Development of a Powered Air Purifying Respirator (PAPR) for Runners

A Technical Report submitted to the Department of Mechanical and Aerospace Engineering

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

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

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Fall 2020

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

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I. Introduction

A powered air purifying respirator (PAPR) is a type of respirator that uses a blower to filter and circulate fresh air through an assembly that fits around a person's head. PAPRs are used by workers in environments where the air is not safe to breathe without a mask. Unlike a traditional mask, PAPRs keep fresh air moving through the device, and also protect a person's eyes from exposure to unfiltered air. Another benefit to using a PAPR over a traditional mask is that the positive pressure on the inside of the assembly ensures that, even with gaps in the material that attaches around the head, air will always be blowing out so that harmful particles cannot enter the assembly, as opposed to masks, which often must be custom fitted to a face to function best. Currently, PAPRs on the market are expensive and bulky. With the arrival of COVID-19 in 2019 and the eventual spread to pandemic status across the globe, demand for masks and PPE for frontline healthcare workers has skyrocketed. Masks are also now widely used by civilians in everyday activities to prevent transmission of the virus between people in public. For these reasons, there is a sector of the market now open for improving current PAPR designs by making them both more comfortable and affordable.

The PAPR design made by the team specifically targeted runners. Runners often want to avoid wearing masks while running because they are uncomfortable, stuffy, and hot. This can endanger both runners and the people they run past. A comfortable, low-cost PAPR could encourage runners to filter their intake of air as well as what they breathe out. This would make runners safer around other people, and also protect runners themselves, during the COVID-19 pandemic. Background research was done on existing PAPRs to find exactly how they work as well as to identify the downsides in the products on the market currently. From this research, the running PAPR was designed with improvements made to a typical design. The project occurred over the period of the Fall Semester 2020, culminating in a final product that was tested to ensure safety regarding the filtering of air as well as comfort during use.

II. Background Research

Powered respirators already exist and are on the market, available for purchase. The average price for a PAPR currently is around $900, not including the costs of batteries and chargers (*Board on Health Sciences Policy; Institute of Medicine*, 2015). This cost would put a PAPR out of the price range of an average American citizen. Because of the high costs, prior to COVID-19, PAPRs were used primarily in hospital settings or work environments where it was essential for the air to be filtered. With the arrival of an airborne respiratory virus that was declared a pandemic by the World Health Organization in March of 2020, the demand for masks and air filtering devices jumped (*Archived: WHO Timeline - COVID-19*, 2020). At the beginning of the pandemic, due to a shortage of PPE for healthcare workers, regular citizens were told to social distance but encouraged not to buy face masks. As the pandemic progressed, citizens were encouraged to wear face coverings at all times when interacting with people outside of their household. Government mandates have also been put in place requiring mask use in public spaces. Because of these laws and mandates being implemented during the 2020 pandemic, mask use as well as use of PAPRs by healthcare workers has gone up. If there were an affordable option for a PAPR, regular citizens would be able to use it while exercising, as mask use is lower during exercising since it is uncomfortable. The gap in runners, as well as other athletes, wearing face coverings during exercise, was the driver behind this project. With an affordable, comfortable PAPR, athletes could work out without breathing into a hot mask, and instead breathe clean, fresh air, while also filtering the output breath they produce.

Specific research was conducted prior to prototyping to determine the components in existing PAPRs. The National Institute for Occupational Safety and Health (NIOSH) lists the following components for an assembly to be defined as a PAPR (*Board on Health Sciences Policy; Institute of Medicine, 2015*):

1. A facepiece, hood, or helmet
2. A breathing tube
3. A canister or cartridge with filter
4. A blower

From the list of the basic components, the idea for the running PAPR could be developed. Existing PAPRs often have exhale valves, and therefore do not filter exhaled breath from the user (*Yale New Haven Health*, 2020). This was then of immediate concern when brainstorming how to improve the PAPR design. Not only should the PAPR developed for runners be more affordable and comfortable, it should also be safer and protect people not using PAPRs around the person exercising.

III. Initial Ideas

Prior to prototyping, initial ideas were generated by group members of team Air Force Run for the design of the device. Individually, team members sketched ideas for what the final PAPR would look like. A common idea for the assembly was using a baseball cap to keep the device on the user's head.

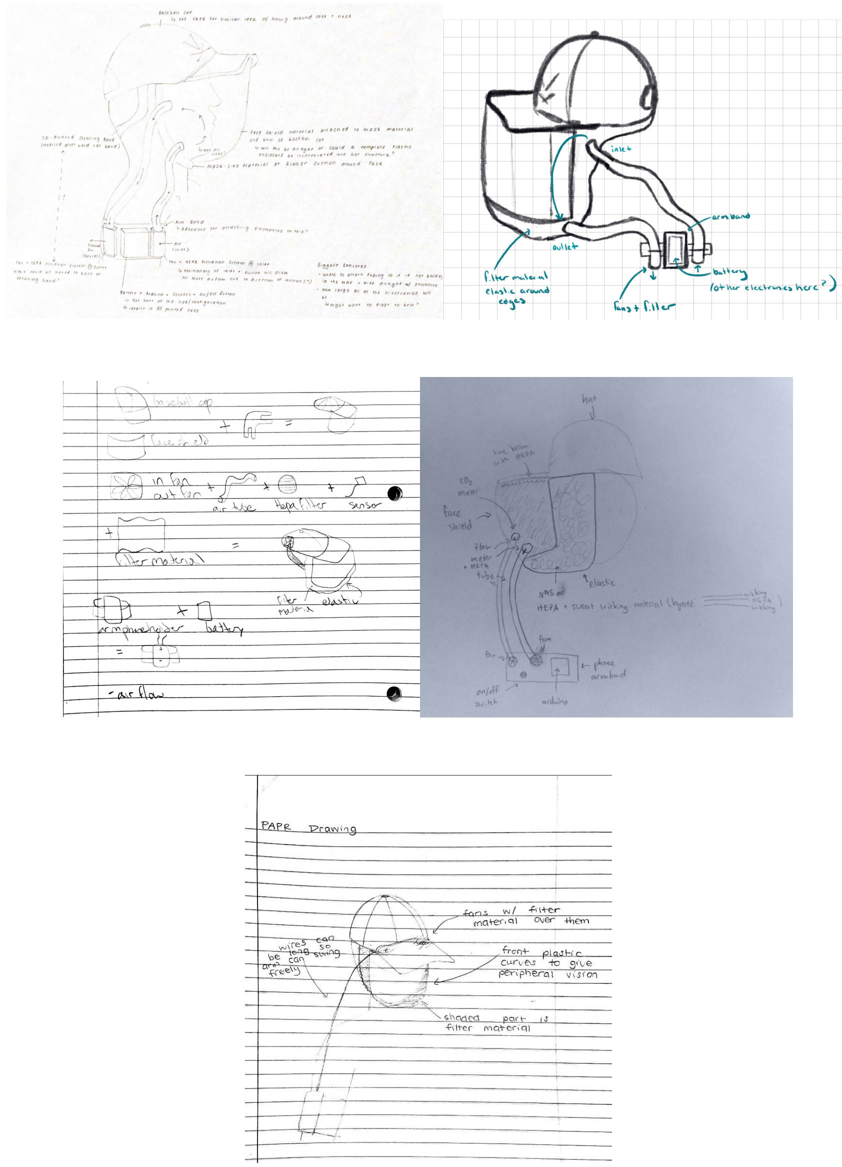

Figure 1: A collection of 5 images, showing the different initial ideas from each team member.

