Additive Manufacturing Powder Removal

Final Design Review

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Abstract
This report presents the final design review of this senior project team. The project is being sponsored by Lawrence Livermore National Laboratory, a federal design agency. Lawrence Livermore National Laboratory is interested in improving their metal additive manufacturing process. The goal of this senior project is to improve the efficiency and safety of a method currently being used to remove metal powders for additively manufactured components. A senior project team in 2017-2018 created the Vibration Induced Powder Evacuator and Reclaimer (VIPER), a device that uses a vibration motor to shake a printed part until it is clean from excess powder. VIPER, however, does not have a system to contain the removed powder. The focus of this project team was to improve VIPER’s design by adding a way to isolate loose powder from the user and implement an automated system to improve the process efficiency. The final design incorporates an enclosure around the VIPER to isolate powder, an improved mounting system to secure the printed part, and a PLC system that drive motors to allow for automatic reorientation of the part. Testing of the final prototype demonstrated that the VIPER was able to remove the majority of powder from printed parts, though powder removal was much more effective when the user would intermittently stop the cycle and tap the part using a mallet. The following document summarizes the background research conducted, design and analysis process, final design direction, manufacturing, assembly, testing procedures and results, lessons learned, and future recommendations.
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1. Introduction

Lawrence Livermore National Laboratory (LLNL) is a federal design agency currently interested in improving their metals additive manufacturing capability, specifically for Powder Bed Fusion. After a metal part is printed, excess powder must be cleaned off the part before it can be heat treated without causing damage and safety concerns. Removing the powder is a labor intensive and time consuming process. The designs that are printed by LLNL are often one off parts which have complex geometries that trap powder in hard to reach spaces, and if the powder is not fully removed, it could potentially damage the heat treatment furnace. LLNL is seeking to improve the efficiency of powder removal, which will save a significant amount of time in the overall additive manufacturing process. Last year, LLNL sponsored a senior project with the goal of developing a system that would facilitate the powder removal process. The device created, VIPER, was mostly successful. However, it lacks a system to isolate the removed powder from the user and surroundings, creating a potentially hazardous work environment. The goal of this project team is to improve upon the current device by developing a way to safely contain the excess powder and to explore automation of the process in order to further reduce the time and labor, and increase reliability of powder removal. The project team consists of Cal Poly mechanical engineering students Andrew Epperson, Melissa O’Neil, Sean McCracken, and Alex Ward. The team has completed building and testing the confirmation prototype. This document serves as the final design review for the project. It includes background information, objectives, specifications, design evaluations, final design descriptions, manufacturing and assembly details, design verification plans, test results, and the overall project management plan, and future recommendations.

2. Background

In order to understand the nature of the problem, investigate potential solutions, and analyze competing products, we performed background research. This background research is summarized in the following sections.

2.1 General Metal Powder Bed Fusion

Powder bed fusion is the additive manufacturing process of using fine metal powder and a high intensity beam to melt layers of metal to result in a three-dimensional part with complex geometries of support structure underneath locations of the part that would otherwise have no material underneath them. The use of support structures can also can relieve high stress points in 3D printed parts, and mitigate distortion by acting as a heatsink [1].

Currently there are three main types of powder bed fusion additive manufacturing processes: Selective Laser Sintering (SLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM). These different printing methods use primarily the same process of selectively heating metal powder to form 3D structures, but the difference lies in how the metal is actually melted. In SLS, the laser only heats the metal powder to slightly below melting, causing the particles to stick to each other. In SLM, the metal is completely melted and the parts are usually stronger, denser, and have fewer voids. The EBM process is similar to the SLM process in that it melts the powder fully, but EBM uses a high intensity electron beam instead of a laser [2]. All three processes are subject to powder traps, or locations where unmelted powder remains in the printed part after the build process. These traps can exist in the support structure, lattice-like part geometry, and internal part features.
2.2 Customer Interviews
In order to understand what problems LLNL wants us to solve with our solution, we had numerous discussions with LLNL engineers, lab managers, and technicians, including a tour with Irene Yee, Keiran Hansen, Thomas Pluschkell, Andrew Furmidge, Steve Burke, and Jonathan Butler. These discussions allowed us to gain an understanding of the current cleaning process used at LLNL, as well as develop the wants/needs list that is discussed in section 4.3 of this report. The current cleaning process is as follows:

1. Additive manufacturing technician puts on appropriate Personal Protection Equipment (PPE).
2. Technician opens powder bed fusion machine.
3. Technician manually shakes the part to remove powder.
4. Technician removes part from powder bed fusion machine and places it on a tray.
5. Technician fastens custom made rods to build plate that create a cube of support around the part so that it can be placed upside down without resting on the part itself.
6. Technician manually removes outer skin on support structure and removes bulk of powder by tapping build plate with rubber mallet.
7. The part is put into a queue for ultrasonic cleaning, which is located at another location at LLNL.
8. The part is shaken and inspected by the heat treatment technician to verify that all powder has been removed. If it passes this inspection it will proceed to be heat treated.

The goal of our project is to replace step 7 of this process, ultrasonic cleaning. This step is currently a major bottleneck as it takes 1 to 1.5 days at a minimum, or longer if there is a queue. Our solution could also potentially provide a workspace to perform steps 4, 5, and 6, and the confidence to not have to perform step 8.

2.3 Material Safety
It is important that our device does not allow the 316L Stainless Steel (316L SS) powder it is removing from parts to escape to the air. US Research Nanomaterials, a vendor of 316L SS powder provides a Safety Data Sheet (SDS) for the material. The SDS states that users of the powder should avoid contact with skin and eyes, and avoid formation of dust and aerosols [3]. The stainless steel powder 316 may cause sensitization by skin and eye contact, and can ignite if it is suspended in the air. It is critical that we contain the powder so that users of our device do not experience negative health effects. Other, more dangerous metals are also used in 3D printing, such as titanium, tungsten, and uranium. Therefore, the containment aspect of our device is important not only for mitigating the risks of 316L SS powder, but also allows the design to more easily evolve in the future to handle parts made from these hazardous metals.

2.4 Automation Research
The team is considering methods of automation in order to minimize manual labor in the powder removal process. Automated industrial systems are structured as a hierarchy, as shown in Figure 2.1.
The information level manages the entire process, and includes production planning and commercial analysis. The supervisory control level monitors the system and provides the human machine interface. For this project, we are mainly concerned with the control and field levels, since the process is small scale and designed to be used on only one part at a time. For smaller control system configurations, programmable logic controllers (PLC) can be used as the primary controller. PLCs are the most widely used industrial controller, and are capable of providing closed-loop control without direct human involvement. They contain a user-programmable memory, allowing the operator to program various functions such as I/O control, timing, Position Integral Derivative (PID) control, arithmetic, and data and file processing [5]. One potential alternative to PLCs would be using an Arduino/Pi system with a shield adapted for use in industrial environments. Such shields are sold by the company Rugged Circuits.

2.5 Existing Products
In order to develop a benchmark for our device and inspire potential solutions, we performed research of existing products. These products included the 2017/2018 senior project as well as industrial solutions. Out research is described in the following sections.

2.5.1 Senior Project 2017/2018
At California Polytechnic State University, a senior project team previously partnered with LLNL during the 2017-2018 school year to design a solution for stainless steel powders [6]. They developed a system called the Vibration Induced Powder Evacuator and Reclaimer (VIPER) as shown in Figure 2.2. To use this system, a printed part is attached by the build plate to a mount with two rotational degrees of freedom. This system allows a user to manually orient the part to drain the powder downward and work the powder through internal passages using handles. The orientation is secured with a spring loaded pin. A vibrational motor inside the canister is then powered to excite the part and shake off excess powder, allowing gravity to carry the freed powder downward.
While their work provides an excellent framework on which to build, the team was unable to perform system level testing after manufacturing and construction of the prototype. Some tests were completed with the vibration motor, indicating that vibration is a valid method of powder removal. Our team plans to perform benchmark testing on this prototype to verify the continuation of this method of powder removal. The team behind this prototype were also unable to address LLNL’s wants relating to a method of powder containment, and process automation, which our team will focus on developing. Should the team decide to retrofit the existing VIPER system, we must also review the design safety factors associated with adjusted loading.

2.5.2 Solukon
In November 2017, the German company Solukon released a series of machines to aid in the removal of metal powder that are similar to the VIPER. These machines are capable of automated removal of metal powder from a part with the use of rotation along two axis and with a variable frequency vibration motor. These machines also can be configured to support inert gas chamber infusion when working with reactive metal powders. The largest model allows a maximum part size of 800 x 400 x 550 mm and a maximum part capacity of 300 kg [7]. While this is a very promising new solution, it falls short of some of our sponsor’s needs. Firstly, the machine has a very large required installation space. Secondly, the device is over $100,000, not including additional hardware and engineering to convert the European power system to US standards. It will also pose a problem for a university program interested in metal AM processes due to its prohibitive cost and large size.

2.5.3 Ultrasonic Cleaning
The method that is currently being used by LLNL to remove powder from their parts is ultrasonic cleaning. Ultrasonic cleaning uses ultrasound passing through an appropriate cleaning solvent to clean items. The ultrasonic waves cause cavitation (the formation of bubbles) that collapse and knock powder and debris loose from the part. The use of ultrasonic cleaning is widespread, but the actual mechanics of how the cavitation and bubble collapse removes material is less understood. Maisonhaute performed research in order to create models that demonstrate how surface conditions affect cavitation.
Maisonhaute’s article on surface acoustic cavitation investigates the shear stresses taking place during the cavitation and how it affects debris removal [8]. A downside of ultrasonic cleaning is that it does not allow for the powder to be reused.

Dry sonication is another method of removing metal powder from parts manufactured using electron and laser beam melting processes. Engineers at the University of Texas at El Paso proposed this powder removal process for reticulated mesh arrays [9]. Dry sonication is similar to ultrasonic cleaning in that it is a process that involves applying sound energy to agitate particles in a part; however, it is done without the part being submerged in a liquid. Since the powder is not exposed to a liquid, it can still be reclaimed for reuse.

### 2.5.4 CO2 Centrifugal Cleaning

Cool Clean Technologies’ Enertia: Centrifugal Immersion CO2 Cleaning System is a solution currently on the market for cleaning debris from complex geometries of parts, both printed and machined. The Enertia is designed to be implemented as an alternative to ultrasonic cleaning and other liquid submersion techniques. The Enertia submerges the part that needs to be cleaned in liquid CO2 and spins it rapidly. The CO2 and centrifugal forces drive debris off the part without damaging the surface. Liquid CO2 has very low viscosity, and can therefore get into small, complex geometries and break away debris. Since parts produced with additive manufacturing have many small and complex geometries, this type of solution may be used to draw inspiration for this project’s powder removal process [10]. A downside of this method is that it would make it difficult or impossible to reuse the powder.

### 2.5.5 Vibration Table

Vibration tables can be used as tools to help remove powder from printed parts. Mechanical vibrations help powder flow through drain holes in the part. Thus, a simple method to remove powder would be to place parts on a vibrating table. Vibration tables, however, are not designed specifically to accommodate metal powder, or to allow reorienting the part. Thus, using a vibration table on its own to clean parts presents challenges in cleanliness and safety.

### 2.5.6 Relevant Patents Table

Table 2.1 includes information regarding relevant patents. These patents encompass more products and processes that could be used for powder removal.
Table 2.1. Relevant Patents with Titles and Descriptions.

<table>
<thead>
<tr>
<th>Patent</th>
<th>Title and Description</th>
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<tr>
<td>9773586</td>
<td>Powered removal for element formed by electron beam melting. Karlen, et al. This patent describes a process of printing a wire inside the part that can be used to break up material in passages for removal. This could be one way to aid powder removal during the actual printing process.</td>
</tr>
<tr>
<td>9254535</td>
<td>Apparatuses, systems and methods for three-dimensional printing. Buller, et al. This patent explains a process for three-dimensional printing that could help reduce or eliminate the need for auxiliary supports. It also describes a number of different ways that powder could be removed, such as using vacuums, magnetic forces, electromagnetic forces, electrical forces, or physical forces. All of these are potential solutions for this project.</td>
</tr>
<tr>
<td>7045738</td>
<td>Powder delivery system and method. Kovacevic, et al. In this patent, a system designed to dispense additive manufacturing powder is described. The patent also contains details about a vacuum powder removal system that could be considered in this design process.</td>
</tr>
<tr>
<td>9776376</td>
<td>Methods and apparatus for three-dimensional printed composites based on flattened substrate sheets. Swartz, et al. Another method for three-dimensional printing is considered, this time based upon layers of substrate. The method for powder removal mentioned in this patent is vibration, which is most likely the method we will use for our project.</td>
</tr>
<tr>
<td>9333541</td>
<td>Powder removal device of a medicine dispenser. Yasunaga, et al. This patent describes a novel medicine dispenser design strips powder adhered to tablets. This can be used as another example of how to potentially use vibration to remove particulate from an object.</td>
</tr>
</tbody>
</table>

The main takeaway from our patent research was that there are many ideas for solving this ubiquitous problem of unwanted powder clinging to objects. Methods ranging from vacuums, electromagnetic forces, and vibration are all viable options as a method of powder removal. The methods explored in our patent and other existing products research will help to inspire ideas during our ideation phases, and inform the viability of ideas.

3. Objectives
The following sections summarize the scope of our project. This includes the problem that our design solves as well as the specifications that our design will meet.

3.1 Problem Statement
Metal powder bed fusion processes use a laser or other heat source to melt layers of metal powder together to form a part. After the part is finished printing, it is important that excess powder that remains on and within the part be removed before heat treatment, as loose powder can severely damage the heat treatment furnace. Currently, the powder removal process is slow and labor intensive, since powder gets trapped within the complex geometries of the parts. Additive manufacturers need an automated way to safely and easily remove excess metal powder because it will reduce cost, improve cleanliness, and save time.

3.2 Boundary Diagram
Figure 3.1 depicts the solution space boundary that is within the scope of our project. It serves as a visual indicator of the current process, and defines the limits within which we can affect the process through our
design, which is within the powder removal step. Additionally, it shows the inputs and outputs of our system. The input to our system is a printed 316L stainless steel part on a 125 mm x 125 mm build plate with residual powder. The output of our system is the powder free part and build plate ready to safely undergo heat treatment.

![Figure 3.1. Boundary Diagram](image)

### 3.3 Customer Needs and Wants

Table 3.1 outlines the customers’ needs and wants for the project. This information was generated from conversations with Lawrence Livermore National Laboratory personnel about the project requirements. The requirements that LLNL provided for a powder removal device are listed under “needs,” while the specifications that are not strictly necessary are listed under “wants.” Our final product will certainly meet all of the “needs.” We will strive to meet the “wants” as well.

<table>
<thead>
<tr>
<th>Needs</th>
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<tr>
<td>Removes Powder</td>
<td>Powder is Reusable/Reclaimed</td>
</tr>
<tr>
<td>Fits on 4x6 footprint</td>
<td>Fits on 4x3 footprint</td>
</tr>
<tr>
<td>Isolates user from powder</td>
<td>Completes 30 runs without maintenance</td>
</tr>
<tr>
<td>Accommodates/Supports largest possible SLM 125 printed parts</td>
<td>Minimal Training to Operate</td>
</tr>
<tr>
<td>Compatible with 316L stainless steel powder</td>
<td>Automated cycle after part fastened</td>
</tr>
<tr>
<td>Does not damage part</td>
<td>Ergonomic</td>
</tr>
<tr>
<td>30 minutes of labor per part</td>
<td>Design/capability justifies cost</td>
</tr>
<tr>
<td>2.5 Hours total process time per part</td>
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<td>Safe to operate</td>
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3.4 Quality Function Deployment

To aid in the conversion of customer needs and wants to engineering specifications, the team employed the Quality Function Deployment (QFD) method. QFD is a structured method to turn customer wants and needs into specifications for a product that will perform better than any existing solutions. We developed a matrix to identify these relationships between customers, customer requirements, current products, engineering specifications, and target specification requirements. We drew on the customer needs and wants outlined in Table 2 as well as our research into existing products in Section 2.5 to produce the QFD matrix shown in Appendix A.

3.5 Specifications

Table 3.2 lays out the specifications that must be completed to meet the expectations of the team and LLNL of a successful project.

<table>
<thead>
<tr>
<th>Spec. #</th>
<th>Parameter Description</th>
<th>Requirement or Target</th>
<th>Tolerance</th>
<th>Risk</th>
<th>Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No Powder Released During “Shake Test”</td>
<td>No Visible</td>
<td>Max</td>
<td>L</td>
<td>T,I</td>
</tr>
<tr>
<td>2</td>
<td>Powder Recyclable</td>
<td>Pass</td>
<td>Min</td>
<td>L</td>
<td>I</td>
</tr>
<tr>
<td>3</td>
<td>Operator Time Required</td>
<td>&lt; 30 mins</td>
<td>Max</td>
<td>M</td>
<td>T,I</td>
</tr>
<tr>
<td>4</td>
<td>Quality Inspection for Part Damage</td>
<td>No Damage</td>
<td>Target</td>
<td>L</td>
<td>I</td>
</tr>
<tr>
<td>5</td>
<td>Weight Capacity</td>
<td>35 lb</td>
<td>Min</td>
<td>L</td>
<td>A,T</td>
</tr>
<tr>
<td>6</td>
<td>Operator Satisfaction Survey</td>
<td>8/10</td>
<td>Min</td>
<td>M</td>
<td>T</td>
</tr>
<tr>
<td>7</td>
<td>Maintenance Interval</td>
<td>&gt; 30 Cycles</td>
<td>Min</td>
<td>H</td>
<td>A</td>
</tr>
<tr>
<td>8</td>
<td>Floor Space Occupied</td>
<td>&lt; 4’x6’</td>
<td>Max</td>
<td>L</td>
<td>I</td>
</tr>
<tr>
<td>9</td>
<td>Total Process Time</td>
<td>&lt; 2.5 hrs</td>
<td>Max</td>
<td>L</td>
<td>T</td>
</tr>
<tr>
<td>10</td>
<td>Pinch Points</td>
<td>0</td>
<td>Max</td>
<td>L</td>
<td>I</td>
</tr>
<tr>
<td>11</td>
<td>No Powder Escaped</td>
<td>No Visible</td>
<td>Max</td>
<td>H</td>
<td>T,I</td>
</tr>
<tr>
<td>12</td>
<td>Compatible with SLM 125 Build Plate</td>
<td>Pass</td>
<td>Max</td>
<td>L</td>
<td>I</td>
</tr>
</tbody>
</table>

Risk: H = High  
M = Medium  
L = Low  
Compliance:  
A = Analysis  
T = Testing  
I = Inspection

Description of Specifications:

1. **No Powder Released During “Shake Test”** - The powder remaining is the powder that is left on or inside the part after the device has completed a cycle. This will be determined using the same method employed by the operators at LLNL, by shaking/tapping the printed part over a solid colored surface, such as black paper, on which any visible powder released can be seen.

2. **Powder Recyclable** - The powder is recyclable if our process of powder removal does not contaminate the powder in some way.

3. **Operator Time Required** - Operator time is simply the time required for the operator to setup or install the part to be cleaned and removing it after it has been cleaned.

4. **Quality Inspection for Part Damage** - We also wanted to make sure that our design didn’t damage the part as it removes the powder, so we included quality inspection for damage to satisfy that.
5. **Weight Capacity** - The weight capacity was chosen by LLNL as the maximum weight of a part that could be built on a SLM 125 Build Plate. This will mainly be determined by analysis of the size of the build plate and the max height the machine can print.

6. **Operator Satisfaction Survey** - As the operator will be using this device, we want to make sure that they are satisfied on how it functions and we will accomplish this with a survey for the operators to complete.

7. **Maintenance Interval** - The maintenance interval was determined by LLNL want for this to be a low maintenance part. This will be determined by the analysis of failure modes on structural weak points and replaceable parts.

8. **Floor Space Occupied** - The floor space occupied was specified by LLNL and by the Cal Poly IME lab that our final design will be used in. This will be determined by inspection of the design to measure the space it will occupy on the workbench.

9. **Total Process Time** - We want the removal of the powder to not hinder the development of parts, so we want to minimize the time required to fully remove all the powder so that the part can move on to heat treatment. This can only be found by simply testing our design and changing its operating cycle time.

10. **Pinch Points** - There should not be any pinch points on our design that are accessible by operators under normal operation. This will be determined by inspecting the design for them.

11. **No Powder Escaped** - The limiting of powder escaping from our device is very important, as it could cause health issues if inhaled or could risk an explosion if it forms a dust cloud. This will be determined by testing our design over a solid colored surface and using visual inspection for any escaped powder.

12. **Compatible with SLM 125 Build Plate** - Since our 3D printer is only able to use a SLM 125 Build Plate, we must fit our own design to this standard. This can be determined by inspection if the plate fits into our design.

### 4. Concept Design

The following section describes the chosen design direction and the process used to select this design.

#### 4.1 Concept Development Process

The design process began with functional decomposition, in which the team identified four major functions that the product should perform. The four functions are:

1. Isolate powder from user and environment
2. Remove powder
3. Secure part to powder removal device
4. Orient part

The team held targeted ideation sessions that focused on each identified function. In the ideation sessions, the team members suggested and recorded ideas for potential designs. These sessions generated over 100 ideas total. The full idea list can be found in Appendix B.

The team also created concept models of some of the initial ideas. The concept modeling sessions allowed the team to work with the VIPER 1.0 and assess how each idea would interface with a similar device.
4.2 Concept Selection Process
After ideation and concept modeling, the team evaluated and deselected ideas which were unfeasible or out of scope. The remaining ideas were further evaluated in a series of Pugh matrices as shown in Appendix C, to determine which ideas merited further evaluation in a weighted decision matrix. A weighted decision matrix was created for each function as shown in Appendix D, yielding the potential designs and considerations discussed below in further detail.

4.2.1 Powder Isolation
The team evaluated the three top ideas for a powder isolation system are shown in Figure 4.2:

Figure 4.2. Sketches of concepts for isolating powder from user.
A. Enclosure around part only
B. Enclosure with sliding tray
C. Enclosure with funnel

Figure 4.2.A shows a small enclosure that will fit over the part only. It would be secured to the VIPER by the user prior to operation. The part-only enclosure requires little additional space from the VIPER, and
will meet the footprint requirements. However, since the enclosure will be vibrating and rotating with the part, there is a risk of the removed powder falling back onto the part.

Figure 4.2.B shows a larger enclosure that encompasses the entire VIPER device. It has a removable tray at the bottom to collect the loose powder. This design is more user friendly than the part-only enclosure, since it does not require the operator to mount the enclosure on the part.

Figure 4.2.C shows an enclosure that covers the part and motor assembly with a funnel that collects the removed powder. Out of the three powder isolation designs, this one was the most simple and most ergonomic, and was thus chosen as the design the team will pursue.

4.2.2 Powder Removal Method
While other methods were considered, the use of vibration stood out as a desirable design path in our initial concept evaluations. The 2017/2018 Senior Project team used vibration for removing powder at a fixed position. The part can be oriented manually using two different axes of rotation to an optimal position for powder removal. During the vibration cycle, the orientation of the part remains fixed. The current team evaluated this method of powder removal against vibration with continuous reorientation of the part.

The fixed orientation method is the most simple design, and is already being used in the current VIPER device. However, adding continuous, automatic turning of the axes will allow the part to be cycled through various orientations during vibration, which can be more effective in removing powder, as well as significantly reducing operator effort. The team chose this concept as the proposed design.

4.2.3 Build Plate Mounting
The design that was formulated by the previous Senior Project team to secure the build plate incorporated a metal drum and two flanges attached at the top. These two flanges have through holes which the operator uses to manually secure the part with nuts and bolts each time. These fasteners were also not attached to the device, making it easy to lose these small parts when removing the plate.

The group focused on a quicker and more ergonomic design for attaching the build plate to the device. After the processes of idea generation and idea refinement, the team evaluated the three top ideas for a build plate mounting system shown in Figure 4.3:
Figure 4.3. Sketches of concepts for mounting build plate on device.

A. Holding part with vice grip
B. Holding part with spring loaded buttons
C. Holding part with permanent threaded rods

Figure 4.3.A shows how the vice grip will secure the build plate to the device. This design would minimize the complexity of the mounting system, be more ergonomic, and require relatively little operator effort to secure the part. However, the design would be quite bulky and would significantly increase the mass of the rotating body. This alteration of the center of mass would cause a greater strain on the system. Additionally, the gradual loosening of the grip when subjected to vibrations would be a significant safety concern.

