3D Metal Printer

Final Report:
April 2019 - Team 3

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0 - Executive Summary

0.1 Project statement

Our team is tasked with continuing the creation of a 3D metal printer. The scope of the project includes creating a printer that utilizes lasers to melt metallic powder to create objects. We are also tasked with choosing and implementing sensors to monitor and evaluate the construction of the object during and after the printing process. The sensors that will be used are Eddy Current scanners, temperature and pressure sensors to ensure that the entire process is done under vacuum (this is so that the metal powder is less volatile) and that the lasers do not cause an excess amount of heat in the chamber. We will also use ultrasounds to scan each layer of the object while it is being printed.

0.2 Purpose

This 3D metal printer will be used for testing on how print quality correlates with the part's performance. That is why the sensors for the non-destructive layers are used. Those sensors will be scanning and evaluating each layer that is created for a part. This will be for testing for defects or any problems in the creation of the part. Industry is making 3D printing more of a standard, so creating 3D printers that can print high quality components is becoming simpler and more standardized. Even though this 3D printing is not built for high speed, it focuses on the quality of printing parts.

0.3 Accomplishments

Our accomplishments for this project were the vacuum sealed chamber, majority of the printer is completed, laser is ready, software updated, and printing sweep is completed. The vacuum sealed chamber is prepared for use, after EH&S approves it. The printer has all of its components are completed, except the powder collection bin. The laser is ready for testing. The CAD converter, printer code, and print bed sweep code are completed and working. All of these accomplishments were not tested in the vacuum-sealed chamber because it the chamber was not approved by EH&S for this semester.

1 - Requirements Specification

Functional
- The printer shall have 3 lasers- a 1064 nm 200 W melt laser, a 1064 nm ultrasound generating laser, and a 1550 nm laser interferometer.
- The printer shall have a powder bed which moves up in order to deposit a new layer of powder.
- The printer shall have a roller to deposit powder from the powder bed to the print bed.
- The printer shall have a print bed which moves down after each layer is sintered by the laser.
- The printer shall have a collection bin which collects any excess powder that is not deposited on the print bed.

- Any component or device that deals with powder must be enclosed in a vacuum sealed chamber that is filled with a nitrogen/argon gas.
- All lasers shall be able to be adjusted to any point within the print bed using some sort of servo control system.
- There shall be a pressure and oxygen sensor inside the sealed powder chamber to check for safety hazards.
- There shall be an oxygen outside of the printer, to alarm the user if oxygen levels in the room are unsafe or low.
- The system shall use an interlock or locking system to prevent the laser to turn on unless the chamber's door is sealed.
- A camera will be added to provide eyesight in the sealed chamber and to visually see if there are any problems.
- Two temperature sensors will be used to measure the temperature of the inside of the sealed chamber as well as the temperature of the sealed chambers' walls. This is for checking to make sure that the powder isn't getting too hot and to know if the sealed chamber is safe to tough.

Non-Functional

- The vacuum chamber should use space efficiently.
- All code should be well documented and understandable to allow future users to edit easily.
- The printer should work as quickly as possible without affecting quality or causing safety issues.

2 - System Design and Development

2.1   Proposed Design

Since the project has already been partially completed, we have very clear goals for the project. The physical design of the printer is almost complete, and we need to add a roller for the metal powder as well as install the three lasers. A figure showing the final physical design of the printer is included below. We also hope to control the printer using the provided PC through a serial connection. Finally, we will expand the software interface to allow expansion to 3D printing from 2D printing. The second figure below shows how we plan to implement the user interface as well as the interaction between the software and hardware. Figure 1 also shows the placements of the lasers and the stepper motors that will be used to control their movement.
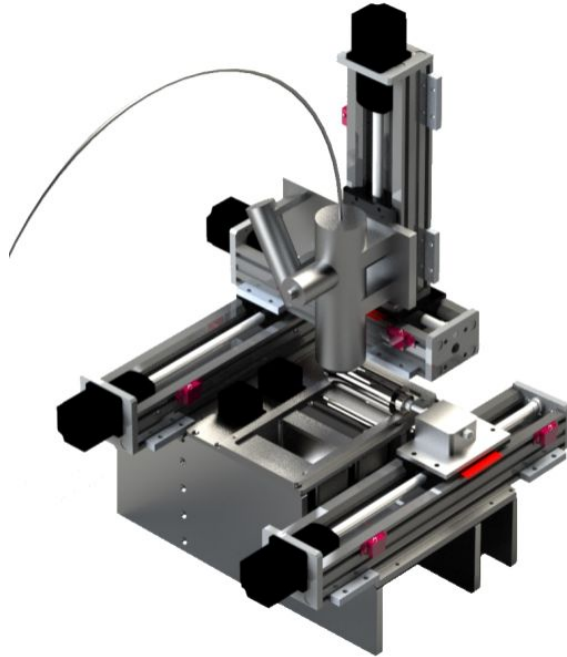
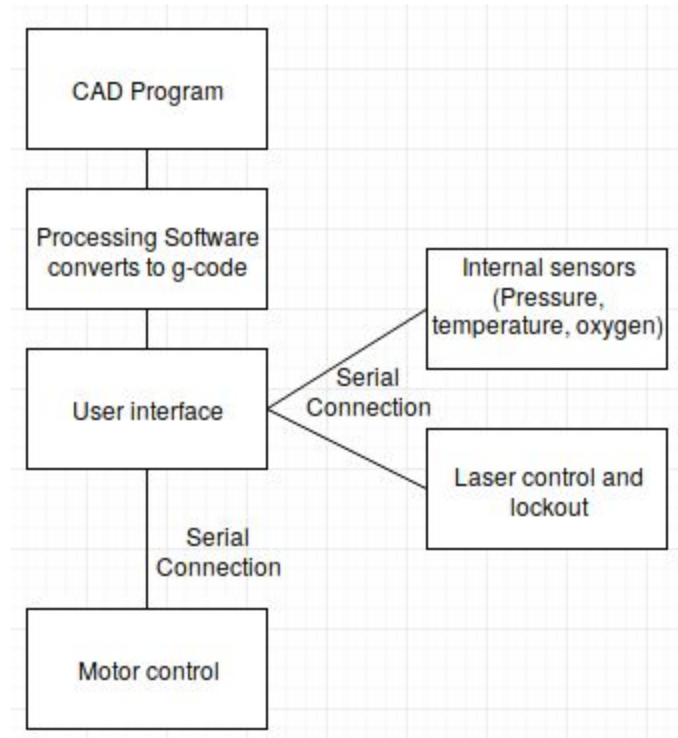Figure 1 - Rendering of final 3D printer.

Figure 2 - Block diagram of software and hardware interaction.

For Figure 1, this shows a rendering of what the 3D printer would look like in its final state. This would include having the components of the print bed, stepper motors, and the laser. The stepper motors will

control the movement of the laser's position and the position of the print bed. The laser will be used to melt the metallic powder to create an object. And the print bed is used for placing the metallic powder on the bed so that it can be used for creating objects.

Figure 2 is representing the block diagram between the hardware and the software. The first block of "CAD program," is representing the CAD program for creating the objects in CAD. This CAD file is then sent to the next block of "Processing Software converts to g-code." The processing software is using C# to convert the CAD file into g-code. The conversion to g-code is needed so that the printer and the CAD file are using the same software and that the CAD file can be created through the printer. This conversion of the CAD file to g-code goes to the next block of "User Interface." This block is used to determine if the printer can continue operations of to discontinue operations. This depends on the two blocks of "Internal Sensors" and "Laser control and lockout." The block for the internal sensors is the input of the sensor values. Depending on these values, this will set the printer to continue operations or discontinue operations. The block about laser control and lockout will be used to identify the controls for the laser. This would include the operation of lasers position and to lock the laser in place for melting a certain location on the print bed. Depending on the inputs of the sensors and the laser control and lockout, will determine the motor controls. The motor controls would be the last block called, "Motor Control." This block dictates the motor controls of how far or what motors get moved to accomplish the task from the previous block. This entire block diagram explains how the code will work overall and implement the motors to create the CAD file.