The 5 pictures in Figure 1 show the different ideas that each group member generated before prototyping began. Components from each idea were taken and combined into the initial prototyping idea. The idea of the baseball hat and the brim providing the breathing volume was universal among the drawings. Some drawings included tubing running between the hat and the battery pack that would power the fans, but it was determined that the prototype could be made without tubing and instead using wires running from the battery pack to the fans if they were placed in the brim of the hat. This would eliminate a component listed by NIOSH as belonging to a PAPR, but not eliminate any of the functions that the device serves. With the fans sitting in the brim of the hat with filter material over them, inhaled and exhaled air would still be filtered. Removing tubing from the design of the running PAPR would make it significantly less bulky than existing PAPRs, achieving one of the group's goals of making the assembly both more comfortable and affordable.

In addition to drawings of the design, safety considerations were brought up during the brainstorming period. A failsafe for the battery was desired, to prevent the user from suffocating in the event that the battery runs out of charge and is no longer able to power the inlet fan. It was also known that a positive pressure would have to be maintained in the assembly, similar to existing PAPRs, to prevent any air from entering unfiltered through leaks in the design.

During this period of time, a schedule was developed for the full semester. This schedule would be used to make sure the team stayed on track and had goals for each week.

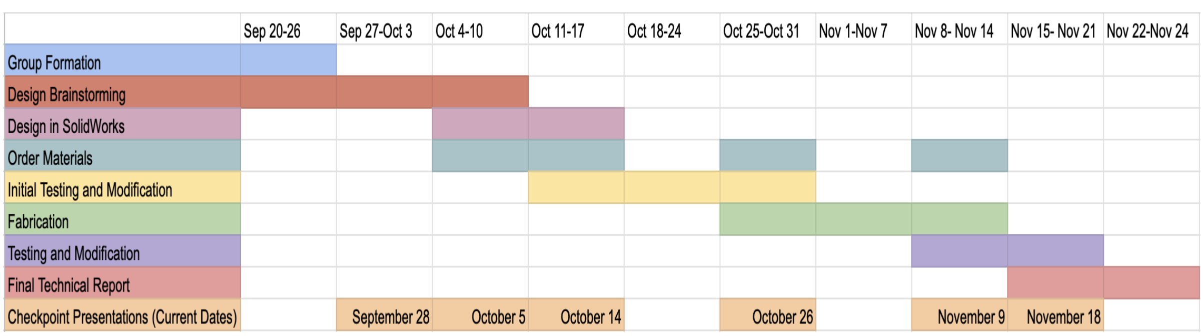

Figure 2: A Gantt chart showing the planned schedule.

It was expected that by the end of the semester, a full prototype would be created that could be tested and used by runners. From the initial drawings and brainstorming, parts were ordered and prototyping began on the running PAPR.

IV. Prototyping

A. Initial Solidworks Modeling

Before making a first physical prototype, SolidWorks was used to design a 3D model of the idea for the assembly on a computer first. The SolidWorks model was constructed using measurements from materials already available, such as the fans and battery pack. The model was used to plan the placement of fans and face shield on the hat. This gave a clear visualization of the layout of the assembly for when physical prototyping began.

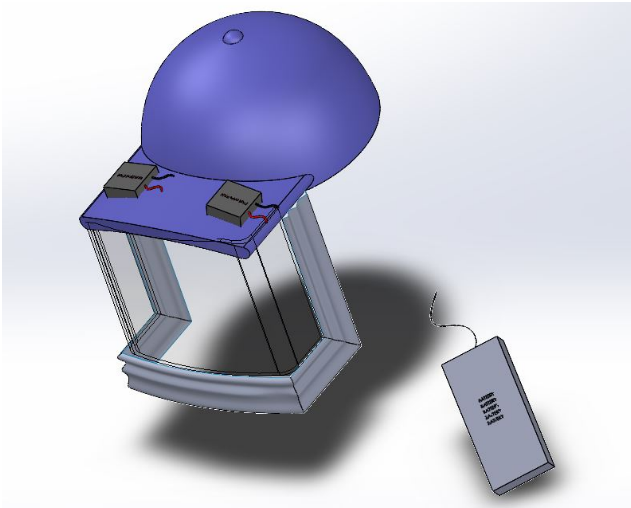

Figure 3: First SolidWorks model of the PAPR.

B. Computational Fluid Dynamic Analysis

A concern when designing the PAPR was the amount and reach of the airflow inside the assembly during use. With the placement of the two fans in the brim of the hat, one blowing in air and the other blowing air out, it was necessary to check that the airflow would fully circulate inside the device before exiting. To confirm that this would happen even with the fans placed close to each other, CFD analysis was performed. SolidWorks contains an add-in for flow simulation, so the fluid region of the PAPR was modeled and then boundary conditions applied to simulate the running of the fans.

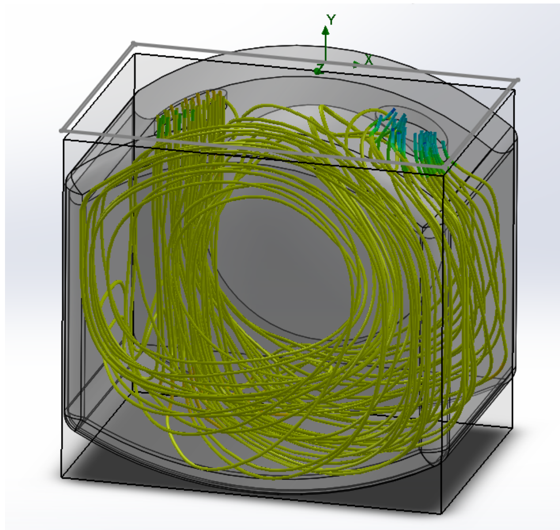

Figure 4: The initial CFD analysis performed on the fluid region.

For the first round of CFD analysis using Flow Simulation, the boundary conditions were set to match the fans being used. 6000 RPM rotating air was set at the inlet, seen as the left circle in the brim in Figure 7. The outlet on the right side of the brim was simply set to be the outside air pressure of 101.325 kPa. The bottom of the enclosure was rounded to simulate the neck piece that would be added to the design. A rounded extrusion was also added to the back of the region, to roughly simulate a person's face sticking into the device enclosure. From the first run, it was evident that there would be adequate air circulation around the entire region before air was blown out of the PAPR. To make the simulation even more accurate to the final PAPR design, a new model of the fluid region was made.

