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G-Code Generation For Multi-Process 3D Printing

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G-CODE GENERATION FOR MULTI-PROCESS 3D PRINTING

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Dedication

I dedicate this work to my parents, Peter and Jenny Bailey, whose unconditional love and support have given me the self-confidence and self-belief to take on the world; and to my wife, Heather, whose love has taken me on this American adventure.

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by

CALLUM PETER BAILEY, MChem

THESIS

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Abstract

Since the inception of stereolithography in the 1980s, interest in 3D printing has exploded, with desktop 3D printers now commercially accessible to the general public. In recent years, next-generation multifunctional technologies have been developed, which combine 3D printing with other technologies such as wire embedding, foil embedding, CNC machining, and robotic component placement, enabling complex parts to be made on a single multifunctional machine.

However, the complexity of these integrated processes exceeds the capabilities of established design tools. To this end, this thesis aims to develop a multi-functional design solution that can automatically generate final control code for next-generation multifunctional machines, where all design specifications are defined from within a single software package.

Specifically, we take on the task of automating a Lulzbot desktop 3D printer, which has been modified to utilize a custom-designed wire-embedding tool as a secondary extruder. While the algorithms presented herein have been tailored to the needs of this custom printer, the modular nature of the solution will facilitate expansion to include other multifunctional printers, including the planned low-cost multi^{3D} multifunctional printer, currently under construction at the W.M. Keck Center for 3D Innovation at The University of Texas at El Paso.

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Chapter 1: Introduction

The advent of modern 3D printing is widely attributed to Charles Hull and his invention of the stereolithography (SLA) rapid prototyping process, over 30 years ago. This process uses photocurable resins and light to create custom three-dimensional solid bodies [1]. Since then, many different additive manufacturing processes have been developed: fused deposition modeling (FDM), Polyjet, laminated object manufacturing (LOM), Prometal, selective laser sintering (SLS), laminated engineered net shaping (LENS), and electron beam melting (EBM) [2]. While initially envisioned to create models, applications of these technologies have since diversified widely: from biomedical prostheses, customized pharmaceuticals, aircraft components, tooling, mass-customized parts, and artwork [3–8].

Fused Deposition Modeling

Patented by Stratasys founder Scott Crump in 1989 [9], The FDM process involves the deposition of a thin strand (typically 0.25 mm diameter) of molten thermoplastic resin to build a three-dimensional structure in a stepwise, layer-by-layer manner. The technology can be used with a wide range of materials, with acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) being the most ubiquitous in consumer 3D printers. Widely-used materials in industrial-grade 3D printers include polycarbonate (PC) and Nylon, as well as proprietary performance polymers such as ULTEM™, a polyetherimide resin manufactured by Sabic (Pittsfield, MA).

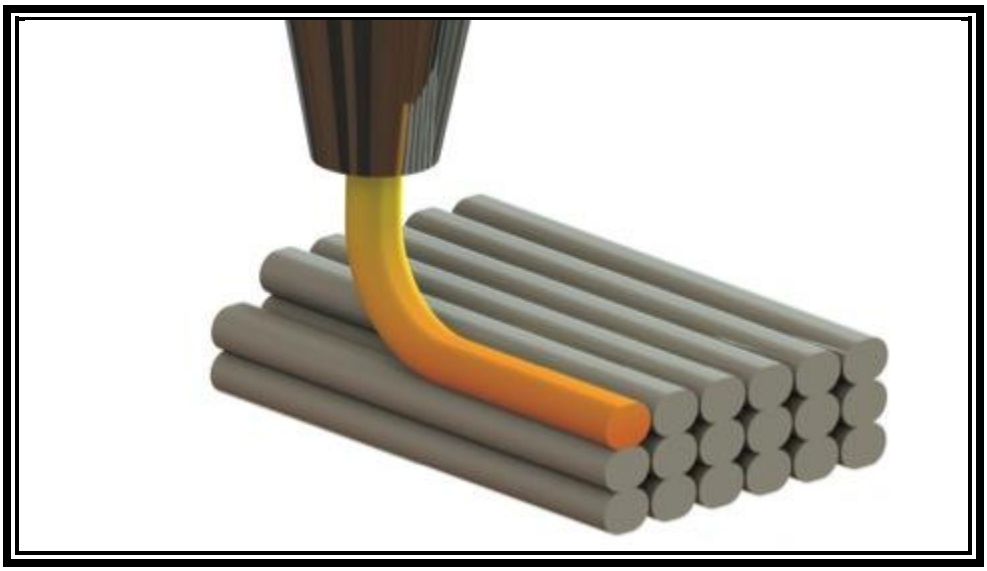

Figure 1.1: Rendering of the FDM process showing how molten polymer expelled from an extruder can create a 3D structure in a stepwise, layer-by-layer process [10].

The ability of the FDM process to utilize so many different materials is one of its great advantages, enhancing design possibilities and customizability beyond the constraints of traditional manufacturing. By leveraging expertise from materials science, as well as electrical and mechanical engineering; customized, functional structures can be created that are directly tailored to the needs of an application. In order to realize these designs, computer-aided design (CAD) technology is employed.

3D Design and Slicing

The process of realizing a 3D print begins in a 3D CAD software package such as Solidworks (a commercial software package) or Blender (an open source software package). This software allows the creation and customization of a 3D model, which is then saved in one of many different file formats depending on the software package. Once the model has been created, the design needs to be interpreted into a series of instructions that correspond to the actions that a 3D printer must take to create the design. The information in these instructions includes the coordinates that the print extruder head must pass through, the speed of the movement between these coordinates, the temperature of the build platform and polymer

extruder head, whether the print extruder head should be extruding polymer, the rate of polymer extrusion, as well as any other miscellaneous input or output (I/O) control associated with the printer. If the printer has more than one extruder, which extruder to use and its temperature must also be specified. The most popular open-source instruction language used to convey this information is G-code, although manufacturers have also developed their own proprietary solutions. The software used to generate the G-code is known as a slicer.

Just as there are many CAD tools available for generating 3D parts, there are many slicers available for converting these parts into printable G-code: including Stratasys Insight (commercial, license-required), MakerBot Desktop (commercial, free to use), Cura (open source), and Slic3r (open source). Insight and MakerBot output proprietary file-formats useable by their print hardware, while Cura and Slic3r output standard G-code files. In common, they all require the 3D model to be presented in a standardized format that the slicer can read. The most popular format is the stereolithography (STL) file format developed by 3D Systems [11]. While originally developed for 3D Systems' stereolithography process, the STL file format is used widely in a variety of additive manufacturing technologies, including FDM. This file format defines the surface geometry of a 3D part through a series of tessellated triangles. These triangles can be parsed by slicing software to convert them into layers of printable G-code coordinates. However, as this file format only stores information on geometry and not material type, it presents severe limitations when trying to utilize it to design and slice multi-material and multi-process parts. An additional limitation is that all STL parts must have volume or area, whereas to provide instructions for a wire-embedding tool, one may only require a line that has no volume or area.

Another capability of the FDM process is that it can be readily interrupted. This allows a print job to be paused, so that external electronic or mechanical components can be inserted into predesigned cavities, and then resumed to encapsulate the components in polymer. By this

method, customized electromechanical devices containing springs, motors, antennas, microprocessors, as well as other circuit components can be created. This capacity of 3D printing to accomplish novel electromechanical designs has sparked interest in multiprocess 3D printing.

Multiprocess 3D Printing

Multiprocess 3D printing involves the use of more than one process in the fabrication of a 3D-printed part. For example, an electromechanical part such as a capacitive touch sensor could be "3D printed" by combining FDM printing technology (to provide a substrate base), with robotic component placement (to add circuit components), a mesh embedding tool (to create a custom-sized mesh as the capacitive touch sensor), and a wire embedding tool (to connect the components electrically) (Figure 1.2 below) [12].

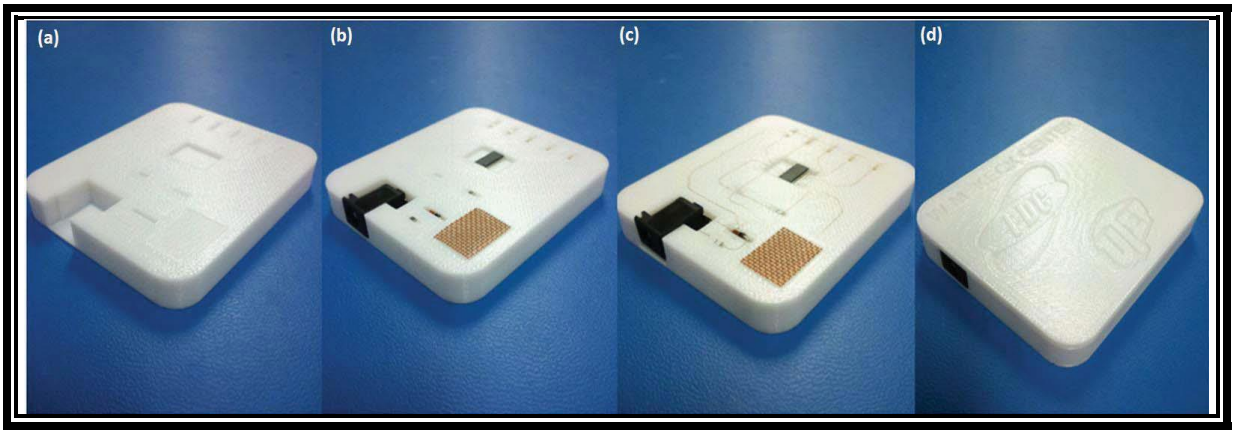

Figure 1.2: Example of the use of an interrupted FDM process to create a 3D-printed capacitive touch sensor [12].
(a) Polycarbonate substrate is printed with cavities. (b) The print is paused and components are placed in their designated cavities. (c) The components are connected with embedded wires. (d) Polycarbonate printing is resumed to complete the part.

The W.M. Keck Center for 3D Innovation at The University of Texas at El Paso (UTEP) has developed a number of multi-technology 3D printing processes (detailed in Chapter 2), which can combine multi-material 3D printing with wire embedding, micromachining, foil embedding, and robotic component placement. Although this technology has been successfully implemented and is functional, it lacks an integrated software environment to oversee the design

process over the differing technologies. This requires the human operator to calculate at what layer a pause should be manually added to a print, and what kind of coordinate offsets need to be introduced to integrate the various design tools.

Chapter 2: Literature Review

Multiprocess 3D Printing of Electronics

Conductive Inks

The *in situ* fabrication of complex electromechanical devices via 3D-printing has been occurring for over 15 years [13]. Some of the earliest 3D-printed complex devices were fabricated by pausing an SLA print process and inserting an external electronic component into a specially-designed cavity in the print [13]. This process was augmented by the introduction of conductive inks to the SLA process by Palmer *et al.* [14] and Medina *et al.* [15], [16], allowing the *in situ* creation of simple circuits during the additive manufacturing process.

Figure 2.1 shows the first three design iterations of a three-axis magnetic flux sensor, printed by stereolithography with conductive ink traces.

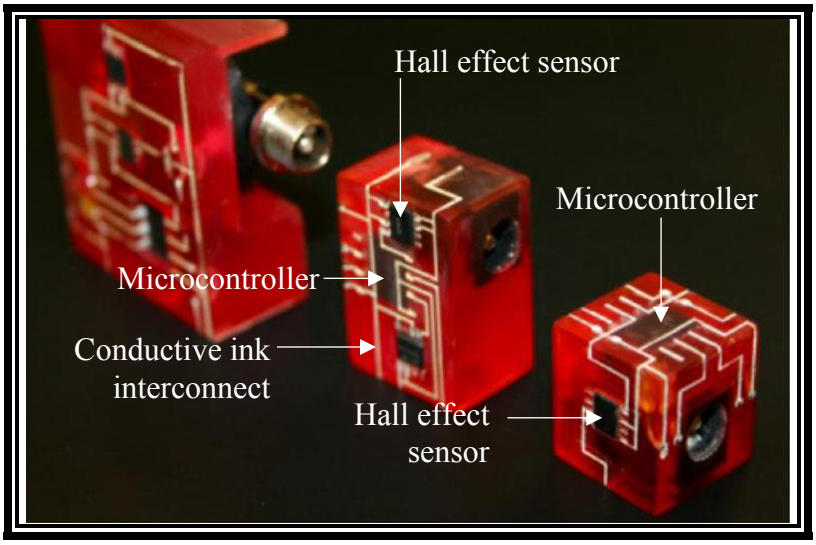

Figure 2.1: The first three generations of a three-axis magnetic flux sensor system, produced using stereolithography, (image courtesy of Emerald Group Publishing Limited) [17]

While combining conductive ink with stereolithography offers high print resolution and relative ease of processing, it also presents some limitations. Stereolithography is limited to photocurable polymers, which tend to be brittle, as well as inherently prone to degradation during long-term UV exposure (as is likely to occur with outdoor use) [18]. Another limitation is

the low conductivity of conductive inks, which tend to be two orders of magnitude less conductive than a traditional bulk metal conductor, such as copper [19]. This limits the use of conductive inks in electronics to applications with low power requirements.

One company that has embraced multimaterial 3D printing with conductive inks is Voxel8 (Somerville, MA), who have produced a low-cost commercial 3D printer with a conductive ink dispenser, allowing printing in PLA and conductive ink [20]. The conductive silver ink in their process is self-supporting, meaning it is capable of creating bridging electrical connections from the polymer substrate to the pins of surface-mounted components or to copper pads on a printed circuit board (PCB). However, the resistivity of the ink is still somewhat higher (50×10^{-8} Ω·m) than bulk copper (1.68×10^{-8} Ω·m) [20].

Table 2.1 Comparison of resistivity for select conductors [20] [21]

Conductor	**Resistivity (nΩ·m)**
Silver wire	16
Copper wire	17
Extruded solder	72
DuPont Ink CB028 Silver	118
DuPont Ink CB500 Copper	507
Voxel8 Conductive Silver Ink	500
Nichrome (Ni-Cr) alloy wire	1000

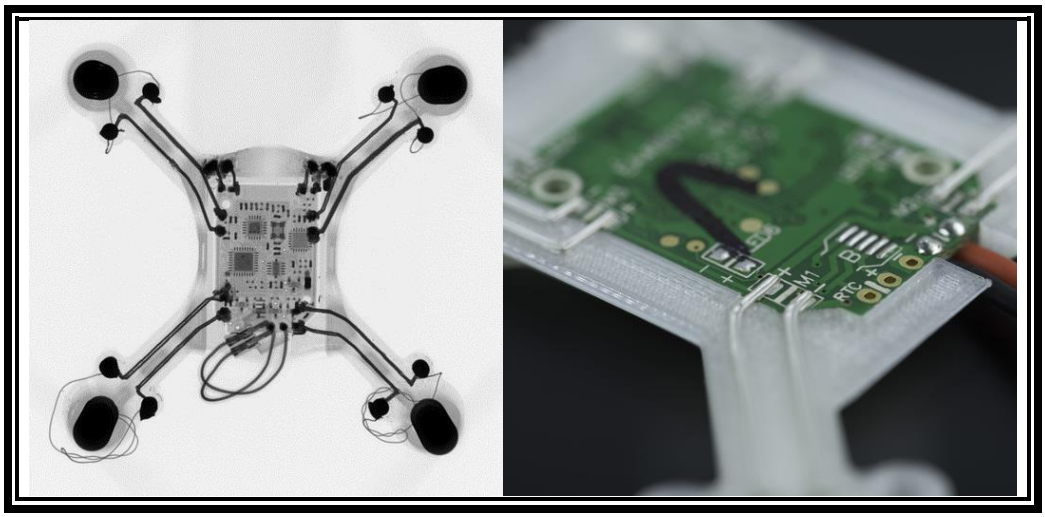

Figure 2.2: An X-ray micrograph of a quad copter drone (left) and printed electrical interconnections to a printed circuit board (right) (image courtesy of Voxel8).

Thermal Wire Embedding

In response to the conductivity limitations of inks, Espalin *et al.* have developed a process that allows metal wires to be embedded during the FDM printing process [17].

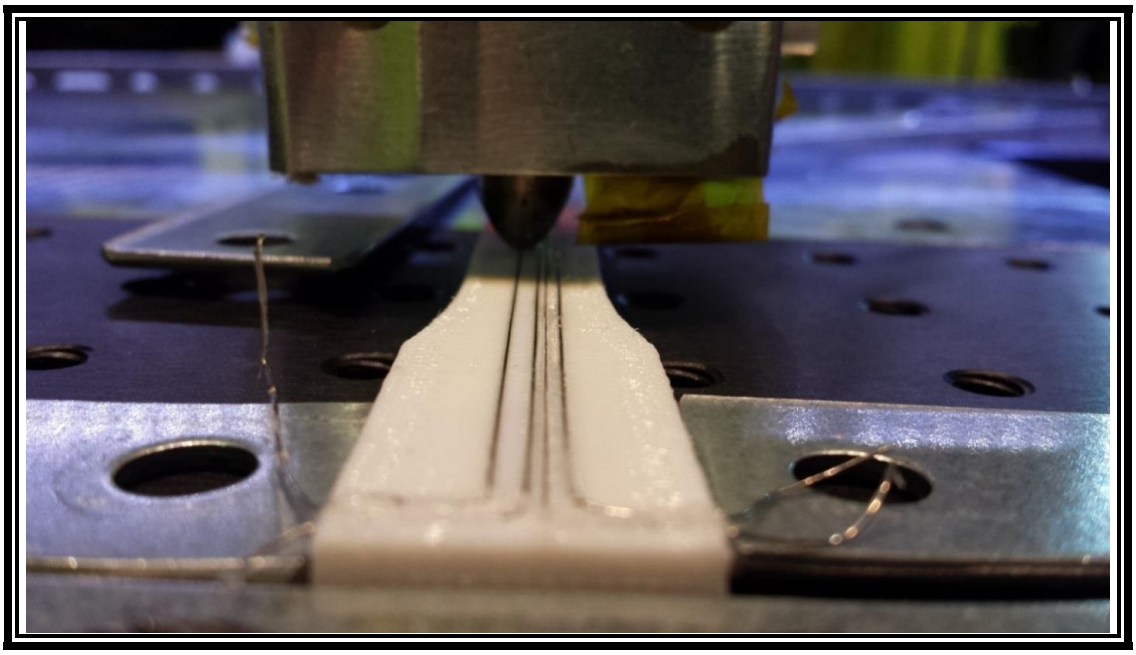

Figure 2.3: Embedding Ni-Cr wire on a tensile specimen for mechanical testing [21].

This process has been combined with FDM in a next-generation hybrid 3D-printing system, referred to as the multi^{3D} foundry system (Figure 2.4 below). Additional capabilities of this system include the ability to perform CNC micromachining (to increase the resolution of fine features beyond that which could be attained by FDM alone), as well as the ability to embed metal foils and to robotically place components [22].

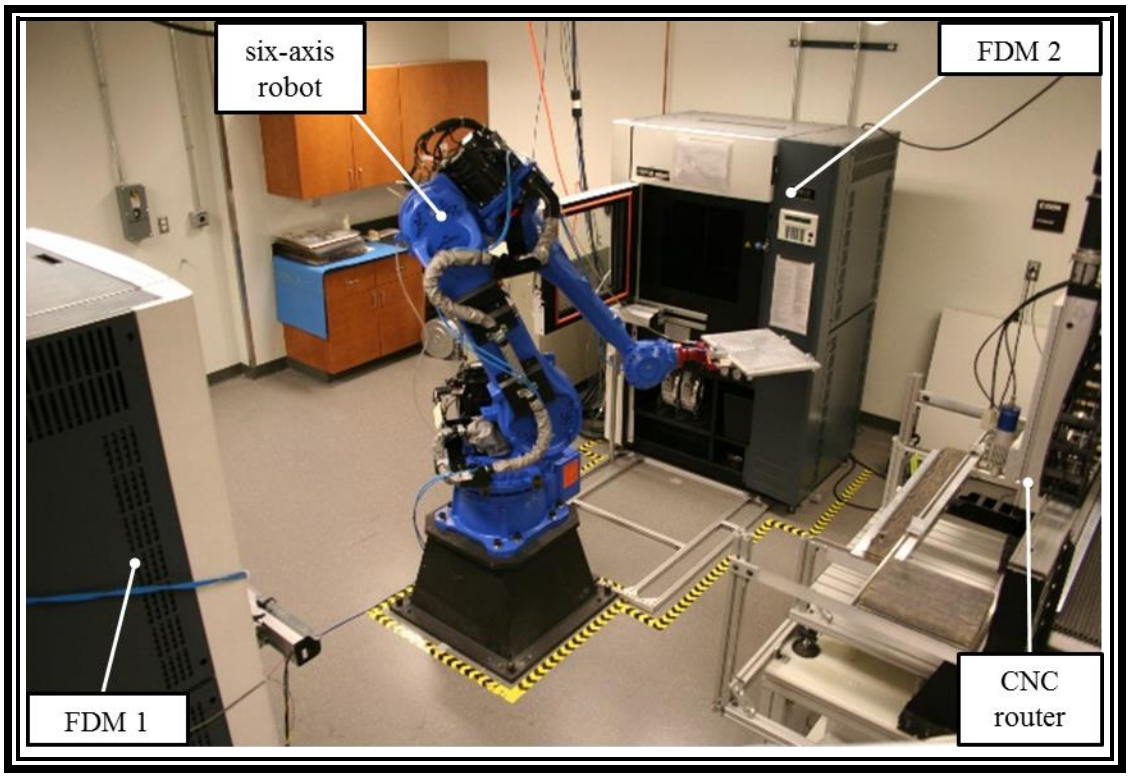

Figure 2.4: multi^{3D} foundry system

The higher conductivity of copper wire versus conductive inks and the ability to embed wire in FDM prints expands the capabilities of 3D printed electronics to include high voltage and high power applications. One such application, illustrated in Figure 2.5 below, is an electro-pulsed plasma thruster that can be used for micropropulsion under vacuum and in microgravity, such as in a CubeSat microsatellite application [23]. This propulsion requires the conductive traces to deliver over 1000 V from the power source

to the thruster: an application that could not be achieved with conductive inks due to their higher resistivity.

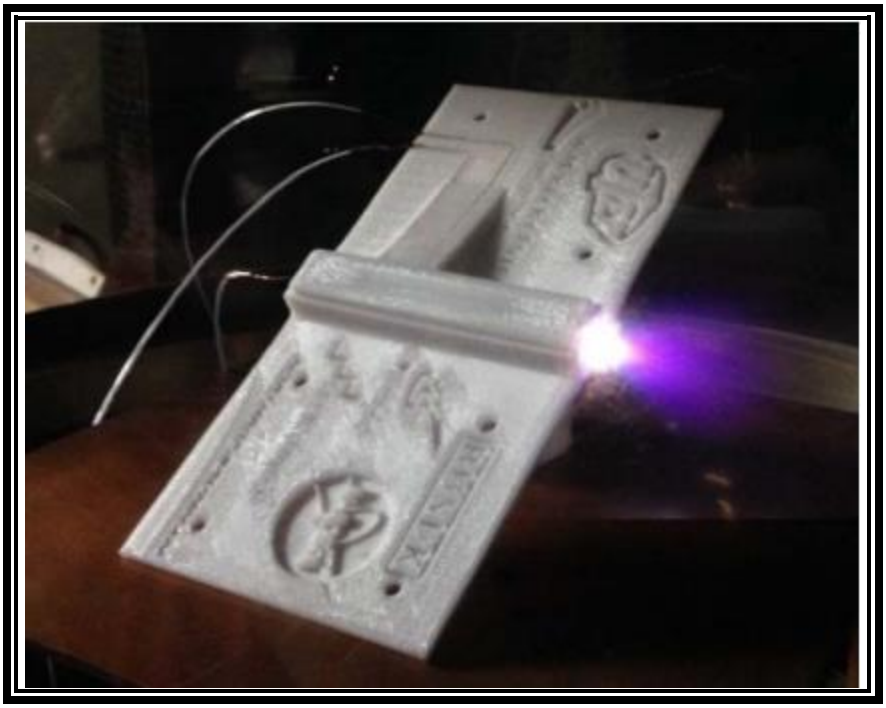

Figure 2.5: Busek electro-pulsed plasma thruster integrated into an FDM printed part, utilizing thermal wire embedding technology to carry high-voltage power to the thruster [23].

This development of multiprocess 3D printing has exceeded the capabilities of traditional computer-aided design (CAD) software tools. To this end, a number of efforts are underway to augment existing tools or create new tools to facilitate next-generation hybrid additive manufacturing.

Software

As described in Chapter 1, conventional 3D printing design tools are based on the use of a 3D CAD tool, such as AutoCAD, Solidworks, and Blender in conjunction with slicing software, such as Cura, Slic3r, MakerBot Desktop, or Stratasys Insight. Some of these packages offer limited support for multi-material printing: e.g. MakerBot Desktop supports its dual-extruder technology by allowing for two STL files to be imported to the same slicing job and for

each solid body to be designated to be printed with a specified extruder. However, this solution still presents some design limitations and complexity. It would be advantageous if the material requirements could be designated during the CAD design stage, with the information preserved through the slicing process and into the final G-code. This is not easy to do with the conventional STL file format, as this file contains only geometric information (in the form of tessellated triangles that define the surface geometry). More advanced file formats have been developed, including the open standard AMF (additive manufacturing file) file format, as well as the 3MF Consortium's 3MF (3D manufacturing format). The AMF format is an ASTM standard, while the 3MF format is supported by some of the largest industry leaders in 3D printing: 3D Systems, Stratasys, Shapeways, GE, HP, Dassault Systèmes, Ultimaker, and Microsoft. Both AMF and 3MF are XML-based (extensible markup language) file formats that provide multi-material support, as well as allowing for the incorporation of metadata. In addition, 3MF provides support for subtractive manufacturing processes, such as CNC machining, and is designed around the principle of extendibility to facilitate the addition of new functionality in the future. Unfortunately, the slicing software has not kept pace with these new developments, and while slicing software may be capable of reading vertex information in these new file formats, it cannot utilize the additional information to generate multi-functional G-code for next-generation hybrid 3D printers.

Voxel8 and Autodesk Project Wire

In response to the limitations of slicing software, hardware designers have had to create their own slicing and G-code-generating solutions. The launch of the Voxel8 printer in 2015 was accompanied by the launch of Autodesk's Project Wire design software. This software allows for conductive ink traces and components to be added to a traditional 3D-printed design, and machine code generated, for printing on the Voxel8 printer. One disadvantage of this approach is that the design environment for Project Wire is more limited than a fully featured CAD solution such as Solidworks or AutoCAD. If different parts of the design need to be modified in different

design tools, this may present difficulties with synchronizing design changes during an iterative design-refinement process. Project Wire's library of integrated circuits (ICs) is also somewhat limited, requiring additional work on the part of the end user to develop their own library of commonly used ICs.

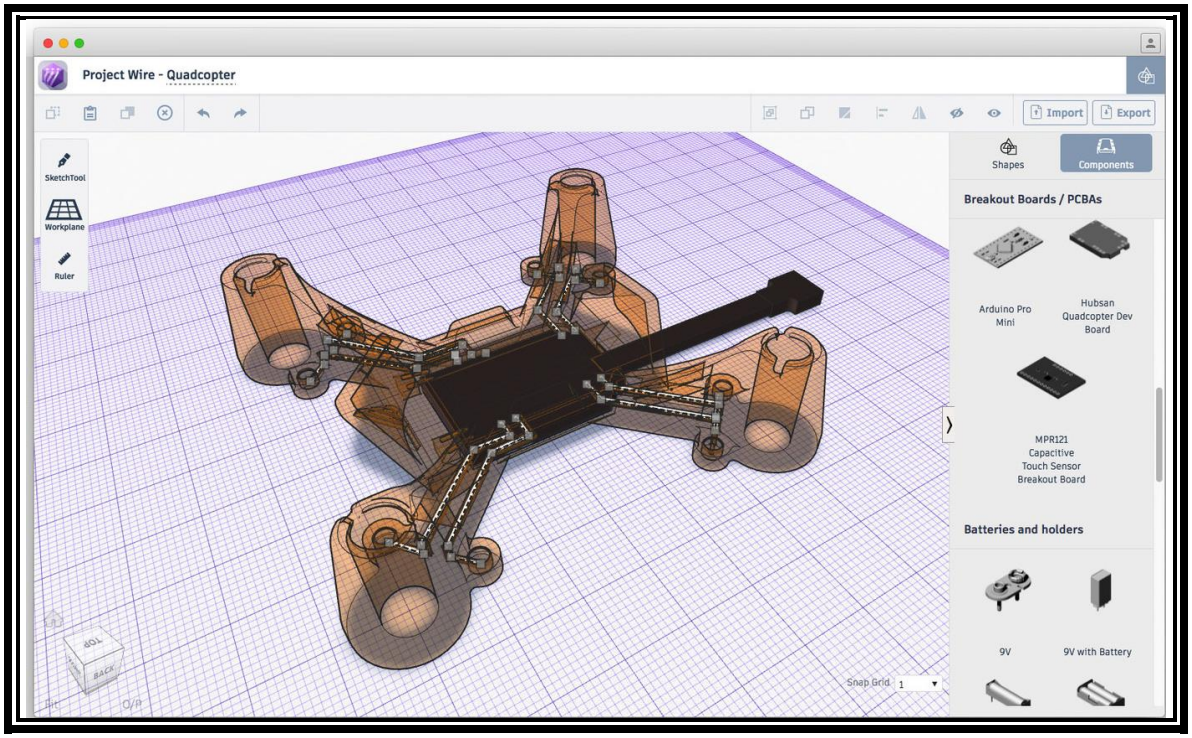

Figure 2.6: Autodesk Project Wire is used to design a quad copter for printing on The Voxel8 printer (courtesy of Voxel8).

User-modified Slic3r

Another approach is to augment existing slicing software. Wasserfall has created an electronics extension for the open-source slicing tool, Slic3r. This modified tool allows for surface-mounted components and wires to be added to an existing design and visualized from within the Slic3r graphical user interface (GUI) [24]. When components or wires are placed, the software automatically adjusts the polymer slicing to provide appropriate cavities and a support layer underneath the components. Figure 2.8, below, shows how a solid layer in yellow is placed underneath wires and components, with a less dense infill layer in pink to improve print speed

where less support is required. The software also provides the ability to import schematics, with netlists, from the PCB software CadSoft EAGLE. After the schematic has been imported from EAGLE, netlist information is preserved to provide “rubber band” connections between components. These “rubber bands” provide a visual indicator of which components should be connected to each other and which pins should be used, prompting the user to provide final routing and way-points to connect the components to each other, whilst avoiding undesirable collisions and short circuits. This implements a PCB design methodology to multi-material printing.

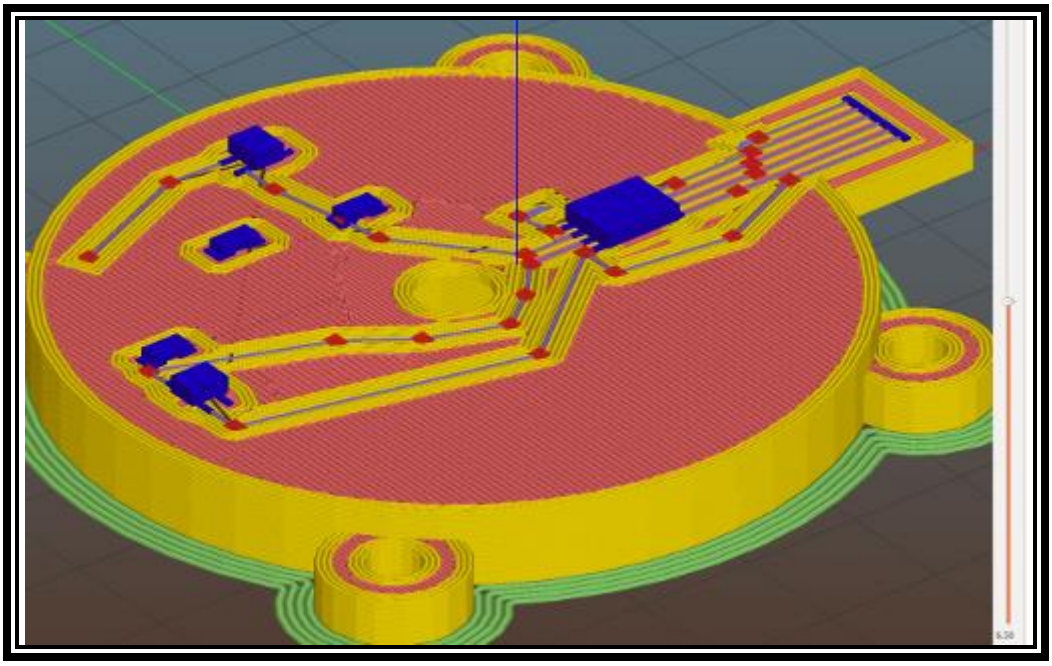

Figure 2.7: GUI from a customized version of Slic3r showing SMD components with routed wire interconnections (courtesy of the Conductive Printing Project [24]).

Computer control enhancements developed by Wasserfall include computer-vision-aided pick and place to allow SMD components to be placed automatically during the print, with computer-vision feedback to ensure correct orientation.

