Revolutionized Additive Manufacturing

Project sponsored by: Lawrence Livermore National Laboratory

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1 Introduction

Lawrence Livermore National Laboratory (LLNL) is currently using metal additive manufacturing (AM) processes to produce high quality, high precision parts through a powder bed fusion (PBF) approach. Unfortunately, when thin walled parts are created with this approach, a large amount of unused powder is left surrounding the final part. Although unused powder can be recycled, the initial volume of material required makes the current process impractical for expensive and rare/precious materials.

1.1 Objectives

Simply, the objective of Revolutionized Additive Manufacturing (RAM) was to reduce the amount of waste in current PBF processes. LLNL requires builds comprised of precious/rare metals which, given the current process material requirements, are extremely expensive or outright impossible. To correct this problem, RAM worked on developing a device that has the ability to formulate powder into specified patterns on a flat build plate so the total amount of powder required is reduced.

Before attempting to develop possible solutions, we decided to focus on what LLNL required; reduction of waste and material requirements in AM builds. Next, characteristics of a device/method that would fulfill these requirements were identified. To start, a list of requirements and specifications were compared and contrasted in an attempt to build a solid foundation for developing a viable solution. This list can be seen in Table 1.1, as well as in the Quality Function Deployment (QFD) matrix in Appendix A.

Although it appears complex at first, the QFD matrix is a simple and powerful tool RAM used to organize customer requirements and engineering specifications in a single matrix. In order to better understand this matrix, you must understand what each section displays.

In the upper left corner of the matrix all of the customers are identified. Just to the right of the identified customers, there is a vertical list of customer requirements; in this column, an ‘H’ indicates a hard requirement which must be met, while an ‘S’ indicates a soft requirement that has flexibility. This list includes requirements from each of the identified customers, and ultimately is the base of the entire matrix.

Once all of the customer requirements were identified, engineering specifications were created to address each of the customer requirements. These specifications can be seen in the middle section of the matrix (running horizontally), with the description at the top, and the target measurements listed toward the bottom respectively. It is important to understand that engineering specifications are measurable quantities, driven by customer requirements, that are essential to determine if the final solution solves the problem satisfactorily. Once customer requirements and engineering specifications were both defined, relationships between them were identified as either strong, weak, or unrelated (seen in the middle of the matrix.) Then, in the "roof" of the matrix, correlations between engineering specifications were categorized as positive, negative, or no correlation.

The final notable feature of this matrix is the analysis of existing products. On the far right, and at the bottom of the matrix, are sections where existing products are evaluated for how well they meet customer requirements and engineering specifications.

Another requirement identified to ensure a high level of powder conservation from our solution was the ability to produce hollow internal features. In other words, the device should be capable of producing borders of powder surrounding an area without powder. If you were to create a hollow cylinder for example, it would require the deposition of material only where structural walls are to be located; any material on the inner region would go to waste.

In order to be applicable to AM processes, another requirement was the ability to build successive layers on top of each other. For simplicity of the first iteration of this problem, we decided layers built on top of each other would have identical cross sections. However, thought was given to future upgrades which could allow for the fabrication of more complex parts, while maintaining powder conservation.

Some aspects of the SLM process need to be carried over in order to maintain final product integrity; primarily, the powder properties. The powder must have a thickness similar to that of standard PBF processes; 30-50 microns. LLNL also specified that the path be no wider than ¼ inch.

Due to the specified pattern thickness and maximum path width that LLNL requested, it was imperative that we knew the powder particle size range that we were dealing with. Although LLNL works with powders in a wide range of diameters, RAM's device targeted powders in the 40-50 micron range. With that said, this number indicates the nominal diameter of powder, and the device will ultimately need to handle powder diameters ranging from 5-105 microns.

A specified tolerance was also needed to ensure the powder design could fulfill the required tolerances of parts. LLNL specified a positional tolerance of ± 0.005 inches at given critical points within the design. Additionally, the speed of the new process was to be such that it would not negatively affect cost. That is to say, it shouldn't be so slow that it is more financially prudent to use SLM (either due to operation hours, energy, or potential production errors). We decided that our solution should be able to configure a powder pattern in no more than five times the duration of one layer being spread by current PBF processes.

Finally, our solution must be capable of laying powder on a standard build plate. We have found that a standard build plate is typically 10”X10”, thus the design/method must operate within these specifications. Additionally, the overall design of the device/method must have the ability to be simply modified to accommodate larger build plates. All powder design specifications can be seen in Table 1.1.

Considering the intent of this device is to facilitate the economic use of rare/precious materials, the utmost care must be taken to ensure that the material’s properties remain unaffected. To this end, our device will not use powder additives or binders. Additionally, the powders will be kept in a sealed reservoir so that they are as protected as possible.

After we determined the conservation, design, and powder property specifications, the final area of elaboration was the solution’s safety, maintenance, and size specifications. LLNL wanted a machine that would have an infinite life cycle in chamber conditions that mirror those of their current AM machines. The prime concern in regards to this point is that current SLM processes require thousands of cycles per build. In regards to the containment chambers, they are typically held at ambient temperatures, contain pressures slightly above atmospheric, and are flooded with argon. Our device/method must comply with these requirements in order to be viable.

LLNL didn’t specify any safety concerns for our project considering it is mainly in the research and development stage, but we decided to implement a few safety and operator specifications to help ease future integration. The device/method must have lockout features to ensure operator safety and the device must be controlled by an external controller.

We developed a list of design specifications that RAM and LLNL feel are important to the success of the this project. Table 1.1 reflects all design specifications, and assesses their risk as high (H), medium (M), or low (L). Table 1.1 also addresses how each design requirement is to be verified; verification methods include analysis (A), testing (T), similarity to existing designs (S), and inspection (I). A quality function deployment (QFD) analysis can also be seen in Appendix A to better understand the importance of each specification, how each specification relates to one another, and how other products or processes do or do not fulfill each specification and requirement.

Table 1.1. Revolutionized Additive Manufacturing list of project specifications, including tolerance, risk, and compliance methods for each specification.

Spec#	**Parameter Description**	**Requirement or Target (units)**	**Tolerance**	**Risk**	**Compliance**
1	Reduce waste	Yes/No	-	H	A, T
2	Build successive layers	Yes/No	-	H	T
3	Hollow internal features	Yes/No	-	H	T
4	Build plate size	10X10 (inches)	nominal	L	I, A
5	Machine footprint	24X24X24 (inches)	nominal	L	I, A
6	Speed of powder deposition process	5X SLM Process	maximum	H	A, T, S
7	Path width	0.25 (inches)	maximum	M	A, T
8	Layer thickness	40 (microns)	± 10	H	A, T, S
9	Material density	65% Tapped density	maximum	H	A, T, S
10	Lockout features	Yes/No	-	L	I, S
11	Life cycle	1 million cycles	minimum	H	A
12	External controller	Yes/No	-	L	I, S
13	Positional tolerance	0.0 (inches)	± 0.005	M	T
14	Reservoir moisture content	0% humidity	maximum	H	T, S, I
15	Functions in chamber conditions	Yes/No	-	M	A, T, S
16	Powder diameters (nominal)	45 (micrometers)	Range from 5-105 microns	L	A, T, I

2 Project Deliverables

RAM's original goal was to develop a solution that deposited powder in specified locations with specified characteristics. It was decided that the best solution for this problem was a simple gravity feed nozzle. The specific geometries and dimensions for the optimal nozzle can only be determined through design iteration. However, nozzle iteration can only be conducted with an efficient testing assembly. This is what RAM was able to deliver: an efficient testing assembly for nozzle iteration.

Due to unanticipated delays in our Standard Operating Procedure (SOP) approval process, RAM was not able to perform as much testing and iteration as we initially intended. However, RAM will ultimately deliver a fully functional test machine that has SOPs approved by the Environmental Health and Safety Department on Cal Poly's campus. While a lot of design requirements were left untested or unsatisfied, what is being delivered is not a failure. The test assembly is in a ready to run state with many user-friendly features to make nozzle iteration as easy as possible. The next step in this project is to start testing simple nozzle designs, flow control devices, and flattening tools so projections of the long-term viability of this solution can be made.

2.1 Delta Mechanism

The Delta Mechanism is a former senior design project that was retrofitted for RAM's purposes. The Delta is a high precision 3-axis gantry that was originally designed for 3D printing. RAM made a number of modifications to both the hardware and the software of the Delta. The Delta, post customization, can be seen in Figure 2.2. The detailed instructions on how to operate the Delta can be found in Appendix P.

2.2 Nozzle Design

A modular nozzle design was created in SolidWorks and printed here on Cal Poly's ABSplus-P430 polymer base 3-D printing machine. An assembled version of the printed nozzle mounted in the Delta Mechanism can be seen in Figure 2.1. An image of the polymer printed nozzle disassembled can be seen in figure 2.3.

The modularity of this nozzle assembly is critical for continuing this study. If future students were to study the effect of nozzle head diameter, nozzle head retaining wall angles, nozzle head surface finish, or nozzle head geometric shape, the nozzle tip would be the only portion that needed to be printed specifically for each iteration; the top modular part of the nozzle could be used through the entirety of testing. With that said, modularity allows for the top part to be redesigned to test various inlet options as well. In either case, designers must ensure that new parts fit assembly and mounting requirements. Engineering drawings for all three parts can be seen in Appendix O.

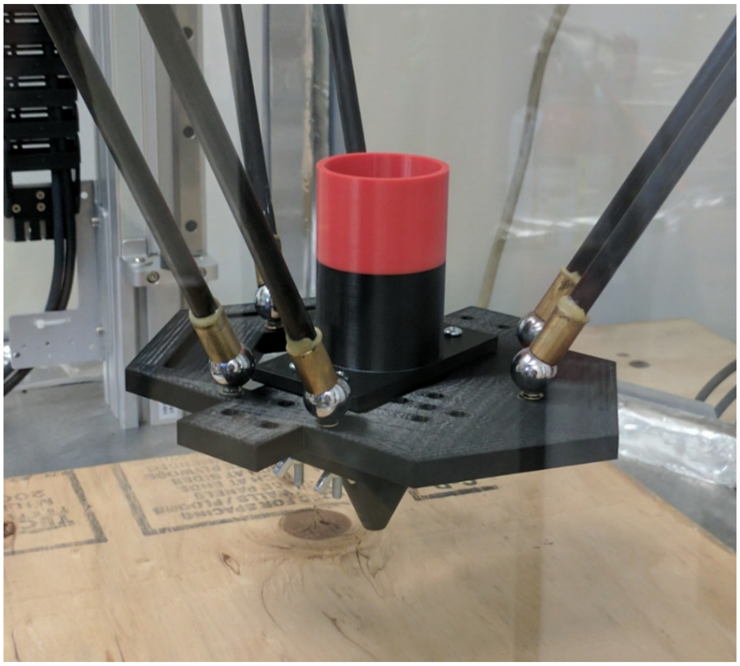


Figure 2.1. Assembled nozzle and traversing plate in delta mechanism.

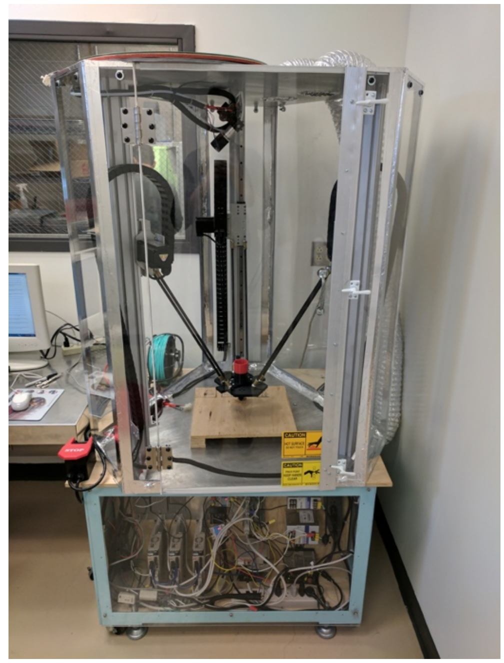


Figure 2.2. Retrofit delta mechanism with nozzle assembly and pour plate.

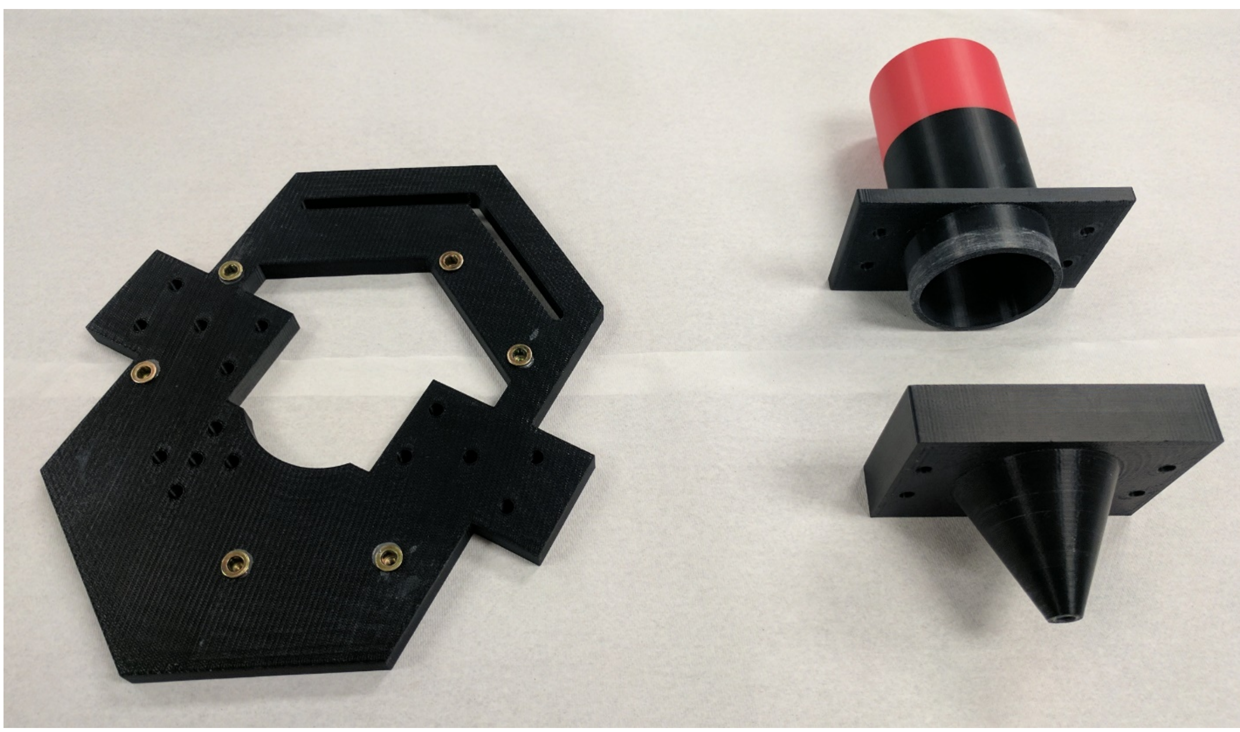


Figure 2.3. Disassembled nozzle and traversing plate assembly.

There is a large slit located on the traversing plate that was designed for the possibility of mounting a GoPro that could record the nozzle deposition process from multiple angles. In addition to the angled slot, a 5-hole bolt pattern was printed into the plate under the assumption that future nozzle iterations will need a stop start mechanism. This start stop mechanism is likely to be a small rotary or linear actuator requiring motors and batteries, which could be easily mounted to the plate using these holes. Furthermore, the slot and holes can be used to mount leveling or flattening devices, sensors, or other hardware a researcher may be interested in integrating into the system.

There are six M4 threaded inserts that were epoxied into the traversing plate so that the ball joints could be reused with other designs. This was done with the understanding that future students might want to fabricate a new traversing plate with specialized features. Considering the steel ball joints have a fairly long lead time, Ram felt that the ability to non-destructively remove the steel balls from the traversing plate would be a desirable feature.

2.3 Other Hardware

The largest modification made to the Delta was to completely seal the system. Originally, the Delta did not have sealed edges or a completely sealed door. RAM used aluminum tape and weather stripping to seal all the edges and the door of the Delta. This ensures that the Delta can be used in a safe manner and minimizes the overall risk to machine operators.

Other modifications made were to remove the glass build plate and to replace the traversing plate. The glass build plate was used in the original design of the Delta, but was only a hindrance to RAM. It was removed from inside the machine, and placed on the top of the Delta. Two pin quick disconnects were added to the wiring of the heated glass build plate so it can be reintegrated into the machine if needed. A custom build plate was fabricated and replaced the glass build plate. The original traversing plate which held the old extrusion nozzle was removed and replaced by the custom 3D printed plate shown in Figures 2.1 and 2.3.

Information about the specifics of the Delta itself can be found in the senior project report binder kept with the machine.

2.4 Software

The main point of interaction with the Delta is through a custom designed Python User Interface (UI). The UI is a command line based interface that walks the operator through all the different options available. While the current code covers a fair amount of pathing options, it can be easily expanded to accommodate future needs of the system.

The Python UI is the main interface, but there is another software used to work with the Delta. MotionWorks is a PLC software used to program the Delta's motion controllers. Currently, the project used to program the PLCs is non-buildable. It cannot be built because of data type errors. Due to this problem, the PLC programming was not altered over the course of this project.

2.5 Standard Operating Procedure

Our standard operating procedure is a written a set of instructions that document how to safely perform work involving the stainless-steel powder. Our SOP is written for all procedures that pose an identified potential risk to the health and safety of RAM team members. Our SOP has been reviewed and approved by Cal Poly's Environmental Health and Safety Department. A hard copy of the completed form will be kept readily accessible in the testing environment. Our SOP can be seen in Appendix N.

2.6 Requirement Satisfaction

Unfortunately, schedule setbacks from the SOP approval process and time taken to retrofit the delta mechanism prohibited our team from performing as much testing as originally intended. Because of this, many design requirements were left untested or unsatisfied. However, the test machine that we are delivering does satisfy some of the original design requirements. Table 2.1 below contains a description of the design requirements, and specifies whether or not our solution meets the requirements, or if the requirement was left untested.

Table 2.1. Design specification description and satisfaction.

Spec#	Design Requirement Description	Requirement Met
1	Reduce waste	Yes
2	Build successive layers	No
3	Hollow internal features	Yes
4	Build plate size	Yes
5	Machine footprint	N/A
6	Speed of powder deposition process	No
7	Path width	Yes
8	Layer thickness	No
9	Material density	Untested
10	Lockout features	Yes
11	Life cycle	Untested
12	External controller	Yes
13	Positional tolerance	Untested
14	Reservoir moisture content	Untested
15	Functions in chamber conditions	Untested
16	Powder diameters (nominal)	Yes

3 Future Recommendations

3.1 Nozzle Iteration Process

Given the machine capabilities of the Delta, there are many directions the project can go from here. RAM believes that the most critical component of the system, especially in early stages of development, is the nozzle. With that said, a logical next step may be to start a nozzle iteration process in order to determine how certain nozzle parameters affect the properties of the deposited powder path.

After consulting with a Cal Poly Statistician, several Cal Poly professors, and LLNL it was determined that the ideal method for a nozzle iteration study is top down optimization. This means that at the beginning of the study you start with two distinctly different nozzle designs; for example, a nozzle with a triangular tip and a nozzle with a circular tip. After depositing predetermined powder paths with each nozzle, desirable path properties obtained from each design will be recorded and compared, and the superior design will be chosen. Then a nozzle with another distinctly different characteristic will be developed and compared to the previously selected nozzle. This process would be continued until sufficient powder path properties are obtained by the nozzle head. From our limited testing, RAM believes that nozzle characteristics such as tip opening geometry, interior wall surface finish, and converging angle will have the most significant impact on the powder path properties. However, it is likely that as further testing is performed, new knowledge will be gained and more important nozzle characteristics will be identified.

Several other nozzle optimization methods were discussed before choosing the top down method. These methods included dimensional analysis and extensive testing of individual nozzle characteristics. Dimensional analysis was deemed unrealistic for the scope of our project due to the complexity of granular flow and the number of independent variables involved. An exhaustive study was also determined to be unrealistic due to time constraints and large prototyping costs.

3.2 Testing Techniques

There are several different qualitative and quantitative testing measurement techniques that can be utilized in determining a powder path's quality. These techniques could be further developed in the future however, RAM feels that the following quantitative and qualitative measurement practices are adequate at this time.

Each nozzle's flowrate should be found before performing in powder path deposition. This process is a simple bucket and stopwatch flowrate measurement test. This flowrate test is further explained in the Environmental Health and Safety approved SOP provided in Appendix N.

The powder path quality will most likely be determined using photos taken on a standard smartphone for qualitative analysis. It has been determined that examining the cross-sectional shape of the powder path will be an effective method in evaluating a powder path's quality. To obtain images of a powder path's cross section, after the path has been deposited, the user can use a thin sharp straight edge to cut the powder path in half and remove the powder on one side of the straight edge. Figure 3.1 is an image of what a typical powder path's cross-section would look like. The photo was taken using a google pixel XL smartphone camera.

Figure 3.1. Sample image of powder path cross section.

The general shape and symmetry of the powder path cross section can be determined from an image similar to Figure 3.1. It is also possible to use MATLAB photo analytics, or other software, to extract powder path dimensions such as shoulder width and base width. The qualities that make up a beneficial powder path cross sectional shape have yet to be determined and would need to be addressed before nozzle iteration and design begins.