Figure 4.3.B shows the way a build plate would be attached with the spring loaded latching method. The user would push the build plate downward, causing separation of the latches until the top build plate surface surpassed the latch edge. This design would decrease the amount of work involved with mounting the build plate to the device. Unfortunately, there would be a large problem with powder filling the cavities that the latches would be depressed into. Additionally, the custom latches and mechanical complexity needed for a powder proof release mechanism led to concerns about manufacturability.

Figure 4.3.C shows the way the build plate would be attached with permanent threaded rods. These rods would both locate the part during installation, and provide threads on which to tighten nuts to secure the part. This was chosen from the three of the designs since it was simple to implement, yet a significant improvement to operator time and ergonomics. Due to the nature of 3D printing steel, the individual build plates will have to be ground down to have a clean surface before another part can be printed. With that in mind, the choice is narrowed down to this design due to that not ever being a problem with the fasteners due to the ability of fastening each build plate to the individual thickness.

4.2.4 Printed Part Orienting
The design that the 2017/2018 Senior Project team incorporated for orienting the part is entirely manual. It consists of handles that can be used to rotate the part on two axes, and locking pins that can be used to fix the part once the desired orientation is reached.

After performing ideation and using Pugh matrices to compare ideas, the three ideas shown in Figure 4.4 remained:
Figure 4.4. Sketches of Concepts for Orienting Printed Part
A. Drivers on both axes (automated cycle)
B. Drivers on both axes (user controlled)
C. Driver on one axis, other axis driven by gear(s)

Figure 4.4.A shows a concept for placing drivers on both axes and having them rotate based on a programmed automated cycle. This cycle would be designed to ensure that the part is rotated to all orientations necessary to drain powder from the part. For this reason, this design would have the most complex software requirements but it would also have the most reliable results. To implement this design on the current device it would first be necessary to replace the handles on the device with motors or another type of driver. We would then need to run wires from the motors to a controller that runs the automated cycle.

Figure 4.4.B shows a concept for placing drivers on both axes and having them be controlled by an operator. The drivers would be placed where the handles currently are. These drivers would be controlled using a user interface. It would be simpler to program a device of this nature than it would to program an automated cycle. However, this design would require more labor time since the user would need to be present during the entire cleaning process. Additionally, this concept would lead to less consistent results since it relies on the user’s ability to orient the part appropriately.

Figure 4.4.C shows a concept for rotating the horizontal axis with a motor and rotating the other axis with a bevel gear. The motor would either continuously rotate or rotate based on a cycle we specify. This design has the advantage of using one motor instead of two. However, it has several disadvantages. It would be difficult to design and manufacture the gears for this system. Additionally, it is likely that this system would be less effective at orienting the part to the positions we require since the axes can not be rotated independently.

Using decision matrices, we ultimately moved forward with placing drivers on both axes and automating the cycle. This method will have a shorter labor time required to clean each printed part, and will lead to more consistent results than the other two ideas.

4.3 Selected Concepts
Figure 4.5 shows a concept CAD model of the team’s preliminary design. The proposed design incorporates the new concepts with the current VIPER. The VIPER will be fitted with an enclosure, new
build plate mounting mechanism, motors to drive the axes, a vibration motor mounted to an adapter plate below the part, and a user interface to control the motors.

![Concept CAD Model of Our Preliminary Design](image)

**Figure 4.5. Concept CAD Model of Our Preliminary Design**

### 4.3.1 Powder Isolation

The selected powder isolation system is a sealed enclosure that will keep dust from escaping, which has doors to allow the user to access the part. The enclosure will attach to the VIPER frame and cover the part/motor assembly. The freed powder will be collected in a funnel at the bottom of the enclosure, allowing the operator to transfer the powder to another container to be recycled. Figure 4.6 shows the concept prototype of the enclosure fitted around the current VIPER design.

![Enclosure with Funnel Concept Prototype](image)

**Figure 4.6 Enclosure with Funnel Concept Prototype**
4.3.2 Powder Removal Method
The chosen powder removal method is continuous vibration with continuous reorientation. This design can easily leverage the current VIPER device, since it is already equipped with a vibration motor and two rotational axes.

4.3.3 Build Plate Mounting
The design that was chosen to mount the build plate was the permanent threaded rods. This was chosen due to its simplicity, robustness, and build plate compatibility.

4.3.4 Printed Part Orienting
The chosen part orientation method is drivers on both axes (automated cycle). Figure 4.5 shows how this concept can be incorporated into our device. In the figure, the handles and locking pins are removed and replaced with stepper motors that have built in drivers and controllers. A user interface that can be used to select and start cycles will be mounted on the enclosure.

4.4 Preliminary Analysis and Testing
The analysis, testing, and observations of the 2017/2018 senior project group helped to guide our design process. We made an effort to design systems that could potentially be compatible with the device that they designed. We also used their analysis and testing to inform the design directions we would take. For example, the 2017/2018 senior project performed calculations to determine loading that would be seen by various components in the VIPER device. These calculations serve as a preliminary check for the feasibility of ideas such as incorporating motors in the system. The 2017/2018 group also performed testing of vibration as a method of powder removal. Though the scope of their testing was limited, it did show that vibration using the vibration motor they selected was effective at removing powder from parts. We performed our own test of the full device to validate the previous design, as described in Section 4.4.1.

Concept modeling and prototyping was helpful in analyzing our design ideas. Preliminary concepts were modeled using basic materials, which assisted in the visualization of how the system’s components would fit together and function. It was particularly helpful to build full scale prototypes and examine how they would fit with the VIPER device built by the 2017/2018 senior project group. Early prototyping as well as working with the VIPER device hands-on helped us to discover flaws and areas for improvement. For example, we determined that using hand cranks and locking pins to orient the device is cumbersome. This observation led us to considering installing motors on the device. Additionally, we determined that the current method of mounting build plates on the device is awkward. This led us to evaluate alternative methods for securing build plates on the device.

4.4.1 Testing 2017/2018 VIPER Design
After PDR, we were able to perform a test of the 2017/2018 VIPER assembly. The results of the test show that vibration is still a feasible method of removing powder, but a stronger vibration motor is needed. The testing procedure we used is as follows:
1. Measure the mass of the pre-vibrated part for a baseline datum
2. Measure the mass of a powder collection device
3. Attached part and the powder collection device
4. Orient the part to a predefined angle
5. Vibrate the part for a predefined amount of time
6. After the time has elapsed, the collection device is detached from the device and its mass is measured. The original mass of the collection device is subtracted from the total mass to get the removed powder’s mass.
7. This process is then repeated until no powder is seen leaving the part
8. Once no powder is being removed with the vibration, we physically hit the part to see if any powder remains.

The results of the test are shown in Figure 4.7. The total mass of powder removed from the test part is 18g. The majority of powder was removed during the first 5 seconds of vibration. At 60 seconds, the part was reoriented. This allowed more powder to be removed.

![Figure 4.7. Mass of powder removed over time.]

When no additional powder was being removed from the vibrations, we removed the part from the device and performed a shake test. The shake test showed that there was still a significant amount of powder remaining in the part. One reason for this is that the vibration motor did not provide sufficient shaking force to effectively remove all powder. Also, the vibrations were not isolated to the part. We observed the entire frame rattling when the motor was turned on. Based on these results, we determined that we need a better vibration isolation system, as well as a motor that can provide a greater vibration amplitude, preferably one with variable frequencies so that we can test the effects of a range of frequencies.

4.5 Risks and Challenges

While the team has identified the proposed design direction as the best path towards answering the problem statement, a number of risks and challenges have also been identified. These risks and challenges, along with ways to mitigate them, are described in the following sections and in the Safety Hazard Checklist in Appendix E.
4.5.1 Fine Powder is Conductive and Abrasive
One of the challenges we will have to overcome is ensuring that the motors and other components will be protected from exposure to the metal powder. Our proposed design direction includes motors inside the enclosure, exposing rotating mechanical parts to fine powder. This can cause abrasive wear. Additionally, the metallic powder could cause electrical shorts if it comes into contact with any electronics. In order to mitigate this, our design should protect components from these negative effects.

4.5.2 Vibration Effects on Structures and Fasteners
Another problem that will have to be addressed is the effects of continuous vibration, particularly on fasteners. Vibration can cause bolts and other fasteners to loosen and eventually come off if not properly maintained or tightened. Since our process could have an extended run time, it is reasonable to assume that the build plate might loosen to the point of falling off and damaging the part if not designed properly. The previous senior project team addressed this problem by determining a standard torque value to attach the fasteners. Our team has performed some preliminary research on vibration resistant fasteners, such as those made by HUCK 360. As we move further along with our design, we will continue research in vibration isolation and damping to improve upon the life and effectiveness of the fasteners.

4.5.3 Delivering Power Through Moving Stages
The final challenge that we will have to overcome is powering a motor through a rotating stage. This is a challenge due to the wires used to power the rotating motor will wrap around the shafts if not properly constructed. Thanks to a recommendation from our advisor, we are now researching a slip ring, which is a device that allows the transmission of power from a stationary to a rotating structure.

4.5.4 PLC Integration
When discussing the automation of our device with our sponsors, they encouraged us to work with PLC’s or a similar controller to ensure a robust and professional design. Our team is inexperienced with PLC’s and their programming which will be a challenge.

5. Final Design
Based on testing of the current prototype and suggestions from our PDR, we updated the design described in Section 4. The final design that was chosen by our team incorporates an automated process that uses vibration to remove stainless steel powder from 3D printed parts. A depiction of our final design is shown in Figure 5.1. All of our drawings can be found in Appendix F and all parts are listed in our BOM in Appendix G.
The following sections elaborate on the mechanical components, power delivery, and automation details of our final design.

5.1 Mechanical Design
The system’s mechanical design components include the enclosure, the printed part mounting and vibration system, and the motors and couplings.

5.1.1 Enclosure
The final design of the enclosure is shown in Figure 5.2. The sheet metal enclosure will attach to the inside of the existing 80/20 frame using fasteners with sealing washers. The main shaft will pass through the holes shown on the sides with shaft seals pressed against the enclosure walls. Wires to power the motors will enter the enclosure via strain relief grommets. The enclosure was originally designed to include two access doors for ease of maintenance. However, due to manufacturing issues, the final product includes only one door at the front and a window at the back. The door and window will be lined with nitrile seals and will be held shut with tight-hold draw latches to ensure proper sealing during operation. The bottom of the enclosure has a funnel shape sloped at 45 degrees to capture the removed powder. A container with sealing material on its edge will clip on to the bottom of the funnel to collect the powder. To ensure that no loose powder escapes during operation, all seams are to be welded.
5.1.2 Mounting System

Our testing of the last team’s prototype showed the previous mounting design was time consuming and awkward for the user, as well as ineffective at isolating vibrations. Our design, as shown in Figure 5.3, improves upon the user experience and vibration isolation.

To simplify the mounting process, we designed an adapter plate that allows the vibration motor to be permanently mounted to the device, as opposed to being removed each time as in the previous design. This plate includes an inset outline of the build plate to aid the user in locating the mounting holes.
between the build plate and adapter plate. This allows the operator to simply place the part, insert fasteners, and tighten them into tapped holes in the adapter plate.

The previous design attempted to isolate vibrations by compressing a damping material between the build plate brackets and a structural canister. Our testing indicated that since the fasteners were still making rigid contact between the build plate and structure, vibrations were being transmitted to the entire structure, making them less effective at removing powder. In order to improve the vibration isolation, we chose a vibration isolator that is classified as a universal mount design. This mount does not allow for any metal to metal contact between the plates, and should isolate the vibration much more effectively. In combination these mounts will be able to support the weight of the adapter plate and printed part.

To ensure our redesigned mounting system could still support the expected loads, the design for the U-channel was analyzed using hand calculations and FEA as shown in Figure 5.4. These calculations can be found in Appendix H. In the FEA the holes for the fasteners at the bottom were treated as pins and the bottom face was treated as a roller. A 35 pound load was split between the two fasteners at the top. This load was chosen because it is the load of the parts these U-channels will support. All of the load was conservatively placed on one U-channel, even though the mounting system will include two. The part was analyzed with the load pointed in all possible orthogonal directions. The factors of safety yielded by this analysis were very high.

![Figure 5.4.FEA Analysis of Mounting System U-Channel](image)

Hand calculations were performed to check the factor of safety of the U-Channel. These calculations can be found in Appendix H. The U-Channel was analyzed in both a cantilever and axial loading configuration. The cantilever configuration proved to be more critical with a factor of safety of 3.6. In the axial loading configuration the factor of safety was 40. The bearing factor of safety of the U-Channel’s fasteners was also checked. For this analysis it was assumed that one fastener was bearing the entire 35 lb load the system was designed to withstand. The bearing factor of safety was calculated to be 28.
5.1.3 Vibration Motor
Our testing of the original design also indicated that the previously selected vibration motor with a nominal frequency of 48.33 Hz and a force of 8 lbf was insufficient to remove all the powder from the part. In addition to improving vibration isolation, our design includes a variable (0-120Hz) DC motor, as shown in Figure 5.5. It is capable of 3.4 times the vibration force supplied by the previous team’s motor. This variable frequency will allow us to either identify the frequency which causes an ideal acceleration (63-224 m²/s) for our system, or to program a frequency sweep through which to subject each printed part during a cycle [11].

![Image 5.5. The Selected DC Vibration Motor from Precision Microdrives [12].](image)

Since the vibration motor is not rated for exposure to dust, we plan to cover it with a 3-D printed dust cover which will fasten onto the adapter plate. The vibration motor wires will penetrate the enclosure via strain relief grommets. The mounting system with the vibration motor cover is shown in Figure 5.6.

![Image 5.6. Mounting system with Vibration Motor Cover](image)
5.1.4 Motors and Couplings
Each axis of rotation will be driven by a stepper motor, as shown in Figure 5.7.

![Driver Motors Attached to the Current Frame](image)

The motors will mount to the current assembly using custom brackets. Detailed drawings of the brackets can be found in Appendix F. Each motor was selected based on the torque and speed requirements of each axis. The torque required to accelerate to the primary axis to 6 rpm in 2 seconds while loaded with the maximum theoretical part size was found to be 524 oz-in, while the secondary axis was found to be 26 oz-in. Detailed calculations are included in Appendix I. The specific motors were selected based on the guideline that the load on a stepper motor should require between 30%-70% of the torque the motor can produce [13].

The primary axis mounting bracket will attach directly to the 80/20 frame as shown in Figure 5.8. The minimum factor of safety of the bracket was calculated to be 3.5. This calculation accounted for the torque applied by the motor and the static weight of the motor. These calculations can be found in Appendix H. FEA was also performed on the primary axis mounting bracket using the same loading conditions. This analysis yielded a factor of safety of 9.9, which is low than what was found with hand calculations. We will reuse the primary axis shaft. The primary axis shaft was designed by the 2017/2018 group to have a factor of safety of 2.8. This factor of safety was based on sizing for a 534 lb-in bending moment. With maximum part weight the shaft will experience a smaller bending moment than this so this shaft will work effectively. We will also reuse the primary axis bearings. They have a factor of safety of 87 based on their load rating and the load they will experience. The motors will transmit torque to the
shafts using couplings. The primary axis motor attaches to the main shaft with a clamping precision flexible shaft coupling. This coupling clamps around the shafts without the need for a set screw. This allows for easy installation to the existing shaft without the need for modifications. The primary axis coupling has a factor of safety of 2.4 based on the coupling’s rated torque. The primary axis coupling is shown in Figure 5.8.

![Figure 5.8. Primary Axis Coupling.](image)

The secondary axis motor will be mounted using two Z-shaped brackets. These brackets have a minimum factor of safety of 23. This factor of safety was based on a loading condition in which the motor is exerting torque and the axis is oriented in a cantilever orientation. FEA performed with the same loading condition yielded a factor of safety of 34. We will reuse the same secondary axis shaft, which was designed to have a factor of safety of 2.24. This factor of safety again is based a bending moment of 534 lb-in, which is less than the shaft will actually experience with max part weight. Additionally, the secondary axis torque is about the same as it was in the previous design so this shaft should be effective. We will also reuse the secondary axis bearing. It is a double bearing, which makes it suited for taking moment load. The factor of safety of the secondary bearing was calculated to be 1.7. This was done using the same 534 lb-in bending moment used by the previous group. The secondary axis uses a set screw flexible shaft coupling as shown in Figure 5.9. This coupling has a factor of safety of 14 based on its rated torque. In order to attach to the coupling, the secondary axis shaft on the current model must be extended. This will be done using a modified spacer and screw that threads into a tapped hole in the current shaft. The spacer will be held in place by a lock washer.
5.2 Power Delivery
Originally, power was to be delivered to the secondary and vibration motors via pancake slip rings. However, we were unable to find slip rings that fit in the system and met the IP6X requirements that could be delivered within our time frame. The final design uses wires that go through the enclosure and directly into the motors instead of the slip rings. The wires are routed through cable glands that keep the enclosure sealed and the wires in place. Also, we added plastic clamps in the base plate and enclosure to route the wires to reduce the risk of getting tangled while the system rotates. Each axis rotation is now limited to <360° to avoid tangling the wires.

5.3 Automation
In order to satisfy our system’s specifications for minimal operator time, our design includes a PLC controller to automate the cycle. A schematic of the proposed control system is shown in Figure 5.10, with each component discussed in further detail below. Details on the exact part numbers and suppliers can be found in the indented BOM found in Appendix G.
5.3.1 Programmable Logic Controller

The controller selected for our system is the Do-More H2 PLC. This controller was selected since it has modules with the proper I/O ports to communicate and send signals to both the stepper and vibration motor drivers. Additionally, common implementations of the PLC are well documented online with video tutorials for programming, which will be very helpful during programming. The selected PLC base and modules are shown in Figures 5.11 and 5.12 respectively.
5.3.2 Stepper Motor Drivers

The motor drivers for the stepper motors were selected for their compatibility with the voltage and amperage requirements for our stepper motors. Additionally, their advanced drive features such as anti-resonance electronic damping and torque ripple smoothing should ensure even control of our stages, and minimize motor slipping. This is particularly important since our stepper motors will be operating under open loop control under the assumption of no slipping. Finally, the SureStep stepper motors shown in Figure 5.13, have online documentation and videos to help set them up with the Do-More H2 PLC.

5.3.3 Vibration Motor Driver and Voltage Regulator

The DC driver for the vibration motor, shown in Figure 5.14, was chosen as it could control the vibration motor speed using pulse width modulation (PWM). A 0-10V signal from the PLC’s analog output determines the PWM percentage in order to supply a varying voltage between 0-Vin, where Vin is the voltage supplied to the motor driver.
Since our vibration motor can run at up to 24V, voltage regulator shown in Figure 5.15 was selected, which takes the 48V supplied by the DC power supply and converts it to 24V.

**5.3.4 DC Power Supply**

To supply the 48V DC power required for the stepper motors, the power supply shown in Figure 5.16 was selected. It will take the 120 VAC input from the wall and convert it to 48V for use by the motor drivers.

**5.3.5 Human Machine Interface**

As part of our control system, the user will need to be able to see system status, start/stop cycles, adjust cycle parameters, and jog system axis. This user input will be supplied through the human machine interface (HMI) panel and expansion bezel shown in Figures 5.17 and 5.18 respectively. These panels were selected as they have sufficient user input buttons, and there is documentation on how to set them up with the selected PLC.
In addition to the user inputs to the automation system under standard operation, an additional input in the form of an emergency stop button was selected to cut off power to the motors in case of an emergency. The selected switch is shown in Figure 5.19.

5.3.6 Limit Switches
The home location of each axis will be set using limit switches. The first stage limit switch is mounted on the enclosure wall as shown in Figure 5.20. The second stage limit switch is mounted on the U-Block base of the first stage as shown in Figure 5.21. The limit switches will be triggered by tabs attached to the shafts using shaft collars.
5.3.6 Electrical Enclosure
In order to mount all the electrical components and safely enclose them, the design includes an electrical enclosure. Originally, the enclosure was to be ordered from nVent Hoffman with custom cutouts to mount the electronics. However, due to time constraints, the enclosure design was changed to a polycarbonate box that we modify ourselves. The electronic components are mounted to a polycarbonate sheet, which is
then mounted inside the box. The box includes modifications to accommodate the HMI, E-stop, power cable, and mounting. The electrical enclosure is shown in Figure 5.22. Detailed drawings of the enclosure and mounting plate can be found in Appendix F.

Figure 5.22. The Electrical Enclosure Shown as Transparent with Internal Components and Attached to Complete System.

5.3.7 Programming

The PLC is programmed using ladder logic with Automation Direct’s Do More Designer software. The code is downloaded on the PLC, and can be accessed and edited by connecting a computer to the USB B port on the PLC. When a link is established between the PLC and computer, the Do More Designer software will prompt the user to download the program for editing. The full ladder logic code can also be found in Appendix J.

The ladder logic program follows a state/task structure. There are three tasks: primary axis motor, secondary axis motor, and vibration motor. The timing between the tasks is set to 1 ms.

Figure 5.23 shows the state transition diagram for the both the primary and secondary axis motors.
Below are brief descriptions of how each state functions.

- Start:
  - On initialization (first scan only), the total cycle time and the pause between movements in the cycle are set. The variables for elapsed cycle time, error flag, and cycle done flag are cleared.

- Stopped State:
  - This state stops the motors. It does so by sending an ASCII stop command to the motor drivers. It also clears error flag and elapsed time variable.

- Cycle Home State:
  - The program transitions to this state after the CYCLE GO button is pressed. Once a cycle is started, both axes return to home position before continuing.

- Cycle Wait State:
  - After one axis has homed, the motor will stop and wait for the other to home before continuing.

- First Turn State:
  - Once both axes are homed, the primary motor rotates 90° CCW. This is so that the part will rotate through an arc facing downwards toward the funnel during the cycle. The secondary axis waits until the primary has completed the turn before transitioning into the Cycle Left State. When the state is complete, it sets the VIBE READY flag, starting the vibration motor.

- Cycle Left State:
  - When the first turn is completed, the cycle begins. In this state, both motors rotate 180° CCW. For the primary motor, this state runs 15s before transitioning to the Cycle Right State. The secondary motor runs for 9s. This gives the motors time to complete the full move. This state also starts the cycle timer, which runs for 15 minutes.
- Cycle Right State:
  - After the motor finishes the CCW rotation, it switches direction and rotates 180° CW. For the primary motor, this state runs for 15s before transitioning back to the Cycle Left State. For the secondary motor, the motor jogs CW until it reaches the limit switch.

- Cycle Done State:
  - When the cycle timer is finished, both axes will stop all motion. This is to ensure that the current command in the motor drivers are cleared before finishing the cycle. Also, the cycle timer is reset.

- Done Home State:
  - After the drivers are cleared, both axes will return to their home positions. Once they reach home, the program transitions back to the Stop State.

- Jog Left State:
  - The program transitions to this state if the JOG LEFT button on the HMI is pressed. This state sends an ASCII jog CCW command to the corresponding motor driver as long as the button is pressed down. Once the JOG LEFT button is released, the program transitions to the Stop State.

- Jog Right State:
  - This state is similar to the Jog Left State. It sends an ASCII jog CW command to the corresponding motor driver when the JOG RIGHT button is pressed. It transitions to the Stop State if the limit switch is activated or the button is released.

- Homing State:
  - The program transitions to this state if any of the HOME buttons are pressed. It sends an ASCII jog CW command to the corresponding motor driver. The motors continue to move CW until the limit switch is activated or the STOP button is pressed.

Figure 5.24 shows the state transition diagram for the vibration motor task.

![State Transition Diagram for the Vibration Motor Task](image)
During the cycle, the vibration motor steps through 3 different frequencies. Currently, freq #1 is off, freq #2 is 50% of the maximum frequency, and freq #3 is the maximum frequency. Freq #1 runs for 1s while freq #2 and #3 run for 5s. Below are brief descriptions of each state.

- **Start:**
  - On initialization, the time between transitions and the three frequencies for the cycle are set.
- **Stop State:**
  - This state stops the motor by turning off the output to the motor.
- **Run Freq States:**
  - The program transitions into the Run Freq #1 state when the VIBE READY flag is set in the primary motor task. Each frequency state changes the frequency of the vibrations by adjusting the voltage supplied to the signal ports of the DC driver. The 3 freq states will transition among each other until the cycle finishes or the STOP button is pressed.
- **Manual Vibration State:**
  - This state will activate the vibration motor when not in a cycle. The frequency of vibration is controlled through the HMI, which allows the user to specify ten different levels of vibration.