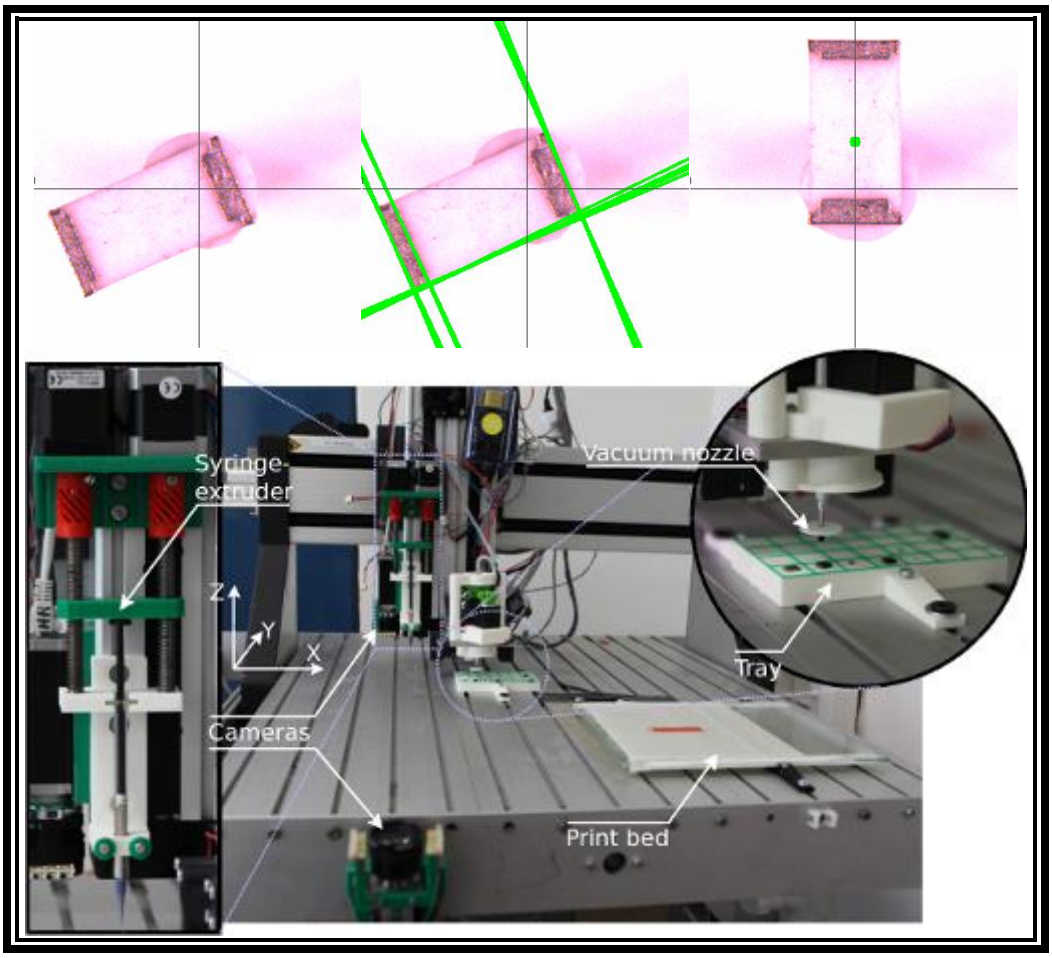

Figure 2.8: Above: Computer image processing to determine orientation (green lines, edge-detection), corrected orientation after rotation, and center of mass (green dot) of a SMD part. Crosshairs indicate the rotation pivot point of the vacuum nozzle [25].
Below: Automatic pick and place with computer vision feedback (courtesy of the Conductive Printing Project)

While the integration of EAGLE PCB libraries to this solution is a more sophisticated solution than that offered by Project Wire, the solution still has the complexity of two design environments, the CAD software for part design, and the slicer for electronics routing.

Autodesk Fusion 360

Autodesk Fusion 360 is another software package attempting to bridge the gap between electrical and mechanical engineering design tools [26]. Following the acquisition of CadSoft and the PCB software EAGLE in June 2016, Autodesk are continuing to integrate support for

importing PCB designs, created in EAGLE, into their Fusion 360 software, as well as the ability to make changes in Fusion 360 and export those changes back into EAGLE. This integration of different design tools creates one of the most holistic approaches to solving the challenges of multiprocess design.

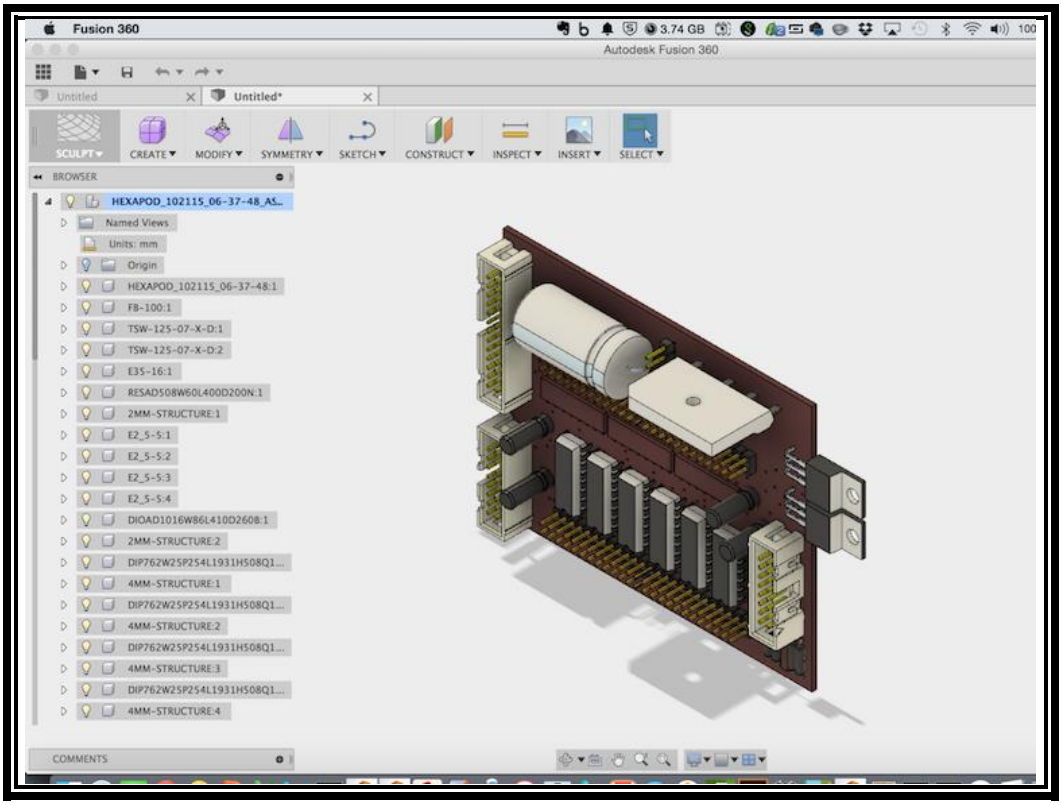

Figure 2.9: An EAGLE PCB design imported into Fusion 360 [26].

While current multiprocess software solutions offer an improvement over unmodified conventional CAD software, the custom nature of the multi-process hardware at the W.M. Keck Center for 3D Innovation requires a custom software solution, with modular design to support a variety of hardware requirements.

Chapter 3: Design specifications

Software objectives: A multi-process design and slicing methodology

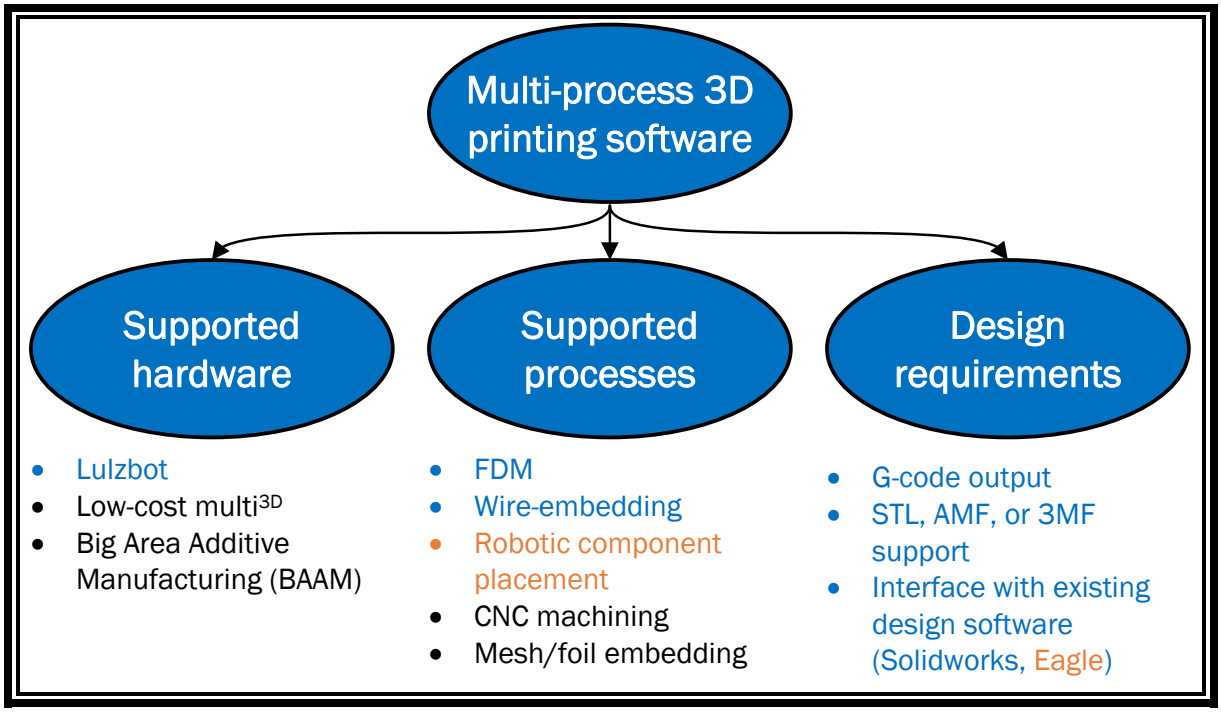

Figure 3.1: Overview of the design requirements of the multi-process G-code generation software. Blue text indicates work within the scope of this thesis. Orange indicates work within the scope of the thesis of Efrain Aguilera (published concurrently). Black text is part of the final design requirements for the software, but outside the scope of the current work.

The challenges and needs of the W.M. Keck Center for 3D Innovation have led to the design objectives of this software: to create a methodology for designing, slicing, and generating toolpaths to be used with next-generation, multi-process additive manufacturing technologies. The specifications of this new methodology include the ability to automatically generate multifunctional G-code from an integrated design environment, which can instruct a multi-technology additive manufacturing machine to switch between different tools or processes as indicated by the design. The processes required within the scope of the final implementation of this design software include: traditional FDM printing, wire embedding, mesh and foil embedding, surface machining, and robotic component placement (also referred to as pick and

place). The mechanical-engineering challenges of these processes are reasonably well-understood, with more comprehensive automation currently limited by the lack of a holistic CAD software solution. Other desirable processes outside the current scope of this software solution include the automated placement of vias, as well as automated laser-welding or soldering to connect components. These mechanical processes require further design refinement and so are outside the scope of the planned low-cost multi^{3D} printer.

Many of these objectives go beyond what could be expected to be achieved by one person or within the timeline of a master's thesis. As such, the scope of this thesis is restricted to the refinement of a multi-process FDM and wire-embedding methodology on the modified Lulzbot printer.

Features of the Lulzbot wire-embedding printer

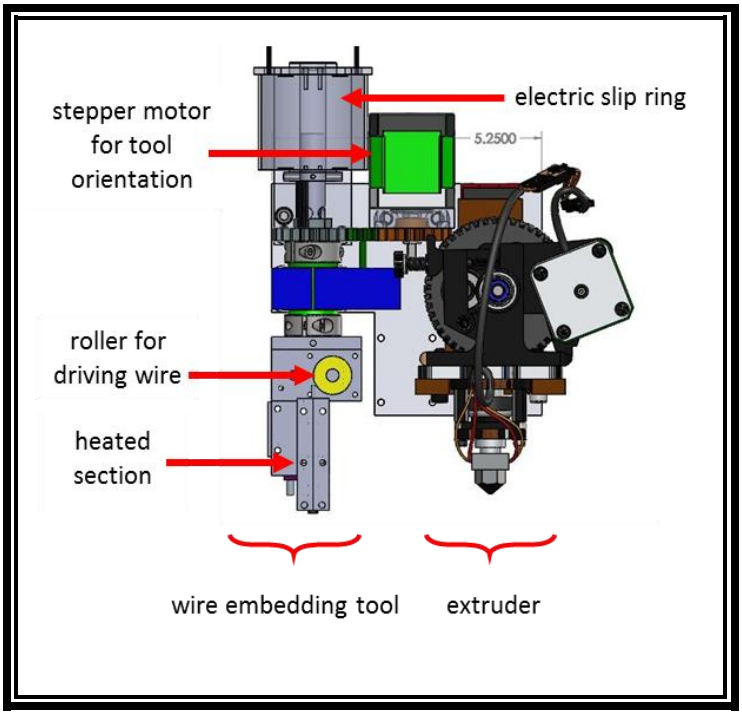

Figure 3.2: Dual FDM, wire-embedding tool head of the modified Lulzbot printer

The Lulzbot wire-embedding printer features both a wire-embedding tool head and an FDM extruder. Mounted on an actuator, the FDM extruder can be raised when not in use and lowered during printing. The wire-embedding tool has a number of features that must be accounted for when generating control code.

Orientation dependence

The most critical feature is the tool's orientation dependence. Earlier iterations of the wire-embedding tool would extrude wire in a direction that was perpendicular to the surface of the polymer. This orientation could cause the wire to snag and occasionally shear. As a result, the tool has been redesigned to extrude and embed at a shallower angle, no longer perpendicular to the print surface. However, this redesign introduced an orientation dependence to the tool. The rotation of the tool can be controlled by setting the E parameter in a G-code command, wherein a clockwise (CW) rotation of the full 360 degrees of a circle is represented, idiosyncratically, by a

G-code E parameter value of approximately 3.88. The syntax for generating a rotation command involves switching to relative positioning (G91), followed by a G1 movement command, combined with an F command (specifying a relative movement speed), and an E command to specify rotation angle. This is suffixed by switching back to absolute positioning (G90), so that the following translational movements of the wire-embedding tool can continue to use absolute coordinates.

```
1 G91; relative positioning
2 G1 F80 E-0.02956; tool rotation
3 G90; absolute positioning
```

Figure 3.3: Tool rotation commands (; indicates a comment): G91, specifies relative positioning; G1 indicates a movement command, while F80 indicates movement speed, and E-0.02956 specifies a relative rotation (in this case, a counter-clockwise rotation of 2.7°); the G90 command returns the tool to absolute positioning.

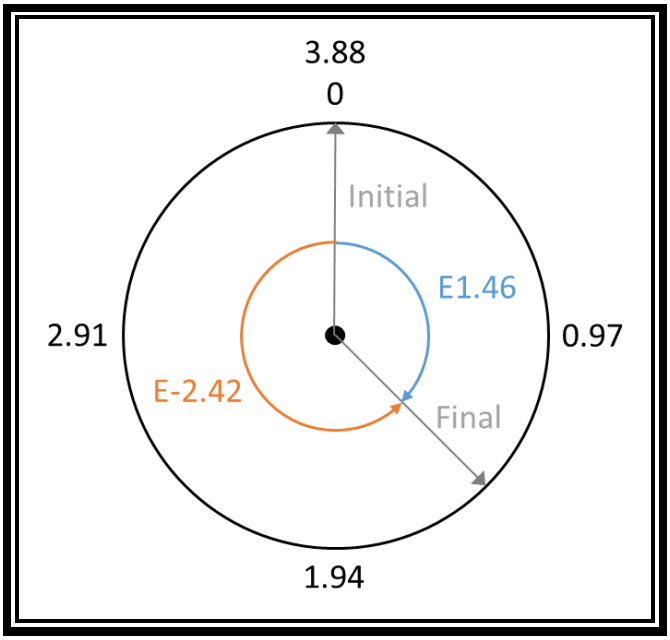

Figure 3.4: How a clockwise or counter-clockwise tool rotation from an absolute initial position of 0° to an absolute final position of 135° can be specified by the E parameter in G-code.

Custom commands

In addition to the regular X, Y, Z coordinates and F speed commands. The wire-embedding tool utilizes a number of custom and less common G-code commands, which must be implemented in the wire-embedding G-code for the tool to function correctly.

Table 3.1 Additional G-code commands utilized by the Lulzbot wire-embedding tool

G-code command	Description
M42 P14 S*x*	Wire Extruder Feed Motor[1] (*x*: 0=off 255=on)
M42 P16 S*x*	Wire cutting tool (*x*: 0=off 255=on)
M42 P18 S*x*	Cooling air (*x*: 0=off 255=on)
M104 T1	Wire extruder temp
G4 P*x*	Dwell (delay) for *x* ms
G90	Absolute G-code references
G91	Relative G-code references
T0	FDM extruder tool
T1	Wire-embedding tool
E	Polymer extrusion (T0) Tool rotation (T1)

[1] This motor is not currently physically implemented on the tool.

Before we determine how we get there, we must first know where we're going. I.e. what is the nature of the post processing G-code that we are striving to generate and how does it differ from the G-code generated by our current slicers or algorithms? By a combination of Efrain Aguilera's original post processing program (whose work will be referred to throughout this thesis, and which will be published concurrently), as well as MatLab scripts, and hand-coded changes, the mechanical engineers in the W.M. Keck Center for 3D Innovation have been able to experimentally determine which G-code sequences should be included in the final output of the post-processing program for optimal control of the Lulzbot printer. To illustrate these G-code commands and their purpose, a sample design has been chosen that will highlight design specifications of the final G-code.

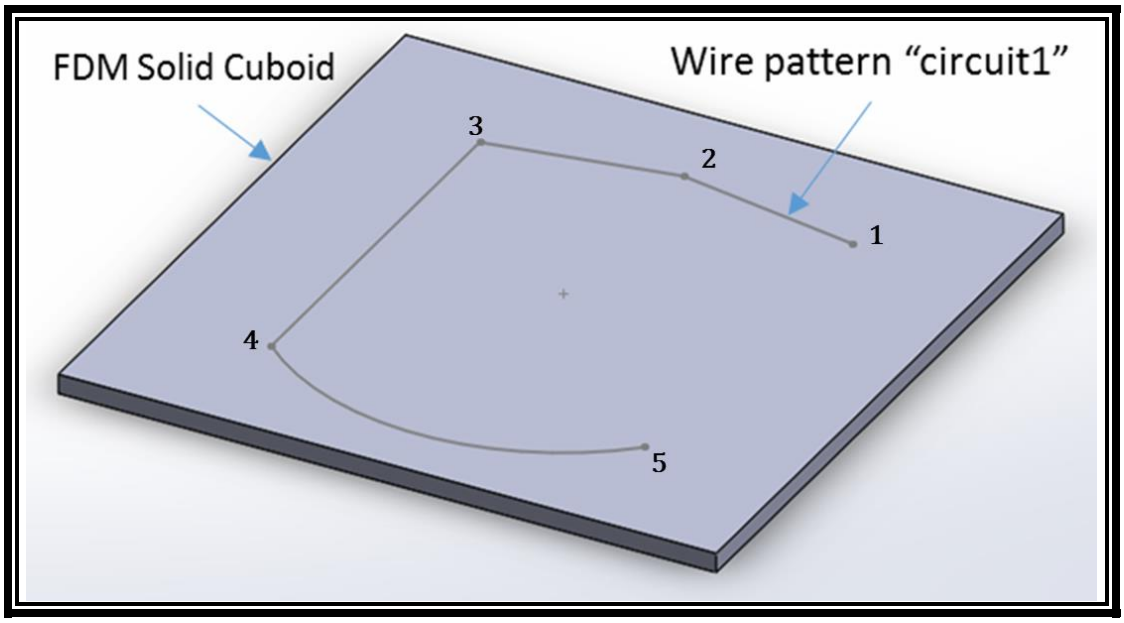

Figure 3.5: A simple pattern of 5 points, 3 lines, and an arc, used to demonstrate features and functionality of the final G-code. The wire patterns are often referred to as "circuits" in accordance with the nomenclature of Efrain Aguilera's original program.

Tool initialization

G-code generated by Cura does not take into account the necessary I/O initialization for the modifications made to the Lulzbot. Figure 3.6 shows four commands that need to be added to the initial FDM printing section of the final output G-code file.

Line 1 explicitly instructs the Lulzbot that any unspecified commands should be applied to the extruder tool and not the wire-embedding tool, while Lines 2-4 turn off custom I/O in the Lulzbot.

Original		Final	
1	M190 S90.000000	1	T0 ; Extruder tool
2	M109 S230.000000	2	M42 P16 S0 ;Turn off Cutter
3	;Sliced at: Tue 15-11-2016 15:22:49	3	M42 P14 S0 ;Turn off ExtruderUP/DOWN
4	;Basic settings: Layer height: 0.25	4	M42 P18 S0 ;Turn off Air
	Walls: 1 Fill: 20	5	M190 S70.000000
5	;Print time: 9 minutes	6	M109 S240.000000
6	;Filament used: 0.326m 2.0g		

Figure 3.6: Lines in red indicate changes to be added to the G-code file before printing.

Initial rotation and staking

Staking is the process whereby a wire is anchored to its starting position in the polymer (point 1, Figure 3.8). The left panel of Figure 3.7 below shows the preliminary code generated by Efrain Aguilera's original algorithm. The right panel shows the final code including modifications to correctly control the wire-embedding tool. Figure 3.8 gives a graphical representation of the tool movements that the code is implementing. A line-by-line description is given below the figures.

Aguilera algorithm		Final	
1	(* SHAPE Nr: 0 *)	1	;(* SHAPE Nr: 0 *)
2	G0 X177.878 Y71.273	2	G0 F320 X177.878 Y71.273
3	M3 M8		~~M3 M8~~
4	G0 Z 3.000	3	G1 F80 E3.01777; tool rotation added by Python/addToolRotation
5	F150	4	G0 F320 Z4.425
6	G1 Z 0.000		~~F150~~
7	F400	5	G1 F320 Z1.425
8	G1 X163.716 Y73.770	6	G4 P1000; Dwell
		7	G1 F320 Z1.925
		8	M42 P18 S0; Air off
		9	G4 P200; Dwell
		10	M42 P18 S255; Air on
		11	G4 P2500; Dwell
		12	M42 P18 S0; Air off
		13	G4 P1000; Dwell
		14	G1 F320 Z1.425
			~~F400~~
		15	G1 F320 X163.716 Y73.770

Figure 3.7: The staking process in G-code: lines in red show changes made to correctly control the Lulzbot wire-embedding tool.

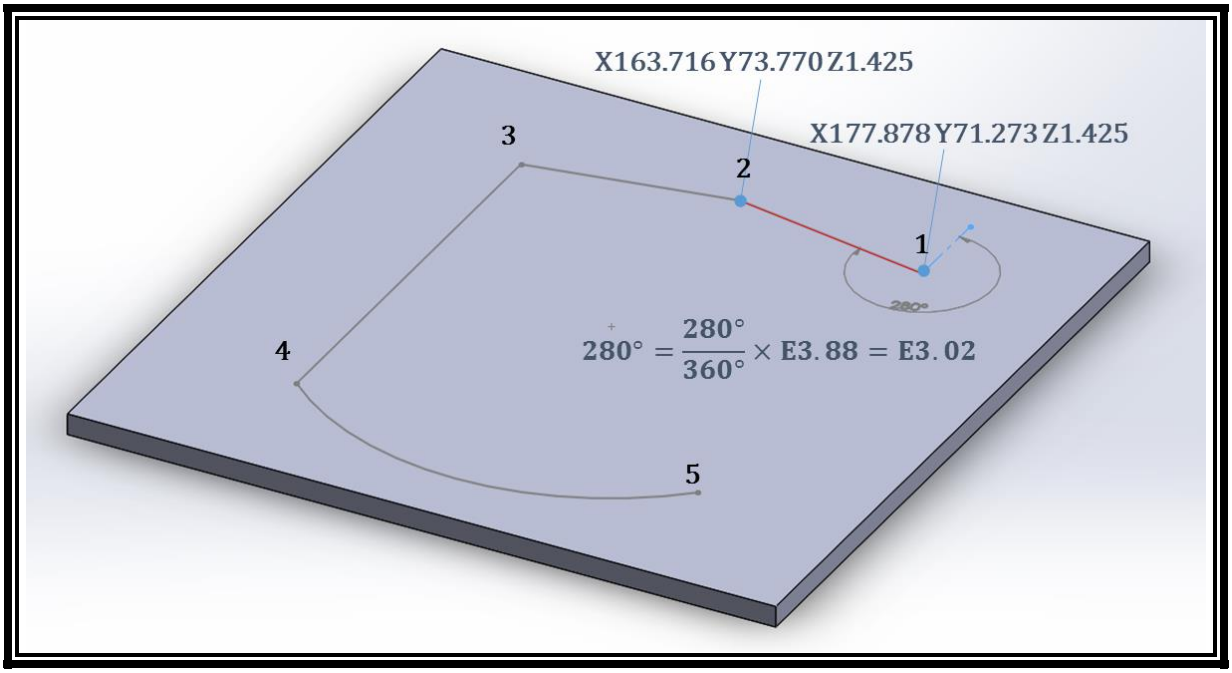

Figure 3.8: Graphical representation from Solidworks of the wire-pattern being implemented by the G-code in Figure 3.7. This code specifies tool orientation, staking at point 1, and translating and embedding wire to point 2 (highlighted in red).

In the right pane of Figure 3.7, line 1 has been changed to a comment, line 2 has been modified to explicitly define movement speed (F320), and a number of undesired lines have been removed. In line 3, a rotation command is specified. As this is the first tool orientation to be specified by the code, it is defined as an absolute rotation value (axis of rotation is the Z-axis), where 0° corresponds to the Y-axis (indicated by the blue dashed line in Figure 3.8). The orientation required to embed the first line of wire is 280°, which corresponds to an E parameter of E3.02 (see Figure 3.8). This rotation is performed high above the polymer surface, before the tool is commanded to begin to descend in line 4. In line 5, the wire-embedding tool head descends again and comes into contact with the polymer surface (point 1 in Figure 3.8). The tool delays for 1000 ms in line 6 and then raises back up 0.5 mm in line 7. Lines 8-12 initiate a 2500 ms blast of air to cool the polymer surface below its glass transition temperature, securing the wire in position in the polymer. Line 13 implements another 1000 ms delay, followed by a 0.5 mm descent in the Z direction to return the tool-head to the polymer surface in line 14 (point 1 again). The tool then immediately begins to translate to the next co-ordinate (point 2), line 15, with wire being pulled and embedded into the polymer as the tool travels away from the staking location.

Additional rotation processing requirements

The next two steps in this pattern demonstrate a peculiarity in how angles of different sizes need to be handled differently. The first turn, at point 2, involves a relative change in direction of 20°, whilst the second turn goes through an angle of 80°. Experimental observation has determined that angle changes of greater than approximately 30° in the polymer plane often result in undesirable effects. One such effect is that the wire is too hot to embed at the vertex of the turn and can be dragged into a gradual curve, instead of creating the desired sharp turn at the vertex. To compensate, additional steps are taken at vertices where turns greater than 30° occur. The sequence of steps involves raising the tool from the polymer plane, followed by cooling, a

mid-air rotation, and returning the tool back to the original position. Figure 3.9 and Figure 3.10 illustrate the sequence.

Aguilera algorithm		Final	
8	G1 X163.716 Y73.770	15	G1 F320 X163.716 Y73.770
9	G1 X149.554 Y71.273	16	G91
10	G1 X149.554 Y41.273	17	G1 F80 E-0.21554; tool rotation added by Python/addToolRotation
		18	G90
		19	G1 F320 X149.554 Y71.273
		20	G1 F320 X149.505 Y71.264 Z1.925; tool taper added by Python/genTaperLine
		21	M42 P18 S0; Air off
		22	G4 P200; Dwell
		23	M42 P18 S255; Air on
		24	G4 P2000; Dwell
		25	M42 P18 S0; Air off
		26	G91
		27	G1 F80 E-0.86223; tool rotation added by Python/addToolRotation G90
		28	G1 F320 X149.554 Y71.273
		29	G4 P1000; Dwell
		30	G1 F320 Z1.425
		31	G1 F320 X149.554 Y41.273

Figure 3.9: Small and large rotations implemented in G-code: lines in red show changes made to correctly control the Lulzbot wire-embedding tool.

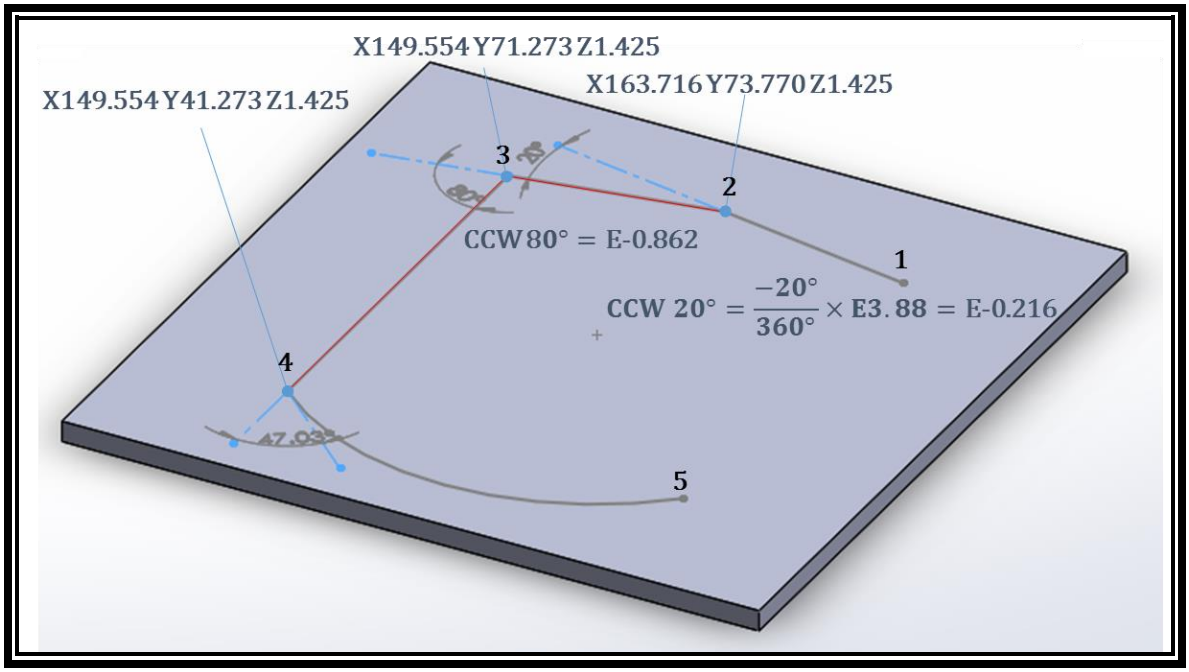

Figure 3.10: Graphical representation of the small (point 2) and large (points 3 and 4) rotations required by the wire-pattern. Turns at points 2 and 3 and the translational lines in red are generated by the G-code in Figure 3.9.

The sequence starts at line 15 (point 2), the endpoint for the sequence in Figure 3.7. At this point, a rotation of 20° is required. Since the rotation is less than 30°, the rotation can be made without lifting the tool from the polymer plane. Lines 16-18 achieve this by switching to relative positioning, initiating a counterclockwise (CCW) turn of 20° (-20°/360° * E3.88 = E-0.216), and switching back to absolute positioning. Line 19 instructs the tool to translate to point 3, embedding wire as it travels. At point 3, we encounter a turn of 80°. Line 20 instructs the tool to continue for 0.05 mm in the same XY direction (a relative change of X-0.049 Y-0.009), whilst simultaneously traveling up 0.5 mm in the Z direction, above the polymer plane. Lines 21-25 instruct the cooling air to blow for 2000 ms. Lines 26-28 command the 80° CCW rotation. Line 29 commands the tool to return to its original XY location in line 19 (point 3). Line 30 instructs the tool to descend back to the polymer surface, before continuing to point 4 in line 31.

G2 and G3 arc processing

G2 and G3 G-code commands specify clockwise and counterclockwise arcs respectively. In the example below, the syntax of the command is G3 X177.878 Y41.273 I14.162 J15.204, wherein “G3” specifies CCW rotation, “X177.878 Y41.273” specifies the end coordinates of the curve (point 5), and “I14.162 J15.204” specifies the vector to get from the start of the arc (line 10, point 4: G1 X149.554 Y41.273) to the origin (Figure 3.12). However, G2 and G3 commands are not recognized by the Lulzbot G-code parser, so these arcs must be interpreted into a series of G1 translational commands and then reprocessed to append the appropriate rotation commands.

Aguilera algorithm with simulated absolute coordinates[2]		Final	
10	G1 X149.554 Y41.273	31	G1 F320 X149.554 Y41.273
11	G3 X177.878 Y41.273 I14.162 J15.204	32	G1 F320 X149.554 Y41.223 Z1.925; tool taper added by Python/genTaperLine
		33	M42 P18 S0; Air off
		34	G4 P200; Dwell
		35	M42 P18 S255; Air on
		36	G4 P2000; Dwell
		37	M42 P18 S0; Air off
		38	G91
		39	G1 F80 E-0.52133; tool rotation added by Python/addToolRotation
		40	G90
		41	G1 F320 X149.554 Y41.273
		42	G4 P1000; Dwell
		43	G1 F320 Z1.425
		44	G1 F320 X150.282 Y40.626
		45	G91
		46	G1 F80 E-0.02883; tool rotation added by Python/addToolRotation
		47	G90
		48	G1 F320 X151.039 Y40.014
		...	...
		165	G91
		166	G1 F80 E-0.02883; tool rotation added by Python/addToolRotation
		167	G90
		168	G1 F320 X177.878 Y41.273

Figure 3.11: G2 and G3 arc to G1 line interpolation in G-code: lines in red show changes made to correctly control the Lulzbot wire-embedding tool. Short lines and rotations between lines 48 and 165, which have syntax similar to lines 45-48, have been omitted for brevity.

[2] The left pane features a simulated input, with the G3 command translated to match the coordinates of Figure 3.10. In reality, the Aguilera algorithm does not translate G2 or G3 coordinates, and so G2 and G3 commands will be converted to G1 commands before the translation component of the Aguilera algorithm is invoked. The explicit nature of how the new and old algorithms are integrated is explained in chapter 4.

