Rapid Prototyping of Electric Circuits Using 3-D Printing

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Current methods of embedding electric circuits into 3-D rapid prototyped (RP) structures have led to difficulties in design, wiring, as well as costs associated with purchasing manufactured printed circuit boards. To circumvent these problems, prior work in the GRAB Lab developed 3-D printable circuits by manually designing channels into 3-D parts using CAD software, printing using a traditional RP method called fused deposition manufacturing (FDM), and the injection of liquid metal through the channels in the part. Injection points were created for each distinct trace of the circuit. Since circuit components were not located at equal distances from an injection point, problems arose upon injection when liquid metal did not arrive at the surface of the part, where the circuit components are placed, at the same time, thereby leading to spillage of the liquid metal. This paper provides a method which automatically generates the RP model from circuit design files created through traditional means and addresses the problem of metal spillage. This process is completed in three steps: (1) a circuit board layout is defined using a schematic capture and printed circuit board (PCB) design tool, EAGLE PCB (2) MATLAB is used to extract information concerning the channels, vias, and through-holes of the circuit, and (3) input scripts are generated to a programmatic solid modeling software, OpenSCAD, to create a series of channels in a RP part that represent the paths of the circuit. Using this automated method, a 555 Timer circuit was created as a proof of concept. In addition to automating this process, a hierarchical tree structure was created that branched from an injection point to each of its respective through-holes. Inherent in this tree structure is the ability to modify channel diameters, thereby controlling volumetric flow rate in each channel. The creation of this tree structure aims to allow future iterations of electric circuits, such as the 555 Timer, in which channel diameters have been modified such that liquid metal arrives at the surface of the part at the same time, thus avoiding metal spillage.

Introduction

Embedding electronic components into 3-D printed robotic parts presents various complications. The fingers of the iRobot-Harvard-Yale (iHY) Hand, shown in Figure 1, have low cost encoders, accelerometers and contact sensors [1-2], but these electronic components are integrated by wiring all of the components by hand, manually packaging the electronics inside a mold, followed by standard injection molding. Complications arise if excess wiring is too near the surface or caught between the halves of a mold.

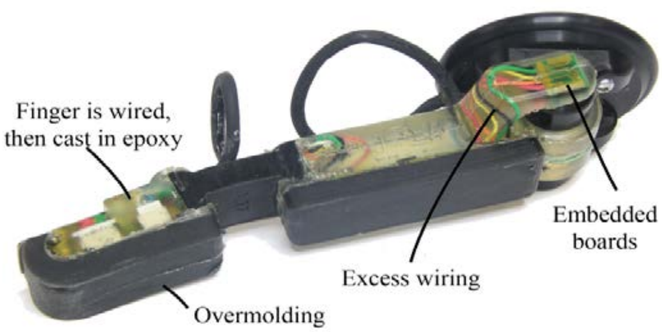

Figure 1 - The fingers of the iHY Hand contain several sensor boards, but the wiring is completed by hand before the epoxy is cast.

Additionally, the costs associated with the purchasing of manufactured printed circuit boards that fit tight constraints or abnormal sizes can be prohibitive. Traditional circuits are created by designing a circuit schematic and circuit board layout, usually with a printed circuit board (PCB) design tool. The circuit board information is then shipped to a board house which manufactures the circuit. This manufactured process requires board features to be etched from copper sheets using various machines and can be quite expensive.

To address these problems, prior work in the GRAB Lab sought to embed traces directly into the 3-D printed body of the finger and then fill those traces with a conductive material. This would eliminate the need to wire components by hand and fix everything into place with epoxy, as well as avoid the costs associated with manufactured PCBs. A method was developed to create 3-D printable circuits by manually designing channels into 3-D parts using a CAD software application known as SolidWorks. Once a 3-D model was created, a fused deposition modeling (FDM) printer was used to create the part. FDM printers are traditionally used for the rapid prototyping of 3-D parts. An FDM printer ejects molten ABS plastic filament to create the part layer by layer. The FDM printer used for the purposes of this project was the Stratasys Fortus 250mc.

Liquid metal was then injected into the 3-D part through the channels in the part. The injection based method consisted of the injection of a metal alloy known as Cerrolow 136 using a syringe, as shown in Figure 2. Cerrolow 136 is a eutectic mixture of bismuth (49%), indium (21%), lead (18%), and tin (12%). Cerrolow 136's melting point of 57.8 °C [3] is low enough such that it does not affect the structure of the 3-D printed part, but high enough above room temperature that metal will remain solid during normal operation. The ABS plastic used by the FDM printer becomes soft at its glass transition temperature, 108 °C [4]. In addition, this metal experiences relatively minor net volume change as it solidifies, which means it will not warp or deform the 3-D part as it cools.

