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THESIS

EVALUATION OF A ROTATING PRINTER HEAD FOR ADDITIVE MANUFACTURING AT VARIABLE RESOLUTION

by

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June 2021

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Nozzle-based additive manufacturing (AM) methods typically require a trade-off between print resolution and mass deposition rates due to a set nozzle size. This requires longer build times for large, highly detailed parts and it would be beneficial to be able to change the resolution on the fly for naval applications. Having a print head that can print at both high resolution and high speed has the possibility to revolutionize the manufacturing industry in general.

The objective of this thesis is to test a new rotating printer head with a nozzle that has a slit opening in a fused filament fabrication 3D printer for in-situ adjustable print resolution. The quantification of the viability of the print head is accomplished through the 3D printing of parts with continuous rotation in which the printer is able to use a variety of nozzle diameters. Control parts will also then be designed and printed in order to compare both the resolution and print speed. Simple shapes printed with the system show that the resolution can be varied between the two slit dimensions and the gaps between printed tracks is reduced compared to other methods, improving part strength. The results show that it is practical to fabricate large but complex and detailed parts using this approach, as opposed to commercial systems that are limited between balancing resolution and speed.

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EVALUATION OF A ROTATING PRINTER HEAD FOR ADDITIVE MANUFACTURING AT VARIABLE RESOLUTION

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Nozzle-based additive manufacturing (AM) methods typically require a trade-off between print resolution and mass deposition rates due to a set nozzle size. This requires longer build times for large, highly detailed parts and it would be beneficial to be able to change the resolution on the fly for naval applications. Having a print head that can print at both high resolution and high speed has the possibility to revolutionize the manufacturing industry in general.

The objective of this thesis is to test a new rotating printer head with a nozzle that has a slit opening in a fused filament fabrication 3D printer for in-situ adjustable print resolution. The quantification of the viability of the print head is accomplished through the 3D printing of parts with continuous rotation in which the printer is able to use a variety of nozzle diameters. Control parts will also then be designed and printed in order to compare both the resolution and print speed. Simple shapes printed with the system show that the resolution can be varied between the two slit dimensions and the gaps between printed tracks is reduced compared to other methods, improving part strength. The results show that it is practical to fabricate large but complex and detailed parts using this approach, as opposed to commercial systems that are limited between balancing resolution and speed.

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I. INTRODUCTION

A. MOTIVATION

Additive manufacturing has been proven as a reliable way to rapidly produce prototypes and one-of-a-kind parts cost effectively. The reason it is still not widely used is due to the two problems this thesis hopes to address; the print speed of a high resolution (quality) part is extremely slow and the resolution of a high-speed part is too low. This is especially true when using Fused Filament deposition (FFF) printers. Having a FFF printer that is capable of high speed and high resolution prints would allow both manufacturers and AM enthusiasts to complete more high quality and high speed prints, thus reducing costs and time. An example of this can be seen in Figure 1, it shows that AM has the ability to cost effectively product highly complex parts. It also shows that there is a range of complexity that conventional manufacturing cannot obtain that is obtainable by AM. By implementing a high resolution and speed printer the breakeven point would be shifted to the left, thus allowing more space for additive manufacturing in traditionally conventional manufacturing areas.

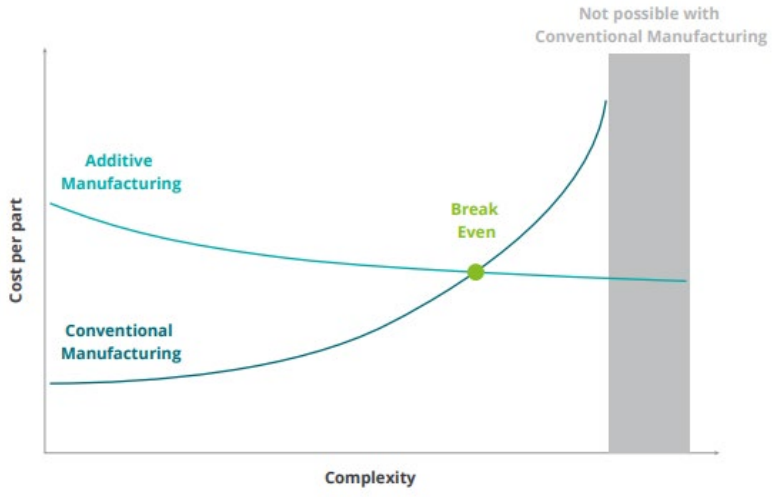

Figure 1. Price per part comparison of AM versus conventional manufacturing. Source: [1].

Developing and testing a high speed and resolution printer will allow researchers and designers to expand upon the idea and create even more improvements. An extremely efficient time and material saving method to accomplish this type of printer is a rotating print head with a slit nozzle opening. A rotating print head would have a slit that the filament is deposited through, and as the print head rotates the slit would get larger or smaller depending on the direction of rotation. The small diameter is used when a high resolution section is needed while the large diameter is used in high speed infill. This method cuts back on both time and material waste compared to other proposed improvements. It also allows users greater flexibility in diameters since there is a range of diameters that can be chosen between the large and the small slit dimensions.

B. OBJECTIVES

The primary objective of this thesis is to implement and test the rotating print head and prove that it is an effective replacement for a conventional print head. To achieve this, a series of prints need to be completed that show that the print head can function as intended. The first test will be to print a straight line where the diameter is constantly changing. Completion of this test showcases that the printer functions as intended and the next test can be implemented. Next, a part with a high resolution exterior will be printed with the infill using a large size. This tests demonstrates that the printer is capable of a printing practical parts as well and has real world applications. Lastly, a speed and quality test will be completed in which an unmodified version of the printer will print the same part as the rotating head printer. The print times will be compared, as well as the quality of the parts.

II. BACKGROUND

A. ADDITIVE MANUFACTURING OVERVIEW

There are seven primary methods in which parts can be additively manufactured, binder jetting, directed energy deposition, powder bed fusion, sheet lamination, material extrusion, material jetting, and vat photo polymerization [2]. While all these methods are available to the public, only two of the methods are common to everyday consumers, which are material extrusion and vat photo polymerization. The specific methods of fused filament fabrication (FFF) and stereolithography (SLA) are the most available to everyone [3]. FFF is the process of feeding a plastic material through a heated nozzle and depositing it onto a print surface, a diagram depicting this can be seen in Figure 2. SLA is the process of using an ultraviolet (UV) laser to cure liquid photopolymer resins into a solid plastic, a diagram depicting this can be seen in Figure 3. Due to the liquid nature of the resin, SLA parts have to undergo post processing to clean and cure the parts.

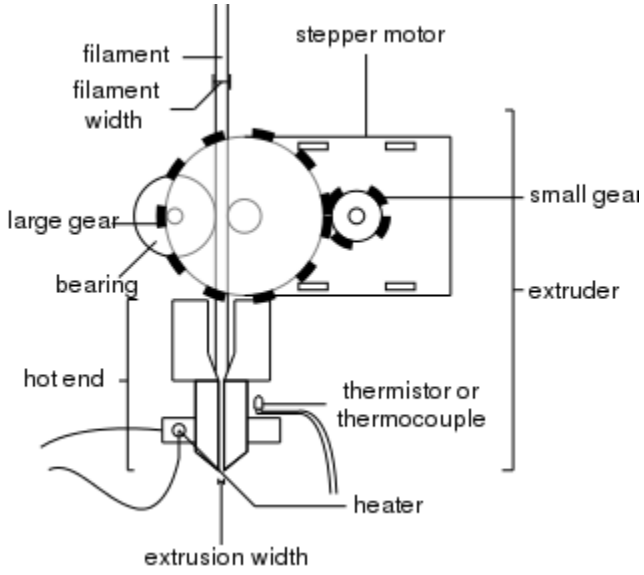

Figure 2. Schematic of FFF function. Source: [4].

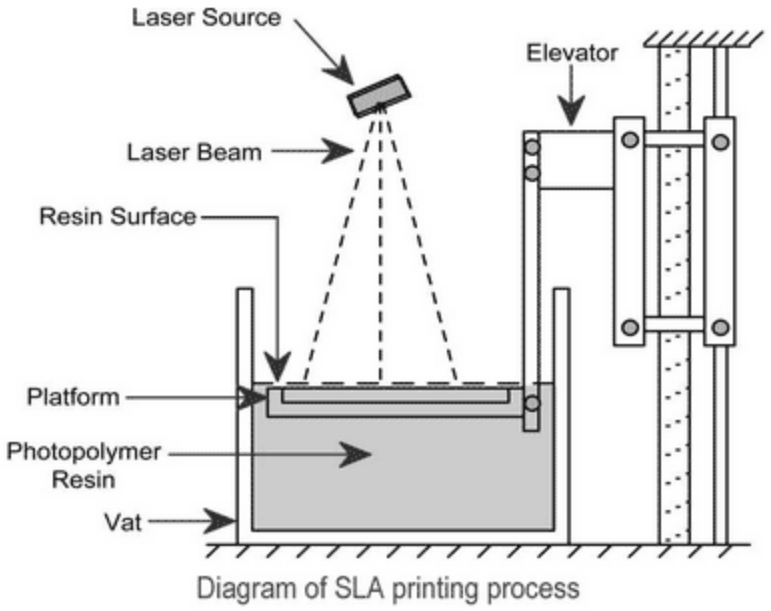

Figure 3. Schematic depicting SLA process. Source: [5].

