Engineering Design Process

Introduction:
We hypothesized that a mask can be designed to provide a low-cost, long-term protective solution to people at high risk of getting severely affected by the COVID-19 virus. To accomplish this, our team aimed to use a 3D-printing engineering solution to create a reusable mask with high filtration efficiency.

Materials and Equipment:

| Printer types                              | Single extruder; Fused Deposition Modeling (FDM); 0.4mm (nozzle diameter)  
|                                           | Single/Double extruder; Fused Filament Fabrication (FFF); 0.4mm (nozzle diameter) |
| Filament types                             | PLA(1.75 mm) and TPU (1.75 mm)                                           |
| Foam lining material                       | High Density Foam Tape, Foam Seal Strip; High-Density Rubber Foam Weather-strip Tape |
| Filter material                            | HEPA Media Vacuum Bags; HEPA media vacuum bags meet HEPA filtration standard of 99.97% efficiency at 0.3 microns |
| Sanding equipment                          | - sand paper and multi tool sander                                         |
| Tie materials                              | 1/8 Inch Braided Elastic Band                                              |
| Slicing software                           | Cura; Creality Slicer;                                                      |
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Build Process:

We identified a freely available prototype 3D-design for a base mask from the internet (https://lowellmakes.com/covid-19-response/) and used this as a template to engineer our mask solution.

![Mask prototype](image)

**Figure 1- Mask prototype**

We calculated the dimensions needed for the mask to effectively cover the average-sized adult’s nose and mouth 4.25” X 3.625” X 2.125” and also a slightly bigger mask with 5.5” X 4.375” X 2.5”. We also designed the accessory pieces that would be needed to create a filter chamber to go over the base mask. These included:

1. A square-shaped filter holder, with a cross pattern
2. A diagonal square, with an “X” shape gap to support the filter from behind in the mask
3. A slatted cap, to cover the filter and filter holder.

![Design calculations](image)

**Figure 2A- Design calculations**

![Base mask](image)

**Figure 2B- Base mask**
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Based on our initial calculations, we printed a test mask. After multiple trial and error sessions, we were able to successfully print a mask that fit on the face well, along with smoothly interlocking accessory components. We used different printers to print the masks. Best results were obtained with Monoprice MP 10 and Creality 10S.

![3D-printed mask with interlocking components](image)

Figure 3- 3D-printed mask with interlocking components

Our next step was to research and identify an effective filter material. We reviewed existing literature on various materials and their effectiveness against the transmission of SARS CoV-19 viral particles. We identified that N95 masks are considered the gold-standard against viral transmission, with >95% effectiveness in filtering out 0.3-micron viral particles. Based on this, we identified and sourced filter material from vacuum bags (HEPA Media Vacuum Bags – Riccar Brand) that have a similar MERV-13 filtration efficiency rating as N95 masks. We cut this material to size (2X2) to fit adequately and snugly into the filter chamber of our 3D printed mask.

Our base mask and accessories needed to be finished and smoothened by hand using a sanding process. For this, we used sand paper and a multi tool sander.

![Effectiveness of Filter Material](image)

![Cut-to-size filters from vacuum bag material](image)

Figure 4- Cut-to-size filters from vacuum bag material

Figure 5- Effectiveness of Filter Material
Evaluation Process:

We tested the effectiveness and fit of our masks.

1. We used the FT32 3M aerosol spray under a glass hood to test the masks, which is identical to the fit testing process used for N95 masks. Our improved mask design demonstrated equivalent barrier effectiveness to N95 masks on repeat testing.

2. Our masks are made of durable plastic (both the base mask as well as accessories) and the filters are disposable. Hence, each mask is extremely durable and can be taken on and off multiple times without breaking or falling apart.

3. The masks were tested by multiple end-users and demonstrated laminar airflow and a comfortable breathing pattern for users, even during fast walking for 15 minutes.

4. There are minimal to no gaps in the lining of the mask. Based on the test results of the prototype and feedback, we incorporated a foam lining over the nasal bridge area to enhance fit and effectiveness of seal. Airflow only occurs across the filter.

5. Our masks were tested for sanitary hygiene. The base 3D printed mask and accessories can be easily cleaned with sanitizers or alcohol or even soap and water prior to reuse. The filters cannot be cleaned and need to be replaced every 24 hours.
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Mask Distribution:

Our masks are designed for use by community members for general use. However, with further performance testing, we believe they can demonstrate superior protective capacity that match the efficiency of N95 masks.

https://threemasketeers202.wixsite.com/masks

Iterative Design Modifications:

We conducted multiple PDSA cycles and based on feedback received from end-users, we made several design modifications:

- Additional foam around entire mask lining for comfort
- TPU filament (flexible filament) usage for the filter holder
- Entire mask print with TPU filament
- Size modifications to mimic the two available sizes of N95 masks
- Reduction of slats on cap to minimize resistance to airflow during respiration

Figure 9 - Foam lining around entire mask
Figure 10 - TPU filament mask
Figure 11 - Old and new cap designs
Conclusions:

- We were able to successfully 3D-print an innovative mask that has provided a low-cost, long-term protective solution to those who need more effective protection than a cloth mask or face shield to stay protected from COVID-19.
- The mask we have engineered is being used by community members who are at high-risk of acquiring COVID-19.
- We are in the process of conducting further efficiency tests like fluid resistance testing, flammability resistance testing and bacterial filtration efficiency of our base mask and other components to ensure long-term use of the entire mask.

Figure 12: Mask ready for distribution