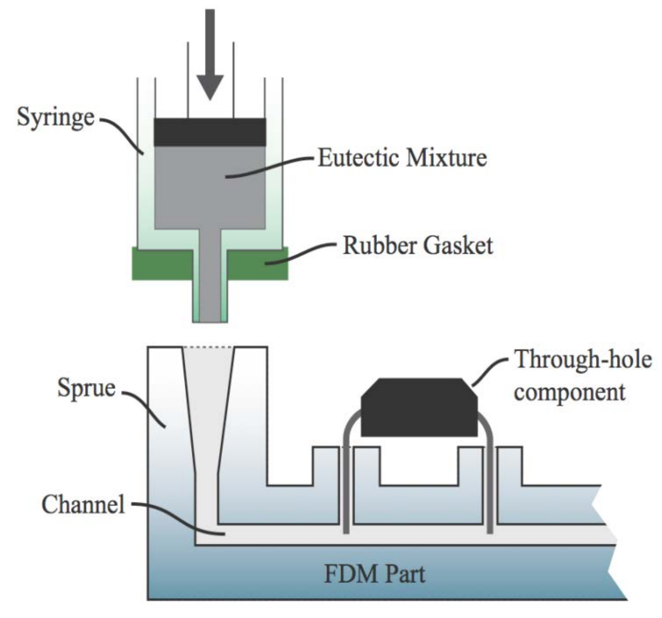

Figure 2 - A schematic of the integrated wiring process, including the printed channels into which liquid metal is injected, the sprue used to fill the trace, and the sealed syringe nozzle used to inject metal into the part.

A single-layered circuit, shown in Figure 3, was successfully created using the previously developed method. The channels represent the paths of the circuit that connect all of the circuit components and replace the electrical traces from a manufactured PCB. Adequate spacing between traces was necessary so that liquid metal would not leak between channels, consequently creating a short circuit. The circuit channels were spaced at twice the minimum feature size, so that two layers of solid ABS plastic lay between them (approximately 1 mm under nominal settings on the Stratasys Fortus 250mc, see Figure 4). Additionally, square profiles were used for the channels in the 3-D part, as noted in Figure 5. This square profile was rotated to create a diamond shaped geometry so as to avoid printing support material in the traces.

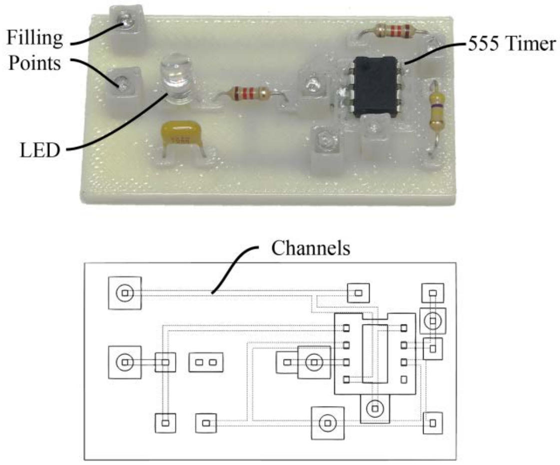

Figure 3 - A circuit having through-hole components was fabricated in a FDM part. This part demonstrates connection of traces to DIP components, and the capability to inject traces that split into multiple paths.

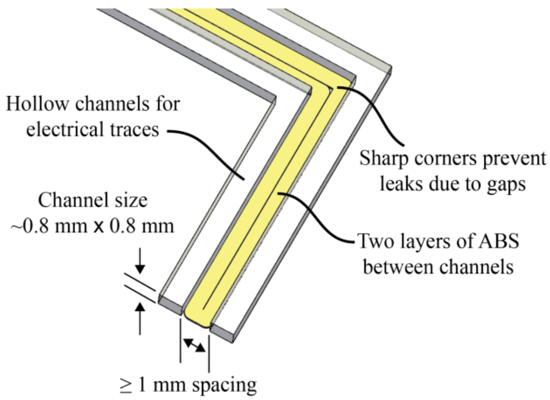

Figure 4 – The channels must be spaced so that two widths of the printed ABS filament can fit between them.

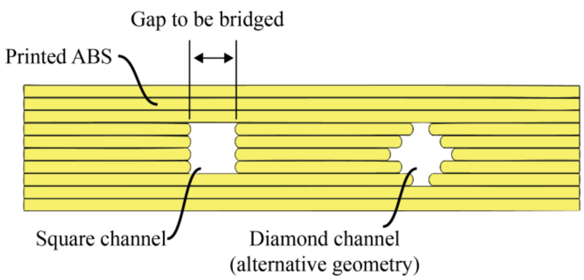

Figure 5 – Channels for the electrical traces were made using square profiles in the printed parts. To avoid printing support material, this square profile was rotated to adopt a diamond shaped geometry.