SLA has become readily available for home use with printers costing only a few hundred dollars, which rivals the price of recreational FFF printers. An example of one of these can be seen in Figure 4, it is the Creality LCD 3D Printer LD-002R and costs a few hundred dollars. SLA printers being available to consumers offers them the advantages of SLA which include high resolution parts, relatively quick print times, and sizeable build volumes. There are a variety of SLA resins that exist with each having distinct uses. High temperature resins, flexible resins, and tough resins are resins available from FormLabs, which all with unique properties and different applications [6]. Each one of these materials corresponds to specific printer settings that are automatically programed. This automatic program combined with the set wattage of the laser allow for extremely little user input into the print parameters which is a disadvantage of SLA. While there are a few different materials to print with using stereolithography there is not a large selection of materials that are curable using a UV laser. This lack of materials is one of the biggest disadvantages of SLA and is the reason it is not used as widely as FFF.

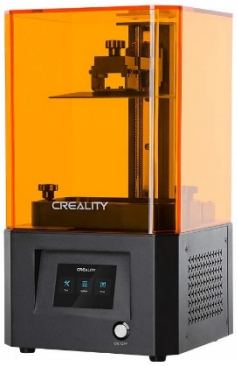

Figure 4. Desktop SLA printer. Source: [7].

FFF is different from SLA in that it is not limited to one class of materials and that the printers have more modifications that can be done with them. FFF and material extrusion in general have the ability to print much more than the commonly used thermoplastics, such as composites, metals, and even concrete [8], [9]. The large material selection of FFF is one of the main reasons that it has become increasingly popular to both independent users and large corporations. An example of a common desktop printer can be seen in Figure 5, it is another printer by Creality and is the Ender-3 Pro. Throughout all of the materials used in FFF there exists given parameters that are recommended by the manufacturer, which is similar to SLA. However, unlike SLA these settings can be modified to a much larger degree to affect many print parameters. Temperature settings on the build plate can be raised to increase the effectiveness of the part staying attached to the build plate. While the nozzle temperature can be adjusted to allow for more favorable cooling properties depending on the ambient temperature.

Figure 5. Desktop FFF printer. Source: [10].

FFF also has another huge advantage over SLA in the fact that the printers can have dual extruders. Dual extruders offer many advantages, with the most versatile and widely used one being the ability to print with multiple materials [11]. Users generally use the second material as a support material that helps print parts with overhangs or complex features, this material is also easier to remove than the filament used for the part. An example of a dual extruder with an overhang and support material can be seen in Figure 6. Dual extruders also have the option of being able to load different color materials, which has made them popular among hobbyists. The biggest advantage that dual extrusion printing offers in regards to print time is the ability to have two independent extruders that can print simultaneously using a mirror print. An example of a mirror print can be seen in Figure 7, it is from a Bolt Pro printer from LeapFrog. This function is limited, however due to the fact that the independent extruders can only print mirror parts, meaning both nozzles cannot work on the same part at the same time. Dual independent extruders only increase the print time of parts when printing mirror parts or printing with two different materials on one part.

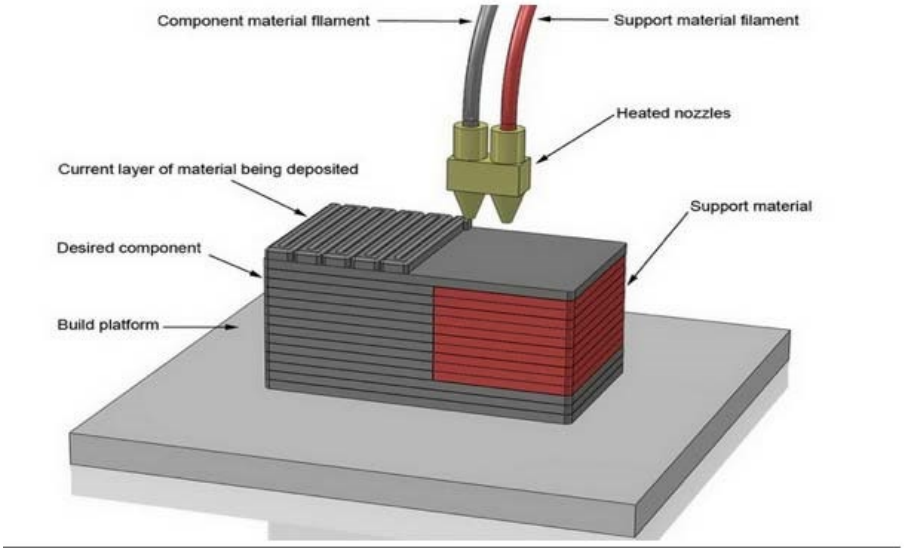

Figure 6. Dual extruder with different filaments. Source: [11].

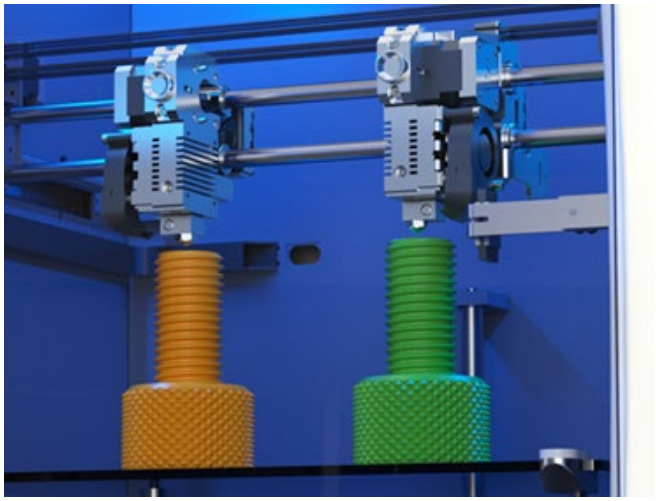

Figure 7. Mirror print example. Source: [12].

FFF also a few significant draw backs that limit its potential, the most severe is the inverse relationship between print speed and print resolution. As briefly mentioned in the introduction, FFF suffers greatly in the fact that it is impossible to have a high quality print that is also printed extremely quickly [1]. Mainly, this is because printers have a single nozzle diameter which drastically limits both the speed and resolution changes that are available to users. For example, a printer with a 1 mm diameter will be able to print much quicker than one with a 0.4 mm diameter due to the increased in fill rate. However, that

print will have a much lower resolution due to the difference in layer height and gaps between lines used in the larger diameter nozzle. For example, if a 100mm x 100mm x 100mm cube was printed using the same filament deposition rate of 3600 mm/min, a 100% infill rate, a layer width equal to the height plus the diameter, and a layer height of half the diameter. Printing the cube with the small diameter would take approximately 2315 minutes, while with the large diameter it would take approximately 370 minutes. The following equation shows how it was calculated, T is the total print time in minutes, A is the surface area of one layer, W is the width of each line, V is the filament deposition rate, H is the total height, and L is the layer Height.

$$T = \frac{(A/W)}{V} * \frac{H}{L}$$

The difference in print times between the two diameters is drastic, especially considering it is an ideal case and does not take into account the time required for pauses during printing. While the print speed of the 0.4 mm nozzle is increasable by raising the filament feed rate, there is a limitation to this due to material flow characteristics, and this also lowers the resolution and part quality of that piece. This back and forth between the two is the biggest limitation of FFF and if a printer was able to print at both a high speed and have high resolution it would revolutionize the market.

B. GCODE EXPLANATION

When using an AM printer, the G-code is extremely important to how the part will both print and function. After designing or scanning a part, users convert the three-dimensional model to a file type readable by the printer software, most commonly an STL file. These files are then uploaded into slicing software that then makes the STL readable to the printer through dividing up the parts into layers and outputs a G-code. Most slicers will add their own unique code at the start and finish of a code that is specific to the printer selected. G-codes are a series of commands given to the printer and as mentioned previously are typically generated using a slicing program but can also be written by hand. There are many variants of G-code that are available for slicing programs to use, this thesis uses the RepRap variant that is used in the Cura slicing program.

RepRap G-code has hundreds of commands that can be given to the printer, all of which are assigned a letter and number and are in the format of Gnnn, Mnnn, Ennn, etc. [13]. This form is set up in the letter then number format because the letters correspond to different categories of commands, such as M being RepRap defined commands and F being the rate at which filament is fed into the extruder. The letters then correspond to a specific command or rate for that command such as G28 telling the nozzle to return to home and M400 adding a pause into the print until all current moves are completed. A standard G-code is made up of thousands of lines of code with some lines contained only a single command with others containing a few commands that combine in order to complete one action. An example of a combination of code can be seen in Figure 8, the G1 corresponds to a movement, the X and Y are absolute positions of the nozzle, and E is the amount of filament that is going to be extruded.

```
G1 X-56.00 Y0.00 E0.316
```

Figure 8. Generic G-code example

C. VARIABLE NOZZLE PRINTING

There currently exists no printer in production that has the ability to print with a variable nozzle extruder, although there has been a theorized designs. One proposed design has an inner nozzle that sits inside of a larger exterior nozzle [14]. When the inner nozzle is lowered the printer prints with its small diameter size, when raised it prints with the larger exterior nozzle. The theorized design for this variable nozzle printer can be seen in Figure 9 and shows the printer in both the raised and lower position.

