) | (data[4] << 4) | ((data[5] && 0xFF) >> 4);
    un_humi = (data[6] << 8) | (data[7] && 0xFF);

    //Get compensated measurements
    temp = Temp_Compens(un_temp); //in DegC*100
    pres = Pres_Compens(un_pres)/256; //in Pa
    humi = Humi_Compens(un_humi)/1024; //in %RH

    //Print out measurements
    printf("T= %d and P= %d and H= %d \n", temp, pres, humi);
    for(int32_t j=10; j>0; j--)
        {for(uint32_t i=3000000; i>0; i--);}; //delay (20ms)
}

i2cClose(handle);

```

```

        gpioTerminate();
    }

void org_compens(unsigned char comp1[25], unsigned char comp2[7])
{
    dig_T1 = (comp1[0] && 0xFF) | (comp1[1] << 8);
    dig_T2 = (comp1[2] && 0xFF) | (comp1[3] << 8);
    dig_T3 = (comp1[4] && 0xFF) | (comp1[5] << 8);
    dig_P1 = (comp1[6] && 0xFF) | (comp1[7] << 8);
    dig_P2 = (comp1[8] && 0xFF) | (comp1[9] << 8);
    dig_P3 = (comp1[10] && 0xFF) | (comp1[11] << 8);
    dig_P4 = (comp1[12] && 0xFF) | (comp1[13] << 8);
    dig_P5 = (comp1[14] && 0xFF) | (comp1[15] << 8);
    dig_P6 = (comp1[16] && 0xFF) | (comp1[17] << 8);
    dig_P7 = (comp1[18] && 0xFF) | (comp1[19] << 8);
    dig_P8 = (comp1[20] && 0xFF) | (comp1[21] << 8);
    dig_P9 = (comp1[22] && 0xFF) | (comp1[23] << 8);
    dig_H1 = comp1[24] && 0xFF;
    dig_H2 = (comp2[0] && 0xFF) | (comp2[1] << 8);
    dig_H3 = comp2[2] && 0xFF;
    dig_H4 = (comp2[3] << 4) | (comp2[4] && 0x0F);
    dig_H5 = ((comp2[4] && 0xF0) >> 4) | (comp2[5] << 4);
    dig_H6 = comp2[6] && 0xFF;

    return;
}

// Returns temperature in DegC, resolution is 0.01 DegC.
// Output value of "5123" equals 51.23 DegC.
int32_t Temp_Compens(int32_t adc_T)
{

```

```

int32_t var1, var2, T;
var1 = (((adc_T >> 3) - ((int32_t)dig_T1 << 1))) * ((int32_t)dig_T2) >> 11;
var2 = (((((adc_T >> 4) - ((int32_t)dig_T1)) * ((adc_T >> 4) - ((int32_t)dig_T1))) >> 12)
* ((int32_t)dig_T3)) >> 14;
t_fine = var1 + var2;
T = (t_fine * 5 + 128) >> 8;
return T;
}

```

// Returns pressure in Pa as unsigned 32 bit integer in Q24.8 format

// (24 integer bits and 8 fractional bits).

// Output value of “24674867” represents  $24674867/256 = 96386.2$  Pa = 963.862 hPa

```
uint32_t Pres_Compens(int32_t adc_P)
```

```

{
    int64_t var1, var2, p;
    var1 = ((int64_t)t_fine) - 128000;
    var2 = var1 * var1 * (int64_t)dig_P6;
    var2 = var2 + ((var1 * (int64_t)dig_P5) << 17);
    var2 = var2 + (((int64_t)dig_P4) << 35);
    var1 = ((var1 * var1 * (int64_t)dig_P3) >> 8) + ((var1 * (int64_t)dig_P2) << 12);
    var1 = (((((int64_t)1) << 47) + var1)) * ((int64_t)dig_P1) >> 33;
    if(var1 == 0)
    {
        return 0; // avoid exception caused by division by zero
    }
    p = 1048576 - adc_P;
    p = (((p << 31) - var2) * 3125)/var1;
    var1 = (((int64_t)dig_P9) * (p >> 13) * (p >> 13)) >> 25;
    var2 = (((int64_t)dig_P8) * p) >> 19;
    p = ((p + var1 + var2) >> 8) + (((int64_t)dig_P7) << 4);
    return (uint32_t)p;
}

```