The injection, or filling, point is the root of each path where the liquid metal is pumped into the circuit. There is one injection point for each distinct trace of the circuit. Liquid metal branches off from an injection point to each of its respective through-holes. Since circuit components were not located at equal distances from an injection point, problems arose upon injection when liquid metal did not arrive at the surface of the part where the circuit components are placed at the same time, thereby leading to spillage of the liquid metal. This problem was most noticeable in the creation of a two-layered robotic circuit. The circuit was also manually designed in SolidWorks. The experiment injection of this circuit proved to be unsuccessful when liquid metal spilled out of holes that were closer to the injection point and the circuit could not be completed.

To resolve the tedious process of designing a 3-D circuit by hand, we automated the process by using a printed circuit board design tool known as the Easily Applicable Graphical Layout Editor for Printed Circuit Boards (EAGLE PCB) [5] and a programmable CAD software application known as OpenSCAD [6]. EAGLE PCB is one of the standard schematic capture and printed circuit board (PCB) design tools used to traditionally create circuits. OpenSCAD is a programmatic solid modeling software application. As opposed to SolidWorks, OpenSCAD possesses programming capabilities that allowed the automation of this process. Using these tools, a method was developed which automatically generated a 3-D model based on the information provided from a defined circuit board layout on EAGLE PCB. This 3-D model was designed by making extrusions in OpenSCAD which reflected the channels of the circuit paths described by EAGLE PCB. A 555 Timer circuit was created as a proof of concept. This method circumvents the need for large manufacturing processes by only requiring a 3-D printer and a method for injecting liquid metal into the 3-D printable circuit.

In addition to automating this process, a hierarchical tree structure was created that branched from an injection point to each of its respective through-holes. Inherent in this tree structure is the ability to modify channel diameters, thereby controlling volumetric flow rate in each channel. The creation of this tree structure aims to allow future iterations of electric circuits, such as the 555 Timer, in which channel diameters have been modified such that liquid metal arrives at the surface of the part at the same time, thus avoiding metal spillage.

Materials & Methods

The process described in this paper consisted of three steps: (1) a circuit board layout was defined using EAGLE PCB (2) MATLAB was used to extract information concerning the channels, vias, and through-holes of the circuit, and (3) input scripts were generated to a programmatic solid modeling software, OpenSCAD, to create a series of channels in a RP part that represent the paths of the circuit.

Definition of Circuit Board Layout

Using EAGLE PCB, the circuit board layout for a two-layered 555 Timer circuit was defined. To do so the circuit board schematic shown in Figure 6 was created on EAGLE PCB. The injection points, labeled JP1-JP8, are installed manually in the circuit schematic such that there is an injection point for each distinct path of the circuit. Each symbol corresponds to a circuit component with distinct properties, such as the specific model of the part and its dimensions. EAGLE PCB used the information from the circuit schematic to create the circuit board layout shown in Figure 5 and represented by a BRD file.