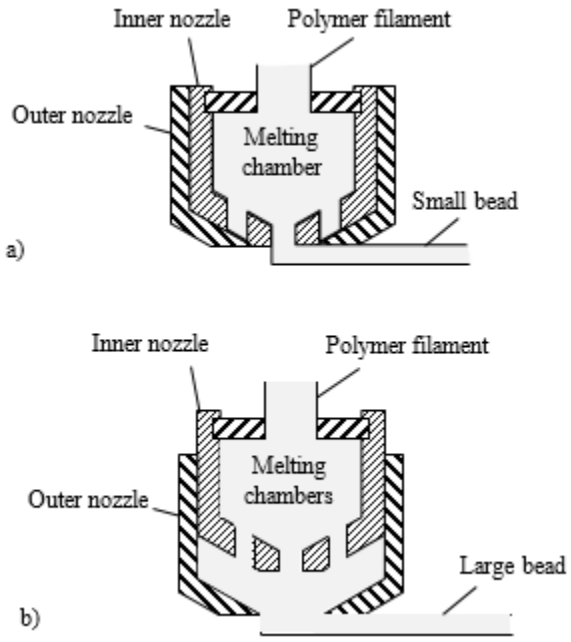

Figure 9. Theorized variable nozzle print head. Source: [14].

Designers of this method did a sample print with an inner diameter of 0.5 mm and an outer dimeter of 1 mm. Print times of the variable nozzle printer in two orientations were then compared to prints with only the interior or exterior diameter. The comparison of times can be seen in Figure 10 and it shows that the print times of the variable nozzle are approximately the same time as the large diameter. Line A represents the small diameter, line B and C represent the variable nozzle in two different print orientations, and line D represents the large diameter. While this finding is incredible it does not take into account the time it would take the printer to fill the melting chamber when switching from the small to large nozzle. It also does not account the time required to move back and forth from a set dispensing area to deposit the extra filament when switching from the large to the small diameter.

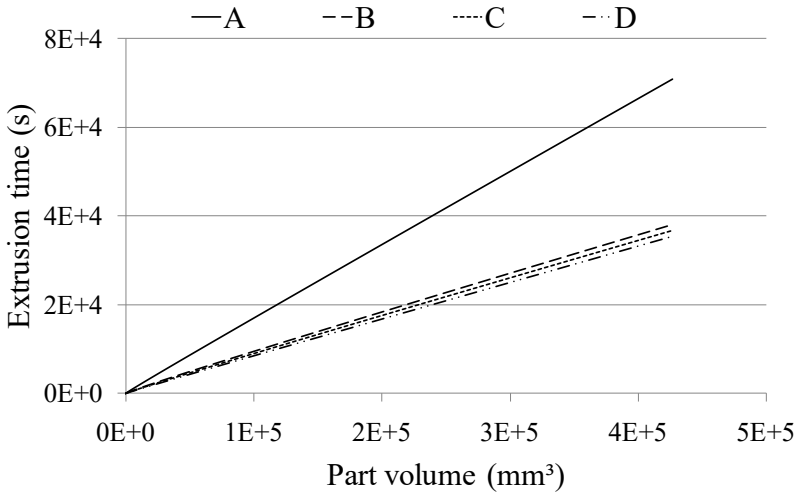

Figure 10. Theoretical comparison of print times. Source: [14].

Having the same print times as a large diameter nozzle while allowing the exterior to have the increased resolution of a small diameter could have drastic effects on how FFF is perceived and used in the workspace. This increase in effectiveness could be multiplied greatly if the printer had a continuum of diameters available instead of only two. Having this continuum would allow users to select the resolution needed while maximizing print speed. This means if the user did not need the resolution of the smallest diameter they could select an intermediate diameter and have an even larger increased print time. While according to Figure 10 this would not have a sizeable increase on print time that is not entirely accurate due the increased time to switch between diameters in variable diameter method [14]. A design with a continuum of diameters could be implemented many different ways with each having their own distinct set of advantages and disadvantages.

D. CURRENT PRINTER METHOD

For this project the type of variable diameter used will be one that changes effective nozzle diameter with the rotation of the print head in relation to its motion. The printer functions similarly to a calligraphy pen or a highlighter, in that when it rotates to zero degrees to the direction of motion, it will print with the largest diameter and when rotated to plus/minus ninety degrees it prints with the smallest diameter. Using this method for a variable diameter printer offers the advantage of being able to choose any diameter size

between the large and small diameter. Since the printer can rotate to both positive and negative ninety degrees it furthers cuts down print times versus a printer than can only move from zero to ninety degrees. Another key advantage of this method is that it cuts down excess waste in movement compared to the method described previously. Since the filament feed rate can be adjusted to account for the different diameters there does not need to be a delay in printing to fill the melting chamber or move to deposit excess filament. Currently the G-code to rotate the print head as well as changing the filament feed rate for the varying diameters has to be written manually. With the further development of this method an automated G-code written would most likely be developed to decrease user coding times.

III. DESIGN AND DEVELOPMENT OF EXPERIMENT

A. PRINTER SET UP

When selecting a printer for this thesis, a dual extruder was used for the ability to disassemble the printer and combine the extruders together. The extruders were combined so that one will have the primary function of rotating the print head to change the diameter and the other's primary function will be to extrude the filament. The stock Qidi Tech X-Pro printer used can be seen in Figure 11, most of the printer is unmodified, with only the extruders seeing a major modification.

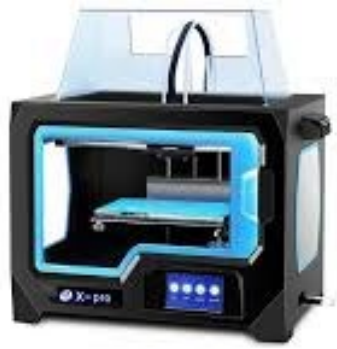

Figure 11. Stock Qidi Tech X-pro. Source: [15].

Figures 12–15 depict a three dimensional model of the modified nozzle and print head. They show that as the print head rotates the effective diameter of the print head increases or decreases depending on the direction of rotation. Figure 12 depicts the print head printing with the largest diameter orientation, with filament having been deposited behind. Figure 13 shows the nozzle opening in the largest diameter orientation, while Figure 14 shows the nozzle opening in the smallest dimeter orientation. Figure 15 show the smallest diameter orientation printing, a drastic change can be seen between the filament width in Figure 12 and Figure 15. More pictures of the schematics from different angles can be seen in the Appendix A.

The print head is rotated by a screw-like mechanism, this rotation is controlled using an Ennn command, as discussed earlier. Instead of specifying the amount of extrusion for that nozzle, the number corresponds to the degree of rotation. Each 0.093 following the E corresponds to one degree of rotation for the print head.

