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Creating a Vacuum Thermoformer Designed to Help Fabricate a Powered Air Purifying Respirator for Children

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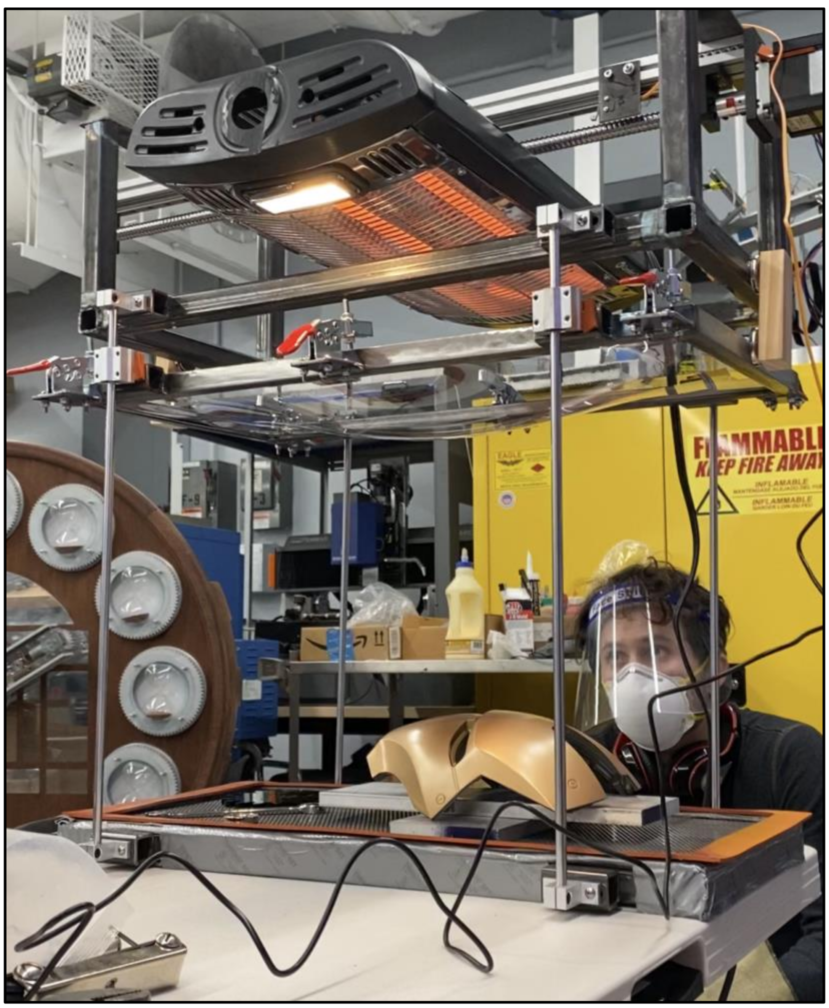


Abstract

The ongoing Coronavirus pandemic demands innovation from scientists and engineers across all disciplines to develop solutions to save lives. As fourth year Mechanical Engineering students at the University of Virginia, our team wanted to contribute by developing a Powered Air Purifying Respirator (PAPR) designed for children as our technical capstone project. We initially set out to develop a PAPR designed for use by students in lower education schools, but as our semester-long project went on, focus shifted toward developing a vacuum thermoformer due to its key role in fabricating a physical prototype. After many trials and errors, we learned a lot about mechanical design, and have developed a relatively low-cost method for creating plastic molds that students can use for future capstone projects. Our work on the thermoformer could be continued in the future to improve its overall performance and ultimately create a more finished design.

1. Introduction: Our Initial Design Project - The Clean-19

Grade school students staying home from school causes numerous problems. One problem is that parents no longer have a place to send their children while they are at work. Since the day cares are also closed because of Covid-19 they are left with two options: leave the kid home with a babysitter or work from home if their job allows. Compared to in-person classes, online classes are more difficult to stay focused during, especially when at home where there are endless distractions. Long-term gaps from in-person schooling can cause students to forget what they previously learned, similar to the “summer slump”. The phenomenon where, after summer break, children forget important concepts learned the year before (The Importance of Reopening, 2020). The longer students are kept from in-person classes the more they will slide down the slump. A solution is needed.

To solve this problem our team first designed a Powered Air Purifying Respirator (PAPR) that filters both inhalation and exhalation, the Clean-19. Providing students with a Clean-19 greatly reduces the risk of COVID-19 allowing schools to reopen in-person confidently. Alternatives to the Clean-19 are students wearing surgical, cloth, or N-95 masks. Not only are these masks uncomfortable, but each child will need to get fit tested to ensure the mask is airtight. Even if the masks fit correctly, transmission is still possible. The student can contract it through their eyes, they can take the masks off without the teacher knowing, and COVID-19 particles occasionally seep through the mask material. For reference, an appropriately worn PAPR has an assigned protection factor (APF) of 1000, while an N-95 mask only has an APF of 10 (Considerations for Optimizing, 2020). With kids only wearing masks, schools will still have to social distance, create COVID bubbles consisting of small groups of students, alter bus routes, and reduce the number of days students come to school, in accordance with the CDC guidelines (FAQ for School, 2020). To plan for these operations requires a lot of time and money.