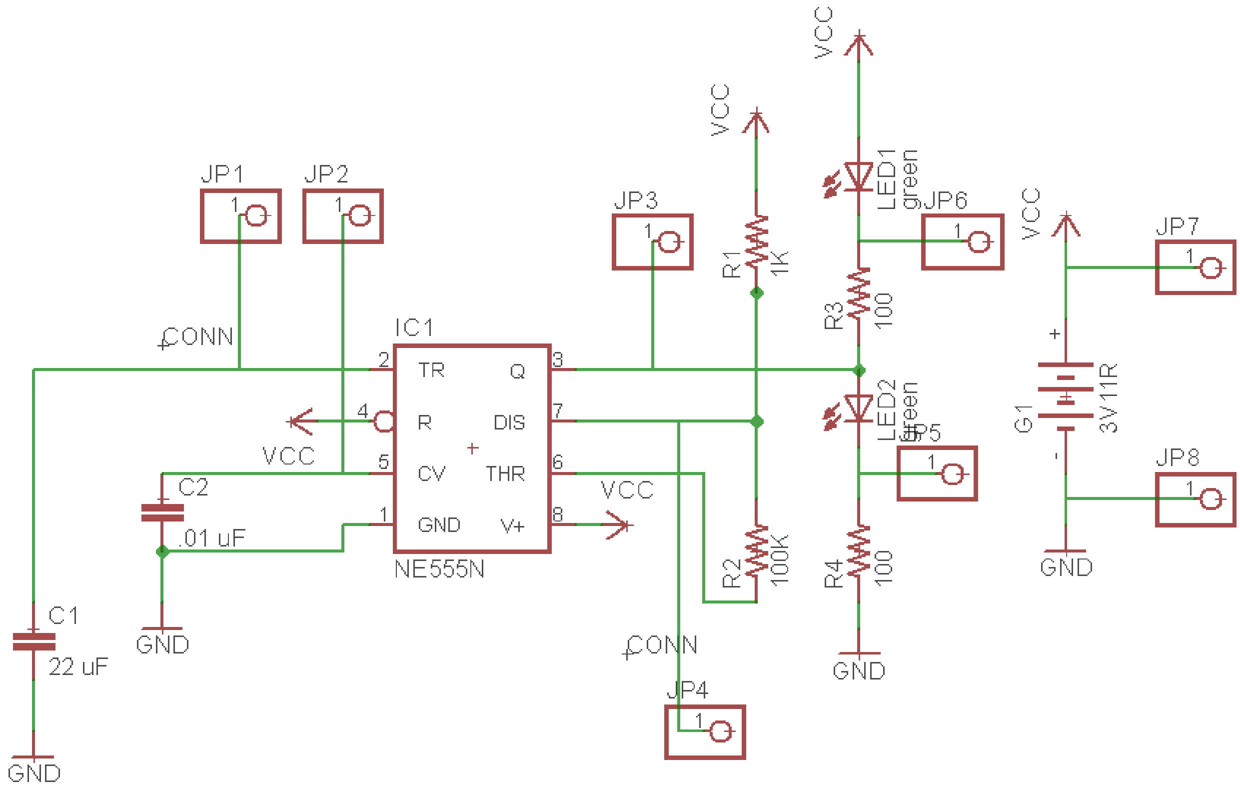

Figure 6 - Circuit Schematic of a 555 Timer circuit from EAGLE PCB Software

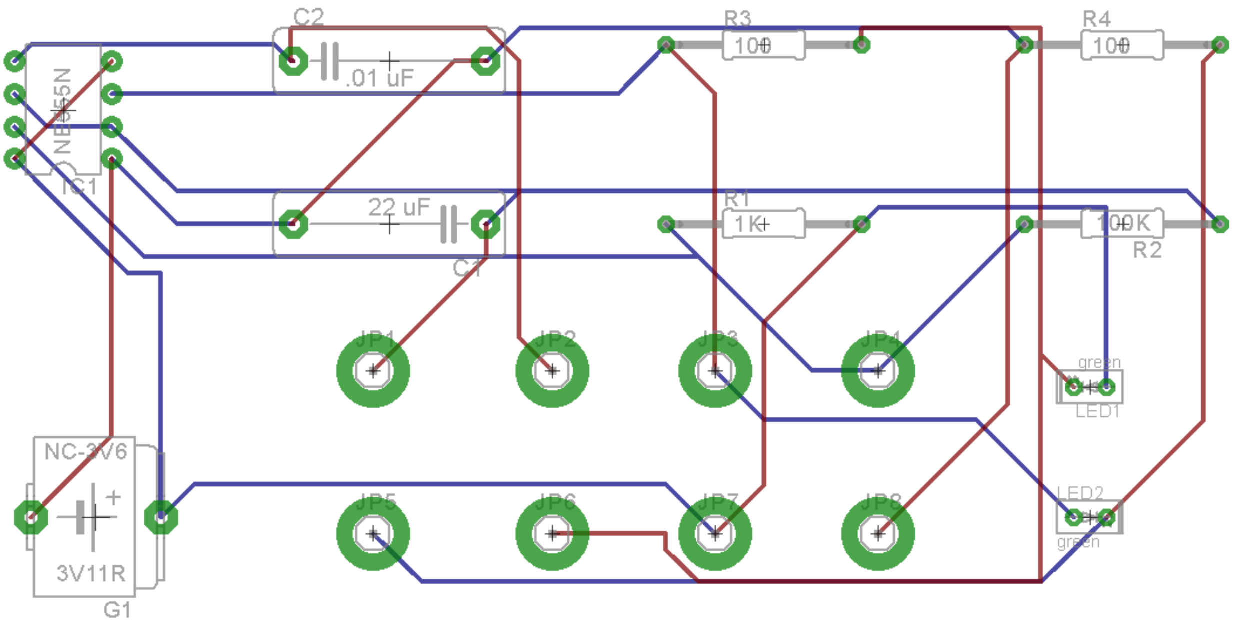

Figure 7 - 555 Timer Circuit created on EAGLE PCB

One of the advantages of using EAGLE PCB's circuit board layout editor is that it possesses auto-routing capabilities. Circuit components can be laid out on the board and, using the Auto-Router function, automatically connected to form traces based on the connections defined in the schematic. This rapid creation of complex, multi-layered circuits is advantageous in the rapid prototyping of our electric circuits using 3-D printing. Figure 7 was created using the Auto-Router function. Specifications or restraints can also be made in the Auto-router function. So as to be within the restrains necessary for the successful 3-D printing of the circuit, distances between traces were set such that there was at least 1 mm of spacing between them.