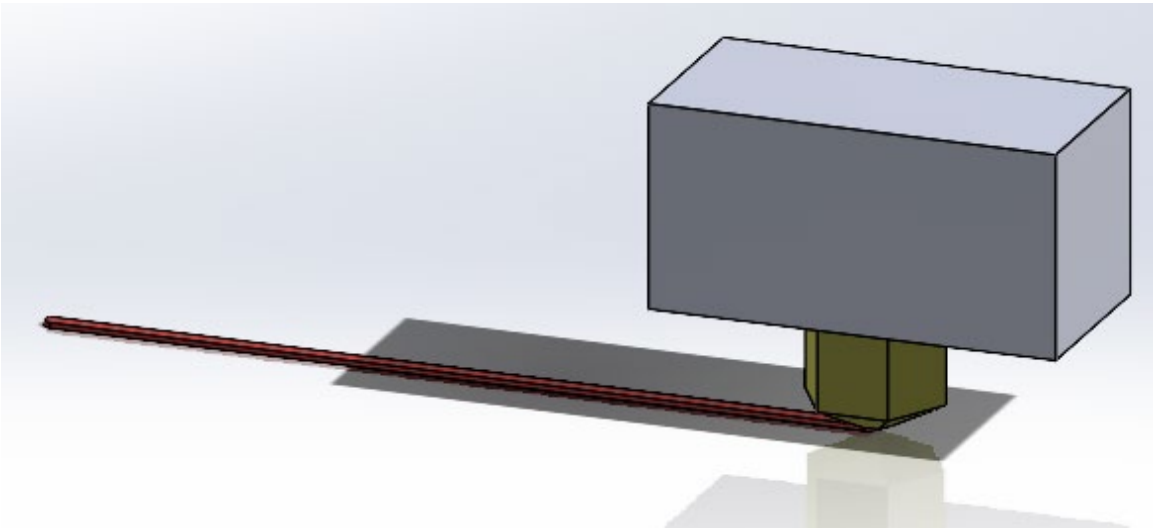

Figure 12. Nozzle printing in largest diameter orientation

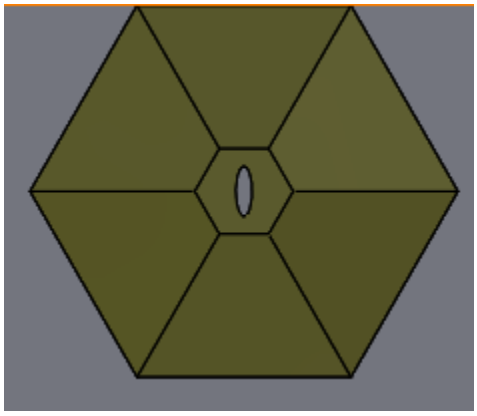

Figure 13. Nozzle opening of largest diameter orientation

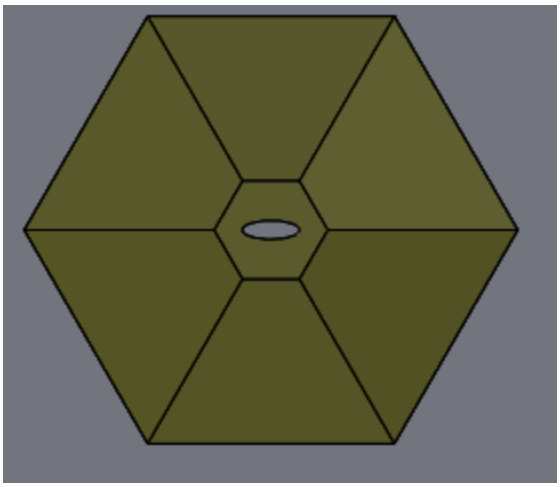

Figure 14. Nozzle opening of smallest diameter opening

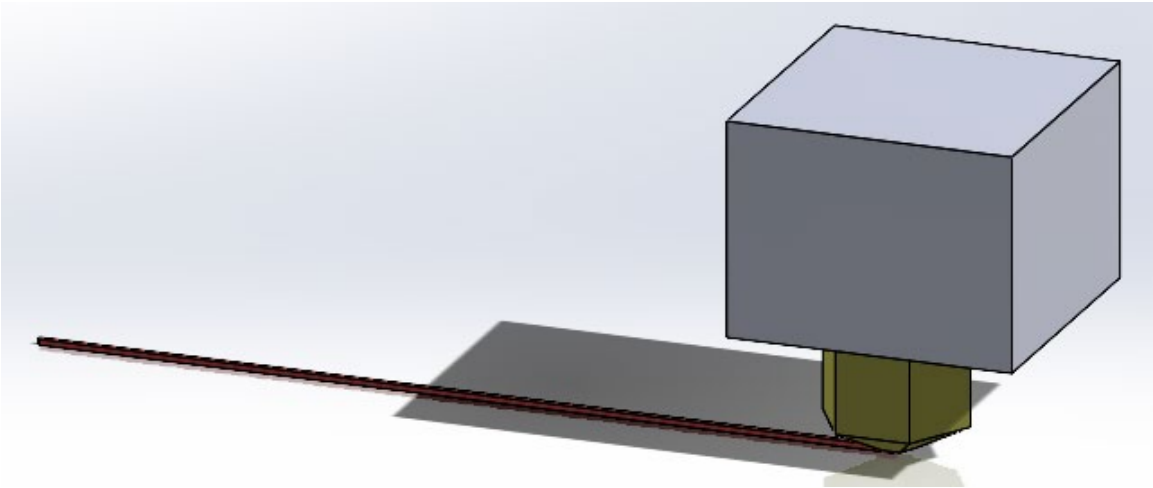

Figure 15. Nozzle printing in smallest diameter orientation

Figure 12 and Figure 15 are models designed in SolidWorks that are similar but are modified compared to the modified print head seen in Figure 16. In this figure, A corresponds to the filament feeding device with the filament to the left of the letter, B is the extruder that the filament is being fed into. C is where the heating wires are connected to the thermocouple, determining if the nozzle temperature needs to be raised or lowered. D is the heating box of the rotational print head, the heating box is a rectangular prism and is connected to the extruder by a screw-like mechanism. The heating shape box differs from the two SolidWorks models seen in Figures 12 and 15. The reason for these two

different shapes is that part of the heating element was cut off to better show the deposited filament and the different width of the printed filament. Also, the models do not include everything that is above the heating element in the extruder. The schematics also do not include the wires, filament, and other things attached or feeding into the extruder.

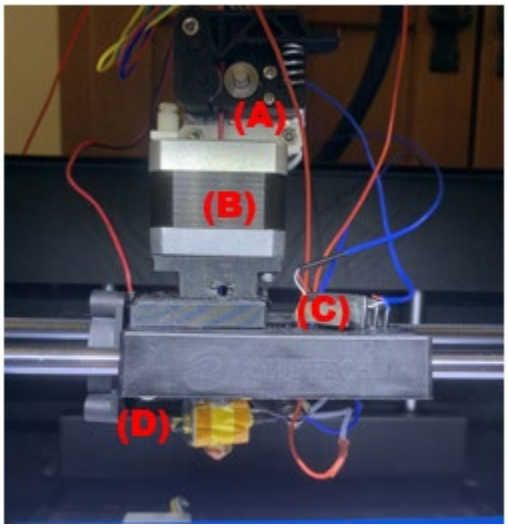

Figure 16. Modified print head

The modified print head looks extremely different than the un-modified version seen in Figure 17. There are a few key differences between the two, the most obvious being the absence of the second extruder in the modified version. This is because the second extruder is not needed for the rotational print head, besides the printer recognized a second extruder in the G-code. A second extruder in the G-code is what is used to rotate the print head. Another key difference is that the heating box (D), was lowered and attached to the extruder with a screw-like mechanism. The reason for the lowering of the heating box is to allow there to be less obstacles when the print head is rotating. The last major difference seen is the abundance of wires in the modified print head, this is because this print head is a prototype and the wires needed to be connected in a not typical manner. Further iterations of the print head can have these wires reconnected with the rest as seen in on top of the fans in Figure 17.

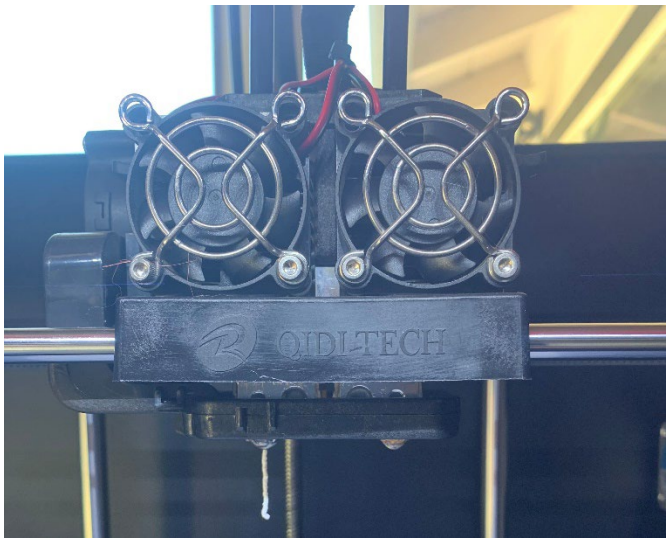

Figure 17. Un-modified print head

B. CODE DEVELOPMENT

1. Straight Line Code Development

As stated earlier, G-Code is the primary way that the computer communicates with the printer and for every print a new code must be developed. For this project the code was handwritten for the straight-line print and a highly modified version of the automated code for the cylinder. When developing the straight line code the start and end script used by Cura for the X-pro were transferred into a word document as a base for the code. Next the command to rotate the print head to positive 90°, which corresponds to the smallest diameter. After rotating code for a purge line was added, which is used to clear out old filament of the extruder so that the filament being used for the print is fresh. After completion of the purge line code is added to move the printer to the starting position, which is at the left center edge of the build plate. With the print head still at 90° the print begins by moving horizontally, the print head is rotated slightly with each small movement. A section of code can be seen in Figure 18 which shows the horizontal movement and rotation of the print head, the entire code can be found in the Appendix B.

```
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-10.00 Y0.00 E0.5
M108 T1
```

Figure 18. G-code from straight-line print

M108 T1 in the first line corresponds to the commands for canceling heating for this layer (M108) and switch to the extruder corresponding to the rotational print head (T1). In line two M400 is a pause command that tells the printer to wait for the current moves to finish before continuing. G1 corresponds to a linear movement but when used on T1 it tells the printer that a rotation is occurring. So in line three E-0.300 tells the printer to rotate the head approximately negative 3.2°, and F2700 tells the printer at what speed to rotate. The M108 T0 in line 4 corresponds to another cancel heat command but then switches the new command to the print head corresponding to filament deposition (T0). The next two lines then correspond to the speed the head is moving and the new position it is moving to. E0.5 in this case corresponds to the amount of filament being fed through the nozzle and not the angle of rotation.

Throughout the code development process a few commands were instrumental in the success of the code running as designed. The two most important commands are the ones both associated with E for each extruder. When using extruder T0 the E command plays a huge role because it controls the filament extrusion amount. This command was the most changed in the development of this code, because over/under extruding can falsely display the thickness of the part. Since the print head was rotated from small to large and back to small, the amount of filament extruded has to be changed every rotation. Determining how much filament to extrude was determined through trial and error due to the amount extruded being variable by up to a micron. Based off of previous codes from a nozzle with a similar diameter a starting extrusion amount was selected. From this the amount of filament for the subsequent rotation is determined by using the equation below. E_0 correlates to the millimeters of filament being extruded, x corresponds to the distance

the print head is moving, and E_1 corresponds to the current absolute rotational position of the print head.

$$E_0 = 0.2875x - 0.1x * (\frac{[E_1]}{8.2})$$

This formula is only applicable to the desired line width for the straight line print, however it is a good starting place for codes that utilize different widths.