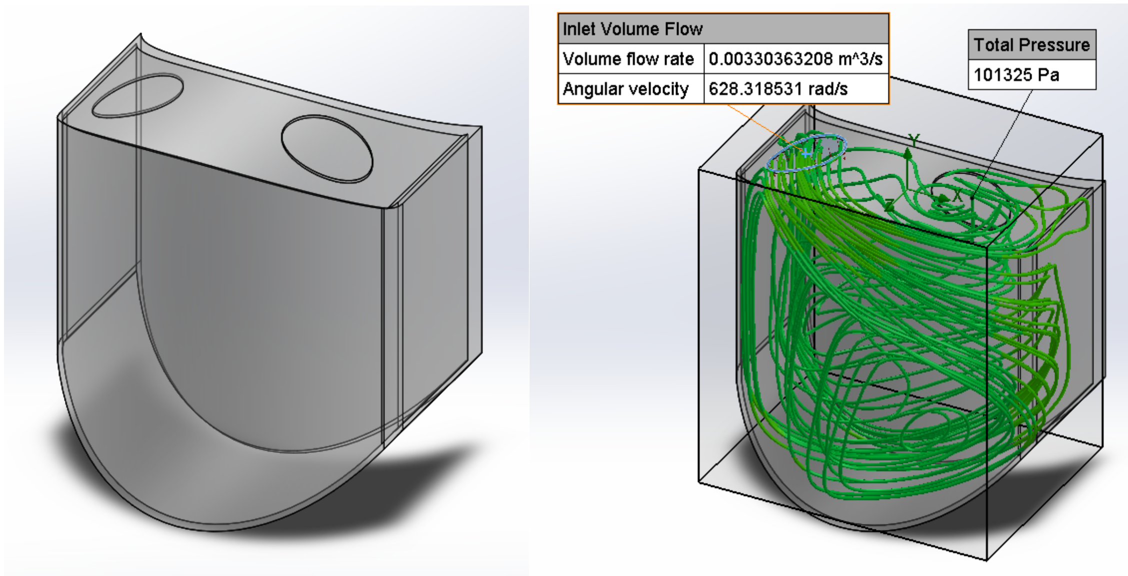

Figure 5: Two images showing the improved fluid region and the results of the simulation.

The enclosure was curved at both the back and the front, and the bottom was curved more dramatically to simulate the bottom of the device. The fans used for this simulation were the same as used previously, and the appropriate volume flow rate and angular velocity were applied at the inlet. With this improved simulation, it was evident that the device would allow for more than adequate air circulation, and that the design with two fans in the brim of the hat was acceptable for the final product.

C. First Prototype

A rough first prototype was made after initial brainstorming and Solidworks modeling. This prototype was made to demonstrate the plan for the full assembly of the final device. The prototype also aimed to ensure the brim of the hat could support the weight of two fans on it.

Figure 6: Two images showing the initial, rough prototype.

The initial brainstorming determined that all potential designs would have to include a clear face shield for the runner to see through. For this first prototype, this face shield was simulated with clear plastic in order to demonstrate which parts of the assembly would be transparent. There was also no circuit or wiring added to the first prototype, as these components would be determined later based on the type of fans chosen and how they would be controlled. Also included in the first prototype was an armband for a battery pack to power the PAPR. This was chosen during brainstorming because runners often wear similar armbands to carry phones while running, and it would be a convenient way to keep the assembly on the head more lightweight.

The first prototype was rough, but gave the team ideas on what to improve in the design generally and also what would work as intended. The fans were light enough to be supported by the hat brim while still being comfortable to the user. The armband was also comfortable to use, and fit the battery pack snugly. There was also no tubing used for this prototype or included in the SolidWorks model, and the team felt comfortable about the design not including this element of traditional PAPRs.

Some ideas not generated in the initial brainstorming were added after designing the first prototype. A lining for the filter material around the neck was desired, so that this material could easily be replaced as the filter got older. The team also began considering what kind of sensor could be used in the device to sense breathing, and where this sensor would be placed in the assembly. This sensor was an important addition that needed to be included in later prototypes to ensure that no suffocation or discomfort while breathing occurred during use of the PAPR.

D. Second Prototype

The second prototype made by the group began to take a more defined shape, incorporating new pieces compared to the first design that would remain to the final product. Casings for the fans and filters were designed and used to hold the fans onto the brim of the hat with screws. Two iterations were made for this prototype; one had a larger diameter and sat fully within the hat's brim, while the other was narrower and sat predominantly on top of the brim. The fan casing that sat higher on the brim allowed a smaller hole to be cut into the hat. This left the brim with better structural integrity, so more weight could be supported.

Figure 7: The second prototype with the two kinds of fan casings attached.

This prototype also incorporated a face shield, replacing the loose plastic used in the rough prototype. The inclusion of the face shield in this iteration of design confirmed that the brim of the hat could support the weight of this as well as the weight of two fans and casings. As this was still an early prototype, the face shield was attached simply using tape. The team recognized that for the final design, a strong adhesive would need to be used to prevent gaps between the face shield and hat brim.

Fabric was also used in this iteration to show how the filter material would eventually fit around the user's neck during operation. This fabric material was attached to the bottom of the face shield for this prototype, and attached using a sewing machine. The fabric was also folded on the opposite side, and sewed down, to provide a channel through which elastic could be run. This design feature would allow the fabric material at the bottom of the PAPR to eventually fit snugly against any user's neck, regardless of size and without a need for fitting.

Figure 8: The first time fabric was attached to the face shield for a prototype.

In this iteration of design, the team also began thinking of sensor designs, and ways to measure the airflow through the device or the force of breath caused by the user. Various ways to do this were researched. Pressure sensors, which could detect any change in pressure inside the mask and therefore indicate if levels of fresh air became dangerously low, were found to be too expensive to purchase. Flow rate sensors, which would measure air flowing through the inlet and outlet, were also considered, but these were found to be expensive as well. The team ultimately decided that any sort of sensor designed to measure properties of air or changes in flow would be impractical, and so a new sensor needed to be designed specifically for this project with the aim of keeping costs as low as possible.

IV. Component Development

The design parameters outlined above presented several design challenges that were considered at each stage in the iterative process. In the "Component Development" section, the evolution of the design components that were crucial to the objectives of the project—fan selection, fan casing design, neck piece and face shield design, sensor design and integration, and circuit design—will be discussed in detail.

A. Fan Selection

In order to design a PAPR for distance runners breathing at elevated rates during strenuous exercise, it was important to implement fans that maximized airflow. It was also important to consider that the fans had to have a small diameter in order for two to be integrated into the brim of the baseball cap. The design objective of maximizing airflow was quantified by comparing the volumetric flow rates in cubic inches per minute across all cooling fans that were tested. The fans that were ordered and tested are summarized in Table 1.