2.2   Design Analysis

Much of the physical design of the printer has been completed, so we are already locked in on a design. The group previous to us considered two options for the design of the printer: the window method and the mirror method. In the mirror method, the laser travels through a window and bounces off a mirror onto the print surface. This method would have used less total space to make, but also would be much more prone to error since the mirror could be accidentally shifted slightly. This method is shown in figure 3. In the window method, which the previous group decided on, the laser points directly onto the printing surface (Credit to the phase I group for the figures). This figure uses more space, but is simpler and less prone to errors.
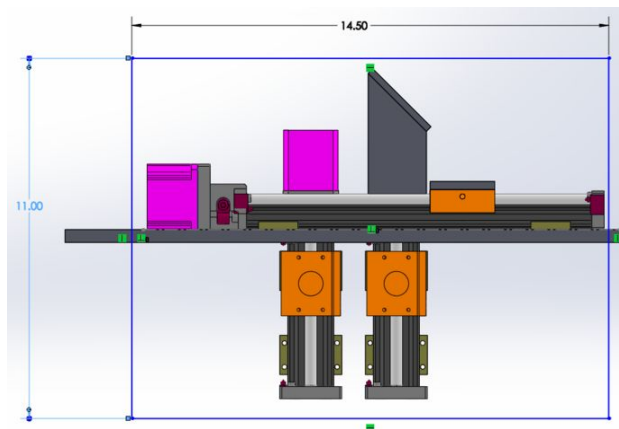
Figure 3: The mirror method.
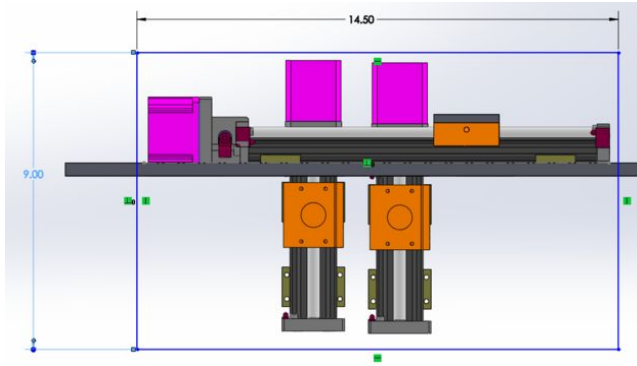
Figure 4: The window method.

There are several large safety concerns for this printer. Since the printer needs to be atmospherically controlled, keeping a sealed chamber is a concern. There is another cause of concern with the class 4 lasers, which have serious radiation and exposure hazards. Both of these issues will be controlled by the chamber that the printer will be housed in. This is good because it keeps the printer in an isolated environment, but any leak will push oxygen out of a room as it gets filled with pure gas. It is critical for us to use a safe chamber due to this.

The other two designed components, the roller and the dispenser have no safety concerns. The roller needs to be made of a material that does not allow for sticking of the aluminum powder to the roller. The dispenser needs to constantly output an evenly dispersed layer of powder. The roller will also push down the layer of powder after it is dispensed, to minimize air gaps in the metal. The Roller design is shown here, in Figure 3.
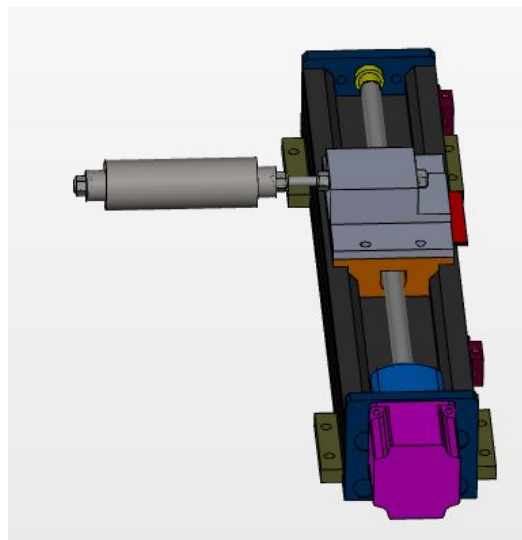
Figure 5: Design of the roller assembly.

The print bed, on which the roller will function, has gone through several stages of design. The bed needs to remain flush with the walls, as well as be able to travel up and down using stepper motors. The final design for the print bed is included in the figure below. There is a powder collection bin directly adjacent

to the print bed, for the roller to push all excess powder into for recollection. The design for this is shown in Figure 4, below.
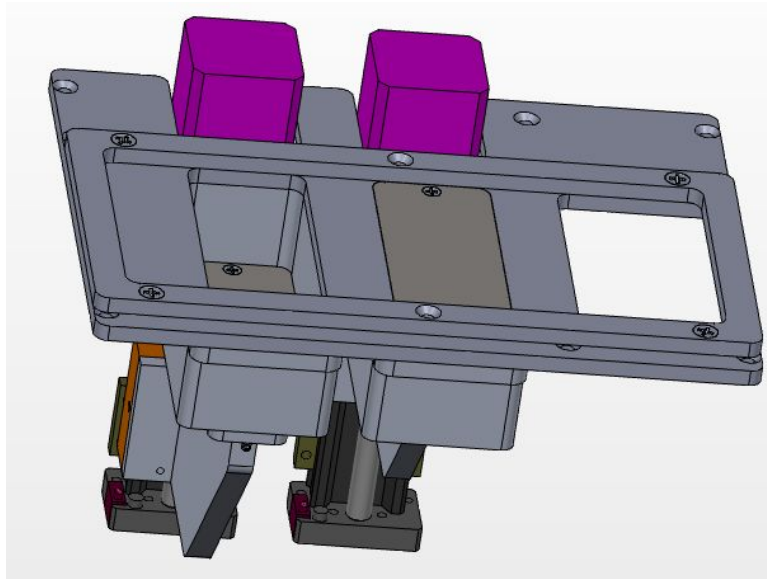
Figure 6: Print and powder bed design.

The plan for depositing the powder is to have two stepper motors which will control the print bed and the powder bed. With each layer of powder deposited and melted, the print bed will move slightly down and the powder bed will move slightly up. The roller will then roll over the powder bed, collecting powder as it does. The roller will then roll over the print bed, depositing a thin layer of powder on top of the previous sintered metal. Finally, the roller will roll back, the powder will be melted, and the process will repeat. The figure below shows a visual representation of how the powder depositing process will work.
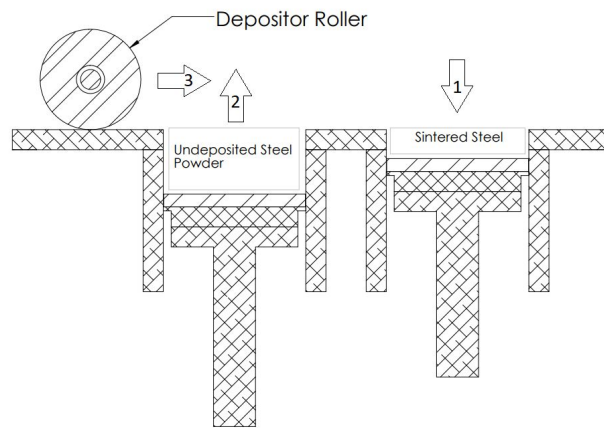
Figure 7: Representation of how the roller deposits powder.

This is the final design, of which most has been implemented. The print bed and dispenser need to be manufactured, which should be done soon. There is no other components of the printer that we need to design, our next step is implementation and testing.