Extract Information Using MATLAB

Our proposed model for the conversion of a 2-D circuit board layout into a 3-D printable circuit needed to incorporate key components from the EAGLE PCB BRD file relevant to the creation of the channels. The circuit board characteristics acquired from the BRD file and used in the design of our model included the following: starting and ending coordinate locations of through-holes or pads, the start and ending coordinates of each wire path, the layer for each wire path, and the injection point locations.

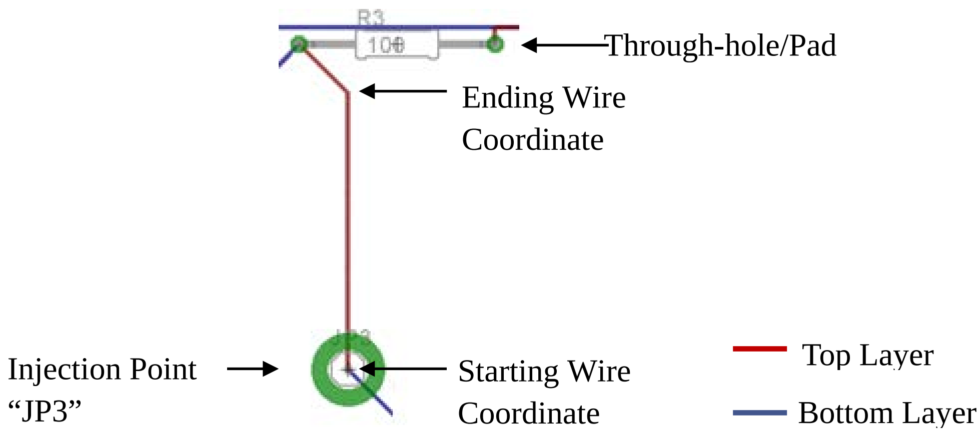

Figure 8 – Diagram of circuit board features extracted from EAGLE PCB and used in MATLAB for the creation of the 3-D printable circuit

The through-holes, or pads, are the locations where the circuit components are inserted. A path’s starting and ending coordinates reveal the location, direction, and length of each extrusion. The layer indicates at what height the channels are created; in the case of the 555 Timer circuit the two layers are the top and bottom layers. The injection point locations represent the start of the wire path(s).

This information was extracted from MATLAB to create the 3-D plot shown in Figure 10. The green lines represent the vertical extrusions, or channels, and the blue and red lines indicate the top and bottom layer channels, which are consistent with the information shown on EAGLE PCB.

The EAGLE PCB information was not only used to create the extrusions for the channels in the 3-D model, but it was also formatted into the form of a tree structure. The tree structure starts at the injection point, which is the root of a path, and branches out to each of the through-holes. The tree structure provides information about the distances from an injection point to each of its through-holes, as well as the diameter of each of the channels. An overall schematic of the extraction of PCB information, the creation of the tree structure, and the use of the tree structure in creating the 3-D part is shown in Figure 11.