Table 1. Fan selection process.

Iteration	Fan Description	Voltage, V	Area, mm by mm	Flow Rate, cfm
1	Wathai Brushless Cooling Fan	12	40 by 40	38.5
2	Noctua PWM Fan	5	40 by 40	17
3	Noctua PWM Fan	12	60 by 60	17
4	Panomounts Cooling Fan	12	60 by 60	29
5	Wathai Centrifugal Blower	5	75 by 75	11.5

The transition from the 2-pin fans in Iteration 1 to the 4-pin, Pulse Width Modulation fan in Iteration 2 was made as the capacity to change the fan speed proportional to breathing rate was desired. Ultimately, this feature was no longer necessary as the decision was made to simply control the fan's on/off status as opposed to the speed based on the wearer's inhalation/exhalation status (see Circuit Design section below). By Iteration 4, the focus shifted to selecting fans that maximized airflow and minimized surface area. After testing and comparing the Paramounts Cooling Fan (Iteration 4) and Wathai Cooling Fan (Iteration 1), it was both quantitatively and qualitatively found that the Wathai Cooling Fan had a stronger airflow through the filter material while taking up less space on the hat brim. Finally, the airflow through filter material from the Wathai Centrifugal Blower (Iteration 5) was compared to that from the Wathai Cooling Fan (Iteration 1) and it was determined that the latter produced the stronger flow from 12 V of power. A boost amplifier was integrated into the circuit such that the 5V signal from the battery pack is amplified to 12V before powering the fans and their optimal operation is achieved. Therefore, the Wathai DC Brushless Cooling Fan introduced in Iteration 1 was selected as the fan to be incorporated into the PAPR that provided a circulating, purified source of air.

B. Fan Casing Design

Fan casings were designed using SolidWorks in an iterative fashion that served two purposes: containing the fan filter assemblies and securing the assemblies into the brim of the hat. The fan casings evolved over the design process corresponding to the fan selection process outlined in the prior section.

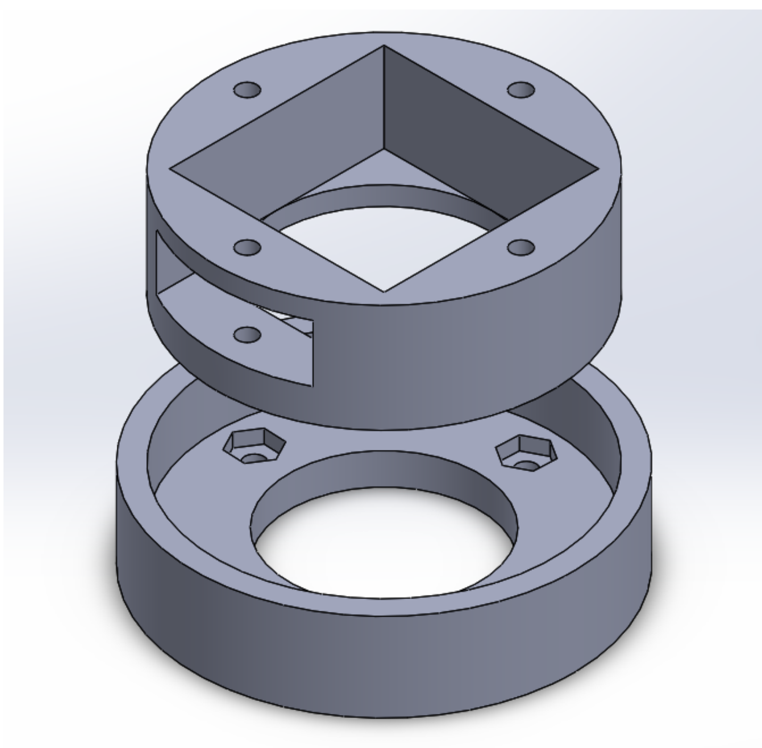

Figure 9: First iteration of the fan casing structure.

The first fan casing design (see Figure 9) involved a solid circular top case surrounding the rectangular fan and a bottom circular base, and these two pieces were fastened using four screws and hex nuts. The wires from the fans exited from one side of the case. This case was designed to fit the 40 mm by 40 mm fans, but was adapted later to fit the 60 mm by 60 mm fans. This iteration proved to be too heavy and the excess material from the solid sides of the top case was identified and removed in later iterations for a lightweight design. This iteration also neglected to consider the placement and removability of the filter material, which is crucial in filtering COVID-19 particles.

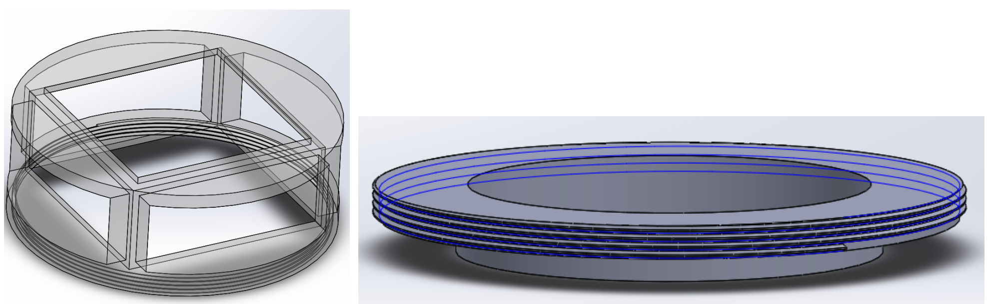

Figure 10: Second iteration of the fan casing structure.

The second fan casing design (see Figure 10) involved a circular top structure that contained the fan with side cutouts to minimize weight, and a threaded base that fastened into the top structure, effectively holding the fan inside of the case. The threaded feature of these 3D printed parts allowed for the removal of the four screws and hex nuts in the previous design, which reduced the surface area of the fan case outside of the fan and therefore reduced the bulk of the case. The bottom of the base of the case had a smaller profile and sat in the brim of the baseball cap. This design neglected to consider the placement and removability of the filter material, and the manner in which the case would be secured into the baseball cap brim.

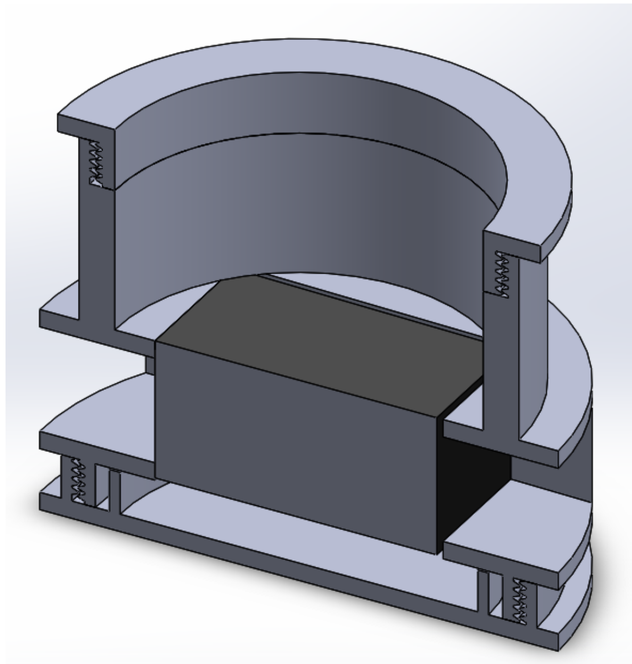

Figure 11: Section view of final design of fan casing structure.