```

}

// Returns humidity in %RH as unsigned 32 bit integer in Q22.10 format
// (22 integer and 10 fractional bits).
// Output value of “47445” represents 47445/1024 = 46.333 %RH
uint32_t Humi_Compens(int32_t adc_H)
{
    int32_t v_x1_u32r;
    v_x1_u32r = (t_fine - ((int32_t)76800));
    v_x1_u32r = (((((adc_H << 14) - (((int32_t)dig_H4) << 20) - (((int32_t)dig_H5) *
v_x1_u32r)) + ((int32_t)16384)) >> 15) * ((((((v_x1_u32r *
((int32_t)dig_H6)) >> 10) * (((v_x1_u32r * ((int32_t)dig_H3)) >> 11) +
((int32_t)32768))) >> 10) + ((int32_t)2097152)) * ((int32_t)dig_H2) +
8192) >> 14));
    v_x1_u32r = (v_x1_u32r - (((((v_x1_u32r >> 15) * (v_x1_u32r >> 15)) >> 7) *
((int32_t)dig_H1)) >> 4));
    v_x1_u32r = (v_x1_u32r < 0 ? 0 : v_x1_u32r);
    v_x1_u32r = (v_x1_u32r > 419430400 ? 419430400 : v_x1_u32r);
    return (uint32_t)(v_x1_u32r >> 12);
}

```

## APPENDIX D — ANALYSIS OF SENIOR PROJECT DESIGN

Please provide the following information regarding your Senior Project and submit to your advisor along with your final report. Attach additional sheets, for your response to the questions below.

**Project Title:** Oxygen Plus

**Student's Name:** Jack Brewer, Sanders Sanabria, Brad Weeks

**Student's Signature:**

Jack Brewer

Sanders A.

Bradley Weeks

**Advisor's Name:** Professor Rich Murray

**Advisor's Initials:**



**Date:** 06/11/21

### • Summary of Functional Requirements

Oxygen+ is a portable ventilator which aims to provide a solution to mild respiratory symptoms by providing an avenue for outpatient care to offset cost and vacancy thresholds for patients and hospitals in the United States, allowing patients to recover while they are in the comfort of their own residences. The system consists of a smartphone-compatible and operable high-pressure oxygen system that allows the patient some opportunity for cord-free mobility.

In addition to manual adjustment, the system can actively monitor and adjust oxygen flow rate and pressure based on the patient's blood oxygen content (SPO<sub>2</sub>). The system also alerts the patient if the system is unable to return their SPO<sub>2</sub> to a healthy level. The final product interfaces with a high-pressure oxygen rich and humidified system.

## • **Primary Constraints**

The primary constraints of the system are as follows: constant monitoring of blood oxygen level, constant supply of oxygenated air (21%-100%), adjustable flow rate of incoming air (0-40 L/min), water, (31-37°C) and humidified air (up to 100% humidity), and lastly, portability for at least 3 minutes. Limiting factors also include the cost associated with the purchase of extremely accurate commercial/medical sensors or components found in professional equipment.

Additionally, the turnaround time for PCB boards reduces the amount of time used to check for errors or additional development time.