An image of the deposited powder path from above will likely be useful for gathering quantitative and qualitative data as well. An example of such an image can be seen in Figure 3.2. Overhead views of the powder path will be useful for gathering information on path width and overall path width uniformity. A nozzles ability to formulate specified geometric patterns can also be evaluated from these pictures. Similar to the powder path cross-sectional photo, MATLAB photo analytics could be utilized to get specific powder path dimensions. However, RAM feels that such procedures are unnecessary until nozzle design is closer to finalization.

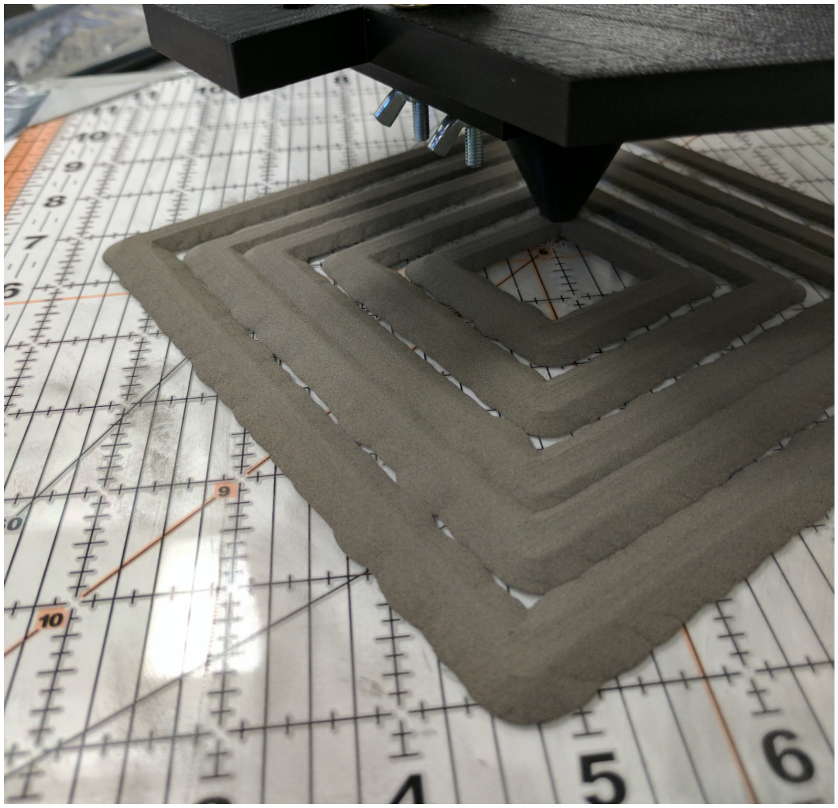


Figure 3.2. Sample image of powder path from above.

3.3 Miscellaneous Testing

Along with performing nozzle iteration testing, RAM believes that the Delta mechanism has capabilities for other miscellaneous testing that will produce beneficial information. Initial testing with the Delta showed that powder dropped from a nozzle piles well above the desired layer thickness. One possible solution to this problem would be to mount a rake or flattening mechanism to the holes or slot in the traversing plate to test methods for reaching the specified layer thickness.

Beyond testing flattening mechanisms, there is also the potential to test various traversing speeds and powder drop heights. Both of these parameters will most likely have a large impact on powder path characteristics.

3.4 Hardware Modifications

The Delta Mechanism is currently set up and capable of laying down powder paths in two dimensional designs on the build plate. However, after performing some initial testing with the current Delta Mechanism setup, there is one hardware modification that RAM recommends a future researcher performs before nozzle optimization occurs.

Figure 3.3 is an image of the current build plate that powder is being deposited onto. The build plate is made up of compressed plywood adhered together by wood glue with a piece of poster board and quilting board aluminum taped to the top surface. The materials chosen for the build plate were not the best design choices: the quilting board appears to be bowed in the center and the plywood doesn't appear to be perfectly flat. Therefore, RAM suggests that another build plate be machined out of aluminum with the same geometry so that the build plate surface is adequately level and flat.

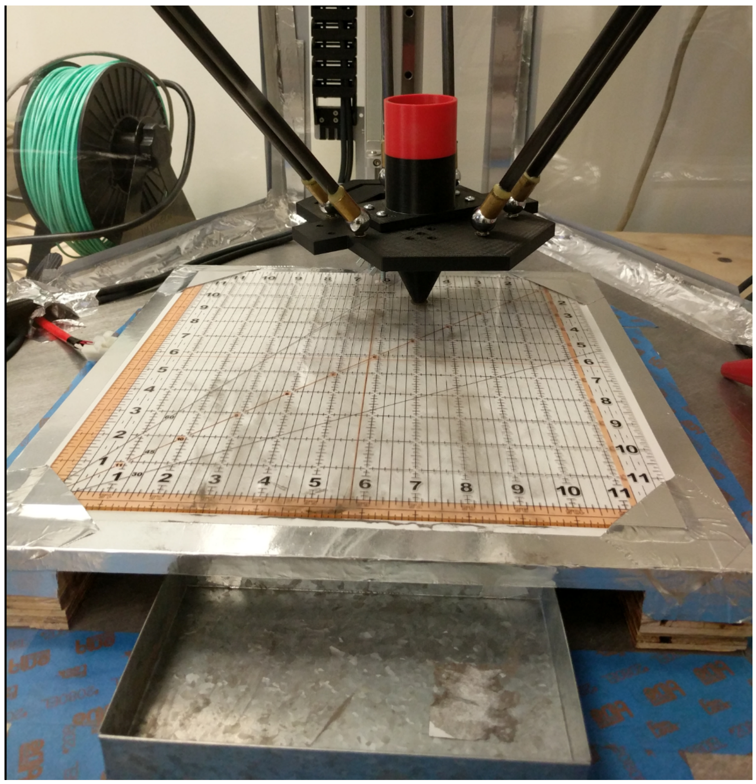


Figure 3.3. Current build plate made from quilting board attached to plywood structure.

3.5 Software Modifications

In order to get the most out of the Delta, there are software modifications to be conducted. They are separated in to two categories: minor and major. Minor modifications are to improve the ease of use of the current software while Major modifications add significant functionality to the Delta. The Major modifications are what will allow the Delta to migrate to a full testing solution.

3.5.1 Minor: Doubles

When running the RAM_Powder_Paths.py functions, the only values that are acceptable are integers. This is generally only a problem for the Calibrate Height (CH) function. This solution for this would be to simply cast the input string as a double rather than an integer.

3.5.2 Minor: Unprotected Input

When running the RAM_Powder_Paths.py functions, there is no protection for incorrect input. That is to say, if the circle function is asking for a “radius” and a user inputs a string, the code will break. This cause a termination of the program, thus the TCP connection. A simple restart of the program will get you back on track, but it will cause the nozzle to return to its initial state (an inch or two off the build plate) potentially causing the powder to pour out in a larger pile under the nozzle. The solution to this problem would be to code in data-type checking loops surrounding each input.

3.5.3 Major: Speed

The speed of Delta is not configurable in its current state. In some instances, (like the circle) it can be manipulated as a function of how many points are being plotted, but it cannot be directly set. The PLCs and the hardware allow for such an adjustment, but the current firmware settings do not. In order to correct this, the PLC project would need to be debugged, modified, and reloaded. The modification could be as simple as adding a speed parameter to current xyz function or it could be a completely new function.

4 Project Background

In order to research and develop AM technologies it is imperative to have a good understanding of existing processes. For starters, one aspect of AM that must be understood is how a CAD model is used . Simply put, 3-D models are sliced into thousands of layers which compose the entire part, then an AM machine will use this information to build successive layers on top of each other at a predetermined thickness. This process is utilized with every method of AM currently in use, but the specific way in which layers are built and fused together varies greatly.

There are currently seven categories of AM processes recognized by the American Society for Testing and Materials (ASTM): Vat photopolymerization, material jetting, binder jetting, material extrusion, PBF, sheet lamination, and direct energy deposition. Along with these seven processes there are multiple processes that utilize combinations of additive and subtractive processes to produce a final part. Although some processes lend themselves more to the problem at hand, a thorough understanding of all current processes and technologies is beneficial when developing solutions.

LLNL currently uses a PBF process which produces high precision parts with desirable tolerances. In this process, a layer of metal powder is spread across a build plate, and a laser is used to melt and fuse powder together in the desired 2-D cross section. This process is then repeated layer-by-layer, and is capable of producing 3-D parts with complex structures. Since the entire build plate must be covered with powder, when thin walled parts are fabricated using this process, there is a lot of excess powder surrounding the final product. One advantage this yields, is that unused powder acts as a support structure for subsequent layers and, to a degree, overhanging features in complex parts. Furthermore, this unused support powder can be recycled for additional use.

A point of note is that downward faces of overhanging features, especially those at an angle of 30 degrees or less (measured from the horizontal plane), will have a worse surface finish and tolerance than the rest of the part. Furthermore, collateral effects of the laser on recycled powder are still being researched, and the initial volume of powder required makes the process impractical for use with expensive or rare materials.

Another AM process that is used with metals is direct energy deposition. Direct energy deposition utilizes a multi-axis system allowing a nozzle to deposit material (typically in the form of powder or wire) onto a specified surface. The material is melted between the nozzle and surface using a laser or electron beam, then solidifies to form the part. This process is very versatile and lends itself well for repairs, modifications, and maintenance on structural parts. However the accuracy, precision, and surface finishes obtained through direct energy deposition often do not meet design requirements, leading to parts requiring labor intensive post-processing.

Material extrusion is an AM process that is being developed mainly with polymers. In this process, a heated material is drawn through a nozzle, then deposited layer-by-layer on a build plate. Each layer is fused together upon deposition because of the material's melted state. One drawback of material extrusion is that the precision and tolerances of the final part are limited by the nozzle thickness. LLNL has begun researching a process called direct metal write which is similar to material extrusion but uses metals with low melting points. This technology is still in the very early stages of development.

Material jetting can also be used to create polymer parts. This process involves using a print head to deposit a material in the form of droplets onto a build platform. Often times a build material and support material will be used in unison in order to achieve overhanging features in parts. Once the material has been deposited it is either allowed to cool and harden, or cured using a UV light, then the build platform is lowered to repeat this process. The main limitation of this process is the types of materials you can use, since the material must be accurately deposited in droplet form.

Another method of AM used with polymers is vat photopolymerization. In this approach a build plate is contained in a tank of liquid photopolymer resin which can be cured with a UV light. Ultimately, the build plate is lowered through the liquid, and cross sections of the part are cured layer by layer in the resin. Vat photopolymerization can produce high precision parts, but like all processes, support structures are required to build overhanging features. Additionally, this process has material limitations since it can only be used with a curable resin material.

Finally, an AM process that is not recognized by ASTM, but has been developed and used within LLNL, is Direct Ink Write. In this process, a shear thinning ink is deposited from a nozzle at room temperature, and shear thinning properties allow this material to flow when exposed to shear forces, while remaining rigid when it is not under shear forces. This ink is deposited layer by layer to create a 3D part, and is cured during post processing to create a structurally solid final part.

Clearly all of these processes have unique advantages and disadvantages. However, none of these methods alone successfully address LLNL's needs to produce high quality, high precision, metal parts without using a large amount powder.

5 Design Development

After acquiring basic knowledge of AM processes, defining customer requirements, and finalizing design specifications, RAM began brainstorming. Initially brainstorming focused on producing numerous ideas which could be combined and refined later. During that phase of the process, creativity and ingenuity were strongly encouraged and ideas were not rejected for impracticalities or complexities. Throughout this process, RAM brainstormed independently, and as a group. Additionally, RAM utilized multiple brainstorming techniques throughout the concept generation process; below are some examples.

5.1 Brainwriting

During the brainwriting exercise, each member of RAM took a page in their logbooks and divided it into four quadrants. Two minutes were then taken in each quadrant to draw or write about a possible solution. After all four quadrants were filled, the logbooks were passed onto a different team member who then took two minutes expanding on each of the original ideas. This process was repeated until each team member had viewed and commented on all other team members' ideas.

5.2 Ideation by Parts

The second brainstorming exercise involved separating the problem into three different subcategories, which were thought about independently of each other. These subcategories were powder transportation, pattern formation, and powder conservation. Each category was carefully considered and specific ways of performing each task were recorded. After creating a list of eleven ways to transport powder, ten ways to formulate patterns, and five ways to conserve powder, every combination of these partial ideas were fused to form complete ideas and potential solutions. During this process, RAM realized that powder conservation was essentially being encompassed by the other two categories. Because of this, powder conservation ideas were neglected. Transporting powder and formulating patterns were combined to form complete ideas and potential solutions. These subcategories can be seen in Appendix C.

5.3 Conceptual Modeling

Another brainstorming technique used was conceptual modeling. Foam board, simple crafting supplies, and sand were used to model different designs based on generated ideas. Throughout this process, we gained a better understanding of how granular material could be transported and formulated. We came up with nine different prototypes which can be seen in Appendix D. Additionally, having the opportunity to observe powder behavior illuminated potential problems such as clumping, clogging, and issues related to the flattening and uniform spreading of powder. Note: sand is orders of magnitude larger than powders used in the PBF process, but the granular flow of sand was enough to suffice for crude testing purposes.

Along with these brainstorming techniques, RAM held multiple brainstorming sessions together, individually, and with LLNL. This provided a list of over fifty ideas to, combine, refine, and ultimately move toward a final solution.

Eventually, RAM began to narrow the selection by comparing ideas based on how well they met customer requirements and design specifications. The steps that were taken in narrowing the list occurred in four main stages. As mentioned before, creativity was crucial during the brainstorming processes, but ultimately led to some very impractical ideas; the first stage of narrowing served to eliminate these unrealistic solutions. Stage two of narrowing involved comparing and contrasting how well ideas satisfied customer requirements using a pugh matrix. The third stage was strictly a "go no-go" reduction method, based on requirements recognized during the design process. Finally, a weighted decision matrix was used to analyze the top seven ideas. This provided a form for selecting the top two candidates to move forward with.

5.4 Initial Common Sense Idea Reduction

After a large list of ideas was generated through creative brainstorming, we quickly reduced the number or ideas by simply considering the practicality of each solution. Ideas that failed to meet customer requirements, seemed overly complex, or were beyond the scope of the project were eliminated during this phase in order to bring focus to more realistic solutions. Ideas such as retractable retaining walls, rake or broom powder removal, and an anti-gravity build plate, were all eliminate at this point due to their inevitable complexities, drawbacks, and/or failure to sufficiently meet specified requirements. This process significantly reduced the amount of ideas we had, but still provided a wide variety of potential solutions to move forward with in the design selection process.

5.5 Pugh Matrix Secondary Idea Reduction

The next method used to guide the decision-making process was a pugh matrix to compare and contrast the initial ideas. This matrix can be found in Appendix E. The pugh matrix has requirements in the left column that are based on those found in the QFD, and has potential solutions listed across the top. A pugh matrix is used by analyzing how well concepts satisfy customer requirements compared to whichever concept is specified as the datum.

In this analysis, a '+' indicates better satisfaction than the datum, a '-' indicates less satisfaction than the datum, and a 'S' indicates equal satisfaction to the datum for a given requirement. The datum of the Pugh matrix was an idea that was initially felt to be stronger and more comprehensive than others. The other ideas within the Pugh matrix were then compared to the datum for each requirement and given a '+', '-', or 's' as per the described convention. Each column was then summed to give an overall rating of each solution compared to the datum.

If the concept is green, then its net sum is positive meaning it satisfies requirements better than the datum. If the idea is yellow, then it's net sum is 0 and it is considered equivalent to the datum. Finally, if the concept is red, then the net sum is lower than the datum. If the concept is maroon, then the net sum is significantly lower than the datum. The Pugh matrix allowed us to extract general trends throughout our ideas and pinpoint each idea's strengths and weaknesses. Ultimately, the pugh matrix gave us insight into which of our initial ideas had the most potential for success.

5.6 Final Go No-Go Idea Reduction Prior to Decision Matrix

After completing the pugh matrix and identifying the best initial concept solutions, the top ideas were presented to LLNL via teleconference. During this teleconference two requirements that had not initially been identified were recognized and added to the QFD and list of design specifications. These requirements were the ability to build successive layers and the ability to create hollow internal features. Ultimately, this was very crucial in guiding the selection of the final solution and led to the elimination of a couple solutions.

5.7 Weighted Decision Matrix

The final tool used in the decision-making process was the weighted decision matrix. This tool can be seen in Appendix F, and ultimately led to the top two solutions that were developed further. This tool is very similar to a pugh matrix in the sense that potential solutions are compared against each other based on how well they satisfy customer requirements and design specifications. However, one crucial difference between a weighted decision matrix and a pugh matrix is that a weight from 0-1 (or 0-100%) is assigned to each design specification in order to distinguish their importance relative to each other. For example, since powder conservation is the primary motivation behind this project it was awarded the highest weight at .25 (or 25%). The weight of each specification is identified in the row labeled "Weighting Factor." Additionally, we added two more specifications to this matrix called simplicity and scalability.

Simplicity was used to compare the complexity of each idea, with a high simplicity score indicating a relatively simple concept. The scalability specification was added in order to account for how well concepts could be scaled in future iterations. For example, concepts which involved grids or other features to formulate powder at a certain resolution would get increasingly complex as the resolution increased.

Once all requirements and specifications were identified and weights were assigned, each potential solution was analyzed by scoring its ability to satisfy each specification. A score of 0 indicated an inability to satisfy a requirement, while a score of 100 indicated complete satisfaction of a requirement. With the weight of each specification applied, each solution was given a total score based on how well it cumulatively satisfied all of the requirements. Based on this analysis, the top two ideas were the blade dispenser with a filler material and a nozzle.

5.8 Final Decision

Throughout the process of idea generation, there were many ideas that contained nozzle, or nozzle like, structures. Nozzles ranged from simple funnels, to vacuum nozzles removing unwanted powders from the build plate. From our analysis using Pugh matrices, along with a weighted decision matrix, a nozzle using gravity based flow was chosen as the best solution for the scope of our project due to its simplicity. Additionally, using a chute attached to the nozzle tip was recognized as a potential add on to aid in controlling path deposition.

It was established that a nozzle based approach would be simple compared to other ideas considering nozzle technology is readily available. Furthermore, if accurate nozzle deposition was achieved, this method would easily satisfy the primary design specifications. Powder conservation would be significant since powder would only be deposited where it is needed, as opposed to a build plate sized layer of material used in the current PBF process. Also, hollow internal features are easily formed due to the control of the nozzle. Another benefit of using a nozzle, is that if done successfully, multiple nozzles could be incorporated into one machine to reduce build times and potentially allow composite metal parts to be built using additive manufacturing methods.

Unfortunately, while nozzles have many potential benefits, they have drawbacks as well. The main problems identified with nozzles are the ability to build successive layers, potential clogging problems, and the fact that powder deposition would most likely be very slow. Since a nozzle needs a flat surface to deposit powder on in order to remain accurate, some kind of filler material or support structure will be needed with this method in order to build successive layers, especially to achieve overhanging features in parts. Possible solutions to this problem include using stencils to contain powder, or using additional nozzles to dispense filler materials. For example, LLNL’s direct ink write process has been identified as one possibility for creating a support structure. However, these solutions add complexity, as well as additional problems to address, such as mixing between filler and build materials, and were ultimately beyond the scope of this project.

A large component to determining the best nozzle solution will be how the nozzle is manipulated around the build surface. The nozzle will be secured to a 3-axis driver system capable of traversing the build plate in the horizontal and vertical plane. The nozzle will be fed from an enclosed powder reservoir located above the system, through a hose, and into the smaller nozzle reservoir. A SolidWorks model of the original concept is shown in Figure 5.1. RAM planned on controlling flow with a servomotor-controlled starting and stopping mechanism, similar to the one seen in Figure 5.2, however this was not implemented into our final solution.

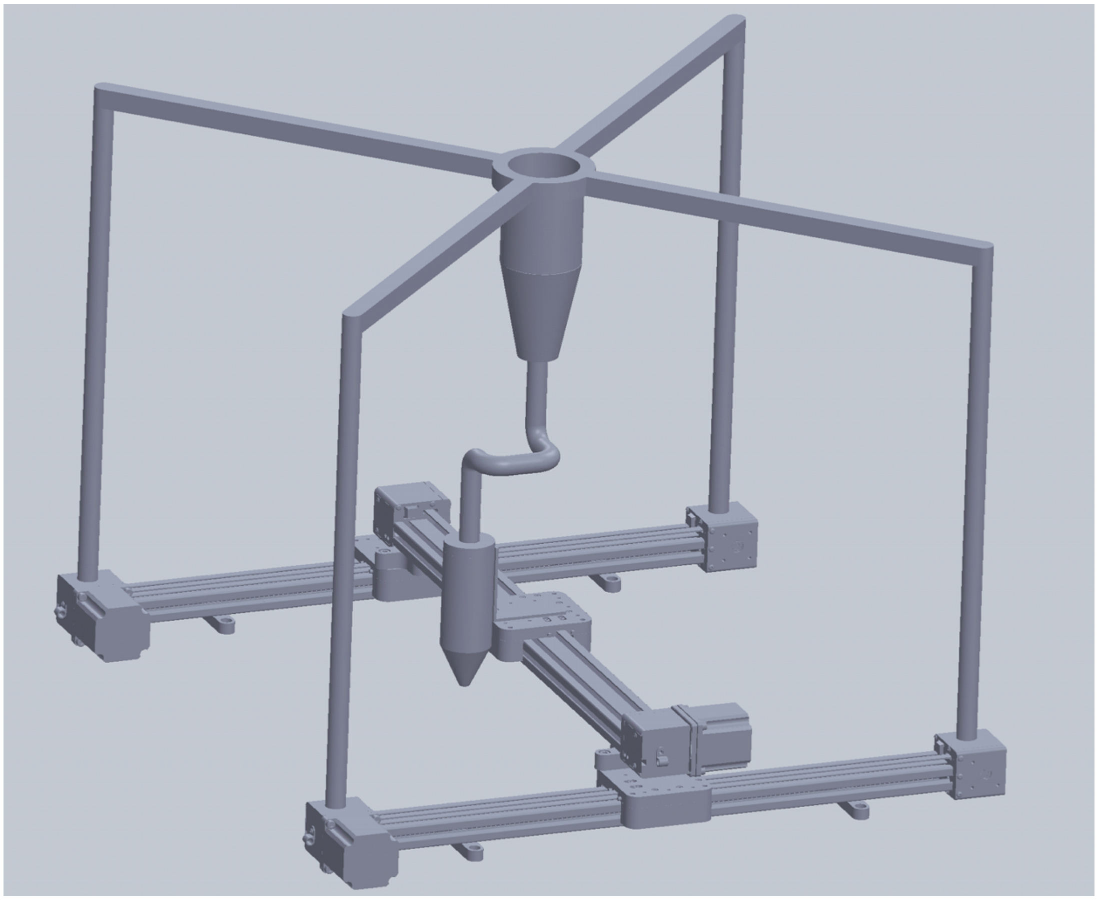


Figure 5.1. 3D model of original final assembly concept consisting of the four main system components.