The schools need a solution like the Clean-19. Unlike other PAPRs in its class it is cheap to manufacture. Other PAPRs cost hundreds of dollars, while Clean-19 could be made for $100. Thus far no PAPR systems have been designed to address the needs of children. Most importantly, Clean-19 will filter both the intake and outflow of air. Every PAPR on the market only filters the intake, and blows your unfiltered aerosolized particles through the air enabling you to spread COVID-19 to others (Considerations for Optimizing, 2020).

When we first designed the Clean-19 our team utilized Solidworks, a Computer Aided Design software. Our first prototype was going to be an iron man shaped helmet that functioned as a dual filtration PAPR (Figure 1).

Figure 1. Initial Iron man helmet design for the Clean-19. From left to right we have the three parts of the mask: The right side of the helmet, the face mask, and the left portion of the helmet.

The helmet was designed with fan holders, one for an intake fan and one for the outtake fan. Once printed the mask would be secured together using screws and nuts. All three pieces of the helmet were going to be 3-D printed and then we would thermoform a piece of plastic over the 3-D printed face mask. This would allow people to read the users facial expressions, something that cannot happen while wearing a usual mask.

Our fan was chosen to meet all necessary minimum PAPR specifications, pictured in Figure 2, is a 5 Volt PWM fan that moves enough air to create a positive pressure environment within our mask. The fans were projected to move 22 or more cfm of air, which is far beyond the necessary 10 cfm designated by the requirements for a loose PAPR system and accounting for the volume of air removed by the exhalation fan (Liverman, Domnitz, & McCoy, 2015). We successfully coded Pulse Width Modulation (PWM) for the fan, which gave us the ability to change the fan speed to maintain a positive pressure while breathing in and out. Our original idea for the mask was to incorporate these into a Proportional Integral Derivative (PID) control system to keep the positive pressure.

Figure 2. CAQL CPU Cooling Fan with PWM capability to be attached within the helmet

In order to have a PID, we needed to integrate a pressure sensor into the system using a Propeller chip. We first used two iterations of the BMP 280 chip, one by SongHe and one by Adafruit. Before trying anything, we were told to read and re-read the BMP 280 data sheet. The BMP 280 sensor can communicate with the chip using SPI or I2C. We were focused on using SPI because of its simplicity when using one sensor. To read the pressure register from the BMP 280 we were given a specific high/low pattern to follow across 4 pins (See Figure 3). First we had to pull the Chip Select pin (CSB) on the sensor low to start the communication between the microcontroller and the sensor. Once the CSB pin is low, we send high low pulses on the clock pin (SCK) to the sensor. At the same time we are sending clock pulses, we also send the byte of the register address we want to read from to the SDI pin on the sensor. In our case we wanted to read the data in the pressure register which is 0xF7 or 11110111 in binary format. After the sensor receives the register address from the SDI pin it should send that register’s data out to the chip from the SDO pin. This was how it was supposed to work in theory, but the sensor did not send pressure data to the chip. However, we did successfully read the chip id register from the sensor, which proved our SPI communication protocol was working.

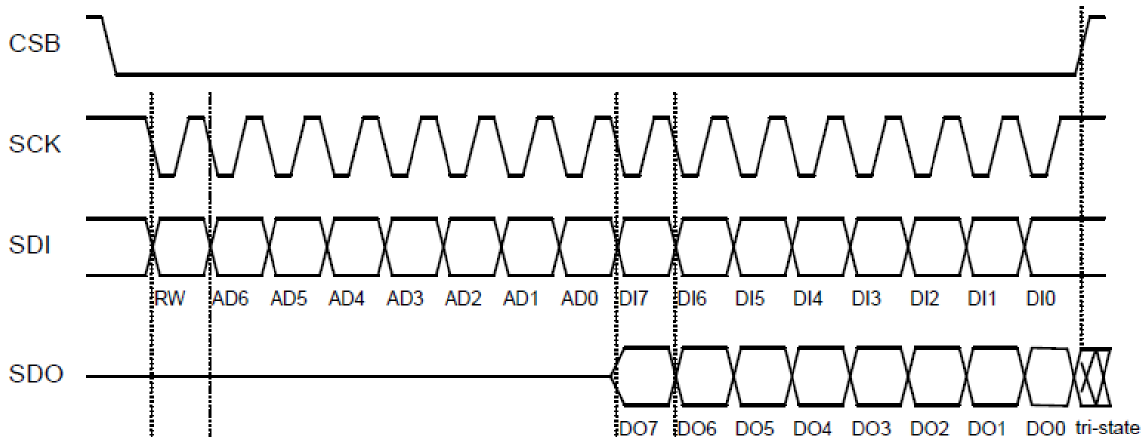


Figure 3. SPI protocol for the BMP 280 sensor

After erring, erring and erring again we still were unsuccessful in integrating the Adafruit sensor with the Propeller chip. We then switched to an Arduino Nano microcontroller and were able to read pressure data off of the Adafruit BMP 280. With the Arduino Nano we would not accomplish a PID control system, but we could still use the pressure data to alter the fan speeds to maintain positive pressure.

While part of our team was working on the electronics to go inside the helmet the other part was working on the creation of the iron man helmet. This was initially done by downloading an iron man .stl file from github and then converting them back into Solidworks part file. Once in a part file we could edit the drawing to incorporate our fans and electronics as seen in Figure 1. Our plan was to first 3-D print and assemble the model, then incorporate the electronics and adjustable head strap into the helmet. After that was completed, we would then attach the filters to the fans using a 3-D attachment pictured in Figure 4, and sew on filter material around the bottom of the helmet to create a semi-airtight seal.