## • **Economic**

**Human Capital:** Oxygen+ presents job opportunities within engineering, sciences, marketing, health, manufacturing, and sales sectors.

**Financial Capital:** Our target customers will be able to obtain this device through a doctor and lease the device through insurance, which will cost less than using a ventilator in a hospital and can be sanitized and reused with a different customer.

**Natural Capital:** This product will contain many electrical and mechanical components including various sensors, a Raspberry Pi 4B+, an oxygen tank, a Lithium-Ion battery, and a variable valve. Many of these parts are not recyclable and therefore, if not carefully maintained, this product has the potential to deplete many natural resources.

**Cost and Timing:** The target cost of the Oxygen+ ventilator is under \$1000; this is heavily dependent on components used in the final design and will increase with the number of sensors and features implemented on the device.

The cost of the project happens at production and throughout the rest of the life cycle due to maintenance and upkeep. Each device will need to be leased out a couple of months to cover the production and maintenance. After the first year, most of the devices should be making only profit.

Original estimated cost of component parts (as of the start of your project): \$605

Actual final cost of component parts (at the end of your project): \$677.30

*Component BOM*



Resistors	Value (Ohms)	Cost (\$)
R1	10k	0.65
R2	1k	0.93
R3	2.2k	0.92
R4	1k	0.93
R5	1k	0.93
R6	330	0.92
R7	100k	0.63
R8	1	0.58
R9	15k	0.92
R10	2.7k	0.92
R11	1k	0.93
R12	180	1.09
R13	1	0.58
R14	180	1.09
Capacitors	Value (Farads)	
C1	100n	0.43
C2	100n	0.43
C3	220u	0.76
C4	100n	0.43
C5	1n	0.36
Inductors	Value (Henrys)	
L1	330u	0.3
L2	180u	0.31
ICs		
IC1	LMC66	2.46
IC2	MCP3021	1.12
Transistors		
Q1	2N2222A	2.28
Q2	T0-220AB	1.77
Q3	T0-220AB	1.77
Diodes		
D1	1N1444	1.33

D2	1N1444	1.33
Header		
JP1	2x1	0.23
JP2	2x1	0.23
JP3	3x1	0.29
JP4	3x1	0.29
JP5	4x1	0.4
JP6	4x1	0.4
JP7	2x1	0.23
Misc.		
SMT->DIP Mount		1.75
Total Cost		30.92

*BOM: Additional Materials*

										USA	
Sub	Sub	Sub	Sub	Description	Qty	P/N	Document	MFG	MFG P/N	LT - Weeks	1 pc Price (USD)
Box	Build - Model 1 - Retail	Configuration			1	0		Custom		6	
1	Final Assy - Unit	Portable Ventilator			1	1	Instr	Custom	---	1	
	1	Main Assembly			1	2	Instr	Custom	---		
		1	PCBA Assy, Assembled and tested		1	2.1	Custom	Custom	---	6	
			1	Double Sided Protoboard		2.1.1	---	UKRAGRAH	BSKC-003	1	1.4
			2	Single channel A-D Converter		2.1.2	Spec	Microchip Te	MCP4901	2	0.80
			3	Resistor, 1k 5%		2.1.3	Spec		---	2	0.04
			4	Capacitor, 10nF Ceramic 50V		2.1.4	Spec		---	2	0.06
			5	Connector, 4pin 5mm		2.1.5	Spec		---	4	0.22
			6	Motor Controller		2.1.6	Spec	TI	L293NE	12	3.30
			7	Switch, 5x5mm hybrid SMT		2.1.7	Spec		---	6	0.32
			8	Capacitor, 10uF Electrolytic 50V		2.1.8	Spec		---	2	0.15
		2	Raspberry Pi 4 Model B+		1	2.2	Spec	Rasp. Pi	---	2	30.0000
		3	Raspberry Pi Housing Case		1	2.3	Spec	Rasp. Pi	4301	2	6.0000
		4	Lable, ID		1	2.4	Custom	3M	---	4	0.0900
		5	5V Voltage Regulator Unit		1	2.5	Spec	TI	MZ21701EV	4	20.0000
		6	Labor, test, overhead, profit (all in) of Sub assem		1	---		---		---	N/A
	2	Ultrasonic Atomization Disk		1	3	Spec	WHDTS	---	---	4	19.0000
	3	Humidity Sensor		1	4	---	AOSONG	DHT11		4	5.0000
	4	Servo Motor		1	5	Spec	Bilda	---		3	32
	5	Pressure Transducer		1	6	Spec	GEMS			4	36.28
	6	Pulse Oximeter		1	7	Spec	iHealth			4	60.01
	7	Oxygen Sensor		1	8	Spec	analytic. Ind	SR-11-917-		4	95.0000
	8	Mass Air Flow Sensor		1	9	Spec	Seeed	AFM3000		4	99.1000
	9	Air Pump		1	10	Spec	Noctua	NF-A4x20		4	14.9500
	10	O-Rings w/ Cylinder Wrench		1	11	Spec	R. R.			2	6.9900
	11	Nasal Cannula		1	12	Spec	Fisher				29.9900
	12	O2 Tank		1	13	Spec	Meret	K870M9		4	46.9500
	13	O2 Tank Variable Valve		1	14	Spec	W.T. Farley	CGA870		4	99.9900