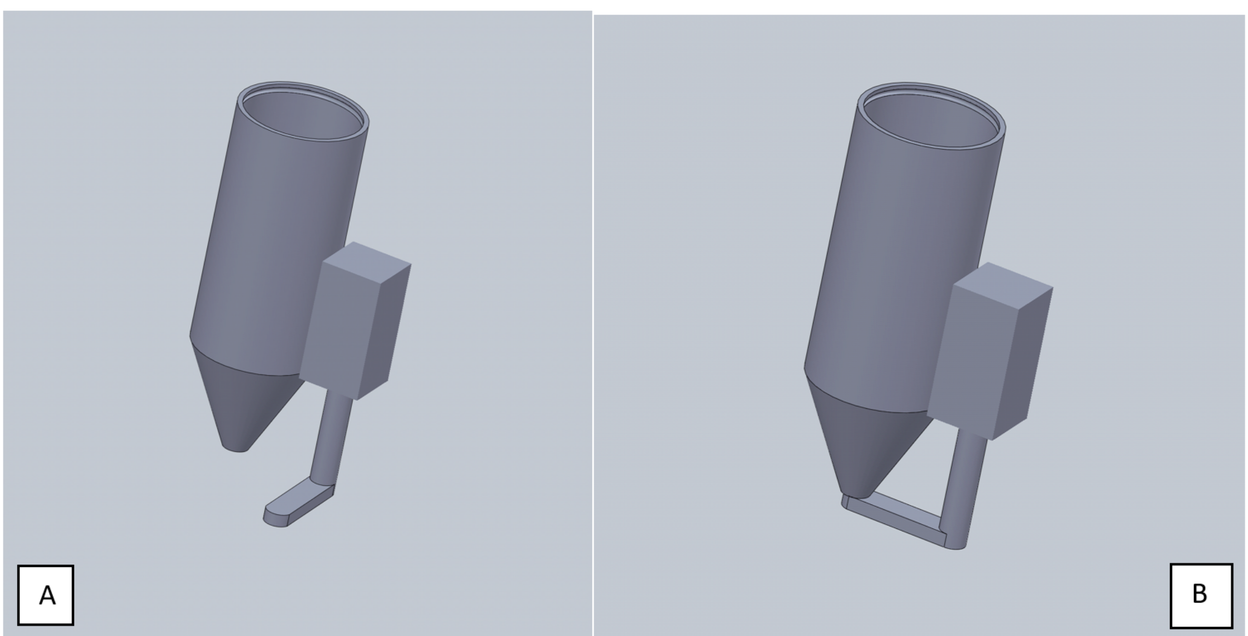


Figure 5.2. SolidWorks model of servomotor controlled start-stop mechanism.

6 FMEA, Original Test Plans, Prototyping, and Original Test Assembly

Initially we started to research granular flow in hoppers, inclined surfaces, and various other flow configurations. However, after some research, the complexity of granular flow became very apparent, and we decided that developing a theoretical model of granular flow was outside the scope of our undergraduate senior design project. With that said, RAM decided to take a testing based approach towards designing each of the four main components. However, before test design began, our team conducted a Failure Mode and Effects Analysis (FMEA) in order to gain a better understanding of the most critical components of our system, and how they might fail.

6.1 Failure Mode and Effects Analysis

After determining that multiple tests were going to be performed, RAM needed to identify all possible modes of failure within each of the four sub components. This included identifying the severity of each failure mode, as well as the likelihood of the failure occurring. To organize this process, RAM utilized a Failure Mode and Effects Analysis (FMEA). RAM's FMEA table can be seen in Appendix H.

Within the FMEA, the furthest left column separates the table into four sub assembly components: the hopper, nozzle, hose, and two-axis driver. The function column describes the overall purpose of each component within the system. The potential effect(s) of failure column outlines what would happen to the system if the specified component failed to perform its function. The severity column relatively quantifies how bad it would be if the component was unable to fulfill its function. The scale within the severity column ranges from 1-10, with 1 being a failure that is relatively easy to fix and not destructive to the assembly's function, and 10 being a failure that is totally destructive to the assembly's functionality or the user's safety. The potential cause/mechanism of failure column pinpoints all possible ways that the component could fail to fulfil its function and the cause in which the failure would occur. Many failures stem from powder clogging, and flow rate inadequacy. The occurrence column relatively quantifies how often RAM feels like this cause/mechanism of failure is likely to occur. The scale within the occurrence column ranges from 1-10 with 1 being nearly impossible to occur (<<1%) and 10 being fairly likely to occur (>10%). RAM did their best to quantify these occurrences, however they are all just best guesses and highly subjective.

The Risk Priority Number (RPN) column within the FMEA is arguably the most important column in the table since it is a quantitative representation of which failure mode RAM should be most concerned with. As seen in RAM's FMEA in Appendix H, the nozzle's ability to lay down the powder to the specified powder bed properties is the most critical area of interest and therefore the testing performed to prevent these failures is the most critical for RAM. The recommended actions column outlines what type of test or analysis will be needed in order to prevent this failure mode.

These recommended actions are how we developed a set of tests to address the possible modes of failure. Once RAM created the test plan, the "how will we address the possible failure" column outlines how RAM's test plan fulfills the failures at hand.

The next column is the target date in which the tests need to be done and the following five columns outline whether or not the test has been performed (N/P means the test has not been performed), and what the estimated final design's failure severity, occurrence, and new RPN values are. The detection column quantifies RAM's confidence in the final design's ability to avoid the failure at hand with 1 being that RAM has absolutely no clue if the final design will successfully avoid failure and 10 being that RAM is absolutely sure that the design will avoid the specified mode of failure.

6.2 Original Test Plans

After completing the Failure Mode and Effects Analysis to pinpoint the different areas of concern for our final design, RAM had some very specific aspects of the design that the test plans needed to address. A list of all of the possible concerns that RAM felt needed to be addressed and five different test plans were created in order to investigate all possible failure modes. Table 6.1 summarizes the tests originally designed by RAM and what the purpose of each test is.

Table 6.1. List of originally planned tests and the purpose for each test.

Test #	Test	Characteristic investigated
1	Preliminary	The Preliminary Test serves to give RAM members a general sense of how powder will flow through a nozzle and formulate on a build plate.
2	Geometry Iteration	The geometry Iteration Test attempts to gain a deeper understanding of the influence of different geometric characteristics of nozzles on their corresponding powder path properties.
3	Drop Height and Speed	The Drop Height and Speed Test investigates the influence of nozzle translational speed and nozzle drop height on their corresponding powder path properties.
4	Two Dimensional	The Two-Dimensional Test explores the optimized nozzle's ability to lay down nonlinear paths more specifically paths of constant curvature on a flat build plate.
5	Hose	The Hose Test will address how changing the diameter and angle of the hose connecting the hopper and nozzle influences the flow rate of the stainless-steel powder.

6.3 Prototyping

On Cal Poly's campus, there are many resources available for rapid prototyping in various forms. Prototyping items such as the various nozzles throughout the geometry iteration test will be essential in analyzing the degree to which a possible nozzle design meets the designated requirements.

In the end, we prototyped two nozzle designs; one for phase 1 testing and another for phase 2. Pictures of these nozzles and associated parts can be seen in Figure 2.3 and Appendix J. Both sets of nozzles were created in SolidWorks and printed on Cal Poly's rapid prototyping machines.

6.4 Original Test Assembly

The test assembly is defined in terms of phase 1 and phase 2. Phase 1 was a single-axis test assembly purchased and assembled by RAM using Cal Poly's resources; phase 2 is a two-axis gantry. Phase 1 was intended to facilitate initial observation and analysis of the powder flow rate, path formation, the effect of various nozzle geometries, and possibly powder drop heights. To this end, a single axis test assembly allowed us to achieve success and become more knowledgeable about the test assembly and its components. A model of the phase 1 test assembly can be seen in Figure 6.1. Photos of the actual phase 1 test rig can be seen in Appendix K.

Phase 2 is intended to build off of phase 1. The intent was to have a two-axis gantry system that can traverse the entirety of the build plate with adjustable speed and a high degree of resolution. Our original plan was to purchase a gantry system similar to the one pictured in Figure 6.2. However, after working with the Industrial and Manufacturing Engineering Department on Campus, we were able to obtain and modify the Delta mechanism which allowed us to satisfy these test requirements. The system is driven by the user-friendly interface detailed in Chapter 2. With a two-axis gantry capable of not only X and Y movement, but variable travel speeds and nozzle heights, our machine is capable of performing many powder deposition tests.

Preliminary testing on the phase 1 test rig has occurred and RAM decided that phase 2 would be more beneficial in nozzle optimization. RAM modified the Delta Mechanism as explained in chapter 2 to act as a phase two test rig. We believe the Delta is fully capable of performing all proposed testing for the beginning of solution development.

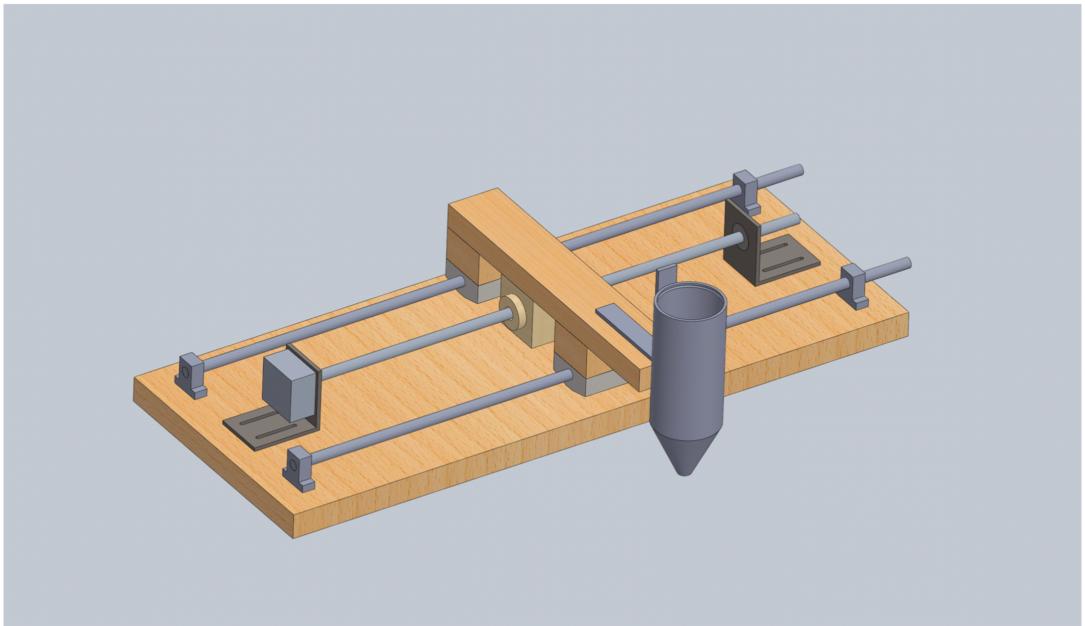


Figure 6.1. SolidWorks model of phase 1 test assembly with mounted nozzle.

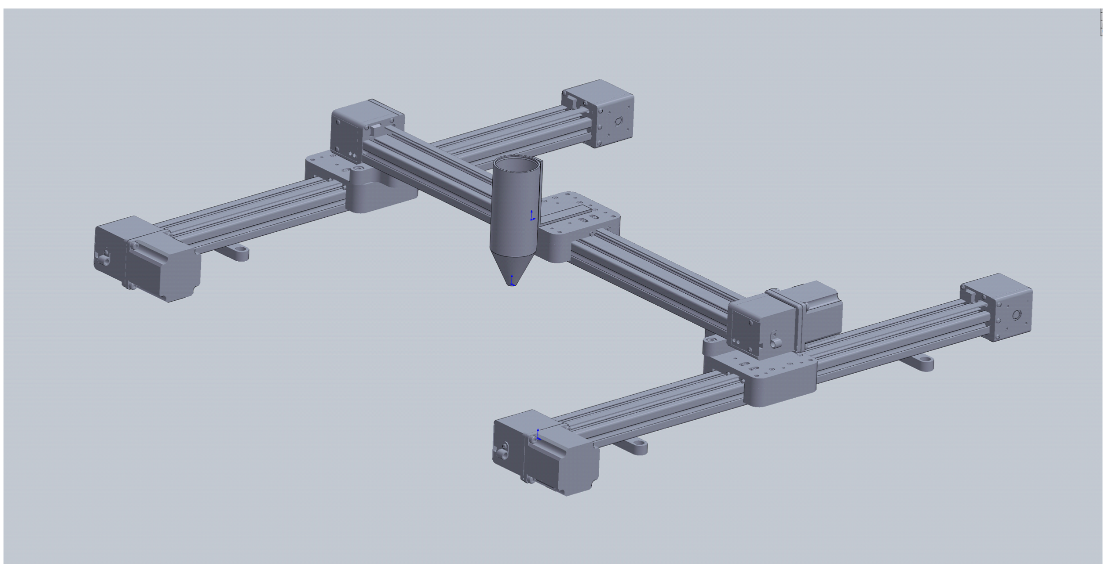


Figure 6.2. SolidWorks model of original phase 2 test assembly with mounted nozzle.

6.5 Original Test Assembly Components

The components of the phase 1 test assembly can be broken into two categories; hardware and electrical.

6.5.1 Hardware

The whole test assembly is mounted on a 12” x 18” piece of ¾” plywood. The carriage, which is a 2” x 9” x ¾” plywood block, is mounted on 8mm linear bearings which run along 8mm diameter stainless steel guide rails. The rails are secured to the base board using 8mm guide rail supports. The mounts are held in place by bolts and wing-nuts. The nozzle is mounted to the carriage by a simple L-bracket and hose-clamp (not shown). The carriage is also fixed to the lead screw of the stepper motor via a custom 2"x2" wood block setup. Ultimately the lead screw pushes the carriage which is guided by the 8mm diameter stainless steel rails and in turn moves the nozzle in a linear path at a steady speed.

6.5.2 Electrical

The carriage is driven by a bipolar stepper motor. The stepper motor is controlled by a Arduino Uno microcontroller and powered by a 6v power supply. Currently the Arduino is powered via a USB port on a computer for ease of coding changes. A full wiring schematic can be seen in Figure 5 below, and the code to control the stepper motor speed and acceleration can be seen in Appendix L.

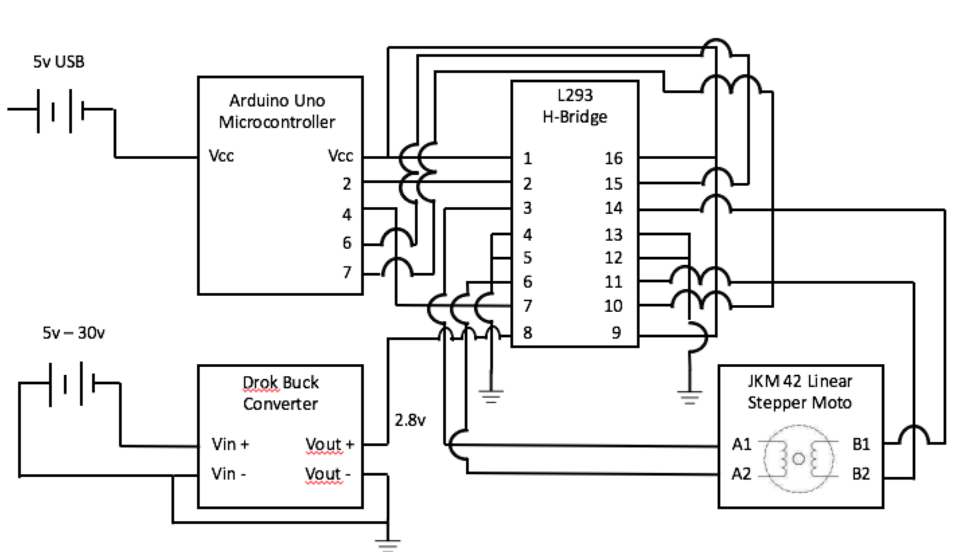


Figure 6.2. Test assembly wiring diagram.

The operation of the test assembly is as follows: The microcontroller runs looping code (seen in Appendix L) that, upon user input of a button press, energizes the stepper motor's coils in rapid succession in order to rotate the lead screw in one direction for a predetermined period. It then, after another button press, energizes the the stepper motor's coils in the reverse direction, in the same fashion, to bring the motor back the other direction. This process can be repeated as long as the user desires, assuming the battery has the stored energy for operation.

When stepper motor coils are energized, the lead screw turns and the carriage is pushed or pulled along the guide rails. With the nozzle hanging off the side of the carriage, this movement will allow the nozzle to dispense a path of powder along a straight line with effective consistency in regards to drop height and speed.

6.6 Operational Risk Management

Operational Risk Management (ORM) is a continual cyclic process which includes risk assessment, risk decision making, and implementation of risk controls, which results in acceptance, mitigation, or avoidance of risk. We have gone through this process in an attempt to identify all potential risks involved with testing and manufacturing of our solution. Where possible, we have engineered out hazardous. When that was not possible, administrative and/or control measures have been implemented. As a last resort, Personal Protective Equipment (PPE) requirements have been implemented. As a result of this process, we have created a risk assessment that can be seen in Appendix M.

7 Other Concepts

As a result of the various design development methods and narrowing down processes, a small number of potential ideas became evident. Due to lack of time, resources, or number of customer requirements fulfilled, all but the one selected concept (seen in Chapter 3) was discarded. Below are the discarded ideas.

7.1 Blade Dispenser (Filler Material)

Within LLNL's SLM machine, the powder dispensing method is slightly different from the standard powder roller used within most SLM machines. In the current process, a known amount of powder is deposited in front of a roller which spreads the powder evenly across the build plate. LLNL is very happy with this powder dispensing method because it leads to a uniform layer of powder across the build plate.

RAM's current idea of a blade dispenser is very similar in nature to that of LLNL's current SLM powder dispenser. It would lay down powder in front of a blade that traverses across the build plate. However, this method would continuously lay powder down in front of the roller only where it is needed. Furthermore, this blade dispenser would lay *both* precious and filler powders down in front of the blade. As the precious powder is being laid down in specified positions (thus reducing the amount of precious material needed for a build), a filler material would be laid down in the places where the precious material was not deposited. Once the material was dropped onto the build plate, the blade would follow behind and flatten out the deposited powder into an even powder bed. One potential approach to this is described and illustrated in the 3D model shown in Figure 7.1.

A blade dispenser using a filler material shows great potential to satisfy requirements that other ideas do not. One example, is the capability to build successive layers and overhanging features with minimal added technology or support. Since it produces its own powder bed, structure would be provided for building additional layers, as well as overhanging features, and there would always be a smooth level surface to deposit the next layer of material. Additionally, since this design integrates the use of multiple materials (rare and filler), it could be easily modified to support composite builds. This ability is one in which LLNL has expressed interest in.

The blade dispenser with a filler material has many positive attributes to it, however, there are also potential problems that have been identified. First, this method would involve a large amount of automation pertaining to the nozzles depositing the right amount of powder into the right sections of the dispenser. Also, since this dispenser moves across the build plate linearly while dropping material, it divides the build plate into a logical grid. The reduction of waste and path tolerance is directly related to the resolution of the logical grid. Complexity of the solution will increase as greater resolution is eventually required. This essentially becomes a scalability problem, but one that needs to be understood.

Another possible problem is whether or not the powder can be spread onto the build plate in a uniform way without ridges being formed due to the pixelated pattern. As seen in Figure 7(B), the dispenser individual sub-reservoirs which would hold a material just before deposition. The dividers will create small gaps in the line of material being dropped. A portion of each gap will be filled in by surrounding material cascading into them, but end result will create a wave or ridge effect across each line of material.

Finally, the largest question regarding this design is the mixing of the build material with the filler material. The precious powder that is being lasered must remain free from contamination in order to maintain the material properties of the final part. However, it is believed that this problem could be resolved by creating a buffer zone between the material interface and the area that's going to be melted or sintered.