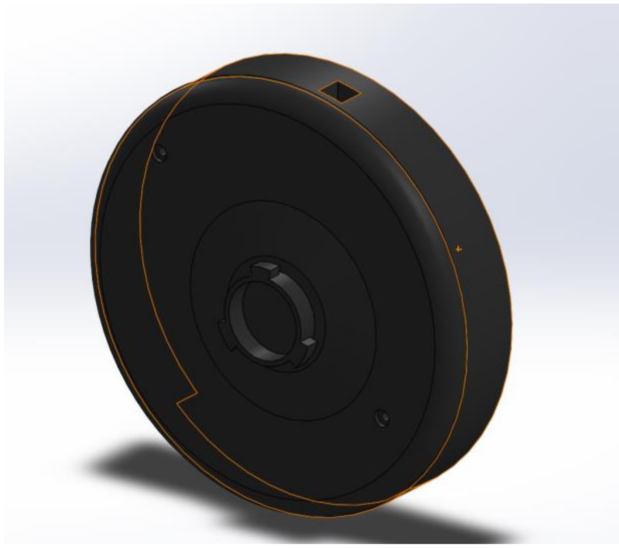


Figure 4. 3-D model of the fan casing to allow filter attachment

Our initial timeline was to have a fully functional design by Halloween for a child to wear. However, we underestimated the cost and scalability of 3-D printing each helmet making this deadline unobtainable. After a group discussion between ourselves and Professor Garner, we decided the best option would be to thermoform the masks. Thermoforming the masks would make manufacturing the masks at scale more feasible and less expensive. We then switched our main focus of our project to creating a vacuum thermoformer that would aid in creating our Clean-19.

2. Vacuum Thermoformer

The vacuum thermoformer design forewent many professional upgrades throughout the semester. The base design was drawn from a prototype featured in the Youtube video "How to

Make a Larger Vacuum Thermoformer" (iliketomakestuff, 2018). The device assembled in the video, shown in Figure 5 below, performed well and had already solved many of the design challenges. Additionally, we compared and contrasted the prototype with professional thermoformers. From the comparison, we took the base design and improved further upon it by first exchanging all parts that were made from wood with steel. This upgrade served the purpose of making the device safer for users since the heater could reach temperatures over 1000 °F. Along this thinking, we also made sure that all of the parts that would be in close proximity of direct heat would function safely with a 350 °F heat tolerance. Safety was an important factor in our design, which is why we decided to use a premade heater and used materials that would not emit toxic fumes upon heating such as not using galvanized steel. Another important upgrade was using a linear actuator to move the heater along the length of the plastic sheet so that it heated the sheet entirely. This idea originated from a flaw in the Youtube version of the thermoformer that only created about an 8 inches by 10 inches melted area. Using the linear actuator, we were able to increase the melted area to about 10 inches by 22 inches. Other professional upgrades from the base design included using toggle clamps for clasping the plastic into the frame, bolts instead of screws so that the device could be disassembled if needed, and using linear guide rods so that the plastic sheet would lower evenly. Lastly, we used a dual stage rotary vane vacuum pump rather than a shop vacuum.

Figure 5. Base design for the vacuum thermoformer.

The ½ horse power vacuum air pump had all its parts connected with quick disconnect fittings. We found that the pre-assembled quick disconnect tubing was quite expensive, so we decided to make our own using plain tubing and attached the quick disconnects ourselves. From the pump, the hose connected to a T-split valve that measured pressure in mmHg, while the other end connected directly to the lower box of the thermoformer.

Many of the design constraints were based upon making sure the size and cost of the device were within certain limits. The overall size of the vacuum thermoformer matched that of the base design from the Youtube video. We changed the sizes of the metal portions of the frame and thermoformer to be sufficiently strong enough for proper function as well as minimizing the cost of the build. Additionally, we made sure that the height of the build area was sufficient for the face shield to be built overtop of a buck, which is a small object that rests beneath the object to be molded so that the plastic wraps well around its edges.

3 CAD Modeling

After planning out and ordering all the parts that were needed, we first wanted to model everything in CAD. We first began by modelling all of the individual parts, consisting of the specific pieces of metal composing the frames, spacers, the guide rods, clamp platforms, and everything else in SOLIDWORKS. Bolted connections were assembled with previously modeled parts downloaded from McMaster-Carr. In total, there were 36 SOLIDWORKS part files comprising 3 sub-assemblies and one complete assembly. We went through a couple of design iterations to create our final model. We had originally designed the top assembly holding the linear actuator and heat lamp to be an A-frame, shown in Figure 6. There were a few problems with this model, however. The first problem was that it would be hard to weld with acute interior angles like those in the top frame. Also, it was necessary to add one more toggle clamp platform on each side so that we could secure the plastic sheet firmly in the racking frame. A square steel tubing was substituted in the final design provided more structural support compared to the initial thin steel sheets from the first iteration.