2.3 Architectural Diagram
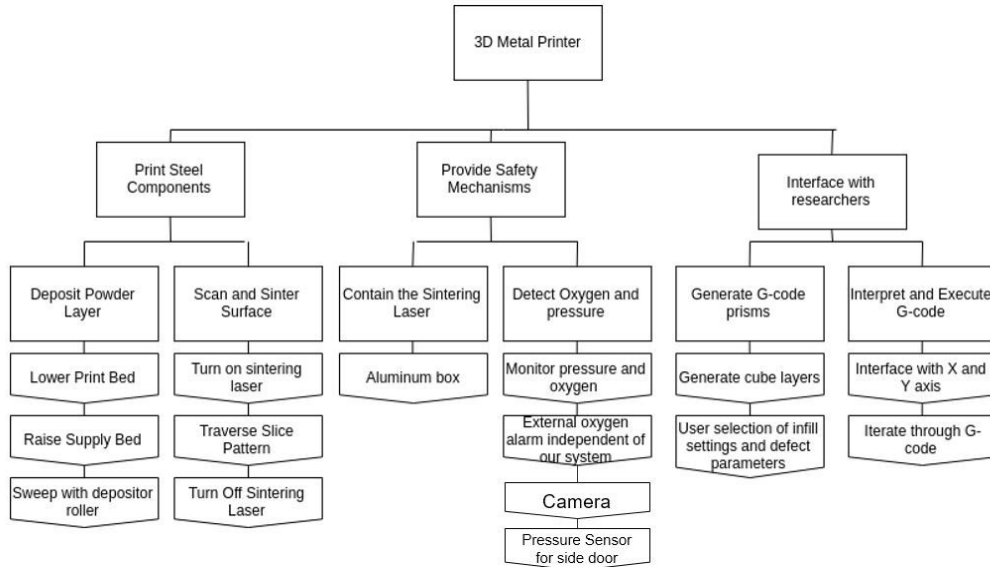
Figure 8: The block diagram for the overall design of the printer.

2.4   Interface Specifications

Our testing interface will be done through a pc connection. We will use this interface to send commands to the machine and also use it to take input data from the sensors and camera. The temperature, pressure, and oxygen levels will all be displayed on the user interface to ensure that the environment remains stable and conducive to printing. There will be a camera in the box, which we will feed to the computer, in order to visually monitor the printing process. We will also include an eddy current sensor, which is meant to be used by the more advanced users, in order to perform NDE. The output of the sensor will also be put on the user interface.

Success in this area will be defined as streamlining the information into one easy-to-navigate user interface. The data previously mentioned from the sensors will be used to ensure that the sensors are correct by testing in a normal, oxygenated environment (other than the oxygen sensor, which cannot be used in this environment without making future readings inaccurate).

3 - Implementation

3.1 Proposed System Block diagram
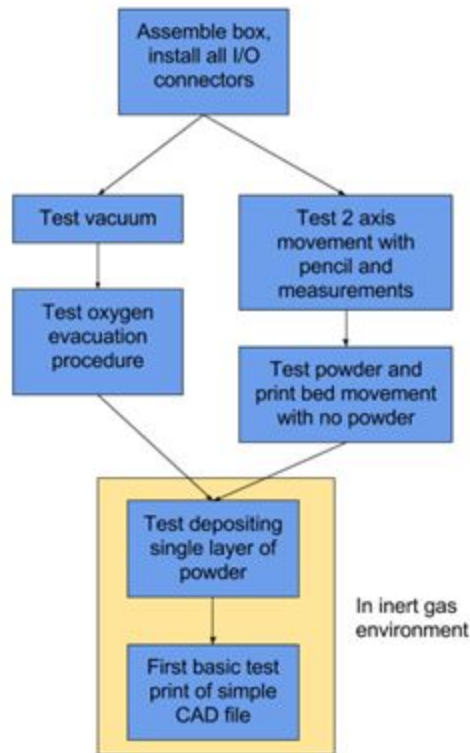
Figure 9: Block diagram of 3d Printer Phase II design.

In Figure 2, this is the part of the project that the following group had left for our group. This shows the phases that need to be completed. The first step is completing the vacuum sealed chamber and installing all the inputs/outputs of the connectors. The vacuum sealed chamber needs to be finished for the wire connections, contact sensor, temperature sensor, and sealing the chamber. The I/O will be the barometer, temperature sensors, contact sensor, stepper motor input connectors, Eddy Current, ultrasound connector, and camera connector. These connectors will be used to give power and send commands to each component. All of these components will be tested for the their expected operation.

The second step is testing the vacuum sealed chamber. This will be testing to see if it is actually truly sealed. This testing will require using the oxygen and pressure sensor to be used to evaluate if the chamber is sealed. That would lead into the next part for the vacuum sealed chamber, which is testing for how much oxygen and creating the argon environment in the chamber.

The third step is evaluating and calibrating the two stepper motors for how the accuracy of the stepper motors. This would test how the laser would be working for the printer. Basically, how accurate the laser will be when melting the metal powder. The metal powder will be tested later on.

The next step is testing the print bed for accuracy with the laser stepper motors. This evaluates how the print bed will move and how it will move with the laser. This will test for the angles and accuracy of how the laser would melt the powder.

The final step for testing the components is placing the 3D metal printer in the vacuum sealed chamber. This will be testing the printer to see if a single layer of metal powder can be melted properly, basically making a simple sketch with the metal powder If the metal powder is melted, then the next step is creating a part with a CAD file. This will test the safety and material evaluation of the part, basically evaluating how the part is being made by each layer. Depending on the quality of the completed part, the printer may have to be calibrated to increase the quality of the printed parts.

The past group completed the main construction of the 3D printer. This would include the base, the stepper motor placement, the stepper motor controllers, and the stepper motors for the print bed. For the coding side, the previous team had coding for the stepper motors for the lasers, coding for the barometer, and the vacuum sealed chamber was built. The vacuum sealed chamber was built and is just waiting for the printer to be done to test it out. This group selected this option for creating the 3D printer because they went for accuracy and not for speed. It will take longer for an object to be created but it would be more accurate for the building process. This is where are group started with. This shaped are design proposal based on what the previous group setup the 3D printer. The previous group even had block diagrams and their timeline showed what and how they wanted to finish the project. So, we are just continuing the project on with extra sensors and calibration techniques that Dr.Bigelow suggested.

3.2 Hardware Implementation

Print Beds and Roller

The core mechanical functions of the printer are to scan and sinter a powder surface, deposit another layer on that surface and supply additional material to the depositor for each rail. Part of the design constraints for the printer was to use the Velmex System, which eventually evolved into being required to use the Velmex BiSlide models. Because the print size and focal length requirements, this led to some difficult geometry.

The first main mechanical function is to contain the powder and control the z direction of a print. The team's solution uses two piston-like structures called the powder beds. To constrain the powder beds, the client specified a necessary print volume of 4 cm by 4 cm by 8 cm. The design includes a small buffer to accommodate this in real life. The design of each print bed needed to both contain and translate the steel powder to be used by the printer,the beds also needed to handle high temperatures. To deposit a layer of

steel, a roller will push powder from the surface of the supply bed to the surface of the print bed. The final beds are made with a bracket that holds a plastic layer that seals against the print walls above the plastic is the steel print bed, which the powder will sinter to. The beds are operated by smaller velmex slides. The rendering in Figure 2 shows the supply bed and the print bed.

The next feature is the roller. In order to deposit powder from one bed to the next, a roller is used. The roller will push the powder from the supply bed to the printing bed. There is a slot for an overflow container to collect excess powder that overflows from the printing surface. The roller rides on bearings between two rails that prevent powder from spreading out and not flowing into the the print bed. The railings compliment the roller so that if a more complicated roller is needed, it can be pressed against the rails and not depress the printing surface. The depositor roller can be seen in Figure 2 to the right side of the printing machine.