### 5.4 Safety Considerations

The following section details the safety considerations taken when designing the project. Appendix K contains a full failure modes and effects analysis, which describes the likelihood and potential effects of component failures, as well as the preventative measures taken to minimize these risks.

Stainless steel powder is considered hazardous by the 2012 OSHA Hazard Communication Standard. Risks associated with the powder include flammability, skin irritation, and eye irritation [3]. One of the goals of this project is to ensure that powder is removed from printed parts safely without being exposed to the operator. To ensure the powder stays isolated from the user during operation, the enclosure is designed to be dust proof. All seams are to be fully welded and the doors and shaft ports are to be fitted with nitrile seals. Even so, care must be taken when opening the doors and handling the removed powder.

Another area of concern is the device’s electronics. The electrical system will have a maximum DC voltage of 48V and a maximum current draw of 10A. The maximum voltage is within the allowable range specified by the senior project safety guidelines. Since we are still working with relatively high voltages and currents, we plan on verifying the electrical design with an electrician to ensure that the system will be safe to construct and operate.

There are also various safety risks involved in operating the device. The device includes rotating machinery and fine stainless steel powder. The enclosure is designed to protect the user from the loose powder and moving components. However, as a precaution, the PLC system selected to control the system includes an emergency stop button. A detailed breakdown of all potential design hazards and planned corrective actions is included in Appendix L.
5.5 Cost Analysis
Table 5.1 shows a list of each subsystem and its cost. Detailed costs for each individual component can be found in the purchasing spreadsheet in Appendix M.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronics</td>
<td>$2598</td>
</tr>
<tr>
<td>Vibration and Mounting</td>
<td>$103</td>
</tr>
<tr>
<td>Main Structure and Stepper Motors</td>
<td>$1178</td>
</tr>
<tr>
<td>Enclosure</td>
<td>$1031</td>
</tr>
<tr>
<td>Fasteners incl. TECO 80/20 components</td>
<td>$390</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$5300</td>
</tr>
</tbody>
</table>

5.6 Maintenance and Repairs
Development of the maintenance schedule will occur as time allows after construction and testing of the concept prototype. Currently, the major area of concern is the vibration motor assembly. The vibration dampers are intended to isolate the rest of the structure from the vibrations. However, there are still fasteners and brackets that are not isolated. We plan on performing analytical calculations to estimate the part lifetimes under these conditions, so as to identify a safe maintenance schedule.

6. Manufacturing
The team purchased the majority of components for the final prototype off the shelf, but a few had to be built and manufactured through the Cal Poly machine shop. Engineering drawings of manufactured parts and assemblies can be seen in Appendix F and all parts are included in the Bill of Materials in Appendix G.

6.1 Enclosure
The enclosure was fabricated in the Cal Poly machine shops. Table 6.1 shows a list of all components in the enclosure assembly and the vendors from which they were purchased. Figure 6.1 shows the enclosure after the sheet metal components have been spot welded together before final welding.
Table 6.1. List of purchased enclosure components.

<table>
<thead>
<tr>
<th>Part</th>
<th>Vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 gauge A1008 steel sheet</td>
<td>OnlineMetals</td>
</tr>
<tr>
<td>Unfinished Brass Surface-Mount Hinge for door</td>
<td>McMaster-Carr</td>
</tr>
<tr>
<td>Buna-N Rubber Strip for door seal</td>
<td>McMaster-Carr</td>
</tr>
<tr>
<td>Shaft-Mounted Rotary Seal for shaft seal</td>
<td>McMaster-Carr</td>
</tr>
<tr>
<td>Static Dissipative Polycarbonate Sheet for window</td>
<td>McMaster-Carr</td>
</tr>
<tr>
<td>Tight-Hold Draw Latch for door</td>
<td>McMaster-Carr</td>
</tr>
<tr>
<td>Handle for door</td>
<td>McMaster-Carr</td>
</tr>
<tr>
<td>Fasteners</td>
<td>McMaster-Carr</td>
</tr>
<tr>
<td>Adhesive: 3M DP604NS</td>
<td>McMaster-Carr</td>
</tr>
<tr>
<td>Rust Preventative Paint</td>
<td>Amazon</td>
</tr>
</tbody>
</table>

Figure 6.1. Enclosure being spot welded in preparation for MIG welding.

The manufacturing process for the Enclosure is described below.

1. Use step shear to cut steel sheets to the specified dimensions (see Appendix F-EN01 - F-EN06 for detailed drawings).
2. Center punch to locate holes.
3. Use center punch and/or punch to add holes at specified locations
4. Use brake to bend sheets to shape.
5. Spot weld the enclosure together using MIG Welding (see Appendix F-EN06 for weld diagram).
6. Finish welds using MIG welding.
7. Clean and paint the welded enclosure to mitigate rusting.
8. Attach nitrile adhesive strips to enclosure.

Manufacturing the enclosure was very time consuming. The machine shops’ only usable sheet metal tools are all located at the hangar. This meant that we were only able to work on the sheet metal manufacturing half the time the machine shops were open. The actual process of cutting, bending, and making holes in the sheet metal was very labor intensive. The sheet metal was 16 gauge, and thus was very thick and heavy. This meant that considerable force had to be applied when using the step shear to cut the sheet metal and the brake to bend it. The sheet metal panels were also very large, making it difficult to drill and press holes.

Welding for the enclosure was performed by Kevin Williams. This was extremely helpful since it was such a big welding job. As part of welding, Kevin had to hammer some of the enclosures plates into position because the angles of their bends and their widths were not perfectly correct. It would have been easier to attain the dimensions we desired if an alternate manufacturing process such as water jet cutting was available to us.

![Image](image_url)

Figure 6.2. (a) Polishing enclosure for painting. (b) Sealing material being attached to enclosure.

The powder containment box (Appendix F-BX01 - F-BX03) was 3D printed in PLA using Alex’s personal printer. Each half of the box was printed separately and then attached together using epoxy putty.
A polycarbonate panel was attached using epoxy to the bottom for extra structural support. The box was then painted to prevent powder from entering the pores of the PLA.

The manufacturing process for the Door is described below.
1. Use horizontal band saw to cut aluminum bars to shape (Appendix F-FR01 - F-FR03)
2. Use ruler and center punch to locate holes.
3. Use drill-press to drill appropriate holes
4. Tap appropriate holes (Figure 6.3)
5. Fasten aluminum bars together using ¼’’-20 socket head screws to make door frame (Appendix F-FR)
6. Mount door on mill using a triangle step block. (Figure 6.4)
7. Use mill to flatten the side of the door if it is not sufficiently flat (Figure 6.4)
8. Cut polycarbonate sheet to size (Appendix F-EN05)
9. Attach polycarbonate window to door frame using 3M DP604NS adhesive and epoxy gun with mixing tips.
10. Install hinges to enclosure wall and door frame using #10-24 screws (Appendix F-EN)
11. Install tight hold draw latches to enclosure wall and door frame using #6-32 screws (Appendix F-EN)

Manufacturing the door was more difficult than we anticipated. The two doors that we manufactured consisted of four aluminum bars each. These bars were cut to length using a horizontal band saw. In total 56 holes had to be drilled for the doors and 40 of these holes had to be tapped. Because of the large amount of holes that had to be drilled and tapped, measures were taken to drill them quickly. Most of the holes were drilled on a drill press. An example of this is shown in Figure 6.3. After the holes were drilled and tapped, the door frame was assembled. There was some misalignment due to holes not being perfectly located. This led to the door face not being perfectly flat in some locations. We determined that the lack of flatness could potentially cause issues when the window was glued to the door frame and when the door came into contact with the sealing material. To flatten the door frame we used a mill. The door frame was mounted on the mill using a triangle step block as shown in Figure 6.4. Then the face was milled using an end mill. After this was done, the door face was sufficiently flat.

![Figure 6.3. Holes being drilled in door frame.](image-url)
6.2 Mounting System

We have purchased a new vibration motor as well as its corresponding clamping mounts. We have also purchased Universal Mount Vibration Isolators and fasteners. We have modified purchased steel sheet stock and purchased aluminum U channels.

<table>
<thead>
<tr>
<th>Part</th>
<th>Vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel Sheet Stock</td>
<td>Online Metals</td>
</tr>
<tr>
<td>U Channel</td>
<td>McMaster-Carr</td>
</tr>
<tr>
<td>Universal Mount Vibration Isolators</td>
<td>McMaster-Carr</td>
</tr>
<tr>
<td>DC Vibration Motor</td>
<td>Precision Microdrives</td>
</tr>
<tr>
<td>Motor Clamps</td>
<td>ServoCity</td>
</tr>
<tr>
<td>Fasteners</td>
<td>McMaster-Carr</td>
</tr>
</tbody>
</table>

The manufacturing process for the Adapter Plate is described below.

1. Cut 0.38 inch stock stainless steel to length and width specified (see Appendix F-MS01 for detailed drawings)
2. Finish cut with mill
3. Use mill to mill out contours
4. Use mill to drill specified holes.
5. Tap specified holes
6. Universal mount vibration isolators inserted into holes in adapter plate
The adapter plate was made of 316 stainless steel, and thus was very difficult to machine. We completely remade the adapter plate once because some of its holes were not tapped as they should have been. After remaking the adapter plate once, we had to modify it so that it could accommodate parts printed on the build plates that Cal Poly uses with their SLM printer. The original adapter plate was made to accommodate parts with a build plate of the size of those sent to us by LLNL. The difference in build plate sizes is shown in Figure 6.5. To accommodate the larger build plate of the Cal Poly SLM parts we milled the groove of the adapter plate wider. The adapter plate manufacturing took longer than expected due to the slower pace of machining stainless steel compared to aluminum, and due to the fact that it had to be remanufactured.

![Image of adapter plate](image-url)

Figure 6.5. Printed parts from LLNL (left) and Cal Poly (right).

The manufacturing process for the U Channel is described below.
1. Use horizontal band saw to cut purchased u channel to 3.5 inches (Appendix F-MS02)
2. Use mill to finish cut
3. Use mill to drill holes specified by drawing

We did not experience difficulties when manufacturing the U channel. Its manufacture consisted of cutting a purchased U channel to size using a horizontal band saw and then drilling holes on a mill.

The manufacturing process for the Mounting Base is described below.
1. Cut aluminum to specified dimensions (Appendix F-SR03)
2. Use belt sander to finish sides
3. Use drill press to drill holes specified by drawing

Manufacturing the mounting base was somewhat difficult. The part was made by modifying the canister base from the previous project. It was made this way because this part was already the desired thickness and it already had the desired hole pattern. It was difficult to cut a rectangular shape out of a circular part. This was done using a vertical band saw. A rectangular outline with the hole pattern at the center was drawn on the canister base. This outline was then cut out using the vertical band saw. The cuts were then cleaned up using a belt sander. Because there was no way to ensure that our cuts were perfectly square, holes for this part were drilled using a drill press. To do this the holes were located based on the center of the hole pattern and a center punch was used to make an indent at their desired location. After the holes were located they were drilled with the drill press.
6.3 Primary Rotation System
We did not manufacture any of the stepper motors or couplings, but we did manufacture the motor mounts and some structural components as described below.

Table 6.3 List of purchased Primary Rotation System Components

<table>
<thead>
<tr>
<th>Part</th>
<th>Vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Stepper Motor</td>
<td>AutomationDirect</td>
</tr>
<tr>
<td>90 Degree Bend</td>
<td>McMaster-Carr</td>
</tr>
<tr>
<td>Clamp Coupling</td>
<td>McMaster-Carr</td>
</tr>
<tr>
<td>Fasteners</td>
<td>McMaster-Carr</td>
</tr>
</tbody>
</table>

The manufacturing process for the Primary Motor Mounting Bracket is described below.
1. Use horizontal band saw to cut purchased 90 degree bend to specified dimensions (Appendix F-PR01)
2. Use vertical band saw to cut length and width dimensions
3. Use vertical band saw to narrow the width of the portion interfacing with the 80/20 frame
4. Mount on vice and use mill to drill holes

The Primary Motor Mounting bracket was made by modifying a purchased 90 degree bend. Cutting the holes with a band saw and drilling the holes with a mill was straightforward. The 1.25” hole for the motor shaft was the most difficult. To avoid breaking a drill bit, intermediate pilot holes were drilled before the 1.25” hole was drilled.

The manufacturing process for the U Block Side is described below.
1. Use vertical band saw to remove length from part as specified in drawing (Appendix F-PR01)
2. Mount part on vice with shaft hole pattern up.
3. Use mill to drill holes specified in drawing (Figure 6.7).
4. Tap holes as specified in drawing.

The U Block Side was made by modifying the VIPER 1.0 U Block Side. This modification involved cutting the part shorter with a band saw and drilling and tapping holes. The hole pattern on the U Block Side was reused.

![Figure 6.8. Holes being drilled in U Block Side.](image)

### 6.4 Secondary Rotation System

The main structure was mostly reused from the previous prototype. Some of the reused parts have been altered. There are some other parts that were purchased and also some that were altered after they were purchased.
Table 6.4: List of purchased Secondary Rotation System Parts

<table>
<thead>
<tr>
<th>Part</th>
<th>Vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Stepper Motor</td>
<td>OMEGA</td>
</tr>
<tr>
<td>Z Bracket</td>
<td>McMaster-Carr</td>
</tr>
<tr>
<td>Steel Spacer</td>
<td>McMaster-Carr</td>
</tr>
<tr>
<td>Set Screw Couplings</td>
<td>McMaster-Carr</td>
</tr>
<tr>
<td>Fasteners</td>
<td>McMaster-Carr</td>
</tr>
</tbody>
</table>

The manufacturing process for the Secondary Motor Mounting Brackets is described below.

1. Use vertical band saw to cut purchased z bar to specified dimensions (See Appendix F-SR01 for detailed drawings)
2. Use mill to finish cut
3. Mount part on vice
4. Use mill to drill holes specified by drawing
5. Draw outline of .8 in radius cutout
6. Use scroll saw to cut out .8 in radius cutout
7. Use dremel tool to finish cut

Manufacturing the Secondary Motor Mounting Brackets presented some challenges. The initial step of cutting the purchased Z Brackets required the use of both a vertical band saw and the mill. This is because the initial cut with the vertical band saw was difficult to get straight due to the shape of the part. After the initial cut was made with the band saw, it was finished with a mill to ensure the sides were flat. Drilling the small holes was simply done using a mill. It was more difficult to make the .8 inch radius cutout. This was done by drawing an outline of the cutout by using a tool in the shop that had a diameter of 1.6 inches. We then used a scroll saw to trace this outline. A dremel tool with a sanding head was then used to clean up the scroll saw cut.

The manufacturing process for the Shaft Extension Spacer is described below.

1. Mount part on mill vice using V block
2. Use mill to shorten the length of purchased spacer
3. Use sanding wheel to add specified flat (Figure 6.8)

Manufacturing the Shaft extension spacer was more difficult than expected. In order to shorten the purchased spacer, we used a mill. This normally should have been done on a lathe since the part was round but there were no lathes available at the time. The part was mounted on the mill using a V Block and parallels. Milling off material from the spacer was slow since the spacer was made of 18-8 stainless steel. After the spacer was shortened to the appropriate length, the flat was added. This was done by pressing the part against the sanding disk by hand and periodically measuring the width of the flat region being created.
As part of manufacturing of the secondary mounting system, the Iron Coupling and M16 Screw had to be modified to be compatible with our device. The Iron Coupling actually had an inner diameter smaller than the expected 1 inch. To fix this issue, we used a lathe to bore out the inner diameter to 1 inch. The M16 screw had an outer diameter that was wider than 1 inch. To fix this we turned the screw on a lathe to a diameter of 1 inch.

The manufacturing process for the U Block Base is described below.

1. Mount part on mill with shaft hole pattern up. (Appendix F-SR03)
2. Drill holes specified in drawing (Figure 6.9).
3. Mount part with side of u block base up.
4. Drill holes specified in drawing.
5. Tap holes.

Manufacturing of the U Block base consisted of drilling and tapping holes in a part originally manufactured by the previous senior project team.
6.5 Programmable Logic Controller

We did not create or manufacturing any of the PLC. The PLC was purchased from AutomationDirect. The electronics are housed in a polycarbonate box that was modified to allow mounting of the enclosure onto the VIPER 2.0 structure. We used a laser cutter to cut the polycarbonate panel to allow for mounting of components. Drawings for the PLC and electronics assembly are included in Appendix F-EE.

Table 6.5: List of purchased Electrical/Automation System Components

<table>
<thead>
<tr>
<th>Parts</th>
<th>Vendors</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU</td>
<td>Automation Direct</td>
</tr>
<tr>
<td>Base</td>
<td>Automation Direct</td>
</tr>
<tr>
<td>Coms Expansion</td>
<td>Automation Direct</td>
</tr>
<tr>
<td>Analog Output</td>
<td>Automation Direct</td>
</tr>
<tr>
<td>DC Power Supply</td>
<td>Automation Direct</td>
</tr>
<tr>
<td>Stepper Motor Drive</td>
<td>Automation Direct</td>
</tr>
<tr>
<td>Regeneration Clamp for Stepper Drive</td>
<td>Automation Direct</td>
</tr>
<tr>
<td>DC Drive</td>
<td>Automation Direct</td>
</tr>
<tr>
<td>HMI Panel</td>
<td>Automation Direct</td>
</tr>
<tr>
<td>HMI Keypad Bezel</td>
<td>Automation Direct</td>
</tr>
<tr>
<td>24 V Voltage Regulator</td>
<td>Amazon</td>
</tr>
<tr>
<td>E-Stop</td>
<td>Amazon</td>
</tr>
<tr>
<td>Electrical Polycarbonate Enclosure and Panel</td>
<td>McMaster-Carr</td>
</tr>
<tr>
<td>Fasteners</td>
<td>McMaster-Carr &amp; TECO</td>
</tr>
</tbody>
</table>

Manufacturing of the Electronics Enclosure is described below.

1. Laser cut holes in mounting panel specified by drawing.
2. Fasten PLC, power supply, motor drivers, voltage regulator, and regeneration clamp to panel as specified by drawing.
3. Drill holes and cutouts specified by drawing into polycarbonate box.
4. Use TECO fasteners and brackets to mount the electrical enclosure on the side of VIPER 2.0 80/20 material.
5. Attach mounting panel with components inside of electrical enclosure.
6. Attach HMI panel, E-stop, and warning labels to electrical enclosure.
6.6 Assembly
For assembling the prototype, we started by disassembling the previous group’s prototype partially. After modifying their parts and manufacturing new ones we then added our own parts and assemblies to the VIPER.

6.6.1 VIPER 1.0 Disassembly
Disassembly of previous device is described below.
1. Remove cylinder from secondary axis
2. Remove handles from primary and secondary axis
3. Remove shaft from secondary axis
4. Remove U bracket from primary axis
5. Remove shafts from primary axis
6. Remove 80/20 struts from side of frame

6.6.2 Enclosure Assembly
Assembly of enclosure is described below.
1. Place 2 Teco drop in T nuts into the slots in the horizontal bars on each side of the frame.
2. Mount the enclosure between the sides of the 80/20 frame using the T nuts and corresponding screws, as shown in Figure 6.12. Use sealing washers between the screws and the enclosure. Ensure that the primary axis holes align with the bearings on the frame.
3. Mount the strike plates for the powder box latches to the bottom of the funnel. Use #6 screws with the corresponding sealing washers and nylon insert lock nuts.

4. Mount the primary axis limit switch to the side of the enclosure, as shown in Figure 6.13.

5. Attach two locking draw latches to the side of the enclosure.

Notes: There are six holes drilled into each side of the enclosure, which were meant to be attachment points to the frame. However, only two holes at a time aligned with the slots in the frame. Thus, we fastened the enclosure using two screws on each side as described in the procedure. We sealed the extra holes using push in rubber bumpers.
6.6.3 Electronics Assembly

Assembly of electronics enclosure is described below.

1. Mount each electronic component to the polycarbonate mounting plate using the corresponding screws and nylon lock nuts. The mounting configuration is shown in Figure 6.14. Drawings of the electronics assembly are included in Appendix J-EE.

![Figure 6.14. Electronic components on mounting panel.](image)

2. Secure the mounting plate with electronics attached to the inside of the polycarbonate enclosure box at the four corners.
3. Mount the E-stop through the bore at the front of the enclosure.
4. Mount the HMI panel through the HMI cutout at the front of the enclosure.

Notes: The E stop did not fit very well inside the enclosure, as the power supply was in the way. If this enclosure is remade, we recommend drilling the E stop hole further away from the power supply to ensure that it has sufficient clearance. Right now, the E stop sits crooked.

6.6.4 Mounting System and Secondary Axis Assembly

Assemble the mounting system and secondary axis according to the drawings found in Appendix F-MS and Appendix F-SR, respectively. The assembly details are described below.

1. Fit two motor clamps around the body of the vibration motor and tighten. Attach the motor clamps to the bottom of the adapter plate using 6-32 screws.
2. Thread the vibration motor wires through PG7 cable glands and through the holes in the motor cover. Tighten the cable glands to the motor cover.
3. Place the o ring in the slot on the vibration motor cover. Attach the vibration motor cover to the bottom of the adapter plate using 6 ¼-20 screws. The cover will fit over the vibration motor.
4. Attach the adapter plate to the U channels using the vibration dampers.
5. Attach the U channels to the mounting base.
6. Reattach the secondary shaft to the bottom of the mounting base.
7. Reattach the other end of the secondary shaft to the U base.
8. Fasten the modified M16 spacer to the end of the shaft using the M16 button head screw.
9. Fit the 1” iron coupling over the spacer. Attach the ¼” iron coupling to the 1” coupling using the buna-n spider.
10. Attach the ¼” spacers between the modified z brackets and the U block base.
11. Attach the secondary stepper motor to the modified z brackets, ensuring that the motor shaft fits into the coupling.
12. Attach the secondary limit switch to the mounting base, as shown in Figure 6.15.

![Figure 6.15. Secondary limit switch placement on mounting base.](image)

13. Attach the secondary limit switch tab to the secondary shaft collar and secure onto the shaft.

### 6.6.5 Door Assembly
Assemble the doors according to the drawings found in Appendix F-FR. Details of the assembly are described below.

1. Fasten the four bars of the door frame together as shown in Appendix F-FR.
2. Spread epoxy around the face door frame. Press window to the frame, ensuring that the holes for the handles align. Hold tightly for at least 4 minutes until epoxy dries.
3. Attach three hinges to the hinge side of the door, and the strike plates of two locking draw latches to the latch side of the door.
4. Attach the handles.

Notes: The holes in the door frame components did not align perfectly. Thus, for some sections of the frame, only one fastener was used instead of the two specified in the drawings.
6.6.6 Installing Mounting System in the Enclosure
Installing the mounting system is described below.

1. Detach the U block base from the U block sides. The U block sides should be attached to the primary shaft. Fit the shaft seals over both sides of the primary shaft.
2. Mount each of the U block sides inside the enclosure by sliding the end of the primary shafts through the enclosure and primary bearings.
3. Reattach the U block base to the U block sides inside the enclosure.
4. Slide the shaft seals so that they press against the enclosure walls.
5. Attach the primary limit switch tab to the primary shaft collar and then to the shaft. Position so that the limit switch is pressed when the mounting system is vertical.

Notes: The shaft seals are difficult to slide onto the shafts and also do not cover the holes in the enclosure entirely. We recommend using larger seals to properly close the gaps in the enclosure.

6.6.7 Installing Primary Stepper Motor
Install the primary stepper motor according to the drawing found in Appendix F-PR. Installation details are described below.

1. Attach the primary motor coupling to the end of the primary shaft.
2. Attach the motor mounting bracket to the main frame on the underside of the horizontal top bar.
3. Secure the primary axis motor to the mounting bracket, ensuring that the shaft fits into the coupling.

Notes: We had to use two washers between the mounting bracket and the frame in order to align the motor shaft with the coupling.

6.6.8 Installing Electronics Enclosure
Installing the electronics enclosure is described below.

1. Fit the electronics enclosure to the motor side of the frame. The primary axis motor will fit through the rectangular cutout on the back of the electronics enclosure. Adjust the height of the two support brackets on the frame so that the enclosure rests on top of them.
2. Fasten the electronics enclosure to the frame using two Teco drop in T nuts.
3. Fasten the electronics enclosure to the brackets.

