Design of a Fan-Powered Face Mask with Advanced Filtration Capability

A Technical Report submitted to the Department of Mechanical Engineering

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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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Introduction

The Covid-19 pandemic has changed the world, registering over 63 million cases and killing approximately 1.47 million people (Johns Hopkins, 2020). Throughout the year, scientists have continued to learn more about this virus, including the mechanisms of transmission, the periods for which individuals remain contagious, and the best ways to slow down its spread. Relatively new discoveries regarding airborne transmission of the virus have increased the recommended protection measures, for this mechanism operates in parallel with the previously proposed large droplet and fomite paths (Morowska & Milton, 2020).

Virus mitigation efforts, including social distancing, mask mandating, group size limitations, ventilation improvements, and curfews, have been implemented around the world in an effort to slow the spread of the novel Coronavirus. Face masks, in particular, are some of the most feasible protective measures against the spread of the virus (Mayo Clinic Staff, 2020). Cloth face masks are the simplest form of face mask, and they are intended to trap respiratory droplets released from infected individuals (Mayo Clinic Staff, 2020). Another common face mask, the surgical mask, does not effectively protect the wearer, and the USFDA has yet to approve any such mask for the protection against coronavirus (Mayo Clinic Staff, 2020). However, N95 masks are certified to block 95 percent of airborne particulates, resulting in the mask and the material itself to be one of the most sought after personal protection equipment (PPE) technologies seen in the healthcare workplace, upon passing a proper fit test (Mayo Clinic Staff, 2020).

As the filtering material becomes more advanced and effective at trapping particles, it is noticeably more difficult to breathe through (Mayo Clinic Staff, 2020). A solution to this restriction of breathing is including a powered fan within the mask to increase the flow of air across the filter material. Devices that integrate a powered fan, such as Powered Air Purifying Respirators (PAPRs), provide plenty of filtered air to the individual, but fail to filter the individual's exhalation (CDC, 2020). Ideally, combining the capability to filter inhalation and exhalation air in non-powered systems with the ease of breathing in fan powered systems would create the ideal user experience, while also protecting the general population.

The final technical deliverable of this project will be a fan-powered mask system that filters both inhalation and exhalation. A current mask design, the continuous positive airway pressure (CPAP) mask, will be repurposed to ensure that the final product's fit on the face of the individual is comfortable and effective. In addition to the CPAP mask, this mask will leverage 3D printed parts, centrifugal blower fans, and MERV-15 material. This material is a highly rated filter seen in heating, ventilation, and air conditioning (HVAC) systems. In addition to meeting health standards, the social perception of overall mask designs must be considered. Advanced half-face respirators resemble military gas masks, and they are not incredibly expensive nor hard to obtain. However, these are rarely seen in public as a virus protection method. The fact that aesthetics matter greatly to the general public has led the group to put a design emphasis on color, sleekness, and compactness. Additionally, the traditional mask removes facial expressions and the ability to read lips from social interactions; choosing a clear CPAP mask as the base of our design is aimed to help with this.

The final deliverable will be assessed using three metrics: Computational Fluid Dynamics (CFD) analysis via SolidWorks, qualitative breathing assessments, and mock fit testing as seen in the healthcare workplace. CFD will be used to assess the overall airflow throughout the system and determine if a proper amount of airflow is being supplied for the user. As CFD can only approximate the real world, physical assessment will provide a breathing comparison between the final deliverable and an N95 mask. Finally, a mock fit test will be performed to determine if the final system properly filters inhaled air. This fit test will consist of spraying Bitrex, a bitter solution, around the user's mask. If the user cannot taste the solution, then the mask functions properly and effectively filters air. (OSHA, 2020).

Goals and Objectives

Based on current mask technology and their respective limitations, the group's main goal was to achieve a series of quantitative and qualitative objectives within the project's allotted time frame. Originally, the group attempted to combine different aspects of traditional face masks and PAPRs while maximizing aesthetic appeal. However, as time went on and prototypes were made, some design goals changed slightly, which will be discussed later.

The face mask aimed to achieve the following quantitative goals: high filtration capabilities, long battery life, and cost effectiveness. Nothing about the final deliverable would mean anything if its ability to filter out potential viruses was not as good as existing technology. For this reason, it was decided to use filter material that is comparable to or already being used by existing medical face masks. Additionally, these masks would ideally be worn all day, so a long battery life was necessary. Since a typical work day is 8 hours, this was set as the battery life goal. Finally, cost was a large factor because existing technologies, such as PAPRs, can be very expensive and not easily affordable for many individuals. Therefore, a goal of around $100 was set for the final face mask deliverable.

The project also established four qualitative goals: breathability, comfort, easily replaceable filters, and aesthetics (later visibility). One of the most important aspects of the design was to create a mask that was extremely effective at filtering out viruses, but without the burden of bulky materials. Additionally, since the mask would be worn for hours on end, it needed to be comfortable. For these reasons, it was decided to create a continuous, gentle breeze over the individual's face via the use of small computer fans. Another consideration is that filter materials, like N95 and MERV-15 cloth, lose their static charge and become less effective over time. To fix this problem, easily replaceable filter units were identified as a crucial design feature. Finally, the initial goal was to create the most aesthetically pleasing mask as possible in order to encourage usage of the mask over others that may not be quite as effective.

As time went on and prototypes were made, there was a shift in the intended objectives from pure aesthetics to visibility. The limitations of the fans and overall pod design was a little more bulky than desired. Without smaller fans, the dream for making this part of the mask as small as possible was not feasible. Therefore, the split pod design offered the option to incorporate a clear face mask concept where an individual’s facial expressions could still be seen. Overall, the majority of these objectives were met throughout the semester and the original Gantt chart did not deviate too far from what actually happened during the semester.

Table 1, shown below, displays the final Gantt chart utilized as a schedule throughout the semester. This was used as a guide to keep the design process on track. Each column represents one week of the semester and green boxes represent when a given task was to be worked on.