Finally, the mechanical system needs to sweep the surface of the powder with the sintering laser. The team's solution uses a 3-axis slide assembly. The printer's x and y coordinates are controlled by horizontal BiSlides from Velmex. There is also a vertical slide to ensure that the laser height is at the proper distance from the surface of the powder.
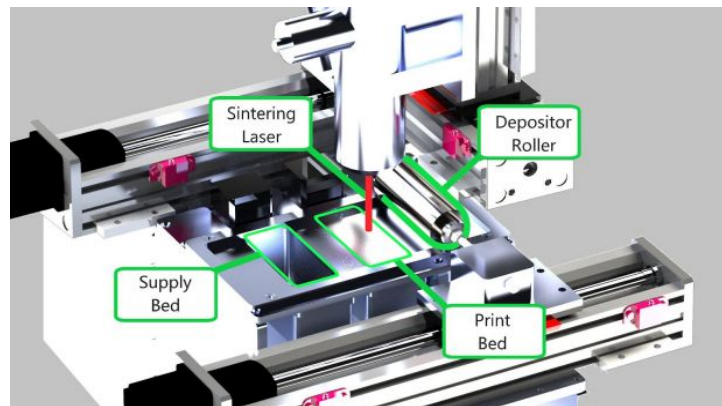
Figure 10: Print Beds, Laser, and Roller Diagram.

Vacuum Chamber

Part of the challenge of selective laser sintering on steel is preventing oxidation of the steel as it is sintered together. Welding techniques usually accomplish this by blowing inert gas over the weld to prevent oxygen getting to the molten metal at its hottest state. This is a bad idea for a machine that deals with powder. In order to accomplish this in industry, professional SLS machines evacuate the air in the printer and fill it with inert gas or nitrogen to prevent oxidation. To achieve this the team needed to design a vacuum chamber to enclose the printer. This constraint brought on several challenges to the design: how

to seal the chamber, how to pass electrical signals into the chamber, how to manufacture the chamber and how to pass the fiber optics into the chamber.

As the team looked at how to encapsulate the printer it became clear the chamber would have to address the ship-in-a-bottle problem of how to get the assembled printer inside the chamber. The intent of the original design was to have two halves that would bolt to each other to form a seal. Chamber would then have a removable door giving access to the sintering end of the printer. In addition, the bottom half of this chamber was originally intended to have all electrical ports and the fiber optic ports to ensure that removing the top would be safe and trivial. In order to allow signals and lasers into the chamber, research was done to select electrical feedthroughs and plumbing hardware was selected to permit gas and signals. The lasers are going to use vacuum rated tubing with specialized gaskets and caps to seal the fiber-optics into the chamber. Another major consideration for the size. The size of the chamber was picked to fit the printer and the fiber optics snaked back to the feed throughs. The client-specified 12 inch bend radius of the fiber optics meant a chamber that was quite a bit bigger than the machinery inside. Fortunately, the team is going to use nitrogen to prevent oxidation, which is a fairly common gas.

The vacuum chamber was manufactured by Sargent Metal Fabricating in Ames, Iowa. The shop cut the aluminum and welded the parts into two large pieces. The vacuum chamber uses rubber gasket material that can handle high temperatures and pressures. The design uses vacuum-sealing washers to help seal the door on. The two halves are fastened with some large bolts that will press the two sides together. A final plate, the door was also produced by Sargent Metal.

After receiving the Vacuum Chamber EH&S felt it was necessary to make changes to enable easier movement of the chamber. The major concern was that the larger top piece of the chamber was too heavy to maneuver without some heavy duty handles. The new arrangement can be seen in figure 4.

Figure 11: Vacuum chamber.

Sensor System

Oxygen Sensor

The oxygen sensor is an AMI 2001LC Trace Oxygen Analyzer. We needed to have a sensitivity around 1000 ppm level. We searched for a number of different systems and settled on on the 20001LC due to a combination of cost and functionality. The system outputs a 4-20mA signal that we convert to a 1 to 5 volt signal using a 250 Ohm resistor. This voltage is used by the arduino's adc to calculate the ppm. This result is then sent to the UI on the computer to be used by the human operator. The setup and connection between the oxygen sensor and the arduino can be seen below as well as an image of the sensor itself in figure Figure 6.

Pressure Sensor

The pressure sensor is a Seed Studio Grove high-accuracy barometer sensor that has uses a HP206C to detect temperature and pressure. It communicates via an I2C interface connected to an arduino. The arduino then outputs the readings in hPa and Celsius via serial to the UI on the computer. There are no safety actions triggered by the temperature and pressure readings. They are instead used by the human operator to take action if deemed necessary. The connection between the I2C ports on the sensor and the arduino can be seen below in Figure 6.

External Oxygen Alarm

In order to meet necessary safety requirements, we use a standalone external oxygen alarm while our system is operating. This BW Honeywell Clip 2.0 monitors for an excessive drop in oxygen level and will sound an alarm if necessary. This alarm signals to the operator that they need to evacuate the room immediately. The main instance where this would be necessary is in the case of a leak in the nitrogen gas tank. The device can be seen in figure Figure 6 below.

(a)   (b)
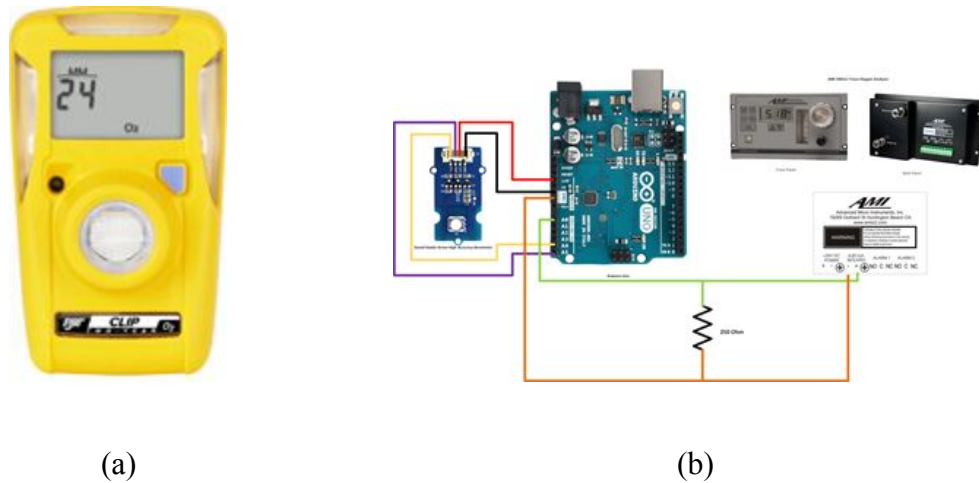
Figure 12. (a): BW Honeywell Clip 2.0, (b): Seed Studio Grove High Accuracy Barometer, Arduino Uno, AMI 2001LC Oxygen Analyzer.

Camera

In order to be able to view the inside of the printer when it is running, we decided to implement a camera inside the vacuum chamber. We needed to make sure that the camera will be able to withstand low pressure and high temperature. We decided to go with a security camera, but we had to made sure that the material is able to withstand high temperature. In order for the pressure inside the camera and the vacuum chamber to equalize, we decided to drill holes on the housing of the camera.

3.3 Software Implementation

Sensor Serial Communication

The Arduino which interfaces with the internal oxygen, pressure, and temperature sensors communicates with the main desktop PC via a serial connection. We devised a very simple serial protocol to communicate this information to the GUI software.
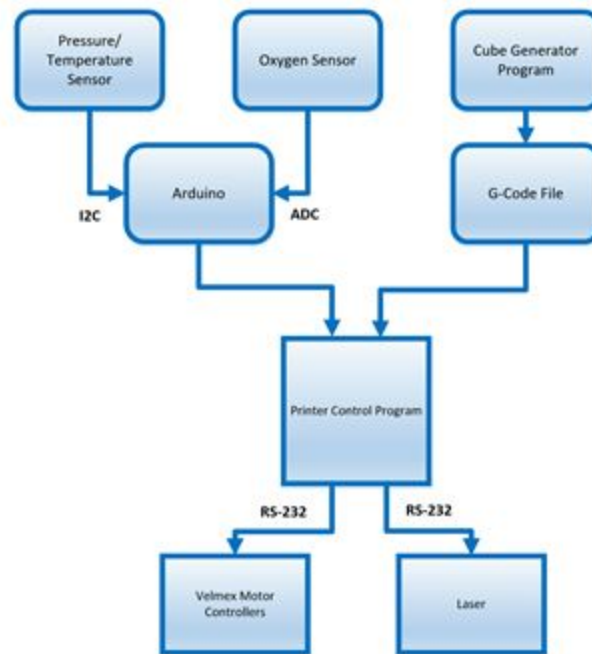
Figure 13: Sensor system integrated to communicate with GUI software.