The final fan casing design (see Figure 11) involved three pieces: a base structure with a wider platform at its bottom, a middle section that enclosed the fan and threaded into the base and top section, and the top section that elevated the filter material above the fan. The base structure would fit inside of the PAPR enclosure and screw into the middle section that is above the baseball hat brim, with wider cross-sections on either side of the brim than the actual cutout in the hat, such that it is effectively secured. The fan casing was designed for the 40 mm by 40 mm Wathai Brushless Cooling Fan, pictured as the black box in Figure 11, which slid into the middle section of the fan case and was secured when the base section was threaded into the middle section. The top section also threaded into the middle section at 1 inch above the fan, and this intersection was where the filter material resided that was also secured in place with gasket material.

Figure 12: Removable Filter Material and Top Section of Fan Casing

The elevation of the filter material by 1 inch above the fan allowed for greater circulation of air. The threaded design allowed for the filter material to be easily replaced, which was an important design consideration for virus particle filtration. The final fan case assembly was 3D printed and incorporated into the final PAPR device.

C. Face Shield and Neck Piece Design

The face mask portion of the PAPR was constructed out of two main portions: the face shield and the neck piece. The purpose of the face shield was to protect the user's face from airborne particles while also allowing others to clearly see the user's facial expressions. As such, a clear plastic design was chosen for the face shield. Originally, the face shield was planned to be fabricated from a sheet of polycarbonate; however, the sheet of polycarbonate proved too thick to curve and fit to the brim of a baseball cap. Eventually, a prefabricated face shield was used in the design. The faceshield's plastic was one sixteenth of an inch in width. The elastic and foam backing were removed from the shield before connecting to the brim of the baseball cap.

The second portion of the face mask was the neck piece. The neck piece accomplished two goals, the first one being to bridge the gap between the face shield and the user's face. This was necessary because the PAPR has to create a seal around the whole face. Additionally, the design would be uncomfortable if the face shield plastic were to touch the face, so the neck piece created a soft fabric alternative. The second goal of the neck piece was to provide a secondary breathing option in case the fans failed. If the fans were to fail, the user would be able to breathe through the material of the neck piece and still be provided filtered air. The first iteration of the neck piece was designed completely out of filter material. The basic design was a rectangular strip sewn to the outer plastic edge of the face shield. An elastic casing was also sewn in to get a better fit around the user's chin and face. This design is featured below. Some flaws were that there was excess fabric around the chin but not enough around the ears to completely form a seal.

Figure 13: Prototype one of the neck piece

The next iteration of the neck piece was also constructed out of filter material, however this time, darts were inserted near the chin area. Additionally, a strip of fabric was added to the edge to make the fabric reach the user's ears to get a better seal when worn. As can be seen below, this iteration also had its set of issues. The main problem was that there was still a large amount of fabric bunching up around the user's chin area. Additionally, the filter material was not removable as it was sewn to the face shield portion.

Figure 14: Second Prototype of neck piece.

For the PAPR, it was important to be able to replace the filter material as it becomes less effective if it got wet. The problem would arise as the PAPR is meant to be worn by runners who might sweat or go out into humid or rainy environments. Therefore, the neck piece needed to be able to have removable filter portions. The third and final neck piece design took the problem into account by having pockets for the filter material. The final design was constructed out of Dri-FIT material as it allows for fast evaporation of moisture and is a very thin fabric that would not add bulk to the piece. Additionally, the fabric allowed for pockets to be sewn in for the filter material so it would still filter the air coming in and out of the PAPR device. The Dri-FIT material was also much softer than the filter material and created a more comfortable experience for the user. The final design can be seen in Figure 15.

Figure 15: Final curved neck piece design with pockets

To solve the problem of material bunching around the chin area, the plastic shield was sewn in a curve around the material to reduce corners. Three separate pockets were sewn to hold the filter material: one for the middle bottom and one on each side for the side face and ear pieces. This allowed for easy insertion of filter material. An elastic channel was also included to help fit the fabric closer to the user’s face. To finish off the neck piece, seam sealant was applied to the stitches that connect the plastic to the fabric. This was done as the needle punched holes through the plastic and provided potential ways for un-filtered air to get into the PAPR. The seam sealant also helped create a better seal for the positive pressure inside the PAPR.

D. Sensor Design and Integration

The team developed a unique sensor design for the PAPR, using an integrated phototransistor in combination with a nitrile diaphragm to measure the breathing of the user of the PAPR. This sensor design is unique to this project, and as far as is known by the group, unlike any other sort of sensor that could measure breathing. Phototransistors and the nitrile diaphragm (a small piece of nitrile taken from a surgical glove) are low cost and therefore provided a very affordable option for building a sensor that would make the PAPR safe and give the team a way to accurately measure breathing.

To accommodate the sensor in the hat brim, a unique sensor casing was also designed using SolidWorks and then 3D printed.

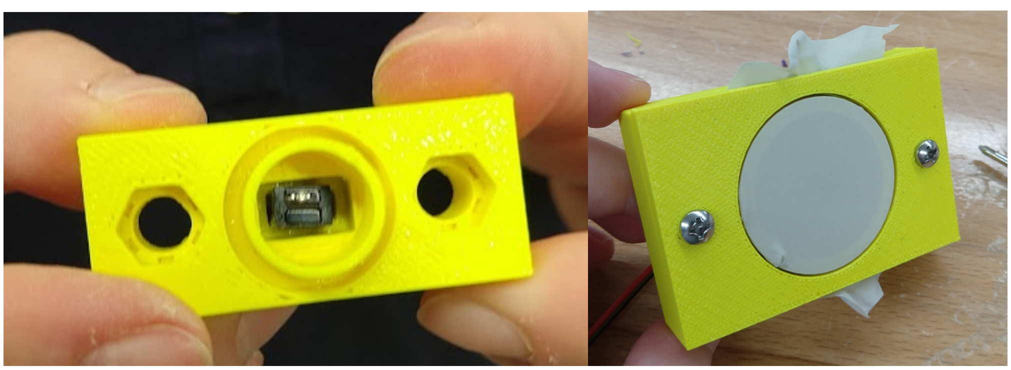

Figure 16: The earlier iterations of sensor casing design.