6.6.9 Installing Doors
Installing the doors is described below.

1. Attach the hinges to the enclosure. Use sealing washers and nylon lock nuts on each fastener.

Notes: While installing the backside door, we realized that the frame did not sit flush against the enclosure and the holes for the hinges did not line up with the enclosure holes. As a result, we were not able to properly mount the door as described. Instead, we used epoxy to glue the door onto the frame and caulk to seal the gaps. Thus, the final prototype only has one functioning door on the frontside.
6.6.10 Wiring Assembly

Wiring:

Stepper motors: We wired the four wires of each stepper motor into the corresponding ports in the stepper drivers. For the secondary stepper motor, we used a size PG11 cable gland to feed the wire through the wire hole in the enclosure. We then connect each stepper driver to the PCL coms expansion module using a RS-232 cables. The primary stepper driver was connected to port A, and the secondary driver to port B. See Appendix N-1 for the schematic.

Vibration Motor: We fed both wires of the vibration motor through PG7 cable glands and out the enclosure through the wire holes. We connect the wires to the corresponding ports on the DC driver. We then connected the 24V voltage regulator to the power input ports of the driver. To enable speed control, we connected Channel 2 of the analog output PLC module to the potentiometer ports of the driver (positive to “wipe” and negative to “low”). To power the analog output, we connected its input ports to the 24V power terminals in the PLC base. See Appendix N-2.

Limit Switches: We used size PG11 cable glands to run the limit switch wires through the enclosure. To power the limit switches, we connected the brown wires to the CH1 + channel on the PLC analog output. We also connect the CH1 - terminal of the analog output to the ground terminal on the digital input to ground both switches. The yellow and blue wires of the limit switches are part of the normally open circuit, which we verified using an ohmmeter. We connect these wires to the PLC digital input module. The primary limit switch connects to Channel 0 and the secondary to Channel 1. See Appendix N-3.

Power Supply: The 48V DC power supply powers both stepper drivers and the the DC driver. We wired the power supply output to the Vin terminals of the regeneration clamp. We then wired the Vout ports on the clamp to the Vin ports of both drivers. We also wired the 48V output to the input terminals on the 24V regulator to power the vibration motor. The power supply is run using 120VAC supplied by standard US wall outlets. To supply power, we connected the one of the two ends of the extension splitter cord to the AC input, running one wire through the E stop. See Appendix N-4.

PLC and HMI: The PLC is also powered using 120VAC from the wall. We connected the other end of the extension splitter cord to the input terminals, again running one of the wires through the E stop. The HMI is connected to the PLC with a single RS-232 cable that goes to the internal serial port on the CPU. See Appendix N-5.

7. Design Verification and Testing

Over the course of the project we have performed various tests to inform our design direction and verify design decisions that we have made. This included benchmark testing of the previous group’s final prototype, structural prototype testing of our new mounting and vibration system, intermediate testing of various components, and testing of our final prototype. A summary of all tests performed is available in the DVP&R table in Appendix O. Detailed test procedures are available in Appendix P.
7.1 VIPER 1.0 Benchmark Testing
The first test we performed was benchmark testing of the VIPER 1.0, last year’s final prototype. This testing is described in section 4.4.1 of this report and Appendix P. From this testing we concluded that a more ergonomic mounting system design and a more powerful vibration motor were necessary.

7.2 Structural Prototype Powder Removal with New Vibration Motor and Mounting System
After we completed our redesign of the VIPER, we built a structural prototype to test the efficacy of our redesigned part mounting and vibration system. Our new design incorporated an adapter plate for part mounting that would replace the previous method of mounting the motor directly to the build plate. It also included a more powerful vibration motor, and a new damping system, as shown in Figure 7.1.

![Figure 7.1 Structural Prototype Powder Removal Test](image)

The testing was performed under a fume hood in the composites lab using the following procedure:

1. Measure the mass of a powder collection device
2. Attached the part to the mounting plate
3. Attach the powder collection device to VIPER using tape such that it covers the part
4. Orient the part upside down
5. Vibrate the part for 5 seconds
6. After the time has elapsed, detach the collection device and measure its mass. The original mass of the collection device is subtracted from the total mass to get the removed powder’s mass
7. This process is then repeated until no powder is seen leaving the part and the mass measurements plateau
8. Once no powder is being removed with the vibration, tap part with mallet to see if any powder remains.
9. Repeat steps 5-8 until all powder is removed.

The measurements taken during this testing is shown in Table 7.1
This testing showed that the new vibration motor was much more effective than the original motor. While vibration alone did not remove all of the powder, occasional tapping of the build plate with the mallet to restart powder flow still enabled all of the powder to be removed from the part. It was also difficult to mimic the continuous reorientation that will be present in the final device, however reorientation was helpful in enabling more powder flow, so we expect even more success once the cycle is implemented. From this testing we concluded that through a combination of vibration, reorientation, and mallet tapping we were able to remove all the powder from the printed parts. We thus decided to move forward with the build of our full system.

7.3 Intermediate Testing
As we received parts and began assembling our final prototype, we performed quick tests to verify the performance and quality of various parts and systems, and reduce the trouble shooting required after full integration.

7.3.1 Benchtop Testing of Automation System
After we received the motors and automation system components, we performed bench top testing to verify that our automation system would work. Since safety concerns restricted us from using the purchased power supply outside of an electrical enclosure, all benchtop tests were run using a lab power supply at 24V. All of the benchtop testing was performed in the Mechatronics Lab (192-118). Intermediate tests performed included:

- Vibration Motor Speed Control
- Stepper Motor Position and Speed Control
- HMI Communication
- Limit Switch Sensing
- Multitasking

An issue identified during this benchtop testing phase was that one of the stepper motor drivers experienced a fatal communication error as a result of an error prone “self test” mode in the configuration program provided by the manufacturer. Luckily we identified this issue early during our intermediate testing and were able to get a replacement driver.
7.3.2 Testing of Basic Functionality after Integration

After the VIPER was fully assembled, we performed intermediate tests to verify the performance of components once assembled together. Tests performed included:

- Verifying system communication and power by commanding the stepper motors to rotate a fixed amount of steps.
- Verifying that the stepper motors stopped when either the e-stop or limit switch was pressed.
- Ensured that the limit switches were placed in a position that allowed for repeatable homing.
- Verified that the wires did not catch when the stepper motors rotated within their expected rotation ranges.

7.4 Transmissibility Ratio Test

In order to determine the optimum frequency to run the vibration motor at, we measured the vibration amplitude at the build plate and first vibration stage at various frequencies using accelerometers as described in Appendix P. The testing protocol followed was:

1. Mount cleaned part on VIPER.
2. Attach accelerometers to oscilloscope.
3. Mount 338c04 accelerometer on build plate using tapped #10 hole.
4. Mount 353b33 accelerometer on frame using tapped #10 hole.
5. Turn on the vibration motor by selecting the analog input value using the HMI VIBE mode.
6. Use the oscilloscope to measure the frequency, peak-to-peak voltage, and noise band of the resulting signal as shown in Figure 7.2.
7. Click the up arrow on the HMI to increase the input to the vibration motor controller by 300 counts.
8. Repeat steps 6 to 7 until maximum Analog count has been reached.
9. Repeat with second accelerometer mounted on: enclosure, primary rotation system, secondary rotation system.

![Image of Oscilloscope](image_url)

Figure 7.2. Photo of Oscilloscope During Data Collection

The measured voltages and calculated acquired during this test are shown in Tables 7.2 and 7.3. Uncertainty calculations were performed as shown in Appendix Q.
Table 7.2 Measured and Calculated Values for Accelerations at the Part Build Plate.

<table>
<thead>
<tr>
<th>Analog Input (x/4095)</th>
<th>Measured Frequency (Hz)</th>
<th>Measured Voltage on Part (mV)</th>
<th>Oscilloscope noise (+/- mV)</th>
<th>Total Uncertainty (+/- mV)</th>
<th>Part Acceleration (g)</th>
<th>Part Acceleration (g)</th>
<th>Absolute Uncertainty (+/- g)</th>
<th>Relative Uncertainty (+/- %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600</td>
<td>44.64</td>
<td>55</td>
<td>12.85</td>
<td>14</td>
<td>0.53</td>
<td>0.53</td>
<td>0.14</td>
<td>0.26</td>
</tr>
<tr>
<td>1900</td>
<td>56.69</td>
<td>233</td>
<td>17.97</td>
<td>23</td>
<td>2.26</td>
<td>2.26</td>
<td>0.28</td>
<td>0.12</td>
</tr>
<tr>
<td>2200</td>
<td>74.07</td>
<td>689</td>
<td>14.06</td>
<td>68</td>
<td>6.49</td>
<td>6.49</td>
<td>0.66</td>
<td>0.10</td>
</tr>
<tr>
<td>2600</td>
<td>88.69</td>
<td>512</td>
<td>18.75</td>
<td>65</td>
<td>5.00</td>
<td>5.00</td>
<td>0.53</td>
<td>0.11</td>
</tr>
<tr>
<td>3000</td>
<td>105.6</td>
<td>1300</td>
<td>43.75</td>
<td>140</td>
<td>12.6</td>
<td>12.6</td>
<td>1.4</td>
<td>0.11</td>
</tr>
<tr>
<td>3400</td>
<td>122.7</td>
<td>1600</td>
<td>78.10</td>
<td>180</td>
<td>15.5</td>
<td>15.5</td>
<td>1.7</td>
<td>0.11</td>
</tr>
<tr>
<td>3800</td>
<td>132.5</td>
<td>1600</td>
<td>101.65</td>
<td>190</td>
<td>15.5</td>
<td>15.5</td>
<td>1.8</td>
<td>0.12</td>
</tr>
<tr>
<td>4200</td>
<td>132.5</td>
<td>1600</td>
<td>62.60</td>
<td>170</td>
<td>15.5</td>
<td>15.5</td>
<td>1.6</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Table 7.3 Measured and Calculated Values for Accelerations at Stage 1

<table>
<thead>
<tr>
<th>Stage 1 Voltage (mV)</th>
<th>Calibration Uncertainty (+/- mV)</th>
<th>Stage 1 Acceleration (g)</th>
<th>Calibration Uncertainty (+/- g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>73</td>
<td>4</td>
<td>0.75</td>
<td>0.04</td>
</tr>
<tr>
<td>131</td>
<td>7</td>
<td>1.34</td>
<td>0.07</td>
</tr>
<tr>
<td>109</td>
<td>6</td>
<td>1.10</td>
<td>0.05</td>
</tr>
<tr>
<td>125</td>
<td>6</td>
<td>1.26</td>
<td>0.06</td>
</tr>
<tr>
<td>120</td>
<td>6</td>
<td>1.22</td>
<td>0.06</td>
</tr>
<tr>
<td>134</td>
<td>7</td>
<td>1.37</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Figure 7.3 shows the calculated acceleration at the part as a function of vibration frequency. The largest accelerations occurred at the highest frequencies, which corresponded to the highest speed of the vibration motor. Increasing the value of counts to the DAC beyond 3100/4095 did not appear to result in a significant difference in vibration frequency or part acceleration. We believe that this is because the vibration motor could not go any faster for the given set up, or was being current limited by the DC motor controller. The set up of the HMI allowed the counts sent to the DAC to be increased in increments of 300. If this test were to be repeated, we would take measurements at smaller intervals in order to better characterize the behavior of the accelerations, particularly near 90 Hz, where there is a dip in acceleration amplitude.
7.5 Weight Test
In order to determine the maximum part weight which could be reliably controlled by our stepper motors, we performed a weight test as described in Appendix P. The testing protocol performed was as follows:

1. Attach weights to build plate using straps starting at 5 lbs. Our test setup is shown in Figure 7.3.
2. Orient primary axis at 90° from the vertical. Verify that the motor can hold part still without slipping.
3. Orient primary axis to 180° from the starting position.
4. Use the Jog commands and HMI homing features to move the primary axis back to its starting position.
5. Note any failures encountered.
6. Repeat steps 1 through 5, incrementing weights each time until total failure occurs or 35 lbs is reached.

Figure 7.4 Weight Test Setup
The results of our testing are shown in Table 7.4. The primary axis stepper motor was only able to reliably lift the 10 lb load. While all structural components were sized to bear the load of the maximum part weight, the motors were sized based on the guideline that the load should require 30-70% of the available power, based on a representative test part. Future iterations of this design would require a larger primary axis stepper motor to allow for heavier parts.

<table>
<thead>
<tr>
<th>Weight (lbs)</th>
<th>Observations when moved down</th>
<th>Observations when moved up</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Jerky but made it fine</td>
<td>Jerky but made it fine</td>
</tr>
<tr>
<td>10</td>
<td>Smooth</td>
<td>Smooth if under constant movement (holding jog button or using home command), stalls if jog button released when on its side</td>
</tr>
<tr>
<td>12.5</td>
<td>Smooth if under constant movement (holding jog button or using home command), stalls if jog button released when on its side</td>
<td>Smooth if under constant movement (holding jog button or using home command), stalls if jog button released when on its side</td>
</tr>
<tr>
<td>15</td>
<td>Smooth if under constant movement, stalls if jog button released when on its side</td>
<td>Moves up until it stalls halfway</td>
</tr>
</tbody>
</table>

7.6 Confirmation Prototype Powder Removal Runtime Determination Test

In order to gather data about the effectiveness of the fully assembled, automated device, the team ran a test as described in Appendix P to determine that amount of time the automated cycle should be run before the operator checks for powder removal progress. Additionally, the testing will determine the total percentage of powder removed by the vibration cycle alone, without any operator intervention. The test procedures were performed as follows:
1. Measure the mass of a powder collection device
2. Attach the part to the mounting plate
3. Attach the powder collection device below printed part so that it will collect powder
4. Run cycle for 5 seconds
5. After the time has elapsed, detach the collection device and measure its mass. The original mass of the collection device is subtracted from the total mass to get the removed powder’s mass.
6. This process is then repeated until no powder is seen leaving the part and the mass measurements plateau
7. Once no powder is being removed with the vibration, tap part with mallet to see if any powder remains.
8. Repeat steps 3-7 until all powder is removed.

Table 7.5 shows the data collected during this test. After 3 minutes and 45 seconds, no more powder was being removed from the part during the vibration cycle. We then manually tapped the part with a mallet until no more powder was released from the part in order to get a measurement of the total powder contained within the part. This testing showed that the automated cycle removed 92.3% of the total powder contained in the part without any operator intervention.
Table 7.5. Confirmation Prototype Powder Removal Runtime Determination Test

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Total Mass (g)</th>
<th>Percentage Powder Removed</th>
<th>Mass of powder removed (g)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>511</td>
<td>0.0%</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>674</td>
<td>57.4%</td>
<td>183</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>702</td>
<td>67.3%</td>
<td>191</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>730</td>
<td>77.1%</td>
<td>219</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>765</td>
<td>89.4%</td>
<td>254</td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>770</td>
<td>91.2%</td>
<td>259</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>771</td>
<td>91.6%</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>225</td>
<td>773</td>
<td>92.3%</td>
<td>262</td>
<td>No more powder is being removed during vibration cycle</td>
</tr>
<tr>
<td>-</td>
<td>795</td>
<td>100.0%</td>
<td>284</td>
<td>Manually tapped with mallet until no more powder remained</td>
</tr>
</tbody>
</table>

7.7 Confirmation Prototype Powder Removal Complete Test

We conducted a total system test in order to determine the ability of our prototype to enable the operator to remove powder from the part while requiring less than 30 minutes of operator time, less than 2.5 hours total process time, while ensuring that no powder escaped the enclosure, and that the part is undamaged. We conducted the test, as described in Appendix P, with two different test parts shown in Figures 7.5 and 7.6.

Figure 7.5. 316L SS Printed Part 1 from IME Dept

Figure 7.6. 316L SS Printed Part 2 from IME Dept
To conduct the test, we performed the following:
1. Place black paper under the VIPER 2.0.
2. Start timers and log moments when time includes operator time.
3. Attach the part to the VIPER 2.0.
4. Run automated cycle for time determined using data from cycle runtime test.
5. Tap on part with rubber mallet to check for remaining powder/reinitiate powder flow.
6. Repeat steps 4-5 until no more powder is released by mallet
7. Once all powder is removed, record the total process time.
8. Remove part from VIPER 2.0.
9. Hold part above black paper and strike it with a rubber mallet as shown in Figure 7.7.
10. Repeat step 9 at various orientations.
11. If no visible powder is released by mallet the part is fully clean.
12. Repeat with Part 2

![Image](image_url)

Figure 7.7. Checking Part 1 for Remaining Powder

The collected data for Part 1 is shown in Table 7.6 with total times shown in Table 7.7. The data for Part 2 is shown in Tables 7.8 and 7.9.
Table 7.6. Recorded Data During Powder Removal Complete Test for Part 1

<table>
<thead>
<tr>
<th>Start (HH:MM)</th>
<th>Stop (HH:MM)</th>
<th>Type</th>
<th>Time Elapsed (HH:MM)</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>00</td>
<td>manual</td>
<td>0:04</td>
<td>Loading part and starting cycle</td>
</tr>
<tr>
<td>0:04</td>
<td>1:00</td>
<td>auto</td>
<td>0:55</td>
<td>1st cycle</td>
</tr>
<tr>
<td>1:00</td>
<td>1:02</td>
<td>manual</td>
<td>0:02</td>
<td>tap</td>
</tr>
<tr>
<td>1:02</td>
<td>1:07</td>
<td>auto</td>
<td>0:05</td>
<td>2nd cycle</td>
</tr>
<tr>
<td>1:07</td>
<td>1:08</td>
<td>manual</td>
<td>0:01</td>
<td>tap</td>
</tr>
<tr>
<td>1:08</td>
<td>1:12</td>
<td>auto</td>
<td>0:04</td>
<td></td>
</tr>
<tr>
<td>1:12</td>
<td>1:13</td>
<td>manual</td>
<td>0:01</td>
<td>tap</td>
</tr>
<tr>
<td>1:13</td>
<td>1:15</td>
<td>auto</td>
<td>0:05</td>
<td></td>
</tr>
<tr>
<td>1:19</td>
<td>1:19</td>
<td>manual</td>
<td>0:01</td>
<td></td>
</tr>
<tr>
<td>1:19</td>
<td>1:37</td>
<td>manual</td>
<td>0:13</td>
<td>manual tapping, jogging, and vibration</td>
</tr>
<tr>
<td>1:37</td>
<td>1:38</td>
<td>manual</td>
<td>0:02</td>
<td>removal</td>
</tr>
</tbody>
</table>

Table 7.7. Calculated Operator and Total Process Time for Part 1

<table>
<thead>
<tr>
<th>Part 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Manual Time: 0:29</td>
</tr>
<tr>
<td>Total Process Time: 1:33</td>
</tr>
</tbody>
</table>

Table 7.8. Recorded Data During Powder Removal Complete Test for Part 2

<table>
<thead>
<tr>
<th>Start (HH:MM)</th>
<th>Stop (HH:MM)</th>
<th>Type</th>
<th>Time Elapsed (HH:MM)</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>00</td>
<td>manual</td>
<td>0:02</td>
<td>Loading part and starting cycle</td>
</tr>
<tr>
<td>0:02</td>
<td>0:15</td>
<td>auto</td>
<td>0:13</td>
<td>1st cycle</td>
</tr>
<tr>
<td>0:15</td>
<td>0:27</td>
<td>manual</td>
<td>0:12</td>
<td>tap, jogging, vibration, unloading</td>
</tr>
</tbody>
</table>

Table 7.9. Calculated Operator and Total Process Time for Part 2

<table>
<thead>
<tr>
<th>Part 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Manual Time: 0:14</td>
</tr>
<tr>
<td>Total Process Time: 0:27</td>
</tr>
</tbody>
</table>

This test yielded mixed results. The test showed that our enclosure successfully prevented powder from escaping during the cycle. Additionally, parts were undamaged during the cycle. The powder removal test was very successful on Part 2, with all powder being removed from the part in under 30 minutes, and only 14 minutes of operator time. Part 1 was less successful. There was still observed to be small puffs of powder when struck with mallet from the small holes around the top of the support structure as visible in Figure 6.1. The support structure of this part was significantly more difficult to remove powder from than the support structure of the parts originally tested from LLNL as shown in Figure 1.1.
Because of this, Part 1 required a long cycle time, as well as a longer manual part powder removal time than Part 2. Future depowdering of a part with a similar support structure which involved removing the “skin” of the support structure first may increase the speed at which powder can be removed, and allow it to all be removed within the operator time window. Some unremoved powder was seen within the countersinks of the build plate after the test cycles were complete in both parts 1 and 2. This powder was not removed during the cycle since it was trapped by the head of the screw which holds the build plate on the adapter plate. In the future, it is recommended to remove this powder manually before mounting to VIPER 2.0.

7.8 Operator Satisfaction Survey
The final design verification performed by our team was the distribution of an operator satisfaction survey as described in Appendix P. The goal of this survey was to measure operator satisfaction with factors such as the ergonomics of the device, the usability of the HMI, and the anticipated usefulness of VIPER 2.0. The survey was taken by Dr. Xuan Wang. The participant was provided with the operator manual, available in Appendix R, and then ran through a mock cycle. The participant was enthusiastic about the device and rated VIPER 2.0 5/5 in all categories. The participant did note that the shaft seal on the right side does not form a complete seal against the enclosure wall.

8. Project Management
The design process began with gathering information to define the problem and determine the project scope which culminated in a Scope of Work document. Next, we performed ideation, down-selection, and initial prototyping and analysis which was described in the Preliminary Design Report. We then performed detailed design of the powder containment method and automation method. We completed tests using the VIPER device built in the 2017/2018 school year, which better informed our design decisions. Our final design was assessed as part of our Critical Design Review by our sponsors and our project advisor. After their approval, we ordered materials and began manufacturing. During manufacturing, we updated our final design in response to various issues we encountered while building the prototype. Once the final prototype was constructed, we completed our final testing and delivered our prototype to the Cal Poly AM labs.
8.1 Key Deliverables
The team’s progress was driven by the following key deliverables described in Table 8.1.

Table 8.1. Key Deliverables Throughout the Project Timeline

<table>
<thead>
<tr>
<th>Deliverable</th>
<th>Description</th>
<th>Due Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scope of Work</td>
<td>Document outlining the goals for the project.</td>
<td>10/19/2018</td>
</tr>
<tr>
<td>Preliminary Design Review (PDR)</td>
<td>First major review of all initial designs of solution.</td>
<td>11/16/2018</td>
</tr>
<tr>
<td>Interim Design Review</td>
<td></td>
<td>1/17/2019</td>
</tr>
<tr>
<td>Critical Design Review (CDR)</td>
<td>Detailed review of all components, costs, analysis, and updated solution.</td>
<td>2/7/2019</td>
</tr>
<tr>
<td>Manufacturing &amp; Test Review</td>
<td>Status of component manufacturing, updated test plan, and updated schedule of project completion.</td>
<td>3/14/2019</td>
</tr>
<tr>
<td>Initial Test Plan and Operators Manual</td>
<td>Detailed testing plan for components and system, a user’s guide detailing how to operate the system and all potential safety hazards.</td>
<td>4/4/2019</td>
</tr>
<tr>
<td>Operators Manual</td>
<td>Complete operator’s manual detailing all safety hazards, all use cases, and general troubleshooting.</td>
<td>5/21/2019</td>
</tr>
<tr>
<td>Project Expo</td>
<td>Final prototype, showcase of the project expo poster.</td>
<td>5/31/2019</td>
</tr>
<tr>
<td>Final Design Review (FDR)</td>
<td>Submitting Final Design Report to Sponsor</td>
<td>6/6/19</td>
</tr>
</tbody>
</table>

8.2 Overall Timeline
We created a Gantt chart in order to plan our project. This chart served as a visual indication of when we planned on completing tasks, and helped the team stay on track. This chart is in Appendix S.

9. Conclusions and Recommendations
The following section summarizes the lessons we learned during the design, manufacturing, and testing process.

9.1 Comments on Manufacturing
During manufacturing, we encountered a number of unexpected issues that increased our build time. The following section summarizes these issues and includes recommendations for future manufacturing.