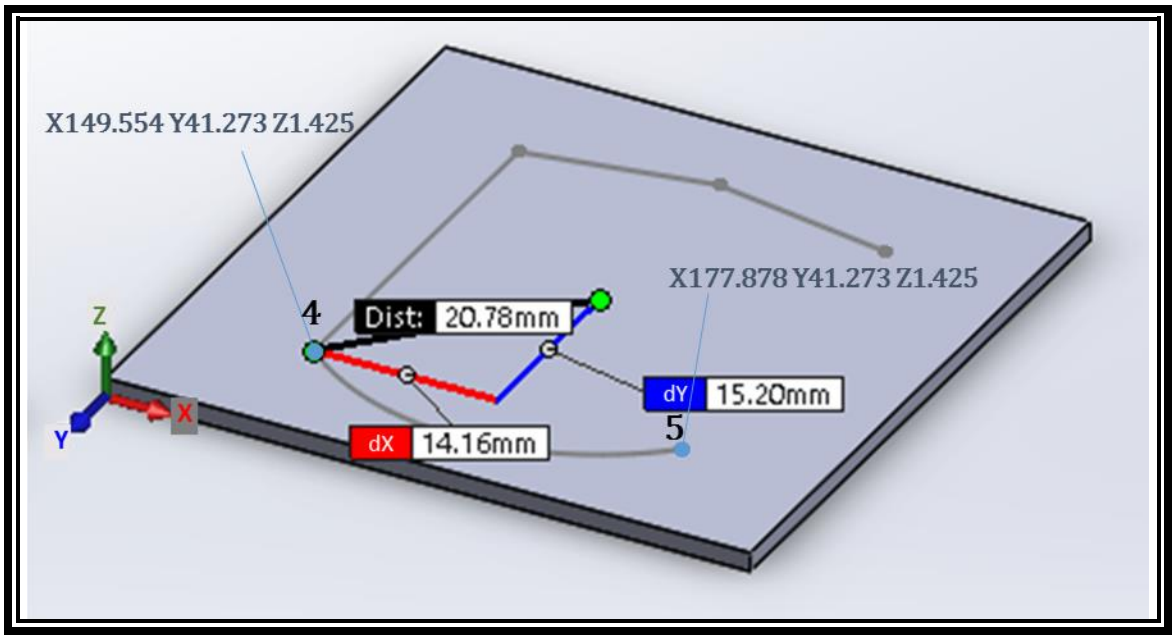

Figure 3.12: Graphical representation of the arc (between points 4 and 5) implemented by the G-code in Figure 3.11. The relation between the I and J components of the G3 command and the origin of the arc is clearly visible.

The sequence starts at Line 31, Figure 3.11 (Point 4, Figure 3.12). The algorithm generates the translational commands at line 44 and line 168 (as well as many intermediate points not listed for brevity) to define the curve in straight sections. These points are then processed by the tool rotation algorithm to generate the remaining code in the figure. The function used to interpolate lines from an arc, **ConvertG2**, is described on page 43.

The wire cutting process

Finally, at point 5, the wire has to be cut to end the "circuit" pattern. This is performed by gradually tapering up from the polymer surface (similar to the procedure for large rotations), blowing cooling air, and instructing the cutting actuator to make cutting strokes.

Aguilera algorithm		Final	
11	G3 X177.878 Y41.273 I14.162 J15.204	168	G1 F320 X177.878 Y41.273
12	F150		~~F150~~
13	G1 Z3.000		~~G1 Z3.000~~
14	G0 Z15.000	169	G1 F320 X177.953 Y41.339 Z1.925; tool taper added by Python/genTaperLine
15	M9 M5		
16	G0 X138.619 Y31.324		
17	M2 (Program end)	170	M42 P18 S0; Air off
		171	G4 P200; Dwell
		172	M42 P18 S255; Air on
		173	G4 P2000; Dwell
		174	M42 P18 S0; Air off
		175	G1 F320 X183.858 Y46.587 Z2.925; tool move added by Python/genTaperLine
		176	G4 P2000; Dwell
		177	M42 P16 S0; Cutter off
		178	G4 P200; Dwell
		179	M42 P16 S255; Cutter on
		180	G4 P200; Dwell
		181	M42 P16 S0; Cutter off
		182	G4 P200; Dwell
		183	M42 P16 S255; Cutter on
		184	G4 P200; Dwell
		185	M42 P16 S0; Cutter off
		186	G4 P200; Dwell
		187	G0 F320 Z16.425
			~~M9 M5~~
		188	G0 F320 X138.619 Y31.324
			~~M2 (Program end)~~

Figure 3.13: The cutting process in G-code: lines in red show changes made to correctly control the Lulzbot wire-embedding tool. A line by-line description is given below.

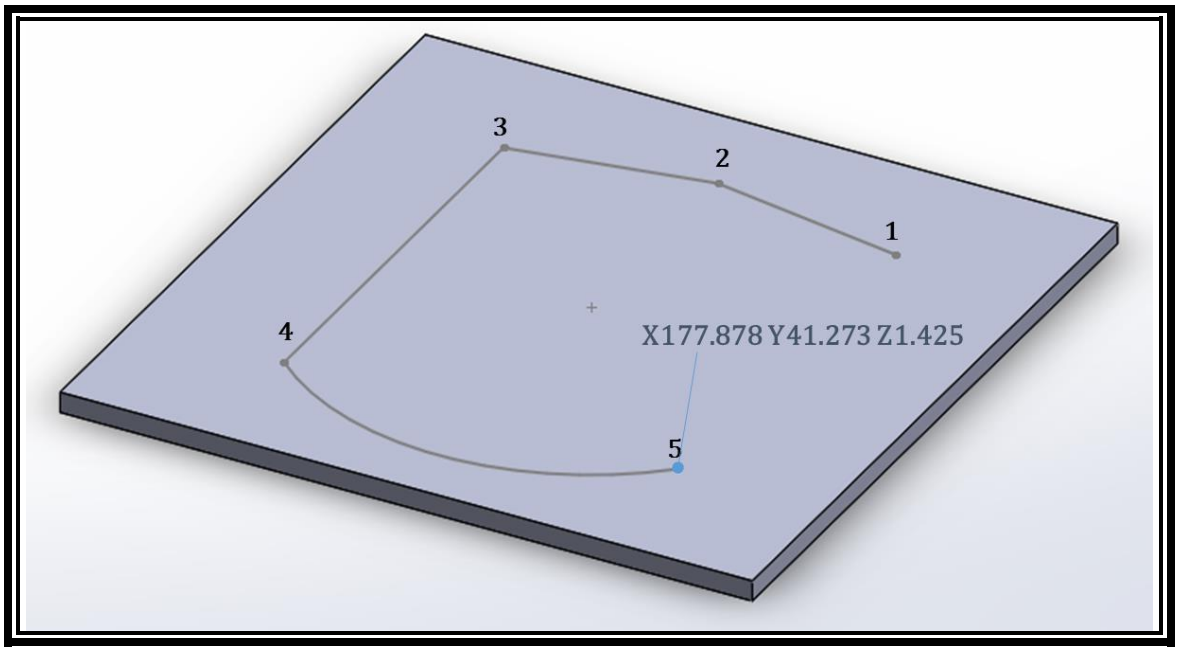

Figure 3.14: Graphical representation from Solidworks of the wire-pattern being implemented by the G-code in Figure 3.13. The tool is already at point 5, so the only remaining step is to cut the wire.

At line 168, the tool is already at point 5. Undesired commands generated as part of the Aguilera algorithm have been removed. In line 169, the tool continues 0.100 mm in the direction of the XY vector (a relative change of X+0.075 Y+0.066) and simultaneously rises up 0.500 mm from the polymer plane in the Z direction. Lines 170-174 initiate a 2000 ms burst of cooling air. Line 175 specifies further movement in the same XY direction and an additional 1.000 mm ascent in the Z direction. Lines 176 – 186 initiate a 2000 ms delay, followed by two cutting strokes. Lines 187 and 188 move the tool up and away from the part.

Foundation layer generation

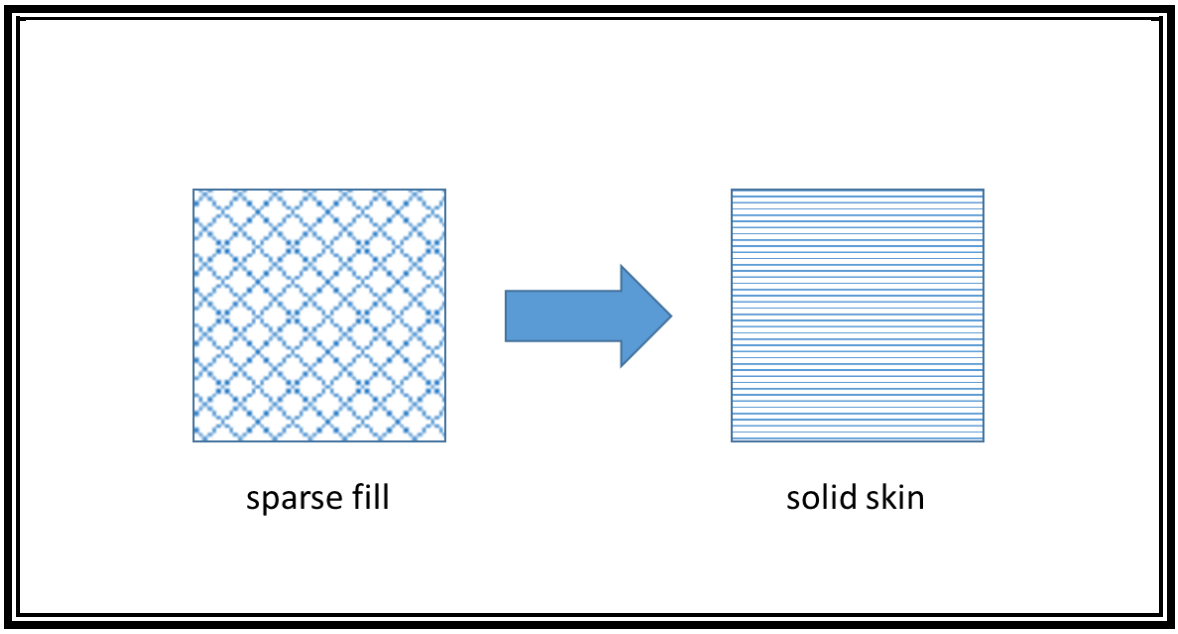

Figure 3.15: Solid polymer skin pattern necessary to provide a suitable foundation for wire-embedding.

Another change necessary for correct wire-embedding is to have a solid foundation layer to embed on. As a print job can be set to print with a sparse fill on internal layers, with densities as low as 10%, we need to verify that the layer where wire embedding is occurring has a suitable foundation. If it doesn't, a suitable foundation should be created. In contrast with the previous steps, which have focused on wire-embedding toolpaths, this G-code modification is a modification to the polymer toolpath G-code. It has been determined experimentally that a thickness of at least 0.75 mm is needed for embedding. If the print layer height is 0.25 mm, this would result in 3 layers of solid skin foundation being required. Figure 3.16 below shows an example snippet of G-code changes required to replace a sparse fill with a solid skin layer. In essence, a series of sparsely spaced diagonal lines is replaced by closely-packed horizontal lines, forming a solid layer referred to in Cura-commented G-code as a SKIN.

Original: sparse FILL generated by Cura		Final: solid SKIN	
1	;TYPE:FILL	1	;TYPE:SKIN inserted by CreateSkin()
2	G1 F2040 X47.550 Y107.654 E152.47214	2	G1 F2400 X95.376 Y106.972 E152.97618
3	G0 F10500 X47.551 Y111.547	3	G0 F10500 X47.876 Y107.472
4	G1 F2040 X52.951 Y106.147 E152.62177	4	G1 F2400 X95.376 Y107.472 E153.90692
5	G0 F10500 X53.114 Y106.147	5	G0 F10500 X47.876 Y107.972
6	G1 F2040 X95.701 Y148.734 E153.80188	6	G1 F2400 X95.376 Y107.972 E154.83766
7	G0 F10500 X95.700 Y148.251	7	G0 F10500 X47.876 Y108.472
	...		...

Figure 3.16: Example of replacing a sparse fill section with a solid skin in G-code

Now the requirements have been specified, the following chapter will describe how the author, in collaboration with Efrain Aguilera, has generated an algorithm to meet the specifications for generating multifunctional G-code to control the modified Lulzbot.

Chapter 4: A method for generating multifunctional G-code

Introduction

As outlined in chapters 1 and 2, the generic STL file format typically used to define solid bodies for 3D printing lacks the ability to fully define a multi-process 3D print. In response to this, the file must either be replaced with a more sophisticated file format or augmented by generating additional files to supplement the STL file and provide the information lacking in the STL file, such as toolpath information for the wire-embedding tool. As one design constraint is to integrate with existing Solidworks design software, a solution had to be found that was compatible with Solidworks capabilities. While Solidworks does offer native support for generating AMF files, the only additional information that can be specified in the file is material color and type, which is inadequate for a process such as wire-embedding. As Solidworks offers a Visual Basic API (application program interface), it may be possible to develop an AMF-exporting macro in the Visual Basic programming language. However, as there is limited access to software libraries that are compatible with the Solidworks Visual Basic API implementation, a simpler approach was adopted. This approach, developed by Efrain Aguilera [27], involves augmenting the STL file with additional files that contain the information necessary to fully define a multi-process, wire-embedding, FDM print. Outlined in Figure 4.1 below, the process involves the generation of an STL file with FDM print information and a DXF file with wire-embedding information, both of which contain a reference shape (generated by a Visual Basic macro), to preserve the translational and rotational geometric information between components. An info.txt file is generated, containing the Z-height for each wire-embedding sub-task[3].

[3] The current implementation only supports wire-patterns parallel to the XY plane.

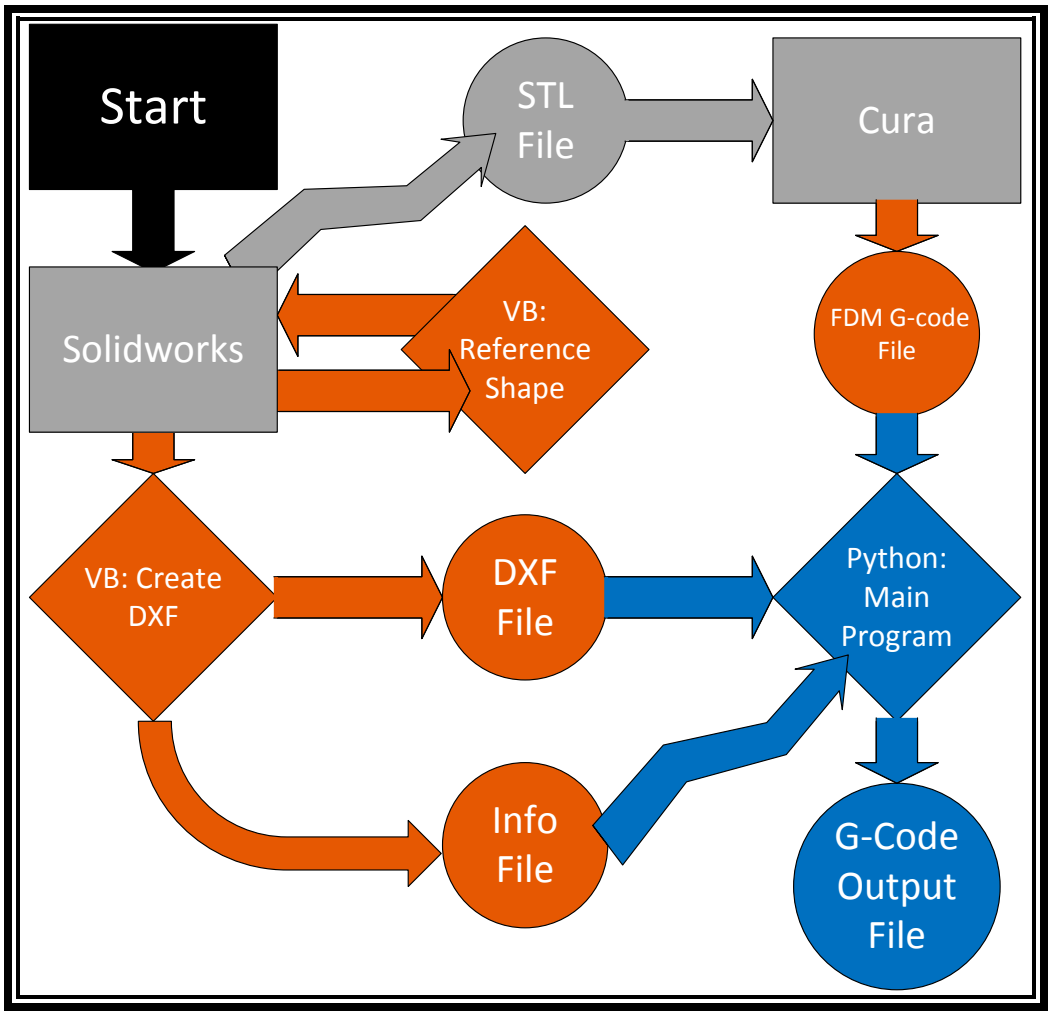

Figure 4.1: Workflow for generating multi-functional G-code (approach developed by Efrain Aguilera). Orange indicates process steps created by Efrain Aguilera; Blue steps indicate work within the scope of this thesis.

As the orange steps refer to algorithms detailed in the concurrently published thesis of Efrain Aguilera, they will only be briefly referred to here. Figure 4.2 - Figure 4.8 show the user experience of traveling through the orange steps of the work flow, from designing a pattern in Solidworks to executing the Python post-processing plug-in from Cura. In addition, a copy of the user procedure, used to train new users on this workflow, is included in Appendix A.

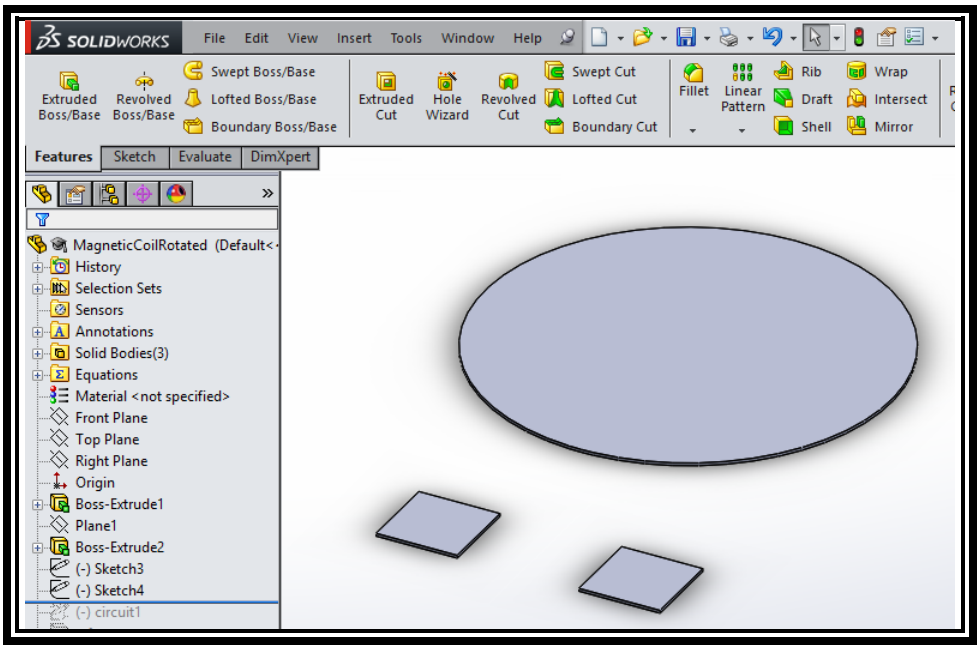

Figure 4.2: A conventional, 3D-printable design is created in Solidworks.

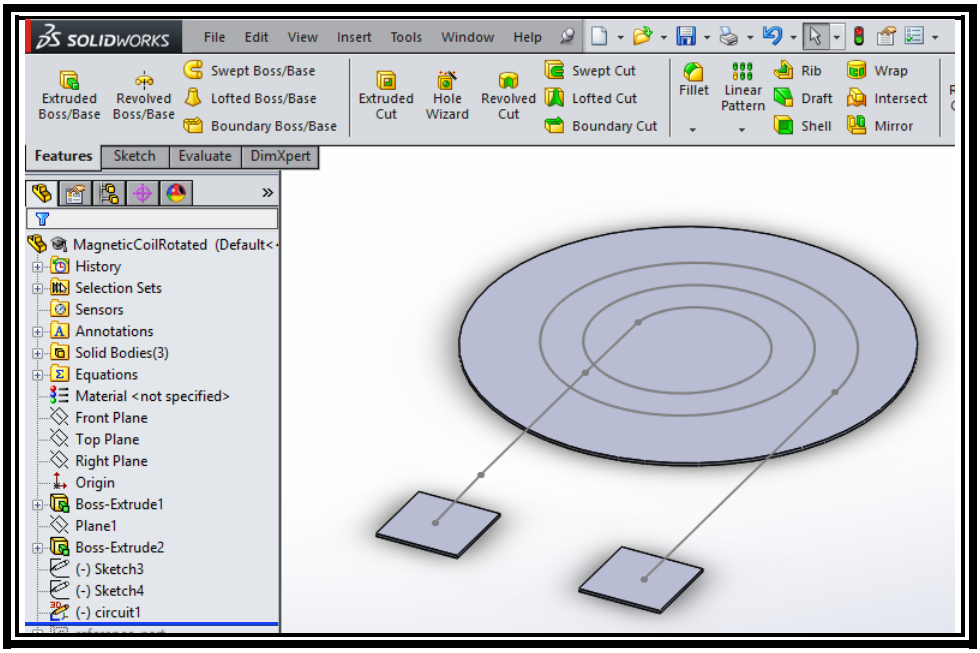

Figure 4.3: A 3D Sketch[4] representing the wire pattern is created and each subsequent wire pattern sketch is renamed to *circuit1*, *circuit2*, *circuit3*… as appropriate.

[4] "3D" as this explicitly defines the sketch in x, y, and z as opposed to a conventional sketch, which only has 2D data explicitly within the sketch and requires a reference to the surface it is drawn on to complete its definition. The explicit x, y, z definition in the 3D sketch is useful in the next step

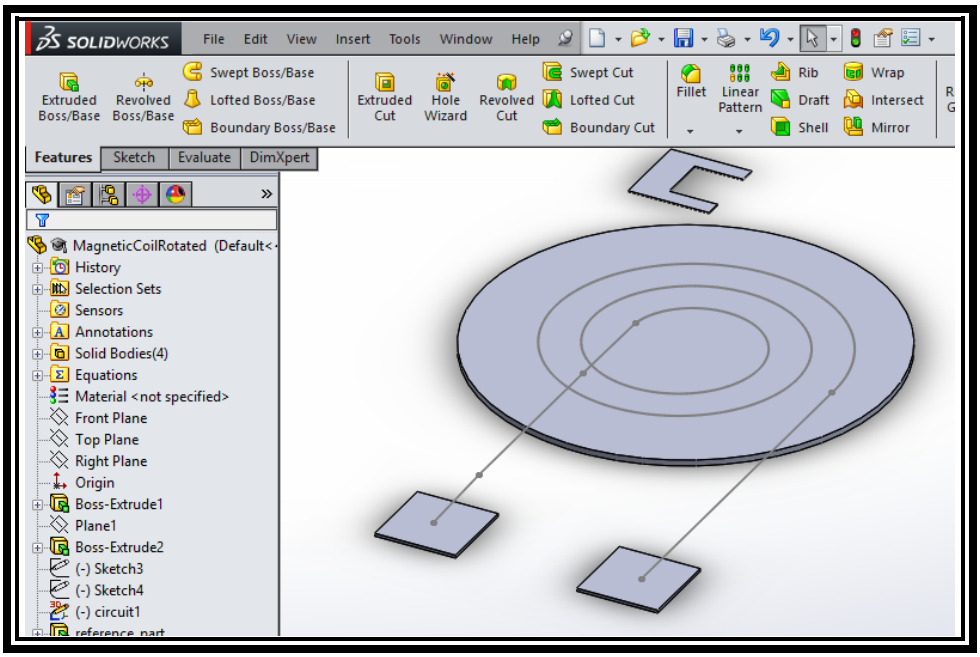

Figure 4.4: A Visual Basic macro is run, which creates a reference part (top of the figure). A second Visual Basic macro is run, which exports each circuit pattern and reference geometry as individual DXF files labeled *circuit1 (Top).dxf*, *circuit2 (Top).dxf*, *circuit3 (Top).dxf*, respectively (when more than one wire pattern is present). The FDM part is saved as an STL file.

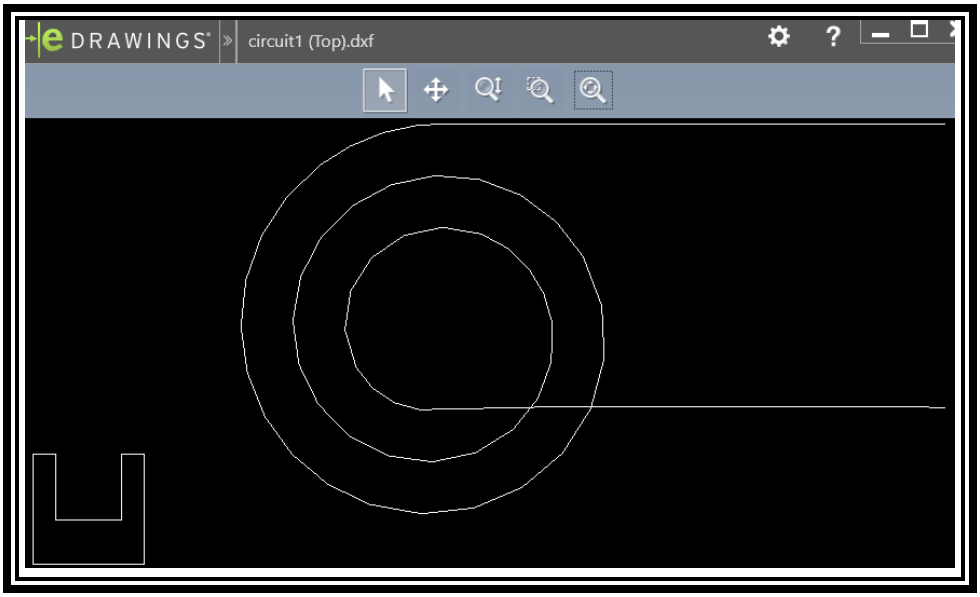

Figure 4.5: Depiction of the DXF file information outputted by the Solidworks Visual Basic macro, featuring the reference geometry.

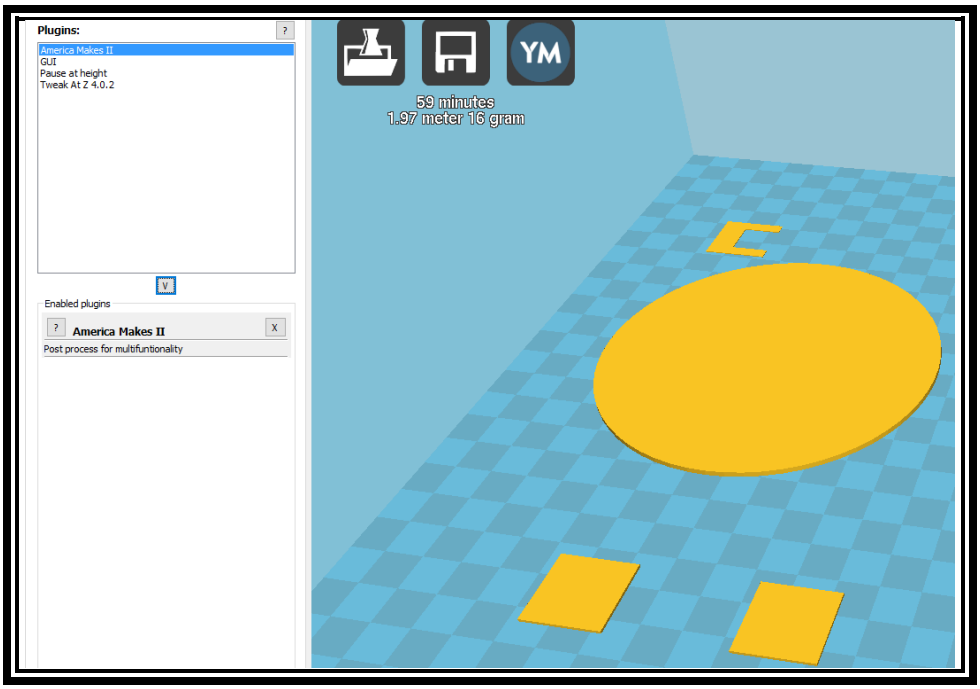

Figure 4.6: The STL file is loaded into the Cura slicing software and the America Makes II Python plugin is loaded from the plugins tab.

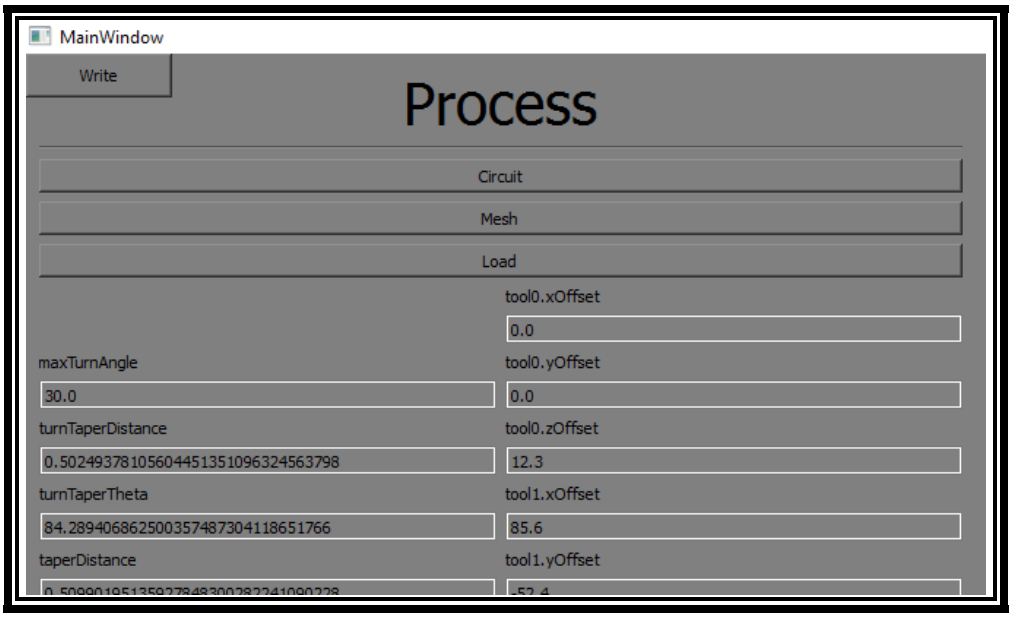

Figure 4.7: The Python plugin opens the Python main post-processing program and a GUI where various processing parameters relating to the multi-process print can be configured. The G-code is generated by clicking *Circuit*.[5]

[5] Edit boxes containing wire-embedding processing parameters indicate a later modification to the GUI from the original Aguilera GUI. Parameter edit boxes were added to the GUI by Jake Lasley.

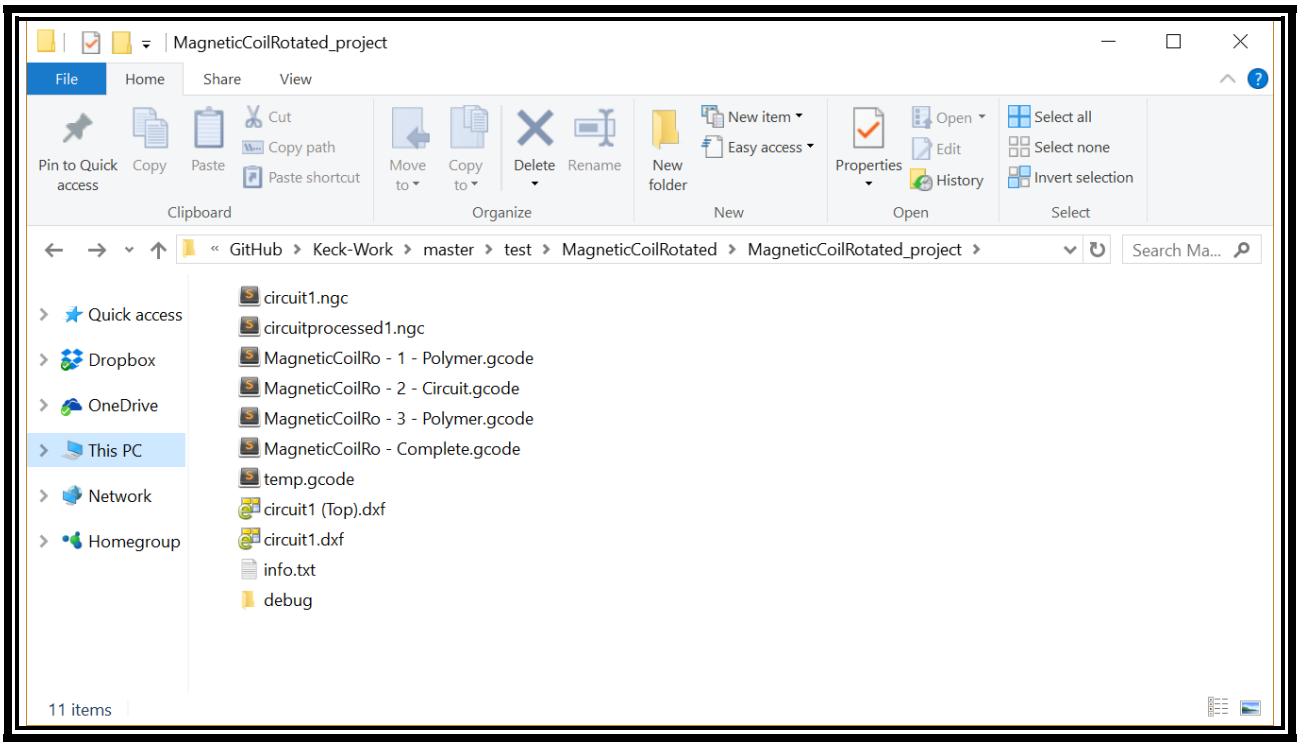

Figure 4.8: Multiple files are generated during the processing steps. *MagneticCoilRo – Complete.gcode* contains the complete print job, while the *MagneticCoilRo – [1,2,3] – [Polymer,Circuit].gcode* files allow individual stages to be printed separately.