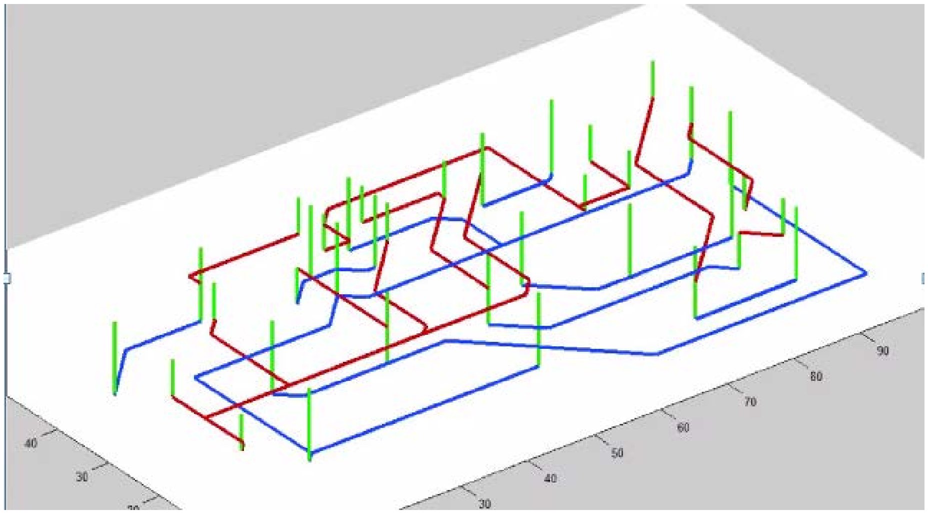

Figure 10- 3-D MATLAB plot showing channels that will be created for 3-D printable circuit

Creation of 3D printable circuit

Once the relevant information from the BRD file was extracted from MATLAB, it was written in a scripted format that could be interpreted by OpenSCAD and exported as an STL file. STL stands for stereo lithography, which is an additive manufacturing process in which prototypes are built one layer at a time by curing a photo-reactive resin with a UV laser or another similar power source. 3-D printing is an additive manufacturing process, which is why the STL file format is common in 3-D printing software. The STL file was then read by the Fortus 250mc to create our 3-D printable circuit.