9.1.1 Sheet Metal Enclosure Manufacturing
The manufacturing process for the enclosure was a difficult task due to the use of steel sheet metal. This was in part due to the fact that the machine shops at Cal Poly have only 4 tools to cut and form sheet metal. These tools had limited availability, which lengthened the manufacturing time. The tools in the machine shop also limited what thickness and types of sheet metal we could work with. Our manufacturing would have been significantly easier if we had access to a water jet to cut the sheet metal for us. Another issue was the welding experience of the team. None of our team members are skilled at welding, so it was a manufacturing risk. Thankfully, the welding professor Kevin Williams was able to help us by taking on the job. If not, it would have been extremely difficult for us to assemble the enclosure.
While this process was difficult, we would still recommend using steel sheet metal for the enclosure. What we would have changed would be to use much thinner sheet metal. We used 16 gauge steel, which was heavy, proved difficult to bend and cut, and provided more than enough structural support. Another possible solution for manufacturing of the enclosure would be using plastic, either ordering parts already formed into the shapes needed or cutting stock pieces. To ensure the enclosure remain sealed, we recommend exploring the use of unique plastic solvents or glues that are specifically designed to make seals.

9.1.2 Adapter Plate Material Selection and Manufacturing
When initially developing our design, one of the concerns brought up was the probability of powder contamination brought about by the adapter plate and build plate grinding together during vibration. If the adapter plate wasn’t stainless steel, the resulting metal powder would be contaminated by whatever material the adapter plate was made from. This resulted in the decision for the material the adapter plate would be made of to be 316L stainless steel.

This decision did solve the problem of contamination, but it did put a strain on manufacturing. We did not account for how difficult it was to machine and tap stainless steel, and how much it would push back our deadlines.

If there would be a need to change or reproduce the adapter plate, we would recommend still using stainless steel. But, due to its hardness, it’s recommended to buy high quality end mills and drill bits designed to machine stainless steel and not use the Machine Shop’s.

9.1.3 Tolerances and Assembly
As careful as we were, not everything we made fit as designed. As mentioned before, it was difficult to manufacture the sheet metal enclosure, which resulted in a few holes that were punched out of tolerance, and the cuts and bends made to the sheets not lining up. The foremost examples being the door hinges/latches and the powder box.

When manufacturing the sheets for the enclosure, a few mistakes were made in the hole placement for the door’s hinges. This resulted in the alteration of the door frames to try and fit the holes in the enclosure. Once we made said door frames, it was evident that the resulting errors in dimensioning added up to only one of the door frame’s hinges lining up. To allow for this, we had to seal the nonfunctional door to keep the integrity of the enclosure and only have one functioning door.

Another complication caused by the sheet metal was the warping from the welding and bending. This caused difficulting in sealing the enclosure since the face of the enclosure was not flush with the door. For the nonfunctional door, we solved this with the use of a clear structural sealant to fill in gaps not covered by the original sealing. For the functioning door, we decided to change out our original nitrile seals for a thicker cellular weather stripping seal that could be compressed and fill the gap.

Our decision to reduce one of the doors to a window had an unfortunate impact. The team did not recognize that it mattered which door was sealed off until it was already adhered. We sealed off the door that the HMI panel originally faced, which was the side the operator would need to access the part from.
When this was discovered, we initially thought we would have to either buy a whole new electrical enclosure or somehow cut a new polycarbonate sheet, but thankfully we found a solution that would require only a few more holes in our original parts. To fix this issue, we decided to simply rotate our electrical enclosure so that the HMI faced the other direction. This was accomplished by drilling holes into the polycarbonate sheet and enclosure to fit in our desired position. The only downside was that a very heavy component of electronics is now higher up than originally designed. This solution works, but should be addressed if the electronics enclosure is ever redesigned.

A smaller issue that occurred was the originally manufactured metal box that collects the removed powder at the funnel opening, did not fit around the bottom of the enclosure. This was due to the sheet metal not fitting together well and the bends not being at the correct angle. Thankfully, we came up with a quick solution by simply 3D printing a simple box that would fit with the bottom of our enclosure. This box ended up being lighter and more ergonomic for the user.

9.2 Comments on Electronics
Overall, the electronics in this system were relatively straightforward. We did not encounter any major issues concerning the electronic components. One concern we do have, however, is the effectiveness of the E stop. The E stop was wired to simply cut power to the system when activated. When the E stop is pressed, however, there is approximately a 3 second delay before the system powers off. We believe this is due to the large capacitor in the 48V power supply holding a significant charge after being powered off. This delay would not be ideal in the event of an emergency, and it is recommended that in any future iterations, the E stop is wired directly to the 48V output on the other side of the capacitor.

Another issue that we did not consider during the design phase is what happens when the stepper motors are unpowered. When the E stop is pressed or the system unplugged, the primary axis swings freely down. Depending or the orientation of the axis when power is lost, this can result in wires getting tangled and the shaft collar which holds the limit switch tab being knocked loose. Ideally, the system would include an emergency brake on the shaft that would close while unpowered. This would stop the axis from swinging when powered off. For right now, it is recommended that the primary axis be homed before powering off.

9.3 Comments on Programming
Programming with ladder logic was easy to learn and the system was simple to control. The most challenging parts of the programming process were in configuring the drivers and debugging the system. While configuring one of the stepper drives, we encountered an unexpected communication error that we were unable to fix. The cause of the error was most likely a faulty driver. We had to contact the manufacturer to exchange the driver for a new one. We learned from this incident how important it is to test all electronic components individually before using them in the final system.

Another challenge was debugging the program. The code for the complete system was initially written before the system was assembled. Due to the constraints of the benchtop setup we had, we were not able to test all components of the system at once. This made it difficult to know whether the full system would work when installed in the final prototype. During our full stage testing, we noticed a bug where the motors would behave erratically after 11 minutes had passed in the cycle. This error did not show up in
the benchtop testing or initial testing. We discovered that the motor driver queues would overflow around this time, since the program was writing commands to the drivers faster than they could execute them. This bug highlights the importance of doing full system tests over longer periods of time, as we would not have noticed this problem if we had never ran the VIPER longer than 10 minutes.

9.4 Comments on Operation
Operation of the final prototype is simple and straightforward compared to the previous team’s prototype. The adapter plate allows quick and easy installation of the part, and the HMI allows easy control of the motors. One major drawback of operation is the lack of a maximum rotation limit. Both axes home on the limit switch. However, they can be jogged in the other direction past 360°. This could cause the wires to become tangled or damaged. Thus, the user must be careful when manually moving the axes that the device is rotating properly. See section 9.5 for recommendations on how to address this issue.

9.5 Comments on Testing
Our full system test successfully removed all powder from a small disk part. It did not remove all powder from a larger disk with a single drain hole, however. We observed during testing that vibrations alone is not perfectly effective in removing powder. In each test, we would stop the cycle and tap the part with a hammer. This tapping would release more powder even when the vibration cycle would not. Restarting the cycle after tapping would usually also release more powder. Ideally, the cycle alone would completely clean the part. However, we found that the operator would have to manually assist the cleaning process by tapping the part intermittently. Even with the required operator interactions, the process was still less labor intensive and more effective than the previous year’s prototype.

The weight test yielded less desirable results. The VIPER was able to carry up to 12.5 lbs instead of the target 35 lbs. Although it cannot support the full target weight, it was able to support all our test parts. These test parts are more representative of the parts the device will be carrying during actual use. It is important, though, that this limitation be taken into consideration when the VIPER is in use.

During the vibration testing, we encountered some difficulty in measuring the vibrations in the mounting system. We were able to effectively measure the part vibrations using an accelerometer. However, the rest of the mounting system had multiple modes of vibration, which were difficult to capture using a single accelerometer in the frequency range we tested in. Thus, while we were able to get good data for vibrations transferred to the part, we were unable to effectively measure vibrations transferred to the rest of the system. This data is important to have, however, since we observed that there are significant vibrations in the frame and enclosure. Thus, we recommend using a more robust vibration test and analysis (see Section 9.5 for more details).

9.6 Next Steps/Future Recommendations

Seals:
Currently, the enclosure is not completely sealed. One of the shaft holes in the enclosure was made slightly too big for the shaft seal, leaving a small gap at the primary axis. We recommend replacing the shaft seal with a larger one that will effectively cover the entire hole.
Door:
Another concern is the door. There is currently no lock or switch on the door, making it possible for the user to open the door while the VIPER is in operation. This creates a loose powder hazard and a crush or entanglement hazard. Although we included a warning label telling the user not to open the door while in operation, it would be more ideal to incorporate a safety catch in the door. This way, if the door is opened unexpectedly, the machine will stop running. We recommend that a switch be wired from Channel 0 of the analog output on the PLC to Channel 2 of the digital input. The PLC program will also have to be modified to recognize the open door. This can be done by downloading the program from the PLC and editing using the Do More Designer program. Alternatively, one can incorporate a lock on the door that engages when the motors are running.

Rotation:
Currently, the system only limits rotation in one direction (using the limit switch). It is possible, then, for the user to jog the axis a full 360° or more. This could tangle the wires. There is a warning in the user manual, however it would be better to incorporate a limit for the maximum rotation angle. This can be done either in the software or by using a second limit switch. Alternatively, the system could be powered using slip rings as described in the original design. The slip rings would need to have IP6X ratings and fit within the system’s size constraints.

Further Testing:
Our full system test revealed that the VIPER is more effective at removing powder from some parts over others. The small disk with larger drain holes was completely cleaned in under 30 minutes, while the larger disk with a single drain hole was still not clean after 1 hr 40 min. We recommend testing the VIPER with a wider variety of parts to determine how effective it is for general use and what types of parts it is capable of effectively cleaning.

We also recommend repeating the weight test with smaller and more securely mounted weights. The weights we used were large 5lb disk weights secured to the device with straps. There was significant sliding and movement of the weights while the system rotated, adding unwanted dynamic forces. Their bulky size also added a more significant moment arm than an actual printed part would have. Though we do not expect an improved weight test will meet the 35 lb requirement, we do think it may yield significantly different results and would be worth investigating.

For the vibration test, we recommend testing vibrations transferred to the mounting system, enclosure, and electronics enclosure. Our test only investigated vibrations in the part and mounting system using single axis accelerometers. We were unable to effectively analyze the signal from the mounting system accelerometer. We believe that the mounting system has multiple modes of vibrations. The combination of these modes and significant noise in the accelerometer made it difficult to draw any conclusions from this data. For future testing, we recommend that other methods of vibration measurement be explored, such as a spectrum analyzer. Additionally, we recommend the use of tri-axial accelerometers so that the peak accelerations experienced at the park can be measured and compared with the values found in our
research. We also recommend taking vibration data at other points in the system to determine the transmissibility throughout the device.

9.7 Conclusion
During the 2018-2019 academic year, the team researched, designed, analyzed, manufactured, and tested the VIPER 2.0, a device used to remove stainless steel powder from parts created using powder bed fusion. This device works by rotating a printed part on two different axes while also vibrating the part using a DC vibration motor. The design incorporates a sealed enclosure, improved part fixturing, motorized axes, and PLC control. A cycle timing test showed that the device was able to remove 92.3% of powder from a hollow disk part in 3 minutes 45 seconds. The remaining powder was removed manually by tapping the part with a mallet. A weight test demonstrated that the device could support parts up to 12.5 lbs. The full system test showed that the effectiveness of the VIPER 2.0 depends on the shape of the part being tested. It successfully removed all powder from a small disk with large drain holes, but was not able to remove all powder from a larger disk with fewer and smaller drain holes. Vibrations alone were not able to fully clean each test part, and the powder removal was much more effective when the user intermittently tapped the part with a mallet. Overall, there are still improvements that can be made to improve the safety and effectiveness of the VIPER 2.0. Even so, the VIPER still has the potential to significantly facilitate the powder removal process. The final prototype was delivered to the Cal Poly AM lab on June 4, 2019.

10. References


Appendix A: QFD House of Quality

QFD: House of Quality

Customer Requirements

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<tr>
<th>Requirement</th>
<th>Importance</th>
<th>Weight</th>
<th>Impact</th>
<th>Matrix</th>
<th>Quality Function Deployment</th>
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House of Quality:

<table>
<thead>
<tr>
<th>Requirement 1</th>
<th>Requirement 2</th>
<th>Requirement 3</th>
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<tbody>
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</table>
Appendix B: Ideation List

How might we collect freed powder?

- Funnel
  - Valve w/ rolling bed (Melissa’s thing)
  - Vibrate funnel
- Removable bottom tray
- Funnel with fine mesh and industrial fan
- Removable enclosure
- Vacuum
- Water sprayed on part and enclosure walls, drain at bottom
  - Automatic or user controlled
  - Water bar glass cleaner (Andrew made this)
- Centrifuge pushes powder to holes at edges
- Powder sifter/reclaimer incorporated
- Powder falls into liquid which is then drained
- Air flow directs powder
- Flush with water
- Positive/negative pressure
- Electromagnets placed on interior or exterior of enclosure

How might we remove powder?

- Vibrate Part continuously
- Gravity
- Impacts
- Dropping from height
- Magnetic field
- Surgical device that has the camera thing at the end of it
- Vacuum chamber
- G-Force simulator for pilots
- Wind tunnel
- Short “jolts” of vibration
- Vacuum sucks out powder
- Magnet pulls off powder
- Liquid sprayed on part
- Part immersed in liquid bath
- Gas shot at part
- Vibrate using orientation motors
- Astronaut g force generator
- Vibrates w/ rotation while sprayed w/ water then sprayed with gas
- Acid
- Chemical reaction
- Burn off powder
- Shaking part vigorously
- Spin part rapidly, powder flies off due to centrifugal force
- “Shelves” built during printing process
- Vaporize powder with laser
- Play skrillex drop really loud inside device, variety of frequencies of drop is probably desirable
- Tie on dog collar and play fetch
- Variable frequency vibration
- Fixed vibration frequency with continuous reorientation of part
How might we secure/hold the part

- Threaded rods with wing nuts
- Toggle lock lever
  - Clamp onto plate surface
  - Clamp through holes
- Vice grip
- Hydraulic clamps
- Thread into housing
- Locking “door” over part
- Magnets
- Snap fit
- Spring buttons
- Locking brackets, “claw” design
- Rubber band
- Removable rods through holes
- Same way as last year
- Set screws
- Vacuum holds build plate
- Slide into slots, secured with fourth wall
- Lever clamp
- “CD drive”
- Therapy
- Glue
- Telekinesis
- Holding by hand
- Telling it not to move

How might we orient part?

- Manual rotation using current setup
- Gyroscopic (3 axis) rotation
- Turntable
- Water wheel
- Place motors where handles currently are -
  - Have them continuously spin
  - Set cycle to cover all orientations
  - Spin continuously but switch direction of rotation of horizontal axis
  - Microwave buttons: operator controls orientation through microwave-like interface
- Motors - We can address motor type after choosing an overall orientation method
  - Stepper
  - Servo
  - Hydraulic
  - DC
  - Brushless DC
  - AC
  - Pneumatic
- Drives
  - Direct
  - Belts
  - Chains
  - Gears
- Robot arm
- Pendulum
  - 2 motors, one to swing pendulum and one to rotate part
  - Geared pendulum that also rotates part as it swings
  - Double Chaotic pendulum
• Hydraulic piston driving a rack/pinion system for one axis, motor for other axis
• Less Bad Locking Pins/Part of setup
• Differential
• Turntable with x-axis rotation isolated from z-axis rotation

How might we isolate powder from the user/environment?
• Enclosure with hinged door
• Large Box Around entire device
• Enclosure closed like boat door
• Part wrapped in foil
• Cover part with large bag
• Small Container Around part only
• Removable Powder Container at bottom
• Container has negative pressure
• Vacuum
• Blowing Powder away from user
• Sticky surface that powder sticks too
• Count on gravity
• Magnets
• Submerged in Liquid
• User wears respirator
• User operates from a different room
Appendix C: Pugh Matrices for Each Function

Function: Collect/Isolate Powder from User and Environment

<table>
<thead>
<tr>
<th></th>
<th>Gravity Fed Funnel w/ Valve</th>
<th>Removable Bottom Tray</th>
<th>Funnel with Fan/Suction to drive Powder Downward</th>
<th>Water to Carry Released Powder out of Enclosure</th>
<th>All or part of enclosure spins to push powder out of openings along outside</th>
<th>Tray on slides &quot;Toaster Oven&quot;</th>
<th>Enclosure only around part</th>
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<td>Powder is Reusable/Reclaimed</td>
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Function: Remove Powder

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<tr>
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<th>Datum: Continuous vibrations at fixed position (current design)</th>
<th>Continuous vibration with continuous reorientation</th>
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### Function: Secure Part to Powder Removal Device

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<th>Mechanical Complexity</th>
<th>Supports Maximum Part Weight</th>
<th>Compatible with Build Plate</th>
<th>Accommodates Maximum Part Size</th>
<th>Does not Damage Part</th>
<th>Minimal Labor to Operate</th>
<th>Ergonomic</th>
<th>Total Plus</th>
<th>Total S</th>
<th>Total Minus</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>+</td>
<td>S</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

### Function: Orient Part

<table>
<thead>
<tr>
<th>Datum: Drivers on both axes (automated cycle)</th>
<th>Drivers on both axes (user controlled)</th>
<th>Place single driver on horizontal axis, rotate other axis with a gear</th>
<th>Differential with motors on outer gears</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safe to Operate</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Removes Powder</td>
<td>S</td>
<td>S</td>
<td>-</td>
</tr>
<tr>
<td>30 Minutes Labor Per Part</td>
<td>S</td>
<td>-</td>
<td>S</td>
</tr>
<tr>
<td>2.5 Hour Total Process Time</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Low Cost</td>
<td>S</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Ergonomic</td>
<td>S</td>
<td>-</td>
<td>S</td>
</tr>
<tr>
<td>Minimal Training to Use</td>
<td>S</td>
<td>-</td>
<td>S</td>
</tr>
<tr>
<td>Software Complexity</td>
<td>S</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Mechanical Complexity</td>
<td>S</td>
<td>S</td>
<td>-</td>
</tr>
</tbody>
</table>

| Total + | 2       | 2       | 0       |
| Total S | 4       | 5       | 6       |
| Total - | 3       | 2       | 3       |
# Appendix D: Weighted Decision Matrices

## Function: Collect/Isolate Powder from the User and Environment

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weights (0-5)</th>
<th>Funnel</th>
<th>Sliding Tray “Toaster Oven”</th>
<th>Part only enclosure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removes Powder</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Powder is Reusable/Reclaimed</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Safe to Operate</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Fits in Small Footprint</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Low Cost</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Minimal Labor to Operate</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Ergonomic</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Low Maintenance Interval</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Clean Process</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Manufacturability</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Mechanical Complexity</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td><strong>Total Score</strong></td>
<td><strong>154</strong></td>
<td>145</td>
<td>122</td>
<td></td>
</tr>
</tbody>
</table>

## Function: Remove Powder

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weights (0-5)</th>
<th>Continuous vibrations at fixed position</th>
<th>Continuous vibration with continuous reorientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removes Powder</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Safe to Operate</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Quick Process Time</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Minimal Labor to Operate</td>
<td>3</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Low Skilled Labor to Use</td>
<td>4</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Low Maintenance Interval</td>
<td>2</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Software Complexity</td>
<td>3</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total Score</strong></td>
<td><strong>94</strong></td>
<td><strong>110</strong></td>
<td></td>
</tr>
</tbody>
</table>
### Function: Hold Printed Part

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weights (0-5)</th>
<th>Permanent Threaded Rods</th>
<th>Vice</th>
<th>Snap Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safe to Operate</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Compatible with Appropriate Build Plate</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Support Maximum Part Weight</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Low Cost</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Minimal Labor to Operate</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Ergonomic</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Low Skilled Labor to Use</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Serviceability</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Low Maintenance Interval</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Manufacturability</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Mechanical Complexity</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total Score</strong></td>
<td><strong>161</strong></td>
<td><strong>132</strong></td>
<td><strong>120</strong></td>
<td></td>
</tr>
</tbody>
</table>
## Appendix E: Design Hazard Checklist

**DESIGN HAZARD CHECKLIST**

<table>
<thead>
<tr>
<th>Team: VIPER 2.0</th>
<th>Advisor: Dr. Schuster</th>
<th>Date: 11/15/18</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Y</strong></td>
<td><strong>N</strong></td>
<td>1. Will the system include hazardous revolving, running, rolling, or mixing actions?</td>
</tr>
<tr>
<td>✔</td>
<td>□</td>
<td>2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?</td>
</tr>
<tr>
<td>□</td>
<td>✔</td>
<td>3. Will any part of the design undergo high accelerations/decelerations?</td>
</tr>
<tr>
<td>✔</td>
<td>□</td>
<td>4. Will the system have any large (&gt;5 kg) moving masses or large (&gt;250 N) forces?</td>
</tr>
<tr>
<td>□</td>
<td>✔</td>
<td>5. Could the system produce a projectile?</td>
</tr>
<tr>
<td>□</td>
<td>✔</td>
<td>6. Could the system fall (due to gravity), creating injury?</td>
</tr>
<tr>
<td>□</td>
<td>✔</td>
<td>7. Will a user be exposed to overhanging weights as part of the design?</td>
</tr>
<tr>
<td>✔</td>
<td>□</td>
<td>8. Will the system have any burrs, sharp edges, shear points, or pinch points?</td>
</tr>
<tr>
<td>□</td>
<td>✔</td>
<td>9. Will any part of the electrical systems not be grounded?</td>
</tr>
<tr>
<td>□</td>
<td>✔</td>
<td>10. Will there be any large batteries (over 30 V)?</td>
</tr>
<tr>
<td>□</td>
<td>✔</td>
<td>11. Will there be any exposed electrical connections in the system (over 40 V)?</td>
</tr>
<tr>
<td>□</td>
<td>✔</td>
<td>12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?</td>
</tr>
<tr>
<td>✔</td>
<td>□</td>
<td>13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?</td>
</tr>
<tr>
<td>□</td>
<td>✔</td>
<td>14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?</td>
</tr>
<tr>
<td>□</td>
<td>✔</td>
<td>15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?</td>
</tr>
<tr>
<td>✔</td>
<td>□</td>
<td>16. Could the system generate high levels (&gt;90 dBA) of noise?</td>
</tr>
<tr>
<td>□</td>
<td>✔</td>
<td>17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?</td>
</tr>
<tr>
<td>✔</td>
<td>□</td>
<td>18. Is it possible for the system to be used in an unsafe manner?</td>
</tr>
<tr>
<td>✔</td>
<td>□</td>
<td>19. For powered systems, is there an emergency stop button?</td>
</tr>
<tr>
<td>□</td>
<td>✔</td>
<td>20. Will there be any other potential hazards not listed above? If yes, please explain on reverse.</td>
</tr>
</tbody>
</table>

For any “Y” responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.
<table>
<thead>
<tr>
<th>Description of Hazard</th>
<th>Planned Corrective Action</th>
<th>Planned Date</th>
<th>Actual Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two motorized rotating stages</td>
<td>Stages are in an enclosure.</td>
<td>5/21/19</td>
<td></td>
</tr>
<tr>
<td>Moving part and component masses expected to be &gt; 5kg</td>
<td>Moving parts will be in an enclosure.</td>
<td>5/21/19</td>
<td></td>
</tr>
<tr>
<td>Door, moving stages, and build plate attachment will all contain pinch points.</td>
<td>Door will have handle, moving stages will be enclosed when in motion, operator’s manual will describe safe build plate mounting.</td>
<td>5/21/19</td>
<td></td>
</tr>
<tr>
<td>The 316L SS powder is explosive/incendiary when suspended in air.</td>
<td>We will enclose powder that is removed. We will isolate electronics from powder to mitigate risk of sparks.</td>
<td>5/21/19</td>
<td></td>
</tr>
<tr>
<td>The 316L SS powder is hazardous when inhaled and can cause skin/eye irritation.</td>
<td>We will enclose powder that is removed. Operator will wear basic PPE. Operator’s manual will describe safe practices for handling powder.</td>
<td>5/21/19</td>
<td></td>
</tr>
<tr>
<td>It would be unsafe to operate the system with the enclosure door open.</td>
<td>Specify in operator’s manual to close door before running cycle. Possible integration of door sensor that is intended to prevent cycle from running with door open.</td>
<td>5/21/19</td>
<td></td>
</tr>
</tbody>
</table>
Appendix F: Detail Drawings
F - FA: Full Assembly
F-EN: Enclosure