Software Overview

The control software for the printer was all written in C# using the WPF Framework. This software runs on a dedicated PC we acquired for the project. There are two major sections of the software: G-code cube generation, and the G-code interpreter. The G-code interpreter software takes any compliant G-code file as input, transposes it to Velmex motor controller commands, and prints in on the 3D Metal Printer. While printing, this software shows progress with command selection as well as sensor readings.

The G-code generator software generates .gcode files which will be compliant and can be used with the G-code interpreter software.

G-Code Generator

After refocusing our efforts and narrowing scope at the beginning of the semester, the primary software goal shifted from slicing and processing existing CAD files to generating G-code for rectangular prisms to be printed. This satisfies the needs of the client, and allowed us to focus more time on developing a variety of user configurable infill generation algorithms.

The G-code generator algorithms take the following inputs and output G-code for drawing the resultant shape:

- Laser spot size

- Z layer thickness

- Height of rectangular prism

- Number of perimeter lines per Z layer

- How to alternate infill hatch direction (checkerboard, random, same direction)

- Number of perimeter lines per infill square

- Infill square size

- Number of infill squares (x/width)

- Number of infill squares (y/height)

- Order of printing infill squares (sequential, random, every other)

- Defect area box location and dimensions

This gives researchers a good number of parameters to play with in order to print shapes which meet their needs. The infill patterns implemented match those specified by our client verbally in team meetings. Furthermore, a feature has been added which allows the creation of a 'defect' in the part. In order to create a defect, the laser is turned off while passing through this region of the part. This will create an area of unsintered metal, which would be a mechanical defect to the part's structure.

All algorithms to generate the G-code are contained in the CubeGenerator.cs file, and the code is commented such that a future student or researcher should be able to understand and modify it.

In order to simplify the G-code generation, our software outputs all x-y movements of the laser head as standard G1 commands, but abstracts Z movement and layer changes into custom defined 'M' commands. Thus, if someone wants to input a G-code program from a standard slicer into our G-code parser, they must modify the parser to implement our custom 'M' commands. This is very similar to how one would specify they brand of plastic 3D printer using a standard slicer, custom handlers for layer changes and other parameters would have to be set up for the slicer. Table 1 summarizes the commands created by the team to operate the printer.

Command	Description	Example
M200 X	Execute layer change of height X	M200 0.25
M201	Turn the melt laser on	M201
M202	Turn the melt laser off	M202v

Table 1: Custom 'M' Commands.
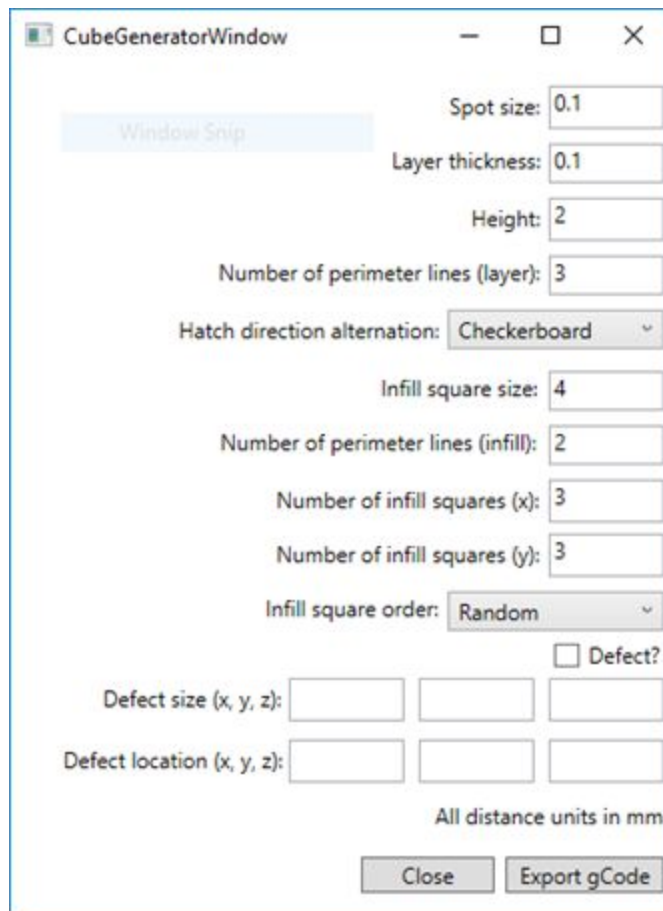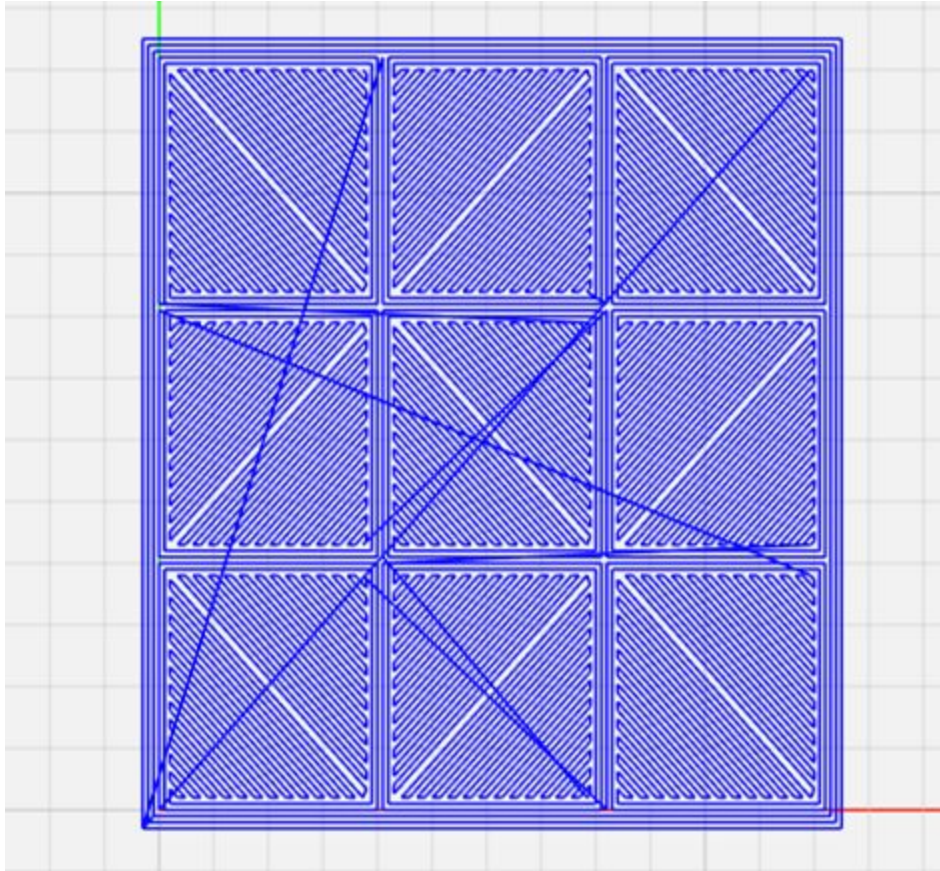
Figure 15: A visualization of the output of the G-code generated by the above screenshot. This shows a top down view of one of the layers. The long lines crossing the entire square show movement of the laser head, but the laser will not be on for these movements.