As Shown in Figure 7.1, this blade dispenser has two rows of slots, each row with its own nozzle. One row is designated to the build material, while the other row is used for the filler material. As the device shifts across the build plate, the nozzles are used to fill certain boxes with a specified amount of powder. Two hinged doors under the dispenser, that span its full length, can be controlled in order to deposit powder from these rows. By filling certain boxes, and not filling others, pixilated patterns can be created in rows, and spread flat by the blade, as this device translates across the build plate. Ultimately this would result in a pattern of the build material surrounded by filler material covering the build plate surface. For reference purposes, the gold flat plate on the bottom of the assembly is the build plate, which is 10"X10" and all other assembly components are to scale. It should be noted that this is a basic concept model, and if chosen, the actual design will be refined to maximize performance.

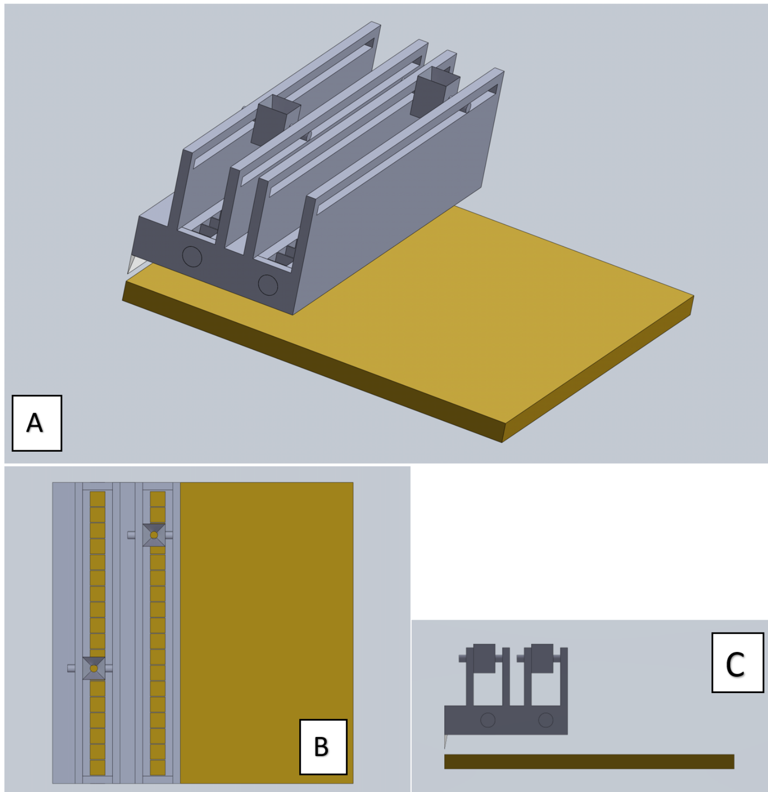


Figure 7.1. SolidWorks model of Blade Dispenser concept. (A) Isometric view of our current blade dispensing assembly. (B) Top view of our current blade dispensing assembly. (C) Side view of our current blade dispensing assembly.

This solution would require many additional components. Two different motors would be required to drive the nozzles back and forth along the powder dispensing device. How the powder would be fed into the nozzles, and how to actuate the plate that drops the powder from the reservoirs onto the build plate would also need to be solved.

7.2 Stamp

Many of the ideas generated attempted to take advantage of LLNL's current SLM technology, and one example of this is RAM's stamp idea. Initially this solution involved spreading a layer of powder across the build plate (similar to the current PBF practice), then, using a stamp to hold desired powder in a specified pattern, excess powder would be removed via compressed air or other means. Upon further consideration, it was realized this solution did not provide a means for creating hollow internal features, such as a cylinder. A slight variation of this idea then arose, a negative stamp, which removed unwanted powder via suction or other means. This solved the problem regarding internal features, however building successive layers still posed challenges.

Ultimately, we felt that this solution would require additional technology (most likely a support structure or filler material) to support building multiple layers. A simple layout drawing of the stamp idea can be seen in Figure 7.2.

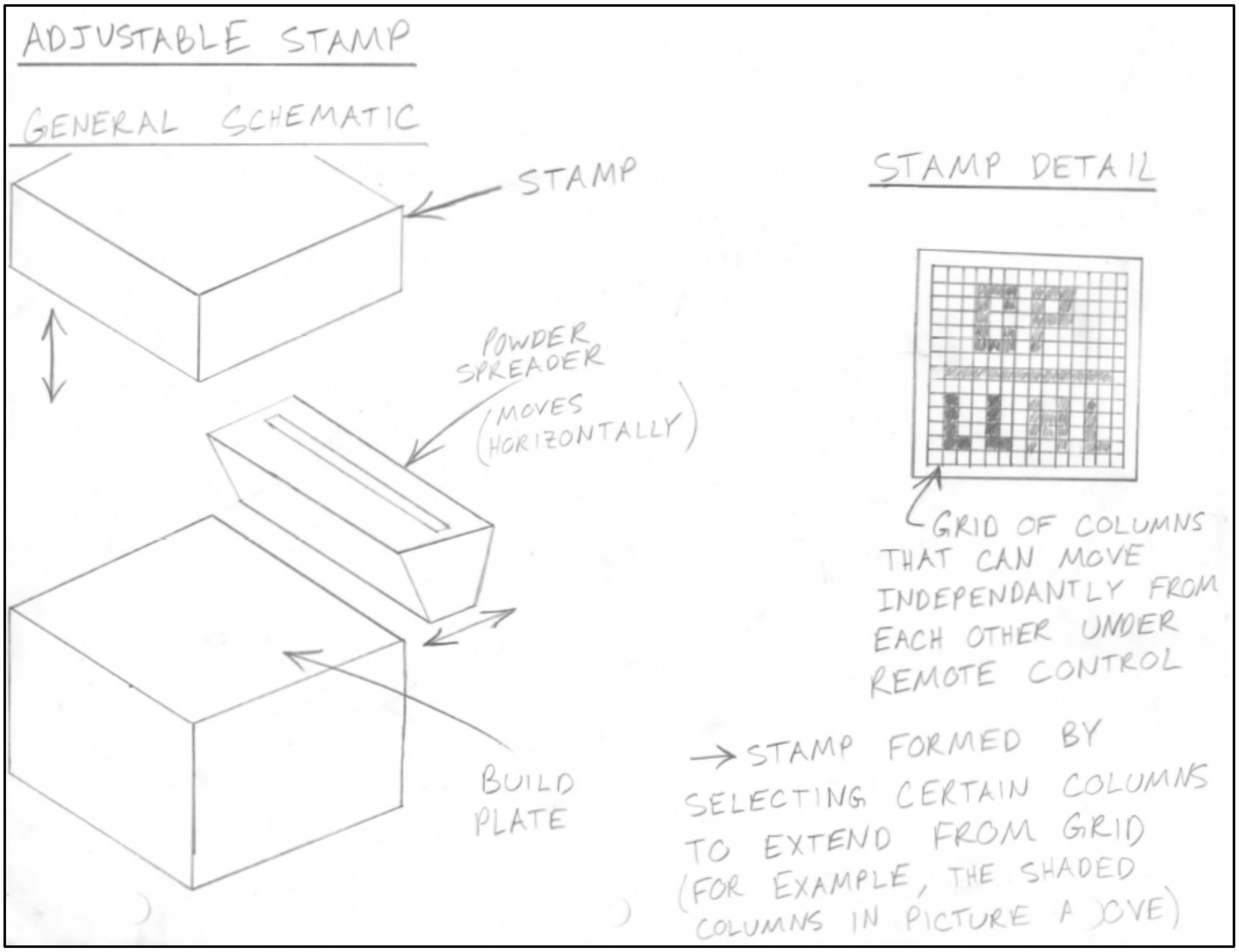


Figure 7.2. Layout drawing of stamp concept.

7.3 Porous Build Plate

Another idea that exploited existing SLM technology was centered around a build plate fabricated from a porous material. Ideally this material would allow airflow, but hold powder on its surface. The idea involved using a vacuum underneath the porous build plate to create suction in a specified pattern. This suction would provide the force to secure powder to the build plate, and then unsecured powder would be removed using compressed air or other means. Prefabricated stencils could be used on the backside of the build plate in order to allow suction in the areas of the build plate where it was needed, and block suction on the build plate where powder is not desired. The initial picture of the porous build plate concept can be seen in Figure 7.3 on the next page.

Unfortunately, this solution involved complex unknown materials for the build plate, and more importantly, building successive layers posed major difficulties within this solution. For these reasons, it was eventually discarded as a non-solution.

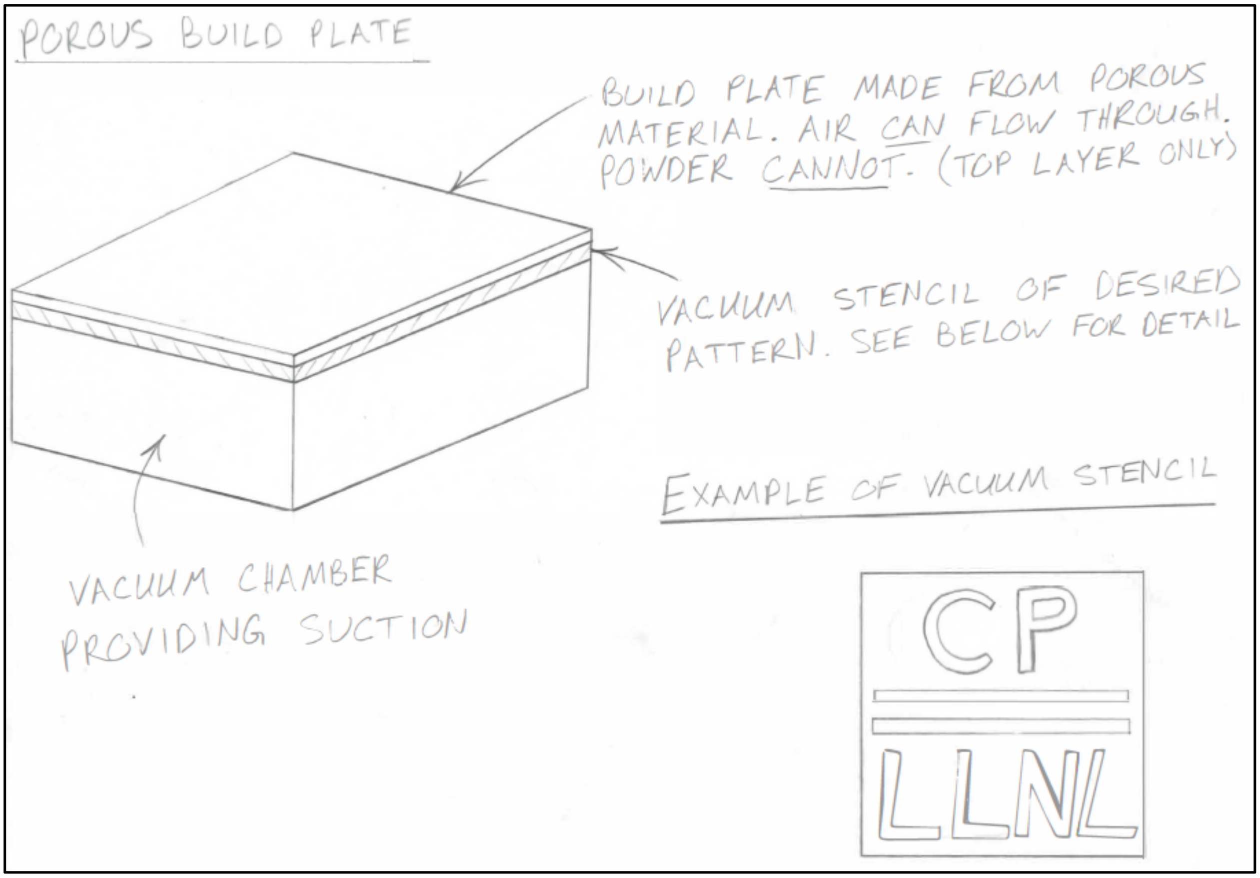


Figure 7.3. Schematic drawing of the porous build plate concept.

7.4 Sandcastle Method

The sandcastle method gets its name since it takes an approach similar to sandcastle molding. Figure 7.4 shows the layout of this powder formation method. (1) Initially a dynamic plate (deformable grid) is placed below a large powder reservoir. The grid is capable of deforming in specified patterns by allowing the depression of certain sections of the grid (pixels) so that they may be filled with powder. (2) Once the powder fills all of the depressed squares, excess powder is removed and a plate is lowered onto the grid surface that holds everything in place while the grid is flipped 180 degrees onto the build plate. (3) Next the plate is pulled out from under the grid, allowing the powder to fall on the build plate. (4) Finally, the deformable grid is lifted and the powder is left on top of the build plate in the specified pattern.

Initially the sandcastle method introduced some interesting techniques to formulate patterns with a powder and for that reason was pushed into the final decision matrix. A refined variation allowed for the build plate itself to be lowered onto the filled depressions (2). Thus, when the system was flipped, the powder would already been on the build plate and the deformable grid could simply be lifted revealing the formed powder. However, due to the complexities involved with the deformable grid, along with foreseen difficulties associated with building multiple layers, this idea was not the most favorable solution.

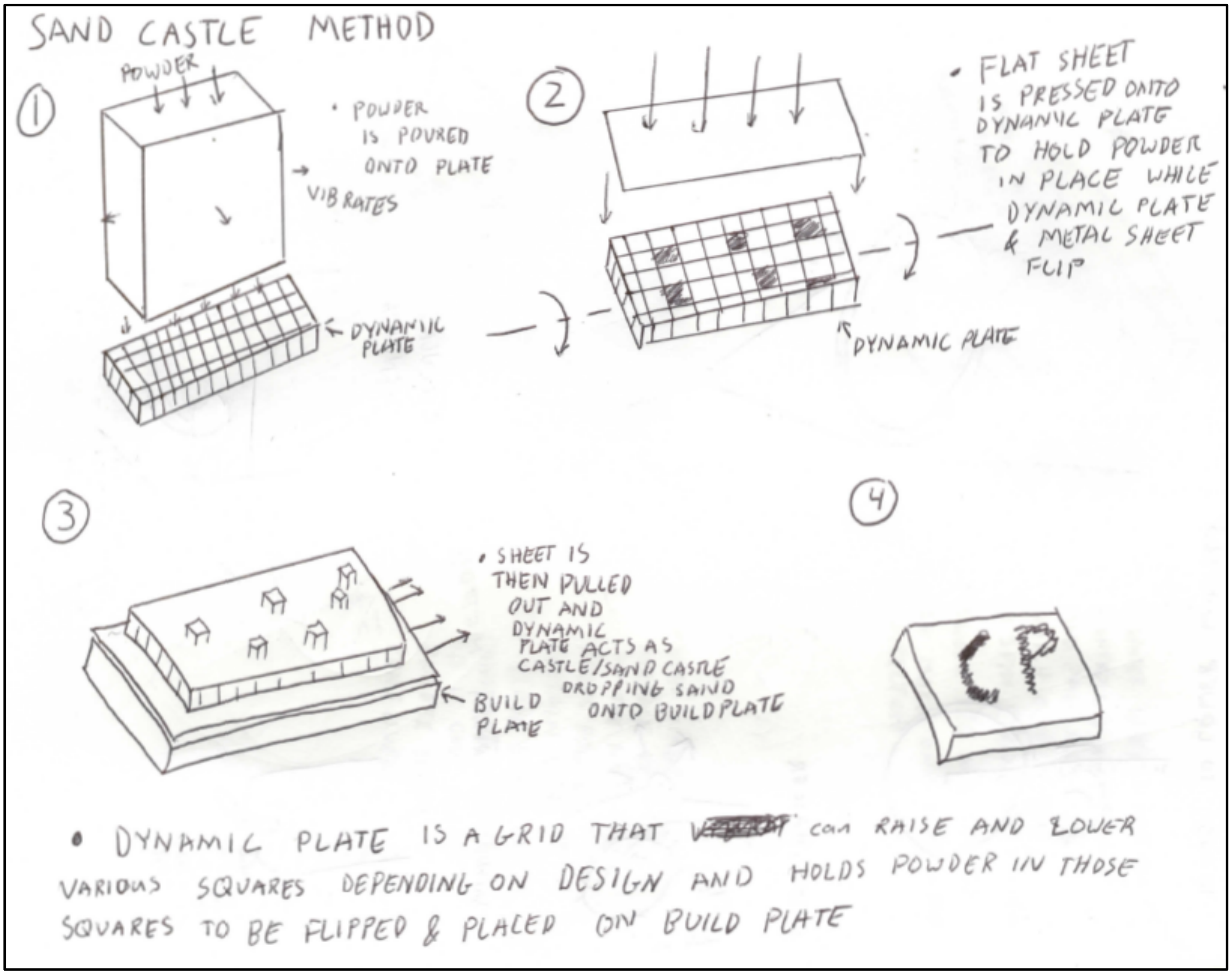


Figure 7.4. Sandcastle method visual aid. Further explains steps 1-4 of the sandcastle method introduced in the above paragraph.

7.5 Powder Wheel

The powder wheel did not perform well in the pugh matrix, however LLNL showed interest in this idea, which led us to consider it in our final decision. This idea involved using the motion and shape of a wheel to control the deposition of powder, as shown in the layout drawing in Figure 7.5 below. The concept involved a wheel rotating through a powder reservoir to collect powder, then deposits this powder as the wheel continues its rotation (conceptually like a ballpoint pen). However, this solution has problems regarding the complexity of the wheel, along with potential problems involved with building successive layers, and for these reasons, is not being developed any further.

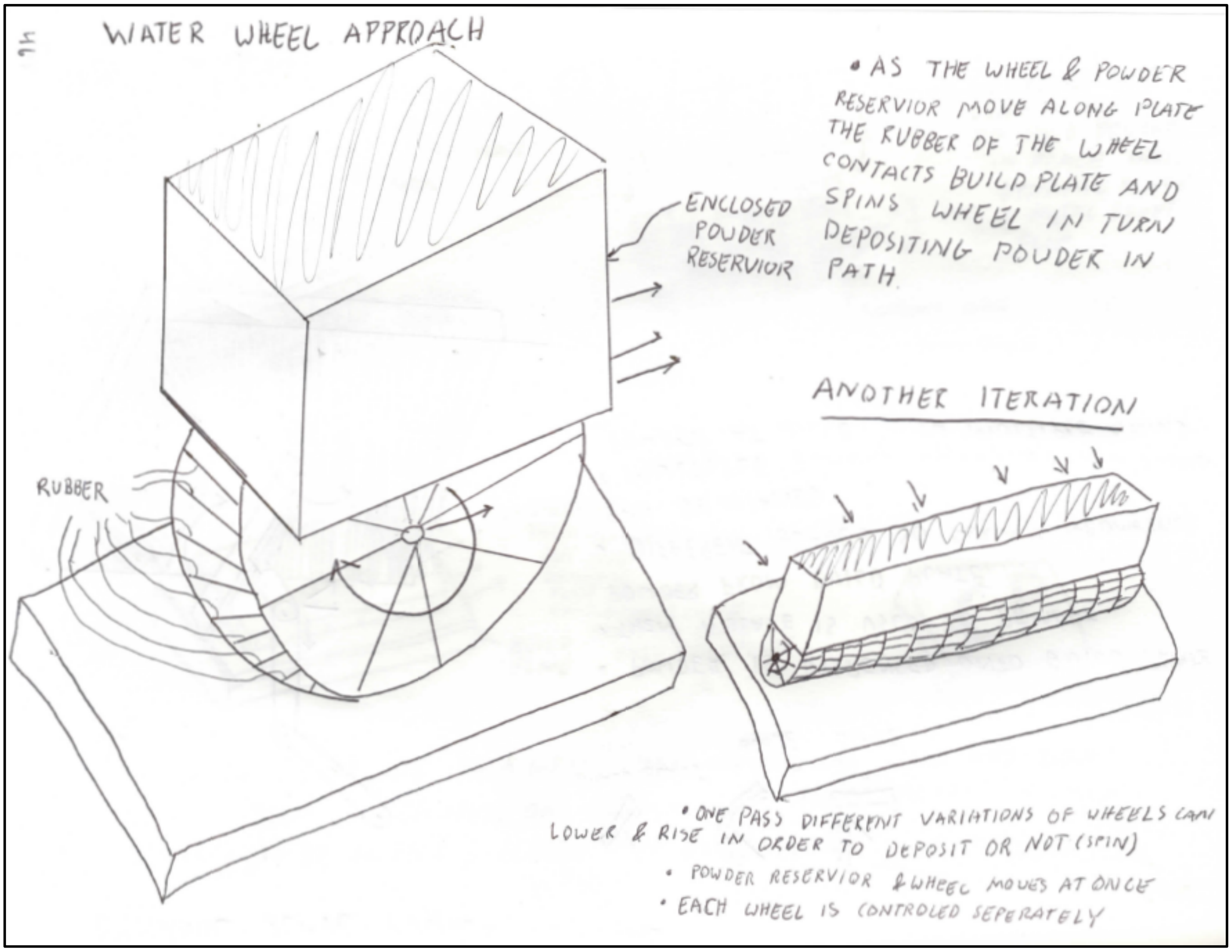


Figure 7.5. Powder wheel approach of a dispensing nozzle.

8 Manufacturing and Management

8.1 Manufacturing

Manufacturing of our solution was primarily conducted “in-house”, utilizing resources available at Cal Poly. Due to a need for iterative testing and design, rapid prototyping was essential to our success. We took advantage of Cal Poly’s various 3D printing technologies to allow us to quickly modify designs and observe how the changes affect our solutions performance.

We prototyped two different types of polymer nozzles using plastic extrusion. One nozzle is affixed to our Phase 1 test assembly which was built using an assortment of parts from different vendors. The other nozzle is affixed to the Delta Mechanism test assembly. The nozzle used within the Delta was designed for modularity and rapid iterability.