2. Continuous Curve Code Development

Upon the successful completion of the straight line print a part that implemented the rotational print head while turning and maintaining a constant diameter needed to be developed and printed. To develop the code for this turn the straight line code was used as a basis and was modified in order to add a reverse S-shaped curve to it in order to lower the position on the Y-axis. The major challenge in this code is that as the print head moves in a direction different than in the lateral-x direction the slit will print at a different diameter, thus the print head needs to be rotated in order to keep the diameter constant. To accomplish this a gradual rotation had to be added that was proportional to the direction change. To simplify the process the curve was broken down into small straight line segments, of which there were four angles. The four angles are -26.56°, -45°, -63.43°, and -90°, the starting orientation is the print head rotated to +90°.

From this starting point a straight line is printed for a few centimeters until the curve is started. Upon the start of the curve the print head is rotated to the new angle with an E-2.00 command, this small segment is then printed at this angle. This process is repeated for each segment with the print head rotating relative to the starting angle of the head by the angle that the segment is being printed at. Since the print head is rotating at the angle the segment is being printed at it will maintain a constant diameter throughout the curve. After the head has rotated -90° the segments are printed in reverse in order to complete the curve, this makes the curve symmetrical and gives it the reverse-S shape. Another straight-line segment is then printed and then the part is complete. The complete code for the continuous curve code is found in Appendix C.

3. Test Part Development

To print a more practical part, one has to be designed that has a high resolution exterior and the ability to have the interior be printed at a high speed. To satisfy these requirements a small cylindrical part was designed in which the exterior uses the smallest possible exterior nozzle diameter and the interior uses the largest. To write this code the model is opened with Cura to develop a base code that can then be then be modified to account for the rotation of the print head. This default code is used both as a time saving step as well as for the implementation of a raft, which will help the part better adhere to the build plate Due to the small size of the cylinder the circular part of the cylinder is actually printed with 24 straight lines, with each line being a few millimeters long. Since each of these lines is printed in a slightly different direction the print head will have to be rotated to a different degree to account for the rotation of the extruder. This constant rotation can be seen n Figure 19, the E commands under the T1 extruder show that after every movement the head is rotated. To complete the high resolution exterior two full rotations are printed in order to further strengthen the exterior with the high resolution printing.

```
M108 T1
M400
G1 E-11.707 F2700
M108 T0
G1 F900
G1 X-9.416 Y-2.523 F900
M108 T1
M400
G1 E-3.412 F2700
M108 T0
G1 F900
G1 X-8.442 Y-4.874 E0.1058 F900
M108 T1
M400
G1 E1.439 F2700
M108 T0
G1 F900
G1 X-6.893 Y-6.893 E0.1058
```

Figure 19. Cylindrical part G-code example

After the completion of the exterior the interior is printed, it is accomplished by printing wide straight sections with the ends of each section being connected with a small straight line. Upon completion of the infill, the entire process is repeated for each layer, until the print is completed. Each layer uses the same starting point with is at the upper y-axis limit of the part, this is also where the layer is finished. Unlike the exterior, the interior does not need multiple passes at each location. This is due to the large diameter filling in the available space in one pass through of each location. While this would also normally happen using a high resolution nozzle size, it would require a significant increase in the number of passes, thus drastically increasing the print time. Typically the interior resolution does not greatly contribute to the strength of the part, this will be discussed further in the Future Work Section.

C. PRINT PROCEDURE

The procedure to print a part successfully is not a difficult one, but when done incorrectly it can add unnecessary waiting or even cause a catastrophic failure of the part. To begin the process the .STL file containing the modified code is uploaded to the printer using either a USB storage device or a wired connection directly to the printer. After the .STL file is uploaded the print bed and extruder should be preheated. The bed should be preheated to approximately 50°C and the extruder should be heated to 210°C. While the bed and extruder are being heated the print bed needs to be manually raised to the correct position.

Manual raising is required due to the modified extruder being taller than the normal extruder. If the bed was not manually raised it would be pressed against the extruder during the entire print process, thus not allowing it to deposit any filament and cause a jam in the extruder. After the bed is manually raised the print bed and extruder should be heated up enough to begin the print. Careful attention must be given during the entire print process because if the print were to fail the user would want to end the print as quickly as possible.

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IV. RESULTS

A. PROOF OF CONCEPT RESULTS

Determining the success of the proof of concept is best accomplished through the comparison of lines printed at a constant diameter with one printed using a constantly changing diameter. This was executed with a series of straight line prints in which the top line was printed using a constantly rotating print head and the bottom line was printed using a single diameter. Examples of these prints can be seen in Figures 20 and 21 where the constant diameter is in Figure 20 and to the left of the changing diameter in Figure 21. As seen by the printed lines, the printer can produce parts that have a continuously changing width. It also does not need to add a pause when the print head is rotated to a new diameter. Both of these steps are crucial because they allow for variable diameter printing and also decrease the total print time, as discussed in the background chapter. The success of these prints proved the viability of the print head in simple measures and allowed more complex parts to be designed and printed.

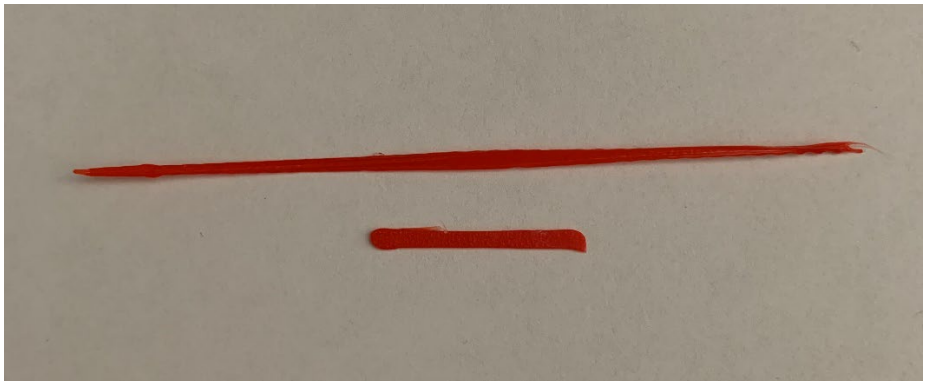

Figure 20. Continuous changing diameter over constant diameter line

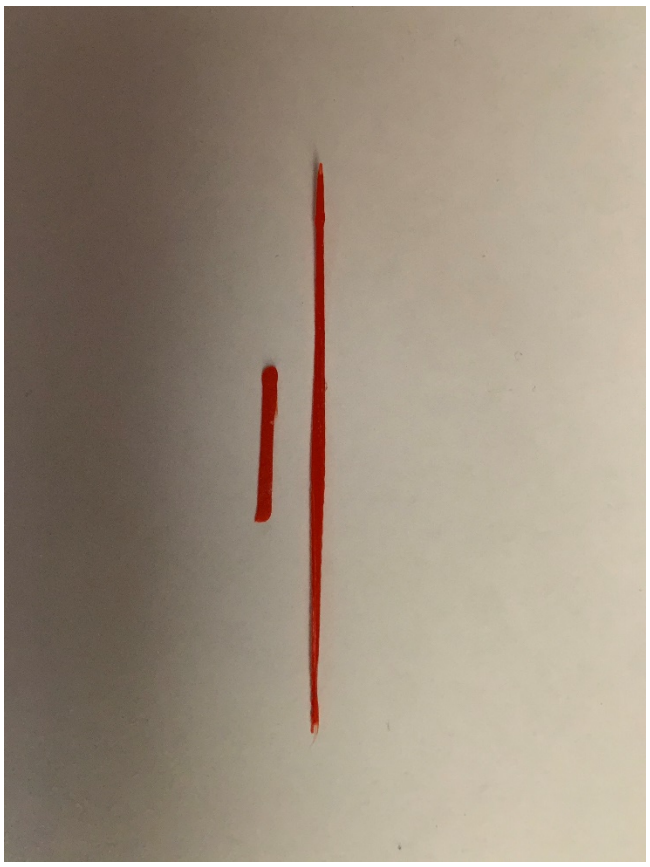

Figure 21. Constantly changing diameter side-by-side with constant diameter

When shown independently and with a closer view it can clearly be seen that the diameter is constantly changing and the print was a success. Examples of the continuously shifting diameter print by itself can be seen in Figures 22 and 23. These figures solidify that the printer functions as intended and that further tests can be complete.