G-Code Interpreter

The main function of the G-Code Interpreter is to parse inputted G-Code and generate Velmex commands. After generating, the Velmex commands can then be outputted serially which will control the stepper motors given the outputted data. The commands can be outputted one at a time for incremental

testing or executed all with another button. Individual commands can be selected to run if required. Also, the parser has a speed parameter which is necessary to set the base speed of the stepper motors.

The generated Velmex commands are separated as four different actions, velmex_move, laser_on, laser_off, and layer_change. These are defined in PrinterAction.cs. Velmex_move is a standard movement of the stepper motors in the x and y direction. Laser_on is an action that will later be used to enable the laser and laser_off will disable the print laser. The layer_change action is multiple velmex commands that are always the same that move the powder bed and supply and the roller in the correct order and timing to setup the next layer for printing.

All algorithms to parse the G-code and generate the Velmex commands are contained in the GCodeParser.cs file, and the code is commented such that a future student or researcher should be able to understand and modify it.

The sensor data is from the Arduino which interfaces with the internal oxygen, pressure, and temperature sensors, and the Arduino sends its values to the computer through the serial protocol.
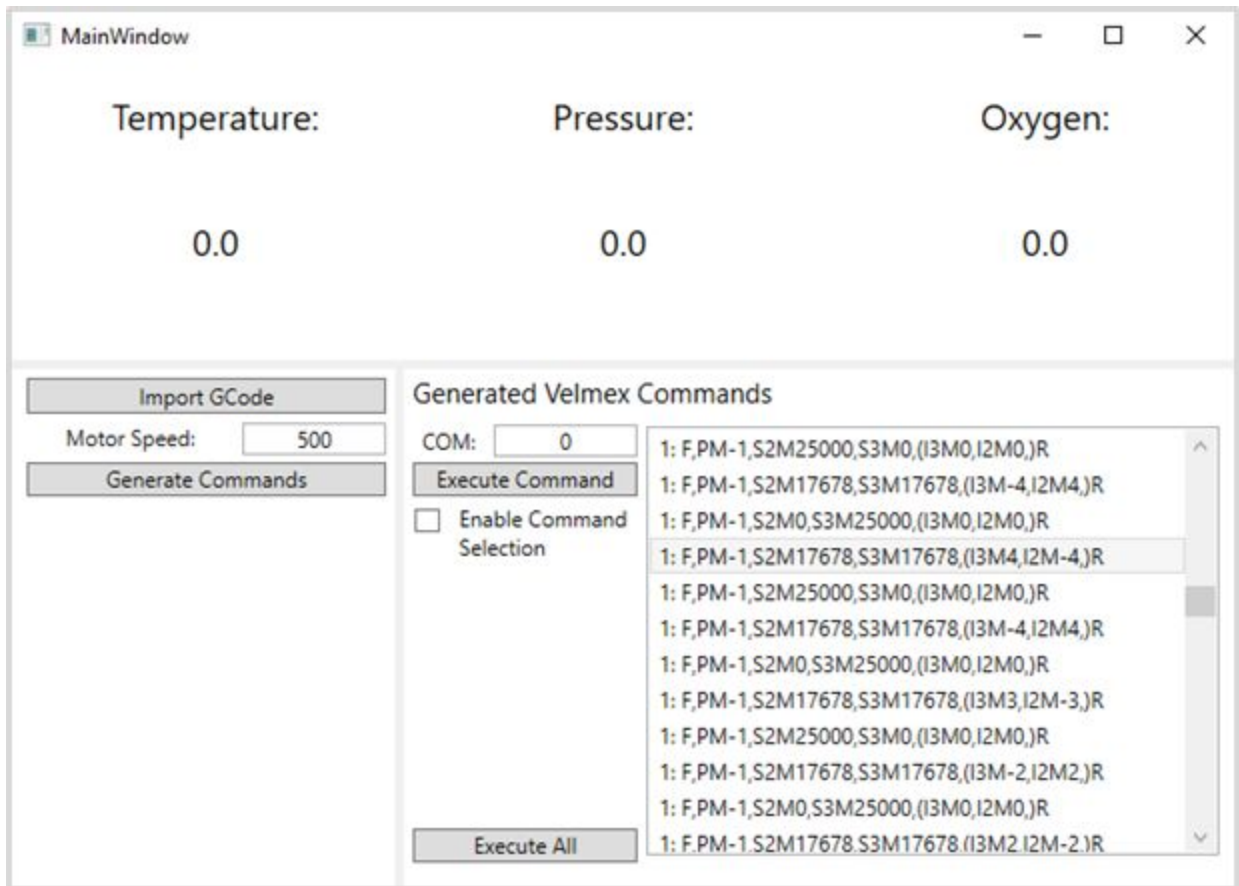
Figure 16: An example of the user interface which displays sensor data and allows for GCode import.

3.4 Assessment of Proposed methods

The strengths of this project include in-line monitoring for laser ultrasound. There will be oxygen sensors, temperature sensors, contact sensors and cameras to monitor the 3D metal printer. However, there are challenges that we have to face when considering the sensors and camera placement. Since the 3D printer will be operating in a vacuum chamber, the sensors and cameras must be able to withstand the difference in pressure. Taking this into account, we need to consider the material of the camera, the temperature limit it can stand, etc. Another alternative will be creating our own camera that meets the specifications.

The weakness of in-line monitoring include the slow operational speed of the stepper motors. Just printing a simple cube will take a while to complete and the stepper motors might even deviate from its path. This cause inaccurate in-line monitoring, which defeats the purpose of our goal.

To make the workload even and efficient, the team discussed an option to accomplish this. The plan that was discussed was having three pairs. Each pair would include each major. So, there would be one pair of computer engineers, one pair of software engineers, and one pair of electrical engineers. We thought this would be beneficial so that the pairs could discuss between each other to generate ideas or solutions. This method also helps with group communication, as there is 3 collaborative groups instead of 6 completely separate solo workers.

As shown above in Figure 2, our 3D printer was planned and discussed with our advisor, Dr. Bigelow. We will finish both the nitrogen/argon sealed chamber and the 3D metal printer. Each of those components then will be tested to properly test the sensors and the functionality of the componentents. After both components pass, then the two components can be built together. This means that the 3D metal printer will be placed inside the sealed chamber to test the laser and the layer of powder. If that test is successful, then the final step would be to convert CAD drawings into the printer and construct those drawings. This would be the true test to see if the printer can complete a task and to see if the CAD drawing is made correctly.

3.5 Applicable Standards and Best Practices

Engineering standards assist with the creation of constraints for designing a technical product. Constraints allow for a group of engineers to critical think for a solution or goal for a project. Projects/devices are held to these standards to be easily transferable between platforms. The standards we will be following are the industry and IEEE standards.
All code generated will be written with supporting documentation in Javadocs style comments. This follows the software standards that are present in the industry standards. Meeting these requirements will allow easier understanding of the coding and how to modified the software.
Using a high power laser requires several safety standards to be followed. All of our team members will take the EHS Laser Safety training, and will work with EHS to ensure that the system and its environment is safe for testing.

The following are IEEE standards that pertain to our project:

270-2006 - IEEE Standard Definitions for Selected Quantities, Units, and Related Terms, with Special Attention to the International System of Units (SI).
This standard defines the physical quantities, units, and the systems of measurements that are used in applied science and technology. The standards emphasizes the use of the International System of Units. This is relevant to the team's project because half of our project is mechanically designed. We need to confirm that the parts of the printer are compatible with the design of the printer. Therefore, our team must be aware of the measurements/units for each part.

1100-2005 - IEEE Recommended Practice for Powering and Grounding Electronic Equipment.
This standard is a collection of best practices for powering and grounding electronic equipment used in commercial and industrial applications. The best practices are designed to enhance equipment performance and maintain safe installation. This is relevant to our project because we will essentially be building a device that needs proper powering and grounding. We will be using several lasers, implementing a sensor system, and powering a printer. We need to be able to properly distribute power and ground these systems for safe handling.