8.2 Management Plan

While all members of RAM had equal weight and authority, each member had special responsibilities. Special duties are organized in Table 8.1 by team member. The table was updated as necessary over the course of the project.

Additionally, a Gantt chart has been created and can be seen in Appendix B. This Gantt chart is the approximate timeline that our team followed throughout the project and was also updated over the course of this project. A PERT chart has also been created and is located in Appendix G. The PERT chart gives a visual and quantitative representation of how long each portion of the design process took, and when each process was performed.

8.3 Budget

The bulk of our expenses were a result of building our phase 1 and phase 2 test assemblies. Some money was also spent on the prototyping of our first two nozzle designs. Table 8.2 shows the expenditures required for building our phase 1 test assembly.

Table 8.1. Revolutionized Additive Manufacturing team member responsibilities.

Team Member	Responsibility
Matthew Walker	Primary point of contact External/Remote Control X,Y Carriage Driver Electrical/Automation Considerations
Winthrop Townsend	Maintain information repository for team Faculty and facility scheduling and communication Flow analysis and design of solution Mechanical functionality within solution
Luca Fuller	Maintain teams travel budget Maintain teams materials budget Flow analysis and design of solution Mechanical functionality within solution

Table 8.2. Expenditures of phase 1 test assembly.

Item	Quantity	Price
JKM 42 Linear Stepper Motor	1	29.99
DROK LM2596	1	9.29
Performed Jumper Kit	1	7.29
1M Double Alligator Clip	1	6.18
L293d Stepper Driver (10 pcs)	1	10.99
Combo Lock	1	6.40
Test Assembly Hardware	-	98.37
8mm Rail shaft guides	2	4.97
8mm Linear bearing guide (4 pcs)	1	7.94
8mm End bearing	1	5.13
Prototype costs	1	69.00
Total	$255.91	

9 Phase 1 and 2 Preliminary Testing Conclusions

9.1 Phase 1 Preliminary Test Conclusions

RAM was able to perform a preliminary nozzle test on the one axis test rig seen in Appendix K. Several different things have been learned about Safety procedures, desired test rig functional characteristics, and post processing.

Throughout the preliminary testing, it became apparent very quickly that whoever is working with powdered stainless steel must work hand in hand with the Environmental Health and Safety (EH&S) Department. In order to be authorized to work with the powder, a respirator training class must be taken, and an approved EH&S SOP must be obtained. Additionally, if testing processes or locations change in any way, EH&S must approve any changes to the SOP.

Once safety concerns were addressed initial testing took place. RAM learned about several weak points in the phase 1 test rigs design. First, we needed to attach the nozzle to the gantry system more rigidly. It was also determined that an accurate way of adjusting nozzle drop height and test rig speed were necessary in moving forward. RAM ultimately felt that the need for two-dimensional carriage capabilities was necessary before testing continued.

Post-Processing techniques changed drastically after one dimensional preliminary testing concluded. Initially a cutting device was going to be manufactured in order to accurately make a powder path cut. MATLAB photo analytics were then going to be used to quantitatively determine powder path cross-sectional dimensions. Throughout the one axis preliminary testing, RAM began cutting powder by hand with a straight edge and taking cross sectional photos with an iPhone 5C. After discussion, RAM feels that a powder path cutting tool is unnecessary and the path qualities can be determined qualitatively through high quality images rather than quantitatively with MATLAB photo analytics.

9.2 Phase 2 Preliminary Test Conclusions

The Delta Mechanism appears to be the most promising test rig. An EH&S approve SOP was obtained for the Delta Mechanism to be operated in Building 41 Room 101B on Cal Poly’s campus. The delta mechanism has the capability of varying 2-D path geometry, nozzle drop height, and nozzle geometry. These are all much needed advances made from the phase 1 test rig. However, there are two main disadvantages with the Delta Mechanism. The Delta Mechanism is unable to vary nozzle traversing speed in an accurate manner and the Delta mechanism build plate is not level which results in varying nozzle drop height as it traverses across the build surface. The nozzle build plate levelness issue can be addressed fairly easily but the nozzle speed variation problem will likely require more software work.

10 Appendices

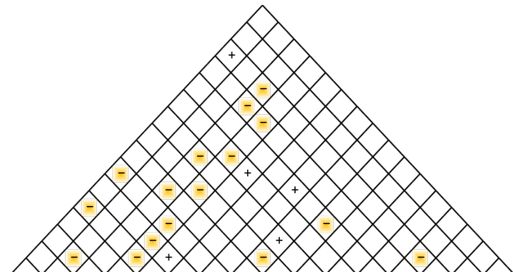
10.1 Appendix A: Quality Function Deployment

Revision: 1
Date: 1/28/2016

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

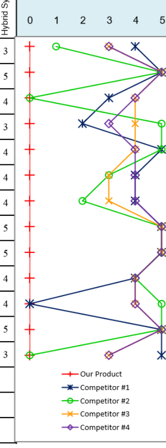
Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

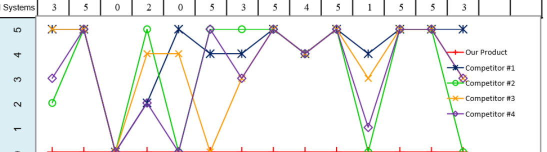


Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Direction of Improvement	▲	▼	◇													
HOW: Engineering Specifications / WHAT: Customer Requirements (explicit & implicit)	Reduce Waste	Build Plate Size	Machine footprint	Speed of powder deposition process	Path width	Powder layer thickness	Material Density per Volume	Lockout Features	Infinte Life Cycle Spec	External Controller	Positional Tolerance (Powder Pattern)	Works in Ambient Temprature, Argon Atmosphere, and more than one Atmosphere of Pressure	Ability to build successive layers	Ability to create hollow internal features		
1 Conserve Atomized Material (H)	●				●		▽				▽					
2 Withstand Chamber Conditions (H)		○	●						●			●				
3 Position Powder in a Specified Pattern (H)	▽	○		▽	●	●	●				●	▽				
4 Maintain Powder Properties Achieved by SLM (H)	▽			○		●	●					▽				
5 Must be Able to Position Powder Within Standard AM Build Plate (H)		●			▽						○					
6 Must be Reasonable Size (S)		▽	●													
7 Must Have an Acceptable Blance Between Material Saved and Time Spent (S)	●			●							▽					
8 Must be Safe to Operate (H)								●		○						
9 Process Must be Controlable from Outside the Chamber (H)										●						
10 Must Have Infinte Life Cycle (H)									●			○				
11 Powder Must Stay Dry, Mositure Free, and be Uncoasted												○				
12 Ability to build successive layers			○										●			
13 Ability to create hollow internal features	●			○										●		
14																
15																
16																
HOW MUCH: Target	Less than 500% (in relation to the part volume)	10 x 10 (inches)	24 x 24 x 24 (inches_)	Less than 5x SLM process	0.25 (inches)	40 +/- (microns)	50%-60%	Yes/No	1 M cycles	Yes/No	.005 (inches)	Yes/No	Yes/No	Yes/No		
Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9	9	9		
Technical Importance Rating	298.62	108.23	190.62	64.643	309.83	117.98	140.81	42.571	164.65	58.816	139.32	136.56	48.736	48.736		
Relative Weight	16%	6%	10%	3%	17%	6%	8%	2%	9%	3%	7%	7%	3%	3%		
Weight Chart																
Current Product Assesment - Engineering Specifications: Our Solution (Not Yet Decided)	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Material Extrusion	5	5	0	2	5	4	4	5	4	5	4	5	5	5		
Powder Bed Fusion	2	5	0	5	0	5	5	5	4	5	0	5	5	0		
Direct Energy Deposition	5	5	0	4	4	0	3	5	4	5	3	5	5	3		
Hybrid Systems	3	5	0	2	0	5	3	5	4	5	1	5	5	3		

WHO: Customers / NOW: Current Product Assesment - Customer Requirements

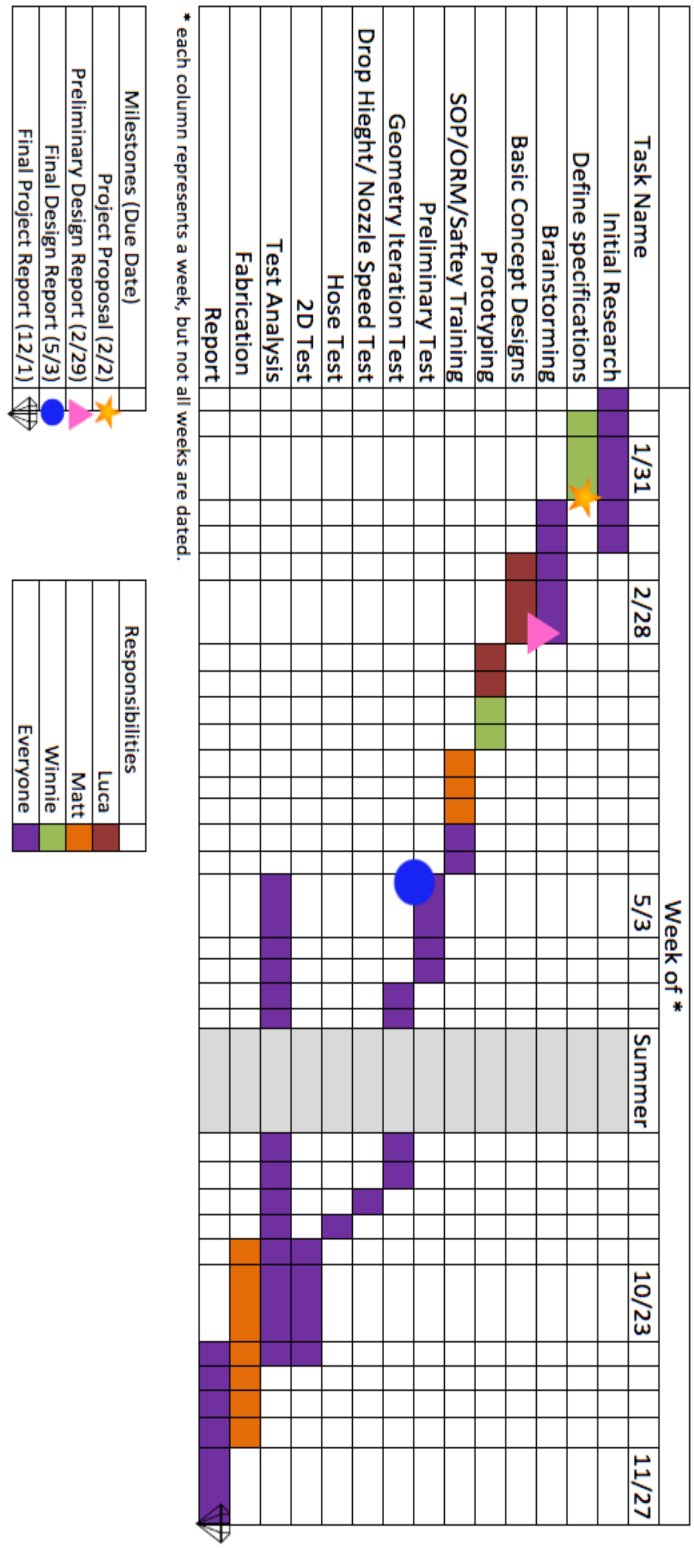
Row #	Relative Weight	Project Manger (LLNL)	Operator (LLNL)	Manufacturer (LLNL)	Maximum Relationship	WHAT: Customer Requirements	Our Solution (Not Yet Decided)	Material Extrusion	Powder Bed Fusion	Direct Energy Deposition	Hybrid Systems
1	23%	100	0	0	9	Conserve Atomized Material (H)	0	4	1	3	3
2	8%	5	4	1	9	Withstand Chamber Conditions (H)	0	5	5	5	5
3	11%	5	3	2	9	Position Powder in a Specified Pattern (H)	0	3	0	4	4
4	2%	5	1	0	9	Maintain Powder Properties Achieved by SLM (H)	0	2	5	4	3
5	4%	4	4	0	9	Must be Able to Position Powder Within Standard AM Build Plate (H)	0	5	5	4	4
6	11%	0	0	3	9	Must be Reasonable Size (S)	0	4	3	3	4
7	3%	4	3	0	9	Must Have an Acceptable Blance Between Material Saved and Time Spent (S)	0	4	2	3	4
8	5%	2	5	0	9	Must be Safe to Operate (H)	0	5	5	5	5
9	5%	3	5	0	9	Process Must be Controlable from Outside the Chamber (H)	0	5	5	5	5
10	10%	4	2	2	9	Must Have Infinte Life Cycle (H)	0	4	4	4	4
11	6%	4	2	1	3	Powder Must Stay Dry, Mositure Free, and be Uncoasted	0	0	5	4	4
12	5%	5	5	0	9	Ability to build successive layers	0	5	5	5	5
13	5%	5	5	0	9	Ability to create hollow internal features	0	5	0	3	3
14	0%										
15	0%										
16	0%										





Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

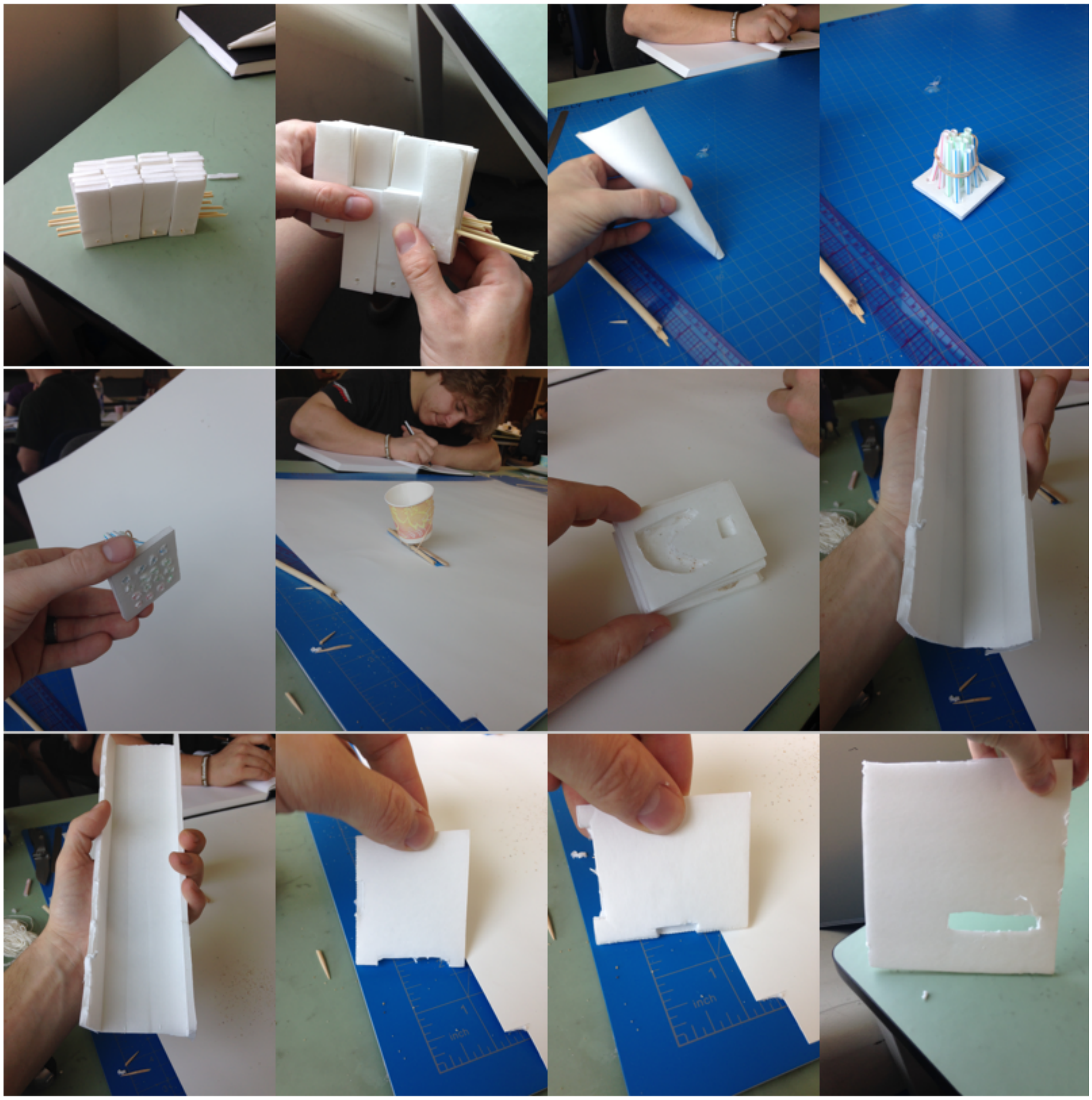
10.2 Appendix B: Gantt Chart



10.3 Appendix C: Brainwriting #2 subcategories

Powder Transportation	Pattern Formation	Powder Conservation
Air	Stencil	Chamber Volume
Gravity	Form Walls	Deposition Precision
Suction	Cast	Recyclability
Rake	Stamp	Variable Build Plate
Sticky Tape	Filter	Filler Material
Friction	Build Plate Manipulation	
Vibes	Wiping	
Electromagnetic	Vacuum	
Static Electric	Tracing	
Springs	Adhesives	
Centripetal Force		

10.4 Appendix D: Foam Board Prototypes



10.5 Appendix E: Pugh Matrix

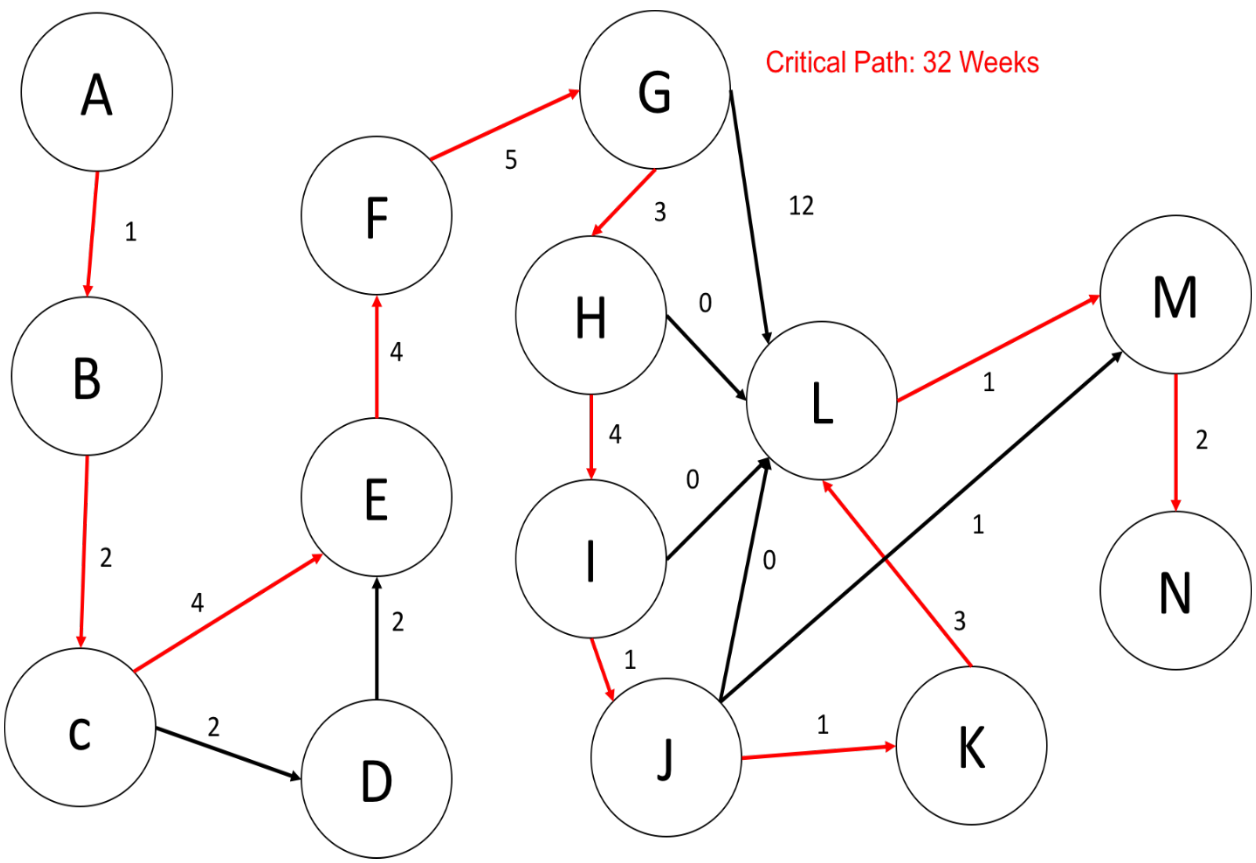
Criteria \ Concept	Deformable chute	Powder wheel	Vacuum	Nozzle followed by blade	Dynamic build plate	Porous Plate	Dynamic wipers	Air wiper blade	Negative stamp	Blade dispenser (filler material)	Blade dispenser (nonfiller material)	Adjustable Wipers	Sand castle	Positive Stamp	DIW part molds/walls	Grid filter
Conserve powder	S	S	S	S	-	S	-	-	S		S	-	S	-	S	S
Withstand chamber conditions	S	S	-	S	S	S	S	S	S		S	S	S	S	S	S
Position powder in a specified pattern	S	S	S	+	-	+	-	-	S		S	-	S	-	S	S
Maintain powder properties achieved by SLM	+	-	+	+	+	+	+	S	+		+	+	-	+	S	S
Position powder within standard AM build plate	S	S	S	S	S	S	S	S	S		S	S	S	S	S	S
Reasonable size	S	S	S	S	S	S	S	S	S	DATUM	S	S	S	S	S	S
Balance between powder saved and time spent	-	-	-	-	-	S	-	S	+		S	-	S	-	-	S
Safe to operate	S	S	S	S	S	S	S	S	S		S	S	S	S	S	S
External control	S	S	S	S	S	S	S	S	S		S	S	S	S	S	S
Infinite life	S	S	S	S	S	S	S	S	S		S	S	S	S	S	S
Powder remains moisture free and uncoated	S	S	S	S	S	S	S	S	S		S	S	S	S	S	S
Ability to build successive layers	-	-	-	-	S	-	-	-	-		-	-	-	-	S	-
sum +'s	1	0	1	2	1	2	1	0	2	-	1	1	0	1	0	0
sum -'s	2	3	3	2	3	1	4	3	1	-	1	4	2	4	1	1
sum S's	9	9	8	8	8	9	7	9	9	-	10	7	10	7	9	11
Net Sum	-1	-3	-2	0	-2	1	-3	-3	1	-	0	-3	-2	-3	-1	-1