	14	Labor, test, overhead & profit of Final Assy		1	---		---			---	
	4	Anti-theft device		1	15	---	stock			4	0.0345
	5	Guide, Quick start		1	16	Y	Custom			4	0.2500
	6	Box, Top & Bottom		1	17	Y	Custom			6	2.5000
	7	Box, packaging insert - egg crate style		1	18	Y	Custom			4	0.3750
	8	Box, Sleeve		1	19	Y	Custom			4	0.8500
	9	Shrink Wrap plastic		1	20	---	stock			4	0.0100
	10	Bar Code Sku Sticker		1	21	---	stock			2	0.0100
										Material Total	605.3795

If made in USA lhrs x \$40/h	Labor+	40.00
If made in Foreign l.5hrs x \$5/h	OH	
Product Shipping leadti	Weeks	1

Total	646.38
-------	--------

Order Lead time to Fulfill - Wee 7

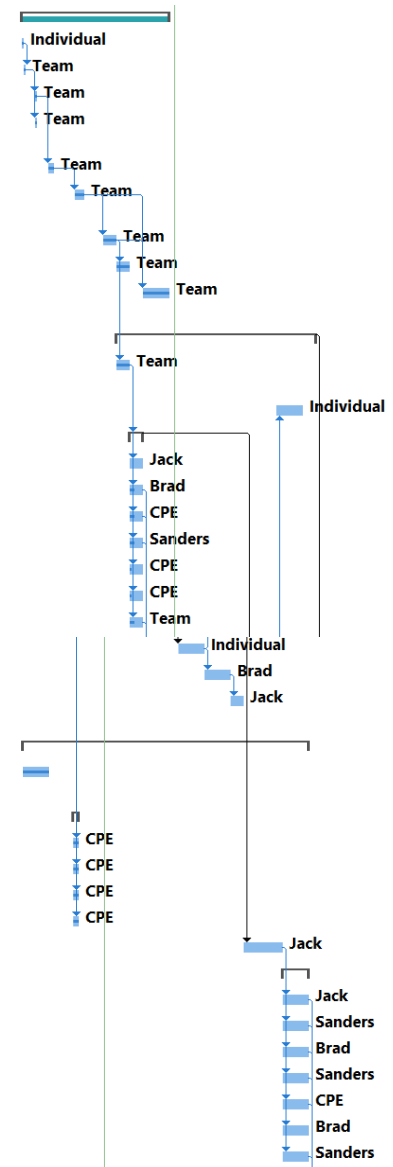
The amount earned will be dependent on how long each device is leased. Leasing the devices at \$150/week it would take 5 weeks of leasing for the devices to make profit. Assuming a life cycle of 2 years and 50% usage each device would make about \$7,500. This profit would be made by the leasing company.

- Timing

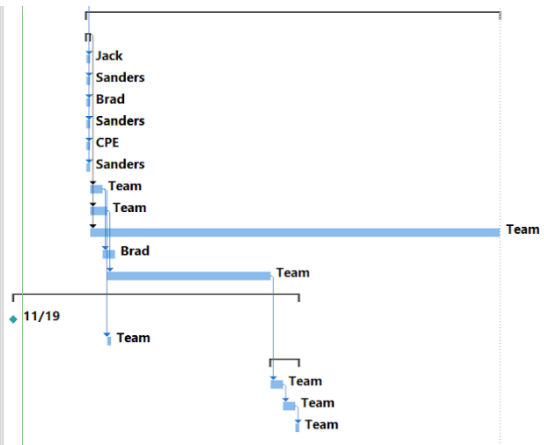
The product would emerge after FDA approval and clinical trials conclude. This could take an one or two additional years after the product is developed. The ventilator should last multiple years as long as the proper care and maintenance is performed. The maintenance needed for the ventilator will mostly be in cleaning and sanitizing the device. There will also be testing done to ensure that the device is operating properly and fixed promptly.

The original Gantt chart was followed closely and therefore, save for some delivery dates of components differing, this is the official Gantt chart for the project.

1	Define	56 days	Mon 9/14/20	Mon 11/30/20		
2	Choose Project	1 day	Mon 9/14/20	Mon 9/14/20		Individual
3	Project Abstract	1 day	Tue 9/15/20	Tue 9/15/20	2	Team
4	Marketing Template	1 day	Mon 9/21/20	Mon 9/21/20	3	Team
5	Business Model Template	1 day	Mon 9/21/20	Mon 9/21/20	3	Team
6	Intital Gantt Chart	3 days	Mon 9/28/20	Wed 9/30/20	4	Team
7	1st Pass Senior Project Report	1 wk	Mon 10/12/20	Fri 10/16/20	6	Team
8	Ethics Analysis	1 wk	Tue 10/27/20	Mon 11/2/20	7	Team
9	Project Presentation	5 days	Tue 11/3/20	Mon 11/9/20	8	Team
10	Final Pass Senior Project Report	2 wks	Tue 11/17/20	Mon 11/30/20	8,7	Team
11	Design	75 days	Tue 11/3/20	Mon 2/15/21		
12	Engineering Requirements	1 wk	Tue 11/3/20	Mon 11/9/20	8	Team
13	Simulations	2 wks	Tue 1/26/21	Mon 2/8/21	22	Individual
14	Block diagram	5 days	Tue 11/10/20	Mon 11/16/20	12	
15	Power	1 wk	Tue 11/10/20	Mon 11/16/20	12	Jack
16	Controller	1 wk	Tue 11/10/20	Mon 11/16/20	12	Brad
17	Display	1 wk	Tue 11/10/20	Mon 11/16/20	12	CPE
18	Humidifier	1 wk	Tue 11/10/20	Mon 11/16/20	12	Sanders
19	Air Pump	1 wk	Tue 11/10/20	Mon 11/16/20	12	CPE
20	Oxygen	1 wk	Tue 11/10/20	Mon 11/16/20	12	CPE
21	Sensors	1 wk	Tue 11/10/20	Mon 11/16/20	12	Team
22	Part Design	2 wks	Tue 1/12/21	Mon 1/25/21	14	Individual
23	Mechanical Casing	2 wks	Tue 1/26/21	Mon 2/8/21	22	Brad
24	Create Materials Listing	1 wk	Tue 2/9/21	Mon 2/15/21	23	Jack
25	Build	109 days	Wed 10/21/20	Mon 3/22/21		
26	Order Prototype Materials	2 wks	Wed 10/21/20	Tue 11/3/20		
27	Prototype Assembly	3 days	Tue 11/17/20	Thu 11/19/20		
28	Sensors	3 days	Tue 11/17/20	Thu 11/19/20	21	CPE
29	Display	3 days	Tue 11/17/20	Thu 11/19/20	17	CPE
30	Humidifier	3 days	Tue 11/17/20	Thu 11/19/20	18	CPE