299-2006 - IEEE Standard Method for Measuring Effectiveness of Electromagnetic Shielding Enclosures.
This standard describes uniform measurement procedures and techniques to determine the efficiency of electromagnetic shield enclosures. This includes welded, demountable builds of materials such as steel plate, aluminum, and copper. This is relevant to the project because we will be using several lasers, including a high beam melt laser. We need to be able to have an enclosure that helps prevent any radiation and reflection to the user. This standard will help ensure that our device is safe to handle

754-2008 - IEEE Standard for Floating-Point Arithmetic
This standard specifies interchange and arithmetic formats and methods for binary and decimal floating-point arithmetic in computer programming environments. This standard is geared toward the software part of our project. Our printer will be controlled by a program that will control the movement of our printer by pushing coordinate values via arrays. We want to be able to store precise values as possible to maintain accuracy of the 3D printed product.

There are also some other standards by the International Organization for Standardization (ISO) for additive manufacturing that we will be following:

ISO/ASTM 52901:2017 - Additive manufacturing -- General principles -- Requirements for purchased AM parts
"Gives guidelines for the elements to be exchanged between the customer and the part provider at the time of the order, including the customer order information, part definition data, feedstock requirements, final part characteristics and properties, inspection requirements and part acceptance methods." (Naden 2018)

ISO 17296-2:2015 - Additive manufacturing -- General principles -- Part 2: Overview of process categories and feedstock
"Explains how different process categories make use of different types of materials to shape a product's geometry. It also describes which type of material is used in different process categories." (Naden 2018)

ISO 17296-3:2014 - Additive manufacturing -- General principles -- Part 3: Main characteristics and corresponding test methods

"Specifies main quality characteristics of parts, specifies appropriate test procedures, and recommends the scope and content of test and supply agreements." (Naden 2018)

ISO 17296-4:2014 - Additive manufacturing -- General principles -- Part 4: Overview of data processing.
"Specifies terms and definitions which enable information to be exchanged describing geometries or parts such that they can be additively manufactured. The data exchange method outlines file type, data enclosed formatting of such data and what this can be used for."

ISO/ASTM 52900:2015 - Additive manufacturing -- General principles -- Terminology
"Establishes and defines terms used in additive manufacturing (AM) technology, which applies the additive shaping principle and thereby builds physical 3D geometries by successive addition of material."

ISO/ASTM 52910:2018 - Additive manufacturing -- Design -- Requirements, guidelines and recommendations
"General guidance and identification of issues are supported, but specific design solutions and process-specific or material-specific data are not supported."

ISO/ASTM 52921:2013 - Standard terminology for additive manufacturing -- Coordinate systems and test methodologies
"Terms included cover definitions for machines/systems and their coordinate systems plus the location and orientation of parts. It is intended, where possible, to be compliant with ISO 841 and to clarify the specific adaptation of those principles to additive manufacturing."

4 - Testing, Validation, and Evaluation

4.1 Test Plan

To test the printer for its completeness and effectiveness we will be using an array of sensors. These sensors include barometer, camera, and temperature sensors. These sensors will be used to regulate the printer to make sure that it runs smoothly without safety concerns. We also plan to test the full movement of the printer using the guide laser, which will mimic the movement of the actual laser. We were unable to test the printer using the actual laser as it still needs to be approved by the environmental health and safety department.

We also had to test components of the printer like the powder bed and roller to make sure that the parts fit perfectly and runs as desired. We found out that the powder bed was off and it was not perfectly aligned with the print bed. After making adjustments, we tested it again by attaching it to the printer and running the software.

4.2 Unit Testing

Camera testing

The camera was tested in a low vacuum pressure chamber to test for its functionality in a low vacuum system. A hole had to be drilled into the camera to equalize the pressure of the inside of the camera with the outside environment. After we drilled a hole, we tested the camera in a vacuum chamber at low pressure and it worked without any failures.

Barometer testing

Testing the barometer was harder than expected because we were not able to change pressure and measure it the way we can with temperature. The first basic test we did was to make sure that the regular output of the sensor matches the expected value for Ames. We would expect that the pressure in Ames would be around 1 atm and the sensor constantly was showing a constant value of around 1 atm. To make sure that the barometer works, we decide to test it in a vacuum chamber at low pressure and made sure that the readings were dropping.

4.3 Interface Testing

Computer to Printer Interface Testing

This testing deals with connecting the printer to the computer to run the program for the printer. The printer would take Velmex commands that would be parsed from gcode. To test that the printer would behave properly, we input g-code commands that we know what the behavior should be and make sure the printer is doing as instructed. Another test we did was verifying the code that generates one infill square is correct, and then verifying the code to generate a full layer is correct, and then verifying that the entire .gcode file is correct for the input parameters.

4.4 System Integration Testing

Laser Alignment Testing

The laser alignment testing was done by attaching a pen to the location of the laser. The pen would be used to draw on a piece of paper to show that software and hardware are both working to get the proper laser location. Figure 15 shows the output of this testing. This test was used to help adjust and calibrate the laser alignment.

Full System Test

In order to do a full system test, we began by writing a test gcode file. This consisted of the print and powder beds moving, the roller moving each time a layer is finishing, and the laser moving to desired locations. We verified that each movement was as desired, and in the correct direction. We also made sure that all commands in the file would run. This test allowed us to run all functioning parts of the printer, to see that it functions properly.

4.5 Validation

With the project on a budget, we will discuss the construction of the 3D printer with Dr. Bigelow. This would include the purchasing of camera, sensors, stepper motors, and other necessary components. Each component will go under testing to make sure each component can survive a vacuum and still operates under those conditions. This would include software to operate the components, which would attached or added on to produce a safe operating 3D metal printer. To assist with the mechanical side of the project, Dr. Bigelow hired some mechanical graduate students that will assist us with the mechanical components that need to be created.

The software testing will have multiple steps. The first step would be connecting and operating the metal printer from a computer. This will help establish that the code is working as well as the printer working. Next, would be programing the oxygen, pressure, and temperature sensor to either operate the printer or shut down the printer. Each sensor would be tested and debug in a vacuum sealed chamber to achieve the proper coding for functionality.

Hardware testing will be testing the two main components, the sealed chamber and the 3D metal printer. The sealed chamber will be tested for a nitrogen/argon environment. This would include the absence of oxygen in the sealed chamber. The 3D metal printer will be tested for the functionality of how it will operate the laser mount. The laser mount is used to position the laser in the proper spot for melting the powder, which is used to create the object. The laser mount will have to be tested for efficiency as well as functionality. This will require some debugging in the coding and calibrating the stepping motors. To test the laser mount outside of the vacuum, we will use a pen to draw out for where the pen is going. This will help us to visually see the operation of the laser mount so that we will be able to calibrate the laser mount properly.

The final testing would be testing the 3D metal printer in the sealed chamber. This will be the first test to see if the powder will be melted properly in the sealed chamber. Testing this will be a good way to make sure that the laser is working properly as well as the code for the laser mount. If the testing proves positive, then the last test would be printing a CAD drawing. This may have multiple problems but it would provide sufficient information about what needs to be fixed.

5 - Project and Risk Management

5.1 Task Decomposition

Thomas Waters (CPRE) Roles & Responsibilities:
- Team Leader
- Hardware to Software connections
- Organizing meetings with Client

- Communicating with Mechanical Engineers
- Ordering components

Arik Rizhsky-Yakobson (CPRE) Roles & Responsibilities:
- Hardware to Software connections
- Laser control interface
- Laser specifications

Armand Hernandez (SE) Roles & Responsibilities:
- Interpreting given code from previous group
- Integrate .stl file to gcode (Using 3d model to be printed)

Jacob Gosse (EE) Roles & Responsibilities:
- Wire layout for Vacuum Chamber
- Sensor Wiring/Testing
- Component Research

Alvin Rymash (EE) Roles & Responsibilities:
- Wire layout for Vacuum Chamber
- Sensor Wiring/Testing
- Component Research

Our plan for working on this project was working in pairs for each part of the project. Working in pairs would help to reflect and generate ideas for a solution to a problem.