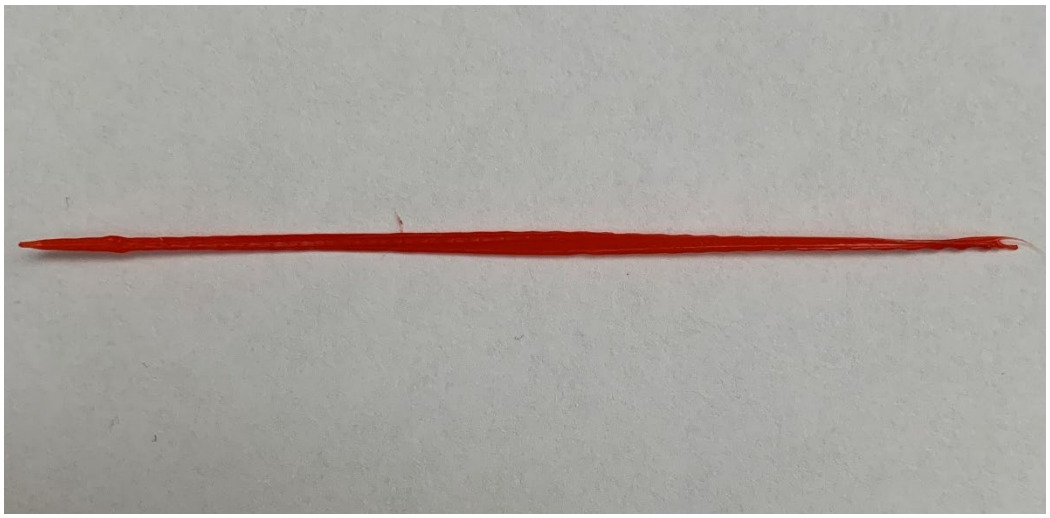

Figure 22. Continuously changing diameter part (Landscape)

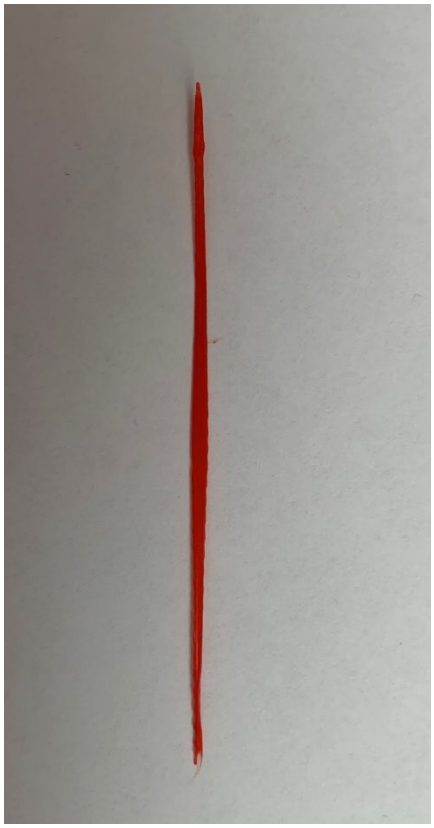

Figure 23. Continuously changing diameter part (Portrait)

B. CONTINUOUS CURVE PRINT

The continuous curve print functions as a stepping stone into printing a practical part. Successfully printing the straight line part proved that the printer does not need to pause in order to change diameters and this print proves that it does not need to pause in order to change directions and diameters simultaneously. As mentioned in the Design and Development chapter, this print has two straight line sections that are connected by a reverse S-shaped curve. The part is designed with a constant diameter which requires that any time there is a change in direction the print head must be rotated accordingly. Figures 24 and 25 show the successfully printed part.

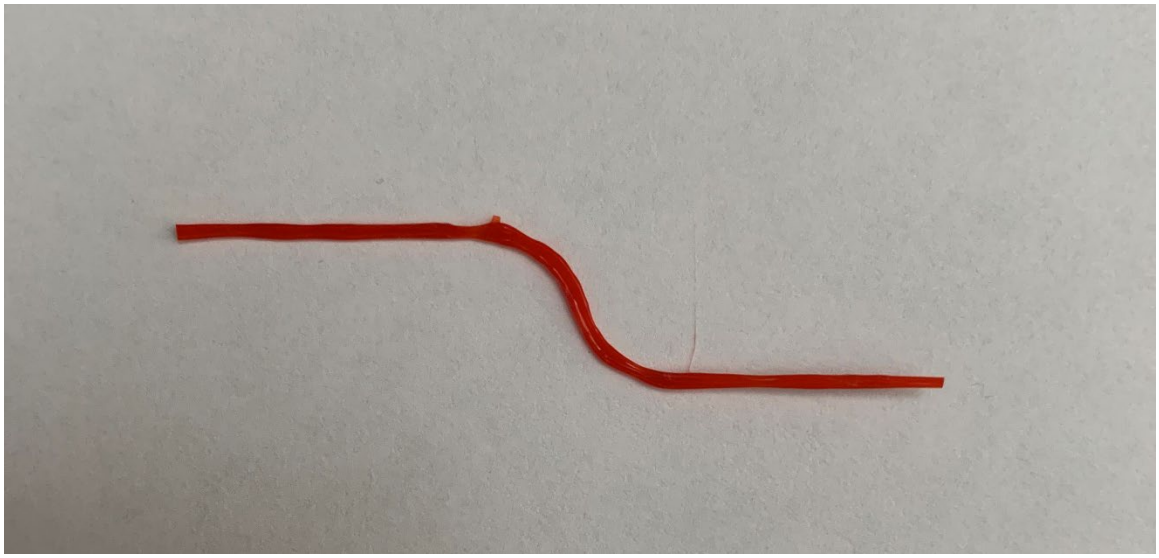

Figure 24. Constant diameter curve (Landscape)

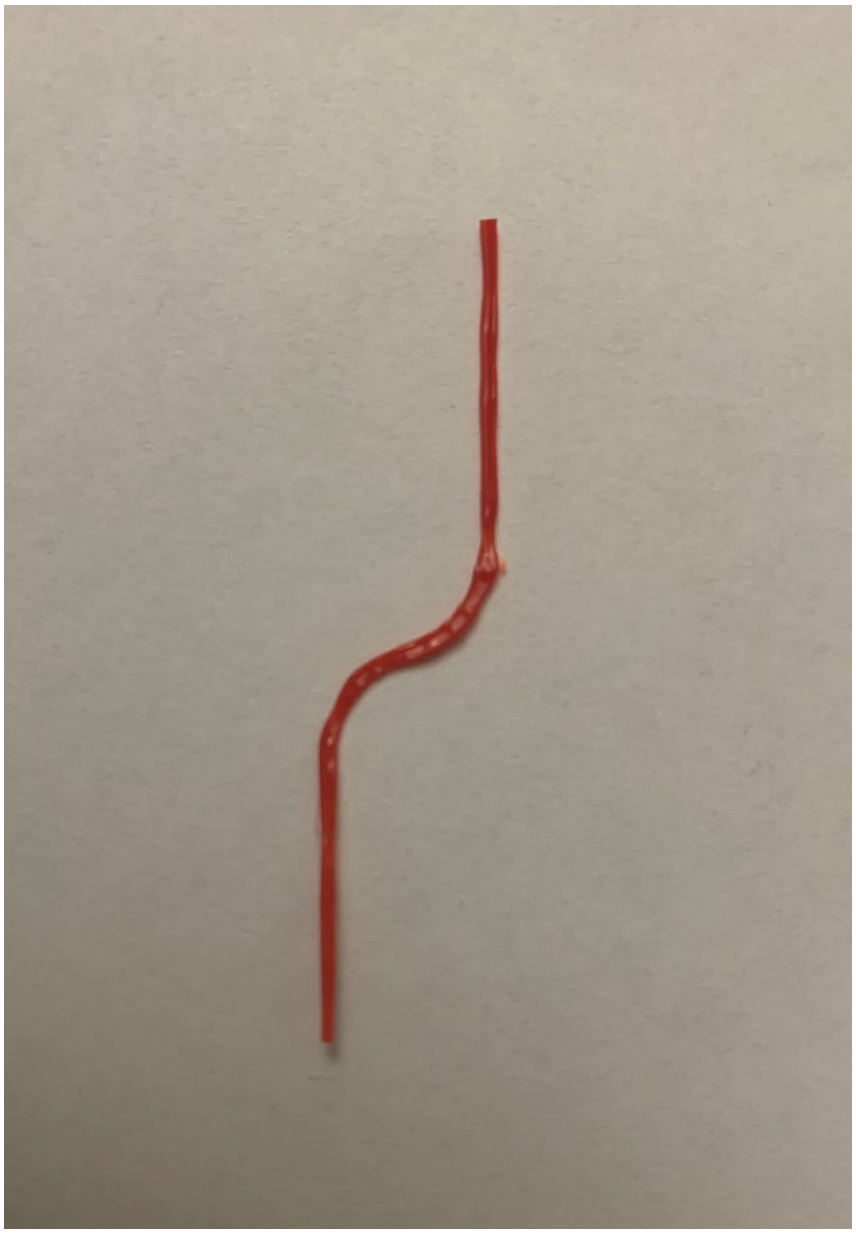

Figure 25. Constant diameter curve (Portrait)

C. CYLINDRICAL PRINT

The success of the cylindrical part is determined by the print resolution, print speed, and effectiveness of the rotational print head on a practical part. A high quality exterior and high print speed show that the printer has accomplished its design purpose. Accomplishing these two feats is an enormous step in the development process and will also for more practical and useable prints to be designed and tested. Printing of the high

speed and high quality part was executed as designed and an example of the part can be seen in Figure 26.