The sensor casing was designed to be screwed together. A hole in the back piece of the casing was large enough to allow the wires of the phototransistor to extend outside of the casing, but small enough to hold the phototransistor itself in place. The concentric holes in the front and back pieces fit together and hold a piece of nitrile between them. As the front and back pieces of the case screw together, the nitrile rubber used in the design would be tightened down, stretched across the opening. This would make for a sort of drum that would move with the breathing of the user inside the PAPR assembly. Multiple iterations were designed for this sensor casing, with different size circles for the circle that the nitrile would be stretched over (see Figure 16). The varying in the size of this part would change how easily the nitrile diaphragm could move with breathing. The initial design (Figure 16, left) included a small circle to reduce the size of the piece and the amount of material used, while the second design (Figure 16, right) was larger to allow the nitrile to move more and react more dramatically to even small changes in breathing.

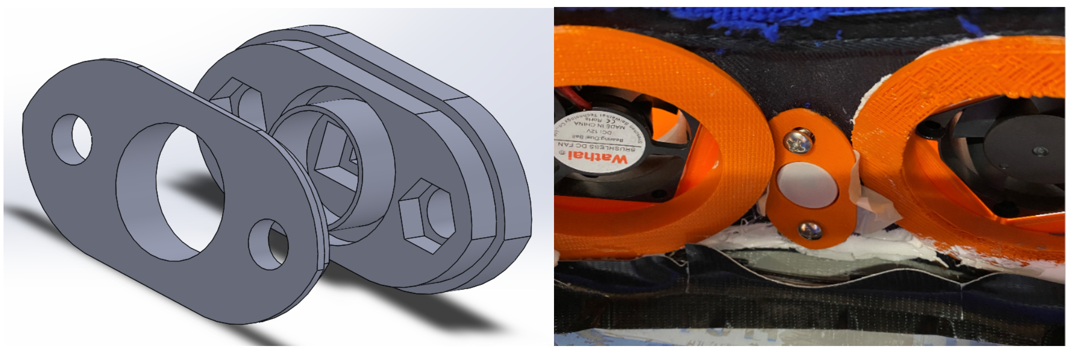

Figure 17: The final sensor casing design.

However, for the final design of the sensor casing, the amount of space available on the brim of the hat required a smaller casing, similar to the first iteration. In addition, more material was cut out around the edges. This gave a more clean, rounded look, as well as saving a small amount of weight. It also made the sensor casing fit more easily between the two fan casings in the brim of the hat. The diameter of the circle in the first iteration of the casing design was found to be adequate to measure breathing, allowing enough movement in the membrane for the phototransistor to detect it. This final design (see Figure 17) was incorporated into the final PAPR build.

E. Circuit Design

The circuit used to read pressure based on the diaphragm went through several iterations throughout the design process. In every version of the sensor design, the phototransistor inside the sensor casing was used to detect how far the diaphragm had deflected inward as a measure of the pressure inside the PAPR. The higher the pressure inside the PAPR, the further the diaphragm would be pushed outwards towards the phototransistor, and if the pressure decreased, the diaphragm would move farther away from the phototransistor again. The phototransistor would then output an analog voltage based on the changes in the distance of the diaphragm; the output voltage would decrease as the diaphragm was pushed closer to the phototransistor and increase as it moved farther away, meaning that higher pressure corresponded to a lower output voltage from the phototransistor.

In the first design for the circuit, this analog output voltage was sent to an operational amplifier (op amp) wired as a non-inverting comparator in order to turn the voltage into a high or low digital signal. The threshold voltage for the comparator was set using a trimmer potentiometer (trimpot) that could be used to make small adjustments in calibrating the circuit. The reference voltage could be set to be equal to the voltage output from the phototransistor that corresponded to the ideal positive pressure for the PAPR. If the pressure was higher than desired, the input voltage to the comparator would be lower than the threshold voltage, and the comparator would output a low signal (0V). If the pressure was lower than desired, the input would be higher than the threshold voltage, and the comparator would output a high voltage (5V). The change in the digital signal as the analog voltage crosses the threshold can be seen in Figure 18.

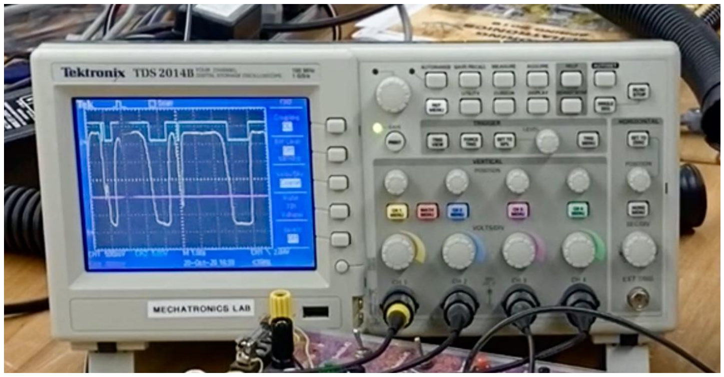

Figure 18: Oscilloscope showing the phototransistor output voltage (yellow) in relation to the threshold voltage (magenta) and the reaction of the comparator output voltage (blue).

It was initially planned to send the digital output signal from the op amp to an input pin on a microcontroller, which would then use this input to control the speeds of the fans. The first microcontroller used was a Parallax Propeller Chip, which would run code to take the input from the op amp and use it to determine how the speed of the fans should be varied using Pulse Width Modulation (PWM). The fans here were powered using a 5V battery, and PWM would be used to vary the fan speeds to somewhere between 0–100% of full speed depending on the need at a given time. Higher than desired pressures would signal the output fan to move faster than the input fan, while lower pressures would do the opposite. After the initial prototyping, it was determined that the code needed to run the fans would be simple enough that it could be run on a smaller ATtiny microcontroller in order to save space and money in the final design. At this point, the team planned to design further prototypes using an Arduino Nano and then transfer the circuit to the ATtiny for the final design. After some experimentation with the Arduino, it was determined that controlling the fans with PWM was unnecessary due to the slow reaction time of the fans making varying the speed beyond turning the fans on and off was inefficient and not particularly helpful. Without the need for PWM, the future versions of the circuit were designed without any microcontroller.

The next version of the circuit (see Figure 19 for diagram), which was designed without a microcontroller, kept the arrangement of the phototransistor and comparator. Instead of being sent to a microcontroller, the signal was sent in two different branches, one with a transistor connected to the inlet fan, and the other with a transistor and a MOSFET connected to the outlet fan. Instead of using code to turn the fans on and off, the signal sent to the transistor was used to switch the fans on. The transistors would allow the fans to turn on when they received a high signal. When the pressure was low, the phototransistor would cause the comparator to output a high signal, which would go to the transistor attached to the inlet fan and allow it to turn on, and conversely, when the pressure was high, the low signal from the compactor would switch the inlet fan off. The MOSFET in the circuit essentially inverted the signal sent to the second transistor, allowing it to receive a 5V high signal when the MOSFET was sent a high signal from the comparator. The outlet fan therefore would be on when the inlet fan was off and vice versa.