10.6 Appendix F: Weighted Decision Matrix

50	Moderate satisfaction : a middle point between complete satisfaction and no satisfaction
25	linor Satisfaction : objective satisfied in some but less than half of the aspec
10	Minimal satisfaction: objective satisfied to a very small extent
0	No satisfaction: objective not satisfied in any aspect

	Design Criteria	Conserve Powder	Withstand chamber conditions	Position powder in specified pattern	Maintain powder properties achieved by SLM	Position powder within standard AM build plate	Reasonable size	Balance between powder saved and time spent	Safe to operate	external controller	Infinite life	Powder remains moisture free and uncoated	Ability to build successive layers	Simplicity	Scaleability	Overall Satisfaction
	Weighting factor	0.25	0.025	0.15	0.1	0.025	0.025	0.05	0.025	0.025	0.025	0.025	0.1	0.1	0.075	
	Powder Wheel	80	100	75	50	100	100	50	100	100	100	100	40	40	100	71.75
	Vacuum	85	100	80	90	100	100	40	100	100	100	100	35	75	100	80.25
	Nozzle followed by blade	90	100	85	90	100	100	50	100	100	100	100	40	75	100	83.25
	Porous Plate	85	100	80	65	100	100	80	100	100	100	100	50	35	100	77.25
	Negative stamp	85	100	80	100	100	100	80	100	100	100	100	45	35	100	80.25
	Blade dispenser (filler material)	85	100	80	90	100	100	80	100	100	100	100	85	35	85	82.125
Methods	Sand Castle	85	100	80	75	100	100	80	100	100	100	100	40	25	85	75.125

10.7 Appendix G: PERT Chart and PERT Table

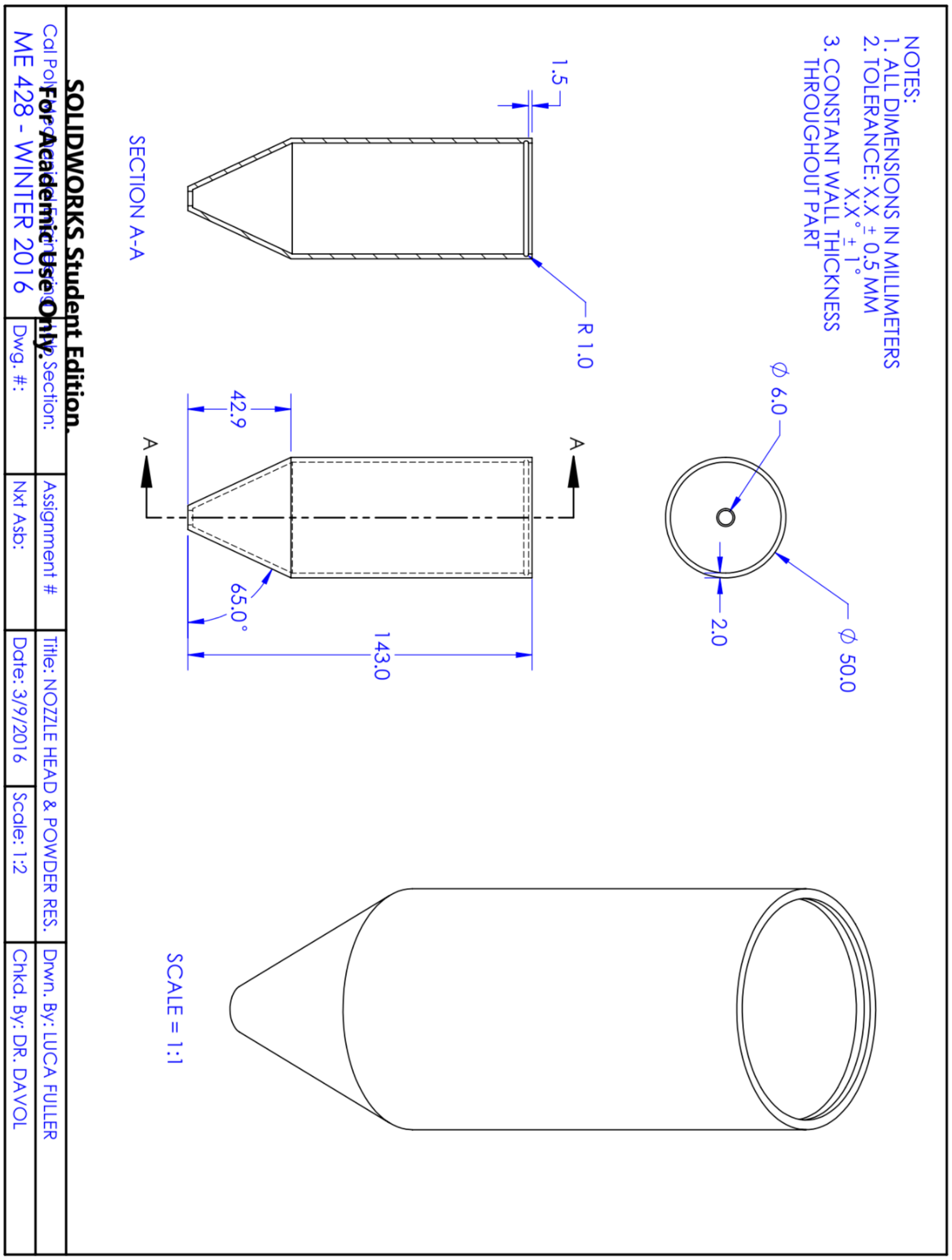


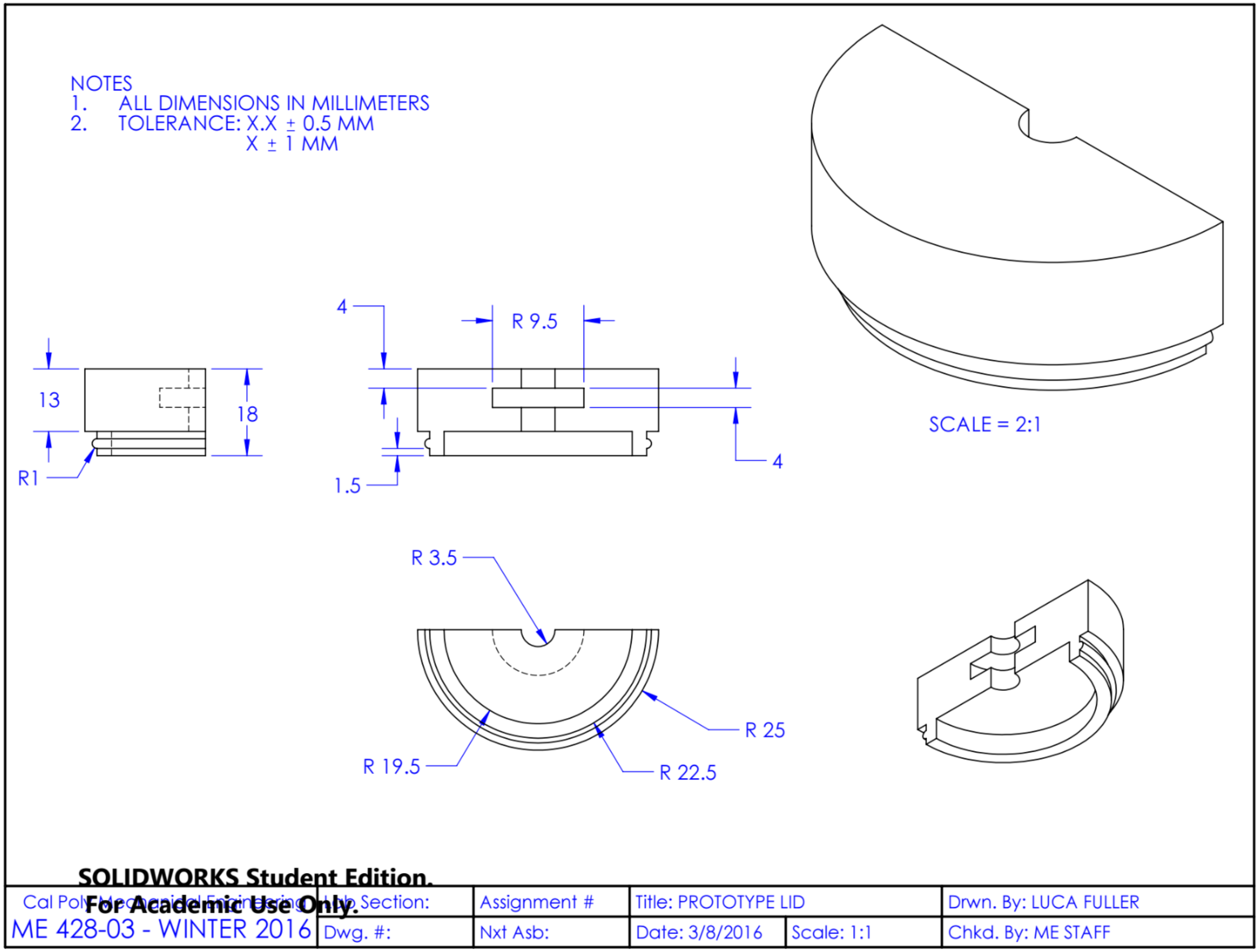
Index	Activity Description	Required Predecessor	Duration (weeks)
A	Initial Research	-	5
B	Define specifications	A	2
C	Brainstorming	B	4
D	Basic Concept Designs	C	2
E	Prototyping	C, D	4
F	SOP/ORM/Safety Training	E	5
G	Preliminary Test Plan	F	3
H	Geometry Iteration Test Plan	G	4
I	Drop Height/ Nozzle Speed Test Plan	H	1
J	Hose Test Plan	I	1
K	2D Test Plan	J	3
L	Test Analysis	G, H, I, J, K	12
M	Fabrication	L	6
N	Report	M	5

10.8 Appendix H: Failure Mode and Effects Analysis

Item	Func	Potential Failure modes	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) Of Failure	Occ	RPN	Recommended Actions	How we will address the possible failure (Test Plan)	Response & Target Complete Date	Action Results: Action Taken	SEV	OCC	DET	RPN
Hopper	Delivers powder to hose	Hopper does not deliver powder to Hose	Powder doesn't flow through the hose and thus the deposited powder line becomes broken	8	Powder flowrate through the hopper is less than the powder flowrate through the nozzle	2	16	Test to develop a deeper understanding of how the height of the powder reservior affects the flowrate through a typical hopper	Test #1 Flowrate Test	5/21/2016	N/P	N/P	N/P	N/P	N/P
								Test needs to be made such that we understand the flowrate the nozzle will be operating at	Test #3 Will Yield a Nozzle Flowrate	8/2/2016	N/P	N/P	N/P	N/P	N/P
					Powder Clogs within the hopper	2	16	Find the stainless steel angle of repose and desing hopper so its andgle of repose is larger than stainless steel angle of repose.	Test #1 Angle of Repose Test	5/21/2016	N/P	N/P	N/P	N/P	N/P
Hose	Transports powder from the hopper to the nozzle	Hose is unable to transport the powder from the hopper to the nozzle at an adaquate flowrate	Powder is not dispensed onto the buildplate at the correct flowrate	8	Connection from hopper to hose or hose to nozzle is inadequate	3	24	Make sure the connections between the hose and hopper and hose and nozzle are flush and do not affect the flowrate	After test #3 is performed and the geometry of nozzle is defined connections can be created	8/9/2016	N/P	N/P	N/P	N/P	N/P
					Acceptable flowrate through the hose is too small to provide powder to nozzle at an adaquate	2	16	Test to define flowrates for a size variation in hose diameter	Test #4 Hose Flowrate Test	10/15/2016	N/P	N/P	N/P	N/P	N/P
Nozzle	Takes powder delivered from hose and lays it down on the buildplate to specs seen in QFD	Nozzle Isn't able to lay down the powder to desired specifications	Powder bed doesn't have the desired properties prior to lasering	10	Nozzle flowrate doesn't fulfill powder bed properties	5	50	Test to determine correct drop height, nozzle translation speed, and flowrate to fulfill powder line specifications	Test #3 Drop Height and Speed Test to Determine Flowrate	8/9/2016	N/P	N/P	N/P	N/P	N/P
					Nozzle geometry doesn't lay down power path of proper geometry	8	80	Test to carry out various nozzle iterations to ensure optimum nozzle performance	Test #2 Nozzle/Chute Iteration Test	10/8/2016	N/P	N/P	N/P	N/P	N/P
					Nozzler powder reservior height negatively affects the flowrate through the nozzzle	4	40	Test to deterrmine how the height of the powder reservior affects the flowrate of the nozzle	Test # 1 Flowrate Test adresses the height of the powder reserviors affect on the flowrate	5/21/2016	N/P	N/P	N/P	N/P	N/P
					Nozzle powder path geometry is inadequate when performing 2-axis designs (curves)	5	50	Two axis test will be needed to determine applicability of iterated nozzle geometry	Test #5 2 axis test	8/30/2016	N/P	N/P	N/P	N/P	N/P
					Nozzle Cloggs	8	80	Test to determine nozzle functionality	Test #1 Nozzle vs. Chute and Test #2 Nozzle Iteration will allow for the functionality of the nozzle to be addressed.	10/8/2016	N/P	N/P	N/P	N/P	N/P
Driver	Translates the nozzle in the xy direction at varying speeds and at constant heights	Nozzle is unable to translate at adquate speed or at a constant height	Powder path properties are inadaquate	10	Driver is unable to handle the weight of the nozzle	2	20	Driver Specifications need to be looked at in depth and compared to what is needed	two axis drivers need to be researched and quotes need to be compared	4/23/2016	Done	8	1	8	8
					Desired speed of the driver is unattainable or inaccurate for powder bed properties	2	20	Driver Specifications need to be looked at in depth and compared to what is needed	two axis drivers need to be researched and quotes need to be compared	4/23/2016	Done	8	1	8	8
					Resolution of the driver is too coarse for tolerances desired	2	20	Driver Specifications need to be looked at in depth and compared to what is needed	two axis drivers need to be researched and quotes need to be compared	4/23/2016	Done	6	1	5	6

10.9 Appendix I: Phase 1 Prototype Drawings




NOTES
1. ALL DIMENSIONS IN MILLIMETERS
2. TOLERANCE: X.X ± 0.5 MM
X ± 1 MM
13
18
R1
4
R 9.5
4
1.5
SCALE = 2:1
R 3.5
R 25
R 19.5
R 22.5
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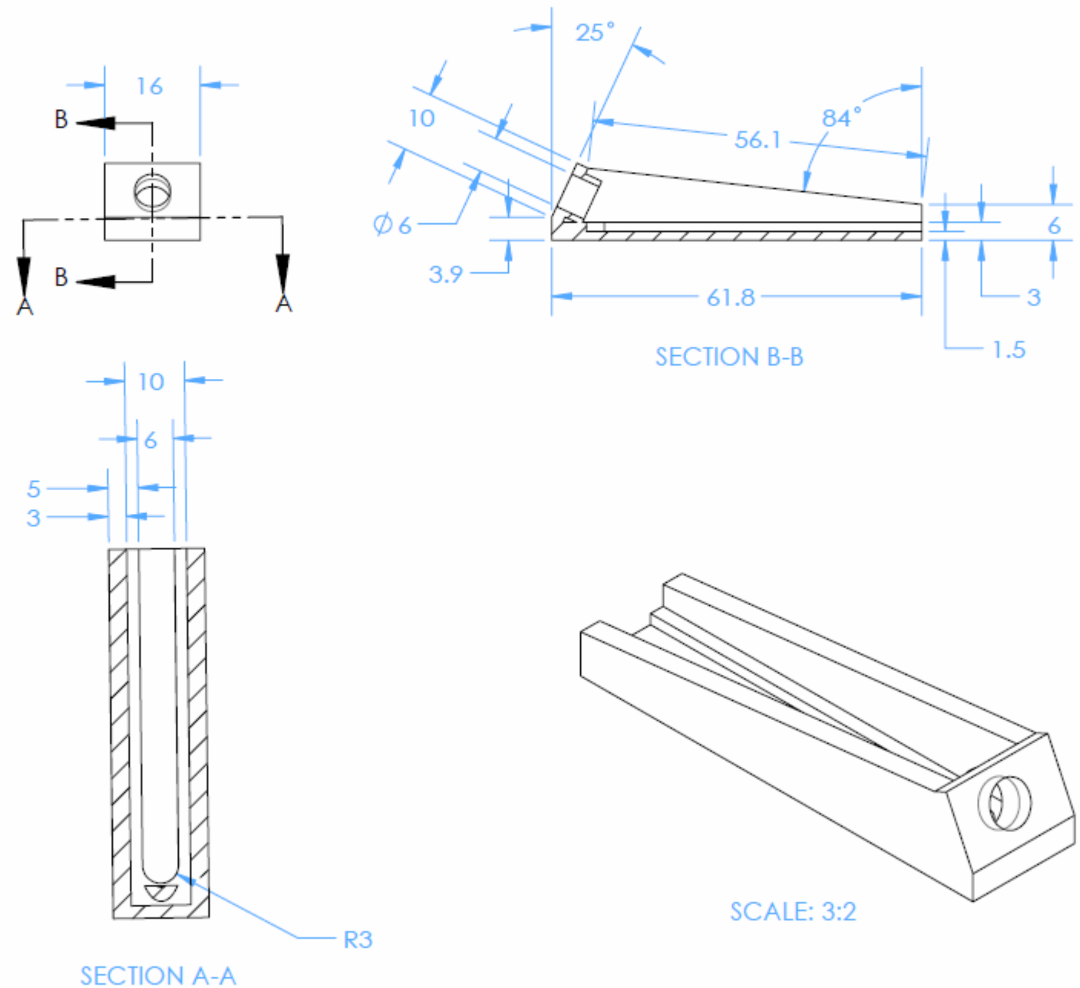
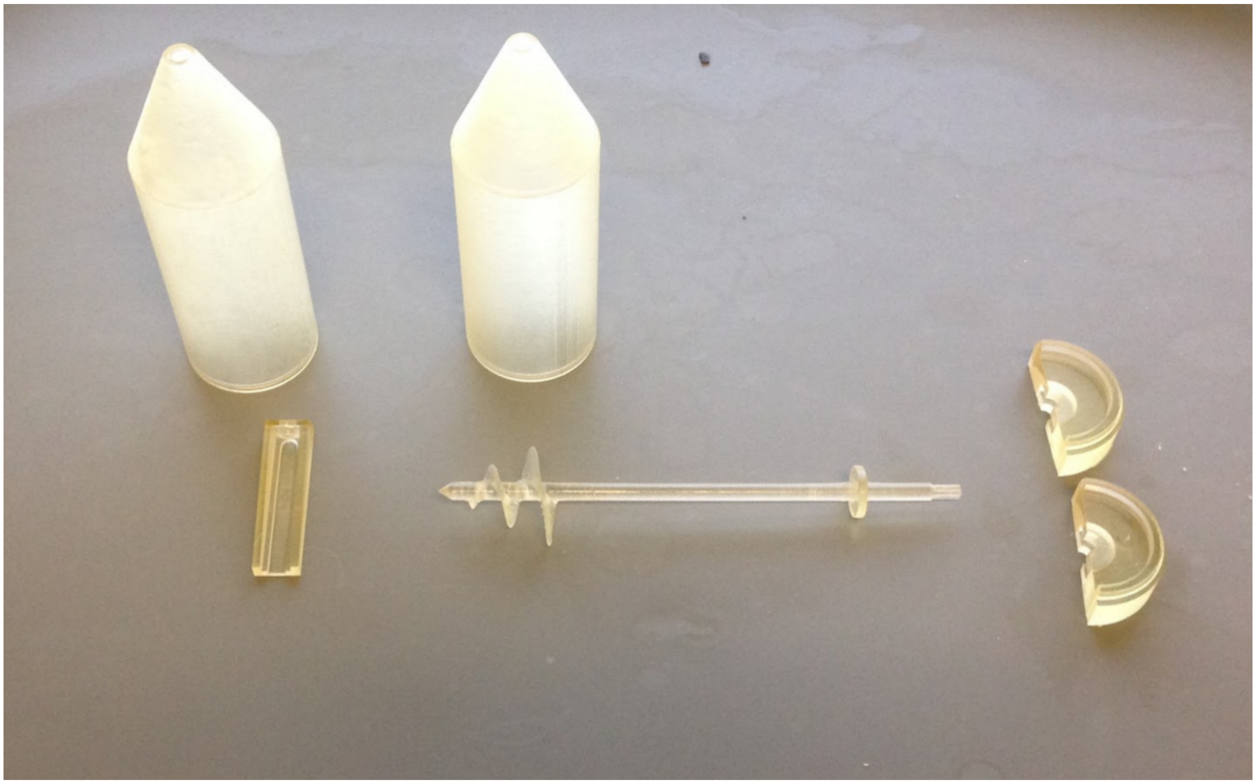
Cal Poly Mechanical Engineering
ME 428-03 - WINTER 2016
Lab Section:
Dwg. #:
Assignment #
Nxt Asb:
Title: PROTOTYPE LID
Date: 3/8/2016
Scale: 1:1
Drwn. By: LUCA FULLER
Chkd. By: ME STAFF