<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART NUMBER</th>
<th>DESCRIPTION</th>
<th>Default/ QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>EN01</td>
<td>Side Panel With Motor</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>EN02</td>
<td>Side Panel</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>EN03</td>
<td>Front Panel</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>EN04</td>
<td>Top Panel</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>EN05</td>
<td>Window</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>BX</td>
<td>Powder Box</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>FR</td>
<td>Door Frame</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>1488A12</td>
<td>Surface Mount Hinge</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>1794A55</td>
<td>Internal Compression Draw Latch</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>1078A3</td>
<td>Handle</td>
<td>1</td>
</tr>
</tbody>
</table>
F-EN03: Enclosure Front Panel

NOTES:
UNLESS OTHERWISE SPECIFIED

1. ALL DIMENSIONS IN INCHES
2. BREAK SHARP EDGES .02 MAX
3. TOLERANCES:
   X,XX = ±0.02
   ANGLES = ±1°
4. MATERIAL: A1008 STEEL
   THICKNESS: 16 GAUGE
F-EN04: Enclosure Top Panel

- ALL DIMENSIONS IN INCHES
- BREAK SHARP EDGES .02 MAX
- TOLERANCES:
  - X.XX = ±0.02
  - ANGLES = ±1°
- MATERIAL: A1008 STEEL
  THICKNESS: 16 GAUGE

NOTES:
F-EN05: Window

NOTES:
UNLESS OTHERWISE SPECIFIED

1. ALL DIMENSIONS IN INCHES
2. BREAK SHARP EDGES .02 MAX
3. TOLERANCES:
   X.XX = ±0.02
   ANGLES = ±1°
4. MATERIAL: POLYCARBONATE
F-EN06: Enclosure Weld Diagram
F-BX_ASSEMBLY: Powder Box Assembly

<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART NUMBER</th>
<th>DESCRIPTION</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BX01</td>
<td>Powder Box 1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>BX02</td>
<td>Powder Box 2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>BX03</td>
<td>Powder Box Base</td>
<td>1</td>
</tr>
</tbody>
</table>

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VPER 2.0

Dwg. #:BX   Nxt Asb:   Date:6/6/19   Scale:1:2   Chkd. By: ME STAFF
F-BX01: Powder Box 1

NOTES:
UNLESS OTHERWISE SPECIFIED

1. ALL DIMENSIONS IN INCHES
2. TOLERANCES:
   X.XX ± 0.02
3. MATERIAL: PLA
4. SHELL THICKNESS: 0.13

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VIPER 2.0

Dwg. #: BX01  Nxt Asb:  Date: 6/6/19  Scale: 1:2
Title: POWDER BOX 1  Drwn. By: ALEX WARD  Chkd. By: ME STAFF
F-BX02: Powder Box 2

NOTES:
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES:
   X.XXX ± 0.02
3. MATERIAL: PLA
4. SHELL THICKNESS: 0.13
F-BX03: Powder Box Base

NOTES:
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES:
   X.XX ± 0.02
3. MATERIAL: POLYCARBONATE
4. THICKNESS: 0.13

12.75
5.75

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VPER 2.0

Dwg. #:BX03    Title: POWDER BOX BASE    Dwn. By: ALEX WARD

Not Asb.: Date: 6/6/19    Scale: 1:2    Chkd. By: ME STAFF
F-FR: Door Frame
F-FR01: Top Bar

NOTES:
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN INCHES
2. BREAK SHARP EDGES .02 MAX
3. TOLERANCES:
   X.XX = ±0.02
   ANGLES = ±1°
4. MATERIAL: 6061 ALUMINUM

4X Ø .27 THRU
F-FR02: Hinge Bar

NOTES:
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN INCHES
2. BREAK SHARP EDGES .02 MAX
3. TOLERANCES:
   X.XX = ±0.02
   ANGLES = ±1°
4. MATERIAL: 6061 ALUMINUM

Dimensions:
- .50
- 1.00
- 7.00
- 1.00
- 13.00
- 1.00
- 15.00
- .25
- .50
- 4X Ø .20 × .65
- 10-24 UNC × .50
- 6X Ø .15 × .63

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Dwg. #: FR02   Nxt Asb:   Date: 2/7/19   Scale: 3:8

Title: HINGE BAR   Drwn. By: ALEX WARD   Chkd. By: ME STAFF
F-03: Latch Bar

NOTES:
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN INCHES
2. BREAK SHARP EDGES .02 MAX
3. TOLERANCES:
   XXX = ± .02
   ANGLES = ± 1°
4. MATERIAL: 6061 ALUMINUM

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VIPER 2.0

Dwg. #: FR03  Nxt Asb:  Date: 2/7/19  Scale: 3:8  Chkd. By: ME STAFF

Title: LATCH BAR  Drwn. By: ALEX WARD
F-MS01: Mounting Base

NOTES:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±.005
   ANGLES = ±1°
3. INSIDE TOOL RADIUS .02 MAX.
4. BREAK SHARP EDGES .02 MAX.
5. MATERIAL: AL 6061
6. FAO

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VIPER 2.0
Dwg. #: MS01
Title: MOUNTING BASE
Date: 5/16/19
Scale: 1:2
Printed By: SEAN MCCRACKEN
Chkd. By: ME STAFF
F-MS02: U Channel

NOTES UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±.005
   X.XXX = ±.001
3. MATERIAL: AL 6061

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VIPER 2.0
Dwg. #: MS02
Title: U CHANNEL
Date: 2/7/19
Scale: 1:2
Chkd. By: ME STAFF

Down. By: SEAN MCCCRACKEN
F-MS03: Adapter Plate

NOTES UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±0.005
   X.XXX = ±0.001
   ANGLES = ±1°
3. MATERIAL: 316L SS

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VIPER 2.0

Dwg. #: M503
Date: 6/5/19
Scale: 1:2
Chkd. By: ME STAFF
F - PR01: Motor Mounting Bracket
NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ± .005
   X.XXX = ± .001
   ANGLES = ± 1°
3. MATERIAL: AL 6061

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Title: U BLOCK SIDE
Dwg. #: PR02
Date: 6/5/19
Scale: 1:2
Drwn. By: SEAN MCCCRACKEN
Chkd. By: ME STAFF
NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±.005
   X.XXX = ±.001
   ANGLES = ±1°
3. MATERIAL: AL 6061
F-SR02: Spacer

NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±.005
   X.XXX = ±.001
   ANGLES = ±1°
3. MATERIAL: 18-8 SS
F-SR03: U Block Base

NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±0.005
   X.XXX = ±0.001
   ANGLES = ±1°
3. MATERIAL: AL 6061

Cal Poly Mechanical Engineering
VIPER 2.0

Title: U BLOCK BASE
Dwg. #: SR03
Date: 6/5/19
Scale: 1:5

Drawn By: SEAN MCCCRACKEN
Chkd. By: ME STAFF
F-CSD201610LG: Electronics Enclosure Layout

NOTES:
UNLESS OTHERWISE SPECIFIED
1. HOLES AND CUTOUTS ARE TO BE ADDED TO 539 x 872 ENCLOSURE FROM MASTER CAS
2. ALL DIMENSIONS IN INCHES
3. BREAK SHARP EDGES .02 MAX
4. TOLERANCES:
   X XXX = ± .03
   XXXXX = ± .005
   ANGLES = ± 1°
F-CSD2016: Electronics Enclosure Panel
# Appendix G: Bill of Materials

## Indented Bill of Material (BOM)

### V.I.P.E.R. 2.0

<table>
<thead>
<tr>
<th>Assembly Level</th>
<th>Part Number</th>
<th>Description</th>
<th>Vendor</th>
<th>Qty</th>
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<td>6-16-18 .687&quot; long TECO BHSCS</td>
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<td></td>
<td>90128A009</td>
<td>6-16-18 .625&quot; long TECO BHSCS</td>
<td>TECO</td>
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Total Parts: 408
Appendix H: Stress Calculations

Aluminum U Channels

FS = 18

FS = 5.3
Aluminum U Channels

FS = 21
ALUMINUM U CHANNEL
LOAD CASE 1

R = 17.5 lb
M = (17.5 lb)(6.33 in)
M = 110.8 lb-in

TREAT AS CANTILEVER BEAM
R = 17.5 lb
M = (17.5 lb)(6.33 in)
M = 110.8 lb-in

FIND MOMENT OF INERTIA
I = \( \frac{1}{12} \) b \( \cdot \) h^3
I = \( \frac{1}{12} \) (3.5 in)(0.13 in)^3
I = 6.4 \( \times \) 10^-4 in^4

CALCULATE BENDING STRESS
\( \sigma_b = \frac{My}{I} \)
\( \sigma_b = \frac{(110.8 lb-in)(0.13 in)}{6.4 \times 10^-4 in^4} \)
\( \sigma_b = 11253 \text{ psi} \)

CALCULATE YIELD FACTOR OF SAFETY
FS_y = \( \frac{S_y}{\sigma_b} \)
FS_y = \( \frac{40000 \text{ psi}}{11253 \text{ psi}} \)
FS_y = 3.6

NOTE: THICKNESS AT TOP AND BOTTOM WAS NEGLECTED.
SHEAR ASSUMED TO BE NEGligible.
ALUMINUM U CHANNEL

LOAD CASE 2

\[ P = 17.5 \text{ lb} \]
\[ M = (17.5)(0.525) = 9.1875 \text{ lb-in} \]
\[ M = 9.1875 \text{ lb-in} \]

MOI HAS ALREADY BEEN FOUND
\[ I = 6.4 \times 10^{-4} \text{ in}^4 \]

CALCULATE BENDING STRESS
\[ \sigma_b = \frac{My}{I} \]
\[ \sigma_b = \frac{9.1875 (0.065 \text{ in})}{6.4 \times 10^{-4} \text{ in}^4} \]
\[ \sigma_b = 933 \text{ psi} \]

CALCULATE AXIAL STRESS
\[ \sigma_a = \frac{P}{A} \]
\[ \sigma_a = \frac{17.5 \text{ lb}}{0.135 \text{ in}} \]
\[ \sigma_a = 130.3 \text{ psi} \]

CALCULATE TOTAL STRESS
\[ \sigma = \sigma_b + \sigma_a \]
\[ \sigma = 933 + 130.3 \text{ psi} \]
\[ \sigma = 1063 \text{ psi} \]

CALCULATE YIELD FACTOR OF SAFETY
\[ FS_y = \frac{S_y}{\sigma} \]
\[ FS_y = \frac{40,000 \text{ psi}}{1063 \text{ psi}} \]
\[ FS_y = 40 \]
ALUMINUM U CHANNEL
CALCULATE BEARING FACTOR OF SAFETY
ASSUME ENTIRE LOAD IS ON ONE BOLT

\[ F_b = \frac{P_i}{A_L} \]

\[ F_b = 3.5 \text{ lb} \]

\[ (0.25 \times 0.04 - 0.13) \text{ in} \]

\[ F_b = 1090 \text{ psi} \]

\[ F_{sb} = \frac{30,000 \text{ psi}}{1090 \text{ psi}} \]

\[ F_{sb} = 28 \]
Primary Motor Mounting Bracket

FS = 9.9

FS = 34
PRIMARY BRACKET CALLED VIPER 2.0

**PRIMARY MOTOR BRACKET FROM MOTOR TORQUE CALCULATIONS**

\[ T_m = 32.75 \text{ in-lb} \]

**FBP WITH MOTOR TORQUE AND WEIGHT**

\[ T_m = 32.75 \text{ in-lb} \]

**CALCULATE BOLT FACTOR OF SAFETY.**

Assume 1 bolt takes all of the load from torque and motor weight. Use G061 aluminium.

\[ \text{bolt_pattern} = \sqrt{2(1.37 \text{ in})} = 32.75 \text{ in-lb} \]

\[ \text{bolt_pattern} = 1.37 \text{ in} \]

\[ T_{torque} = \frac{T_m}{1.37 \text{ in}} = 32.75 \text{ in-lb} / 1.37 \text{ in} = 24.0 \text{ in-lb} \]

\[ F_{with} = T_{torque} + W_m = 24.0 \text{ in-lb} + 8.4 \text{ lb} = 32.4 \text{ lb} \]

\[ F_{bolt} = \frac{W_m \times \rho \times d^2}{(0.25 \text{ in})(0.5 \text{ in})} = \frac{32.4 \text{ lb} \times 0.25 \text{ in}}{(0.25 \text{ in})(0.5 \text{ in})} = 120 \text{ lb} \]

**CALCULATE STRESS, WHERE MOTOR IS MOUNTED**

\[ \sigma = \frac{F_{bolt}}{A} = \frac{120 \text{ lb}}{(0.25 \text{ in})(0.5 \text{ in})} = 300 \text{ psi} \]

\[ \sigma = 300 \text{ psi} \]

**FS = \frac{5}{\sigma} = 1 \text{ psi} \]

**FS = 470,000 psi**

**FS = 152**

**CALCULATIONS CONTINUED ON NEXT PAGE**
PRIMARY MOTOR BRACKET CONTINUED

SOLVING FOR REACTIONS

\[ T = T_m = 32.75 \text{ lb-in} \]
\[ R = 8.4 \text{ lb} \]
\[ M = (8.4 \text{ lb})(4.46 \text{ in} + 2.5 \text{ in}) \]
\[ M = 55.5 \text{ lb-in} \]

SOLVE FOR STRESS

ASSUME PURE SHEAR IS NEGLECTIBLE

FIND BENDING STRESS

\[ \sigma_b = \frac{Mc}{I} = \frac{52.5 \text{ lb-in})(3.285 \text{ in})}{(3.285 \text{ in})(0.34 \text{ in})^3} = 12800 \text{ psi} \]

FIND TORSION STRESS

USE \( J = \frac{3}{2} \rho R^4 \)

WHERE \( \rho \) IS A FUNCTION OF \( \frac{t}{b} \)

\[ \frac{t}{b} = (3.285 / 0.34) = 9.64 \Rightarrow \rho = 0.3 \]

\[ \sigma = \frac{Tc}{J} = \frac{52.75 \text{ lb-in})(3.285 \text{ in})}{0.3 (3.285 \text{ in})(0.34 \text{ in})^3} = 1990 \text{ psi} \]

FIND VON MISSES STRESSES

\[ \sigma_{\text{vm}} = \sqrt{\sigma_b^2 + 3 \sigma_t^2} = \sqrt{(12800 \text{ psi})^2 + 3(1990 \text{ psi})^2} \]

\[ \sigma_{\text{vm}} = 13260 \text{ psi} \]

\[ F_S = \frac{S_y}{\sigma_{\text{vm}}} = \frac{47000}{13260} \]

\[ F_S = 3.51 \]
Secondary Motor Mounting Brackets

FS = 58

FS = 34
DETERMINING BOLT LOAD FROM SECONDARY AXIS TORQUE BOLT PATTERN TOP VIEW

\[
F = \frac{1}{4} r^2 \\
= \frac{1}{4} r \\
= \frac{1580 \text{ in.}}{4(1.32 \text{ in.})} (16 \text{ oz}) \\
F = 1.87 \text{ lb}
\]

BREAKING \( F \) INTO COMPONENTS

\[
\frac{\sqrt{2}}{2} \ F = \ F_2 \sin(45^\circ) \\
F_1 = F_2 = F \sin(45^\circ) \\
F_1 = F_2 = 1.32 \text{ lb}
\]
ANALYZE Z-BRACKET AS CANTILEVER BEAM

WM PLACED AT CENTROID OF MOTOR TO ACCOUNT FOR ADDITIONAL MOMENT LOAD
ANALYZE AT LOCATION OF DOT

STATICS

\[ V_x = W_m = 1.32 \text{ lb} \]
\[ V_y = F_m = 2.64 \text{ lb} \]
\[ T = M_1 - M_2 \]
\[ I = 2.46 \text{ lb-in} - 0.36 \text{ lb-in} \]
\[ I = 1.6 \text{ lb-in} \]
\[ M_x = (1.32 \text{ lb})(1.36 \text{ in}) \]
\[ M_y = (1.32 \text{ lb})(2.64 \text{ lb}) \]
\[ M_z = 3.64 \text{ lb-in} \]

\[ M_y = (3.56 \text{ in})(W_m) \]
\[ M_y = (3.56 \text{ in})(1.32 \text{ lb}) \]
\[ M_z = 4.7 \text{ lb-in} \]

ASSUME PURE SHEAR IS NEGLIGIBLE FOR TORSION USE J = \( \frac{4}{3} I \)
WHERE J IS A FUNCTION OF \( a/b \)
\[ a/b = (2.52)(0.13) = 19.3 \]
\[ J = (0.332)(2.52 \text{ in})(0.13 \text{ in})^3 = 1.84 \times 10^{-3} \text{ in}^4 \]
\[ C = \frac{I}{J} = (1.6 \text{ lb-in})(1.32 \text{ lb}) = 10.96 \text{ psi} \]
\[ \sigma = \left( \frac{M_1}{I} \right) + \left( \frac{M_2}{I} \right) \]
\[ = \frac{(3.64 \text{ lb-in})(1.26 \text{ in}) + (4.7 \text{ lb-in})(0.065 \text{ in})}{2} \]
\[ = 689 \text{ psi} \]
\[ \sigma_{vm} = \sqrt{\sigma^2 + 3C^2} = \sqrt{(689)^2 + 3(1096)^2} = 2020 \text{ psi} \]
\[ FS = \frac{\sigma}{\sigma_{vm}} = 23 \]
\[ FS = \frac{47000}{2020} = 23 (2024 A1) \]
TOP VIEW OF LOAD ON 2 BRACKET LOAD ON BOLTS FROM SECONDARY AXIS CALCS. WEIGHT OF MOTOR IN CANTILEVER DIRECTION IS ANALYZED.

\[ R_{11} \uparrow \quad F_2 = 1.32 \text{ lb} \quad F_1 = 1.32 \text{ lb} \]

\[ W_m = 1.32 \text{ lb} \quad 1.86 \text{ in} \]

\[ F_1 = 1.32 \text{ lb} \]

TURN \( F_1 \) LOADS INTO COUPLING (M1) MOVE \( F_2 \) LOADS, CREATING EQUIVALENT MOMENT (M2) LET \( F_2 + F_2 = F_m \).

\[ F_m = 2 F_2 \]

\[ F_m = 2 (1.32 \text{ lb}) \]

\[ F_m = 2.64 \text{ lb} \]

\[ M_1 = (1.86 \text{ in})(1.32 \text{ lb}) \]

\[ M_1 = 2.46 \text{ lb-in} \]

\[ M_2 = (0.65 \text{ in})(1.32 \text{ lb}) \]

\[ M_2 = 0.86 \text{ lb-in} \]

FINDING BEARING FACTOR OF SAFETY:

\[ F_{in} = \sqrt{F_1 + \frac{w_{in} y^2 + F_2^2}{2}} \]

\[ F_{in} = \sqrt{(1.32)^2 + \frac{1.32^2}{2} + 1.32^2} \text{ lb} \]

\[ F_{in} = 2.38 \text{ lb} \]

\[ \sigma_b = \frac{F_{in}}{0.13 \text{ in}} \]

\[ \sigma_b = 31.5 \text{ psi} \]

USING 2024 AL SHEAR STRENGTH

\[ F_{sa} = 41,000 \text{ psi} \]

\[ F_{sa} = 41.05 \text{ psi} \]

\[ F_{sa} = 160 \text{ psi} \] (HIGH)
# Factor of Safety Table

<table>
<thead>
<tr>
<th>Component</th>
<th>Factor of Safety</th>
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<tbody>
<tr>
<td>Primary Bracket</td>
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<td>@ Motor</td>
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<tr>
<td>@ Frame</td>
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<tr>
<td>Fasteners</td>
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<td>Primary Shaft (Previous Group)</td>
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<td>Primary Bearings (Previous Group)</td>
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<tr>
<td>Z Bracket</td>
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<td>Cantilever</td>
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<td>Fasteners</td>
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<td>Secondary Shaft (Previous Group)</td>
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<tr>
<td>Secondary Bearing</td>
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<tr>
<td>U Channel</td>
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<td>Cantilever</td>
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<td>Damping Mounts</td>
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<td>Printed Part Mounting</td>
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<td>Bearings</td>
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<tr>
<td>Shafts</td>
<td>2.24</td>
</tr>
</tbody>
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## Appendix I: Motor Torque Calculations

### Torque Calculations

- **FOS-1:**
  - \( Nm2ozin = 141.6119323 \)
  - \( time2rot = 10 \)
  - \( t2speed = 2 \)
  - \( \omega = 2 \cdot (1/time2rot) \pi \)
  - \( mprime = 48.3 \)
  - \( yCOM = 0.8 \)
  - \( Iy = 839.63 \)
  - **Primary rotating stage in \( lbm-in^2 \)**
  - \( Ix = 166.61 \)
  - **Secondary rotating stage in \( lbm-in^2 \)**
  - \( g = 32.2 \)
  - \( \alpha = \omega / t2speed \)
  - \( Iybar = Iy + (mprime) \cdot (yCOM)^2 \)

### Primary Axis

- **Dynamic torque in the primary axis**
  - \( dprimetorque2lbfin = (Iybar \cdot \alpha) / g \)
  - \( dprimetorque2nm = dprimetorque2lbfin \cdot 0.11298482933333 \)
  - \( dprimetorqueozin = dprimetorque2nm \cdot Nm2ozin \)

- **Static torque in the primary axis**
  - \( sprime2nm = 2.741 \)
  - \( sprime2lbfin = sprime2nm / 0.11298482933333 \)
  - \( sprime2ozin = sprime2nm \cdot Nm2ozin \)

- **Total torque in the primary axis**
  - \( primetorque2ozin = dprimetorqueozin + sprime2ozin \)

- **Factor of Safety**
  - \( Nm \) to \( oz-in \) conversion ratio
  - \( Time \) to fully rotate in \( seconds \)
  - \( Time \) to reach final speed
  - \( rad/sec \)
  - \( Mass \) of primary rotational stage
  - \( Distance \) in \( y \) to the center of mass
  - \( Moment \) of inertia in the \( y \) axis of the
  - \( Moment \) of inertia in the \( x \) axis of the
  - \( Gravity \) Constant in \( ft/sec^2 \)
  - **Angular acceleration in \( rad/sec^2 \)**
  - **Adjusted MOI with parallel axis theorem in \( lbm-in^2 \)**
Secondary Axis

Dynamic torque in the secondary axis
\[
d\text{sectorque} \left\{ \text{lb}\cdot\text{in} \right\} = \frac{1x\cdot\alpha}{g} \\
d\text{sectorque} \left\{ \text{N}\cdot\text{m} \right\} = \frac{0.11298482933333}{g} \\
d\text{sectorque} \left\{ \text{oz}\cdot\text{in} \right\} = \frac{d\text{sectorque} \cdot N\cdot\text{m}}{2\pi\cdot\text{in}}
\]

Total torque in the secondary axis
\[
d\text{sectorque} \left\{ \right\} = d\text{sectorque} \left\{ \right\} \cdot d\text{sectorque} \left\{ \right\}
\]

\[
d\text{display}(d\text{sectorque} \left\{ \right\}) \\
d\text{display}(d\text{sectorque} \left\{ \right\})
\]

primetorquetot = 524.0534

sectorquetot = 26.0085

Published with MATLAB® R2018b
Appendix J: PLC Ladder Logic

Main Code

6/4/2019

1

$On
ST1

RUN
Program
motor1

2

RUN
Program
motor2

3

$On
ST1

RUN
Program
Vibrations

4

{ NOP }

H2-DM1E reference
## Appendix K: FMEA

<table>
<thead>
<tr>
<th>System</th>
<th>Function</th>
<th>Potential Failure Mode</th>
<th>Potential Effects off Failure Mode</th>
<th>Severity</th>
<th>Potential Causes of Failure Mode</th>
<th>Planned Preventative Activities</th>
<th>Occurrence</th>
<th>Planned Detection Activities</th>
<th>Detection</th>
<th>RPN</th>
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<tbody>
<tr>
<td>System</td>
<td>Function</td>
<td>Potential Failure Mode</td>
<td>Potential Effects of Failure Mode</td>
<td>Severity</td>
<td>Potential Causes of Failure Mode</td>
<td>Planned Preventative Activities</td>
<td>Occurrence</td>
<td>Planned Detection Activities</td>
<td>Detection</td>
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## Appendix L: DesignSafe Risk Analysis