Table 1: Final Gantt Chart displaying the overall design schedule

Date	9/28 - 10/4	10/5 - 10/11	10/12 - 10/18	10/19 - 10/25	10/26 - 11/1	11/2 - 11/8	11/9 - 11/15	11/16 - 11/24
Task								
Component Sizing	■	■						
Fan Design		■	■					
Mask Body Design		■	■	■	■			
Battery			■	■				
Risk & Safety Analysis					■	■	■	■
Testing and Iteration					■	■	■	■

Design Process

Prototype I

The very first idea for this prototype was similar to any normal funnel; take fluid from a larger area to a smaller area, with an increase in velocity. Ideally, the same thing would be possible with air using the radial fans and cone assembly, shown below in Fig. 1. The entire mechanism consisted of the 3D printed funnel, a computer fan, a 3D plastic frame, a sheet of MERV-15 filter material, and finally another 3D printed plastic frame.

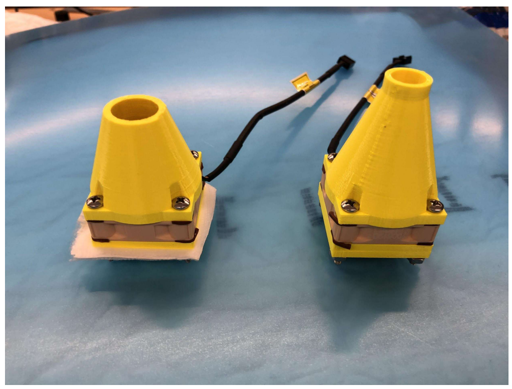
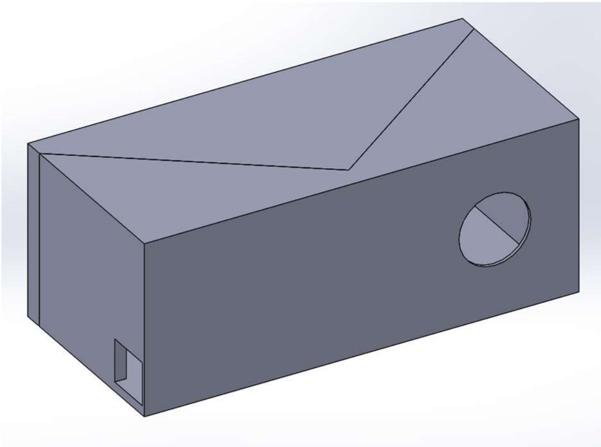
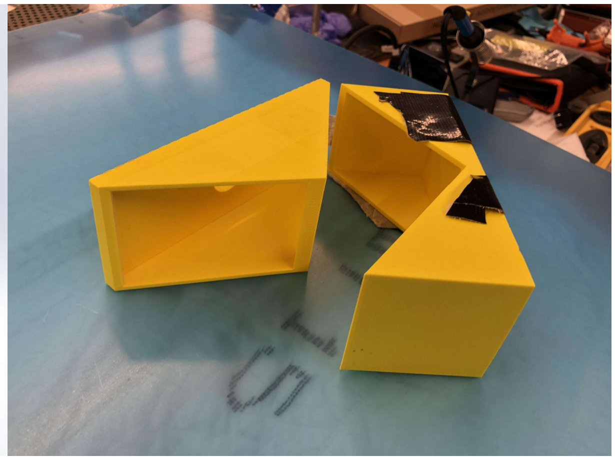


Figure 1: Funnel Assembly Prototype

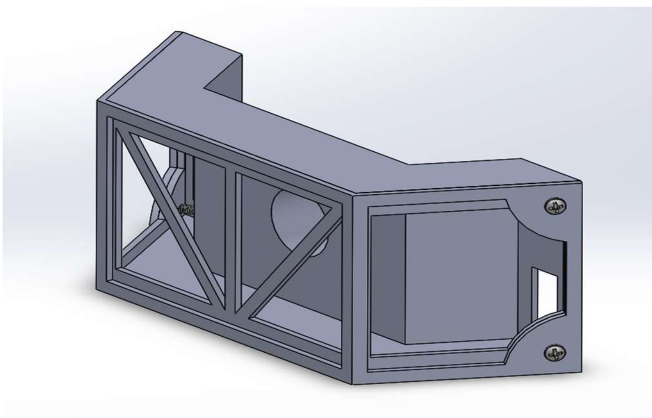
Then, the entire assembly was sandwiched together with four bolts, one at each corner. While the idea seemed promising in theory, this prototype showed that a funnel design like this would not be effective with the current fans and filter material. The MERV-15 was too thick and too close to the fan, meaning the radial fan itself was not as strong as necessarily required for the mask design.

Prototype IIA and IIB

Once the fan type had been chosen, the next step was to build a crude model of the mask. This model was not intended to be the most visually appealing or compact design, but it was meant to validate the effectiveness of the blower style fans and the ability to breathe through a filter material. Two concepts, seen in Figs. 2-5, were designed in this round of prototyping.

Figures 2 and 3: Prototype IIA in SolidWorks on the left and printed out on the right




Figures 4 and 5: Prototype IIB in SolidWorks on the left and printed out on the right

Once 3D printed and tested, it became clear that both designs have some similar strengths. First, both designs interfaced quite easily with the CPAP masks because they were designed to fit into the front hole which is standard on CPAP masks. Second, each design offers a large area for the filter material to be utilized. This is an important aspect of the design because the larger the filter area, the longer the filter can be used before it needs to be replaced and the easier it is to breathe through the filter. When printed out and tested, the masks were quite easy to breathe through when filter material was placed in the proper position. MERV-15 was used to filter the air going in and out of the masks in this round of testing. This was promising news because ease of breathing was a very important criteria for the mask's overall success.