The Python G-code Post-processor

A collaboration

The work on the Python G-code processor has been highly collaborative in nature. To help credit the work of the different contributors, the flowcharts and diagrams outlining the algorithm have been color coded to highlight who contributed to each step. Some hierarchical organization changes and variable name changes have occurred with respect to the code in Efrain Aguilera's concurrent publication, but do not affect the internal function of his algorithms.

AmericaMakes.py

AmericaMakes.py is a Python plug-in for Cura that initializes the post processor. The script initializes an executable that prompts the user for the file path of the folder where the files in Figure 4.8 were generated and saves the file path information in a variable, "out". The script

then uses the Cura slicer to generate G-code for the FDM print (without any wire-embedding information) and places this G-code in a file called *temp.gcode* in the folder designated by the "out" variable.

It then initializes and passes the "out" value to another executable, *main.exe* (which was compiled from a Python script, *main.py*).

main.py

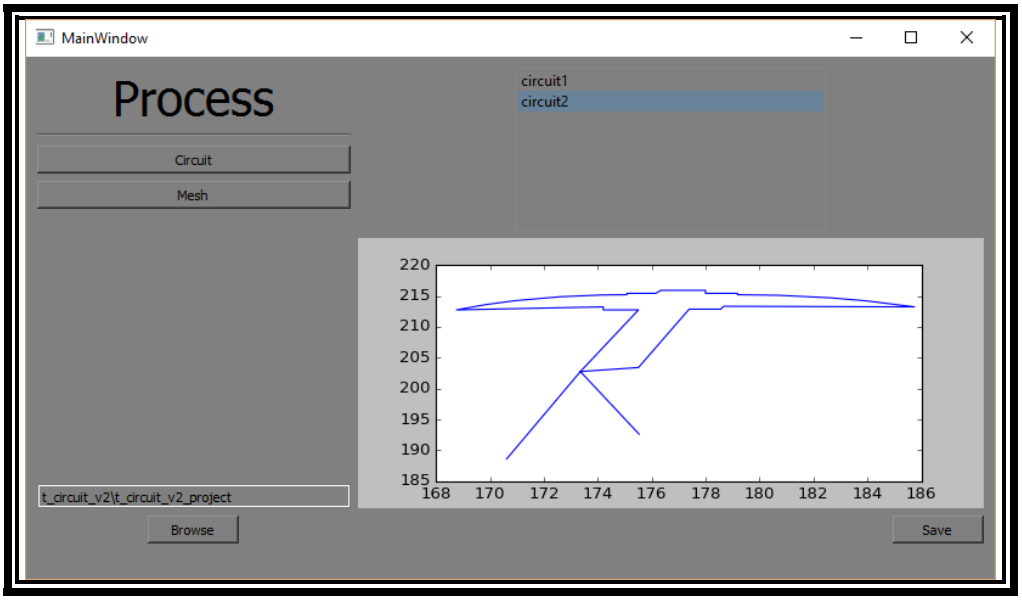

Figure 4.9: Early version of the GUI, developed by Efrain Aguilera.

Originally developed by Efrain Aguilera, the *main.py* script initializes a GUI that guides the user through the code generation progress. The GUI has been modified by Jake Lasley to include access to wire-processing parameters (Figure 4.7 above). The user starts G-code generation by selecting the *Circuit* button. The *main.py* script then begins to parse the input files *info.txt*, *circuit 1 (Top).dxf*, and *temp.gcode* generated in the earlier steps (Figure 4.10 below). It starts by reading *info.txt*, which was generated by the Solidworks macro and contains the information about the z height that each "circuit" or wire-pattern is found at. These height values in mm are stored in a list, *circuitZheights*, for later use. The script then uses the length of list *circuitZheights* to determine how many circuits are present and then initializes a loop to convert

each of their corresponding DXF files (previously generated by the Solidworks macro) into a simple G-code file. It does this by using an open-source software executable *DXF2GCODE.exe* [28], which generates a .ngc (G-code) file, such as *circuit1.ngc*, for each DXF. The G-code in these NGC files does not contain any machine-specific processing commands, such as fan control, wire-cutting control, or tool rotation – these commands are added by the *LulzProcessNGCcircuits* function (Figure 4.11).

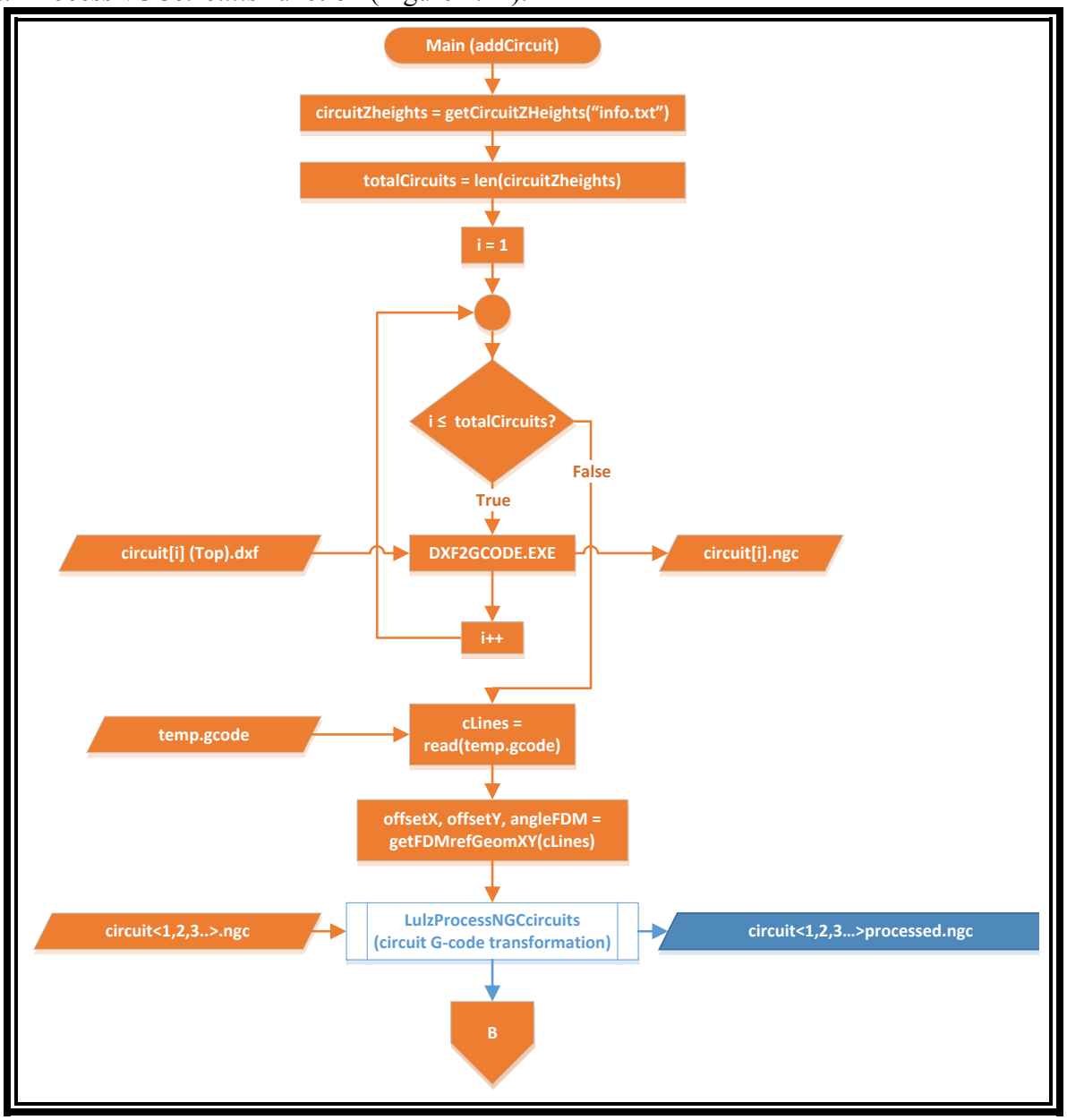

Figure 4.10: Overview (1 of 3) of the steps of the *addCircuit* function of the *main.py* program. Orange indicates process steps created by Efrain Aguilera; Blue indicates process steps developed within the scope of this publication. Part B continues in Figure 4.17, page 53.

The LulzProcessNGCcircuits function

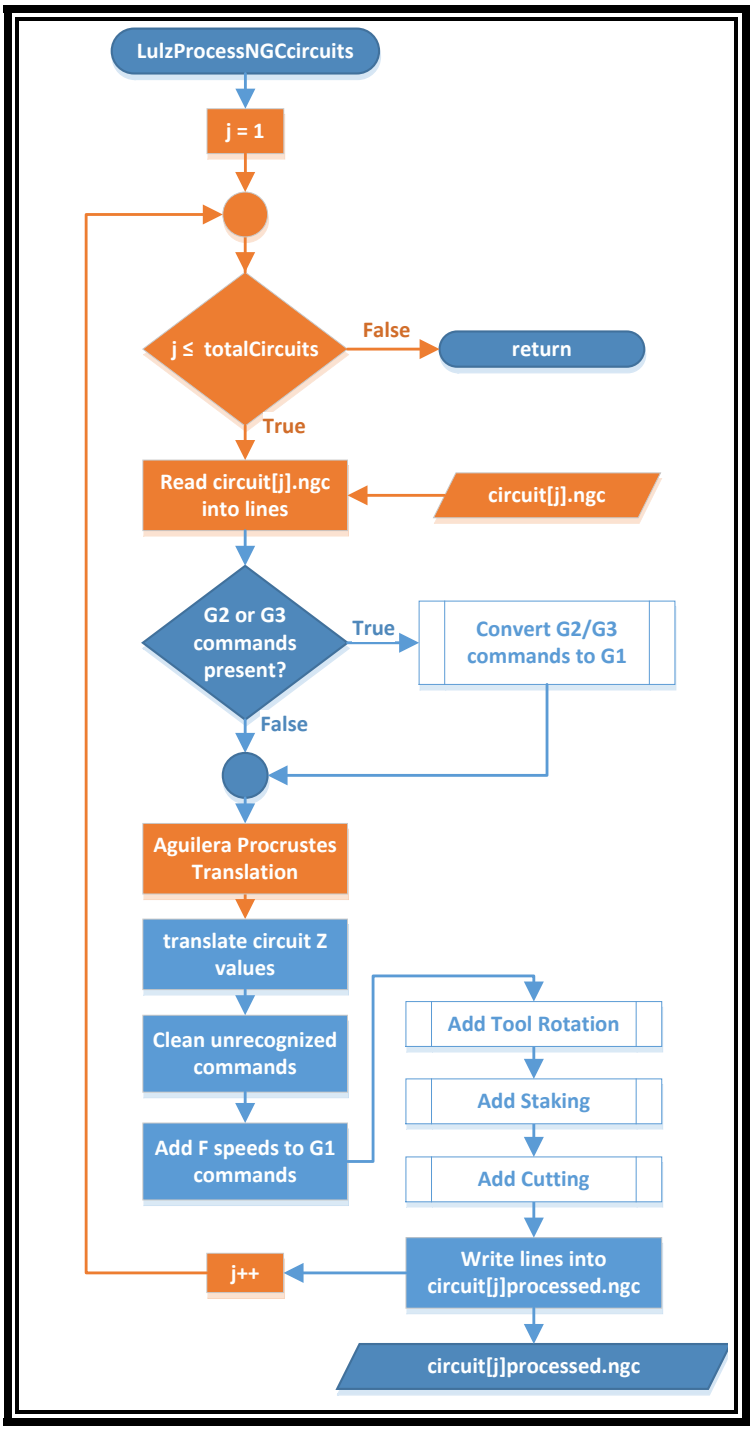

Figure 4.11: Overview of the *LulzProcessNGCcircuits* algorithm which generates wire-extruding G-code for the modified Lulzbot. Orange indicate steps generated by Efrain Aguilera. Blue steps relate to this publication. In this algorithm, the input is the *circuit[j].ngc* file generated by *DXF2GCODE.exe*; the output is the *circuit[j]processed.ngc* file which contains correctly-formatted G-code for each circuit pattern.

The *LulzProcessNGCcircuits* function takes the basic G-code output by *DFX2GCODE.exe* and processes it, so that it can be correctly parsed by the modified Lulzbot printer. It does this by setting up a loop to apply the function sequentially to each of the circuit patterns generated. The first step of the body of the loop reads the basic G-code output of *DXF2GCODE.exe* into a list called *lines*. It then scans the list for any occurrence of G2 or G3 text, indicating a G2 or G3 arc command is present, which needs to be replaced. If found, the *lines* list is passed into the *convertG2* function (Figure 4.12).

ConvertG2

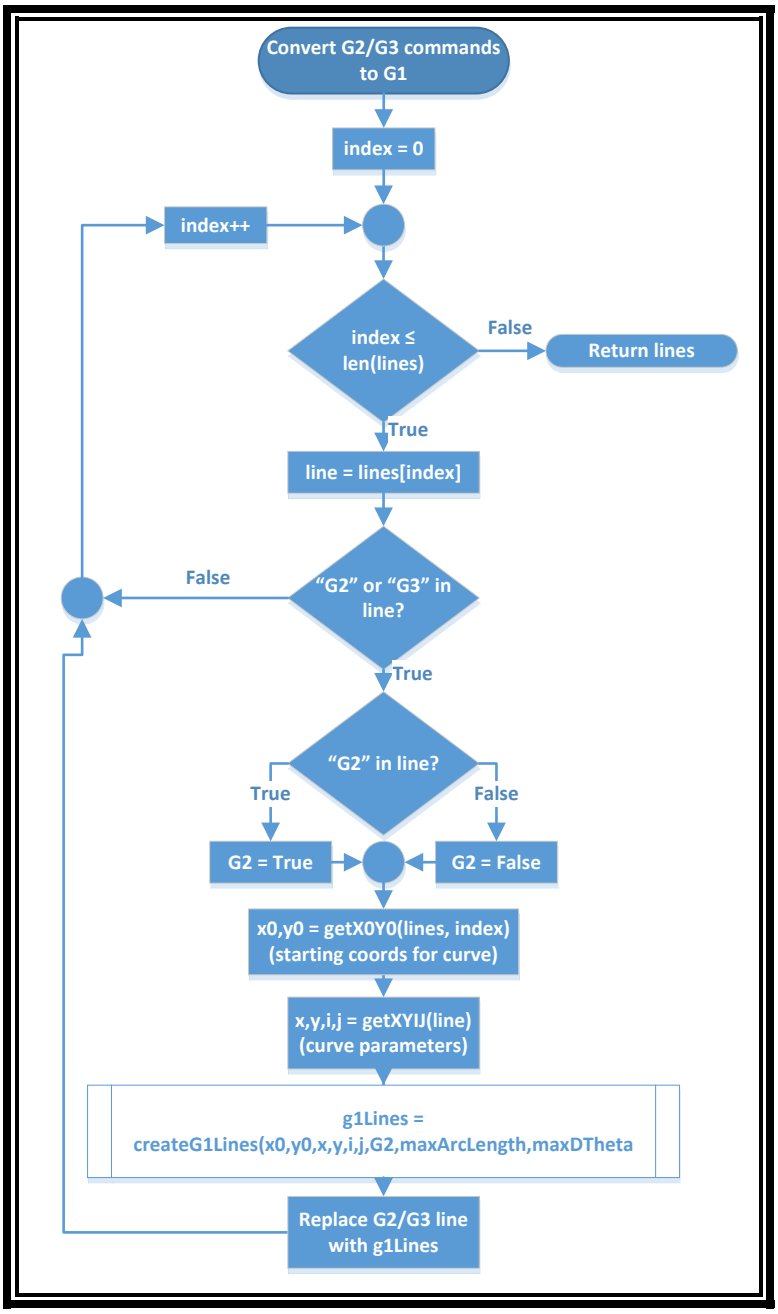

Figure 4.12: G2 conversion algorithm. All steps in this function relate to this publication.

The convertG2 function reads through each line of G-code in the lines list; if it encounters a "G2" or "G3" in a line, it sets variable *G2* to *True* for a G2 command and *G2* to *False* for a G3 command (this will be used to specify positive or negative sign in a later step). The *getX0Y0* function reads back from the current line to find the most recent G command,

which determines the X, Y starting coordinates of the curve (For syntax of G2 and G3 commands, see **G2 and G3 arc processing**, page 26); the *getXYIJ* function parses the G2 or G3 command's X, Y, I, and J values and saves them in their respective variables. These seven variables (*x0, y0, x, y, i, j, G2*) along with *maxArcLength* and *maxDTheta* parameters are fed into the function *createG1Lines* to generate straight line segments to replace the curve.

CreateG1Lines

```
1.  def createG1Lines(x0, y0, x, y, i, j, G2, maxArcIncrementLength, maxDTheta):
2.      g1Lines = []
3.      Cx, Cy = centerCalc(x0, y0, i, j)
4.      r = radiusCalc(i, j)
5.      initialAngle = initialAngleCalc(i, j)
6.      finalAngle = finalAngleCalc(Cx, Cy, x, y)
7.      arcTheta = arcAngleCalc(finalAngle, initialAngle, G2)
8.      arcLength = getArcLength(r, arcTheta)
9.      nIncrements = math.ceil(arcLength / maxArcIncrementLength )
10.     DTheta = arcTheta / nIncrements
11.     if (DTheta > maxDTheta):
12.         nIncrements = math.ceil(arcTheta / maxDTheta)
13.         DTheta = arcTheta / nIncrements
14.     arcIncrementLength = arcLength / nIncrements
15.     if G2 == True:
16.         sign = -1
17.     else:
18.         sign = 1
19.     index = 1 #don't need first point
20.     while (index <= nIncrements):
21.         theta = initialAngle + (sign * index * DTheta)
22.         theta = normalizeTheta(theta)
23.         x1 = round((r * math.cos(theta) + Cx), 3)
24.         y1 = round((r * math.sin(theta) + Cy), 3)
25.         line = createG1Line(x1,y1)
26.         g1Lines.append(line)
27.         index += 1
28.     return g1Lines
```

Figure 4.13: Algorithm for creating a list of straight line G1 commands for a given G2 command

The function starts by calculating the center coordinates of the arc from *x0, y0*, *i* and *j* (*Cx = x0 + i; Cy = y0 + j*) and the radius from *i* and *j* ($r = \sqrt{i^2 + j^2}$). The initial angle is calculated in radians using *atan2(-j,-i)*, with atan2 from the Python math module performing the arctangent function while ensuring the resulting angle is in the appropriate quadrant. The final angle is calculated in a similar fashion: *atan2((y-Cy), (x-Cx))*. *getAngleCalc* then determines the total

angle being turned through based on the initial and final angles and whether the turn is clockwise (*G2 = True*) or counterclockwise (*G2 = False*). The arc length is then calculated from the radius and arc angle. It then calculates the number of increments to split the arc into by dividing *arcLength* by *maxArcIncrement* length and then rounding up to the nearest integer. In the case of the default *maxArcIncrement* length of 1.0 mm, this will result in segments slightly shorter than 1 mm, due to the rounding up. It then divides the *arcAngle* by *nIncrements* to determine the theta value traveled through in each segment. If this angle is too large (greater than 10° by default), the increments will be recalculated to ensure the generated lines have sufficient resolution to accurately represent the curve. The *arcIncrementLength* of an individual line is then determined by dividing *arcLength* / *nIncrements*. A loop is then set up to calculate the coordinates for each point, based on their *r*, *theta* polar coordinates from *Cx*, *Cy*. The parameter *r* is constant for any given arc and theta varies by *initialAngle + (sign * index * DTheta)*, with the index incrementing on each loop iteration. The polar coordinates are converted into Cartesian values and stored in *x1*, *y1* variables. These variables are then used to generate G1 lines with standard G-code syntax (although no F value for wire-embedding speed has been explicitly defined at this point). Each line is appended to the *g1Lines* list to return back up to the parent *convertG2* function. The final step of the *convertG2* function replaces the original G2 or G3 command with the contents of the *g1Lines* list.

X, Y, Z translations and F wire-embedding speed

Returning to Figure 4.11, the *LulzProcessNGCcircuits* algorithm continues by performing a Procrustes translation function (detailed in Efrain Aguilera's thesis), which translates the G0 and G1 commands to their correct locations relative to the FDM *temp.gcode* and the XY tool offsets. As the G2 and G3 commands have already been converted to G1, these commands are also correctly translated. However, the Z values are ignored by the Aguilera Procrustes Translation and must be adjusted by a separate function, *transformCircuitZ(lines, zHeight)*. This function acts on all lines and modifies Z values by adding the *zHeight* of the

current layer (including tool Z offset) to any G0 or G1 command with a Z parameter. The function then returns the modified lines to the parent *LulzProcessNGCcircuits* function. The next function removes undesired F and M commands generated by *DXF2GCODE.exe* as well as ensuring comment lines are appropriately prefixed with a ";" character (which the Lulzbot recognizes as a comment). Next, the *wire-embed-speed* parameter is added to all G1 and G0 lines to ensure the correct speed is explicitly specified.

AddToolRotation

```
1.  newlines = []
2.  firstE = True
3.  for index, line in enumerate(lines): #this is the same as using a while loop starting
    at index = 0
4.      if line[0:9] == ";(* SHAPE":
5.          firstE = True
6.      elif firstE == True:
7.          if line[0:2] == "G0":
8.              x1 = CreateSkin.getCoOrd(line, 'X')
9.              y1 = CreateSkin.getCoOrd(line, 'Y')
10.             x2, y2 = getNextXY(lines, index)
11.             E = getAbsAngleE(x1, x2, y1, y2)
12.             newline = "G1 F" + str(fE) + " E" + "%.5f" % E + "; tool rotation added by Pyt
    hon/addToolRotation\n" #Absolute tool rotation for first point in the shape.
13.             firstE = False
14.             newlines.append(line) #original line
15.             newlines.append(newline) #additional line to specify rotation
16.             continue
17.     elif CreateSkin.getCoOrd(line, 'X') > 0: #there is an X
18.         x1 = CreateSkin.getCoOrd(line, 'X')
19.         y1 = CreateSkin.getCoOrd(line, 'Y')
20.         x2, y2 = getNextXY(lines, index)
21.         if x2 == -1: #no next XY. End of shape.
22.             newlines.append(line) #original line
23.             continue
24.         E2 = getAbsAngleE(x1, x2, y1, y2)
25.         relE = getRelAngleE(E, E2)
26.         E = E2
27.         newlines.append(line) #original line
28.         rotationLine = "G1 F" + str(fE) + " E" + "%.5f" % relE + "; tool rotation added by
     Python/addToolRotation\n" #Not yet appended. Stored as variable. Use depends on if statem
    ent below.
29.
30.         if ((relE > maxTurnE) or (relE < maxTurnE * -1)): #big CW or CCW turn
31.             dx, dy, x1, y1 = getDXDYx1y1(lines, index) #get taper vector
32.             comment = "tool taper added by Python/genTaperLine"
33.             taperLine, x2, y2, z2 = genTaperLineX2Y2Z2(distance, theta, x1, y1, z1, dx, dy
    , F, comment) #x2, y2, z2 can be ignored/discarded. Not needed in this application.
34.             newlines.append(taperLine) #taper (come up)
35.             newlines.append(gM42(Air, off)) #air off
36.             newlines.append(gDwell(shortDwell)) #dwell200
37.             newlines.append(gM42(Air, on)) #air on
38.             newlines.append(gDwell(moveDwell)) #dwell2000
```

```
39.             newlines.append(gM42(Air, off)) #air off
40.             newlines.append("G91\n") #specify relative positioning
41.             newlines.append(rotationLine) #specify relative rotation
42.             newlines.append("G90\n") #specify absolute positioning
43.             newlines.append(line) #move back to original XY (original line again)
44.             newlines.append(gDwell(moveShortDwell)) #dwell1000
45.             newlines.append("G1 F%d Z%.3f\n" % (F, z1)) #go back to original Z
46.         else: #small turn
47.             newlines.append("G91\n") #specify relative positioning
48.             newlines.append(rotationLine) #specify relative rotation
49.             newlines.append("G90\n") #specify absolute positioning
50.         continue
51.
52.     newlines.append(line)
53. return newlines
```

Figure 4.14: Part of the *addToolRotation* function, used to generate correct tool orientation.

The function *addToolRotation* is invoked to add commands that will correctly orient the wire-embedding tool during wire embedding. A loop is set up to read through the *lines* list again (which contains all previous G-code translations and modifications) and appends each unchanged line as well as modified lines into a new list named *newlines*. The algorithm first looks for the comment *";(* SHAPE"* which indicates the start of a new circuit pattern. The first tool orientation for a new circuit pattern is specified as an absolute rotation with respect to the Y axis in the XY plane. After the *";(* SHAPE"* line, the algorithm looks for the first occurrence of a G0 command, which will contain the X and Y coordinates of the first point in the circuit pattern. To get the appropriate angle, the algorithm also finds the next X, Y coordinates, which it saves to the *x2* and *y2* variables. The *getAbsAngleE(x1, x2, y1, y2)* function then finds the absolute angle (with respect to the Y axis) of the line defined by a start point of x1, y1 and an end point of x2, y2 in units of E (where 360° is approximately E3.88). A line with correct G-code syntax is then generated, including rotation speed (F) and angle (E), as well as a comment. The *firstE* variable is set to *False*, so future commands will generate relative angle rotations. The original line (containing the tool X, Y translation command) is appended to *newlines*, followed by the rotation command that was just generated. The algorithm continues on to the next line, evaluating any line that has an X coordinate specified (indicating a line that needs to be modified

for rotation). When it finds a line to be modified, it parses the X and Y coordinates into *x1* and *y1*, as well as the next X and Y coordinates into *x2* and *y2*. If there are no next X and Y coordinates, the end of the circuit has been reached and an additional rotation line does not need to be generated – only the original *line* is appended to *newlines*. If next X and Y coordinates were found, the *getAbsAngleE(x1, x2, y1, y2)* is invoked and the value saved to *E2*. It then uses the previous absolute angle *E* with *E2* to find a relative angle between them *relE* using the function *getRelAngleE(E, E2)*. This function generates an angle between -180° and +180° in terms of E units. It does this by taking the difference between *E* and *E2*; if this generates an angle equivalent to larger than 180°, such as 270°, it will be converted to an opposite rotation, i.e. -90° to ensure the tool takes the more efficient rotational path and to avoid unnecessary torsional strain on the wire. After the relative rotation is generated, *E2* is saved to *E* in preparation for the next iteration of the loop. The original *line* (for translation) is appended to *newlines* and the relative rotation command with correct G-code syntax is saved in the *newline* variable, but is not yet appended to the *newlines* list. The algorithm then checks if the magnitude of the rotation (*relE*) generated is larger than the *maxTurnE* (default is equivalent to 30°). If it is, the extra tapering steps in Figure 4.14 lines 34 – 45 are generated (corresponding to the **Additional rotation processing requirements** described on page 24). If the angle is small (under 30°), lines 47-49 are appended. Once all lines have been evaluated and modified, the *newlines* list is returned to the *LulzProcessNGCcircuits* parent function.

AddStaking

```
1.  def addStaking(lines, z):
2.      def genMoveUpLine(line, dZ):
3.          zStartPos = line.find('Z') + 1
4.          zEndPos = line.find('\n')
5.          zVal = float(line[zStartPos:zEndPos])
6.          NEWzVal = zVal + dZ
7.          newline = line[:zStartPos] + "%.3f\n" % NEWzVal
8.          return newline
9.
10.     #After rotation and move down
11.     firstZ = True
12.     newlines = []
13.     for index, line in enumerate(lines):
14.         if line[0:9] == ";(* SHAPE":
15.             firstZ = True
16.         elif firstZ == True:
17.             if "Z%.3f" % z in line: #if z == 0.75 then Z0.750
18.                 newlines.append(line)
19.                 newlines.append(gDwell(moveShortDwell))
20.                 newlines.append(genMoveUpLine(line, 0.5))
21.                 newlines.append(gM42(Air, off))
22.                 newlines.append(gDwell(shortDwell))
23.                 newlines.append(gM42(Air, on))
24.                 newlines.append(gDwell(stakeAirDwell))
25.                 newlines.append(gM42(Air, off))
26.                 newlines.append(gDwell(moveShortDwell))
27.                 newlines.append(line) #move back down
28.                 firstZ = False
29.                 continue
30.         newlines.append(line)
31.     return newlines
```

Figure 4.15: The addStaking function.

The addStaking function is a simple function that looks for the first occurrence of a Z coordinate at the polymer surface (specified by variable *z*) for each new shape (circuit). When it finds that Z value, it appends lines 19-27 to perform the desired sequence described in **Initial rotation and staking**, page 22.

AddCutting

```
1.  def addCutting(lines, taperDistance, taperTheta, z1, taperF, moveDistance, moveTheta,
    moveF, strokes):
2.
3.      def genEndCoolingLines():
4.          coolingLines = []
5.          coolingLines.append(gM42(Air, off))
6.          coolingLines.append(gDwell(shortDwell))
7.          coolingLines.append(gM42(Air, on))
8.          coolingLines.append(gDwell(coolDwell))
9.          coolingLines.append(gM42(Air, off))
10.         return coolingLines
11.
12.     newlines = []
13.     for index, line in enumerate(lines):
14.
15.         if ((line[0:2] == "G1") and ("Z%.3f" % (z1 + 3) in line)): #replace verticle Z mov
    ement with taper, cool, move, and cut.
16.
17.             #get the xy plane vector (used to get the direction for taper and move)
18.             dx, dy, x1, y1 = getDXDYx1y1(lines, index - 1)
19.
20.             #taper
21.             comment = "tool taper added by Python/genTaperLine"
22.             taperLine, x2, y2, z2 = genTaperLineX2Y2Z2(taperDistance, taperTheta, x1, y1,
    z1, dx, dy, taperF, comment)
23.             newlines.append(taperLine)
24.
25.             #cool
26.             coolingLines = genEndCoolingLines()
27.             for line in coolingLines:
28.                 newlines.append(line)
29.
30.             #move and dwell
31.             comment = "tool move added by Python/genTaperLine"
32.             moveLine, x2, y2, z2 = genTaperLineX2Y2Z2(moveDistance, moveTheta, x2, y2, z2,
     dx, dy, moveF, comment) #to generate the move line, we use the taper function with a thet
    a of 0 degrees.
33.             newlines.append(moveLine)
34.             newlines.append(gDwell(moveDwell))
35.
36.             #cut
37.             j = 1
38.
39.             newlines.append(gM42(Cutter, off))
40.             newlines.append(gDwell(shortDwell))
41.             while j <= strokes:
42.                 newlines.append(gM42(Cutter, on))
43.                 newlines.append(gDwell(shortDwell))
44.                 newlines.append(gM42(Cutter, off))
45.                 newlines.append(gDwell(shortDwell))
46.                 j += 1
47.         else:
48.             newlines.append(line)
49.     return newlines
```

Figure 4.16: The *addCutting* function.

The *addCutting* function shares some similarities with the tapering movements used for large turns. The function begins by reading through the input *lines* (G-code), looking for an increase in Z height by 3.0 mm (line 15). Originally generated by *DXF2GCODE.exe*, this precise change in Z indicates that the end of a circuit pattern has been reached. Once this change in Z has been found, the XY plane unit vector is calculated (i.e. the XY vector that defined the direction the tool was traveling in) and the last X and Y coordinates are saved in the *x1* and *y1* variables. Using this information, along with *taperTheta* and *taperDistance* to specify angle from the XY plane and magnitude of displacement, a taper displacement is specified to move the tool up from the polymer plane (but continuing in the same XY direction). A series of commands in *genEndCoolingLines* causes the air blower to cool the part. A second movement is generated by lines 32 and 33. After a short delay, the appropriate number of cutting strokes are generated, depending on the *strokes* variable (lines 34-46).

At this point all the necessary changes have been made to the body of the circuit G-code and it is saved to the file *circuit[j]processed.ngc* (Figure 4.11, page 42); *j* is incremented, and the next circuit pattern is processed. If there are no circuit patterns remaining, the *LulzProcessNGCcircuits* function is finished and it returns control to the *addCircuit* function in *main.py*.

main.py (addCircuit) continued (part B)

Figure 4.17, below, shows the next steps in the *addCircuit* function after *LulzProcessNGCcircuits* has executed. As most of these stages of the function are outside the scope of this thesis, other than *CreateSkin* and the use of the *circuit[j]processed.ngc* file, they are only summarized briefly.

A loop is set up to add the modified circuit code generated by *LulzProcessNGCcircuits* to the appropriate section of the FDM polymer print, thereby starting the process of physically merging the two G-code files. It does this by parsing the Z value for the layer height, every time a new layer is encountered, specified by a ";LAYER" comment in the G-code lines. If the Z value of the layer matches the Z value of the current *j* index of the *circuitZheights* array, a match has been found. The function *CreateSkin* ensures an appropriate polymer foundation is placed beneath the wire and the contents of *circuit[j]processed.ngc* (the wire-embedding code) are appended at the end of the layer (immediately before the start of the next layer of FDM printing).