### DesignSafe Report

<table>
<thead>
<tr>
<th>Item Id</th>
<th>User / Task</th>
<th>Hazard / Failure Mode</th>
<th>Initial Assessment Severity Probability</th>
<th>Risk Level</th>
<th>Risk Reduction Methods / Control System</th>
<th>Final Assessment Severity Probability</th>
<th>Risk Level</th>
<th>Status / Responsible / Comments</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1-1</td>
<td>All Users Common Tasks</td>
<td>mechanical: drawing-in / trapping / entanglement User's body or clothing stuck or caught in rotating stage</td>
<td>Serious Unlikely</td>
<td>Low</td>
<td>warning labels, standard procedures, instruction manuals, special clothing, fixed enclosures / barriers</td>
<td>Serious Remote</td>
<td>Low</td>
<td>Complete / Alex</td>
<td></td>
</tr>
<tr>
<td>1-1-2</td>
<td>All Users Common Tasks</td>
<td>mechanical: pinch point Door closing on user's finger</td>
<td>Moderate Unlikely</td>
<td>Low</td>
<td>standard procedures, separate hazard / people in time or space</td>
<td>Moderate Remote</td>
<td>Negligible</td>
<td>Complete / Alex</td>
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<td>1-1-3</td>
<td>All Users Common Tasks</td>
<td>mechanical: unexpected start System cycle starts when user is not prepared</td>
<td>Serious Unlikely</td>
<td>Medium</td>
<td>delayed start, visible alarm or signal, standard procedures, separate hazard / people in time or space, E-stop control</td>
<td>Serious Remote</td>
<td>Medium</td>
<td>Complete / Melissa</td>
<td></td>
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<tr>
<td>1-1-4</td>
<td>All Users Common Tasks</td>
<td>electrical / electronic: energized equipment / live parts User exposed to wiring or electrical components</td>
<td>Serious Remote</td>
<td>Low</td>
<td>use to electrical codes (NEC/IEEE), fixed enclosures / barriers, warning label(s), standard procedures</td>
<td>Serious Remote</td>
<td>Low</td>
<td>Complete / Alex &amp; Melissa</td>
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<td>1-1-5</td>
<td>All Users Common Tasks</td>
<td>electrical / electronic: lack of grounding (earthing or neutral) User touching ungrounded energized part</td>
<td>Serious Remote</td>
<td>Low</td>
<td>use to electrical codes (NEC/IEEE), prevent energy buildup, fixed enclosures / barriers</td>
<td>Serious Remote</td>
<td>Low</td>
<td>Complete / Melissa</td>
<td></td>
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<tr>
<td>Item Id</td>
<td>User / Task</td>
<td>Hazard / Failure Mode</td>
<td>Initial Assessment Severity Probability</td>
<td>Risk Level</td>
<td>Risk Reduction Methods / Control System</td>
<td>Final Assessment Severity Probability</td>
<td>Risk Level</td>
<td>Status / Responsible / Comments / Reference</td>
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<td>1-1-6</td>
<td>All Users Common Tasks</td>
<td>electrical / electronic : shorts arcing / sparking likely energized parts to metal powder or other conductive material</td>
<td>Moderate / Unlikely</td>
<td>Low</td>
<td>wire to electrical cords (NEC/IEC), fixed enclosures / barriers, use IP 6 X rated parts</td>
<td>Moderate / Unlikely</td>
<td>Low</td>
<td>Complete Sean</td>
<td></td>
</tr>
<tr>
<td>1-1-7</td>
<td>All Users Common Tasks</td>
<td>electrical / electronic : improper wiring / Human error</td>
<td>Moderate / Unlikely</td>
<td>Low</td>
<td>wire to electrical cords (NEC/IEC), fixed enclosures / barriers, warning label(s), standard procedures</td>
<td>Moderate / Unlikely</td>
<td>Low</td>
<td>Complete Alex</td>
<td></td>
</tr>
<tr>
<td>1-1-8</td>
<td>All Users Common Tasks</td>
<td>electrical / electronic : unexpected start up / motion System cycle starts when user is not prepared</td>
<td>Catastrophic / Unlikely</td>
<td>Medium</td>
<td>delayed start, visible alarm or signal, standard procedures, separate hazard / people in time or space. E-stop control</td>
<td>Catastrophic / Unlikely</td>
<td>Medium</td>
<td>Complete Melissa</td>
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<td>1-1-9</td>
<td>All Users Common Tasks</td>
<td>electrical / electronic : overvoltage overcurrent, Faulty power supply or faulty writing for power supply</td>
<td>Catastrophic / Unlikely</td>
<td>Medium</td>
<td>wire to electrical cords (NEC/IEC), prevent energy buildup, fixed enclosures / barriers</td>
<td>Catastrophic / Unlikely</td>
<td>Medium</td>
<td>Complete Andrews</td>
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<td>1-1-10</td>
<td>All Users Common Tasks</td>
<td>ergonomics / human factors : posture / Spine inside of enclosure causing user to orient their posture into difficult positions</td>
<td>Minor / Unlikely</td>
<td>Negligible</td>
<td>standard procedures, instruction manuals</td>
<td>Minor / Remote</td>
<td>Negligible</td>
<td>Complete Andrew</td>
<td></td>
</tr>
<tr>
<td>1-1-11</td>
<td>All Users Common Tasks</td>
<td>ergonomics / human factors : lifting / bending / twisting User attaching parts to mount in difficult positions</td>
<td>Minor / Unlikely</td>
<td>Negligible</td>
<td>standard procedures, instruction manuals</td>
<td>Minor / Remote</td>
<td>Negligible</td>
<td>Complete Andrew</td>
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<tr>
<td>1-1-12</td>
<td>All Users Common Tasks</td>
<td>fire / explosions : static electricity State build up from parts or human interaction causing an ignition source</td>
<td>Serious / Remote</td>
<td>Low</td>
<td>prevent energy buildup</td>
<td>Serious / Remote</td>
<td>Low</td>
<td>Complete Sean</td>
<td></td>
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<tr>
<td>Item Id</td>
<td>User / Task</td>
<td>Hazard / Failure Mode</td>
<td>Initial Assessment Severity Probability</td>
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<td>Risk Reduction Methods / Control System</td>
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<tr>
<td>11-13</td>
<td>All Users</td>
<td>fire and explosions; ignitable dust; ignition caused by sparking or other electrical failures</td>
<td>Serious Remote</td>
<td>Low</td>
<td>wire to electrical codes (NEC/IEC), prevent energy buildup</td>
<td>Serious Remote</td>
<td>Low</td>
<td>Complete Sean</td>
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<tr>
<td>11-14</td>
<td>All Users</td>
<td>noise/vibration; equipment damage; loosening of fasteners</td>
<td>Moderate Unlikely</td>
<td>Low</td>
<td>Use of Thread Lock</td>
<td>Moderate Unlikely</td>
<td>Low</td>
<td>Complete Alex</td>
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<tr>
<td>11-15</td>
<td>All Users</td>
<td>environmental / industrial hygiene; irritants; SS powder is a skin and eye irritant</td>
<td>Moderate Unlikely</td>
<td>Low</td>
<td>safety glasses, separate hazard / people in time or space, fixed enclosures / barrie, warning label(s), instruction manuals, respiratory protection, gloves</td>
<td>Moderate Remote</td>
<td>Negligible</td>
<td>Complete Melissa</td>
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## Appendix M: Cost Spreadsheet

<table>
<thead>
<tr>
<th>Company/Part</th>
<th>Parts Per Pkg</th>
<th>Pkg's Purchased</th>
<th>Cost per pkg</th>
<th>Purchase Cost</th>
<th>Part Number</th>
<th>Purchasing Method</th>
<th>Date Purchased</th>
<th>Date Received</th>
<th>Link</th>
</tr>
</thead>
</table>
| CPU          | 1             | 1               | $405.00      | $405.00       | M2-DM1E     | Procard          | 2/28/19       | 3/4/19       | https://www.autone |}
| CPU Memory Cartridge backup battery | 1 | 1 | $3.00 | $3.00 | D0-MC-BAT | Procard | 2/28/19 | 3/5/19 | https://www.autone |
| Universal Cable Kit | 1 | 1 | $42.50 | $42.50 | FA-CABKIT | Procard | 2/28/19 | 3/6/19 | https://www.autone |
| LiIon Teflich Primary | 1 | 1 | $23.50 | $23.50 | AEML0542213-3 | Procard | 2/28/19 | 3/7/19 | https://www.autone |
| Limit Switch Secondary | 1 | 1 | $26.00 | $26.00 | AEML05242122-3R | Procard | 2/28/19 | 3/8/19 | https://www.autone |
| DC/DC | 1 | 1 | $55.00 | $55.00 | D-H06N3D | Procard | 2/28/19 | 3/9/19 | https://www.autone |
| Comm Expansion | 1 | 1 | $181.00 | $181.00 | H2-SPRO | Procard | 2/28/19 | 3/10/19 | https://www.autone |
| Analog Output | 1 | 1 | $171.00 | $171.00 | F2-020A-2 | Procard | 2/28/19 | 3/11/19 | https://www.autone |
| DC Power Supply | 1 | 1 | $192.00 | $192.00 | STP-PWR-4810 | Procard | 2/28/19 | 3/12/19 | https://www.autone |
| Stepper Motor Drive | 1 | 1 | $279.00 | $279.00 | STP-DVR-8000 | Procard | 2/28/19 | 3/13/19 | https://www.autone |
| Regeneration Clump for Stepper Drive | 1 | 1 | $90.00 | $90.00 | STP-DVR-A-C-050 | Procard | 2/28/19 | 3/14/19 | https://www.autone |
| DC Drive | 1 | 1 | $135.00 | $135.00 | GD01-48-10C | Procard | 2/28/19 | 3/15/19 | https://www.autone |
| HMI Panel | 1 | 1 | $163.00 | $163.00 | EAI-335MV-N | Procard | 2/28/19 | 3/16/19 | https://www.autone |
| I/O Panel Bezel | 1 | 1 | $88.00 | $88.00 | EA-MG-B22 | Procard | 2/28/19 | 3/17/19 | https://www.autone |
| Panel Mounting Brackets | 1 | 1 | $18.00 | $18.00 | EA-MG-SJL-M-88X | Procard | 2/28/19 | 3/18/19 | https://www.autone |
| Function Key label replacements | 1 | 1 | $10.00 | $10.00 | EA-MG-SJL-M-FKL | Procard | 2/28/19 | 3/19/19 | https://www.autone |
| USB A & B Programming Cable | 1 | 1 | $18.50 | $18.50 | USB-RJ45AB10 | Procard | 2/28/19 | 3/20/19 | https://www.autone |
| RS-232C Serial Communication Cable, R02 - R02 | 1 | 1 | $19.50 | $19.50 | DV-100038 | Procard | 2/28/19 | 3/22/19 | https://www.autone |
| Primary Axis Steering Motor | 1 | 1 | $185.00 | $185.00 | STP-MTRN-A-34277 | Procard | 2/28/19 | 3/23/19 | https://www.autone |
| Insulated Screw Driver | 1 | 1 | $6.75 | $6.75 | TW-MD-VPH-1 | Procard | 2/28/19 | 3/24/19 | https://www.autone |
| USB/RS 232 Programming Cable | 1 | 1 | $43.50 | $43.50 | EA-MG-PGM-CBL | Procard | 4/11/19 | 4/16/19 | https://www.autone |

**McMaster-Carr**

- Easy-to-Install Vibration-Damping Mount
- Steel Plate Thick, 1-3/4” by 1-3/4” x 1-1/4” x 1/2” x 1/16” thick
- Hinges
- GI-Resistant Burnt In-Rubber Strip (SIA)
- Shaft Seal 1” Shaft diameter
- Polycarbonate Window 24” x 24” by 1/8”
- Door Latches
- Box
- Door Handle/Latch
- 5/16”-18 3/4” Long Socket Head Screw
- Aluminum Door Frame 1” by 1” (8” long)
- Primary axis Motor Coupling
- Secondary Motor Coupling 1/4”
- Secondary Motor Coupling 1/2”
- Flexible Shaft Coupling Hub
- M5x0.7mm STL Nylon Insert Locknut
- M4 Flat Washer
- 1/4“-20 STL Nylon Insert Locknut
- 1/4“-20 3/4“ Long Socket Head Cap Screw
- #6 Flat Washer
- #6-32 Nylon Insert Locknut
- #6-32 Socket Head Cap Screw
- #8 Flat Washer
- #8-32 Nylon Insert Locknut
- #8-32 5/8” Long Socket Head Cap Screw
- #4 Flat Washer
- #4-20 Nylon Insert Locknut
- #4-20 5/8” Long Socket Head Cap Screw
- M4 x 0.7mm 20mm Long Socket Head Cap Screw
- 1/4” Flat Washer
- 5/16” Flat Washer
- 5/16”-18 Nylon Insert Locknut
- 5/16” Sealing Washer
- M8x1.25mm 30mm Long Button Head Socket Cap Screw
- 1/4“-20 1” Long Socket Head Cap Screw
- 1/4“-20 Hex Nut
- 1/8“-16 Hex Nut

<p>| Team | (M) | 4/11/19 | 4/16/19 | <a href="https://www.mcma">https://www.mcma</a> |</p>
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<tr>
<th>Company/Part</th>
<th>Parts Purchased</th>
<th>Plugs Purchased</th>
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<td>$12.35</td>
<td>0-94112</td>
<td>Procard</td>
<td>2/28/19</td>
<td>3/1/19</td>
<td></td>
</tr>
<tr>
<td>Misumi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaft Collar, D-shapped</td>
<td>1</td>
<td>1</td>
<td>$20.46</td>
<td>$20.46</td>
<td>PSTD1350-12</td>
<td>Procard</td>
<td>2/28/19</td>
<td>3/15/19</td>
<td></td>
</tr>
<tr>
<td>Nova Depot</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plywood panel 3/4&quot; by 47 7/8&quot; 180° thick</td>
<td>1</td>
<td>1</td>
<td>$7.74</td>
<td>$7.74</td>
<td>n/a</td>
<td>Team (M)</td>
<td>4/10/19</td>
<td>4/10/19</td>
<td></td>
</tr>
<tr>
<td>Fasteners for mounting onto panel</td>
<td>24</td>
<td>1</td>
<td>$15.23</td>
<td>$15.23</td>
<td>n/a</td>
<td>Team (M)</td>
<td>4/10/19</td>
<td>4/10/19</td>
<td></td>
</tr>
<tr>
<td>Power Grab Ultimate Clear 9 fl. oz. Construction Adhesive</td>
<td>1</td>
<td>1</td>
<td>$9.88</td>
<td>$9.88</td>
<td>n/a</td>
<td>Team (M)</td>
<td>5/18/19</td>
<td>5/18/19</td>
<td></td>
</tr>
<tr>
<td>Counting Gun</td>
<td>1</td>
<td>1</td>
<td>$3.57</td>
<td>$3.57</td>
<td>n/a</td>
<td>Team (M)</td>
<td>5/18/19</td>
<td>5/18/19</td>
<td></td>
</tr>
<tr>
<td>M8 x 6 mm Pan-Head Machine Screw</td>
<td>3</td>
<td>2</td>
<td>$0.76</td>
<td>$1.52</td>
<td>n/a</td>
<td>Team (M)</td>
<td>5/18/19</td>
<td>5/18/19</td>
<td></td>
</tr>
<tr>
<td>Cellular Rubber Weatherstrip Tape 9/16&quot; x 9/16&quot; x 10 ft</td>
<td>1</td>
<td>1</td>
<td>$8.58</td>
<td>$8.58</td>
<td>n/a</td>
<td>Team (M)</td>
<td>5/18/19</td>
<td>5/18/19</td>
<td></td>
</tr>
<tr>
<td>Vinyl Foam Weather-Goal Self-Stick Tape</td>
<td>1</td>
<td>1</td>
<td>$8.58</td>
<td>$8.58</td>
<td>n/a</td>
<td>Team (M)</td>
<td>5/18/19</td>
<td>5/18/19</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>$5,299.83</strong></td>
</tr>
</tbody>
</table>
Appendix N: Wiring Diagrams

Appendix N-1: Stepper Motor Wiring
Appendix N-2: Vibration Motor Wiring Schematic

[Diagram of vibration motor wiring schematic]
Appendix N-3: Limit Switch Wiring Schematic
Appendix N-4: Power Supply Wiring Schematic
Appendix N-5: PLC and HMI Wiring Schematic

AC Wall Power

E stop

To Analog Output

RS-232 Cable
## Senior Project DVPR

**Date:** 9/5/2018  
**Team:** V.I.P.E.R. 2.0  
**Sponsor:** Lawrence Livermore National Laboratory  
**Description of System:** Metal powder remover  
**DVPR Engineer:** Melissa O'Neill and Andrew Epperson

### TEST PLAN

| Item No. | Specification # | Test Description | Acceptance Criteria | Test Responsibility | Test Stage | Quant Type | Start date | Finish date | Test Result | Quantity Pass | Quantity Fail | NOTES |
|----------|-----------------|------------------|---------------------|---------------------|------------|------------|------------|-------------|-------------|---------------|----------------|----------------|-------|
| 1        | 1               | VIPER 1.0 Powder Removal Benchmark Test | No Visible | Andrew | CP | 1 | Sys | 12/8/2018 | 12/8/2018 | Fail | 0 | 1 | Needs stronger vibration and more vibe isolation |
| 2 | 1 | Structural Prototype Powder Removal with New Vibration Motor and Mounting System | No Visible | Seam | SP | 1 | Sys | 3/1/2019 | 3/1/2019 | Fail | 0 | 1 | Vibration alone not enough, reorientation helped a lot, and with occasional tapping with mallet we think that the final system will still meet time requirements |
| 3 | n/a | Transmissibility Ratio Test | n/a | Alex | PP | 1 | Sys | 5/28/2019 | 5/28/2019 | Pass | 1 | 0 | Highest accelerations observed at max duty cycle to vibration motor |
| 4 | 5 | Weight Capacity | 35 lb | Seam | PP | 1 | Sub | 6/5/2019 | 6/5/2019 | Fail | 0 | 1 | Primary axis stepper motor only able to reliably lift 10 lb load on build plate |
| 5 | n/a | Confirmation Prototype Powder Removal Runtime Determination Test | n/a | Andrew | PP | 1 | Sys | 5/23/2019 | 5/23/2019 | Pass | 1 | 0 | 92% of total powder was removed by automatic cycle without any operator intervention |
| 6 | 1, 3, 5, 11 | Confirmation Prototype Powder Removal Complete Test | 1. No Visible  
3. <30 min  
9. <2.5 hr  
11. No Visible | All | PP | 1 | Sys | 6/2/2019 | 6/2/2019 | Mixd | 1 | 1 | First test part was unable to remove all the powder within the 30 min operator time limit. Second test part was able to remove all powder within 14 min operator time and 27 min local process time |
| 7 | 8 | Operator Satisfaction Survey | 4.6 | Melissa | PP | 1 | Sys | 6/4/2019 | 6/4/2019 | Pass | 1 | 0 | Survey taken by Dr. Xuany Wang of the IME Department |
Appendix P: Test Procedures and Results

Test Procedure

Item 1: VIPER 1.0 Powder Removal Benchmark Test

Date Performed: 12/6/18

Location Performed:
Cal Poly Composites Laboratory

Engineers present:
Melissa O’Neil, Alex Ward, Sean McCracken, Andrew Epperson

Description of Test:
Use previous team’s prototype with a printed part to determine system efficacy at powder removal

Acceptance Criteria:
If after simulated cycle is complete, there is no visible powder removed from part on the dark surface below part when tapped with mallet.

Required Materials:
1. VIPER 1.0
2. Nitrile gloves
3. Powder collection device (plastic bag)
4. Fume hood
5. Digital Scale
6. Allen wrenches
7. Tape
8. Table with dark surface
9. 316L SS Printed Test Part from LLNL with remaining powder (Figure 1.1).

Figure 1.1. 316L SS Printed Test Part From LLNL
Testing Protocol:
1. Measure the mass of a powder collection device
2. Attach vibration motor to back of build plate/part
3. Attach the part to the mounting brackets
4. Attach the powder collection device to VIPER using tape such that it covers the part
5. Orient the part upside down
6. Vibrate the part for 5 seconds
7. After the time has elapsed, detach the collection device and measure its mass. The original mass of the collection device is subtracted from the total mass to get the removed powder's mass.
8. Repeat process until no powder is seen leaving the part and the mass measurements plateau.
9. Once no powder is being removed with the vibration, tap part with mallet to see if powder remains.

Data:

<table>
<thead>
<tr>
<th>Time Vibrated (s)</th>
<th>Orientation</th>
<th>Mass of Removed Powder (g)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Straight Down</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Straight Down</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Straight Down</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Straight Down</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Straight Down</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>Straight Down</td>
<td>16</td>
<td>No more powder removed at this orientation</td>
</tr>
<tr>
<td>65</td>
<td>Rotated Secondary Axis 90°</td>
<td>17</td>
<td>More powder removed after changing orientation</td>
</tr>
<tr>
<td>75</td>
<td>Rotated Secondary Axis 90°</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>105</td>
<td>Rotated Secondary Axis 90°</td>
<td>18</td>
<td>No more powder removed by device, but more was removed by tapping with mallet</td>
</tr>
</tbody>
</table>

Observations:
- Significant vibrations transferred through the frame
- Took a lot of time to mount motor and part to device
- Many holes/fastener did not line up correctly making assembly process lengthy and difficult for operator
- Vibration motor seems too weak to produce the necessary accelerations to induce powder flow
- Shake test failed

Pass / Fail: **Fail**
Test Procedure

Item 2: Structural Prototype Powder Removal with New Vibration Motor and Mounting System

Date Performed: 3/1/19

Location Performed:
Cal Poly Composites Laboratory

Engineers present:
Melissa O’Neil, Alex Ward, Sean McCracken, Andrew Epperson

Description of Test:
Use previous team's prototype with modified mounting and vibration system to determine effectiveness of:
- New Precision Microdrive 334-800 125G Vibration Motor
- Universal Mount Vibration Isolators
- New Mounting/Adapter Plate Design

Acceptance Criteria:
If after simulated cycle is complete, there is no visible powder removed from part on the dark surface below part when tapped with mallet.

Required Materials:
1. VIPER 1.0 with modified mounting system
2. Fasteners
3. Nitrile gloves
4. Powder collection device (plastic bag)
5. Fume hood
6. Digital Scale
7. Allen wrenches
8. Vibration motor 334-800 from Precision Microdrive
9. 24 VDC Power Supply
10. Tape
11. 316L SS Printed Part with remaining powder (Figure 1.1)

Testing Protocol:
1. Measure the mass of a powder collection device
2. Attach the part to the mounting plate
3. Attach the powder collection device to VIPER using tape such that it covers the part
4. Orient the part upside down
5. Vibrate the part for 5 seconds
6. After the time has elapsed, detach the collection device and measure its mass. The original mass of the collection device is subtracted from the total mass to get the removed powder’s mass.
7. This process is then repeated until no powder is seen leaving the part and the mass measurements plateau
8. Once no powder is being removed with the vibration, tap part with mallet to see if any powder remains.
9. Repeat steps 5-8 until all powder is removed.

Data:

<table>
<thead>
<tr>
<th>Time Vibrated (s)</th>
<th>Orientation</th>
<th>Mass of Removed Powder (g)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Straight Down</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Straight Down</td>
<td>31</td>
<td>Majority of powder came out within first 5s</td>
</tr>
<tr>
<td>10</td>
<td>Straight Down</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Straight Down</td>
<td>35</td>
<td>No more powder removed at this orientation. Times data collection over. Speed over powder removal is promising</td>
</tr>
<tr>
<td>-</td>
<td>Pointed Opening Downward</td>
<td>38</td>
<td>Varied vibration frequency. Vibrated until no more powder was removed at this orientation</td>
</tr>
<tr>
<td>-</td>
<td>Various</td>
<td>44</td>
<td>Varied vibration frequency and orientation, occasionally hitting with mallet to restart flow</td>
</tr>
</tbody>
</table>

Observations:
- Still significant vibrations transferred through frame.
- First shake test failed. After tapping part with mallet, more powder was removed by device.
- Shake test was repeated 3 times before success. Each mallet tapping resulted in more powder being removed by the device.
- While vibration alone did not remove all the powder, occasional tapping with mallet to restart powder flow still enabled all powder to be removed.
- Difficult to mimic “continuous reorientation” that will be present in final device, but reorientation was helpful in enabling more powder flow

Pass / Fail: **FAIL**
Test Procedure

Item 3: Transmissibility Ratio Test

Date Performed: 5/28/19

Location Performed:
Cal Poly Vibrations Laboratory

Engineers present:
Melissa O’Neil, Alex Ward, Sean McCrackin

Description of Test:
Measure the vibration amplitude at the build plate and first vibration stage as a function of input provided to the DC motor controller to determine the optimum frequency to run the vibration motor at. Data about vibration transmissibility could also be useful for future iterations of this design.