Each mask had its flaws, however. For example, in Fig. 3, one large sheet of filter material was sandwiched between the two halves of the mask making the filter material more difficult to replace. The mask in Figs. 4 and 5 had a similar issue where the outerplate, which secured the filter onto the mask, must be unscrewed to remove the filter material. Both masks also extended out from the face far too much. Since the masks attached to the frontmost point of the CPAP and appeared very boxlike, even the light weight plastic created a significant moment which tended to pull the user's head down, making it somewhat uncomfortable and tiring to wear the mask. Another problem which manifested itself once it was printed out and worn was the obstruction of the user's vision. As can be gleaned from Figs. 6 and 7, both masks made it difficult to see the ground in front of the user, creating a possibly dangerous blindspot.

Figures 6 and 7: Prototype IIA on the left and IIB on the right being worn with CPAP masks

The models had some differences which are worth pointing out. The mask in Fig. 2 had designated inlet and outlet blower fans. Since a blower fan can only function in one direction, the two sides of the mask could not be perfectly symmetrical. In Prototype IIA, the inlet fan is placed on the right side of the mask and the outlet fan is placed on the left side of the mask. This design forces air to go through the inlet fan, then through the filter material into the breathing chamber in the center of the mask. The purified air can be inhaled by the user, then it travels through a different section of filter material to the exhaust fan where it is expelled out of the mask. In contrast to three chambers, the mask design in Prototype IIB has one central chamber where two fans were located. These fans were meant to agitate the air inside the mask which would offer a pleasant sensation for the user by preventing air from stagnating in the mask. Interestingly, when both fans were on in Prototype IIB the airflow created from each fan interfered and seemed to cancel out. For this reason the mask was more comfortable to wear when only one fan was on.

In this stage of the design process, the battery was located externally. This decision was made with weight and size considerations in mind. The bulk of two fans already offered significant size constraints and the weight of a battery would only add to the moment problem, which presented itself once the masks were printed and worn. The benefit of having a self-contained battery was considered less important than the benefit of having a smaller, lighter mask. In this prototype, the battery would be located externally and connect to the fans via wires.

Another consideration during this stage of prototyping was a pressure sensor and a microcontroller chip. The chip would take data from the sensor and rev up and rev down the fans with each breath in and out. The purpose of this idea was to facilitate breathing while wearing the mask. However, during testing it was obvious that breathing in and out was quite easy even without computer controlled fans. The constant power supplied to the fans also created a comfortable environment within the mask. For models similar to these two prototypes, a microcontroller and pressure sensor were deemed unnecessary to accomplish easy breathing and a comfortable mask.

Overall, these two models offered a proof of concept and helped steer the direction of the project. The main takeaways from this stage of prototyping were three-fold. First, connecting the mask to the anterior hole in the CPAP pushed the mask quite far off the face. This made for a significant moment-arm making the mask feel heavy on the head. Second, the MERV-15 material was easy to breathe through and the blower fans had the required power to make wearing the material comfortable. Third, the pressure sensor and microcontroller were not needed to vary fan speeds in order to make this mask comfortable to wear. Breathing through the mask was easy, and the mask was refreshing with steady state fan operation.

Prototype III

As mentioned above, Prototype IIA and IIB were used to develop basic familiarity with the centrifugal blower fans and the MERV-15 filter material. Although these early designs were relatively simple, it was determined that the air produced from just one blower fan would suffice. This section details the third prototype in the overall design process, which focused on the size and aesthetics of the overall apparatus.

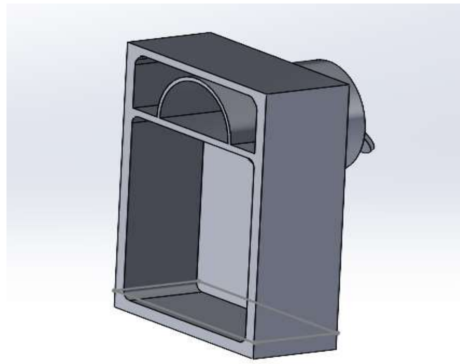


Figure 8: Prototype III - Single Compact Chamber Design

Fig. 8 displays this compact design concept. This prototype was designed to attach to the front of the CPAP mask, while containing one centrifugal blower fan and one sheet of MERV-15 filter material. This prototype is much smaller than Prototypes IIA and IIB and uses less 3D printing material. Additionally, the area between the MERV-15 filter material, intended to attach to the open face of the design shown in Fig. 8, and the blower fan was significantly reduced, for the blower fans were determined to be strong enough to pull air directly through the filter. In earlier prototypes, it was also determined that separating or organizing the directions of airflow would enhance the user's experience. Below, Fig. 9 shows the detailed design of this built-in separation scheme.

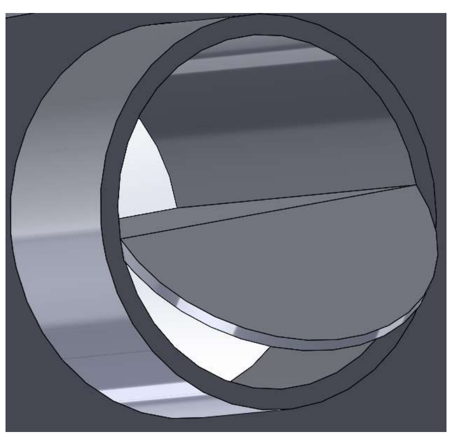


Figure 9: Enlarged View of Built-in Separation Scheme

An untampered CPAP has just one hole in the center of the mask; Fig. 9 shows the feature of the 3D printed apparatus that would be inserted into this hole. While still minimizing the size of the apparatus, a small and simple system was designed to separate the air flowing into the CPAP mask from the blower fan and the exhaust from the user. As seen in Fig. 8, the blower fan would sit in the large chamber below the dividing wall in the apparatus. The air exiting the fan would then travel through the lower half of the duct shown in Fig. 9 and into the CPAP mask. In addition to the barrier within the cylindrical duct, a fin was added and angled to prevent minimal interference between the user's exhalation and the incoming airflow. Finally, the user's exhalation was designed to exit the CPAP mask through the top half of the duct and upper chamber, as shown in the combination of Figs. 8 and 9.