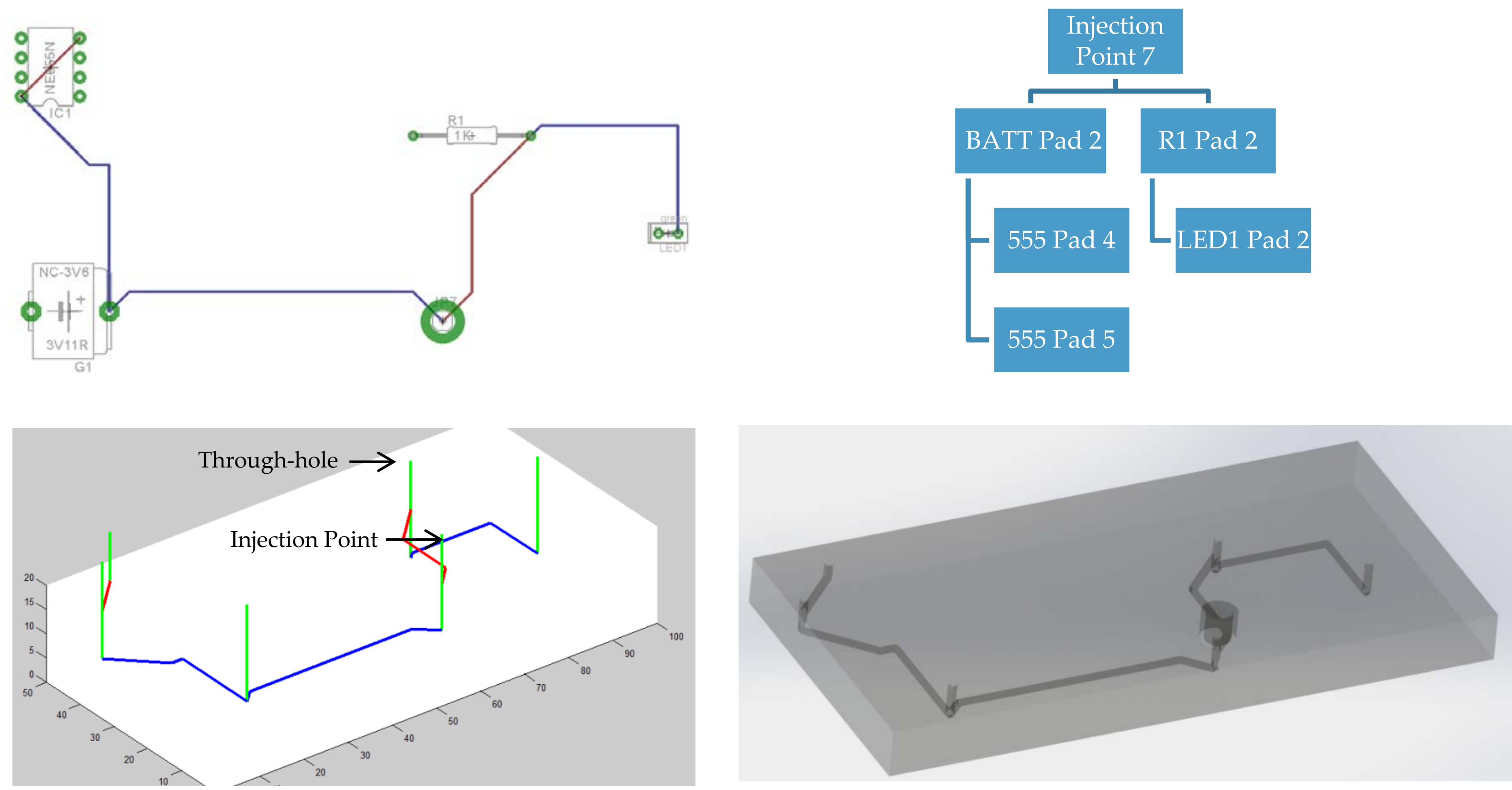

Figure 11 - Overall schematic of the extraction of a wire path from EAGLE PCB and how this information is used to create the 3-D printable circuit. The top left shows a distinct trace for one of the circuit paths. The top right is an abstract representation of this path in the form of a tree structure, in which the injection point is the root of the tree structure. The bottom left is a MATLAB plot showing the various extrusions that result from the creation of this tree structure. The bottom right is a sample 3-D model of how the information from MATLAB would be interpreted to create the series of extrusions that make up the channels of the circuit.

Results

The circuit board layout for the 555 Timer was correctly defined according to the necessary specifications for 3-D printing. MATLAB extracted the information from the BRD file and created the hierarchical tree structure. It is possible to make modifications to properties of this tree structure, such as the channel diameters, for future iterations of electric circuits such as the 555 Timer. The information was then put into a format that was able to be read by OpenSCAD to create the appropriate extrusions. The 3-D model in the STL format is shown in Figure 12. Figure 13 is one of the 555 Timer circuits created using our method.

Injections were attempted to determine connectivity between traces, but without any modifications to channel diameters of the tree structure. The latest iteration of the 555 Timer circuit, shown in Figure 14, demonstrated expected results of metal spillage at the surface of the part. Of the 26 through-holes in the 555 Timer circuit, 19 of them reached the surface of the part before excessive metal spillage occurred and the injection was stopped. There were no signs of metal spillage on the inside of the 3-D part, outside of the channels.