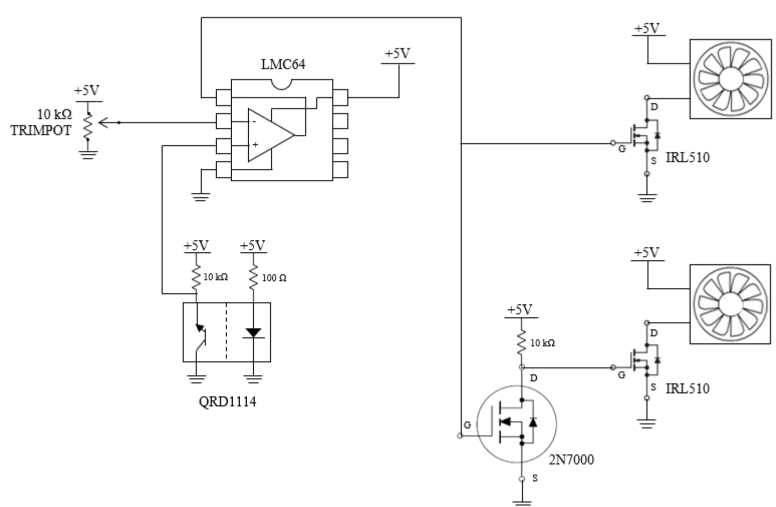

Figure 19: Circuit diagram for the second major prototype of the pressure sensor circuit.

The final version of the circuit, diagrammed in Figure 20 and pictured in Figure 21, again retained the phototransistor and diaphragm arrangement but added a second op amp, this one wired as an inverting comparator. The output voltage of the phototransistor was sent to both of these comparators, and they both used the same reference voltage of 0.69V in the final design. This meant that the two comparators always output opposite signals, e.g., when the input voltage was higher than the reference voltage, the inverting comparator would output a low signal and the non-inverting one would output a high signal. These signals were then sent to a Darlington transistor array. The transistors were here again used to switch on and off the fans, which in this version were connected to a boost amplifier to convert the 5V from the battery to 12V. The first four pins were connected to the non-inverting comparator, and the second group of four pins were connected to the inverting comparator. Of the transistor pins connected to the non-inverting comparator, the three switched on the fan blowing air into the PAPR, and the fourth turned on a yellow LED, which acted as an indicator that the inlet fan is on. The pins connected to the inverting comparator were wired similarly, switching on the fan blowing air out of the PAPR and a green LED indicator light. As the two groups of transistors always receive opposite input signals, only one fan would be running at any given time: the outlet when the pressure was too high and the inlet when the pressure was too low.

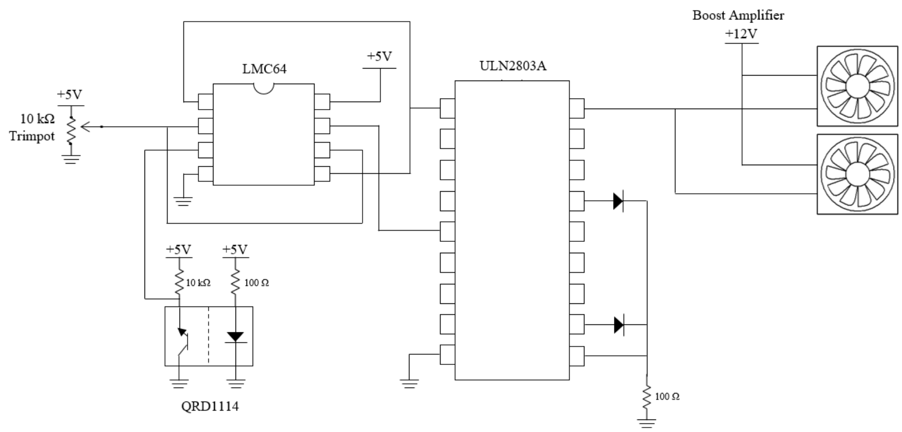

Figure 20: Circuit diagram of the final pressure sensor circuit.

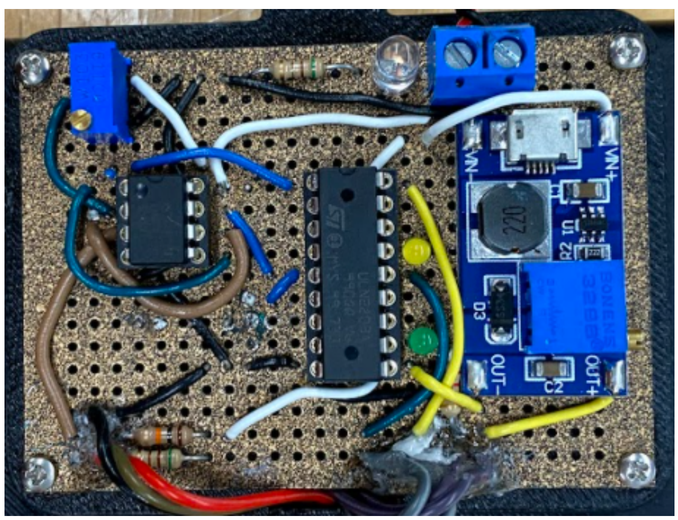

Figure 21: Final completed circuit for the pressure sensor

VI. Final Device

The final product developed by the team incorporated the last iterations of all components and their designs described in earlier paragraphs, and built off the earlier prototypes for general assembly and component placement. The final PAPR design was also more polished, as the prototyping was complete and the looks of the assembly mattered more.

Figure 22: The final device, both in use and not in use.

As the development of the device was complete, caulking was used to seal the space between the hat brim and the components on top of the PAPR. Adhesive was also used when attaching the neck piece to the assembly, ensuring no air escaping through this joint. As seen in Figure 22, the colors of the final design were made to match UVA school colors, and the hat used for the final product was a UVA hat. Black tape was also used around the edge of the hat brim to neaten up the appearance of the PAPR. The idea of wires running from the armband to the fans in the brim of the hat was successful throughout all prototype iterations and in the final design, and is visible in Figure 22 as well.

Figure 23: The inside of the device in its final phase.

A sweatband material was also added to the inside of the hat for the final design (see Figure 23). This added material reduced pressure on the front of the user's head and helped to reduce moisture that could potentially build up on the inside of the face shield.

VII. Testing and Results

The final PAPR was tested based on three criteria: filtering ability, sensor accuracy, and comfort while running. First, the PAPR's filtering ability was tested using Bitrex bitterant. In a control test performed with the user wearing no mask, the user was able to slightly taste the bitterant. The bitter substance was then sprayed around the user while the user was wearing the PAPR with the inlet fan running. During this test, the user did not smell or taste the bitterant at all, suggesting that the inlet fan successfully filtered out the particles of bitterant.

