3D Printed Electronics

A Thesis Presented for the

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Degree

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To my Dad. Mum, Chitalu and Mwila, thank you for the continuous love and support.

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Abstract

Additive manufacturing is revolutionizing the way we build and produce a plethora of products spanning many industries. 3D printing, a subset of additive manufacturing, has shown strong potential in reduced energy use, sustainability and cost effectiveness. Exploring avenues that this technology can be utilized is key to improve productivity and efficiency in various applications; for example electronic systems and devices manufacturing.

Electronic systems and sub-systems are built using a variety of materials and processes, which require a large carbon footprint, significant waste products and high production time. We have seen experiments of printed electronics using inkjet printing technology to provide a flexible and cheap production alternative to the traditional methods. Inkjet printing has been problematic and still faces numerous challenges such as quality and speed, in its use in electronic system manufacturing. In addition, inkjet printing does not integrate the other aspects of manufacturing like enclosure and final product assembly.

We propose the application of 3D printing technology to support an integrative process for combining circuit board fabrication, solder mask process, electronic component pick and place and enclosure manufacturing. Though we have seen 3D printed circuits, they are crude and lack complexity. The extent of most of these 3D printed circuits have functionality of a button or switch. They do not have the ability to support analog functions with components like an op- amp or a digital circuits to the level of a complex computing system. The integration of these separate processes, circuit board fabrication, solder mask process, electronic component pick and place, and enclosure manufacturing, into a single high efficiency 3D printing additive manufacturing process will yield significant savings in energy use, carbon footprint, waste product, and production time and cost.

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Chapter 1

Introduction

The electronics industry is growing rapidly with emergence of new technology every day. Additive Manufacturing (AM) has become a game changer in the way we build things and it has immense potential to further integrate into more processes in various industries, specifically the electronic industry.

While the electronics (consumer) industry is a multi-billion dollar industry, it is rapidly growing and so is the demand. Electronic device manufactures are not only looking for cost effective and efficient manufacturing solutions, but ones that will also lessen the carbon footprint, significant waste material, and high production time [13]. Energy efficient solutions and lower production time are not only good for the environment but lower cost, which benefits the manufacturers. So it is imperative to come up with solutions that address most, if not all, of these factors[3]. Advances have and are being made in the drive to find solutions that can be integrated into electronic devices manufacturing using 3D printing, a subset of additive manufacturing. One of theses efforts is inkjet printing based. Where conductive nanoparticle liquid inks are used to print traces on 3D printed substrate, plastic or paper and/or encased in 3D printed cases. Though this approach meets some of the solutions to the goals stated above, it has challenges. Ink prices and properties such as stability, aggregation and viscosity have to be considered and can be a hindrance to electronic integration that is efficient [15].

This thesis will introduce and serve as a guide that showcases the application of 3D printing technology to support advanced 3D manufacturing of integrated electronic

devices. The current electronic device manufacturing process has many steps that consist of the circuit board fabrication, solder mask process, electronic component pick and place, board soldering/cleaning, and enclosure manufacturing. This proposed integrative process of combining these separate processes into one that will yield 3D printed circuits using conductive polymer filament, and can support digital and analog circuits with an extended level of complexity. All this while saving energy, reducing time from concept to product, reducing carbon footprint and the cost of manufacturing consumer electronic products.

Chapter 2

Literature Review and Background

In this chapter, a literature review is conducted on additive manufacturing (AM) - 3D printing and the relation to the manufacturing of electronics. A background on printed electronics and the various types of printing will be evaluated.

2.1 History of Additive Manufacturing

Additive Manufacturing (AM) is a process of building 3D objects or designs by joining deposited material layer by layer, be it metals or plastics [12, 19]. It was first introduced in the late 1980s and was called Rapid Prototyping (RP) [29]. Computer-Aided Design (CAD) software was used to model designs that where then brought to life by process of stereolithography (SL), which solidified thin layers of liquid polymer that was ultraviolet (UV) light sensitive [20, 29].

By the 1990s, 3D Printer manufactures were emerging and the accessibility of CAD tools was increasing as well as development [5]. In the 2000s, AM gained more media traction, a functioning kidney was 3D Printed, though it was not until some few years later that one was actually transplanted into a patient [5]. Later, in the mid-late 2000s, high-definition color 3D printers were introduced and the beginning of a move towards commercialization. This opened doors to more 3D printer innovation, making AM technology more accessible and available [5].

Today AM continues to reach new heights as researchers and industry continue to developing the technology and its printers for many applications. The applications include the medical field, automotive industry, aerospace, food industry, architecture and electronic devices. As recent as 2015, we saw the World's first 3D printed car, figure 2.1 below. This was as a result of the combined effort of Local Motors and Oak Ridge National Laboratory (ORNL)[10]. We are possibly moving towards a future were most, if not all, cars will be manufactured using 3D printing.



Figure 2.1: World's First 3D Printed Car, Strati [10].