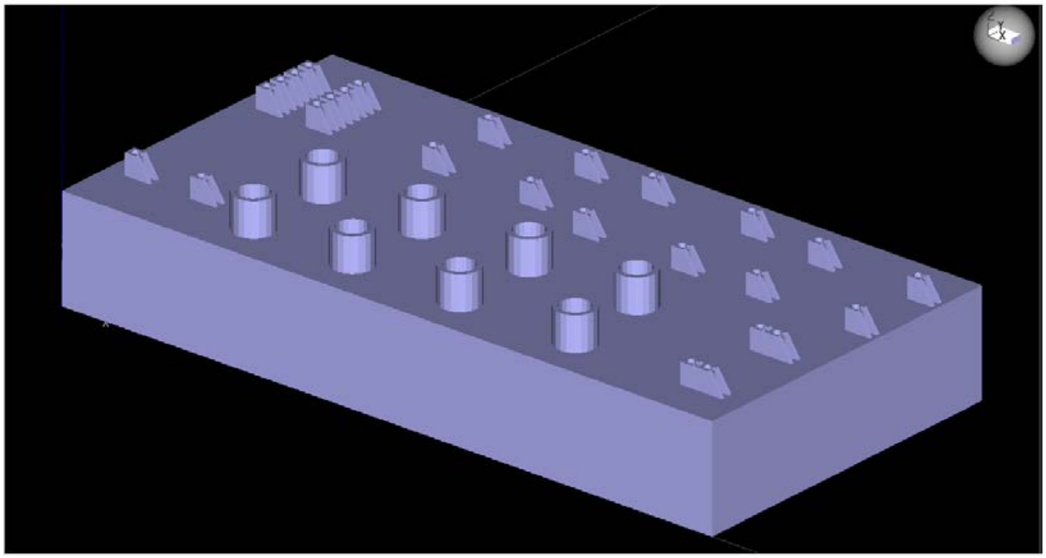

Figure 12 – STL model of 555 Timer Circuit

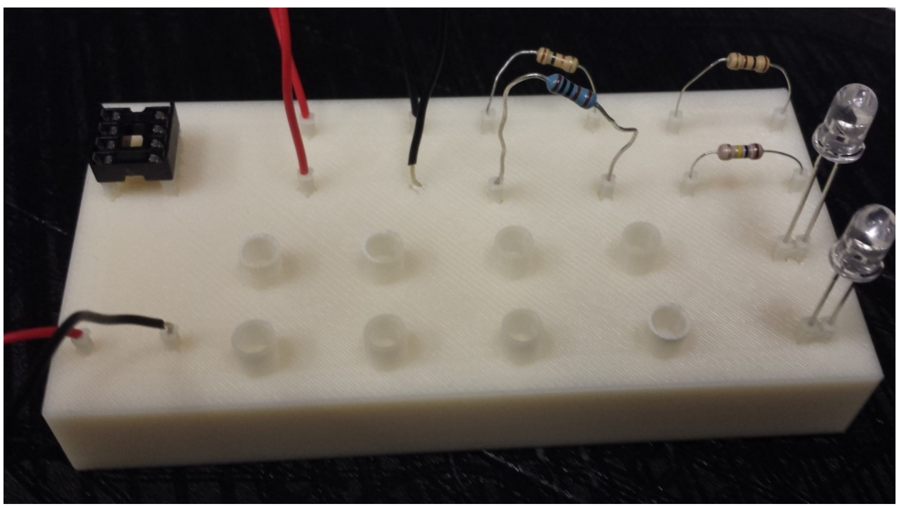

Figure 13 - 555 Timer Circuit

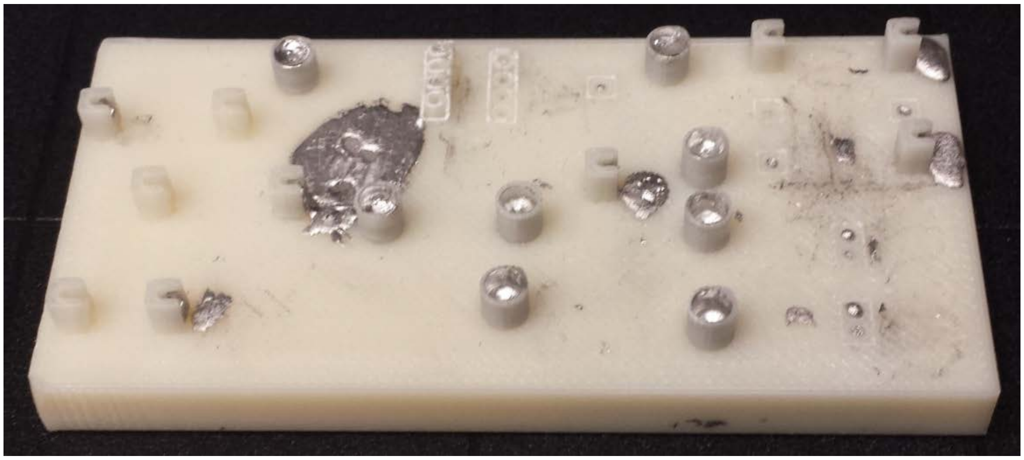

Figure 14 – Latest iteration of 555 Timer. Liquid metal was injected at each filling point until it reached all of the through-holes within that trace or excessive metal spillage occurred.

Discussion

Although there is much promise in being able to rapidly prototype electric circuits using 3-D printing, our existing code is limited to creating at most two-layered circuits. We expect that no major modifications would have to be made to the existing code to accommodate for circuits consisting of three layers or more.

Problems that were also encountered included metal leakage from traces that were too close to each other. It was necessary to go back to EAGLE PCB to modify the Autorouter function and space out the circuit components such that there was enough space for two contours of ABS plastic to surround each channel. The compactness of these circuits is limited by the resolution of the FDM printer. It may be useful to use other types of 3-D printers, as long as there is no need for support or a method for removing the supports from these small channels can be developed.

OpenSCAD is very helpful in the fact that it is programmable and creates the 3-D models with high enough resolution for the purposes of this project, but the rendering time for this software is slow compared to other types of CAD software, such as Solidworks. If we can find a faster type of CAD software that is also programmable, it would allow our automated process to be even faster.

The creation of the tree structure is advantageous to allow future iterations of electric circuits, such as the 555 Timer, to have injections where the liquid metal reaches the surface of the part, where the circuit components are connected, at the same time. This can be done by changing the channel diameters so as to control volumetric flow rate. The next step in designing a functional 3-D printable circuit is to create a function which considers the varying distances from an injection point to each of its through-holes and provides appropriate diameters for each of the channels.

Acknowledgements

The STARS program supported the research done by providing funding and the tools necessary to write and present the findings from this research.

The author would like to thank John Swensen, his research mentor, for all of his guidance throughout this project. The author would like to thank Professor Aaron Dollar for his support and overseeing of the project with John Swensen, which allowed me to conduct research this summer at the GRAB Lab.

The author would also like to thank Dr. Moreno, Dr. Nelson, Dr. Purushothaman, Dr. Nelson, and Raymond Ma for their help and advice throughout the research writing process.

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