Despite designing a prototype that was far more compact than earlier concepts, Prototype III still fell short of an ideal design with respect to aesthetics. Moving forward, the group determined that an entirely new design approach was necessary in order to create a sleek, fan powered mask.

Prototype IV

Issues with prior designs encouraged this prototype to focus on facial visibility at the expense of compact size. This section details issues and lessons learned from the fourth prototype.

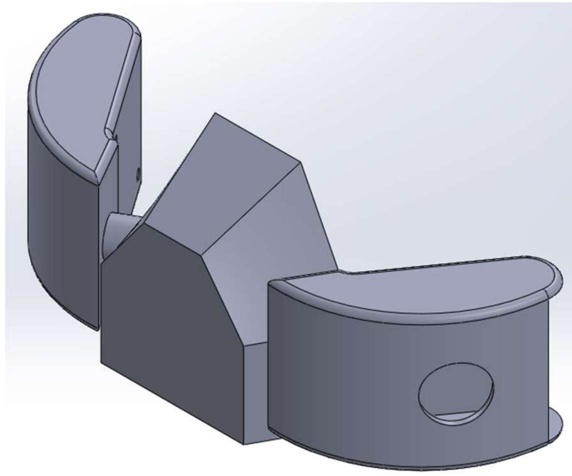


Figure 10: Prototype IV - Separated Contouring Design

The fourth prototype, shown in Fig. 10, considered various aspects: separated inlet and outlet compartments, facial visibility, and compartment contouring. The separated inlet and outlet compartments of this prototype allowed for components to be moved away from the front of the face and helped promote airflow across the face. Moving components to the sides of the mask was crucial when trying to conserve facial expressions, and two separate compartments interfacing with the sides of the CPAP mask provided a solution. Prior prototypes were designed to interface with the pre-existing front hole within CPAP masks in order to prevent unnecessary holes from being cut, risking the system not being airtight. Despite this challenge, prioritizing the view of facial expressions drove designs to accept this risk and interface with the sides of the CPAP mask. As mentioned above, the use of two fans in Prototype IIB prevented air from properly flowing into the central mask area. Separated inlet and outlet compartments promote proper airflow across the face to combat this issue.

Finally, the contouring of the design was considered to improve the aesthetics of the overall prototype. This prototype was contoured to match the CPAP mask's curvature, but this was challenging because the CPAP mask was unmodeled. Contouring efforts were too complex due to the geometries of the mask being difficult to reproduce exactly in SolidWorks. Although no exact model existed, a general CPAP mask model was produced for this prototype as seen in Fig. 11 below. This mask model was utilized in all flow simulation and prototype assemblies in SolidWorks moving forward.

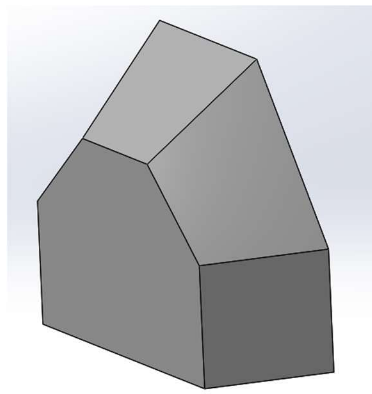


Figure 11: General CPAP Mask Design

Prototype V

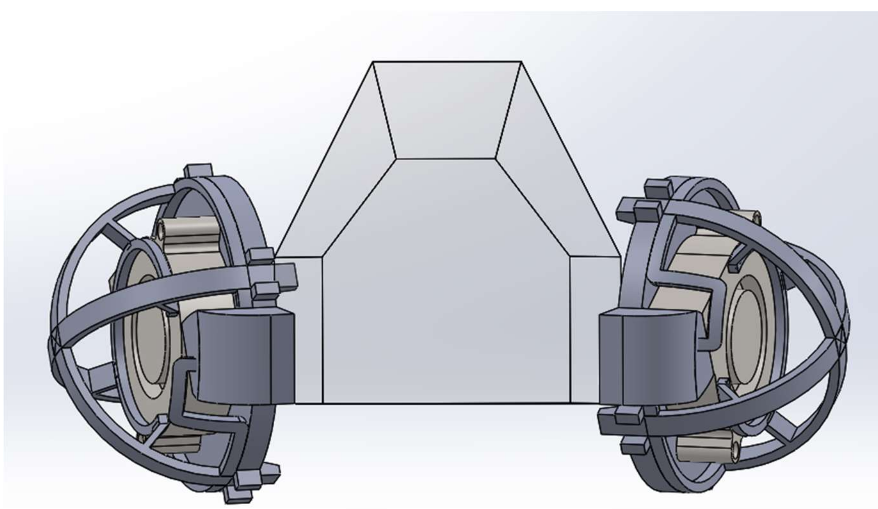
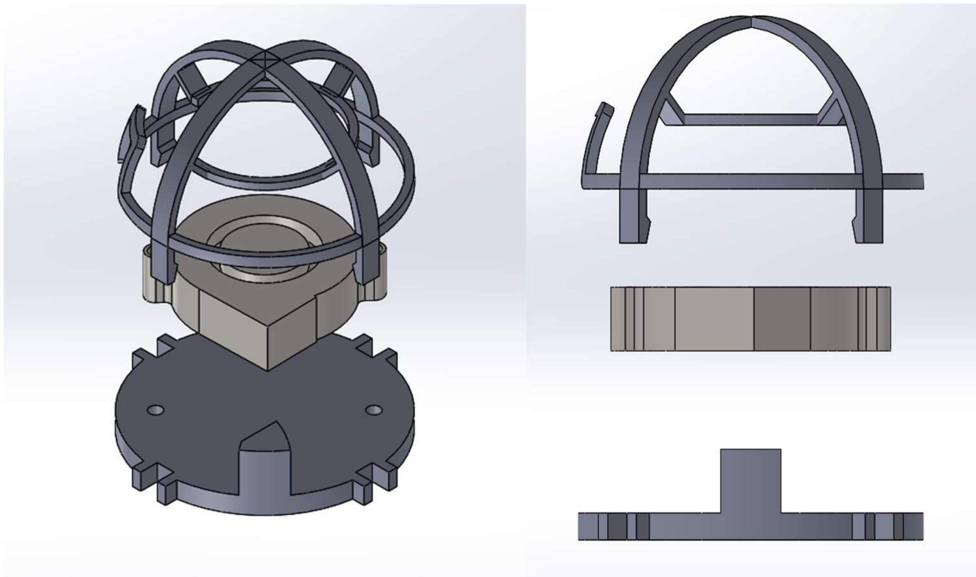