31	Controller	3 days	Tue 11/17/20	Thu 11/19/20	16	CPE
32	Order Materials	3 wks	Tue 2/16/21	Mon 3/8/21	11	Jack
33	Assembly	10 days	Tue 3/9/21	Mon 3/22/21		
34	Power System	2 wks	Tue 3/9/21	Mon 3/22/21	32	Jack
35	Display	2 wks	Tue 3/9/21	Mon 3/22/21	32	Sanders
36	Control System	2 wks	Tue 3/9/21	Mon 3/22/21	32	Brad
37	Humidifier	2 wks	Tue 3/9/21	Mon 3/22/21	32	Sanders
38	Air Pump	2 wks	Tue 3/9/21	Mon 3/22/21	32	CPE
39	Casing	2 wks	Tue 3/9/21	Mon 3/22/21	32	Brad
40	Sensors	2 wks	Tue 3/9/21	Mon 3/22/21	32	Sanders



41	Validate	505 days	Tue 3/23/21	Mon 2/27/23	
42	Functionality	5 days	Tue 3/23/21	Mon 3/29/21	
43	Power System	5 days	Tue 3/23/21	Mon 3/29/21	34 Jack
44	Display	5 days	Tue 3/23/21	Mon 3/29/21	35 Sanders
45	Control System	5 days	Tue 3/23/21	Mon 3/29/21	36 Brad
46	Humidifier	5 days	Tue 3/23/21	Mon 3/29/21	37 Sanders
47	Air Flow	5 days	Tue 3/23/21	Mon 3/29/21	38 CPE
48	Sensors	5 days	Tue 3/23/21	Mon 3/29/21	40 Sanders
49	2nd Iteration	3 wks	Tue 3/30/21	Mon 4/19/21	42 Team
50	Clinical Trails	1 mon	Tue 3/30/21	Mon 4/26/21	42 Team
51	Patients	25 mons	Tue 3/30/21	Mon 2/27/23	42 Team
52	Customer Feedback	3 wks	Tue 4/20/21	Mon 5/10/21	49 Brad
53	FDA Approval	10 mons	Tue 4/27/21	Mon 1/31/22	50 Team
54	Release	348 days	Thu 11/19/20	Mon 3/21/22	
55	Alpha Prototype	0 days	Thu 11/19/20	Thu 11/19/20	Team
56	Senior Project Expo	1 wk	Tue 4/27/21	Mon 5/3/21	49 Team
57	Introduce to Market	35 days	Tue 2/1/22	Mon 3/21/22	
58	Advertisement	3 wks	Tue 2/1/22	Mon 2/21/22	53 Team
59	Secure Customer	3 wks	Tue 2/22/22	Mon 3/14/22	58 Team
60	Lease Ventilator	1 wk	Tue 3/15/22	Mon 3/21/22	59 Team



The next steps of the project will be to test the 2nd iteration of the pcb and perform the necessary safety tests. After this the ventilator will need to undergo trials to determine if it can perform its function with actual patients. During these trials, the ventilator will continue going through improvements.

- **If manufactured on a commercial basis:**

- Estimated number of devices sold per year: 1200

- Estimated manufacturing cost for each device: 400

- Estimated purchase price for each device: Lease Only

- Estimated profit per year (50 % Usage, device only): \$4,440,000

- Estimated cost for user to operate device, per unit time (specify time interval): \$150/week

- **Environmental**

The solder used to mount the components onto the circuit board includes lead. Lead can be released into the air and groundwater throughout its life cycle in other sectors. However, at the end of this device's life cycle the solder may pose a threat to such areas if not recycled properly. Each device contains approximately an ounce of solder, and therefore each year an estimated 75 pounds of solder are potentially waiting to be released into the environment if not recycled properly.

The project directly uses oxygen, air, and metal. It indirectly uses natural resources that are used to provide power, such as coal, solar, wind, etc.

The project uses natural resources, thus, by itself it will harm those resources until more sustainable methods are developed. However, the ventilator will use less power and materials than what is currently available and being used. Due to this the overall impact of the project will be positive and preserve natural resources.