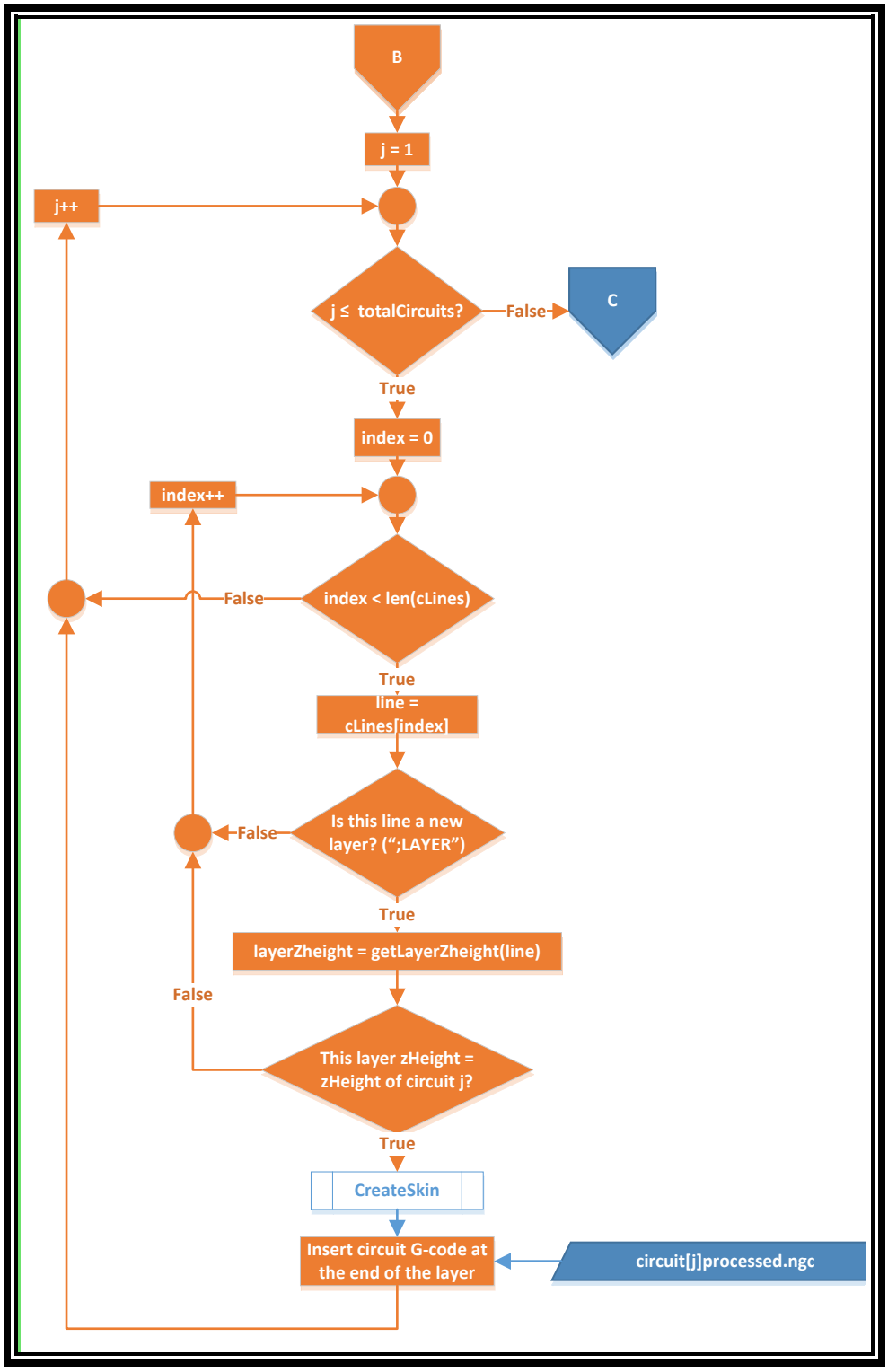

Figure 4.17: Overview (2 of 3) of the main.py *addCircuit* function. Orange indicates process steps created by Efrain Aguilera; Blue indicates process steps within the scope of this publication. Continued from Figure 4.10, page 41.

CreateSkin

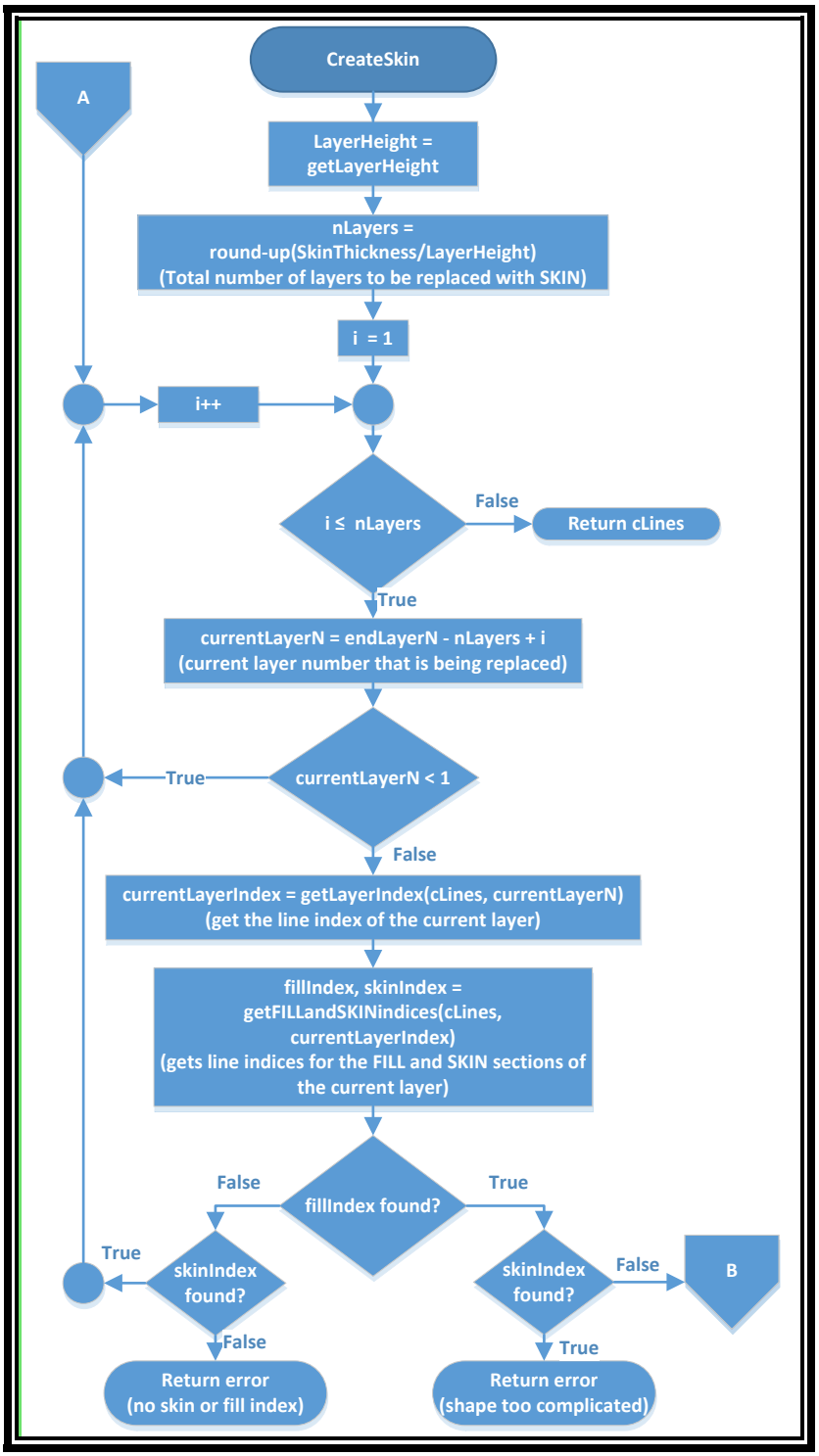

Figure 4.18: Overview (1 of 2) of the *CreateSkin* function. All process steps illustrated are within the scope of this publication. Continued in Figure 4.19.

The *CreateSkin* function creates a solid foundation for wire embedding, replacing sparse fill layers with solid skin layers. The current scope of the function is only capable of processing simple shapes with a single exterior perimeter (i.e. no donuts or a layer with multiple shapes or islands). Future versions of the algorithm will be capable of handling more complex shapes. Currently, more complicated shapes must be printed with 100% density to ensure the wire embedding process has a suitable foundation. Even so, the current function is quite detailed, so only an overview of the sub-functions will be discussed here. The full contents of *CreateSkin.py* are posted in Appendix B, for reference.

From Figure 4.18, the function begins by examining the G-code in *temp.gcode* to calculate the layer height. It determines this by subtracting the Z height of layer 1 from the Z height of layer 2, with the resulting difference being the layer height. The next step determines how many layers need to be replaced to create a suitable foundation, where *SkinThickness* is a variable specifying how thick the foundation should be (default 0.75 mm) and the *LayerHeight* is the value calculated in the previous step (default 0.25 mm). With default values, this will result in 3 layers to be replaced to create the foundation. This result is saved to *nLayers*. A loop is set up to replace the sparse fill with solid skin on each of the designated layers. Within the body of the loop, the current layer number is determined by subtracting *nLayers* from *endLayerN* and adding the loop index (i.e. if wire embedding occurs on Layer 5, by default, *currentLayerN* values of 3, 4, and 5 will be generated to replace the sparse fill on Layers 3, 4, and 5). The next step determines the line index for the start of the specified layer. From this value, the line indices are determined for FILL and SKIN sections within the specified layer. Within the scope of the current algorithm, only two outcomes are "allowed": 1. A FILL index IS NOT found, but a SKIN index IS found (in this case, the layer already has a solid SKIN and no change is required) 2. A FILL index IS found, but a SKIN index IS NOT found (in this case, the algorithm will continue to replace the FILL section with a SKIN section, Part B Figure 4.19). If neither a FILL index nor SKIN index is found, then no valid shape could be found in this layer and an error is

generated. If both a FILL index and SKIN index are found, the shape is too complicated for the current algorithm to parse correctly and an error is generated.

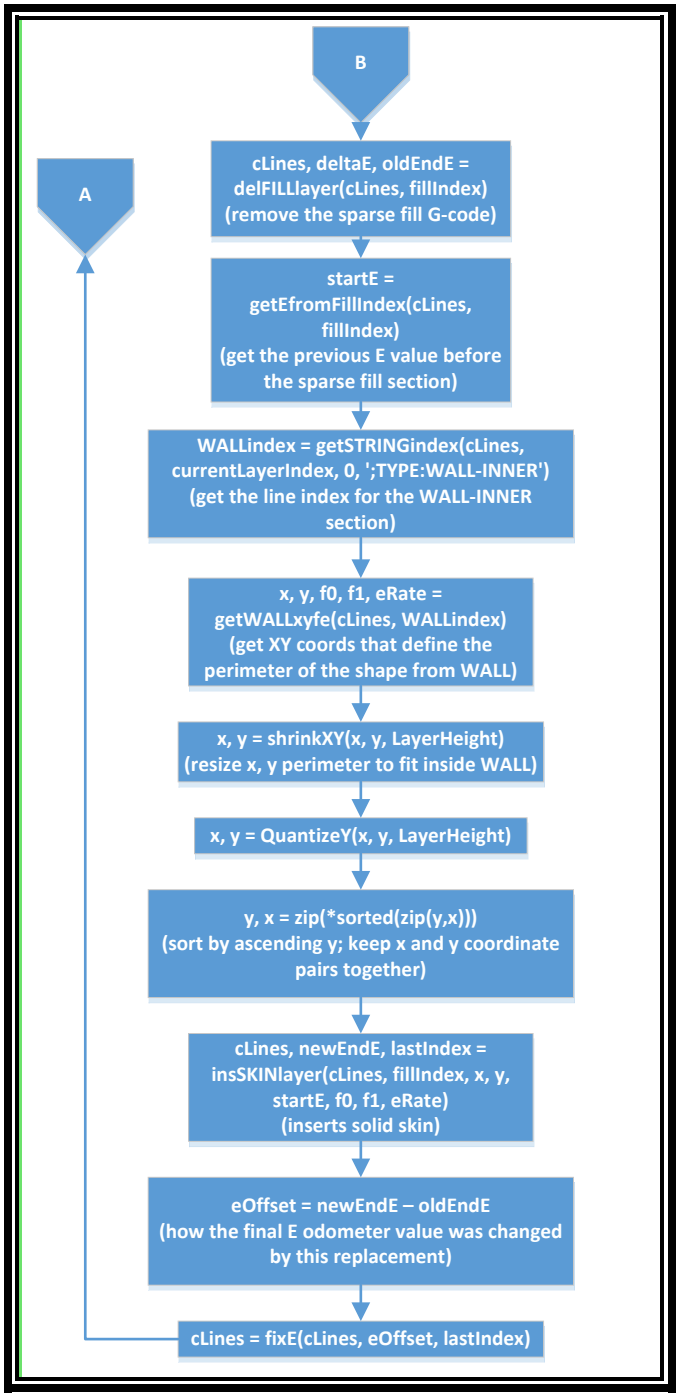

Figure 4.19: Overview (2 of 2) of the *CreateSkin* function.

In the case where a spare FILL was found, with no SKIN section, the function continues by removing the FILL section of G-code. It then finds the E (total polymer extruded) value from the immediately preceding line of G-code to use as a starting point for calculations that generate SKIN G-code. It then finds the line index for the WALL-INNER section of G-code. The WALL-INNER is a series of G-code coordinates that define the perimeter of the shape, which needs to be filled with a solid SKIN. The next function, *getWALLxyfe*, collects all X and Y coordinates that define the perimeter into X and Y lists; the function also stores the G0 move speed to *F0* and G1 move speed to *F1*, so that new G-code can be generated with equivalent movement speeds. The *shrinkXY* function converts the XY coordinates into a contour and uses the *pyclipper* library [29] to resize the contour, so that the perimeter is slightly smaller than the original WALL. This is necessary so the resulting G-code won't overlap with the existing WALL perimeter. The resized contour is converted back into XY coordinates and returned to the parent function. These coordinates are fed into the *QuantizeY* function to create a series of evenly spaced horizontal lines based on the *layerHeight*, which define the generated solid SKIN pattern.

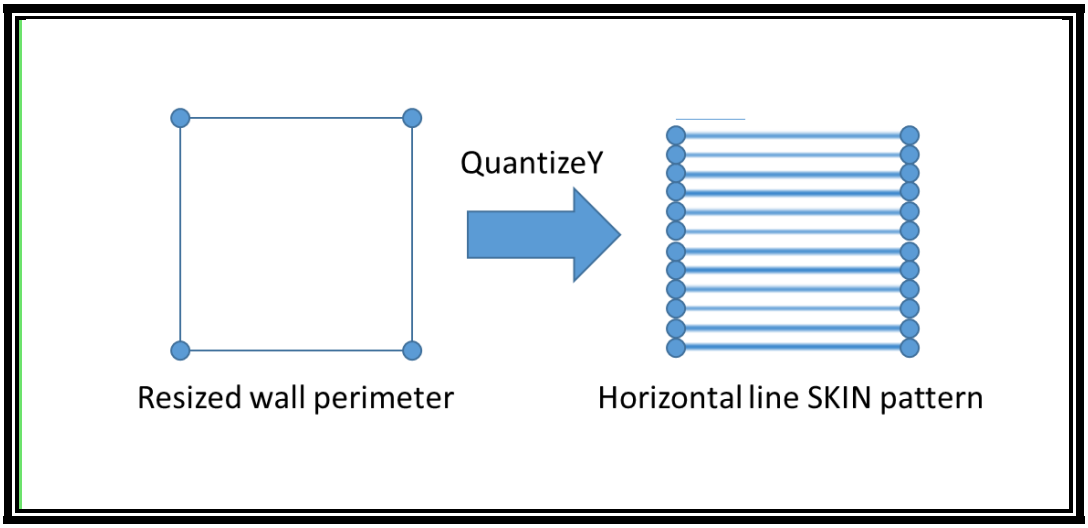

Figure 4.20: *QuantizeY* function.

The resulting quantized coordinates are sorted by Y-value to ensure correct printing. These sorted coordinates are fed into the *insSKINlayer* function to generate the final G-code for

the SKIN section with the correct syntax. Finally, the remainder of the G-code has to be fixed to account for the changes to the E extrusion value. The old value for E at the end of the deleted sparse FILL section is compared to the new value for E at the end of the added solid SKIN section. The difference between new and old E is added to all subsequent E values by the *fixE* function to ensure correct printing. The loop then continues until all necessary sparse FILL layers have been replaced by solid SKIN. With the foundation modified, control is passed back to *addCircuit* in main.py, Figure 4.17 page 53, which proceeds by inserting the circuit pattern G-code before continuing on to part C below.

main.py (addCircuit) continued (part C)

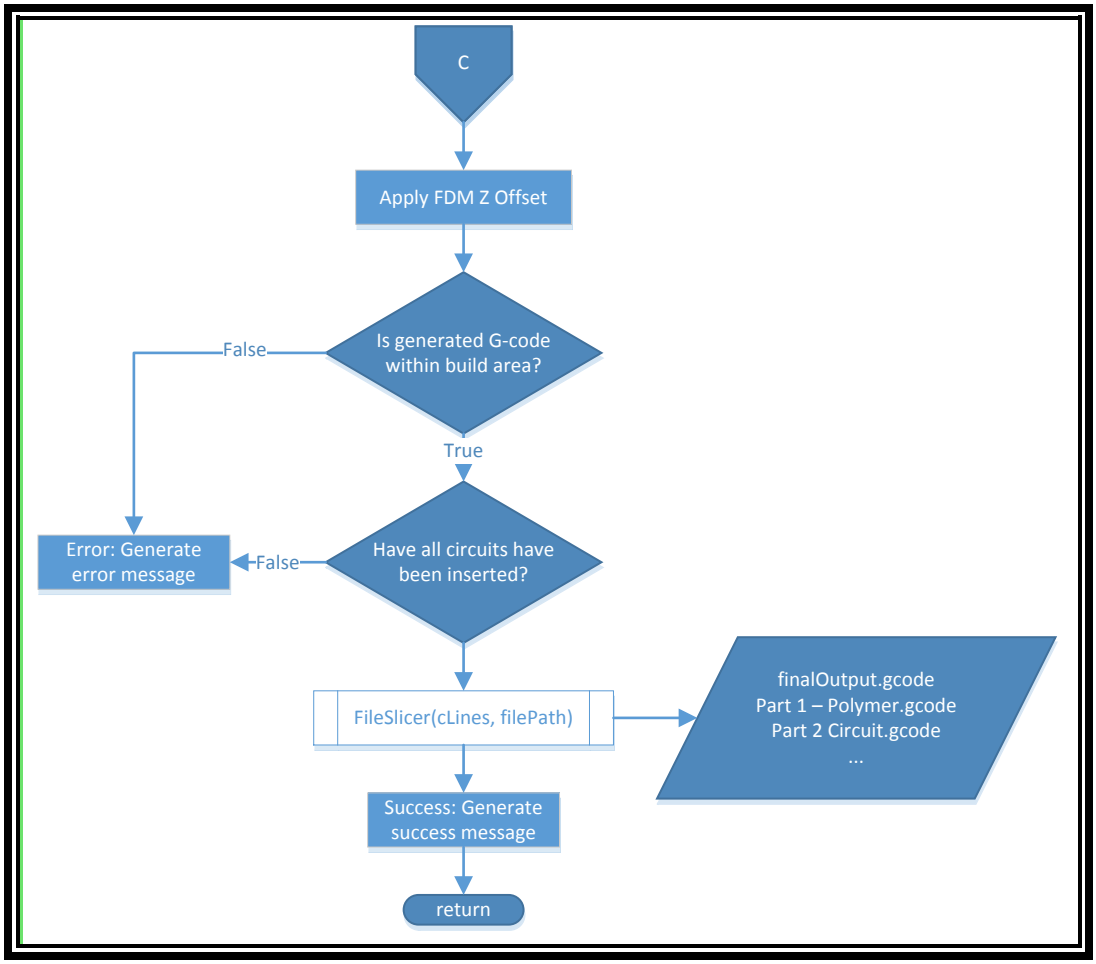

Figure 4.21: Overview (3 of 3) of the main.py *addCircuit* function. All process steps illustrated are within the scope of this publication. Continued from Figure 4.17, page 53.

At this point, the tool0.zOffset parameter is applied to all FDM polymer lines, but skips lines that relate to headers, footers, or circuit G-code.

```
1.  def transformPolymerZ(lines, zOffset): #changes the Z value by adding the z height of t
    he circuit plane to all values of Z
2.
3.      def modifyZ(line, zOffset): #modifies an individual line to change the value of Z
4.          zStartPos = line.find(" Z") + 1
5.          zEndPos = line.find(" ", zStartPos)
6.          if zEndPos == -1:
7.              zEndPos = line.find("\n")
8.          Z = CreateSkin.getCoOrd(line, "Z")
9.          Z = Z + zOffset
10.         newline = line[0:zStartPos+1] + "%.3f" % Z + line[zEndPos:]
11.         return newline
12.
13.     newlines = []
14.
15.     skip = True #We don't want to modify Z in the header or footer lines
16.     for line in lines:
17.
18.         if skip == False:
19.             if "M104 S0" in line: #Footer of file reached -> Stop modifying Z
20.                 skip = True
21.
22.             elif ";TYPE:CUSTOM CIRCUIT" in line:
23.                 skip = True
24.
25.             elif line.find(" Z") >= 0: #There is a Z in the line
26.                 if ((line.find(";") == -
    1) or (line.find(";") > line.find(" Z"))): #Make sure the Z is not part of a ";" G-
    code  comment
27.                     newline = modifyZ(line, zOffset)
28.                     newlines.append(newline) #append Z modified line
29.                     continue
30.         #skip all lines before layer 0
31.         elif ";LAYER:0" in line: #We're at Layer 0 -> Start modifying Z
32.             skip = False
33.
34.         elif ";END:CUSTOM CIRCUIT" in line:
35.             skip = False
36.
37.         newlines.append(line) #append unmodified line
38.
39.     return newlines
```

Figure 4.22: *transformPolymerZ(lines, zOffset)* modifies all polymer lines by the zOffset.

This is followed by a sanity check of the generated G-code to ensure it remains within the Lulzbot build area.

```
1.  def checkBoundaryLimits(cLines, BoundaryMin, BoundaryMax):
2.      minVals = [-1,-1,-1] #set up lists; (-1) values should be overwritten
3.      maxVals = [-1,-1,-1]
4.      BoundaryCheck = True
5.      minVals[0], maxVals[0] = getMaxMin(cLines,'X')
6.      minVals[1], maxVals[1] = getMaxMin(cLines,'Y')
7.      minVals[2], maxVals[2] = getMaxMin(cLines,'Z')
8.      i = 0
9.      while i < len(minVals):
10.         if minVals[i] < BoundaryMin[i] or maxVals[i] > BoundaryMax[i]:
11.             BoundaryCheck = False
12.         i += 1
13.     if  BoundaryCheck == False:
14.         errorText = "BoundaryCheck Failed. Print out of build plate range. Try repositi
    oning the print in Cura and restart this plugin. minVals: %s, maxVals: %s, BoundaryMin:
     %s, BoundaryMax: %s" % (minVals, maxVals, BoundaryMin, BoundaryMax)
15.         ErrorMessage(errorText)
16.
17.     return BoundaryCheck
```

Figure 4.23: *checkBoundaryLimits(cLines, BoundaryMin, BoundaryMax)* ensures generated G-code remains within the build area.

Finally, *layerZmatch* is compared to *totalCircuits*. If both values match, the total circuit patterns inserted equals the total circuit patterns generated and the *FileSlicer* function is invoked to generate the final G-code output, complete with appropriate tool-changing header and footer instructions.

FileSlicer

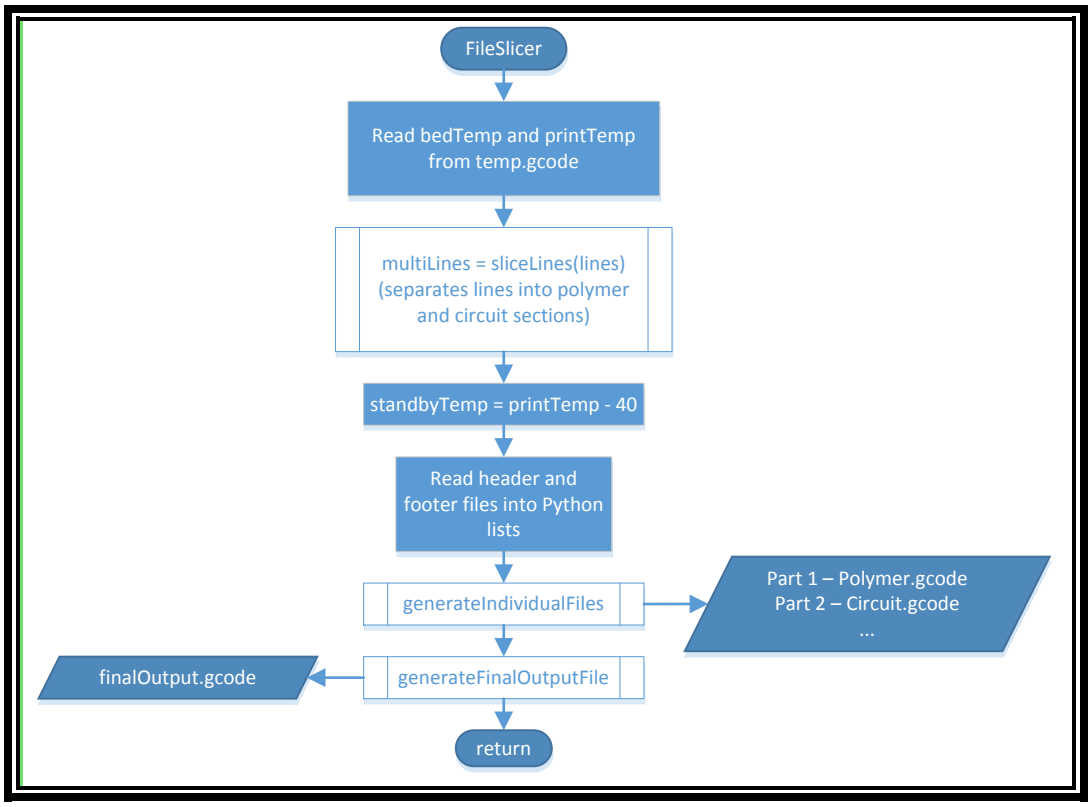

Figure 4.24: *FileSlicer(cLines, filePath)* generates the final G-code files with appropriate headers and footers.

The *FileSlicer* function starts by reading *temp.gcode* to determine the build plate temperature and print extruder temperature that were selected in Cura and saves the values to variables. It then invokes the *sliceLines* function to separate the *lines* list into polymer and circuit sections and stores the result into *multiLines*.

```
1.  def sliceLines(lines): #separates lines into polymer and circuit sections. Truncates the f
    ooter.
2.      tempLines = []
3.      tempLines.append("T0 ; Extruder tool\n")
4.      tempLines.append("M42 P16 S0 ;Turn off Cutter\n") #initialization of Lulzbot I/O
5.      tempLines.append("M42 P14 S0 ;Turn off ExtruderUP/DOWN\n")
6.      tempLines.append("M42 P18 S0 ;Turn off Air\n")
7.      multiLines = []
8.      lastElist = []
9.      fileTypes = ["Polymer"]
10.     for index, line in enumerate(lines):
11.         if line[0:-1] == ";TYPE:CUSTOM CIRCUIT":
12.             lastE = getLastE(lines, index-1)
     #get Last E (saves the current value of how much polymer has been extruded)
13.             lastElist.append(lastE)
14.             multiLines.append(tempLines)
15.             tempLines = []
16.             fileTypes.append("Circuit")
17.         elif ";END:CUSTOM CIRCUIT" in line:
18.             tempLines.append(line) #append line
19.             multiLines.append(tempLines)
20.             tempLines = []
21.             if "M107" in lines[index+1]:
22.                 break
23.             else:
24.                 fileTypes.append("Polymer")
25.                 continue
26.         elif index > 40 and "M107" in line:
27.             multiLines.append(tempLines)
28.             tempLines = []
29.             break
30.
31.         tempLines.append(line)
32.
33.     return multiLines, fileTypes, lastElist
```

Figure 4.25: *sliceLines(lines)* function within *fileSlicer* function separates the polymer and circuit sections.

The *sliceLines* function begins by appending initialization commands to the top of the first polymer section, including I/O initialization and explicitly declaring the T0 FDM extruder tool. It continues appending lines to the first polymer section until the text "*;TYPE:CUSTOM CIRCUIT*" is encountered. At this point, the polymer lines are appended to index 0 of the multi-dimensional list *multiLines* and a circuit section is created. The last E value is saved to a list. This value serves as an odometer of how much material has been extruded and will need to be preserved when FDM printing resumes after the circuit section.

When the comment "*;END:CUSTOM CIRCUIT*" is found in the G-code, the circuit section is ended and its contents appended to the next index in *multiLines*. If the next line contains a M107 command, the end of the print job has been reached and the function is complete; else, another polymer section is started and the loop continues. The next *elif* statement (line 26) also checks for an M107 footer command, this time at the end of a polymer section (such as when the wire-embedding layer was not the final layer and the wire pattern has been covered by additional polymer). This should cause the original footer to be truncated, so it can be replaced with a custom template.

Returning to Figure 4.24, a standby temperature is saved to a variable – this lower temperature is used on the polymer extruder during wire embedding to reduce polymer leakage. Header and footer files are read from the disk into lists.

Generating files

```
1.  def generateIndividualFiles(multiLines, fileTypes, lastElist, PolymerFileHeaderLines, Poly
    merFileFooterLines, PolymerFinalFooterLines, CircuitFileHeaderLines, CircuitFileFooterLine
    s, CircuitFinalFooterLines):
2.      lastEindex = 0
3.      for index, lines in enumerate(multiLines):
4.          tempLines = []
5.          if fileTypes[index] == "Polymer":
6.              if index == 0:  #first section preserves current file header
7.                  tempLines.extend(lines)
8.                  tempLines.extend(PolymerFileFooterLines)
9.
10.             else:
11.                 tempLines.extend(PolymerFileHeaderLines)
12.                 tempLines.append("G92 E%.5f; last E value from previous polymer file\n" %
    lastElist[lastEindex])
13.                 lastEindex += 1
14.                 tempLines.extend(lines)
15.                 if index == len(multiLines) -
     1: #last part of the print, so need a final footer.
16.                     tempLines.extend(PolymerFinalFooterLines)
17.                 else:
18.                     tempLines.extend(PolymerFileFooterLines)
19.
20.
21.         elif fileTypes[index] == "Circuit":
22.             tempLines.extend(CircuitFileHeaderLines)
23.             tempLines.extend(lines)
24.             if index == len(multiLines) -
     1: #last part of the print, so need a final footer.
25.                 tempLines.extend(CircuitFinalFooterLines)
26.             else:
27.                 tempLines.extend(CircuitFileFooterLines)
28.
29.         writeFile(tempLines, filePath, getFileName(filePath) + " - Part %d -
    %s.gcode" % (index + 1, fileTypes[index]))
```

Figure 4.26: *generateIndividualFiles* function within *fileSlicer* function separates the polymer and circuit sections.

Two functions generate files. The *generateIndividualFiles* function generates files that allow the print job to be executed as discrete jobs. I.e. the polymer part is printed and then the printer stop and waits for the circuit job to be initiated. This can be useful for debugging or if an error occurs during part of the print job and the operator wishes to attempt to salvage the overall job by reattempting the problem section. The first section (a polymer section) in *multiLines* already has correct header information, so these lines are appended to *tempLines*, followed by the polymer file footer to correctly end the print, whilst leaving the extruders and print bed hot for

the next job. The *tempLines* are written to "Filename" – 1 – Polymer.gcode. Subsequent polymer sections are handled by lines 10 – 18. These sections require a header to be appended to the top to correctly initialize the print, as well as a G92 command with the last E value to correctly "rezero" the extrusion odometer (if this wasn't added, the first print command would cause a very large amount of material to be extruded, equal to the amount used in the earlier parts of the print job). The next if statement checks whether this was the final part of the print to determine which footer to use – i.e. should all heaters be turned off? The circuit sections are handled in a similar manner, except no special treatment is needed for the first circuit section. The single file output function, *generateFinalOutputFile*, has a similar algorithm, albeit with slightly different intermediate footers and with all outputs appended to the same list and ultimately the same file (Figure 4.27).

```
1.  def generateFinalOutputFile(multiLines, fileTypes, lastElist, PolymerIntermediateHeaderLin
    es, PolymerIntermediateFooterLines, PolymerFinalFooterLines, CircuitIntermediateHeaderLine
    s, CircuitIntermediateFooterLines, CircuitFinalFooterLines):
2.      lastEindex = 0
3.      finalOutputLines = []
4.      for index, lines in enumerate(multiLines):
5.          if fileTypes[index] == "Polymer":
6.              if index == 0: #first part of file, so use original header from Cura
7.                  finalOutputLines.extend(lines)
8.                  finalOutputLines.extend(PolymerIntermediateFooterLines)
9.              else:
10.                 finalOutputLines.extend(PolymerIntermediateHeaderLines)
11.                 finalOutputLines.append("G92 E%.5f; last E value from previous polymer fil
    e\n" % lastElist[lastEindex])
12.                 lastEindex += 1
13.                 finalOutputLines.extend(lines)
14.                 if index == len(multiLines) -
     1: #last part of the print, so need a final footer.
15.                     finalOutputLines.extend(PolymerFinalFooterLines)
16.                 else:
17.                     finalOutputLines.extend(PolymerIntermediateFooterLines)
18.
19.         elif fileTypes[index] == "Circuit":
20.             finalOutputLines.extend(CircuitIntermediateHeaderLines)
21.             finalOutputLines.extend(lines)
22.             if index == len(multiLines) -
     1: #last part of the print, so need a final footer.
23.                 finalOutputLines.extend(CircuitFinalFooterLines)
24.             else:
25.                 finalOutputLines.extend(CircuitIntermediateFooterLines)
26.
27.     writeFile(finalOutputLines, filePath, getFileName(filePath) + " - Complete.gcode")
```

Figure 4.27: The *generateFinalOutputFile* function within *fileSlicer* function combines all G-code into a single print job.

Summary

In summary, a method has been presented for generating multiprocess G-code from a unified design environment. The method is capable of fulfilling the control requirements of the Lulzbot wire-embedding tool and provides operator access to the tool's control parameters.