Figure 12: Prototype V - Hemispherical Pod Design

Above, Fig. 12 shows the fifth prototype, which features hemispherical fan pods. This was the last prototype before the final design was created, and this section will outline both its salient features and some important lessons learned. There are three prominent features and two categories of lessons learned.



Figures 13 and 14: Hemispherical Pod Exploded View

The most notable feature of this design is the pods, which are responsible for filtration. Shown above in Figs. 13 and 14 are two exploded views of the pod design. For the following discussion, the top piece will be called the dome, and the bottom piece will be called the base plate. The middle item is the blower fan. Conceptually, all air enters the mask through one pod and exits through the other pod. Although it is not shown in this model, the pods are tightly covered with filter material. The pods filter air the same way other prototypes did, however, they allow for quick filter replacement because they attach to the base plate with a simple snap fit. Filters must be replaced daily in order to ensure maximal filtration, so it is important that replacement is easy to do.

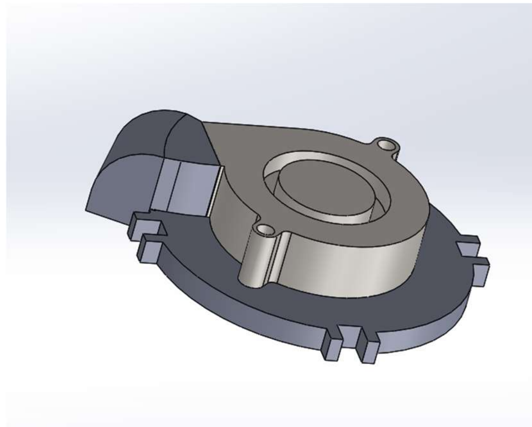
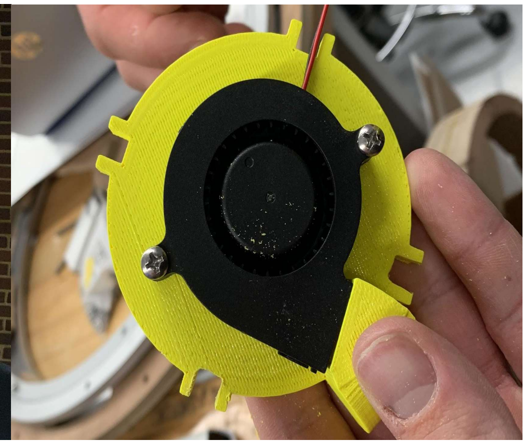


Figure 15: Base Plate and Fan Integration

The second important feature of this prototype was its redirection of flow into the mask. Since the blower fans push air tangentially, a 90 degree bend was integrated into the base plate of the pod. This feature is seen above on the left side of Fig. 15. The outlet of this bend was glued to a hole that was cut into the CPAP mask.

The third main feature of this mask is its attachment to the head. A ski goggle strap was attached to the sides of the CPAP mask, and it was adapted to avoid the ears. This strap accommodated many different head sizes because it was adjustable. These three features, pods, flow redirection, and ski goggle strap, were the most important qualities of this prototype.

This prototype also brought some issues to light. First, the snap fits on the dome were much too brittle. The tabs quickly snapped, making them impossible to use. Second, the snap fit did not provide enough force to effectively seal the dome to the base plate. This caused leakage of unfiltered air into the pod.

Figures 16 and 17: Pod Sizing Test

Aside from snap fit issues, the pods were also sized incorrectly. First, the base plate was unnecessarily thick and uncomfortably angular. Its thickness felt heavy in the hand, and its sharp corners poked at the user, shown in Fig. 17. Also, the base plate exceeded the radius of the fan by an unnecessary amount. This made the pods appear large on the face, shown in Fig. 16.

The last issue with this prototype was the 90 degree bends. Since these bends ended flush with the base plate, they did not fit to the contour of the CPAP mask. As such, they had to be glued at an awkward angle to the mask. This prototype is most similar to the final product in that it leverages pods and attaches with a ski strap. However, it exposed some important improvements to make for the final design.

Final Design

Introduction

In this section, the three prominent features of the final design will be explored. These are the mask, the pods, and the battery and head attachment. The entire final product can be seen in Fig. 18.