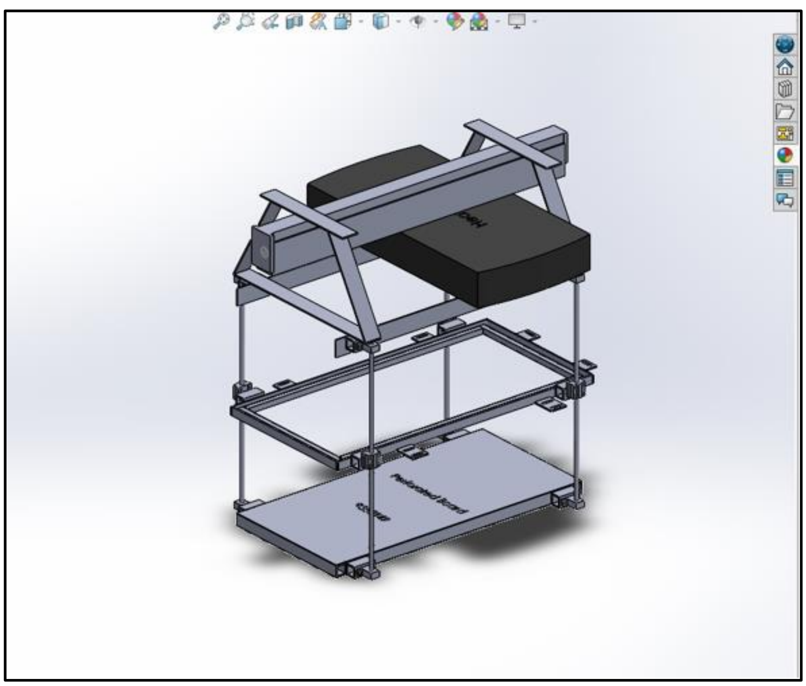


Figure 6. First “A-Frame” SOLIDWORKS Assembly Model

We later added the bolted connections that we believed would connect the spacers to the guide rods, and these were kept in the final assembly. A closer view of these connections are shown beside the final model later in Figure 7. Without having an exact CAD model of the ball bearing slides, we had to model our own. However, we did not account for the fact that the throughole on the outside of the slide would be smaller than the threaded hole on the front. When actually assembling the physical thermoformer, we ended up running into problems and had to use different sized bolts to hold the slides to the spacers connected to the middle frame. We learned that we should never assume anything, and instead measure everything when creating a CAD model of a part. The ball bearing slide showing the inaccurately modeled throughole is shown below.

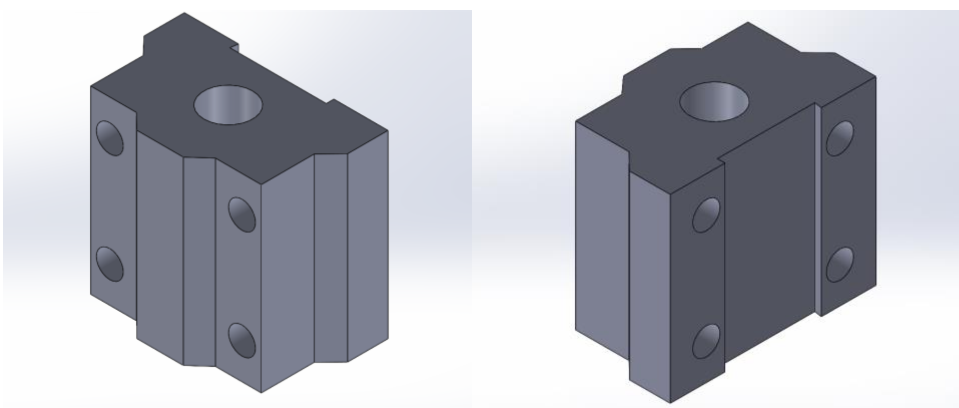


Figure 7. Our model of the ball bearing slide for the linear guide rod.

The larger, more detailed components of the assembly were more generally modeled, such as the heating fan, just to know that we left enough clearance for it to fit within the top frame assembly. This also proved to be a flaw in our CAD design, because we did not account for the correct sized bolts that would be used. All of our modeled parts and sub-assemblies came together to form the final assembly shown in Figure 8 below, which we used to construct our physical thermoformer prototype.