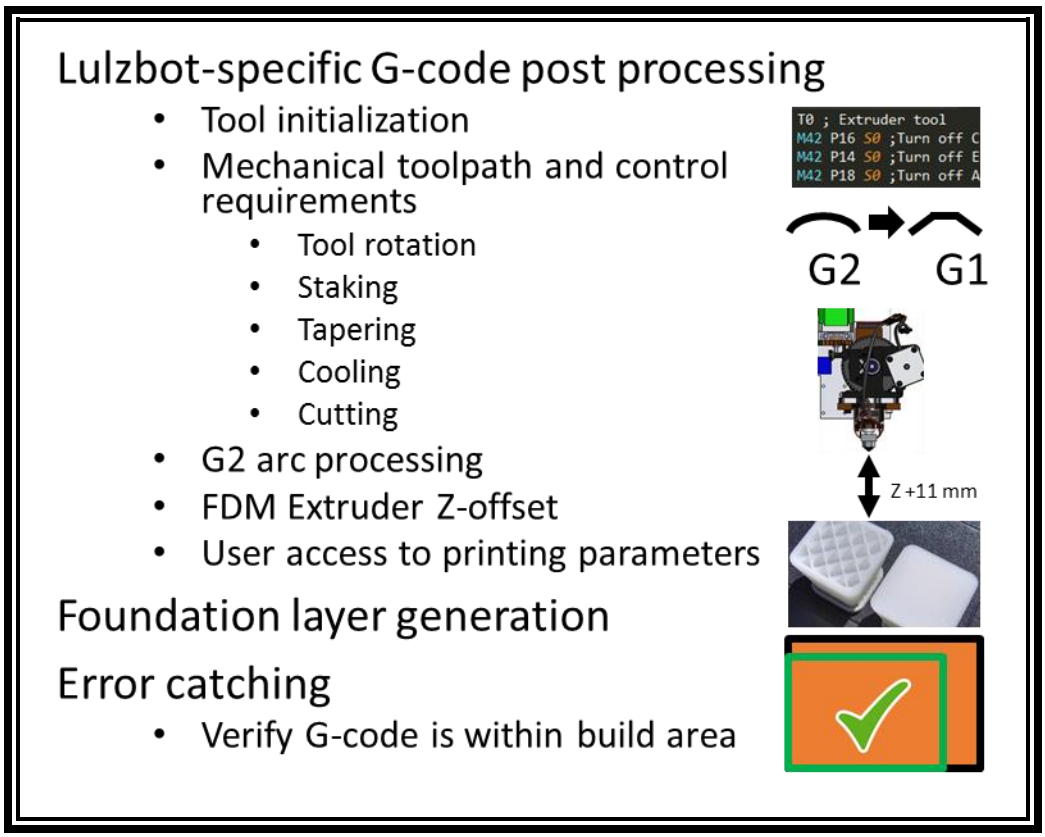

Figure 4.28: Summary of G-code post-processing requirements that have been addressed.

Chapter 5: Results and Characterization

Custom Printing Parameters

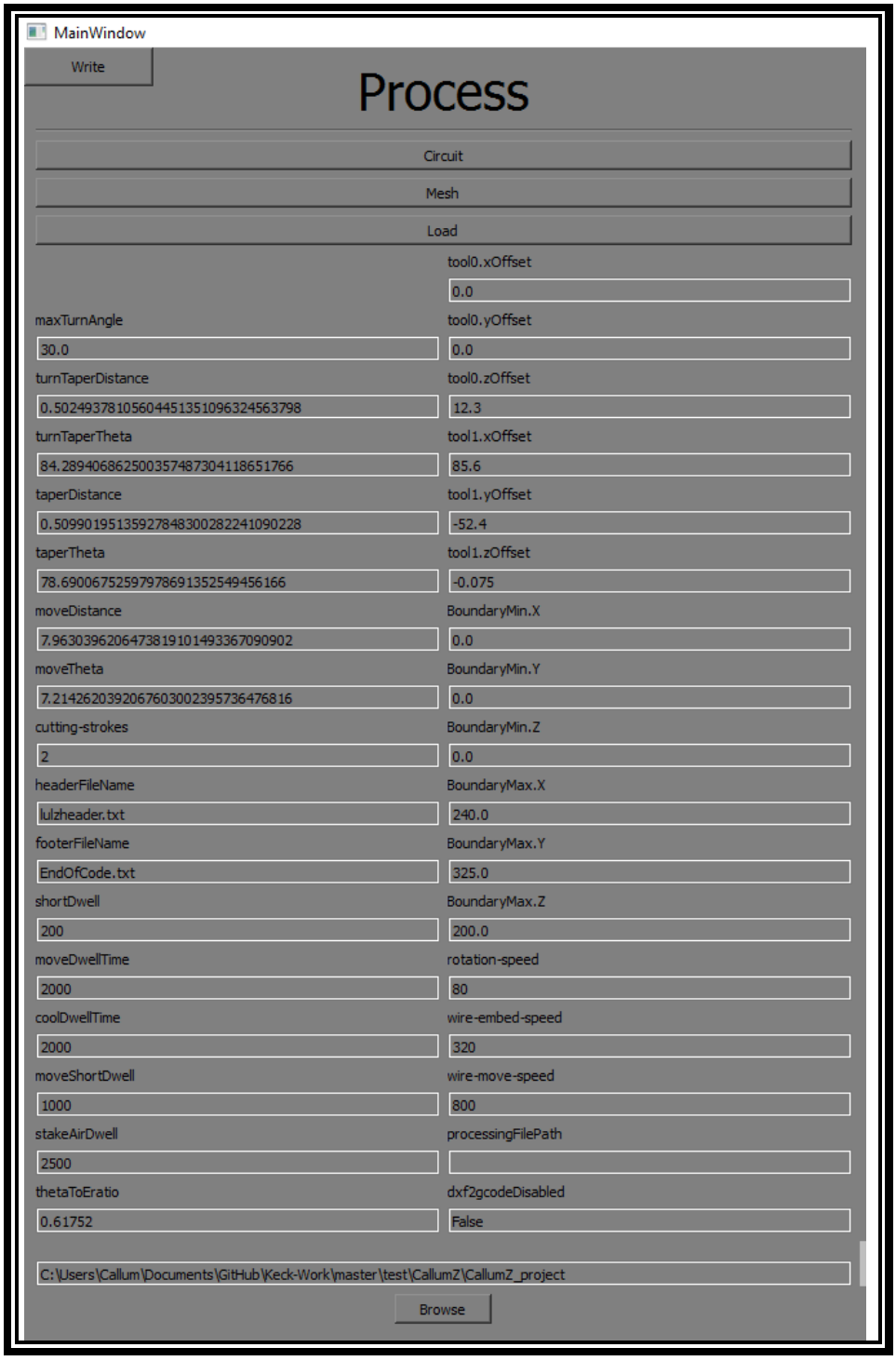

Figure 5.1: Parameters available in the GUI.

The GUI provides parameter access to the printer operator. Figure 5.1 shows the layout of the GUI and default parameter values. The first three parameters relate to basic control of tool orientation: *maxTurnAngle* corresponds to the maximum angle the wire-embedding head can turn in degrees, before it needs to be raised for additional processing steps (as described in Chapter 3). *turnTaperDistance* and *turnTaperTheta* are parameters for the additional processing steps for a turn greater than *maxTurnAngle*. The next five parameters relate to the cutting algorithm: *taperDistance* and *taperTheta* specify the displacement vector (magnitude and angle from the polymer plane) that the tool should take after reaching its last point before a cut. Then *moveDistance* and *moveTheta* specify an additional displacement vector before the cut, while *cutting-strokes* specifies the number of times the cutting actuator should activate for each cut. These parameters are followed by a number of Dwell parameters, which specify delay times in ms between various commands. The *thetaToEratio* is a radians-to-E-rotation value conversion used by the addToolRotation function (1 radian corresponds to 0.61752; 2π radians corresponds to 3.88); this value can be adjusted to larger values if the tool is not rotating sufficiently for a given angle and *vice versa*. A number of x, y, and z offsets are specified, with *tool0* corresponding to the FDM extruder and *tool1* corresponding to the wire-embedding tool. The *BoundaryMax* parameters specify the minimum and maximum dimensions of the build area; these parameters are compared with the G-code coordinates generated to ensure the print job is contained within the build area. The parameters *rotation-speed*, *wire-embed-speed*, and *wire-move-speed* specify the "F" value (speed) to be used when generating G-code lines for wire-embedding head tool rotation, embedding wire in polymer, and moving between wire-embedding coordinates. Of the last two parameters, *processingFilePath* is defunct and will be removed in a future version of the GUI, whereas *dxf2gcodeDisabled* is a special parameter, that when set to *True* will disable the *DXF2GCODE.exe* functionality of the program. The purpose of this is to allow the user the option to open the *DXF2GCODE.exe* GUI and specify specific parameters for creating the basic G-code file instead of the standard parameters used by the Python program. The most common current use for this feature is to reverse the direction of the G-code generated

by *DXF2GCODE.exe*; e.g. if the script generated wire-embedding G-code for a spiral with the embedding starting at the center of the spiral and ending on the outside, the user could reverse this direction by disabling DXF2GCODE and manually reversing the direction of the G-code generation (see Figure 5.13, page 82, for an example). In future versions of the GUI, it is planned to introduce a feature that will allow this tool reversal to be implemented automatically from the wire-embedding GUI.

Testing

For the purposes of evaluating the successfulness of this software solution, a number of test print jobs have been generated. The following print functions (and their tunable parameters) will be tested: **Staking** (*tool1.zOffset, moveShortDwell, shortDwell, stakeAirDwell*), **straight lines** (*wire-embed-speed, tool1.[x,y,z]Offset*), **small turns** (*maxTurnAngle, thetaToEratio, rotation-speed*), **large turns** (*maxTurnAngle*, *turnTaperDistance*, *turnTaperTheta, thetaToEratio, shortDwell, moveDwell. moveShortDwell, rotation-speed*), **cutting** (*taperDistance*, *taperTheta*, *moveDistance*, *moveTheta, cutting-strokes, shortDwell. moveDwellTime, coolDwellTime*), **G2 conversion** (maxArcLength [not in GUI], macArcTheta [not in GUI]), and the **CreateSkin** function.

Table 5.1 Parameters used to generate the most successful execution of each print job.

Parameter	Z cal.	XY Cal.	Feature Demo	Square Coil	Increasing Angles	Coil	Solenoid
Tool0.zOffset/mm	13.0	13.0	13.0	12.3	12.3	13.0	13.0
Tool1.xOffset/mm	91.0	89.0	90.0	89.0	89.0	90.0	89.0
Tool1.yOffset/mm	-55.6	-55.6	-55.6	-55.6	-55.6	-55.6	-55.6
Tool1.zOffset/mm	0.6	0.5	0.6	0.0	0.0	0.6	0.6
Wire-embed-speed/ (mm/min)	320	320	320	320	320	320	320
Rotation-speed/ (mm/min)	80	80	80	80	80	80	80
thetaToEratio/(E/rad)	0.635	0.635	0.629	0.635	0.635	0.635	0.629
maxTurnAngle/°	30	30	30	30	30	30	30
turnTaperDistance/mm	0.50	0.50	0.50	0.50	0.50	0.50	0.50
turnTaperTheta/°	84.29	84.29	84.29	84.29	84.29	84.29	84.29
stakeAirDwell/ms	3000	3000	3000	3000	3000	3000	3000
shortDwell/ms	200	200	200	200	200	200	200
moveShortDwell/ms	1000	1000	1000	1000	1000	1000	1000
coolDwellTime/ms	3000	3000	3000	3000	3000	3000	3000
moveDwellTime/ms	4000	4000	4000	4000	4000	4000	4000
taperTheta/°	100	100	100	100	100	100	100
taperDistance/mm	0.5	0.5	0.5	0.5	0.5	0.5	0.5
moveTheta/°	7.21	7.21	7.21	7.21	7.21	7.21	7.21
moveDistance/mm	7.96	7.96	7.96	7.96	7.96	7.96	7.96
cuttingStrokes	4	4	4	4	4	4	4

Z Calibration

Design

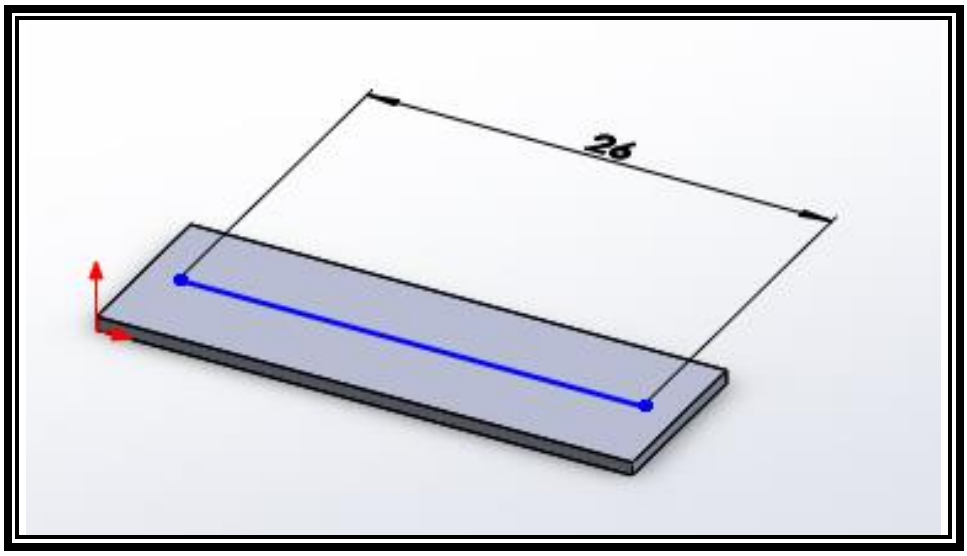

Figure 5.2: A fast and simple Z calibration job to determine wire-embedding efficacy and to allow for a quick iterative adjustment of tool1.zOffet.

As more than one printing iteration may be required to fine-tune the correct wire-embedding parameters, a quick-to-print calibration job is desirable. In Figure 5.2 above, a 30 mm × 10 mm × 1.5 mm polymer cuboid has been designed, with a 26-mm length of wire at a Z-height of 0.75 mm. A layer height of 0.25 mm is used in the Cura slicer, resulting in 3 print layers below the wire and 3 print layers above it.

Results

Figure 5.3: Top: Z Calibration job with 100% infill immediately after wire embedding; Middle: Z Calibration job with 100% infill after the top layers have been printed. Bottom: Z Calibration job with 20% infill, utilizing *CreateSkin* to create 100% fill below the wire and sparse (20% fill) above the wire. The poor coverage of the top layer is a print artefact, unrelated to *CreateSkin*.

Table 5.2 Z calibration job results (G-code generation & print process). Each print function is assessed for whether the algorithm succeeded (✓) or failed (✗) to generate G-code, and whether the print process succeeded (✓), failed (✗), considered a partial success (½), or was not attempted (–). N/A indicates the print function was not utilized.

Job	Staking	Straight lines	Small turns	Large turns	Cutting	G2 Conv.	Create Skin	Exec. Time/s
Z cal.	✓|✗	✓|✓	N/A	N/A	✓|✗	N/A	✓|½	0.38

While all G-code was generated as designed (in a 0.38 s program run time), neither the staking nor cutting functions were executed correctly by the printer. The wire had to be held manually with pliers for staking to occur. However, tool offsets were reasonably well calibrated with the wire positioned centrally and embedding correctly with manual staking. The cutting

mechanism actuated, but the wire did not cut, perhaps due to a dull blade. The *CreateSkin* function produced an adequate foundation for wire embedding, although the start of each line would have benefited from additional polymer extrusion (in a manner similar to Figure 5.8 below). No turns are present in this job, besides initial tool orientation, which occurred correctly. The artefact in the bottom image of Figure 5.3 is due to the designation of only one SKIN layer to finish the piece. This was selected for expediency, to generate a FILL pattern after the first layer. Typically, three SKIN layers would be used on both the top and the bottom of a sparse FILL print, but this would have required more layers and a longer print.

XY Calibration

Design

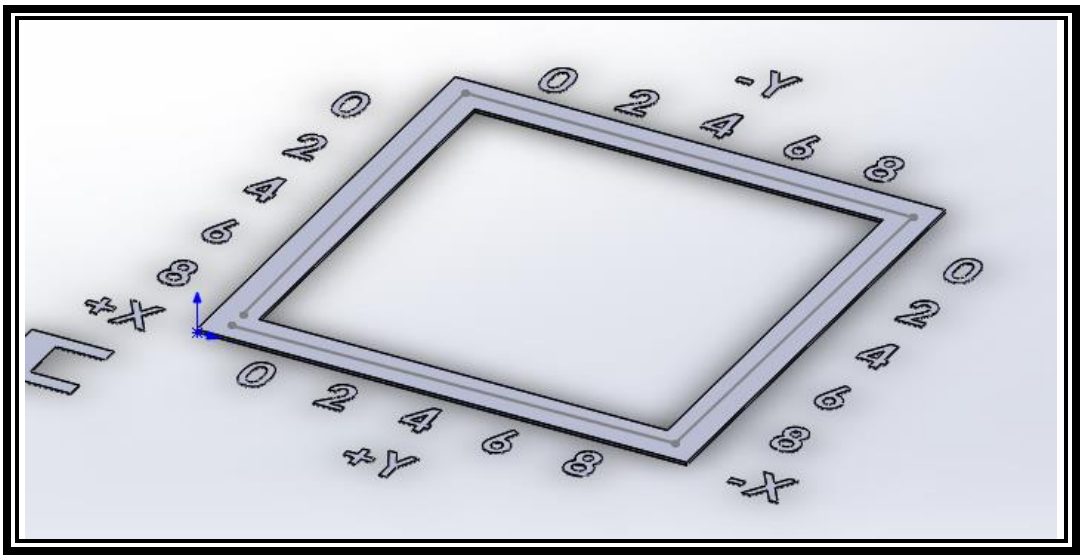

Figure 5.4: XY calibration job

This design was intended to provide a means for fine-tuning X and Y calibration of the wire-embedding tool with respect to the FDM extruder. Adjacent the 0, the wire is exactly centered, whereas adjacent the 8, the wire is offset by ± 0.8 mm in the X or Y direction. If the tool X or Y offset is within 1 mm accuracy, the operator could determine how to adjust the offset by judging where the wire was most centrally located and adding the corresponding offset of the

adjacent number. I.e. if the wire is most centrally located adjacent to +Y 8, then 0.8 mm should be added to the Y-offset in the parameters window.

Results

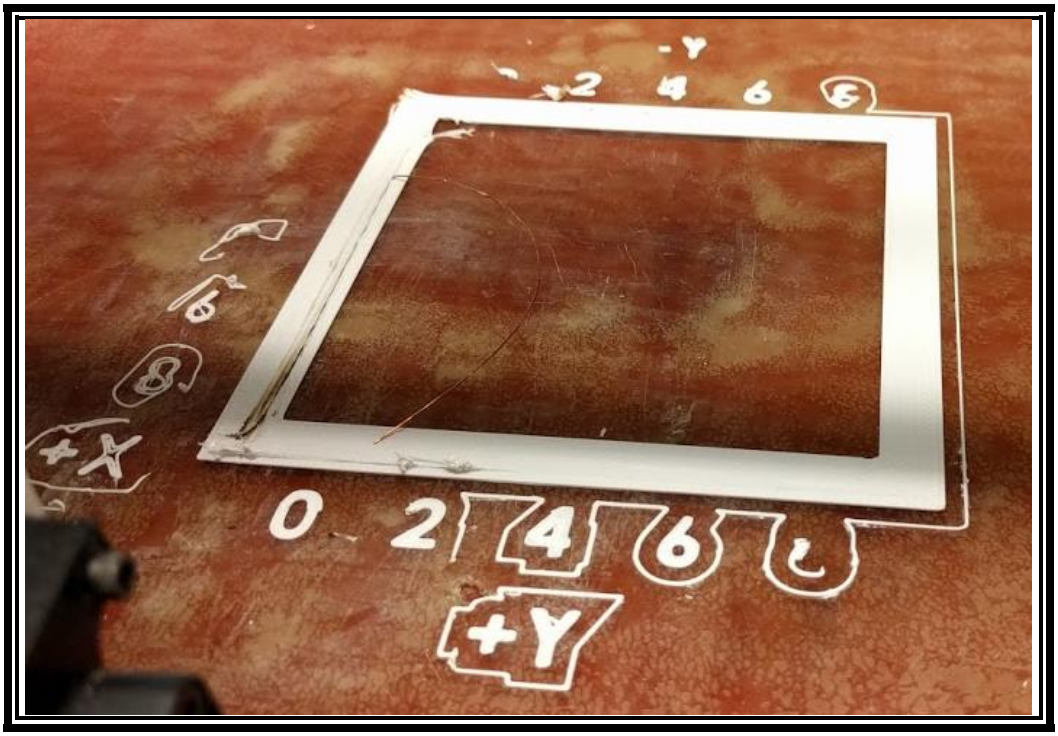

Figure 5.5: Unfortunately, the XY calibration job did not live up to expectations.

Table 5.3 XY calibration job results (G-code generation & print process).

Job	Staking	Straight lines	Small turns	Large turns	Cutting	G2 Conv.	Create Skin	Exec. Time/s
XY cal.	✓|✗	✓|✓	N/A	✓|✗	✓|✗	N/A	✓|–	0.29

This was quite a large print job. Indeed, it proved to be marginally too large for the build plate. The BoundaryMax.X parameter was adjusted from 240 mm to 241 mm to allow the G-code to be generated, however this resulted in the tool hitting the right side of the Lulzbot during wire-embedding on the right side. Another issue which came to light during this job was an anisotropy in the extruder-to-build-plate distance. Whilst a linearly-changing anisotropy can be accounted for by build plate leveling, in this instance the tool appeared to be sagging slightly in the center – perhaps due to the additional weight of the custom tool. This inconsistency is a more

significant issue for large prints, which cover more of the build plate, making the creation of a uniform print distance more challenging.

The print failed to stake without manual intervention. At the first 90° turn, in spite of mechanically acting in accordance with the algorithm, the wire did not remain embedded correctly and was pulled loose as the tool continued to the right.

A future version of the calibration job will be designed to a smaller size to try to avoid anisotropy and build area issues.

FeatureDemo

Design

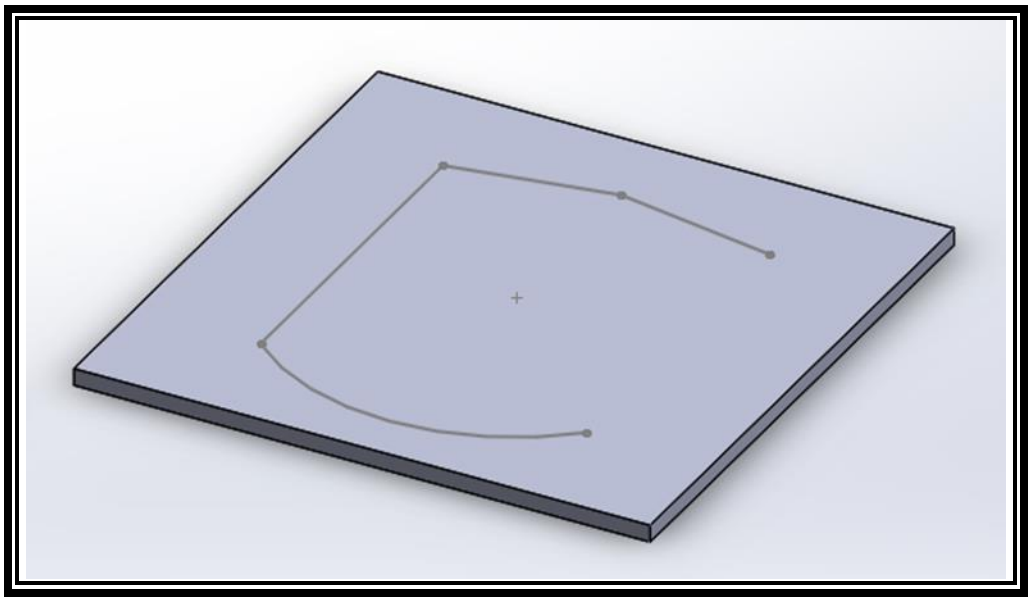

Figure 5.6: FeatureDemo design

The FeatureDemo was designed to test a range of aspects of the Python processing algorithm, including G2 arcs, large turns, small turns, as well as the *CreateSkin* function.

Results

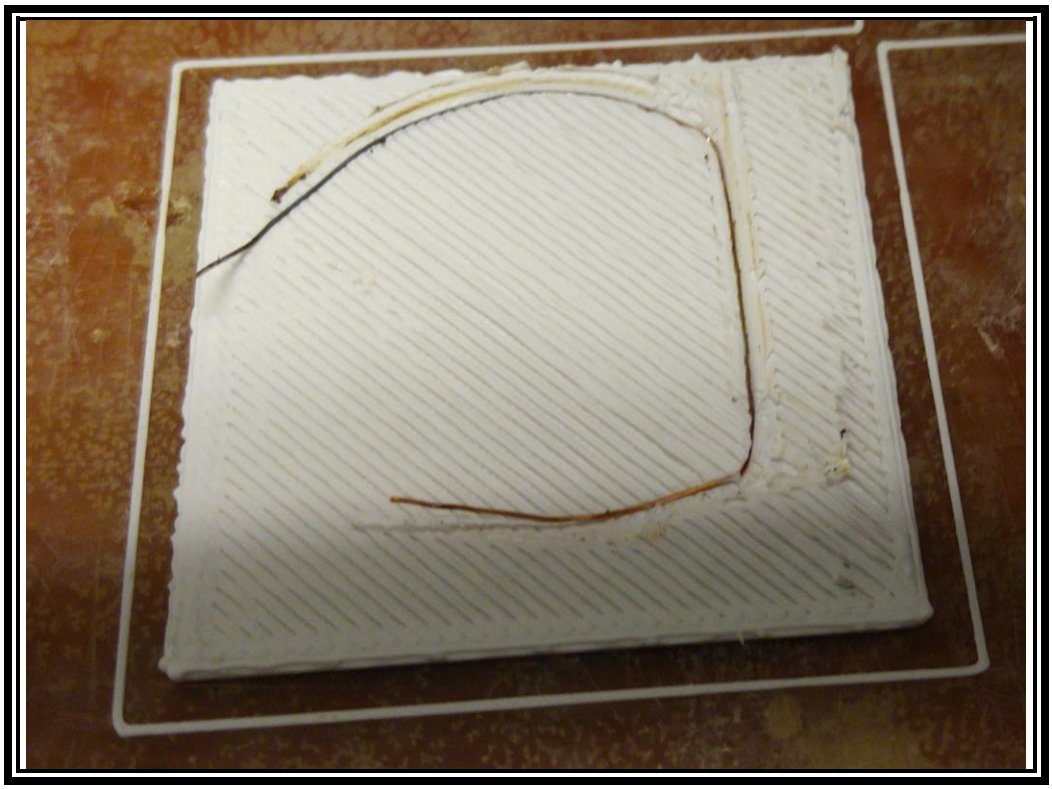

Figure 5.7: FeatureDemo print result

Table 5.4 FeatureDemo job results (G-code generation & print process).

Job	Staking	Straight lines	Small turns	Large turns	Cutting	G2 Conv.	Create Skin	Exec. Time/s
FeatureDemo	✓|✗	✓|✓	✓|½	✓|✓	✓|✗	✓|✓	✓|½	0.33

The FeatureDemo job printed with reasonable success. Whilst staking and cutting again required manual intervention, the G2 arc was successfully converted to G1 commands and printed well, and the two large turns (at the end of the arc and the end of the vertical section) executed perfectly. The final small turn showed some de-embedding, however this may have been due to the failure of the cutting mechanism and the subsequent rise of the tool head with the wire still attached, causing it to de-embed.

Figure 5.8: CreateSkin in FeatureDemo

The CreateSkin algorithm provided an adequate foundation for wire embedding. In Figure 5.8, the sparse FILL diamond pattern can still be seen beneath the printing SKIN layer. The CreateSkin algorithm prints horizontal lines from left to right. It can be seen from this figure, that the initial section of the line on the left has insufficient polymer extruded and future versions of this algorithm would benefit from increased polymer extrusion at the start of a line.

SquareCoil

Design

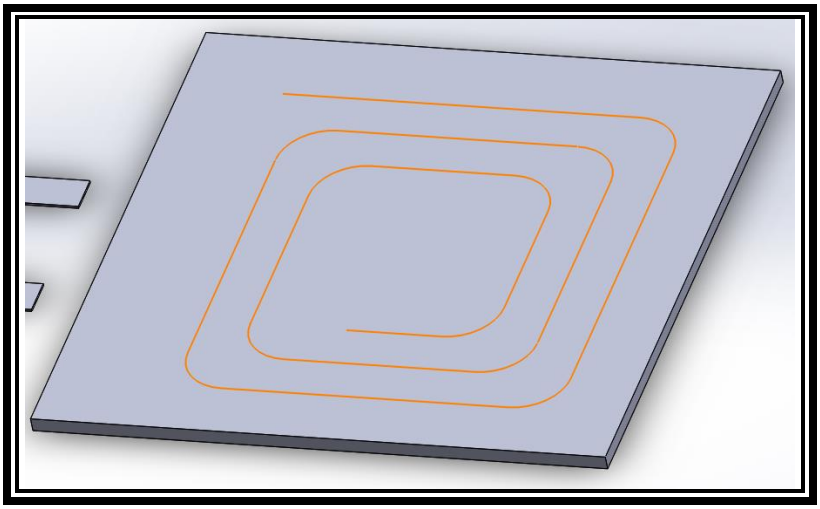

Figure 5.9: SquareCoil design

This design features straight edges and tapered corners, which generate G2 arc commands. Unlike the other designs, which feature 3 layers (0.75 mm) thickness before the wire embedding layer, this piece was designed with 6 layers (1.50 mm) thickness beneath the wire-embedding layer.

Results

Figure 5.10: SquareCoil print result

Table 5.5 SquareCoil job results (G-code generation & print process).

Job	Staking	Straight lines	Small turns	Large turns	Cutting	G2 Conv.	Create Skin	Exec. Time/s
SquareCoil	✓|✗	✓|✓	✓|✓	N/A	✓|✓	✓|✓	✓|–	0.44

This job printed fairly successfully. Whilst staking required manual intervention, automatic cutting was successful – perhaps as this job was the first job performed of the set and

the cutting blade was sharper or due to the increased thickness of the foundation. There were no large turns in this piece, the rounded corners being the result of a G2 to G1 conversion and a rapid series of small turns – both the G2 conversion and the small turns executed very successfully. *CreateSkin* was not invoked in this instance as the part was printed with 100% infill. However, a theoretical 20% infill processing test, was able to successfully generate G-code.

IncreasingAngles

Design

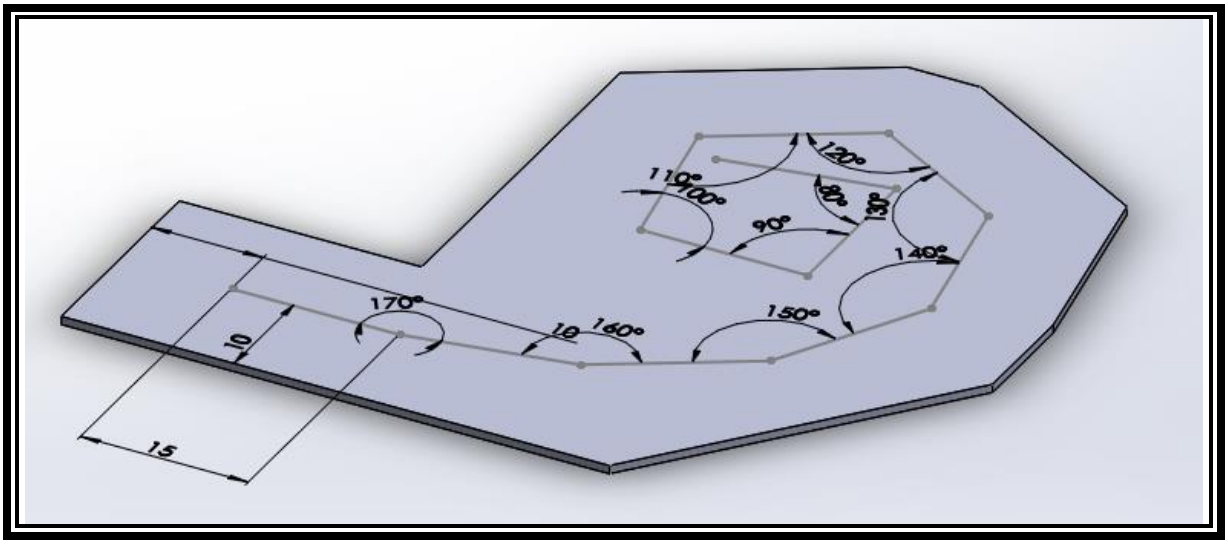

Figure 5.11: IncreasingAngles design

This design featured gradually increasing CCW turns, incrementing by 10° each time, spaced 15 mm apart, with a first angle of 10°, and a final angle of 100°. The 10°, 20°, and 30° turns are classified as small turns and the remaining turns classified as large turns.

Results

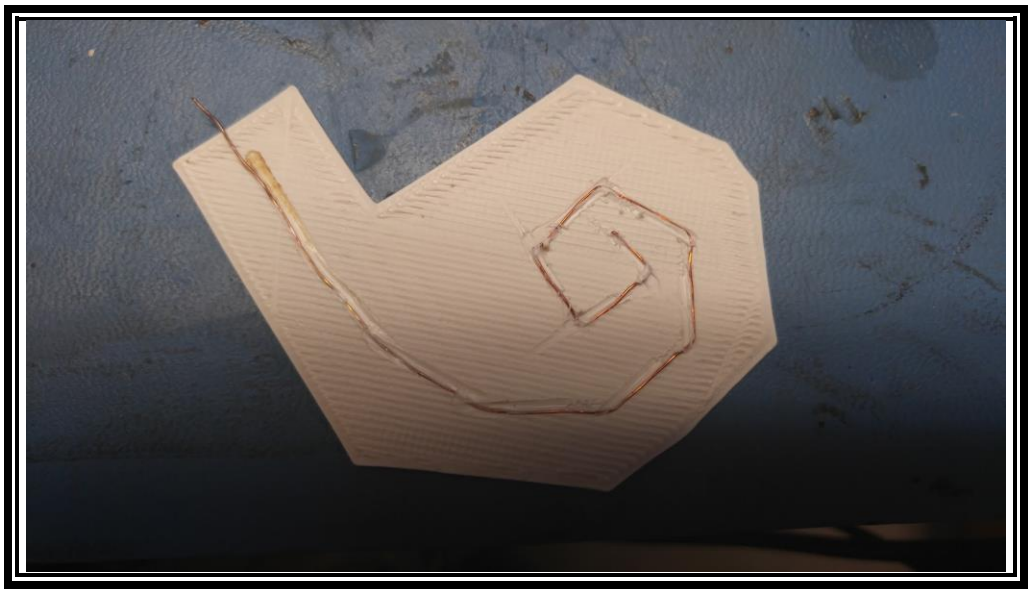

Figure 5.12: IncreasingAngles print result

Initial processing and simulation (Figure 5.14) revealed staking was to occur on the internal part of the spiral (not ideal). To reverse direction, the *DXF2GCODE.exe* GUI was opened and the G-code direction manually reversed (Figure 5.13) and output saved to *circuit1.ngc* overwriting the previous version with the undesired directionality. The job was then reprocessed with the *dxf2gcodeDisabled* parameter set to *True*, causing the manually-created *circuit1.ngc* file to be used, generating final G-code with the preferred directionality.