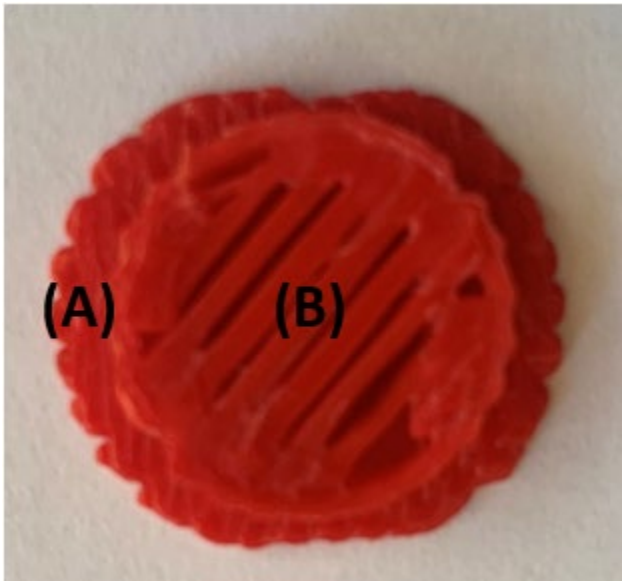

Figure 26. Top view of cylindrical part (B) printed on a raft (A)

As seen in Figure 26 the width of the exterior using the small diameter is smaller than the large diameter print width of the interior even though two complete revolutions were completed using the small diameter. The raft that the cylinder is printed on can be seen in Figure 26 (A) under and on the outside of the cylinder, it is used to help adhere the cylindrical part (B) to the build plate. The drastic difference between the two diameters showcases the range of possibilities for the rotational print head. As can be seen by the constant width of the exterior it can be seen that as the print head rotates it is able to maintain a constant diameter. This is crucial because if this was not possible then the printer would not be functional, but since it is able to hold a constant diameter the print is considered a success. Also seen in Figure 26 is the less than 100% infill percentage, it should be noted that this is related to the slicing settings and not a result of printer error.

V. CONCLUSION

A. SUMMARY

The goal for this thesis was to design, print, and evaluate test parts for a new rotational print head printer and evaluate its effectiveness as an AM printer. These parts were printed successfully and show that the rotational print head is both viable and an improvement upon current print head methods. On-the-fly resolution changes have been proven possible and functional with the straight line and cylinder parts. The slit method was also proven viable as keeping a constant diameter when traversing in any direction other than the horizontal as seen in the continuous curve and cylinder parts. The cylindrical part demonstrated that complex parts are plausible but require substantial coding.

B. FUTURE WORK

To further validate the functionality of the rotational print head mores tests should be performed with different parts. The most important of which is the design and testing of dog bone samples in which the exterior is printed at a multitude of resolutions. These tests will serve a variety of purposes including further displaying the on-the-fly diameter changes of the printer at the curved sections. They will also establish a data base comparing exterior resolution and strength. This data base will be the first of its kind directly comparing the two parameters and will allow manufacturers to make more informed decisions about their resolution selection based upon the strength needs of the part. The dog bones will be designed similarly to the cylindrical test part, so that the exterior of the part will be completed in two passes with the higher resolution diameter. Printing of the interior will then be completed in the largest diameter orientation, this process will be repeated for every layer in the same way as the cylindrical part.

Figure 27 shows a sample dog bone in a slicer software, the exterior would be printed with the desired resolution, while the interior is done at the highest diameter orientation. To simplify the printing of the interior it can be printed with only movements in the X direction, which would mean the print head would not need to be rotated between

lines. This would save time and would not have a large effect on the strength in the tensile test, due to most of the strength coming from the resolution of the exterior layers.

Figure 27. Proposed dog bone sample design

Another important step in the development of the rotational print head is the continued development of the python code used in assisting the G-code writing process. Continued development of this code will allow more complex parts to be developed and tested which will further contribute to the versatility of the printer.

APPENDIX A. SOLIDWORKS MODEL OF ROTATIONAL PRINT HEAD

Figures 28–31 show different angles of the same SolidWorks model presented in Chapter III. It can be clearly seen that the width of the part is drastically greater in the large diameter orientation.

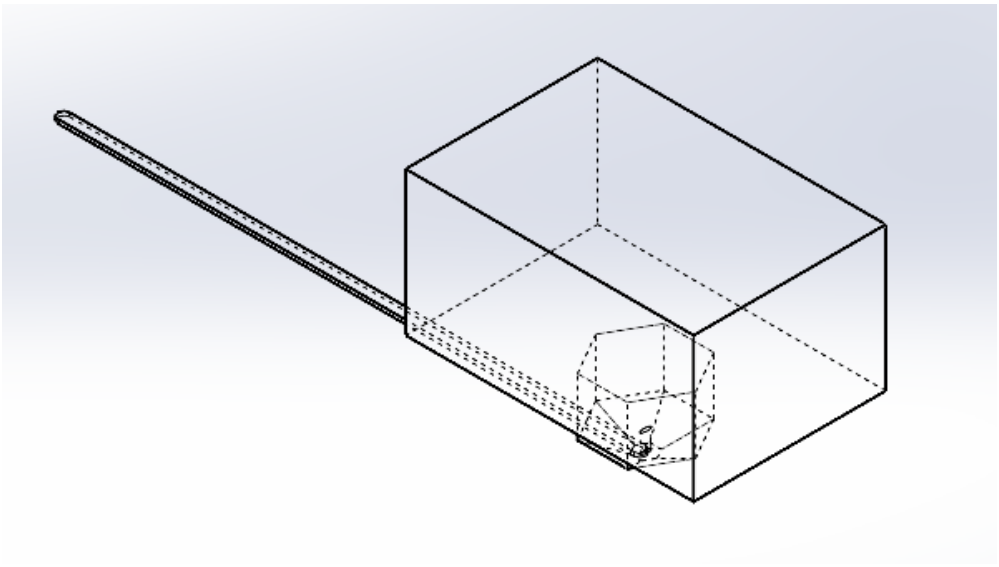

Figure 28. Large diameter orientation with trimmed heat box (Hidden view)

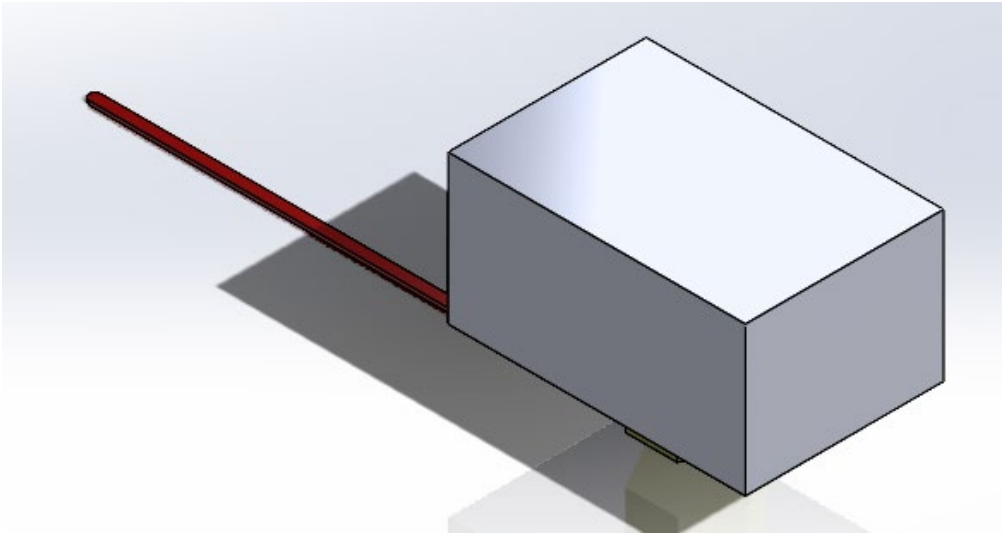

Figure 29. Large diameter orientation with complete heat box

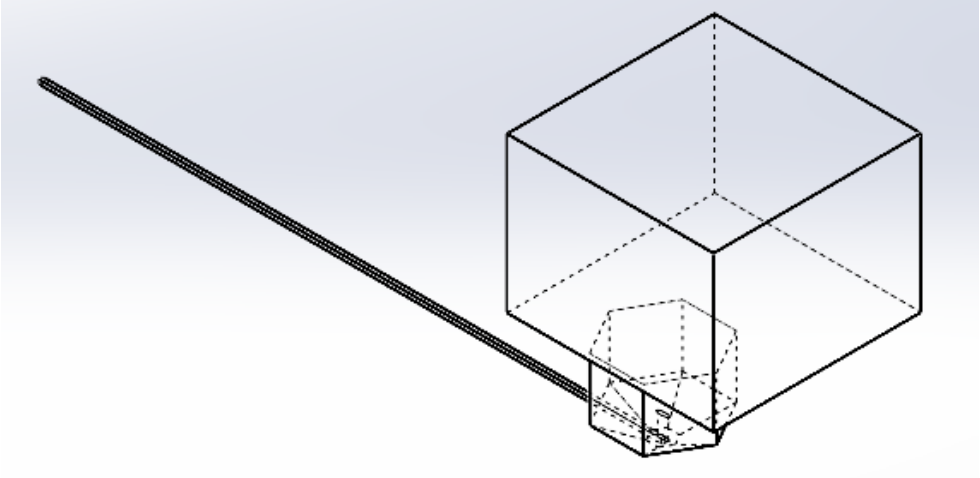

Figure 30. Small diameter with trimmed heat box (Hidden view)