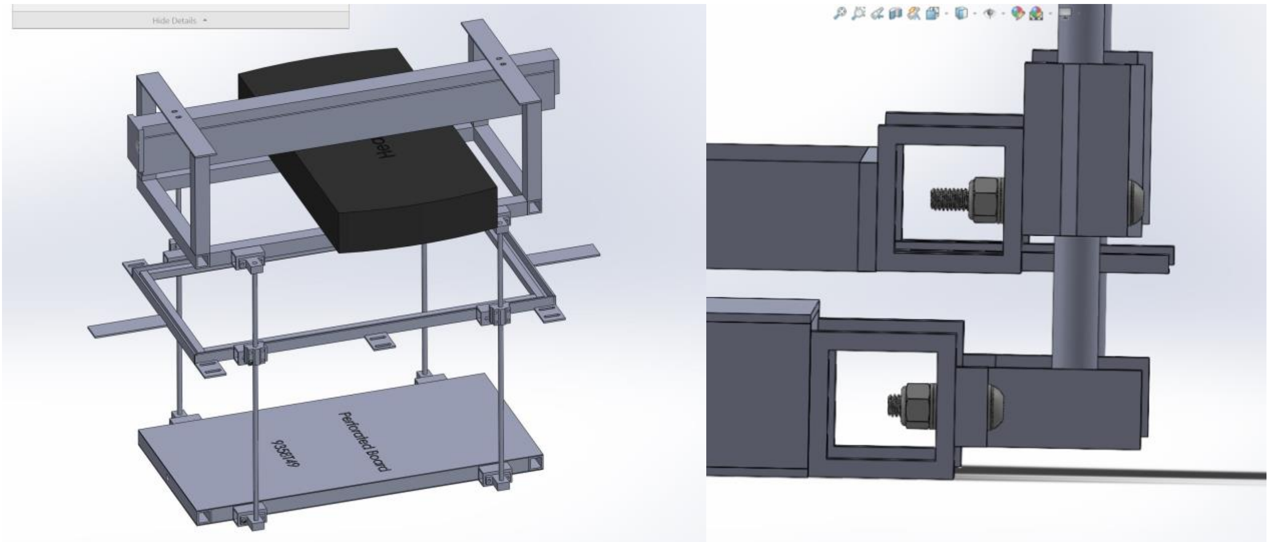


Figure 8. Final Thermoformer Assembly and Bolted Connections

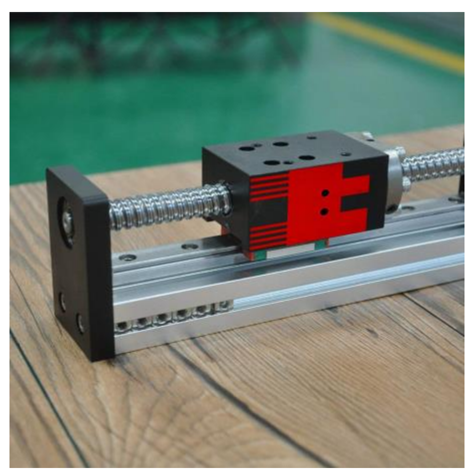
4. Assembly

Physically assembling the thermoformer was predominantly done later in the semester near the conclusion of the project. Numerous iterations of part ordering, small errors in part properties, delayed completion of a comprehensive Solidworks model, and numerous hours of welding required by Professor Garner largely contributed to this delayed assembly.

The first order of business was assembling the three necessary frames for the thermoformer, but before that could be done, many of the pieces needed to be cut or milled. The spacers that attach to each frame needed to be milled as slots to allow for some tolerance since welding isn't necessarily a precise art. A picture of the milling process for these pieces is shown in Figure 9. Additionally, the cross beams on the top frame which connect to the linear actuator needed to be cut into segments using a band saw.

After all of the ordered pieces were modified as necessary, the welding process could begin. Professor Garner possessed the steel that composed the vast majority of the frame, and was welded to the necessary 1 ft. by 2 ft. dimensions at each level. Four steel pillars were then welded to the top frame, which were welded to the eight-inch flat steel bar. Lastly, the milled pieces were welded to each level of the frame to allow for spacing between the linear guide rods and the frame.

In order to connect the heat lamp to the linear actuator, some modifications were necessary to the original product, shown in Figure __. The mounting point that was originally connected to the heat lamp needed to be removed. After the bracket was broken off, the lamp was disassembled to access the back panel for drilling. Four holes were drilled through the posterior metal sheet and the lamp was then mounted to the red and black trolley of the linear actuator, shown in Figure __.



After the heat lamp and linear actuator assembly was complete, both items were connected to the top frame. In this connection, the group ran into tolerancing issues as the bolts ordered were too long to fit into the slots for the linear actuator. To compensate for the fit, shims were added to ensure a tight connection. Then, the pressure clamps were attached to the sliding frame. There were six total connections, and each was adjusted to ensure pressure was placed on the compressing frame for the plastic.

All frames were then connected to their respective mounting agents in the linear guide rod kit, shown to the right in Figure __. The top and bottom frames were attached to the end positions of the linear guide rods, and the sliding frame was connected to the ball bearing sliders. The guide rods had to be adjusted a number of times to ensure a relatively smooth vertical movement of the sliding frame. Additionally, the imprecise nature of welding left the linear guide rods slightly off perpendicular to the ground, so shims were required on some guide rods to prevent a smooth movement of the sliding frame.

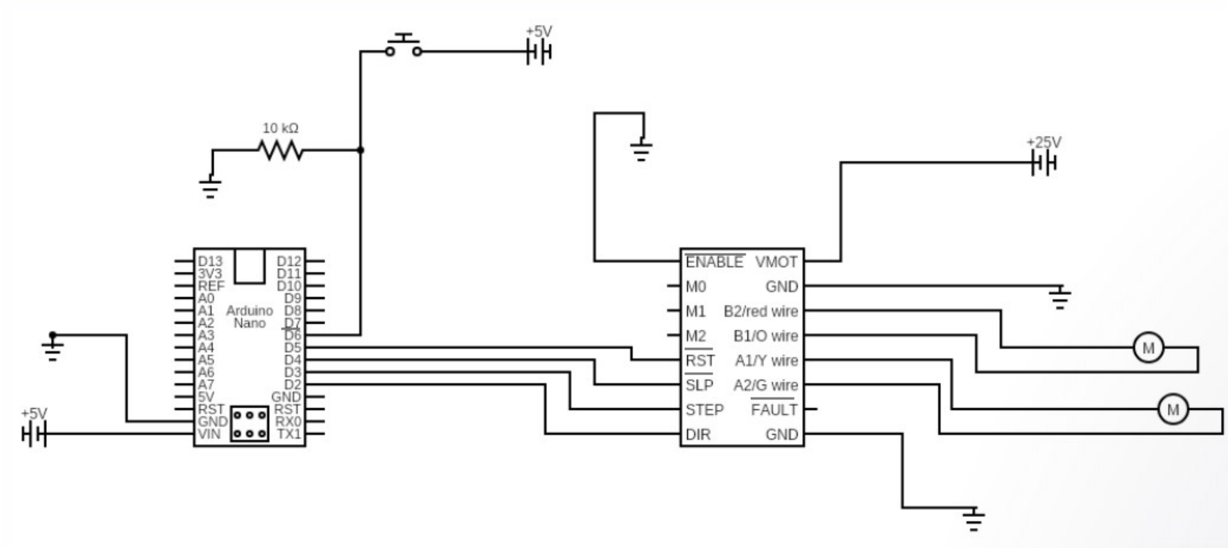
Once the main structure of the thermoformer was completed, the soldered circuit board, created by Professor Garner, was connected to an acrylic sheet. A 3D printed part was designed to clamp onto the stepper motor, and the acrylic sheet was then mounted to the 3D part. The measurement of the stepper motor to create said part was done with a pair of calipers, as shown in Figure Y, and the model was deliberately oversized to ensure a loose fit for ease of removal should any electronics need to be repaired or modified.