The project's impact will be indirectly by using natural resources that can have negative effects on the environment. Due to the project's reusability and compactness, the impact should be minimal and improve as better ways to produce power are developed.

- **Manufacturability**

Much of the circuitry will be able to be prefabricated by a PCB vendor. Sensors, servos, and the power supply will have to be attached manually. Mechanically, the casing will have to be manufactured, and the oxygen tank, along with the raspberry pi will have to be installed manually as well. Each device will also have to be rigorously and individually tested to meet FDA and FCC requirements to ensure their compliance and quality is up to standard.

- **Sustainability**

In order to keep these devices out of landfills, the decision to reuse and repair is more beneficial both economically and sustainably. When making the decision to reuse available parts or repair a broken segment instead of tossing it into a landfill, this both extends the lifetime of the device and keeps more devices out of landfills. With a longer device lifetime, the 'bottom' of the Weibull (bathtub) distribution is extended, and because the current business model is a lease-per-time arrangement, the longer a device is in use the more value it adds to the company, the more people it can help, and the longer it stays out of a landfill.

- **Ethical**

This device deals with the collection and radio transmission of sensitive health data, therefore the discussion of secure transfer of sensitive data arises. This transmission and storage must be encrypted and securely transferred to a secure healthcare server, where the contents will remain unseen except by the specific healthcare professional intended.

- **Health and Safety**

Proper cleaning and ventilation of all equipment is necessary between different users of the device to prevent the spread of any diseases or pathogens. The systems also alerts the user when the battery is low so that they may be aware of how much power is left on the device, or to notify them they need to plug the device in if they wish to continue operating the device.

- **Social and Political**

This project is one born out of the current state of the world with COVID-19 ravaging communities and rendering hospitals non-vacant. With such a device in the market the duty to make certain the affordability and access to such a device is paramount. The average cost to rent a ventilator is approximately \$350/week. Our presented cost is \$150/week, and the margin is still very positive as far as profit is concerned. This means there is an opportunity to provide healthcare to communities which would otherwise not be able to support it, given the insurance would permit the device's prescription.

- **Development**

A new tool that was used for development of this project was Eagle. Eagle was used initially for creating schematics of the ventilator since it allowed creation and use of custom symbols. When it came time to create a pcb for the project it was decided to use Eagle for the layout due to the amount of information and tutorials readily available for it. This program was very simple and useful, with one of its biggest benefits being that changes made to the schematic were immediately and automatically implemented into the layout. This also allowed for component footprint changes to be quickly implemented.