Figure 18: Full image of final design in use

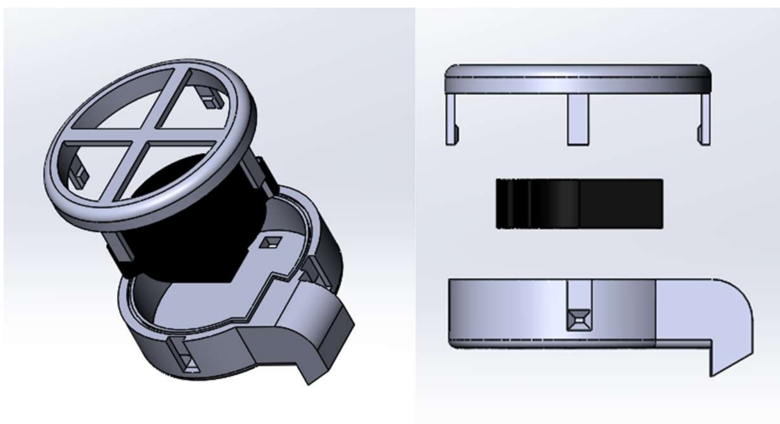
Mask

Figure 19: Front view of clear CPAP mask

Fig. 19 above displays the front view of the clear CPAP mask in the final design. Two rectangular holes were cut in either side of the mask with a dremel so the pods could interface with the sides of the mask. A band saw was used to cut off the front portion of the mask to enlarge the pre-existing hole. This was done to create a large flat surface on the mask to prevent light distortion from making facial expressions hard to see. A cut piece of acrylic was then super glued to cover this hole and create an airtight seal. Leak tests were conducted by filling the mask with water and looking to see if any drops appeared around the seal.

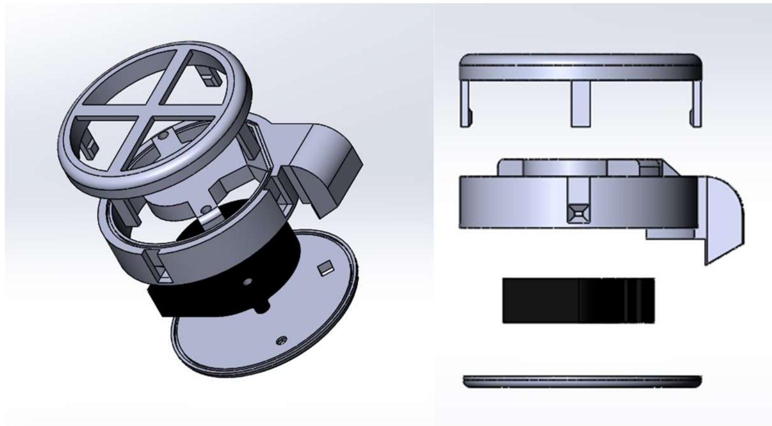
Pods

As mentioned in the section on prototype V, the pods serve as the primary filtration units of the mask. Each pod houses one fan. and one is responsible for intake and the other exhaust. Since blower-style fans are asymmetrical, the intake and exhaust have different internal features, but their external features accommodate the same interchangeable filter. Both pod styles will be explored in turn.



Figures 20 and 21: Intake Pod Exploded View

The intake pod shown in Figs. 20 and 21 is simpler in design than the exhaust pod. It consists of three parts: the replaceable filter, the fan, and the back plate. The replaceable filter works like the dome from *Prototype V*, but its filter surface is planar rather than spherical. Structurally, it is much more sound, and its snap fits are much more aptly sized. The back plate has rigid walls and smooth surfaces on all sides. Air flows through the filter, into the top of the blower fan, and out of the 90 degree bend in the back plate into the mask.



Figures 22 and 23: Exhaust Pod Exploded View

The exhaust pod shown in Figs. 22 and 23 is more structurally complex than the intake pod. Since the blower fan's intake is at the top, a duct connects the 90 degree bend to the top of the fan. This allows the fan to suck air out of the mask through the 90 degree bend. The air is then blown out the side of the fan and through the filter.

Notably, both pod designs have holes for the assembly hardware and the electrical wiring. After assembly, these holes are filled with caulk to assure airtightness.

Battery Holder and Headband

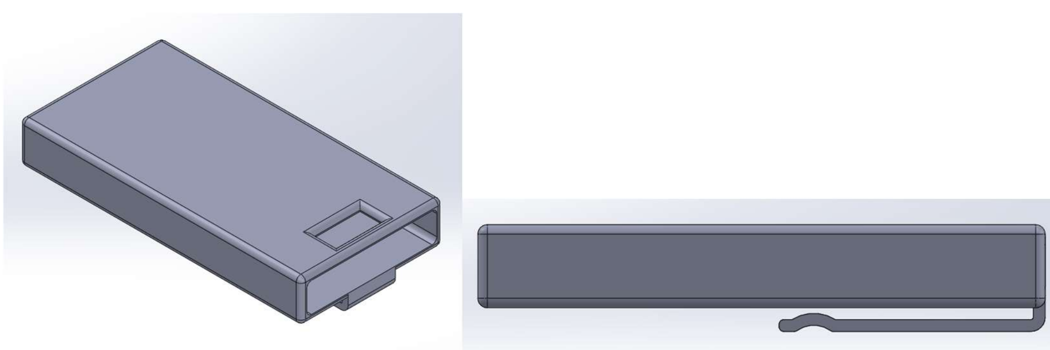


Figure 24 and 25: Battery Holder - Isometric View and Side View

Fig. 24 shows an isometric view of the battery holder in the final design, and the battery holder clip is shown in Fig. 25. This clip allows for the holder to stay on the elastic necklace shown in the figure below. The large hole in the part allows the battery to slide into the holder, while making the USB port on the battery accessible. The small hole allows for the LEDs that show the remaining battery life to be visible as seen in Fig. 26.

Figure 26: Battery Holder - Application

The headband is a repurposed ski goggle headband with a small cut on either side to give the user's ears room as seen in Fig. 27. To interface with the mask, the headband was cut down the middle and super glued above and below the hole used for the pod connection, shown below in Fig. 28.

Figure 27 and 28: Headband with cut to accommodate ear; headband interfacing with mask

Testing and Analysis

Bitrex Test

Bitrex tests are qualitative tests which leverage a subject's sense of taste to measure a mask's filtration efficacy. Tests are generally conducted in a small room or under a hood, where a bitter substance, called Bitrex, can be effectively distributed. The subject enters the room or hood without a mask to experience the bitter taste. Then, the subject dons the mask under investigation and reenters the room or hood. The subject compares their experience without a mask to their experience with the mask to evaluate the efficacy of the mask at filtering the bitter particles.