Once the electronics were in place, magnetic bearings were created to hold the top frame and the sliding frame together during heating. The magnets used were quite strong, and made removal difficult by a single individual. Another modification was that the caps of the clamps for the compressing frame were removed, as the depth of the clamp was too great and could not lock into position in order to hold the compressing frame.

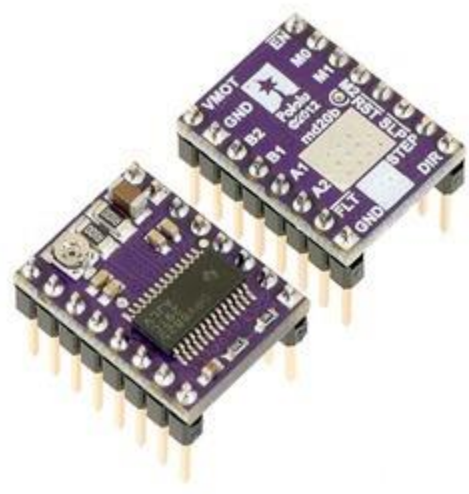
The largest issue encountered during assembly was that of the bottom frame's seal for the vacuum. The metal sheet ordered that was meant to be welded to the bottom of the bottom frame was stainless steel, which was incompatible to weld with the rest of the non-stainless steel. In turn, an improved approach using duct tape as a sealant for the bottom frame was instituted, as shown in Figure Z. Furthermore, the sliding frame and the bottom frame did not compress as uniformly as intended, and left gaps between the silicon lining and the sliding frame as a result. To compensate for this discrepancy, further use of duct tape was implemented to attempt to fill in the smaller gaps around the two frames.

5. Mechatronics for Thermoformer

The vacuum thermoformer constructed is a mechatronic system including mechanical, electrical, and computer science elements. The primary mechatronic system in the thermoformer consists of the single axis linear slide controlled by a stepper motor, an arduino nano microcontroller, and a DRV8825 Stepper Motor Driver. The circuit diagram for the system can be seen below.

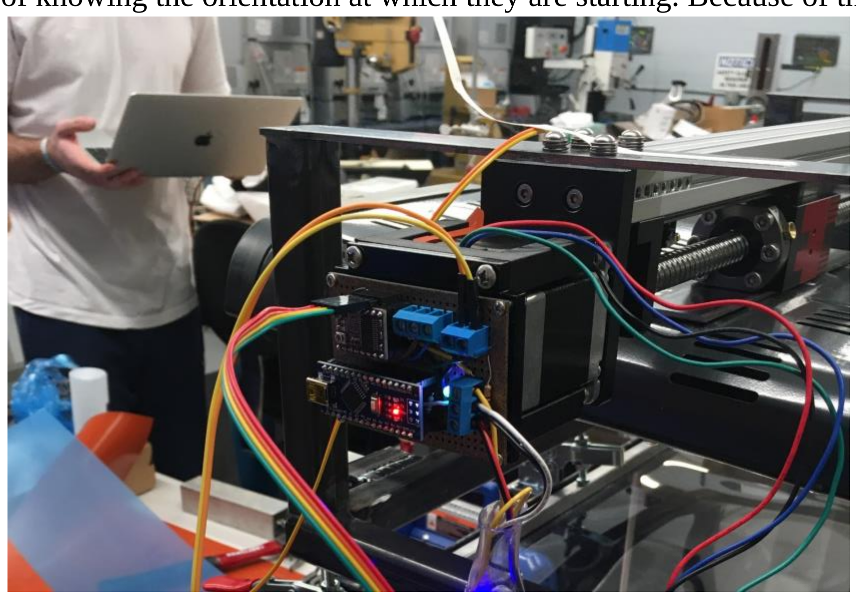


The stepper motor requires a power supply of 25 volts and 1.5 amps, a power that cannot be delivered by a standard microcontroller. To solve this problem, a stepper motor driver was used. This stepper driver is capable of taking a control signal from a microcontroller and using that signal to control a circuit of much higher current and voltage. This can be seen in the figure below, with the stepper driver on the right and the microcontroller on the left. The motor is connected to the A1, A2, B1, and B2 pins, while the external 25 volt power supply is connected to the VMOT pin of the stepper driver. The RST, SLP, STEP, and DIR pins represent the control aspect of the system. The DIR pin will set the direction of motion of the slide to either be forward or backward depending on whether a HIGH or LOW signal was sent, while the STEP pin instructs the motor to step when HIGH and do nothing while LOW. In order to provide smooth motion the STEP pin is sent alternating HIGH and LOW pulses. The speed of the slide can be varied by altering the amount of time that the microcontroller waits between high and low pulses. The direction of these pins was controlled using the arduino nano. A limit switch was also implemented on one end of the linear slide so that the thermoformer would not hit the end of



the slide. This was done using a simple button with a 10kΩ pull down resistor and a pin of the arduino nano.