Acceptance Criteria:
Successful acquisition of useful vibration data.

Required Materials:
1. VIPER
2. Cleaned SLM part, 4.0 lbs (Figure 1.1)
3. Accelerometer 338c04
4. Accelerometer 353b33
5. Accelerometer Cables
6. Scope Probe Cables
7. HP 54600B Oscilloscope (Figure 3.2)

Testing Protocol:
1. Mount cleaned part on VIPER.
2. Attach accelerometers to oscilloscope.
3. Mount 338c04 accelerometer on build plate using tapped #10 hole.
4. Mount 353b33 accelerometer on frame using tapped #10 hole.
5. Turn on vibration motor by selecting the analog input value using the HMI VIBE mode.
6. Use oscilloscope to measure the frequency, peak-to-peak voltage, and noise band of the resulting signal.
7. Click the up arrow on the HMI to increase the input to the vibration motor controller by 300 counts.
8. Repeat steps 6 to 7 until maximum Analog count has been reached.
9. Repeat with second accelerometer mounted on: enclosure, primary rotation system, secondary rotation system.

Figure 3.2 Photo of Oscilloscope During Data Collection

Data:

Table 3.1 Measured and Calculated Values for Accelerations at the Part Build Plate.

<table>
<thead>
<tr>
<th>Analog Input (kHz)</th>
<th>Measured Frequency (Hz)</th>
<th>Measured Voltage on Part (mV)</th>
<th>Oscilloscope Noise (µV)</th>
<th>Total Uncertainty (µV)</th>
<th>Part Acceleration [g]</th>
<th>Part Acceleration (±g)</th>
<th>Absolute Uncertainty (±g)</th>
<th>Relative Uncertainty (±%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>44.84</td>
<td>55</td>
<td>12.86</td>
<td>14</td>
<td>0.53</td>
<td>0.53</td>
<td>0.14</td>
<td>0.26</td>
</tr>
<tr>
<td>1900</td>
<td>56.99</td>
<td>293</td>
<td>17.97</td>
<td>29</td>
<td>2.26</td>
<td>2.26</td>
<td>0.26</td>
<td>0.12</td>
</tr>
<tr>
<td>2000</td>
<td>74.07</td>
<td>869</td>
<td>14.06</td>
<td>68</td>
<td>6.40</td>
<td>6.40</td>
<td>0.66</td>
<td>0.10</td>
</tr>
<tr>
<td>2500</td>
<td>88.69</td>
<td>512</td>
<td>18.75</td>
<td>55</td>
<td>5.00</td>
<td>5.00</td>
<td>0.58</td>
<td>0.11</td>
</tr>
<tr>
<td>3000</td>
<td>105.8</td>
<td>1300</td>
<td>43.75</td>
<td>140</td>
<td>12.6</td>
<td>12.6</td>
<td>1.4</td>
<td>0.11</td>
</tr>
<tr>
<td>3100</td>
<td>122.7</td>
<td>1500</td>
<td>75.10</td>
<td>180</td>
<td>15.6</td>
<td>16.5</td>
<td>1.7</td>
<td>0.11</td>
</tr>
<tr>
<td>3400</td>
<td>132.5</td>
<td>1800</td>
<td>101.56</td>
<td>190</td>
<td>15.6</td>
<td>16.5</td>
<td>1.8</td>
<td>0.12</td>
</tr>
<tr>
<td>3700</td>
<td>130.7</td>
<td>1500</td>
<td>93.76</td>
<td>180</td>
<td>15.6</td>
<td>16.5</td>
<td>1.7</td>
<td>0.11</td>
</tr>
<tr>
<td>4000</td>
<td>132.5</td>
<td>1800</td>
<td>62.90</td>
<td>170</td>
<td>15.6</td>
<td>16.6</td>
<td>1.6</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 3.2 Measured and Calculated Values for Accelerations at Stage 1

<table>
<thead>
<tr>
<th>Stage 1 Voltage (mV)</th>
<th>Calibration Uncertainty (+/- mV)</th>
<th>Stage 1 Acceleration (g)</th>
<th>Calibration Uncertainty (+/- g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>73</td>
<td>4</td>
<td>0.75</td>
<td>0.04</td>
</tr>
<tr>
<td>131</td>
<td>7</td>
<td>1.34</td>
<td>0.07</td>
</tr>
<tr>
<td>100</td>
<td>6</td>
<td>1.10</td>
<td>0.06</td>
</tr>
<tr>
<td>125</td>
<td>6</td>
<td>1.28</td>
<td>0.06</td>
</tr>
<tr>
<td>120</td>
<td>6</td>
<td>1.22</td>
<td>0.06</td>
</tr>
<tr>
<td>134</td>
<td>7</td>
<td>1.37</td>
<td>0.07</td>
</tr>
</tbody>
</table>
The largest vibration amplitude at the part was observed at the highest frequency.

The accelerometers only measured accelerations in a single axis. Thus, while the data we obtained is useful in comparing the relative magnitude of the accelerations, in order to obtain a total acceleration, a tri-axial accelerometer should be used in future testing.

Increasing the value of counts to the DAC beyond 3100/4095 did not appear to result in a significant difference in vibration frequency or part acceleration. We believe this is because the vibration motor could not go any faster for the given set up, or was being current limited by the DC motor controller.

The set up of the HMI allowed the counts sent to the DAC to be increased in increments of 300. If this test were to be repeated, we would take measurements at smaller intervals in order to better characterize the behavior of the accelerations, particularly near 90 Hz.

We took data at the first stage in order to identify where transmissibility to the rest of the system would be minimized, however no obvious signal could be recognized. We believe the resulting signal was a combination of vibrating modes in the system and significant noise. It was difficult to identify the uncertainty of our measurement and we are unable to draw any conclusions from the data. If this test were to be repeated, we recommend exploring other vibration measurement devices such as a spectrum analyzer which may aid in identifying the transmitted vibrations.

Pass / Fail: PASS
Test Procedure

Item 4: Weight Test

Date Performed: 6/3/19

Location Performed:
Cal Poly Composites Laboratory

Engineers present:
Melissa O’Neil, Alex Ward, Sean McCrackin

Description of Test:
Attach weights up to 35 lbs to test maximum part size to determine functionality of device under the largest possible load.

Acceptance Criteria:
Stepper motors can orient part without skipping steps
Stepper motors can hold part in specific position without slipping

Required Materials:
- VIPER 2.0
- 2.5 lb Weights
- 5 lb Weights
- Straps to secure weights onto build plate

Testing Protocol:
1. Attach weights using straps to the build plate starting at 5 lbs.
2. Orient primary axis at 90° from the vertical. Verify that the motor can hold part still without slipping
3. Orient primary axis to 180° from the starting position.
4. Use the Jog commands and HMI homing features to move the primary axis back to its starting position.
5. Note any failures encountered.
6. Repeat steps 1 through 5, incrementing weights each time until total failure occurs or 35 lbs is reached.
### Observations:

<table>
<thead>
<tr>
<th>Weight (lbs)</th>
<th>Observations when moved down</th>
<th>Observations when moved up</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Jerky but made it fine</td>
<td>Jerky but made it fine</td>
</tr>
<tr>
<td>10</td>
<td>Smooth</td>
<td>Performed this test twice. The first time, when jogging back up and released at half way, the motor stalled. The second time the weights were mounted more rigidly and it didn’t stall</td>
</tr>
<tr>
<td>12.5</td>
<td>Smooth if under constant movement (holding jog button or using home command), stalls if jog button released when on its side</td>
<td>Smooth if under constant movement (holding jog button or using home command), stalls if jog button released when on its side</td>
</tr>
<tr>
<td>15</td>
<td>Smooth if under constant movement, stalls if jog button released when on its side</td>
<td>Moves up until it stalls halfway</td>
</tr>
</tbody>
</table>

- The primary axis stepper motor was only able to reliably lift the 10 lb load.
- While all structural components were sized to bear the load of the maximum part weight, the motors were sized based on the guideline that the load should require 30-70% of the available power, based on a representative test part.
- Future iterations of this design would require a larger primary axis stepper motor to allow for heavier parts.

Pass / Fail: **FAIL**
Test Procedure

Item 5: Confirmation Prototype Powder Removal Runtime Determination Test

Date Performed: 5/23/19

Location Performed:
Cal Poly Composites Laboratory

Engineers present:
Melissa O'Nei, Alex Ward, Andrew Epperson

Description of Test:
Determine the amount of time the automated cycle should be run before the operator checks powder removal progress.

Acceptance Criteria:
- Data is gathered showing how long a cycle should run before no more powder is removed.
- Data is gathered showing how much powder was removed during the cycle without operator intervention.

Required Materials:
- VIPER 2.0
- 316L SS Printed Part with remaining powder (Figure 1.1)
- Nitrile gloves
- Scale
- Allen wrenches
- Black paper

Testing Protocol:
1. Measure the mass of a powder collection device
2. Attach the part to the mounting plate
3. Attach the powder collection device below printed part so that it will collect powder
4. Run cycle for 5 seconds
5. After the time has elapsed, detach the collection device and measure its mass. The original mass of the collection device is subtracted from the total mass to get the removed powder’s mass.
6. This process is then repeated until no powder is seen leaving the part and the mass measurements plateau.
7. Once no powder is being removed with the vibration, tap part with mallet to see if any powder remains.
8. Repeat steps 3-7 until all powder is removed.

Data:

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Total Mass (g)</th>
<th>Percentage Powder Removed</th>
<th>Mass of powder removed (g)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>511</td>
<td>0.0%</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>674</td>
<td>57.4%</td>
<td>163</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>702</td>
<td>87.3%</td>
<td>191</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>730</td>
<td>77.1%</td>
<td>219</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>765</td>
<td>89.4%</td>
<td>254</td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>770</td>
<td>91.2%</td>
<td>259</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>771</td>
<td>91.6%</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>225</td>
<td>773</td>
<td>92.3%</td>
<td>262</td>
<td>No more powder is being removed during vibration cycle</td>
</tr>
<tr>
<td>-</td>
<td>795</td>
<td>100.0%</td>
<td>284</td>
<td>Manually tapped with mallet until no more powder remained</td>
</tr>
</tbody>
</table>

Observations/Notes:

- A limitation of this test is that since the cycle was stopped to weigh the removed powder and then restarted the part likely was not oriented in all possible positions. This is because since reorientation is achieved by the two axis rotating back and forth at different periods, the beginning of the cycle will move the part through the same orientations every time.

Pass / Fail: **PASS**
Test Procedure

Item 6: Confirmation Prototype Powder Removal Complete Test

Date Performed: 6/2/19

Location Performed:
Cal Poly Composites Laboratory

Engineers present:
Melissa O’Neil, Alex Ward, Andrew Epperson

Description of Test:
After full build is complete, go through complete automated cycle with attached part to determine effectiveness of powder removal, the effectiveness of the enclosure to contain the powder, the total operator and process time, and ensure part is undamaged.

Acceptance Criteria:
After the device completes a predefined cycle
- There is no visible powder removed from part on black paper below part when tapped with mallet.
- There is no visible powder on black paper outside the enclosure (no escaped powder)
- Total operator time is less than 30 minutes
- Total process time is less than 2.5 hours
- The part is undamaged

Required Materials:
1. VIPER 2.0
2. Nitrile gloves
3. Scale
4. Allen wrenches
5. Black paper
6. 316L SS Printed Parts with remaining powder shown in Figures 6.1 and 6.2
7. Timer
Figure 6.1. 316L SS Printed Part 1 from IME Dept

Figure 6.2. 316L SS Printed Part 2 from IME Dept

Testing Protocol:

1. Place black paper under the VIPER 2.0.
2. Start timers and log moments when time includes operator time.
3. Attach the part to the VIPER 2.0.
4. Run automated cycle for time determined using data from cycle runtime test.
5. Tap on part with rubber mallet to check for remaining powder/reinitiate powder flow.
6. Repeat steps 4-5 until no more powder is released by mallet.
7. Once all powder is removed, record the total process time.
8. Remove part from VIPER 2.0.
9. Hold part above black paper and strike it with a rubber mallet as shown in Figure 6.3.
10. Repeat step 9 at various orientations.
11. If no visible powder is released by mallet the part is fully clean.
12. Repeat with Part 2
Figure 6.3. Checking Part 1 for Remaining Powder

Data:

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<th>Stop (HH:MM)</th>
<th>Type</th>
<th>Time Elapsed (HH:MM)</th>
<th>notes</th>
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<td>auto</td>
<td>0:56</td>
<td>1st cycle</td>
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</tr>
<tr>
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<td>1:07</td>
<td>auto</td>
<td>0:05</td>
<td>2nd cycle</td>
</tr>
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<td>1:08</td>
<td>manual</td>
<td>0:01</td>
<td>tap</td>
</tr>
<tr>
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<td>1:12</td>
<td>auto</td>
<td>0:04</td>
<td></td>
</tr>
<tr>
<td>1:12</td>
<td>1:13</td>
<td>manual</td>
<td>0:01</td>
<td>tap</td>
</tr>
<tr>
<td>1:13</td>
<td>1:18</td>
<td>auto</td>
<td>0:05</td>
<td></td>
</tr>
<tr>
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<td>1:19</td>
<td>manual</td>
<td>0:01</td>
<td></td>
</tr>
<tr>
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<td>1:37</td>
<td>manual</td>
<td>0:19</td>
<td>manual tapping, jogging, and vibration</td>
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<tr>
<td>1:37</td>
<td>1:39</td>
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<td>0:02</td>
<td>removal</td>
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<tr>
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<tbody>
<tr>
<td></td>
<td>Total Process Time:</td>
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</tbody>
</table>

<table>
<thead>
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<th>Stop (HH:MM)</th>
<th>Type</th>
<th>Time Elapsed (HH:MM)</th>
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<tbody>
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<td>auto</td>
<td>0:13</td>
<td>1st cycle</td>
</tr>
<tr>
<td>0:15</td>
<td>0:27</td>
<td>manual</td>
<td>0:12</td>
<td>tap, jogging, vibration, unloading</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part 2</th>
<th>Total Manual Time:</th>
<th>0:14</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Process Time:</td>
<td>0:27</td>
</tr>
</tbody>
</table>
Observations/Notes:

- No powder on black paper under enclosure after either part was cycled.
- Parts were undamaged.
- There was still observed to be small puffs of powder when struck with mallet from the small holes around the top of the support structure as visible in Figure 6.1. The support structure of this part was significantly more difficult to remove powder from than the support structure of the parts originally tested from LLNL as shown in Figure 1.1. Because of this, Part 1 required a long cycle time, as well as a longer manual part powder removal time than Part 2. Future depowdering of a part with a similar support structure which involved removing the “skin” of the support structure first may increase the speed at which powder can be removed, and allow it to all be removed within the operator time window.
- No powder was observed to come from part 2 after only 27 minutes of total process time.
- Some unremoved powder was seen within the countersinks of the build plate after the test cycles were complete in both parts 1 and 2. This powder was not removed during the cycle since it was trapped by the head of the screw which holds the build plate on the adapter plate. It is recommended to remove this powder manually before mounting to VIPER 2.0.

Part 1 - Pass / Fail: FAIL

Part 2 - Pass / Fail: PASS

Enclosure Powder Containment - Pass / Fail: PASS
Test Procedure

Item 7: Operator Satisfaction Survey

Date Performed: 6/4/19

Location Performed:
Cal Poly IME Laboratory

Engineers present:
Alex Ward, Sean McCracken

Description of Test:
Have experienced SLM printer operators go through the process and rate their satisfaction with VIPER 2.0.

Acceptance Criteria:
- 4/5 average satisfaction rating

Required Materials:
- VIPER 2.0
- Operator Satisfaction Survey as written by the team
- Operator Instruction Manual
- Clean 316L SS printed part
- SLM Operators

Testing Protocol:
1. Ensure VIPER 2.0 is powered.
2. Provide the Operators with the Viper 2.0 Instruction manual.
3. Give the Operators time to review the manual and record any questions they have.
4. Ask the Operators to go through the process of powder removal with the clean 3D printed part
5. Provide Operators with Satisfaction Survey and collect their responses.
Data:

## Operator Satisfaction Survey

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<th></th>
<th>1(Poor)</th>
<th>2</th>
<th>3(Indifferent)</th>
<th>4</th>
<th>5(Awesome)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Ease of part installation</td>
<td>2</td>
<td>3</td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>2. Usability of Human Machine Interface</td>
<td>2</td>
<td></td>
<td>3</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>3. Ergonomics of the device</td>
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<td></td>
<td>3</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>4. Operator manual effectiveness</td>
<td>2</td>
<td>3</td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5. Anticipated usefulness of device</td>
<td>2</td>
<td></td>
<td>3</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>6. Overall satisfaction</td>
<td>2</td>
<td></td>
<td>3</td>
<td></td>
<td>4</td>
</tr>
</tbody>
</table>

Questions:

Are there any other safety concerns?  
Some openings need to be covered/closed.

Any other comments or questions?  
Perfect!

---

Figure 7.1. Completed Operator Satisfaction Survey by Dr. Xuan Wang

Pass / Fail: **PASS**
Appendix Q: Transmissibility Ratio Test Uncertainty Calculations

Sample Calculation for Analog Input to DC Motor Controller of 3400/4045.

- Accelerometer Conversion (mV/g) = 103.3
- Accelerometer Sensitivity = ±7% ±10%
- Measured Voltage from 338C04 Accelerometer $V_{acc} = 1594$
- Oscilloscope Resolution Due to Noise for this Data Point = ±101.55 mV

\[ U_{total} = \sqrt{U_{calibration}^2 + U_{meas}^2} \]

\[ U_{total} = \sqrt{(0.10 \times 1594 \text{ mV})^2 + (101.55 \text{ mV})^2} \]

\[ U_{total} = \pm 1.9 \times 10^2 \text{ mV} \]

- Voltage Measured $V_{tot} = 1.60 \times 10^3 \pm 0.19 \times 10^3 \text{ mV}$

- Converting to g's

\[ A [g] = \frac{V_{tot} [\text{mV}]}{103.3 [\text{mV/g}]} \]

\[ A = \frac{(1.60 \times 10^3 \pm 0.19 \times 10^3 \text{ mV})}{103.3 [\text{mV/g}]} \]

\[ A = 15.5 \pm 1.8 g \]
Appendix R: Operator’s Manual

Operator’s Manual

Potential Hazards/Toxicity:

316L SS powder is very fine and dense, requiring careful handling procedures due to particulates possibly being exposed in open air. The nominal particle size is ~40 microns but single particles can vary from 5 to 120 microns in diameter.

May cause an allergic skin reaction Suspected of causing cancer Causes damage to organs through prolonged or repeated exposure.

Personal Protective Equipment (PPE)

Hand Protection:
Nitrile gloves will be worn when working/ handling the powder. (MSDS)

Eye Protection:
Safety glass with side shields conforming to z87+. (MSDS)

Skin and Body Protection:
Lab personnel working with the chemicals need to wear full-length pants or its equivalent, closed-toe footwear with no skin being exposed, and a lab coat.

Hygiene Measures:
Wash hands after working with the hazardous substances and when leaving the lab/shop.

Respirators are recommended, not required during any open powder activity. Medical clearance and fit test not required for filtering facepiece respirators.
Getting Started

The VIPER 2.0 is a device designed to remove excess powder from metal 3D printed parts. The printed parts are installed inside a sealed enclosure. Two stepper motors reorient the part while a vibration motor shakes the excess powder out of the part. Currently, the VIPER 2.0 only supports 316L stainless steel printed parts and size SLM 125 build plates.

Figure 1. VIPER 2.0 assembly.
Powering Up

Before powering up, ensure the electronics enclosure door is closed and properly latched. The VIPER 2.0 runs on 120 VAC power, and can be plugged into a standard US wall outlet. When plugged in, the HMI screen should light up and display the main menu.

Functions

1. Automated Cycle
   The “CYCLE” option in the main menu on the HMI screen will run an automated part cleaning cycle. Each cycle takes 10 minutes to complete. See General Part Cleaning for details on how to run the cycle.

2. Homing the Axes
   Each axis can be set to return to their home positions individually. To do so, select the “HOME” option (the F2 button) in the main menu. The “HOME ALL” option will home both axes at the same time. The “HOME PRIMARY” and “HOME SECONDARY” options will home only their respective axes. To stop the homing process at any time, select the “STOP” option (F5 button). This will stop both axes in place.

3. Jogging the Axes
   Each axis can be rotated individually. To do so, select the “JOG” option from the main menu (the F3 button). The primary axis can be jogged up and down, and the secondary axis can be jogged left and right. DO NOT jog either axis farther than 3/4 of a turn from their home positions. This may cause the wires to become tangled.

4. Emergency Stop
   In case of emergency, press the red E-stop button above the HMI screen. This button will cut power to the motors. CAUTION: There is no brake equipped for either axis. When the E-stop is triggered, the primary axis will freely swing downwards. Ensure that there is nothing in the way of the axis when it swings down. To restore power to the motors, turn the E-stop button clockwise until it clicks.

General Part Cleaning

Required Materials:

1. VIPER 2.0
2. Nitrile gloves
3. Face mask
4. Allen wrenches  
5. Torque wrench  
6. Four #10-24 screws  
7. Rubber mallet  
8. Black paper  
9. Uncleaned 316 SS Printed Part

Mounting the Part
1. Home the axes if necessary.  
2. To home the axes: select the “HOME” option in the main menu by pressing the F2 key. Select “HOME ALL” and press “GO”. Wait until both axes stop moving.  
3. Before handling any parts containing powder, put on face mask (optional) and nitrile gloves.  
4. Attach powder collection box to bottom of the funnel using the four latches.  
5. Open the enclosure door.  
6. Place the part to be cleaned into groove of the VIPER 2.0 mounting system, ensuring all holes are lined up.  
7. Secure the part to the mounting plate using four #10-24 screws at each corner of the build plate.  
8. Close and latch the door.

Running the Automated Cycle
1. Ensure that the door is closed and latched, and that the powder collection box is securely fastened to the funnel.  
2. Select the “CYCLE” option in the main menu by pressing the F1 button.  
3. Start the cycle by pressing “GO” (the F3 button). The cycle is programmed to run for 10 minutes. During this time, do not open the door or remove the powder collection box.  
4. When the cycle finishes, the screen will read “DONE”. Open the door and tap the part with a rubber mallet. If more powder falls out of the part, close the door and run another cycle. Repeat until no more visible powder is released by the mallet.  
5. To stop the cycle early, press “STOP” (the F5 button). Both axes will stop in place, and the vibration motor will turn off.

Uninstalling the Part
1. Once the cycles have been completed, open the door and remove the four screws securing the part to the mounting system.  
2. Remove the part from the VIPER 2.0.  
3. Hold the part above black paper and tap with rubber mallet. If no powder is released by the mallet, the part is fully cleaned.  
4. Carefully remove the powder collection box from the funnel. Pour the powder into a designated recycling or disposal container.
**Troubleshooting**

The axes do not move or the stepper motors skip steps:
1. Stop the current operation by pressing the “STOP” button (F5) on the screen. Check to see if there is anything caught in the axes or bearings.
2. Check the rubber shaft seals on the inside of the enclosure. Ensure that they are not getting caught between the shaft and enclosure.
3. Check the wires inside the enclosure. Ensure that they are not tangled or getting caught in the assembly. Readjust the wire positions if necessary by routing them through the plastic wire clamps inside the enclosure.

Powder is not being effectively removed from the part:
1. Ensure that the part is secured tightly to the mounting system.
2. Ensure that the dampers on the mounting plate are securely fastened.
3. Between cycles, it may be necessary to remove the part from the VIPER 2.0 and tap it harder with a mallet. This will loosen trapped powder and make it easier for the powder to flow out.

There is excessive noise or vibrations during a cycle:
1. Stop the cycle and slightly loosen the dampers on the mounting plate. They may be too tight to effectively isolate the vibrations to the part.