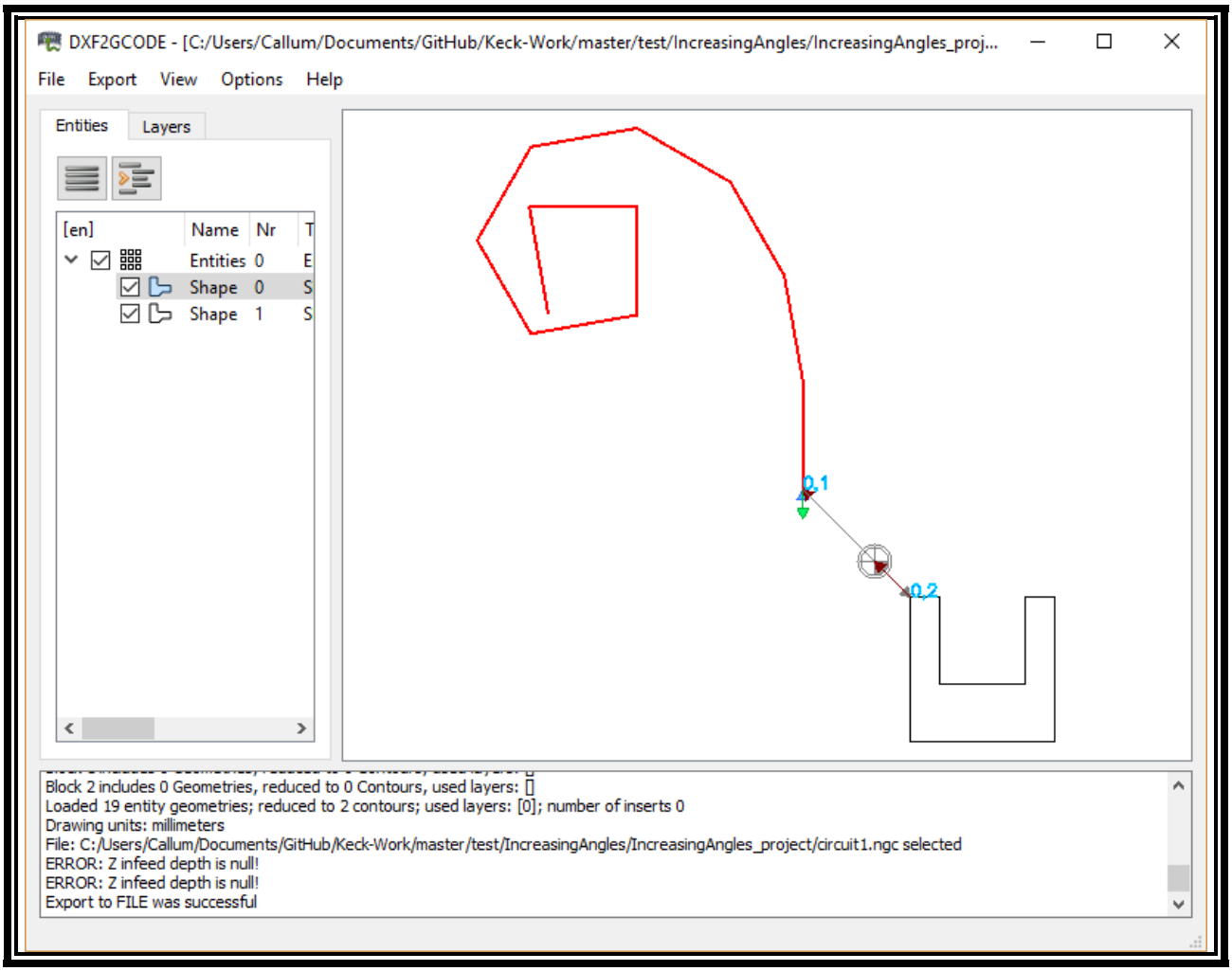

Figure 5.13: Using the *DXF2GCODE.exe* GUI to manually reverse staking and print directionality.

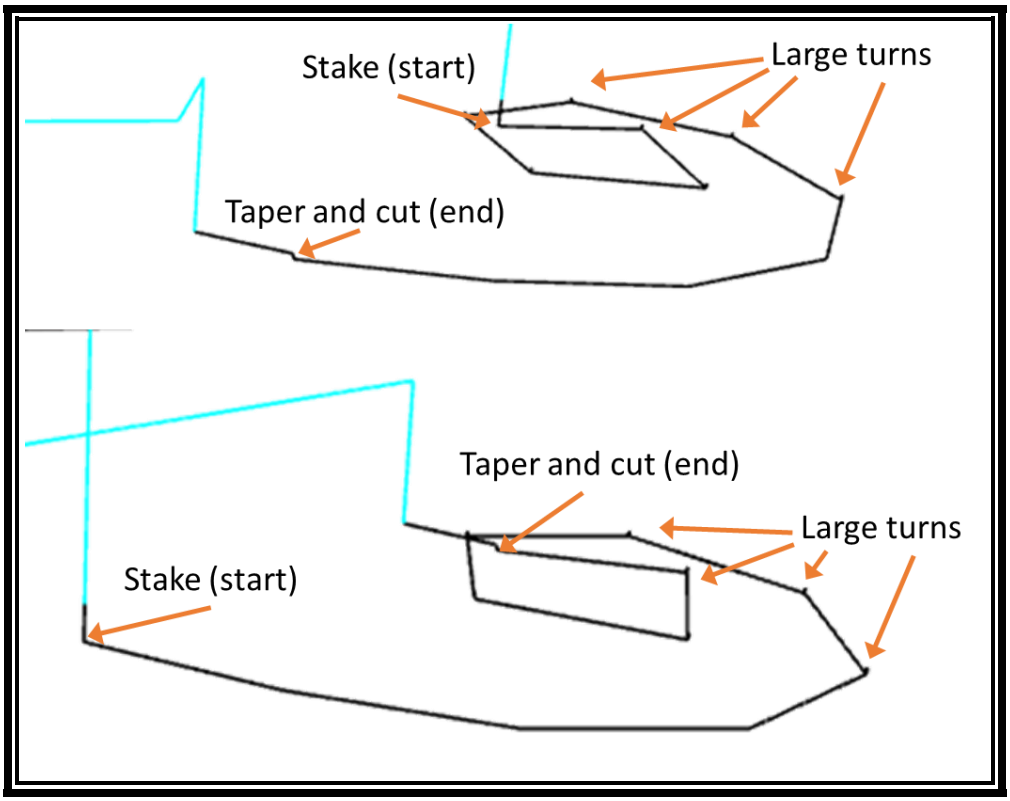

Figure 5.14: Generated G-code of wire tool-path visualized using web-based toolpath simulator (colors inverted) [30].The upper image features the disfavored original direction; the lower image features the favored reversed direction.
It is preferable to have a straighter initial section (lower) to improve initial staking and wire-embedding. Light blue shows G0 commands. Black shows G1 commands. Large turns can be visualized by the small Z rise causing a "bump" for angles greater than *maxTurnAngle* (30°)

Table 5.6 Test (G-code generation & print process).

Job	Staking	Straight lines	Small turns	Large turns	Cutting	G2 Conv.	Create Skin	Exec. Time/s
IncreasingAngles	✓|✓	✓|✓	✓|✓	✓|✓	✓|✗	N/A	✓|–	0.33

The favored reverse direction, with staking occurring at the straighter section of the print, proved very successful, as this was the only print job of the test set to stake automatically without human intervention. The small and large turns all executed very successfully and only the cutting step required manual intervention, although in this case the cutting blade came into contact with more than one wire simultaneously, which may have made for a more challenging cut.

Coil

Design

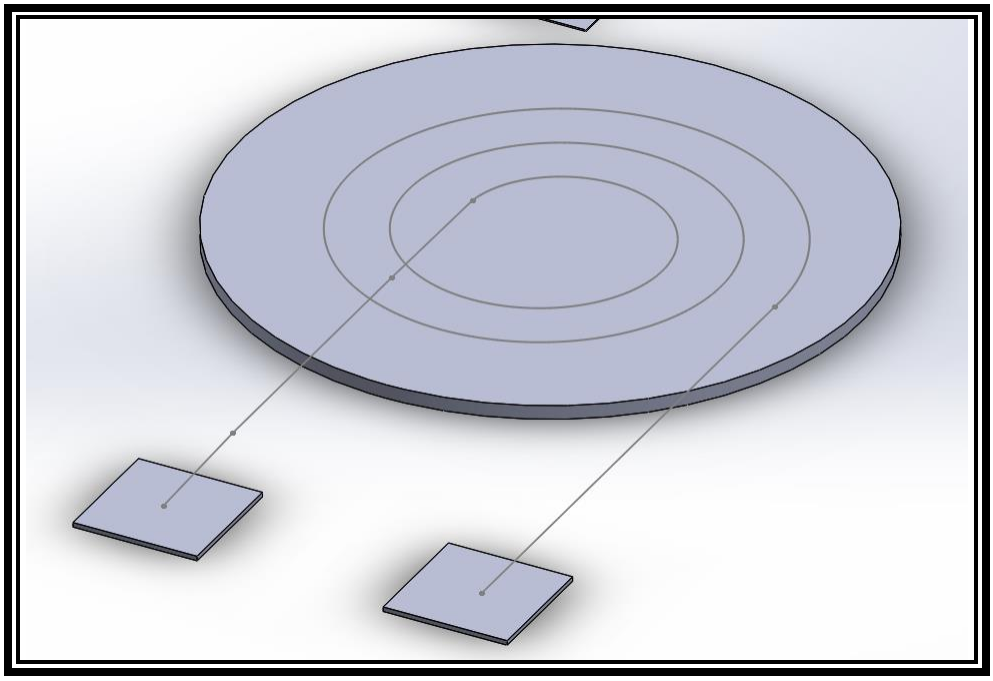

Figure 5.15: Coil design.

The coil design features wires staked to an external platform to provide external leads. As multiple discrete shapes exist in the same layer, the *CreateSkin* function is not capable of processing this job, so it must be printed with 100% infill for the job to be processable by the Python program. The coil is placed in the center of the 6 layers, so it is encased by the polymer. A functional version of this design would utilize magnet wire to ensure the coil does not short circuit, although in the implementation below, the polymer displaced by the tool head may have serendipitously provided electrical insulation between the overlapping wires.

Results

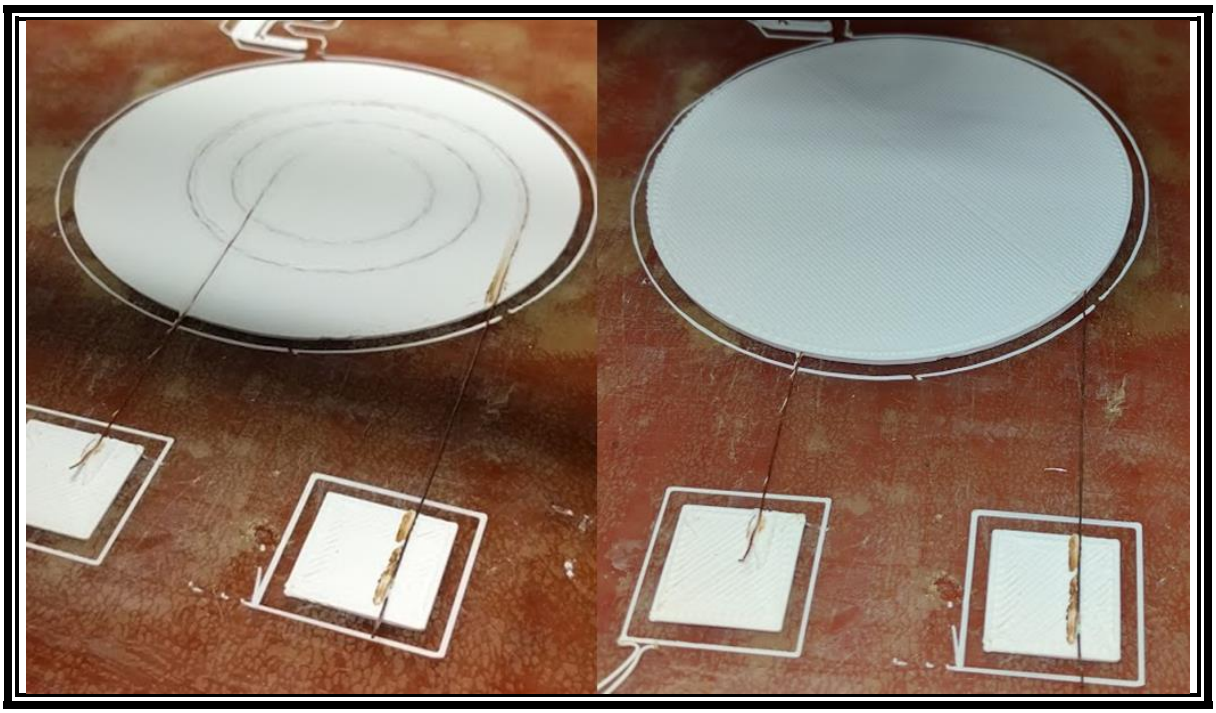

Figure 5.16: Coil job immediately after wire-embedding layer (left)
and after the top layers have been printed (right)

Table 5.7 Coil job results (G-code generation & print process).

Job	Staking	Straight lines	Small turns	Large turns	Cutting	G2 Conv.	Create Skin	Exec. Time/s
Coil	✓|✗	✓|✓	✓|✓	N/A	✓|✗	N/A[6]	✗	0.25

The coil job printed successfully, with the exception of automatic staking and cutting. Interestingly, the G2 arc-conversion function was not needed, as the *DXF2GCODE.exe* elected to interpret the coil as straight line sections. This is likely because G2 and G3 arc syntax has a constant radius, whereas the radius of this coil changes continuously.

[6] DXF2GCODE.exe converted the coil to G1 commands and did not generate G2 arcs.

Solenoid

Design

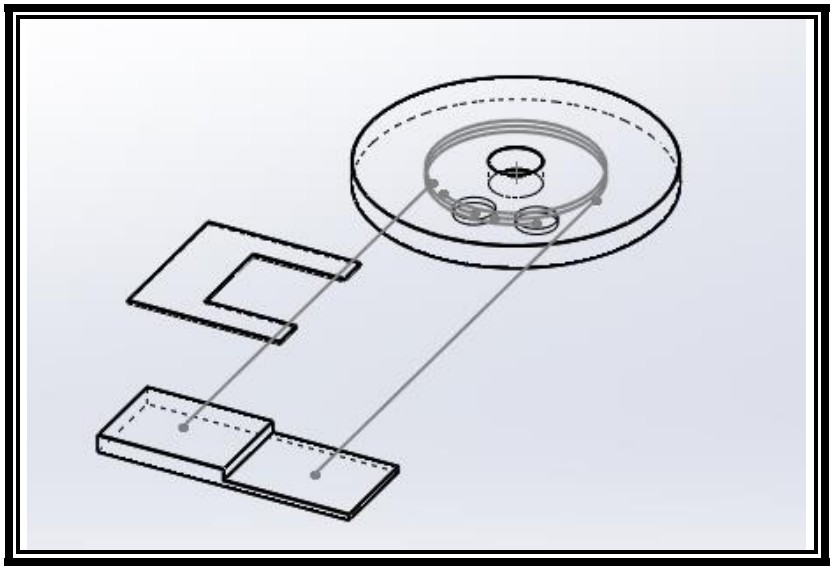

Figure 5.17: Solenoid design.

The solenoid design features three embedded wires on different layers. The first and final layers are staked to an external platform. This allows the wire to be cut and to leave external leads. The intent of the design is to connect the discrete layers through the via holes with solder or another conductor to create a continuous solenoid of 3 turns. The center of the design features a cavity for inserting a ferromagnetic core. The external platforms result in multiple shapes in a single layer, which precludes the *CreateSkin* algorithm from processing sparse FILL shapes. As such, this job must be processed with 100% infill.

Results

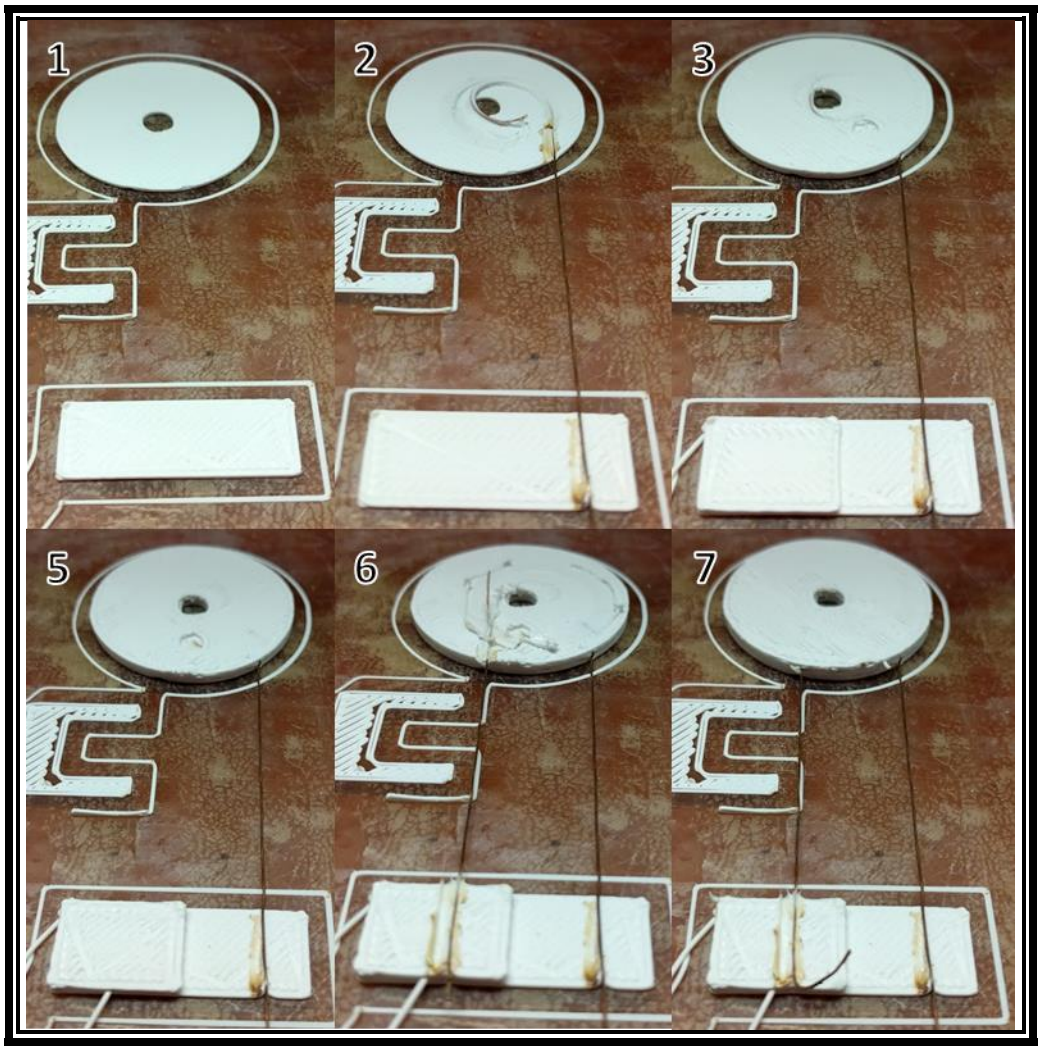

Figure 5.18: Solenoid print job parts 1-7, alternating between Polymer (odd numbers) and Circuit pattern (even numbers). Part 4 circuit pattern is omitted as it completely failed to stake or embed.

Table 5.8 Solenoid job results (G-code generation & print process).

Job	Staking	Straight lines	Small turns	Large turns	Cutting	G2 Conv.	Create Skin	Exec. Time/s
Solenoid	✓|✗	✓|✓	✓|✗	N/A	✓|✗	✓|✗	✗	0.72

While the program was capable of successfully generating a seven-part print job, featuring six tool transitions and three wire patterns, the execution of the print encountered significant problems with respect to the wire pattern, with the second wire failing to embed entirely. Automatic staking and cutting were also not successful. Further work is needed to

determine whether the difficulties encountered are due to the small radius of the circle, unoptimized process parameters, or limitations of the tool design. One can take heart that the algorithm was able to successfully generate G-code and tool transitions in the correct sequential order, with correct wire-embedding tool rotations, without appearing to have any deleterious effects on the FDM printing process, and that these issues may be solvable through parameter optimization.

Chapter 6: Discussion

Evaluation of print functions

Table 6.1 Evaluation of print functions on a variety of jobs: each print function is assessed for whether the algorithm succeeded (✓) or failed (✗) to generate G-code, and whether the print process succeeded (✓), failed (✗), considered a partial success (½), or was not attempted (–). N/A indicates the print function was not utilized.

Job	Staking	Straight lines	Small turns	Large turns	Cutting	G2 Conv.	Create Skin	Exec. Time/s
Z cal.	✓|✗	✓|✓	N/A	N/A	✓|✗	N/A	✓|½	0.38
XY cal.	✓|✗	✓|✓	N/A	✓|✗	✓|✗	N/A	✓|–	0.29
FeatureDemo	✓|✗	✓|✓	✓|½	✓|✓	✓|✗	✓|✓	✓|½	0.33
SquareCoil	✓|✗	✓|✓	✓|✓	N/A	✓|✓	✓|✓	✓|–	0.44
IncreasingAngles	✓|✓	✓|✓	✓|✓	✓|✓	✓|✗	N/A	✓|–	0.33
Coil	✓|✗	✓|✓	✓|✓	N/A	✓|✗	N/A[7]	✗	0.25
Solenoid	✓|✗	✓|✓	✓|✗	N/A	✓|✗	✓|✗	✗	0.72

Staking

The staking algorithm, while generating the desired G-code, was only successful in one job (**IncreasingAngles**): all other jobs required the wire to be held manually for initial staking. Whether this was due to unoptimized parameters, a mechanical flaw in the algorithm, or mechanical issues with the machine (such as the air blower being incorrectly aligned) will require further investigation. However, if changes to the algorithm are deemed necessary, the modular framework of the Python program should make implementing any changes relatively straightforward. Indeed, as the algorithm was successful in the **IncreasingAngles** job case, an optimist may believe such issues to be "teething troubles" of a new process.

A possible future change to the algorithm could be to use a single slow stroke of the cutting tool in an attempt to stake the wire.

[7] DXF2GCODE.exe converted the coil to G1 commands and did not generate G2 arcs.

Straight lines

All jobs were successful in generating G-code and printing embedding straight lines of wire, so long as the initial staking was implemented (automatically or with manual intervention).

Small turns

In all cases a *maxTurnAngle* = 30° was used, so small turns are defined as those that involved a tool rotation of less than or equal to 30°. G-code was generated as intended for all jobs. Actual print quality showed some variation, with discrete small turns at a vertex generally implemented more successfully than continuous small turns as part of an arc, although both instances had successes and failures. As well as parameter optimization, future plans for the tool include the implementation of an additional small motor to actively feed the wire, instead of relying on the wire to be passively fed by staking and translational movement of the tool head. Such an enhancement should reduce the instance of wires "cutting corners" and could be particularly useful for tight radius circles, such as the solenoid job.

Large turns

Within the test set, large turns had a two-out-of-three success rate for printing. The one failure occurred on the XY calibration job, which encountered a number of problems related to its large size and extruder-to-build-plate distance anisotropy. In a broad sense the large-turns algorithm and its implementation appear to have been successful.

Cutting

Whilst the cutting commands operated as expected, the mechanism of cutting tool did not, with the exception of the **SquareCoil** job, which was able to implement a successful cut. It may be that these print jobs are too thin and the surface polymer too close to its glass transition temperature to provide a suitably solid surface to cut against. Indeed, with a build plate temperature of 110 °C and a typical glass transition temperature of ABS in the range of 105 °C, this may well have been the case. In addition, the one successful cutting job, the **SquareCoil**, featured double the foundation thickness of the other print jobs, providing extra thermal

insulation from the build plate. Future experiments will be attempted with a lower build plate temperature.

G2 conversion

G2 arc conversion had mixed fortunes: whilst the algorithm resulted in successful prints on the **SquareCoil** and **FeatureDemo** jobs, the **Solenoid** job completely failed on the circular portion. To determine whether this failure was due to the G2 conversion function or due to other parameters and causes will require further experimentation. However, it appears the algorithm is fundamentally sound and only parameter optimizations may be required.

CreateSkin

This algorithm, while broadly functional, has plenty of room for improvement, such as extruding polymer in both left-to-right and right-to-left directions, ensuring adequate polymer is dispensed initially, and expanding the algorithm to be compatible with more complex designs featuring multiple shapes in a single layer.

Initially implemented as a quick fix to the problem of providing a foundation for wire-embedding above a sparse filled interior, a better long term solution may be to implement existing SKIN generating functionalities from the Cura libraries and developing closer integration between the Cura slicer and the post-processing program.

Proposed Features and Future Work

Whilst great progress has been made during the development of this multi-material printing algorithm, a number of areas for improvement remain. One such area would be in developing automated wire-embedding out of the XY plane. It may be possible to achieve this by switching design tools, as Autodesk Fusion 360 has shown some promise for multi-process support and also supports a Python API as opposed to the Visual Basic API of Solidworks. There is also room to optimize execution speed of the code, if required, as the current implementation involves many iterations of reading all lines and acting on them sequentially. However, this has

not presented an issue for the test files processed so far, which typically exhibit processing times of less than one second.

Working with the mechanical engineers, who are the primary operators and designers of the Lulzbot, has revealed GUI interface changes, such as reducing the number of parameters on the main GUI screen, adding support for changing the G2 arc conversion parameters (*maxArcLength, maxDTheta*) in the GUI, and the ability to switch start and end points for wire-embedding patterns. Many of these features are under implementation by the W.M. Keck Center for 3D Innovation GUI wunderkind, Jake Lasley. An integrated toolpath simulator is being developed by Mike Licerio.

Efrain Aguilera, whose work is published concurrently, has made progress in developing support for importing defined print cavities directly into Solidworks from integrated circuit components defined by modified Cadsoft EAGLE hardware libraries. This lays the groundwork for automatically incorporating interconnected integrated circuits into FDM designs.

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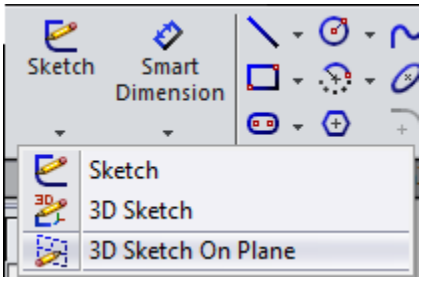
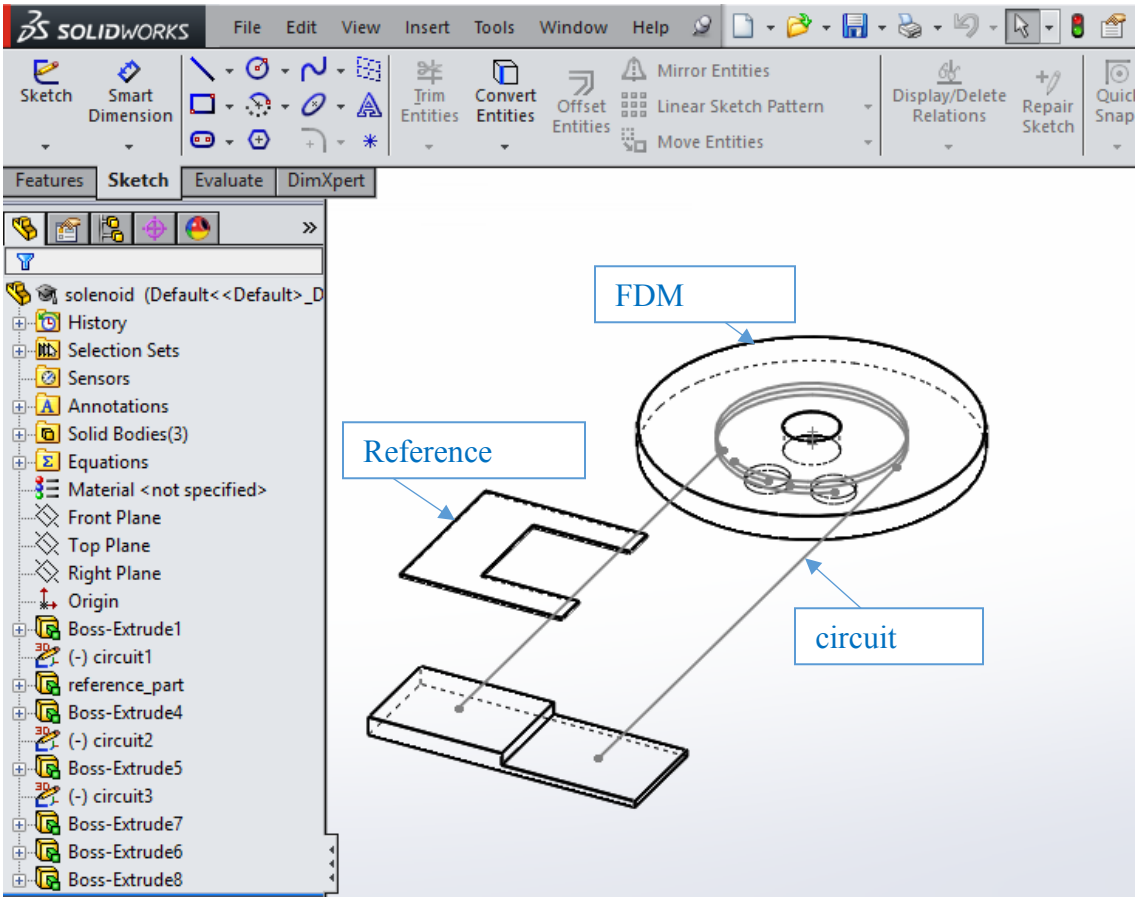
Appendix A: Software user procedure

1. Create Solidworks 3D-printable part as normal.
2. Create a reference plane, parallel to the XY build plane where you want your circuit or select the face on which you wish to place your circuit.
3. Add circuit elements as 3D Sketch On Plane.

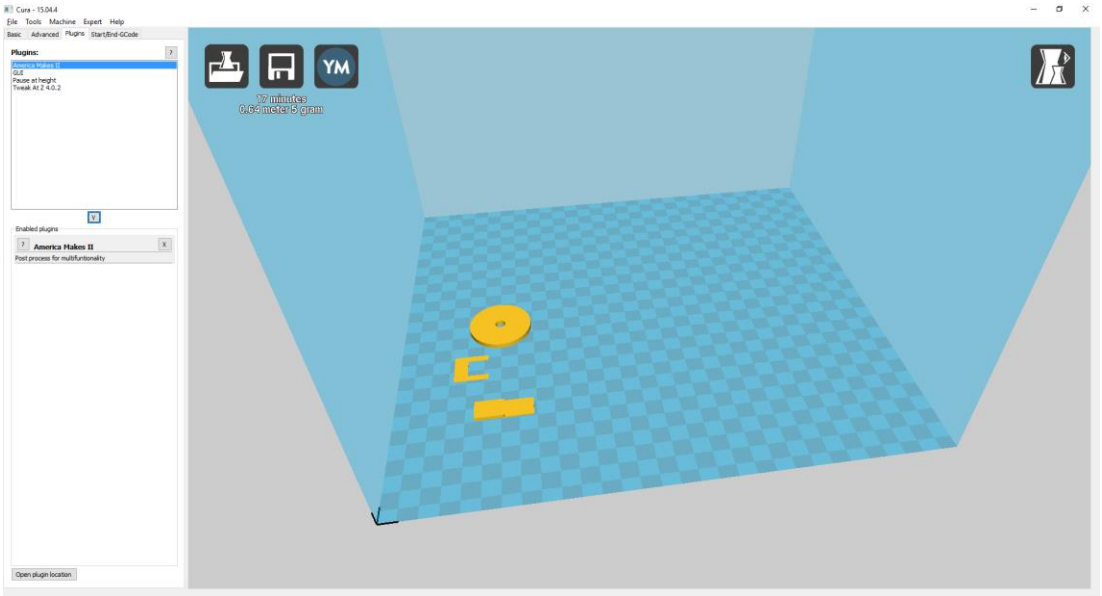


4. Rename the 3D sketches circuit1, circuit2…
5. Save
6. Tools->Macro->Run *createReference.swp*

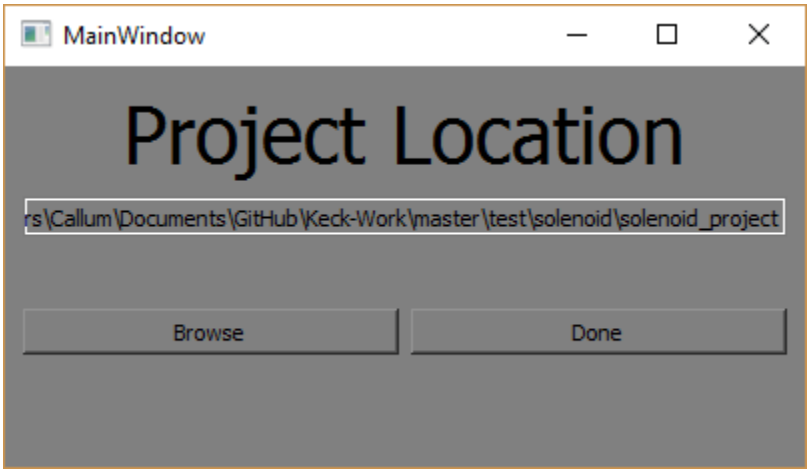


7. Move the reference shape, so it does not overlap with your part. (select the sketch, hover over the middle of the shape, until the move arrows icon appears)
8. Save
9. Tools->Macro->Run *Export_dxf_new_and_improve.swp*; This will create a new subfolder in the location where your Solidworks part is saved with .ngc files.