Because an arduino nano was used as the microcontroller for the system, the programming language used was arduino, which is based on C/C++. Stepper motors are controlled only by high and low pulses, consequently, when they are powered on they have no way of knowing the orientation at which they are starting. Because of this a homing algorithm



(setup()) initializes when the thermoformer is first powered on. This homing sequence sends the linear slide in the direction of the limit switch until it reaches the switch, then continues with the rest of the program. After the homing sequence has been completed, the standard motion of the thermoformer begins. The linear slide is directed away from the limit switch by an experimentally determined number of steps, then changes direction and returns until the limit switch is reached again. Additionally, the speed is reduced near the edges to more evenly heat the surface of the plastic. This feature allows for the plastic to retain its dipped shape to prevent cooled areas of the plastic from affecting the formation of the final mold.

stepper_motor_v2

```
int fast = 1000;
int slow = 5000;

int dir_pin = 2;
int step_pin = 3;
int sleep_pin = 4;
int reset_pin = 5;
int switch_pin = 6;
int count = 0;


void setup() {
  // put your setup code here, to run once:
  digitalWrite(sleep_pin, HIGH);
  digitalWrite(reset_pin, HIGH);
  Serial.begin(9600);
  for (int i = 0; i < 6000; i++) {
     if (digitalRead(switch_pin) == LOW){
      digitalWrite(dir_pin, HIGH);
      count = 0;
      break;
    }
    digitalWrite(step_pin, LOW);
    delayMicroseconds(slow);
    digitalWrite(step_pin, HIGH);
    delayMicroseconds(slow);
    count = count+1;

  }
}
```

```
void loop() {
  // put your main code here, to ru
  for (int i = 0; i < 1000; i++){
    digitalWrite(step_pin, LOW);
    delayMicroseconds(slow);
    digitalWrite(step_pin, HIGH);
    delayMicroseconds(slow);
    count = count + 1;
    Serial.println(count);
  }
  for (int i = 0; i < 2900; i++){
    digitalWrite(step_pin, LOW);
    delayMicroseconds(fast);
    digitalWrite(step_pin, HIGH);
    delayMicroseconds(fast);
    count = count + 1;
    Serial.println(count);
  }
  for (int i = 0; i < 1000; i++){
    digitalWrite(step_pin, LOW);
    delayMicroseconds(slow);
    digitalWrite(step_pin, HIGH);
    delayMicroseconds(slow);
    count = count + 1;
    Serial.println(count);
  }
  digitalWrite(dir_pin,LOW);
  for (int i = 0; i < 1000; i++){
    digitalWrite(step_pin, LOW);
    delayMicroseconds(slow);
    digitalWrite(step_pin, HIGH);
    delayMicroseconds(slow);
    count = count + 1;
    Serial.println(count);
  }
```

```
  for (int i = 0; i < 3900; i++) {
    if (digitalRead(switch_pin) == LOW){
      digitalWrite(dir_pin, HIGH);
      count = 0;
      break;
    }

    digitalWrite(step_pin, LOW);
    delayMicroseconds(fast);
    digitalWrite(step_pin, HIGH);
    delayMicroseconds(fast);
    count = count + 1;
    Serial.println(count);
  }
  for (int i = 0; i< 2000; i++){
    if (digitalRead(switch_pin) == LOW){
      digitalWrite(dir_pin, HIGH);
      count = 0;
      break;
    }
    digitalWrite(step_pin, LOW);
    delayMicroseconds(slow);
    digitalWrite(step_pin, HIGH);
    delayMicroseconds(slow);
    count = count + 1;
    Serial.println(count);
  }

}
```

6. Future Improvements (Ryan)

Knowing everything we know now, we would have gone about designing and creating our thermoformer very differently. Nevertheless, we completed a working prototype that has the potential to be built upon in the future. Firstly, we would have put together a better way to keep the sliding frame connected to the top frame when not in use. The last minute idea to hold it together with magnets glued to wooden blocks worked for our purposes, but could be improved to make it feel like a more finished design. Initially, we had planned this out in CAD by placing ten holes around the bottom surface of the top frame. The magnets we had bought would be screwed into these holes, hanging down about an inch to latch on to the racking frame below. However, we realized this would be infeasible due to the strength of each 100 lbf magnet. The twisting action of the wooden handle allowed for easier removal of the racking frame from the top frame. However, we leave it to any student in the future to devise a more elegant solution to this. The original design and the physical wooden handle connected to the magnets is shown in Figure __ below.