A makeshift Bitrex test was conducted on the final product described in this report. Although Covid-19 protocol prevented the use of a hood or special room, the test was simply conducted outdoors. Bitrex was released in a cloud around a subject without a mask, then the same was done after the subject donned the mask. There was no comparison between the two trials. The mask effectively prevented any bitter substance from making its way into the subject's mouth. Although this test was unconventional, it still speaks to the filtration capacity of the mask and the MERV-15 material used.

Flow Simulation

As another test to examine the performance of the final design, a fluid dynamics simulation was conducted in SolidWorks. This simulation was utilized to help examine the airflow and pressure throughout the mask-pod system. Both of these metrics help to analyze the safety of the system. The CFD analysis showed a positive pressure environment inside the mask. The positive pressure has the added benefit of preventing unfiltered air from leaking into the mask if there is an unintended poor fit. The CFD also shows ample airflow which is necessary to ensure the user receives enough oxygen to stay conscious.

The flow simulation software contained in SolidWorks needed three different inputs in order to solve for the desired results: the fluid within the system and the boundary conditions for the inlet and outlet of the system. The fluid within the system was defined as air due to the system pushing air across the face during use. The inlet boundary condition was based on research conducted into the average resting respiration rate and volume for the average human. These values were found to be 12 to 16 breaths per minute and 500 mL respectively, leading to an inlet volume flow of 7 L/min defined on the face of the inlet pod cover (Frothingham, 2018; Johns Hopkins, 2020). Due to SolidWorks requiring one flow condition and one pressure condition to perform flow simulation, the outlet boundary condition was defined as environment pressure (101 kPa) on the face of the outlet pod cover.

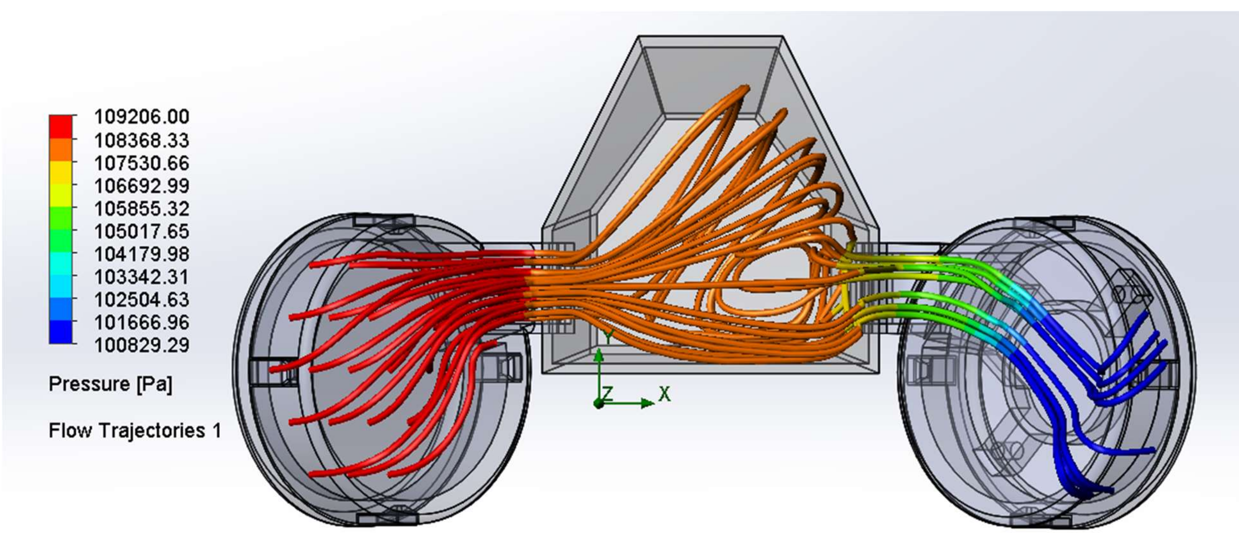


Figure 29: Back view of flow simulation displaying airflow trajectories and pressure values within system

Figs. 29 and 30, above and below, show the results of the flow simulation with the parameters described previously. Two views are included to provide a better perspective of the exact flow trajectories throughout the entire design. As seen in both figures, proper airflow exists within the mask body, meeting the first requirement of the system. The colorbar present on the side of both figures displays that positive pressure is maintained throughout the system. Most importantly, the mask body maintains a positive pressure, ensuring COVID-19 cannot get into the system due to an imperfect fit.

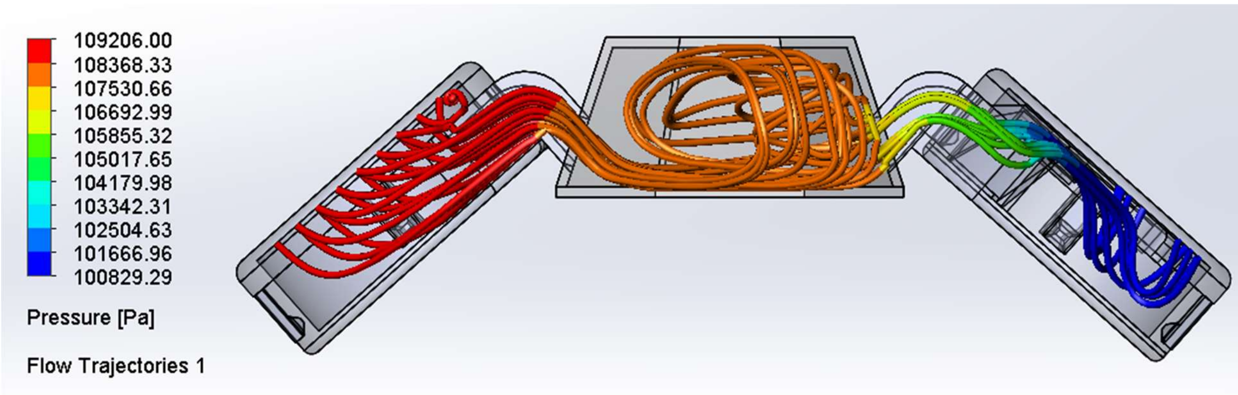


Figure 30: Top view of flow simulation displaying airflow trajectories and pressure values within system