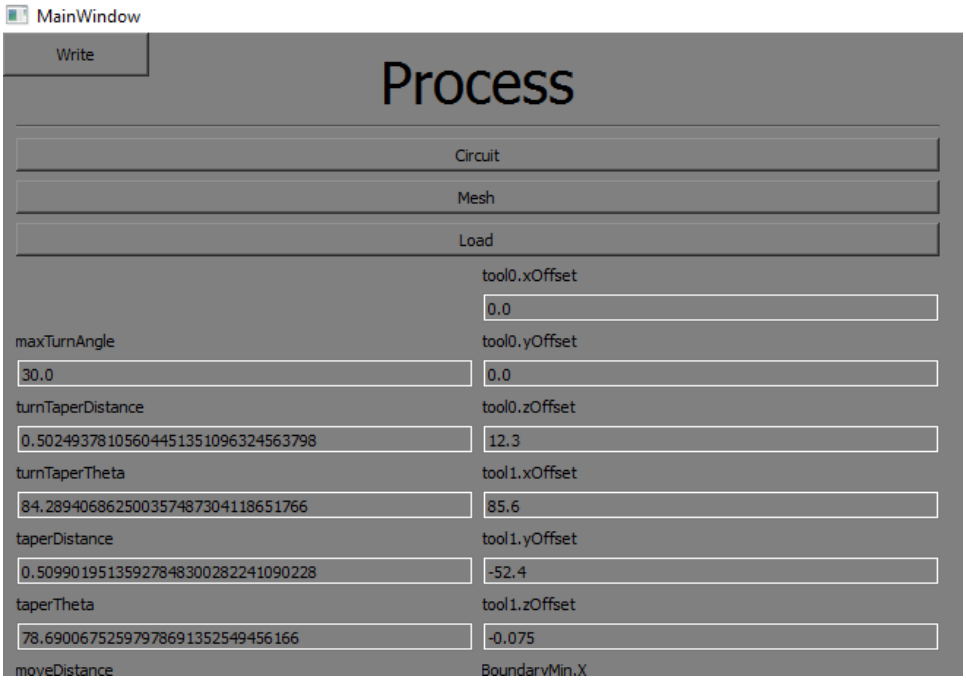
10. Save
11. Save as STL
12. Close Solidworks (if desired)
13. Open Cura 15.04.4 (do not update Cura version)
14. File->Load Model file; load your STL
15. Correctly orient the part, making sure the reference part is flat and in contact with the build plate. Also, position the part towards the left as illustrated by the screenshot below.
16. Navigate to the plugins tab.
17. Enable America Makes II, by clicking on the down arrow.



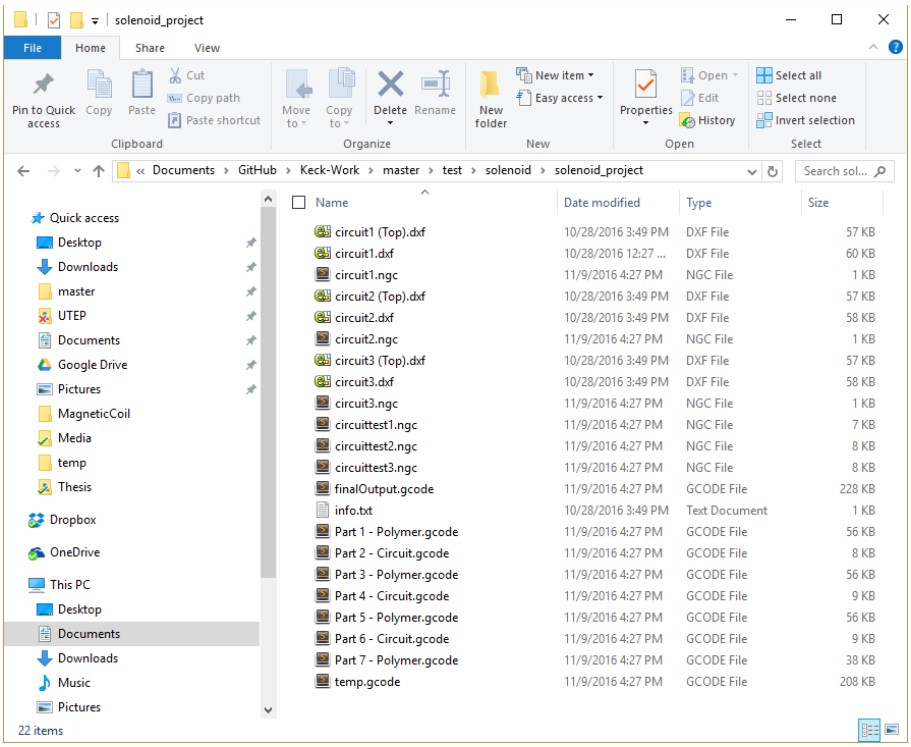
18. Click browse and enter the file path where the folder was created (containing the ngc files).



19. Click Done. A *temp.gcode* file will be created in the folder.
20. Disable the America Makes II plugin.
21. A GUI will open. Click load and select the json file you wish to use for your saved printing parameters (*defaults.json* is fine)
22. Click Circuit to generate the circuit.



23. If successful, a success message will be displayed and the circuits will be listed in right of the GUI. You can click on them to preview the shape. **Close the GUI**.
24. If errors occur, error messages should be displayed and additional debugging information is available in main.exe.log.
25. A number of files should have been generated in the directory: *finalOutput.gcode* contains complete print information with transitions between polymer and wire embedding handled in a single print job; Part 1, Part 2… contain polymer or wire-embedding only jobs that can be used to more closely monitor print stages or to resume a print from a specific stage after a failure.


solenoid_project
File
Home
Share
View
Pin to Quick access
Copy
Paste
Cut
Copy path
Paste shortcut
Clipboard
Move to
Copy to
Delete
Rename
Organize
New folder
New item
Easy access
New
Properties
Open
Edit
History
Open
Select all
Select none
Invert selection
Select
« Documents › GitHub › Keck-Work › master › test › solenoid › solenoid_project
Search sol...
Quick access
Desktop
Downloads
master
UTEP
Documents
Google Drive
Pictures
MagneticCoil
Media
temp
Thesis
Dropbox
OneDrive
This PC
Desktop
Documents
Downloads
Music
Pictures
Name
Date modified
Type
Size
circuit1 (Top).dxf 10/28/2016 3:49 PM DXF File 57 KB
circuit1.dxf 10/28/2016 12:27 ... DXF File 60 KB
circuit1.ngc 11/9/2016 4:27 PM NGC File 1 KB
circuit2 (Top).dxf 10/28/2016 3:49 PM DXF File 57 KB
circuit2.dxf 10/28/2016 3:49 PM DXF File 58 KB
circuit2.ngc 11/9/2016 4:27 PM NGC File 1 KB
circuit3 (Top).dxf 10/28/2016 3:49 PM DXF File 57 KB
circuit3.dxf 10/28/2016 3:49 PM DXF File 58 KB
circuit3.ngc 11/9/2016 4:27 PM NGC File 1 KB
circuittest1.ngc 11/9/2016 4:27 PM NGC File 7 KB
circuittest2.ngc 11/9/2016 4:27 PM NGC File 8 KB
circuittest3.ngc 11/9/2016 4:27 PM NGC File 8 KB
finalOutput.gcode 11/9/2016 4:27 PM GCODE File 228 KB
info.txt 10/28/2016 3:49 PM Text Document 1 KB
Part 1 - Polymer.gcode 11/9/2016 4:27 PM GCODE File 56 KB
Part 2 - Circuit.gcode 11/9/2016 4:27 PM GCODE File 8 KB
Part 3 - Polymer.gcode 11/9/2016 4:27 PM GCODE File 56 KB
Part 4 - Circuit.gcode 11/9/2016 4:27 PM GCODE File 9 KB
Part 5 - Polymer.gcode 11/9/2016 4:27 PM GCODE File 56 KB
Part 6 - Circuit.gcode 11/9/2016 4:27 PM GCODE File 9 KB
Part 7 - Polymer.gcode 11/9/2016 4:27 PM GCODE File 38 KB
temp.gcode 11/9/2016 4:27 PM GCODE File 208 KB
22 items

Appendix B: CreateSkin.py

```
1.  import sys
2.  import csv
3.  import math
4.  import pyclipper
5.  import os
6.  #import CBdebug
7.
8.  #dumpFile = CBdebug.dumpFile
9.  def dumpFile(dumplist, filename): #debugging tool
10.     fullPath = projectPath + "\\debug"
11.     if not os.path.exists(fullPath):
12.         try:
13.             os.makedirs(fullPath)
14.         except OSError as exc: # Guard against race condition
15.             if exc.errno != errno.EEXIST:
16.                 raise
17.     with open(fullPath + "\\" + filename, 'wb') as f:
18.         for item in dumplist:
19.             f.write("%s" % item)
20.
21. def InterpolateX(x1, x2, y1, y2, LayerHeight): #find interpolated x value for a given y st
    ep
22.     #print "x1 == %f x2 == %f y1 == %f y2 = %f LayerHeight = %f \n" % (x1, x2, y1, y2, Lay
    erHeight)
23.     if y2 == y1: #horizontal line
24.         x2new = x2 #use original value for x2
25.
26.     elif x2 == x1: #verticle line
27.         x2new = x2 #no change in x
28.
29.     else:
30.         m = (y2-y1)/(x2-x1) #gradient
31.         x2new = x1 + LayerHeight/m if y2>y1 else x1 -
     LayerHeight/m #positive LayerHeight if y2>y1, else negative LayerHeight
32.         x2new = round(x2new, 3)
33.     return x2new
34.
35. def gOutput(lines):
36.     with open('gCodeOut.txt', 'wb') as f:
37.         f.write(lines)
38.
39. def getMagnitude(x1, x2, y1, y2):
40.     magnitude = ((x2 - x1)**2 + (y2 - y1)**2)**0.5
41.     return magnitude
42.
43. def eRateCalc(x1, x2, y1, y2, e1, e2):
44.     magnitude = getMagnitude(x1,x2,y1,y2) #magnitude of distance traveled
45.     eRate = (e2-e1)/magnitude #mmExrude/distance
46.     return eRate
47.
48. def gExtrude(x1, x2, y1, y2, f1, eRate, e): #move and extrude
49.     #need to account for filament thickness
50.     magnitude = getMagnitude(x1, x2 ,y1, y2) #magnitude of distance traveled
51.     eInc = round(eRate * magnitude, 5) #how much material to extrude based on distance tra
    veled and extrusion rate
52.     endE = e + eInc
```

```
53.     line = "G1 F" + str(f1) + " X"+ '%.3f' % x2 + " Y" + '%.3f' % y2 + " E" + '%.5f' % end
    E + "\n" #formatting ensures correct number of decimal places
54.     return line, endE
55. 
56. def gGo(x, y, f): #move without extruding
57.     #need to account for filament thickness
58.     line = "G0 F" + str(f) + " X"+ '%.3f' % x + " Y" + '%.3f' % y + "\n"
59.     return line
60. 
61. def insSKINlayer(cLines, fillIndex, x, y, startE, f0 = 9000, f1 = 3000, eRate = 0.005684):
     #takes a series of points and generates GCode to connect them with straight lines.
62. 
63.     index = fillIndex
64.     e = startE
65.     i = 0
66. 
67.     sLayerLines = [] #below code needs to be edited 06/13/2016 CB
68.     while (i < len(y)-1):
69.         x1 = x[i]
70.         x2 = x[i+1]
71.         y1 = y[i]
72.         y2 = y[i+1]
73.         if (y2 == y1):
74.             line = gGo(x1, y1, f0)
75.             sLayerLines.append(line)
76.             line, e = gExtrude(x1, x2, y1, y2, f1, eRate, e)
77.             sLayerLines.append(line)
78.         i += 1
79. 
80.     i = 0
81.     while (i < len(sLayerLines)):
82.         if (index == fillIndex + 1): #special case
83.             line = ';TYPE:SKIN inserted by CreateSkin()\n'
84.         else:
85.             line = sLayerLines[i]
86.             i += 1
87.         cLines.insert(index, line)
88.         index += 1
89. 
90.     endE = e
91.     lastIndex = index
92. 
93.     return cLines, endE, lastIndex
94. 
95. def QuantizeY(x, y, LayerHeight): #creates two new arrays xNew and yNew, where all y value
    s are rounded to multiples of LayerHeight, corresponding to filament thickness
96.     LayerHeight = LayerHeight * 2.0 #modify quantization for correct line spacing
97.     newIndex = 0
98.     i = 0
99.     xNew = [round(x[0],3)]
100.        yNew = [round(y[0],3)]
101.        print "len(x) == ", len(x)
102.        print "\n"
103.        while (i < len(x)):
104.            x1 = xNew[newIndex]
105.            x2 = x[i+1] if i+1 < len(x) else x[0] #next point -
     loop around for last point
106.            y1 = yNew[newIndex]
107.            y2 = y[i+1] if i+1 < len(x) else y[0] #next point -
     loop around for last point
108. 
```

```
109.            if (y2 == y1): #horizontal line special case
110.                print "y2 == y1"
111.                if (x2 == x1):
112.                    print "x2 == x1"
113.                else:
114.                    print "x2 != x1 - horizontal line"
115.                    xNew.append(round(x2,3))
116.                    yNew.append(round(y2,3))
117.                    newIndex += 1
118.                    print "newIndex = ", newIndex
119.                i += 1
120.
121.
122.            elif (abs(y2-
    y1) < LayerHeight): #drop points until gap is at least LayerHeight.
123.                print "abs(y2-y1) < LayerHeight"
124.                i += 1
125.
126.                #check to see if next 2 points are horizontal line -
      debugging code 7/18/2016. Solves the rectangle -> triangle fill bug; ask Callum.
127.                x1 = x[i]
128.                x2 = x[i+1] if i+1 < len(x) else x[0] #next point -
     loop around for last point
129.                y1 = y[i]
130.                y2 = y[i+1] if i+1 < len(x) else y[0] #next point -
     loop around for last point
131.                if (y2 == y1): #horizontal line special case
132.                    print "y2 == y1"
133.                    if (x2 == x1):
134.                        print "x2 == x1"
135.                    else:
136.                        print "x2 != x1 - horizontal line"
137.                        xNew.append(round(x2,3))
138.                        yNew.append(round(yNew[newIndex],3))
139.                        newIndex += 1
140.                        print "newIndex = ", newIndex
141.                    i += 1
142.                #end debugging code 7/18/2016
143.
144.            else:
145.                xNew.append(InterpolateX(x1, x2, y1, y2, LayerHeight))
146.                yNew.append(round(y1 + LayerHeight, 3)) if (y2>y1) else yNew.append(round(y
    1 - LayerHeight, 3))
147.                newIndex += 1
148.
149.        with open(projectPath + '//debug//outputShape.txt', 'wb') as csvfile:
150.            outputwriter = csv.writer(csvfile, delimiter=',',quotechar='|', quoting=csv.QUO
    TE_MINIMAL)
151.            outputwriter.writerow(xNew[:])
152.            outputwriter.writerow(yNew[:])
153.
154.        dumpFile(xNew, "xNew.txt")
155.        dumpFile(yNew, "yNew.txt")
156.        return xNew, yNew
157.
158.    def getLayerHeight(cLines, Layer1=1): #get LayerHeight (in mm) by taking the difference
     between 2 layers from the GCODE file. Layer 1 and Layer 2 by default or specify a differe
    nt Layer.
159.        currentLayerN = Layer1
160.        Layer2 = Layer1 + 1
161.        index = 0
```

```
        z = []
        while (currentLayerN <= Layer2):
            LayerName = ';LAYER:' + str(currentLayerN)
            while index < len(cLines):
                line = cLines[index]
                if (line[0:len(LayerName)] == LayerName):
                    while line[0:2] != 'G0':
                        index += 1
                        line = cLines[index]
                    zPos = line.find('Z') + 1
                    if zPos == 0:
                        print "ERROR: z not found on index = ", index
                        LayerHeight = -1
                        return LayerHeight
                    z.append(float(line[zPos:len(line)]))
                    index += 1
                    break
                index += 1
            currentLayerN += 1
        z1 = z[0]
        z2 = z[1]
        if (z1 > 0) and (z2 > 0):
            LayerHeight = z2 - z1
            print "LayerHeight = ", LayerHeight
        else:
            print "ERROR: LayerHeight z1 or z2 not found."
            LayerHeight = -1
        return LayerHeight

    def getLayerIndex(cLines, currentLayerN):
        index = 0
        LayerName = ';LAYER:' + str(currentLayerN)
        while index < len(cLines):
            line = cLines[index]
            if (line[0:len(LayerName)] == LayerName): #(line[0:(len(LayerName)+1)]
                print "LayerIndex ==", index
                return index
            index += 1
        print "ERROR: LayerIndex not Found. currentLayerN =", str(currentLayerN)
        return -1

    def getFILLandSKINindices(cLines, currentLayerIndex):
        index = currentLayerIndex
        fillIndex = -1
        skinIndex = -1
        LAYERcount = 0
        index += 1
        while (index < len(cLines)):
            line = cLines[index]
            if line[0:7] ==';LAYER:':
                break
            elif line[0:10] ==';TYPE:FILL':
                fillIndex = index - 1
            elif line[0:10] ==';TYPE:SKIN':
                skinIndex = index - 1

            index += 1

        return fillIndex, skinIndex

    def getEndIndex(cLines,startIndex):
```

```
223.        index = startIndex
224.        count = 0
225.        while (index < len(cLines)):
226.            line = cLines[index]
227.            if line[0] ==';':
228.                count += 1
229.                if (count > 1):
230.                    if line[0:7] ==';LAYER:': #if the FILL being replaced occurs immediatel
    y before a new ;LAYER, the line we are interested in is immediately before ;LAYER
231.                        endIndex = index - 1
232.                    else:
233.                        endIndex = index -
     2 #if the FILL being replaced occurs before another sub-layer structure ;WALL-
    INNER ;WALL-OUTER; etc. the line we are interested in 2 before the ; comment line
234.                    return endIndex
235.            index += 1
236.        endIndex = index - 1
237.        print "getEndIndex: End of file reached."
238.        return endIndex
239.
240.    def getE(line):
241.        ePos = line.find(' E') + 2
242.        if (ePos > 1):
243.            e = float(line[ePos:len(line)])
244.        else:
245.            e = -1
246.            print "E NOT FOUND", line
247.        return e
248.
249.    def getZ(line):
250.        zPos = line.find('Z') + 1
251.        if (zPos > 1):
252.            z = float(line[zPos:len(line)])
253.        else:
254.            z = -1
255.            print "ERROR: Z NOT FOUND"
256.        return z
257.
258.    def delFILLlayer(cLinesInput, fillStartIndex):
259.        index = 0
260.        cLinesOutput = []
261.        fillEndIndex = getEndIndex(cLinesInput,fillStartIndex)
262.
263.        while (index < len(cLinesInput)):
264.            line = cLinesInput[index]
265.            if ((index < fillStartIndex) or (index > fillEndIndex)):
266.                cLinesOutput.append(line)
267.            index += 1
268.
269.        #Since we are deleting lines, we need to know what the value of E was that was dele
    ted to adjust the absolute extrusion values in the rest of the file.
270.        print "fillEndIndex = ", fillEndIndex
271.        endE = getE(cLinesInput[fillEndIndex])
272.
273.        print "fillEndIndex + 3 = ", (fillEndIndex + 3)
274.        nextE = getE(cLinesInput[fillEndIndex + 6]) # change the hardcoded "6" to some rais
    ing index that keeps trying until it gets an E value.
275.
276.        if (endE > 0) and (nextE > 0):
277.            deltaE = nextE - endE
278.        else:
```

```
279.            deltaE = -1 #ERROR
280.            print "ERROR: deltaE NOT FOUND"
281.
282.        return cLinesOutput, deltaE, endE #deltaE code can probably be deleted. Probably on
    ly need endE. 6/21/2016 CB
283.
284.    def getCoOrd(line, charName): #get an X, Y, or Z coord, E value, or F or G int value
285.        charName = str.upper(charName) #uppercase if it isn't already
286.        if line[0:2] == "G0" or line[0:2] == "G1" or line[0] == "F": #or line[0:3] == "G28"

287.            commentPos = line.find(";")
288.            startPos = line.find(charName) + 1
289.            if commentPos >= 0 and startPos > commentPos: #ignore comments
290.                startPos = -1
291.        else:
292.            startPos = -1 #ignore everything that isn't G0, G1, F, M
293.
294.        if (startPos > 0): #we have a match
295.            #pointPos = l
296.            endPos = line.find(';', startPos)
297.            if endPos == -1:
298.                endPos = line.find(' ', startPos)
299.            else:
300.                spacePos =  line.find(' ', startPos)
301.                if (spacePos > -1) and (spacePos < endPos):
302.                    endPos = spacePos
303.            if endPos == -1:
304.                endPos = line.find('\n', startPos)
305.            if endPos == -1:
306.                print "endPos not found."
307.            try:
308.                charVal = float(line[startPos:endPos])
309.            except ValueError:
310.                print line, charName
311.                print "meow"
312.                raise
313.            if ((charName == 'F') or (charName == 'G')):
314.                charVal = int(charVal)
315.        else: #no match
316.            charVal = -1
317.            #print "ERROR: charVal NOT FOUND, ", charName
318.        return charVal
319.
320.    def getZfromLayerIndex(cLines, currentLayerIndex):
321.        index = currentLayerIndex
322.        index += 1
323.        line = cLines[index]
324.        while line[0:2] != 'G0':
325.            index += 1
326.            line = cLines[index]
327.        z = -1
328.        while (z == -1):
329.            z = getCoOrd(line,'Z')
330.            index += 1
331.            if (index >= len(cLines)): #ERROR
332.                print "ERROR: getZfromLayerIndex index >= len(cLines); Z not found"
333.                return -1
334.            line = cLines[index]
335.        return z
336.
```

```
337.    def getEfromFillIndex (cLines, fillIndex):#gets the previous E value before ;TYPE:FILL

338.        index = fillIndex
339.        e = -1
340.        while (e == -1):
341.            index -= 1
342.            line = cLines[index]
343.            e = getE(line)
344.            if (index <= 0): #ERROR
345.                print "ERROR: getEfromFillIndex index <= 0; E not found"
346.                return -1
347.        return e
348.
349.    def getSTRINGindex(cLines, currentLayerIndex, stringN, string): #returns the index of t
    he line before the text ;TYPE:WALL-OUTER
350.        index = currentLayerIndex
351.        index += 1
352.        while (index < len(cLines)):
353.            line = cLines[index]
354.            if line[0:len(string)] == string:
355.                if (stringN == 0):
356.                    return index - 1
357.                elif (stringN > 0):
358.                    stringN -= 1
359.                else: #error
360.                    print "ERROR: stringN < 0 for currentLayerIndex == ", currentLayerIndex
    , string
361.                    return -1
362.            index += 1
363.        print "ERROR: getSTRINGindex not found for currentLayerIndex == ", currentLayerInde
    x, string
364.        return -1
365.
366.    def getWALLxyfe(cLines, WALLindex):
367.        x = []
368.        y = []
369.        e = []
370.        index = WALLindex + 2 #skip a few lines
371.        f1 = -1
372.        while (index < len(cLines)):
373.            line = cLines[index]
374.            if line[0:2] == 'G0':
375.                f0 = getCoOrd(line, 'F')
376.                break
377.            elif line[0:2] == 'G1':
378.                x1 = getCoOrd(line, 'X')
379.                y1 = getCoOrd(line, 'Y')
380.                if ((x1 != -1) and (y1 != -1)):
381.                    if (f1 == -1):
382.                        f1 = getCoOrd(line, 'F')
383.                    e1 = getCoOrd(line, 'E')
384.                    x.append(x1)
385.                    y.append(y1)
386.                    e.append(e1)
387.            index += 1
388.
389.        eRate = eRateCalc(x[0],x[1],y[0],y[1],e[0],e[1])
390.        if f1 == -1:
391.            print "ERROR: getWALLxyfe f1 not found. WALLindex = ",WALLindex
392.        dumpFile(y, "y.txt")
393.        dumpFile(x, "x.txt")
```

```
394.        return x, y, f0, f1, eRate
395.
396.    def fixE(cLines, eOffset, lastIndex):
397.        index = lastIndex + 1
398.        while index < len(cLines):
399.            line = cLines[index]
400.            if line.find(';') == 0: #skip ;LAYER: lines
401.                index += 1
402.            elif line.find('G91') == 0: #reached end of file; G91 is relative positioning
403.                return cLines
404.            else:
405.                eStartPos = line.find('E') + 1
406.                if (eStartPos > 0):
407.                    eEndPos = line.find('\n')
408.                    oldE = float(line[eStartPos:eEndPos])
409.                    newE = oldE + eOffset
410.                    newE = round(newE, 5)
411.
412.                    #print "newE =",newE
413.                    #print "line =",line
414.                    #print "eStartPos:eEndPos =",eStartPos, eEndPos
415.
416.                    #line = line[:eStartPos] + str(newE) + line[eEndPos:]
417.                    #line = line[:eStartPos] + '%s' % float('%.6f' % newE) + line[eEndPos:]

418.                    line = line[:eStartPos] + '%.5f' % newE + line[eEndPos:]
419.
420.                    #print line
421.                    cLines[index] = line
422.                index += 1
423.        return cLines
424.
425.    def add_path(pc, path):
426.        pc.AddPath(path, pyclipper.JT_ROUND, pyclipper.ET_CLOSEDPOLYGON)
427.
428.    def XYtoContour(x, y):
429.        x = list(x) #convert tuple to list
430.        y = list(y)
431.        contour = []
432.        i = 0
433.        while i < len(x):
434.            x[i] = int(x[i] * 1000)
435.            y[i] = int(y[i] * 1000)
436.            contour.append([x[i], y[i]])
437.            i += 1
438.        return contour
439.
440.    def ContourToXY(contour):
441.        x = []
442.        y = []
443.        i = 0
444.        while i < len(contour[0]):
445.            x.append(contour[0][i][0] / 1000.0)
446.            y.append(contour[0][i][1] / 1000.0)
447.            i += 1
448.        return x, y
449.
450.    def shrinkXY(x, y, LayerHeight):
451.        offset = LayerHeight * -2000.0
452.        contour = XYtoContour(x, y)
453.
```

```
454.        pc = pyclipper.PyclipperOffset()
455.        add_path(pc, contour)
456.        resizedContour = pc.Execute(offset)
457.        if len(resizedContour) != 1: #if the shape is too narrow, the contour will be pinch
    ed off and split into two new contours, which is beyond the scope of the current algorithm
    .
458.            print "ERROR: shrinkXY: 0 or more than 1 contours returned. Shape may be too na
    rrow. len(resizedContour) =", len(resizedContour)
459.            return -1, -1
460.        x, y = ContourToXY(resizedContour)
461.
462.        return x, y
463.
464.    def CreateSkin(cLines, endLayerN, filePath, SkinThickness=1.0):
465.        global projectPath
466.        projectPath = filePath
467.
468.        error = 0
469.        LayerHeight = getLayerHeight(cLines)
470.
471.        if (LayerHeight > 0):
472.            nLayers = int(math.ceil(SkinThickness/LayerHeight)) # number of Layers of solid
     fill to put below the wire (rounded up to ensure thickness >= SkinThickness)
473.        else:
474.            error = 1
475.            return cLines, error
476.        #remove previous material
477.        #cLines, e = deleteLayers(cLines, finalLayerNumber, nLayers)
478.
479.        i = 1
480.        while (i <= nLayers):
481.
482.            currentLayerN = endLayerN -
     nLayers + i #number of current layer. currentLayerN of ;LAYER:3 is 3
483.            if currentLayerN < 1: #if number of SKIN layers takes us below LAYER 1, skip th
    ose layers.
484.                i += 1
485.                continue
486.            print "currentLayerN = ", currentLayerN
487.            currentLayerIndex = getLayerIndex(cLines, currentLayerN) #Provides the index of
     the line which includes ;LAYERx where x is the first LAYER to be replaced. -
    1 if not found. -2 if more than 1 found.
488.
489.            if (currentLayerIndex > 0):
490.                fillIndex, skinIndex = getFILLandSKINindices(cLines, currentLayerIndex)
491.            else:
492.                error = 1
493.                return cLines, error
494.
495.            if (fillIndex > 0): #one FILL type is present. This is the hex pattern that wil
    l be replaced by a solid skin.
496.
497.                if (skinIndex == -
    1): #no SKIN type is currently present. We will only replace the hex FILL in simple shapes
     that have no solid SKIN in any part of the layer.
498.
499.                    dumpFile(cLines, "tB4DELfillLAYER.gcode") #debugging
500.                    cLines, deltaE, oldEndE = delFILLlayer(cLines, fillIndex) #deltaE is th
    e difference between the last E value deleted and the next E value in the original GCODE.

501.                    dumpFile(cLines, "tempDELfillLAYER.gcode") #debugging
```

```
502.
503.                     if (deltaE <= 0): #ERROR
504.                         print "ERROR: deltaE <= 0. currentLayerN = ", currentLayerN
505.                         error = 1
506.                         return cLines, error
507.
508.                     startE = getEfromFillIndex(cLines, fillIndex) #gets the previous E valu
    e before ;TYPE:FILL
509.                     if (startE == -1): #ERROR
510.                         print "ERROR: getEfromFillIndex failed to find e. currentLayerN = "
    , currentLayerN
511.                         error = 1
512.                         return cLines, error
513.
514.                     WALLindex = getSTRINGindex(cLines, currentLayerIndex, 0, ';TYPE:WALL-
    INNER')
515.                     if (WALLindex < 0): #no WALL_INNER, try to find WALL_OUTER instead
516.                         WALLindex = getSTRINGindex(cLines, currentLayerIndex, 0, ';TYPE:WAL
    L-OUTER') #second argument (0) corresponds to how many WALL-
    OUTER to skip. In a later implementation, this will allow for processing of shapes with mo
    re than  WALL_OUTER in the same layer.
517.                         if (WALLindex < 0): #ERROR
518.                             error = 1
519.                             return cLines, error
520.
521.
522.                     x, y, f0, f1, eRate = getWALLxyfe(cLines, WALLindex) #get XY points tha
    t define the shape from WALL
523.                     if (f1 == -1): #ERROR
524.                         error = 1
525.                         return cLines, error
526.
527.
528.                     x, y = shrinkXY(x, y, LayerHeight) #reduce area of x, y so it fits with
    in the WALL. Maintain layer separation
529.
530.                     x, y = QuantizeY(x, y, LayerHeight) #Interpolates points. Must be perfo
    rmed before the sort.
531.
532.                     y, x = zip(*sorted(zip(y,x))) #sort by ascending y; keep x and y coordi
    nate pairs together.
533.                     #dumpFile(x, "xSorted.txt")
534.                     #dumpFile(y, "ySorted.txt")
535.
536.                     if (x == -1): #ERROR shrink XY returns x == -1 and y == -
    1 in the event of an error.
537.                         error = 1
538.                         return cLines, error
539.
540.                     dumpFile(cLines, "tB4INSskinLAYER.gcode")
541.                     cLines, newEndE, lastIndex = insSKINlayer(cLines, fillIndex, x, y, star
    tE, f0, f1, eRate)
542.                     dumpFile(cLines, "INSskinLAYER.gcode")
543.
544.                     eOffset = newEndE - oldEndE
545.                     #eOffset can be positive or negative
546.
547.                     if (eOffset != 0):
548.                         cLines = fixE(cLines, eOffset, lastIndex) #fix the absolute extrusi
    on values in the GCODE
549.                     dumpFile(cLines, "tFixE.gcode")
```

```
550.
551.                     print ";FILL replaced with ;SKIN in layer", currentLayerN
552.                 else:
553.                     print "ERROR: Shape too complicated. Circuit needs to be in a layer abo
    ve the reference shape. ;FILL and ;SKIN both found in layer", currentLayerN
554.                     error = 1
555.                     return cLines, error
556.             elif (skinIndex > 0):
557.                 print ";SKIN found in layer ", currentLayerN #no replacement necessary. 100
    % SKIN layer already exists.
558.             else:
559.                 print "ERROR: No ;FILL or ;SKIN found in layer", currentLayerN
560.                 error = 1
561.                 return cLines, error
562.             i += 1
563.         return cLines, error
```

Vita

The elder of two sons of Peter and Jenny Bailey, Callum Peter Bailey was born in St. Helier, Jersey, an island in the English Channel. In 2002, after completing his secondary education at Victoria College, Callum matriculated into Hertford College at the University of Oxford to read for an undergraduate master's degree in chemistry. In 2006, he completed his thesis on *Nuclear Magnetic Resonance Structural Investigation of β-Amino Acid Foldamers* which resulted in his attainment of an upper second-class honours degree classification.

After his degree, Callum embarked on a gap year adventure, traveling to Thailand, Malaysia, Singapore, Australia, New Zealand, the United States, and Canada. During his time in the US, he met his future wife, Heather, whom he married in 2008 before relocating to Houston, TX. In Houston, Callum found employment as an industrial R&D chemist, working for the French multinational oil company, Total. At Total, Callum worked in both the Base Chemicals and Polymers research departments, where he led the design and construction process of a lab-scale polystyrene pilot plant. It was during this process that an interest in industrial automation and 3D printing (in which high-impact polystyrene is a common feedstock) was kindled.

In the summer of 2014, Heather was admitted to medical school at the Paul L. Foster School of Medicine in El Paso, TX. Taking the opportunity for a career change and to develop his interests in process automation, Callum enrolled at The University of Texas at El Paso to study for a master's degree in electrical engineering. Shortly after arriving, he met 3D-printing guru, Dr. Eric MacDonald, who inducted him into his research group and the W.M. Keck Center for 3D Innovation. In the group Callum initially worked on applications for 3D printed parts, including a project funded by Lockheed Martin to develop 3D printed hinges featuring electrical

connections. Later, Callum transferred to developing control programming and the work described in this publication.

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This thesis was typed by Callum Peter Bailey