5.2 Project schedule

Tasks	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15	W16	W17	W18	W19	W20	W21	W22	W23	W24
Stepper Motor Research		█	█	█																				
Powder Application Research			█	█	█																			
Laser Mounting Research						█	█	█																
Understanding Previous Groups's Work	█	█	█	█	█																			
Testing Previous Group's Work					█	█	█	█																
Stepper Motor System Testing							█	█	█	█														
Powder Roller Testing									█	█	█	█												
Container Pressure Testing									█	█	█	█												
Container Argon/Nitrogen Testing										█	█	█	█	█										
Sensor Research							█	█	█	█														
Sensor Testing							█	█	█	█	█	█												
Saftey System Research							█	█	█	█														
Saftey System Testing										█	█	█	█	█										
Melt Testing																								
Code Research	█	█	█	█	█	█																		
Bug Testing						█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█
System tweaking and improvements									█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█
Software Implementation for CAD software									█	█	█	█	█	█	█	█								
Full Project Testing																				█	█	█	█	█

Figure 17 : PROPOSED Gantt Chart of Senior Design Fall and Spring Semesters

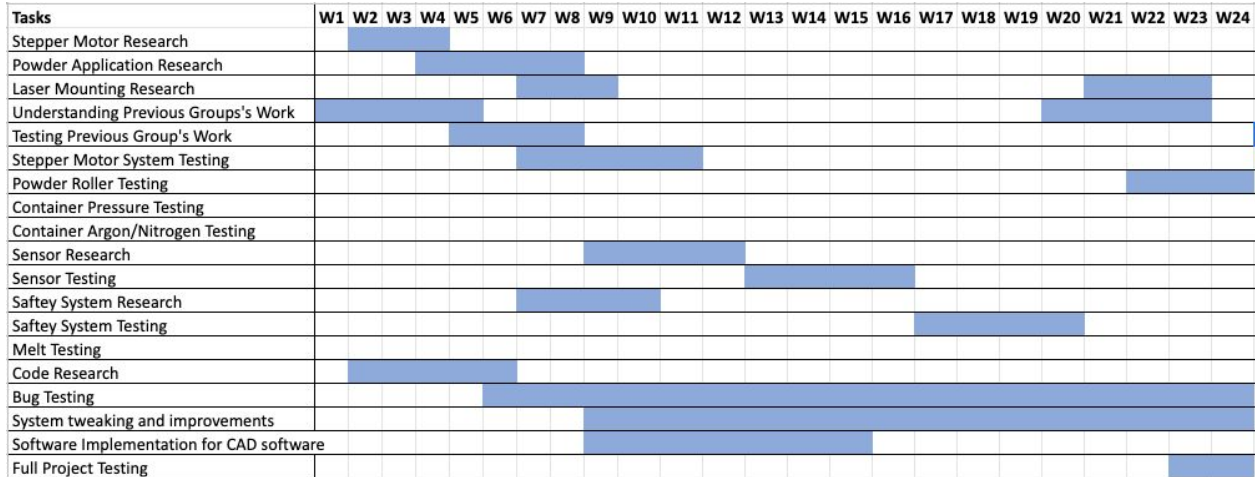| Tasks	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15	W16	W17	W18	W19	W20	W21	W22	W23	W24
Stepper Motor Research		█	█	█																				
Powder Application Research			█	█	█																			
Laser Mounting Research					█	█	█	█	█											█	█	█	█	
Understanding Previous Groups's Work	█	█	█	█	█															█	█	█	█	
Testing Previous Group's Work				█	█	█	█	█																█
Stepper Motor System Testing							█	█	█	█	█													
Powder Roller Testing																					█	█	█	█
Container Pressure Testing																								
Container Argon/Nitrogen Testing																								
Sensor Research								█	█	█	█	█												
Sensor Testing													█	█	█	█								
Saftey System Research							█	█	█															
Saftey System Testing																█	█	█	█					
Melt Testing																								
Code Research		█	█	█	█																			
Bug Testing					█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█
System tweaking and improvements								█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█
Software Implementation for CAD software								█	█	█	█	█	█	█	█									
Full Project Testing																						█	█	█

Figure 18: ACTUAL Gantt Chart of Senior Design Fall and Spring Semester

5.3 Risks and Mitigation

Looking at Figures 17 and 18, this semester's plans have changed dramatically. There were multiple issues that occured this semester. The first thing that affected this project that the project lost two mechanical engineers. This left the project with only one mechanical engineer left. The mechanical engineer had to complete the print bed, the roller, the powder collection bin, the vacuum sealed chamber, and the laser mounts. This slowed the project extremely, since there was less mechanical engineers to work on the components. It slowed us down, which required us to work on some of those components ourselves.

Another issue that came up was that there were some problems with putting the printer together. This would include parts from the print bed. After test fitting and measurements, we concluded that some parts had to be fixed to get the proper dimensions. This slowed us down again because we had to go to the HIVE or the Chemistry Machine shop to get the parts properly fixed. This took a few days get the parts completed.

The last major issue was that the 1064nm 200 W melt laser needed the proper power cable. The laser didn't came with a power cable. So, we had to create the power cable. This became a problem when we had to find the proper power cable that could handle the current and voltage to the laser. The current and voltage required was 20 Amps and 200-240 volts. This took some time to find the proper cable to order and then that cable had to be stripped to add the connector. This power cable requires a special plugin, which is not in the room for our project. This means that we had to move the printer to a different room to even test the guide laser, which is needed to test the laser alignment with the actual guidance laser.

5.4 Lessons Learned

Coordinating 5-6 seniors in engineering makes it very difficult to schedule group meetings. We found much more success with our group when we broke into two-person teams, with matching majors. This allowed us to focus on individual problems, and those that could meet would update the rest of the group.

We also found that more digital communication improved communication, as we could share information without having to physically attend meetings all the time.

We learned that initial projections and estimates change drastically when people who are thought to be able to work on the project suddenly leave (two of the three mechanical engineers working on the project left). We all have a better understanding of implementing features to a design, and how much work is required for each specification desired.

6 - Conclusion

6.1 Closing remarks for the project

The group from last year left us with a prototype that can take in some input and makes the motors draw a grid on a piece of paper as substitute for a laser. Although the project was already started in previous semesters and there was a good start on some of the beginning design, we still had quite a few challenges and decisions we needed to make in order to complete everything. Our main challenges during this semester was getting the program to interact correctly with a CAD file and to find a camera which is within our budget that will work under the high-pressure vacuum that we will create for the printer. We struggled to finish the vacuum chamber and having parts completed and then properly fitted. EH&S was another obstacle we had to deal with, as they required us to get approval from them before being able to use the more sensitive parts of our project such as the full-powered laser and vacuum chamber.

6.2 Future work

Our current goals for the future are to get the printer working as intended with the ability to create a metal cube and hopefully it will be able to read a CAD file and print the design based on the file given. The laser will need to be functional as well as the roller that will be used to lay down the metal powder. We also hope to implement sensors to ensure that the environment for the printer is safe. These sensors will run through an Arduino and send an alarm to the user's computer if there is any issue. These sensors will include temperature, pressure, and oxygen sensors. All the parts are already tested to make sure it will work under low pressure. Hopefully in the future, all the parts including the sensors will be placed in the vacuum chamber and run a sweep that prints a cube.

Another original plan of ours was to implement eddy current sensors to the metal printer. However due to time constraints, we were unable to get to that part. Therefore, a potential direction of this printer is the implementation of eddy current sensors, which is used to test for defects and is very high in accuracy.

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