Next, the accuracy of the sensor was tested. The distance between the photoresistor and diaphragm was adjusted until the user's breathing caused the sensor to activate and switch the fans on and off. The photoresistor was then sealed into place. To test the sensor, the user breathed deeply (to simulate the deep breaths taken while running). When the user breathed out, these deep breaths caused the inlet fan to turn off and the outlet fan to turn on, and when the user breathed in, the inlet fan turned on and the outlet fan turned off. Although the sensor did not function fully consistently due to the variation in how deep each breath was, it successfully responded to changes in pressure caused by the user breathing in and out.

Finally, the user jogged around the testing area while wearing the PAPR with the fans running. The user found that the hat and face shield felt comfortable and fairly sturdy while running. In addition, the user found that the PAPR allowed for much easier breathing than a cloth mask or N95, suggesting that the PAPR design meets the goal of making running easier and more comfortable, while still offering the protection of a mask to the users and those around the user.

VIII. Discussion

Going into this capstone project, there were certain goals in place that needed to be met in order to achieve the goal of creating a functional PAPR. Firstly, the PAPR design needed to filter air coming in and out of the device while creating a positive pressure environment so that the user would not have to go through a fit test. This design feature was tested and confirmed with testing conducted on the pressure sensor. Positive pressure was achieved in the PAPR through controlling the inlet and outlet fans based on the pressure found within the hat. Pressure was maintained in the hat as caulking was put around all the inserts into the hat such as the fan casings and sensor casings. Additionally, the seal provided by the neck piece was used to help reduce air leakage.

Secondly, the PAPR needed to be light and comfortable enough to run in while wearing. This goal was achieved through the use of 3D printed parts. The ABS was light enough to construct the fan casings and still sit on the brim of the hat. Additionally, weight was cut wherever possible as can be seen in the design process of the face shield. The fan and sensor casings' weight was offset by tightening the baseball cap. A sweat band was also added to the front brim of the hat to create comfort for the user.

Finally, the PAPR's total cost needed to be less than the current PAPRs on the market to make the product more affordable. Table 2 displays the materials included in the final device and the cost associated with the amount of material used. The cost was estimated for materials such as the filter material, duct tape, ABS plastic, and jumper wires in the circuit. The calculations neglect to include tool costs, such as that of the 3D printers and soldering iron, and operating costs such as the maintenance and repair of the 3D printers. The final cost was determined to be $132.20, which is roughly a 85% reduction in cost compared to the leading PAPR by 3M (3M, 2020). The cost per device has the capacity to be reduced if mass produced as materials such as electronic components and adhesives can be purchased in bulk. This accomplishes the objective for producing a relatively inexpensive PAPR, as it may be considered a more comfortable alternative to fabric masks.

Table 2. Cost breakdown of final PAPR device.

Item Description	Unit Cost	Unit Type	Amou nt	Total Cost
Main Components				
Cooling Fans	$9.98	each	2	$19.96
UVA Baseball Cap	$19.45	each	1	$19.45
USB C Battery Pack	$16.99	each	1	$16.99
Running Armband	$14.95	each	1	$14.95
Disposable Face Shield	$2.56	each	1	$2.56
Performance Headband	$5.99	each	1	$5.99
Filter Material	$14.35	per ft^2	1.3	$18.66
Dry Fit Material	$18.00	per 2	0.5	$9.00
3D Printed Parts	$22.98	per 960 cm^3	0.16	$3.68
Adhesives/Fasteners				
Seam Sealant	$7.50	bottle	0.1	$0.75
Vinyl, Plastic, and Fabric Adhesive	$10.95	bottle	0.1	$1.10
2-56 Screws	$7.04	per 100	0.04	$0.28

2-56 Hex Nuts	$1.00	per 100	0.04	$0.04
6-32 Screws	$3.45	per 100	0.02	$0.07
6-32 Hex Nuts	$1.28	per 100	0.02	$0.03
Duct Tape	$6.63	per 12 yds	0.083	$0.55
Sensor Components				
Phototransistor	$0.95	each	1	$0.95
Nitrile Gloves	$6.20	per 20	0.025	$0.16
Electronic Components				
Circuit Board	$4.25	each	1	$4.25
Darlington Transistor	$1.19	each	1	$1.19
Jumper Wires	$5.59	per 120	0.25	$1.40
Resistor	$0.15	each	4	$0.60
LED	$0.37	each	3	$1.11
Trimpot	$0.47	each	1	$0.47
Boost Amplifier	$6.95	each	1	$6.95

Op Amp	$1.08	each	1	$1.08
			Total	$132.20

IX. Conclusion

The development of a PAPR designed specifically for long distance runners was the goal for Air Force Run at the start of the project. Through weeks of planning, prototyping, and redesigning, the goals of the team were met with a design that performed and tested well. The team learned through the project how to better design components to integrate with each other, and how to follow through on goals set at the start of the work. The final product was reasonably polished, and performed as intended. Given the timeframe for the team to develop a product that filtered air and could be comfortably worn during exercise, Air Force Run felt satisfied with the work produced.

X. Future Work

Future improvements to the PAPR device include polishing the design to make the appearance more sleek. An example of this would be to store the wires in a more aesthetically pleasing and hidden configuration. In addition, more effective adhesives or fastening techniques to secure the plastic face shield to the hat brim and the 3D printed assemblies into the hat brim would allow for a more professional looking device. A more thorough testing process to confirm the effectiveness of the PAPR would be ideal. Lastly, further refinement of the 3D printed parts to minimize material would result in a more lightweight and secure device.

A future design challenge involves a way to make the calibration of the sensor an adjustable and non-permanent process. This would allow for more robust and accurate readings and would improve the functionality of the design as multiple users could wear the PAPR. This is because one's inhalation and exhalation within the enclosure will have an effect on the pressure sensor readings that differs from another wearer's. One idea to accomplish this would be to incorporate a 3D printed adjustable casing for the sensor that would allow the user to manipulate the height of the sensor in small increments and secure its position during use, as opposed to the position that was made permanent with caulk in the current design.

XI. References

3M. Powered and Supplied Air Respiratory Protection. Retrieved November 30, 2020, from https://www.3m.com/3M/en_US/company-us/all-3m-products/~/All-3M-Products/Personal-Protective-Equipment/Powered-Supplied-Air-Respirators/

Archived: WHO Timeline - COVID-19. (2020, April 27). Retrieved November 21, 2020, from https://www.who.int/news/item/27-04-2020-who-timeline---covid-19

Board on Health Sciences Policy; Institute of Medicine. The Use and Effectiveness of Powered Air Purifying Respirators in Health Care: Workshop Summary. Washington (DC): National Academies Press (US); 2015 May 7. 3, Why, Where, and How PAPRs Are Being Used in Health Care. Available from: https://www.ncbi.nlm.nih.gov/books/NBK294225/

Yale New Haven Health. (2020, July). Retrieved from https://www.ynhhs.org/-/media/files/ynhhs/covid_employees/ppe/sbar-paprs-elastomerics-or-ip-07212020.pdf?la=en&hash=B6AFEC04A1F8739EDEEE8C7119AC73F67964B622