NOTES:
1. ALL DIMS IN MILLIMETERS
2. TOLERANCE:
X.X ± .5 MM
XX ± 1 MM
XX° ± 1°



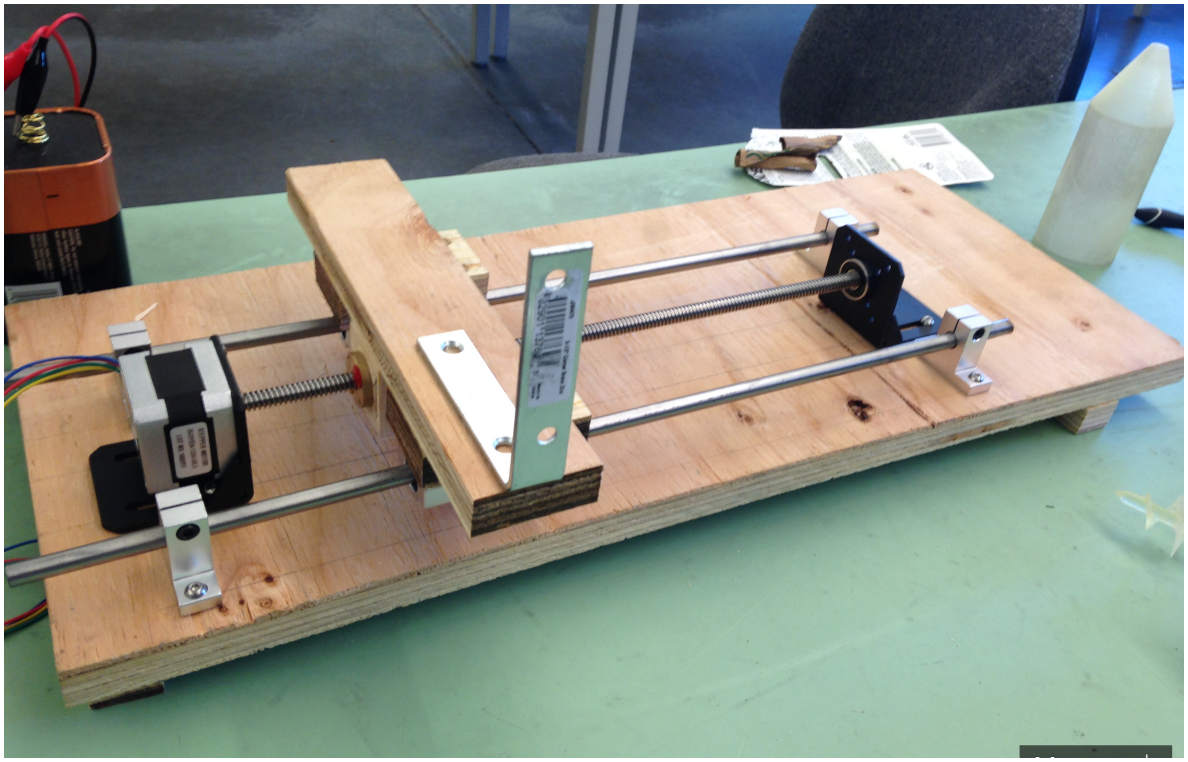
Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: PROTOTYPE CHUTE	Drwn. By: WINTHROP TOWNSEND
ME 429 - SPG 2016	Dwg. #:	Nxt Asb:	Date: 4/17/2016	Scale: 1:1	Chkd. By: DR. DAVOL

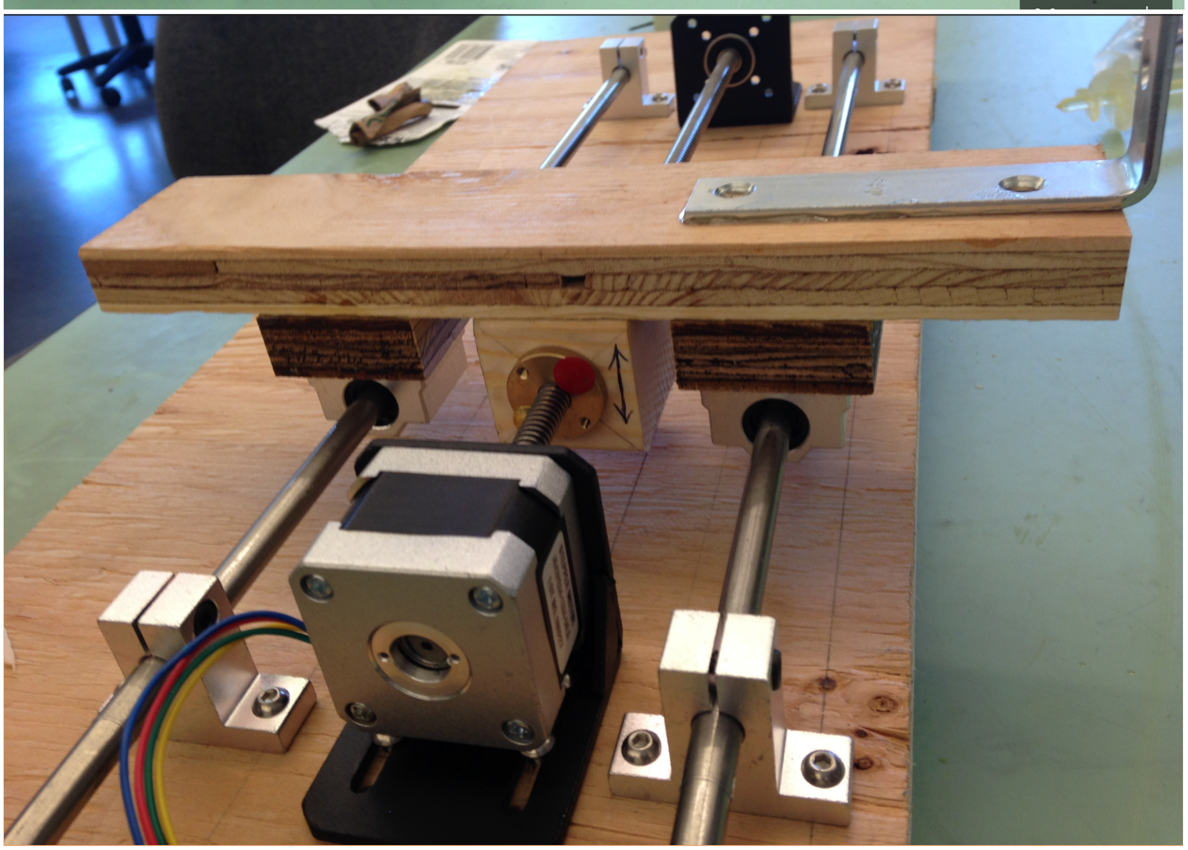
10.10 Appendix J: Phase 1 Prototype Pictures



*First set of prototypes include auger (seen in middle) which was not used throughout testing.

10.11 Appendix K: 1-D Test Rig Pictures





10.12 Appendix L: 1-D Controller Sample Code

```
#include <AccelStepper.h>

#define HALF4WIRE 8

// Motor pin definitions
#define motorPin1  2     // A1
#define motorPin2  4     // A2
#define motorPin3  6     // B1
#define motorPin4  7     // B2

// Initialize with pin sequence IN1-IN3-IN2-IN4 for using the AccelStepper with 28BYJ-48
//AccelStepper stepper; // Defaults to AccelStepper::FULL4WIRE (4 pins) on 2, 3, 4, 5

AccelStepper stepper1 (HALF4WIRE, motorPin1, motorPin2, motorPin3, motorPin4, true);

void setup() {
  stepper1.setMaxSpeed(1200.0);
  stepper1.setAcceleration(100.0);
  stepper1.setSpeed(100);
  stepper1.moveTo(12000); //250 full rotations @ 48 steps each = 12,000 steps

}//--(end setup )---

void loop() {

  //Change direction when the stepper reaches the target position
  if (stepper1.distanceToGo() == 0) {
    stepper1.moveTo(-stepper1.currentPosition());
    delay(500);
  }
  stepper1.run();
}
```

10.13 Appendix M: Operational Risk Management Risk Assessment

RAM Risk Assesment

Task	Hazard	Probability					Severity				Risk	Control
		Frequent	Likely	Occasional	Seldom	Unlikely	Catastroph	Critical	Moderate	Negligible		
Assemble test-rig so that it accurately and safely controls the deposition of material within the work area.	Improperly assembling the test, allowing for misplacement of material and/or spills.					x				x	Low	Multiple revisions, peer/professor review design and assembly process.
Moving material from storage location to testing area	Material container breaking.					x			x		Medium	Transport material in provided container within another carrying device (bag, backpack, etc.) PPE
Transfer material from storage container to test-rig hopper	Spilling material within testing area and/or on person(s) conducting the test.				x				x		Medium	Pouring material from larger storage container into a smaller, more manageable container. Then, pouring from smaller container into hopper using a funnel. PPE
Remotely operate test-rig to deposit material upon testing surface	Electrical malfunction causing sparks or fire potentially resulting in the ignition of airborne particulates.					x		x			Medium	Ground all electrical components. Ensure are connections are secure and properly shielded. No exposed jumpers, wires, or contacts.
Remove material from testing surface	Spilling material from collections device and/or coming into contact with the material				x				x		Medium	Ensuring that only person is operating in the test area at a time. PPE.
Place material either back in hopper for further testing or in its storage container for later use	Spilling material within testing area and/or on person(s) conducting the test.				x				x		Medium	Pouring material from collection device into hopper/storage container using a funnel. PPE.

10.14 Appendix N: Standard Operating Procedure

Revolutionized Additive Manufacturing (RAM) 3-Axis Testing: Iron based powder gravity driven flow through nozzle.

Purpose: The main objective of our testing is to find geometries and dimensions of powder lines that are formed by funneling powder through a nozzle onto a flat surface. This will include obtaining both qualitative and quantitative data from pictures and measurements taken.

The secondary object is to determine the viability of the Delta-Mechanism as a comprehensive test environment. The importance of the Delta-Mechanism as a testing environment is two-fold: It provides 3-axis of motion in an easy to use format and it provides the necessary speed capabilities required to fully test a nozzles performance.

The iron based powdered that we will be using is AMA 316 L cl C. The powder is very fine and dense. The chemical makeup can be seen in Table 10.1. The nominal particle size is ~40 microns but single particles can vary from 5 to 120 microns in diameter.

Table 9.1. Composition of stainless-steel powder

*** Section 3 - Composition / Information on Ingredients ***

EC #	Component	Percent	Symbols	Risks
231-111-4	Nickel 7440-02-0	3-14	Xn Carc.Cat.3	R:40-43
231-157-5	Chromium 7440-47-3	1-20	-	-
231-096-4	Iron 7439-89-6	40-95	-	-
231-107-2	Molybdenum 7439-98-7	1-4	-	-
231-159-6	Copper 7440-50-8	0-4	-	-
231-105-1	Manganese 7439-96-5	0-2	-	-

This preparation has been evaluated using criteria specified in European Union Directives 67/548/EEC and 1999/45/EC.

Potential Hazards/Toxicity: Caution: May cause sensitization by inhalation and skin contact. Limited evidence of carcinogenic effects.
Inhalation of metal fumes may cause metal fume fever, a flu-like illness generally lasting 24 hours or less.

Potential Health Effects:
Chromium: Industrial exposure to chromium may cause dermatitis, skin ulcers, perforation of the nasal septum, as well as cancer of the lings, nasal cavity and paranasal sinuses.
Molybdenum: May cause irritation to the skin, eyes and respiratory tract.
Nickel (Xn Carc. Cat. 3 Risk: 40-43): This product is or contains a component that has been reported to be possibly carcinogenic based on its IARC, ACGIH, NTP, or EPA classification. Systemic effects from ingestion of nickel include capillary damage, kidney

damage, myocardial weakness and central nervous system depression. Allergic skin sensitization reactions are the most frequent effect of exposure to nickel compounds. Contact with nickel compounds may also result in allergic sensitization reactions. Nickel is a possible human carcinogen.
Iron: Chronic inhalation of iron has resulted in mottling of the lungs, a condition referred to as siderosis. This is considered benign pneumoconiosis and does not ordinarily cause significant physiologic impairment.
Copper: Chronic copper poisoning is typified by hepatic cirrhosis, brain damage and demyelination, kidney defects, and copper deposition in the cornea as exemplified by humans with Wilson's disease. It has also been reported that copper poisoning has led to hemolytic anemia and accelerates arteriosclerosis. Exposure can cause: Damage to the lungs. Stomach pains, vomiting, diarrhea. Blood effects.
Manganese: Prolonged exposure to high concentration of manganese-containing dusts and/or fumes may result in the development of a neurological disorder – Manganism. It is not expected that Manganism will develop if exposures are maintained below the limits cited in section 8 of MSDS attached. Symptoms of Manganism develop very gradually over a period of years and can include headache, irritability, insomnia, and muscle cramps. In severe cases severe muscle rigidity, and impairment of gait may develop. The symptoms are not always reversible upon cessation of exposure.

Carcinogenicity:

No carcinogenicity data available for this product. The carcinogenic effect of nickel has been well documented in occupationally exposed nickel refinery workers. Lung and nasal cancers were the predominant forms of cancer in the exposed workers. In experimental animal injections of nickel produced injection site tumors although some of these tumors metastasized. Upon inhalation of nickel, lymphosarcomas were observed in mice and aveolar carcinomas in guinea pigs.

Other Toxicological Information

Exposure to metal dusts and oxides may cause metal fume fever. Metal fume fever is temporary flu-like condition characterized by chill, fever, muscle aches and pains, nausea and vomiting. Typically, they symptoms appear within a few hours after exposure and subside within 2-3 days with no permanent effects.
Asthma induced by occupational exposure to nickel and cobalt has been documented. The asthma can result from either primary irritation of from al allergic response. Contact dermatitis in workers exposed to nickel compounds is one of the most prevalent effect of nickel exposure.

Engineering Controls: The test machine and metal powder will be isolated to Building 41-101-B. Tests will only be conducted in this room, and proper signage will be placed on the door to indicate that testing is in progress, and the room is closed to unauthorized personnel. Furthermore, appropriate gloves, safety glasses, and respirators, will be worn in conjunction with long-sleeves, pants, and closed-toe shoes while working with the powder.

Personal Protective Equipment (PPE)

Hand Protection: Nitrite 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 will 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 may be required under any of the following circumstances:

- As a last line of defense (i.e., after engineering and administrative controls have been exhausted).
- When Permissible Exposure Limit (PEL) will or may be exceeded, or the airborne concentration is unknown.
- Regulations require the use of a respirator.
- There is potential for harmful exposure due to an atmospheric contaminant (in the absence of PEL)
- As PPE in the event of a chemical spill clean-up process

Respirators will be required. Prior to obtaining a respirator, an exposure assessment of the process or procedure must be conducted. Next, lab personnel must obtain respiratory protection training, a medical evaluation, and a respirator fit test through EH&S. This is a regulatory requirement.

First Aid Procedures for Chemical Exposures

If inhaled:
Evacuate the victim to a safe area as soon as possible. Loosen tight clothing such as a collar, tie, belt or waistband. If breathing is difficult, seek medical attention. If the victim is not breathing, perform mouth-to-mouth resuscitation. WARNING: It may be hazardous to the person providing aid to give mouth-to-mouth resuscitation when the inhaled material is toxic, infectious or corrosive. Seek immediate medical attention.

In case of skin contact:
In case of contact, immediately flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes. Cold water may be used. Wash clothing before reuse. Thoroughly clean shoes before reuse. Get medical attention, as necessary.

In case of eye contact:
Immediately flush eyes with plenty of water for at least 15 minutes. Check for and remove any contact lenses. Get medical attention.

If swallowed: If the material is ingested, get immediate medical attention or advice. Do not induce vomiting.

Special Handling and Storage Requirements

Handling Procedure: Do not breathe fumes or dust from this material. Keep this product from heat, sparks, or open flame. Use non-sparking tools when opening and closing container. Wet mop or HEPA vacuum is recommended to clean up any dusts that may be generated during handling and processing. Wash hands and face thoroughly before eating, drinking, or smoking.

Storage Procedure: Keep the container tightly closed and in a cool, well ventilated place. Store away from incompatible materials. Do not handle or store near open flame, heat or other source of ignition. Good housekeeping and engineering practices should be employed to prevent the generation and accumulation of dusts.

Spill and Accident Procedure

Chemical Spill Dial 911 and 756-6661

Spill – Assess the extent of danger. Help contaminated or injured persons. Evacuate the spill area. Avoid breathing vapors. If safe, confine the spill to a small area using a spill kit or absorbent material. Keep others from entering contaminated area (e.g., use caution tape, barriers, etc.).

Small (<1 L) – If you have training, you may assist in the clean-up effort. Use appropriate personal protective equipment and clean-up material. Double bag spill waste in plastic bags, label and arrange hazardous waste pick-up.

Large (>1 L) – Evacuate spill area. Dial **911** and EH&S at 756-6661 for assistance. Remain available in a safe, nearby location for emergency personnel.

Chemical Spill on Body or Clothes – Remove clothing and rinse body thoroughly in emergency shower for at least 15 minutes. Seek medical attention. *Notify supervisor, advisor or P.I. immediately.*

Chemical Splash Into Eyes – Immediately rinse eyeball and inner surface of eyelid with water from the emergency eyewash station for a minimum of 15 minutes by forcibly holding the eye open. Seek medical attention. *Notify supervisor, advisor or P.I. immediately.*

Medical Emergency Dial 911 or 756-6661

Life Threatening Emergency, After Hours, Weekends And Holidays – Dial 911

Note: All serious injuries must be reported to Supervisor/PI within 8 hours. Note: Any and all loss of consciousness requires a 911 call

Non-Life Threatening Emergency –
Students: Seek medical attention at the campus Health Center **M, T, Thu, Fr 8:00 am – 4:30 pm and W 9:00 am – 4:30 pm**
Emergency Medical services in the community are available at any time at hospital emergency rooms and some emergency care facilities.

All injuries must be reported to PI/Supervisor immediately and follow campus injury reporting. Follow procedures for reporting of student, visitor injury on the EH&S website at:
http://afd.calpoly.edu/riskmgmt/incidentreporting.asp

- Paid staff, students, faculty: seek initial medical attention for all non-life threatening injuries at:
    - MED STOP, 283 Madonna Road, Suite B (next to See's Candy in Madonna Plaza)
      (805) 549-8880 Hours: M-F 8a - 8p; Sat/Sun 8a - 4p
    - **After MED Stop Hours:** Sierra Vista Hospital Emergency Room
      1010 Murray Avenue (805) 546-7651, Open 24 hours

All injuries must be reported to PI/Supervisor immediately and follow campus injury reporting for employee injuries (Workmen's Comp.). Follow procedures on the EH&S website at: http://afd.calpoly.edu/riskmgmt/incidentreporting.asp

Needle stick/puncture exposure (as applicable to chemical handling procedure) – Wash the affected area with antiseptic soap and warm water for 15 minutes. For mucous membrane exposure, flush the affected area for 15 minutes using an eyewash station. Seek medical attention. *Note: All needle stick/puncture exposures must be reported to supervisor, advisor or P.I. and EH&S office immediately.*

Decontamination/Waste Disposal Procedure

General hazardous waste disposal guidelines:

Label Waste

- Affix a hazardous waste tag on all waste containers as soon as the first drop of waste is added to the container. Generic waste labels can be found here: http://afd.calpoly.edu/ehs/docs/hazwaste_label_template.pdf

Store Waste

- Store hazardous waste in closed containers, in secondary containment and in a designated location
- Double-bag dry waste
- Waste must be under the control of the person generating & disposing of it

Dispose of Waste

- Dispose of regularly generated chemical waste as per guidelines on EH&S website at: http://afd.calpoly.edu/ehs/docs/csb_no6.pdf
- Prepare for transport for pick-up. Use secondary containment.

Call EH&S at 756-6661 for questions.

Empty Containers-

- Dispose as hazardous waste if container once held extremely hazardous waste (irrespective of the container size) A list can be found at: http://afd.calpoly.edu/ehs/docs/extremely_hazardous_wastes.pdf
- All other containers are legally empty once a concerted effort is made to remove, pour out, scrape out, or otherwise completely empty the vessel. These may be disposed of as recycling or common trash as appropriate.

Safety Data Sheet (SDS) Location

Online SDS can be accessed at: http://siri.org/msds/index.php
or MSDS can be seen attached below.

Procedure

Caution: Sensitizer & potential carcinogen. All work to be conducted in an isolated workspace and with personal protective equipment as described earlier.