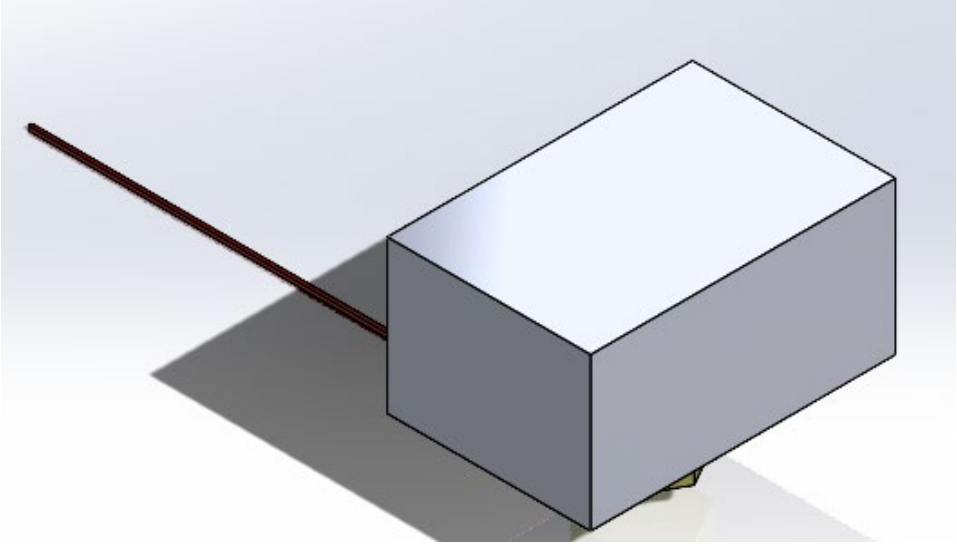

Figure 31. Small diameter orientation with complete heat box

APPENDIX B. STRAIGHT LINE CODE

```
G90
M83
M106 S255
M140 S50
M104 S200 T0
M104 S0 T1
M146 r255 g0 b0
M907 X100 Y100 Z40 A100 B100
M612 X0.0 Y0.0
M108 T1
G92 E0
M108 T0
M7
M6 T0
G92 E0 X0 Y0 Z0
M146 r255 g255 b255
M108 T0
G1 Z0.500 F900
M108 T0
G1 Y-10 F700
G1 X-40 E9 F700
G1 X40 E25 F700.0;
M108 T1
M400
G1 E8.2 F2700
M108 T0
G1 F900
G1 X-70.00 Y0.00 E0.2
M108 T1
M400
G1 E0 F2700
M108 T0
G1 F900
G1 X-68.00 Y0.00 E0.2
M108 T1
M400
G1 E0 F2700
M108 T0
G1 F900
G1 X-66.00 Y0.00 E0.2
M108 T1
M400
```

```
G1 E0 F2700
M108 T0
G1 F900
G1 X-64.00 Y0.00 E0.2
M108 T1
M400
G1 E0 F2700
M108 T0
G1 F900
G1 X-62.00 Y0.00 E0.2
M108 T1
M400
G1 E0 F2700
M108 T0
G1 F900
G1 X-60.00 Y0.00 E0.2
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-58.00 Y0.00 E0.215
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-56.00 Y0.00 E0.230
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-54.00 Y0.00 E0.245
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-52.00 Y0.00 E0.260
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
```

```
G1 X-50.00 Y0.00 E0.275
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-48.00 Y0.00 E0.290
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-46.00 Y0.00 E0.305
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M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-44.00 Y0.00 E0.320
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G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-42.00 Y0.00 E0.335
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-40.00 Y0.00 E0.350
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-38.00 Y0.00 E0.365
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-36.00 Y0.00 E0.380
M108 T1
M400
```

```
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-34.00 Y0.00 E0.395
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-32.00 Y0.00 E0.410
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-30.00 Y0.00 E0.425
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-28.00 Y0.00 E0.440
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-26.00 Y0.00 E0.455
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-24.00 Y0.00 E0.470
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-22.00 Y0.00 E0.485
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
```

```
G1 X-20.00 Y0.00 E0.500
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-18.00 Y0.00 E0.515
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-16.00 Y0.00 E0.530
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-14.00 Y0.00 E0.545
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-12.00 Y0.00 E0.560
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-10.00 Y0.00 E0.575
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-8.00 Y0.00 E0.560
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-6.00 Y0.00 E0.545
M108 T1
M400
```

```
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-4.00 Y0.00 E0.530
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M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X-2.00 Y0.00 E0.515
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X0.00 Y0.00 E0.500
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X2.00 Y0.00 E0.485
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X4.00 Y0.00 E0.470
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X6.00 Y0.00 E0.455
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X8.00 Y0.00 E0.440
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
```

```
G1 X10.00 Y0.00 E0.425
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M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X12.00 Y0.00 E0.410
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X14.00 Y0.00 E0.395
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X16.00 Y0.00 E0.380
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X18.00 Y0.00 E0.365
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X20.00 Y0.00 E0.350
M108 T1
M400
G1 E-0.300 F2700
M108 T0
G1 F900
G1 X22.00 Y0.00 E0.335
M108 T1
M400
G1 E-0.300 F2700
M108 T0
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G1 X22.00 Y0.00 E0.320
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M400
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M108 T0
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G1 X24.00 Y0.00 E0.305
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G1 E-0.300 F2700
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G1 F900
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G1 F900
G1 X28.00 Y0.00 E0.275
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G1 X32.00 Y0.00 E0.245
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G1 E-0.300 F2700
M108 T0
G1 F900
G1 X34.00 Y0.00 E0.230
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G1 E-0.300 F2700
M108 T0
G1 F900
G1 X36.00 Y0.00 E0.225
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M400
G1 E-0.300 F2700
M108 T0
G1 F900
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G1 E-0.300 F2700
M108 T0
G1 F900
G1 X40.00 Y0.00 E0.200
M108 T1
M400
G1 E0 F2700
M108 T0
G1 F900
G1 X42.00 Y0.00 E0.200
M108 T1
M400
G1 E0 F2700
M108 T0
G1 F900
G1 X44.00 Y0.00 E0.200
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M400
G1 E0 F2700
M108 T0
G1 F900
G1 X46.00 Y0.00 E0.200
M108 T1
M400
G1 E0 F2700
M108 T0
G1 F900
G1 X48.00 Y0.00 E0.200
M108 T1
M400
G1 E0 F2700
M108 T0
G1 F900
G1 X50.00 Y0.00 E0.200
M140 S0
M104 S0 T0
M104 S0 T1
G1 Z140 F3300
M107
M146 r0 g0 b0
M18
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APPENDIX C. CONTINUOUS CURVE LINE CODE

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G90
M83
M106 S255
M140 S50
M104 S200 T0
M104 S0 T1
M146 r255 g0 b0
M907 X100 Y100 Z40 A100 B100
M612 X0.0 Y0.0
M108 T1
G92 E0
M108 T0
M7
M6 T0
G92 E0 X0 Y0 Z0
M146 r255 g255 b255
M108 T0
G1 Z0.500 F700
M108 T0
G1 Y-20 F700
G1 X-30 E9 F700
G1 X10 E12.5 F700.0
M108 T1
M400
G1 E8.2 F2700
M108 T0
G1 F700
G1 X-70.00 Y10.00 E0.32
M108 T1
M400
G1 E0 F2700
M108 T0
G1 F700
G1 X-68.00 Y10.00 E0.32
M108 T1
M400
G1 E0 F2700
M108 T0
G1 F700
G1 X-66.00 Y10.00 E0.32
M108 T1
M400
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G1 E0 F2700
M108 T0
G1 F700
G1 X-64.00 Y10.00 E0.32
M108 T1
M400
G1 E0 F2700
M108 T0
G1 F700
G1 X-62.00 Y10.00 E0.32
M108 T1
M400
G1 E0 F2700
M108 T0
G1 F700
G1 X-60.00 Y10.00 E0.32
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M400
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M108 T0
G1 F700
G1 X-58 Y10.00 E0.32
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G1 E0 F2700
M108 T0
G1 F700
G1 X-56 Y10.00 E0.32
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M400
G1 E0 F2700
M108 T0
G1 F700
G1 X-54 Y10.00 E0.32
M108 T1
M400
G1 E0 F2700
M108 T0
G1 F700
G1 X-52 Y10.00 E0.32
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M400
G1 E0 F2700
M108 T0
G1 F700
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G1 E0 F2700
M108 T0
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G1 X-48 Y10.00 E0.32
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M400
G1 E0 F2700
M108 T0
G1 F700
G1 X-46 Y10.00 E0.32
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G1 E0 F2700
M108 T0
G1 F700
G1 X-44 Y10.00 E0.32
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G1 E0 F2700
M108 T0
G1 F700
G1 X-42 Y10.00 E0.32
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M108 T0
G1 F700
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M108 T1
M400
G1 E0 F2700
M108 T0
G1 F700
G1 X-38 Y10.00 E0.32
M108 T1
M400
G1 E0 F2700
M108 T0
G1 F700
G1 X-36 Y10.00 E0.32
M108 T1
M400
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G1 F700
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M108 T0
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G1 E0 F2700
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M108 T0
G1 F700
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G1 X-24 Y10.00 E0.32
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G1 E0 F2700
M108 T0
G1 F700
G1 X-20 Y10.00 E0.32
M108 T1
M400
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M108 T0
G1 F700
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G1 E0 F2700
M108 T0
G1 F700
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M108 T0
G1 F700
G1 X-12 Y10.00 E0.32
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G1 E-2 F2700
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M108 T0
G1 F700
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M400
G1 E-0.0 F2700
M108 T0
G1 F700
G1 X-8.5 Y9.25 E0.12
M108 T1
M400
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M108 T0
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G1 E-2 F2700
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G1 E0 F2700
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M108 T0
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G1 E0 F2700
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G1 E0 F2700
M108 T0
G1 F700
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G1 E0 F2700
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M140 S0
M104 S0 T0
M104 S0 T1
G1 Z140 F3300
M107
M146 r0 g0 b0
M18
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