Flow simulation is very extensive, but certain challenges were faced during analysis. The blower fans used in the final design could not be accurately modeled within SolidWorks. This makes it difficult to account for the pressure difference created by the fans within the system and to see how that impacts airflow and pressure throughout the system. As discussed above in the Design Process section, a non-exact model of the CPAP mask used could not be created within SolidWorks. This led to a modified mask design being used for the flow simulation conducted, meaning the exact airflow and pressure within the mask body could not be determined. Lastly, there was no way to simulate the user breathing into the system and how this added volume and pressure would impact the system. Despite these challenges, a solid conceptual understanding of the design's ability to maintain proper airflow and pressure was gleaned from flow simulation testing in SolidWorks.

Cost Breakdown

As mentioned earlier in the report, having an effective mask that is also relatively inexpensive was crucial in order to make the technology more available to the general public. With that being said, the cost for every prototype throughout the semester was not calculated and would total to an amount far higher than the initial goal of $100. However, the final mask cost breakdown was just slightly above the mark and will be discussed in this section.

The main components considered for the design come from the cost of the CPAP mask, head strap, battery, blower fans, acrylic sheet, and 3D printed parts; in other words, combining materials, like nuts and bolts and different adhesives, were not broken down and monetized for the final cost breakdown. The CPAP mask used was ordered from Amazon and cost $21, followed by the ski goggle strap which cost $20, the external battery which was $17, and the two blower fans which cost $10.

Finally, the cost for the acrylic front piece that was attached to the modified CPAP mask and 3D printed plastic were a little more ambiguous. The sheet of acrylic cost nearly $14, but about a hundred ovals could be made from a single sheet; this would bring the cost down to only $0.14 per part. Additionally, the amount of 3D printed plastic was not fully calculated. It was approximated that the final iteration of mask design would have used about $40 of plastic in total. If these masks were to be made commercially, a cheaper alternative, such as injection molding, could be incorporated to lower the cost of the mask components. Overall, the final product was designed and manufactured for around $100 with a final estimated cost of $108.14.

Wear Testing

During wear testing, three activities were evaluated: donning the mask, prolonged use, and doffing the mask. To don the mask, a few steps must be taken. First, the battery necklace and mask must be put on. Then, the battery has to be plugged into the fans' electrical leads. This process is difficult because the wires are directly under the chin and out of visible range.

During prolonged use, the mask is very comfortable. The cushioned CPAP mask material sits comfortably on the face, and the ski goggle strap spreads the load across a wide area on the head. The airflow through the mask is superb; it makes the mask very comfortable to breathe through. The fans, however, make a low hum, making it more difficult to hear those around you.

Finally, doffing the mask is simple. Just remove the battery and mask from the face and unplug the wire leads. Overall, the mask is comfortable to wear for prolonged periods of time, it is just slightly difficult to put on (and take off).

Conclusion

Throughout the entire design process, there were numerous mistakes and modifications made in the lab in order to hone in on our final design. The group did err, err, and err, but less, less, and less as prototypes progressed. One of the most helpful things done during this project was early prototyping and testing to get on the right track earlier in the semester. Additionally, more time was spent in the lab actually building the mask and figuring out how to put together a fairly polished final project. Despite this information, many mistakes and errors were encountered that caused a shift in the major goals and objectives of the project.

By the time final mask assembly took place, the group had already decided on a specific type of CPAP mask. However, during later testing, other face masks, not just CPAP masks, were thought to be more comfortable and should be experimented with further. Additionally, addressing the comfort of the face mask after all day wear, having an alternative and less forceful fit would be advantageous. The ski goggle strap was found to be a thicker and more comfortable fit on the head, but it was too elastic and forced the CPAP mask to press against the mouth and nose a little more than expected. The final important mistake came from the initial goal to make a small, sleek, and aesthetically pleasing face mask. During the design process, it was determined that this was not feasible and that focusing on another aspect, like visuals for reading facial expressions, would be a better use of time. Ultimately, the final product missed the mark on making a mask that would be very appealing to the eye.

Looking forward, future improvements to the final design certainly exist. While 3D printing material alone creates hurdles with respect to air-tight component mating, the make-shift O-rings made of caulk located in the fan pods were not ideal. In order to create an air-tight O-ring system, the material application must be as uniform as possible. While the caulk was elastic, the uneven application still led to potential air gaps. While the group was satisfied with the airflow produced by the centrifugal blower fans, the design could be improved with smaller yet powerful fans or pumps, for the size of the pods and overall system would be reduced, creating a more appealing fan-powered mask. On the subject of fit testing, the availability of Bitrex solution was key, for this same testing agent is used in official respirator testing. However, as mentioned earlier, conducting this fit test outdoors was unconventional, so using a small controlled area or fume hood would increase the legitimacy of the test. Finally, there is much improvement to be done to the battery and holder system. The search for a small, powerful, and safe battery may be never ending, but a smaller unit and its wiring could be attached more discreetly to an arm strap, backpack or belt. Ultimately, the design looks like a clear gas mask and is not something that the group believed people would love to be caught wearing. While the final product would not have made the cut for the Paris Fashion Week Catwalk, it proved to be a functional mask which met almost all of the criteria laid out at the beginning of the semester.

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