Required Equipment:

1. Prototype Nozzle (see prototypes in prototype section below)
2. Powder Scale
3. Paper cup
4. Waste cup
5. Funnel
6. Stopwatch
7. 3D test environment – Delta Mechanism

8. Camera
9. Ruler
10. 14” x 14” elevated pour plate
11. Waste tray
12. Paint Brush
13. Small squeegee

Standard Operating Procedure:

Test Assembly Setup:

1. Place warning signage on entry/exit doors that indicate testing is in progress, and only authorized personnel are permitted in the room with proper protective equipment
2. Ensure that all non-essential personnel have been escorted from the vicinity.
3. Ensure that all essential personnel have donned proper PPE.
4. Position the elevated pour plate in the Delta Mechanism.
5. Slide waste tray into slot under the elevated pour plate (this is for returning powder to the hopper/container after each test).
6. Energize the control system.
7. Energize the Delta-Mechanism.
8. Close and latch the Delta-Mechanism door.

Mass Flow Rate Test:

1. Place paper cup on powder scale, record tare weight, and tare to zero scale reading.
2. With the nozzle opening plugged with ruler, fill prototype nozzle to its 4 cm height marked on the nozzle reservoir using standard funnel.
3. Simultaneously unplug the nozzle by removing the ruler from the nozzle opening, and start stopwatch.
4. After approximately 10 seconds, gently plug nozzle with the ruler and stop the stopwatch.
5. Record weight of powder in the measuring cup on the scale, and the time on the stopwatch.
6. Cautiously pour the powder back into original powder container using funnel.
7. Repeat steps 1-6 two more times
8. Repeat steps 1-7 for 6 cm, 8 cm, and 10 cm heights above the plane where nozzle convergence starts.

2D Path Test

1. On the control system, load the desired xy pathing file.
2. Run the program, and allow the nozzle to reach the “fill” position.
3. Fill the nozzle’s reservoir to the 8-cm mark, by pouring powder from the main storage container through a funnel.
4. Start gantry motion again, and allow the xy pathing file to execute to completion. **Please note:** During the final steps of each xy pathing file, the gantry will move off the pour plate, and pause over the waste tray to empty the rest of the powder.

5. Take desired pictures of powder path, and path cross sections.
6. If the test is to be repeated or another xy pathing file is to be executed, repeat steps 2-5; if testing is complete, move to the standard clean-up procedure.

Image of partially modified Delta Mechanism:

Standard Cleanup Procedure:

1. Power down all electronic systems except for the HEPA ventilation system.
2. Ensure that all personnel in the room have donned their PPE.
3. Open the Delta-Mechanism door.
4. Carefully brush powder off pour plate and onto waste tray.
5. Wipe down pour plate with damp hazardous waste rag, and leave inside Delta Mechanism.
6. Using a funnel, carefully pour powder from the waste tray into the original powder container.
7. Seal original powder container and place in large storage container.
8. Place lid on large storage container and store in designated location.

9. Place hazardous waste rags in hazardous waste container.
10. Power down the HEPA system.
11. Hazardous waste container is to be disposed of with Cal Poly Environmental Health and Safety Department.
12. Isolate the Delta Mechanism, metal powder, and large storage container in 41-1

Spill Protocol Procedure:

Standard Cal Poly EH & S spill procedure can be seen in Spill and Accident Procedure section located on page 4 above.

The following procedure is to be followed when a team member unintentionally drops a finite amount of powder from a height greater than three (3) inches and powder becomes air born and/or is deposited onto the ground.

1. Assess that all members of team are uninjured and safe.
2. Notify supervisor, advisor or P.I., and EH & S to determine following protocol.
3. Wait for approximately 5 minutes until powder settles.
4. Once 5 minutes have passed, have teammates use a damp hazardous material rags to wipe down all possible powder coated areas.
5. Close powder container and put away all materials following the standard cleanup procedure.
6. Turn off paint booth ventilation and vacate room.
7. Place “do not enter” signs on closed paint booth door and retrieve damp hazardous material rags.
8. Wipe down area of concern within paint booth with damp hazardous rags, disposing contaminated rags (into proper receptacle) often.

NOTE:

Any deviation from this SOP requires approval from PI.

Date: 4/12/2016 **P.I. or Supervisor:** Dr. Davol (ME Department)

Documentation of Training (signature of all users is required)

- The Principal Investigator must ensure that his/her laboratory personnel have attended appropriate laboratory safety training or refresher training within the last one year.

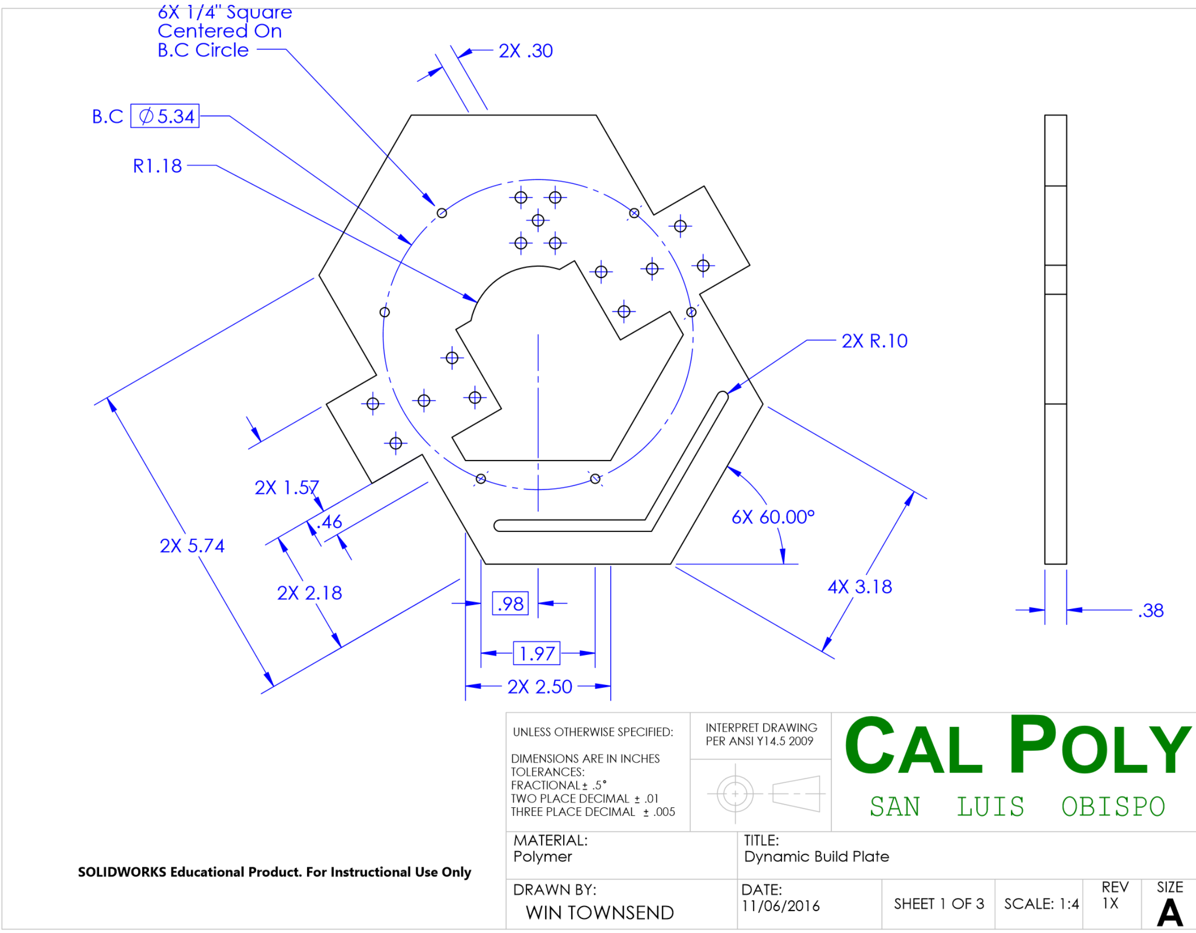
- Training must be administered by PI or Lab Manager to all personnel in lab prior to start of work with particularly hazardous substance or newly synthetic chemical listed in the SOP.

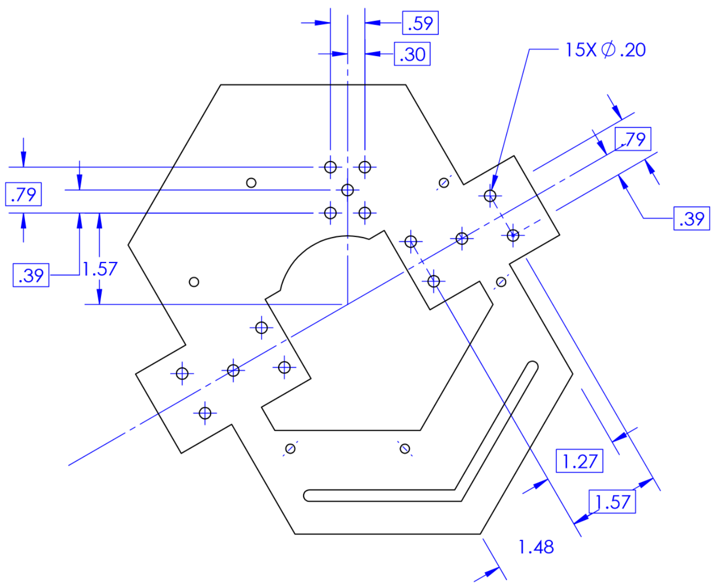
- Refresher training will need to be provided when there is a change to the work procedure, an accident occurs, or repeat non-compliance.

I have read and understand the content, requirements, and responsibilities of this SOP:

Name	Signature	Date
		5/31/2016
		5/31/2016
		5/31/2016
		5/31/2016

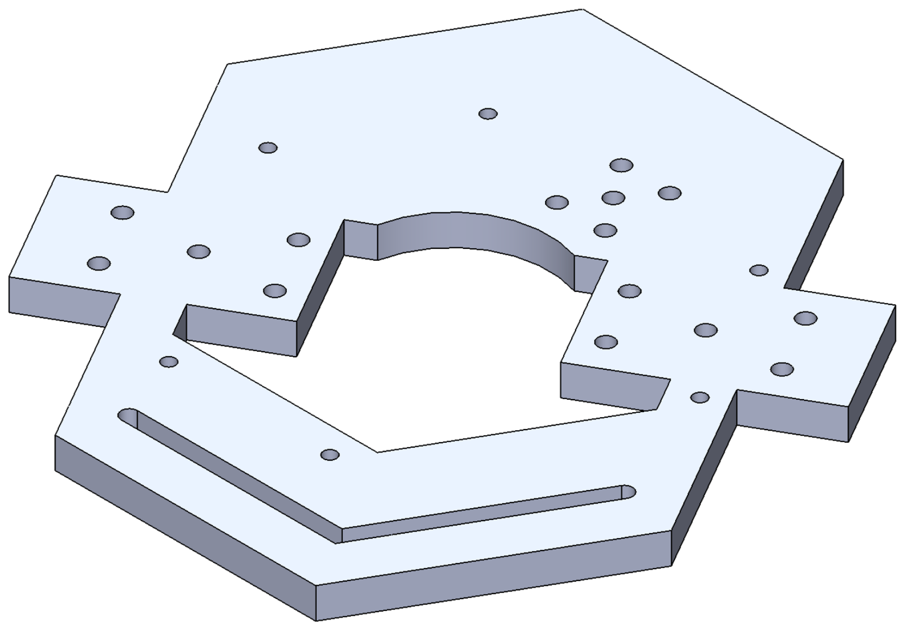
10.15 Appendix O: Phase 2 Nozzle Drawings





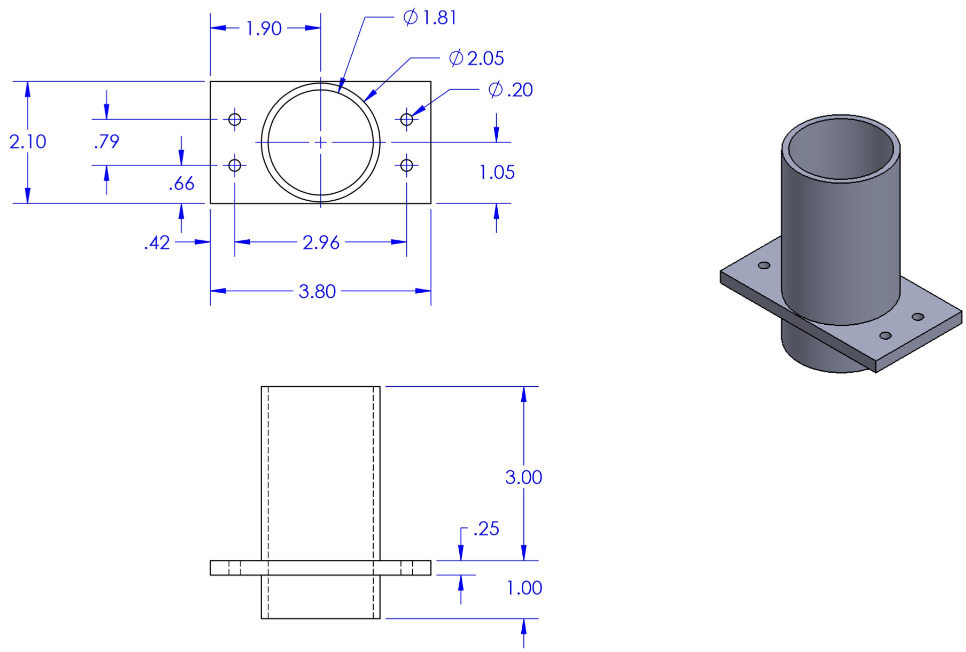
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± .5° TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ANSI Y14.5 2009	CAL POLY SAN LUIS OBISPO

MATERIAL: Polymer	TITLE: Dynamic Build Plate				
DRAWN BY: WIN TOWNSEND	DATE: 11/06/2016	SHEET 2 OF 3	SCALE: 1:4	REV 1X	SIZE A

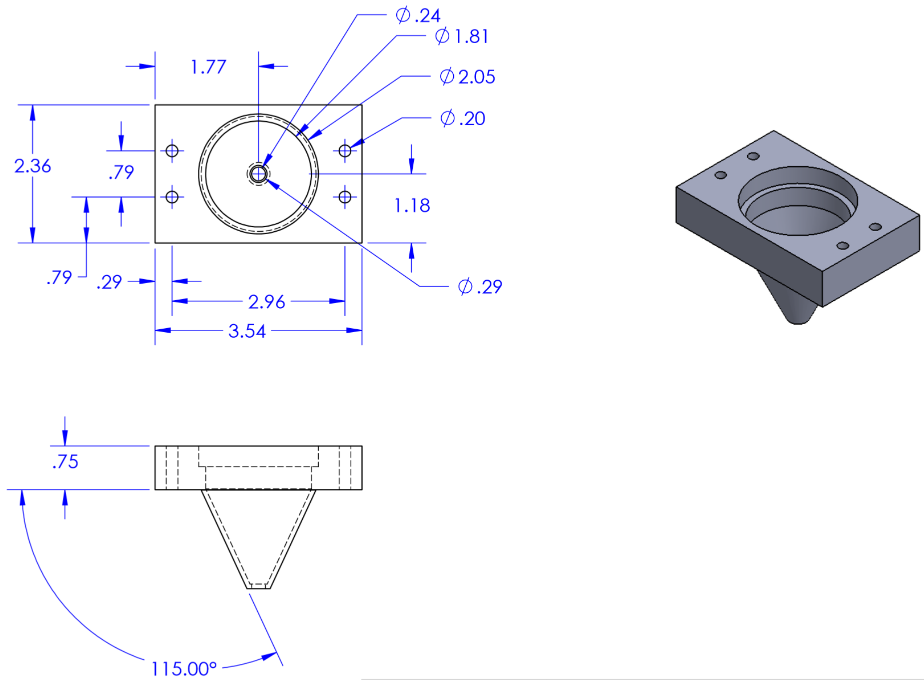


SOLIDWORKS Educational Product. For Instructional Use Only

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± .5° TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ANSI Y14.5 2009	CAL POLY SAN LUIS OBISPO
MATERIAL: Polymer	TITLE: Dynamic Build Plate	
DRAWN BY: WIN TOWNSEND	DATE: 11/06/2016	SHEET 3 OF 3 · SCALE: 1:4 · REV 1X · SIZE A



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± .5° TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ANSI Y14.5 2009	**CAL POLY** SAN LUIS OBISPO
MATERIAL: Polymer	TITLE: Powder Nozzle Reervior #1	
DRAWN BY: WIN TOWNSEND	DATE: 11/15/2016	SHEET 1 OF 1 · SCALE: 1:2 · REV 1X · SIZE **A**



SOLIDWORKS Educational Product. For Instructional Use Only

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± .5° TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ANSI Y14.5 2009	CAL POLY SAN LUIS OBISPO

MATERIAL: Polymer	TITLE: Powder Nozzle Tip Iteration #1				
DRAWN BY: WIN TOWNSEND	DATE: 11/15/2016	SHEET 1 OF 1	SCALE: 1:2	REV 1X	SIZE A

10.16 Appendix P: User's Manual

General Information

System Overview

The Delta 3D Printer was a previous ME senior design project that was retrofitted to meet the needs of RAM. The specifics on the Delta itself can be found in Deltaronic Solutions binder located near the Delta printer. Minor changes have been made to hardware while additional control files have been created to operate the Delta in the way that RAM required. This manual explains and outlines how to operate the Delta in terms of RAM's project.

System Configuration

The Delta operation is carried out through desktop PC physically located next to the Delta printer. The software used for configuring the PCLs is MotionWorks. However, due to lack of experience with PLCs, the PLCs and their firmware was not changed. MotionWorks may be need for trouble shooting (explained later). The primary method for interaction with the Delta is via a Python script created by RAM.

Getting Started

Starting the Delta

The desktop computer located adjacent to the Delta printer is what is used to operate the Delta. The following steps should be executed in order:

- Power on the computer and monitor
- Log On to the computer using the "Delta" account
- Password: Yaskawa1
- Energize the Delta by pressing the green "START" button on the front-left of the Delta
- Wait for the Delta to start up. You'll know this has happened because it will move a little (about 1-2 min)
- Open IDLE using the desktop shortcut
- From IDLE's Python Shell, open the RAM_Powder_Path.py file
- File->Open…->Desktop->Yaskawa Delta Project->RAM_Powder_Paths
- Run the Python script by either pressing F5 or from the newly opened window clicking Run->Run Module

If successful, the Delta will move the nozzle toward the build plate. At this point, you will be able to follow the instructions in the Python Shell and carry out the different testing options that the Delta is currently capable of.

Running the Delta

Once the Python Shell has successfully established a connection with the Delta, a set of instructions will be displayed in the terminal window. The instructions fully articulate all the options possible for the Delta. If the instructions are followed properly, there should not be any problems. There are, however, some instances where either a connection cannot be established, or an incorrect input causes the connection to be terminated. In this case, see the follow section for troubleshooting.

Troubleshooting

Failure to Establish Connection

In order to communicate with the Delta, a TCP connection between the desktop and the Delta must be established. On occasion, a connection cannot be established. The following are different methods to attempt to establish a connection

Retry

The most common instance of "failure to connect" is when a new connection is attempted too quickly following the termination of another connection. The typical solution for this problem is to wait 10 seconds then retry the connection.

Unresponsive

Another instance of "failure to connect" is when an initial connection cannot be established. If this happens, power down the Delta and follow these steps:

- Open MotionWorks software: Desktop->Yaskawa Delta Project ->Deltronic_MW
- Open the monitoring window
- Once MotionWorks completely opens, energize the Delta
- Once the monitor turns green and says "running," open IDLE and run the RAM_Powder_Paths.py

If this process does not work. Power everything down and wait five minutes then try again. It may take more than one attempt at this process, but it has always corrected the problem.

Modifications

Modifications to the Python Code

The code is pretty well documented and self-explanatory. However, there may be a need to add functionality or adjust the current code. If this is required, ensure that a copy of the original code is made and placed in a safe folder/location.

Modifications to the PLC Code

Currently, the PLC project that is associated with the Delta is non-buildable. It has many errors that seem to be mostly associated with custom data types. This is a problem left over from the creators of the original Delta project. Debugging the original project fell outside the scope and capabilities of RAM, therefore was not pursued.

In order to make adjustments to the PLC firmware, it is HIGHLY recommended that it be carried out by someone with a in depth understanding of PLCs, gCode, and MotionWorks.

Modifications to the Hardware

RAM retrofitted the Delta to make it more versatile for future applications. There may come a need/desire to use the Delta for something other than nozzle iteration. In this case, there are two quick approaches to adapting the Delta to your needs. The first is to simply remove the nozzle apparatus and fit your device on the platform. The second would be creating your own platform using the same dimensions for ball-joint placement as the current platform. If the second way is selected, the ball joints from the current platform can be removed and transferred over. Extra threaded sleeves for the ball-joints can be found in or around the Delta.

Limitations

Currently the Delta, with respect to RAM, does not offer a complete solution. There are few limitations.

Speed

The speed of Delta is not configurable in its current state. In some instances, (like the circle) it can be manipulated as a function of how many points are being plotted, but it cannot be directly set. The PLCs and the hardware allow for such an adjustment, but the current firmware settings do not. In order to correct this, the PLC project would need to be debugged, modified, and reloaded.

Doubles

When running the RAM_Powder_Paths.py functions, the only values that are acceptable are integers. This is generally only a problem for the Calibrate Height (CH) function. This solution for this would be to simply cast the input string as a double rather than an integer.

Unprotected Input

When running the RAM_Powder_Paths.py functions, there is no protection for incorrect input. That is to say, if the circle function is asking for a “radius” and a user inputs a string, the code will break. This cause a termination of the program, thus the TCP connection. A simple restart of the program will get you back on track, but it will cause the nozzle to return to its initial state (an inch or two off the build plate) potentially causing the powder to pour out in a larger pile under the nozzle.

The solution to this problem would be to code in data-type checking loops surrounding each input.