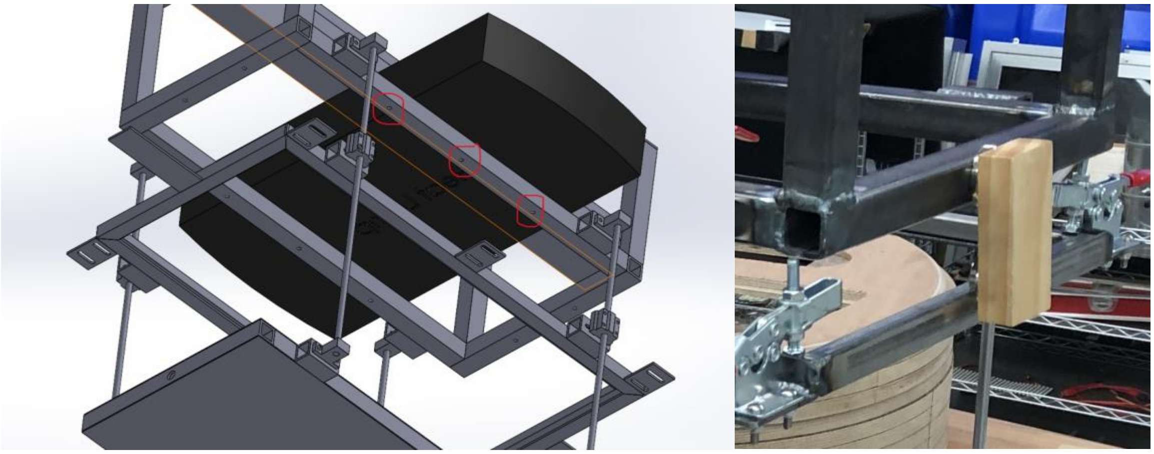


Figure _. Original placement of locking magnets in the CAD Model vs wooden block design

Many features could be added to our thermoformer prototype beyond this. One thing we wanted to do, but ran out of time, was to seamlessly switch power between the vacuum pump and the heating lamp because of the huge amount of power they draw from an electrical socket. To test our prototype, we initially cut power to the heat lamp before turning on the vacuum and lowering the racking frame, which was a clumsy process to continue doing. This could be resolved with a solid state relay connected between the two power sources. When one switch or button is pressed, power could automatically be shifted from the lamp to the pump, avoiding any large current draws and electrical surges. The relay was also initially designed to be connected to a Hall Effect sensor, which would be tripped by breaking the magnetic lock holding the racking frame to the top frame and allow for the solid state relay to divert the power as explained before.

Many features could be added regarding electronics and microcontrollers, such as temperature and vacuum pressure sensing. However, the most critical area to fix and improve upon would be the vacuum suction. As we mentioned before, we were unable to create a perfect vacuum seal between the racking frame, silicone gasket, and the perforated board at the bottom. From our CAD model we did not envision we would run into problems with this, as everything was modeled completely flat. However, imperfections in the physical assembly and tiny angles between the welded pieces resulted in small gaps that allowed air to escape, preventing the pressure to drop. If we had allowed for more time for testing and prototyping, we would have been able to resolve these problems and provide a better solution. Before moving on to any other features, this is the most important problem to fix.

7. Using the Thermoformer for a PAPR Design (Jack)

With our functional thermoformer we were able to create custom shaped plastic molds shown in Figure _. After completing the seal on the vacuum chamber, we would have created three different molds and secured them using bolted connections. As the thermoformer is not capable of handling objects more than a few inches tall because the plastic would stretch and break, the mask would have to be divided into segments which would then be brought together and sealed. The rigid shell would then have been cut to allow for the 3D printed fan bay to be inserted. After the mask and fan complex was assembled, we would have integrated the electronics, filters, and head strap, thus completing our original idea: the Clean-19. The battery pack and the circuit board were projected to rest above the user's head, while the Niosh filters would clamp onto the holsters designed on the outside of the fan bay. This first iteration would likely have problems in functionality, and would have to be Bitrex testing to ensure a proper seal. Additionally, the timings for the duty cycles of the fans for PWM would likely need to be adjusted in order to reach the appropriate internal pressure of the mask.

Figure ___. The face shield portion of our Iron Man helmet PAPR created from thermoformed plastic

8. Conclusion

The project was a great learning experience for the design and fabrication of a complex system. Though the group fell short of the intended goal to create a functioning dual filtration system, the development of a functional thermoformer was an exceptional engineering process.

The team learned a few valuable lessons that will guide engineering efforts in the future. First, extensive design in the planning stages of the project, especially that in Solidworks, provides a large payoff later in the process. A completely refined Solidworks model would have prohibited many of the problems that the team encountered during the design process. For example, the Solidworks model did not possess dimensions for the clamps. In the model, the team assumed the clamps were too complicated to model as well as mostly unnecessary since they were not projected to interfere with the rest of the assembly. However, the clamps prevented the sliding frame from pushing against the top frame in a flush manner, leading to an improvised approach for the magnet locking system.

Additionally, the team recognized that most engineering processes are simpler in theory than in application. For example, the assembly of the thermoformer, once welded, was projected to happen relatively quickly but did not account for issues in bolt sizes, tolerancing for the linear guide rods, and disassembly of some components. Furthermore, ensuring the proper parts are ordered further exacerbated this problem, and more careful analysis and planning for material orders could have prevented a number of problems in the final product.

Lastly, and perhaps most importantly, is that the engineering process sometimes requires a shift in methodology, which was evident from the team’s work on the pressure sensor for the mask system. Transitioning to a different problem solving method is often the most beneficial step to success if the current method is not on track to succeed.

The project will hopefully benefit future lab generations in their endeavors. With minor modifications to the seal of the vacuum in the bottom frame, the thermoformers should be functional for future use. In terms of the project, the original intention to 3D print the mold of the mask was likely not the most useful engineering approach. For a prototype or a piece of art the

3D printing approach would have been successful. However, thinking like engineers, the thermoformer allows for a more permanent and faster solution for the production of mask shells in the future.

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