2.2 Electronic Device Manufacturing

2.2.1 Traditional Electronic Device Manufacturing

Figure 2.2 shows a general depiction of the process of manufacturing electronic devices. The first step is taking the concept to design, a parts list is created, cost is analyzed and the following processes include masking, fabrication and inspection, testing, packaging and delivery. Figure 2.3 shows what the thesis goal would achieve by combining the circuit board mask, fabrication and inspection and product packaging into one process.This eliminates high production times and cost, while reducing the the carbon footprint.

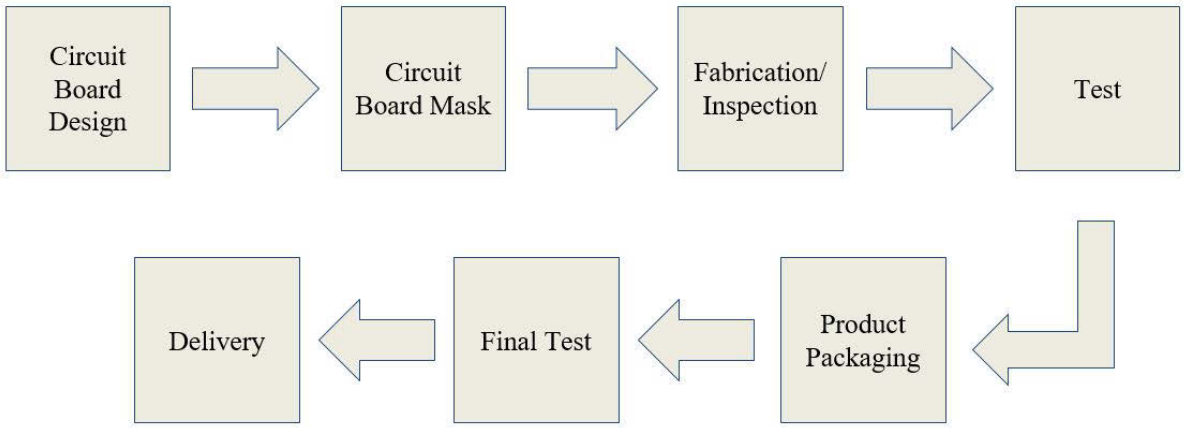


Figure 2.2: Traditional Electronics Device Manufacturing

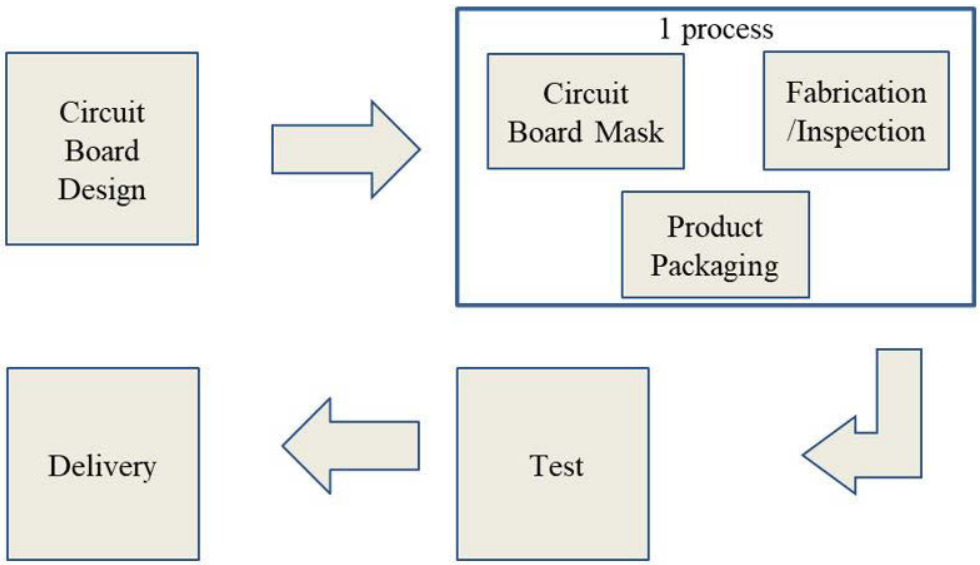


Figure 2.3: Thesis Research Goal

2.2.2 Printed Electronics

There are many motivations for printed electronics other than just uniting the worlds of printing and electronics. Other reasons include lower costs and implementation for flexible electronics, for example, wearable electronics or RFID Tags. There are also many processes for printing electronics. These include offset printing, gravure printing, flexographic printing, screen printing, and inkjet printing [9, 24]. Except for inkjet printing, the other processes are conventional printing technologies [24]. We shall focus on the most promising and pursued of the technologies, inkjet printing.

Inkjet Printing

Inkjet printing is a type of printing involving either continuous or drop-on-demand deposition of liquid material [23]. These liquid materials or inks can consist of nanoparticle ink or metal-organic ink. The printing can virtually be done on any substrate but considerations have to be made pertaining to the substrate and ink compatibility for accuracy and quality. Figure 2.4 below shows the two of types inkjet printing technologies, continous inkjet printing (CIJ) and drop-on-demand (DOD) inkjet printing [27].

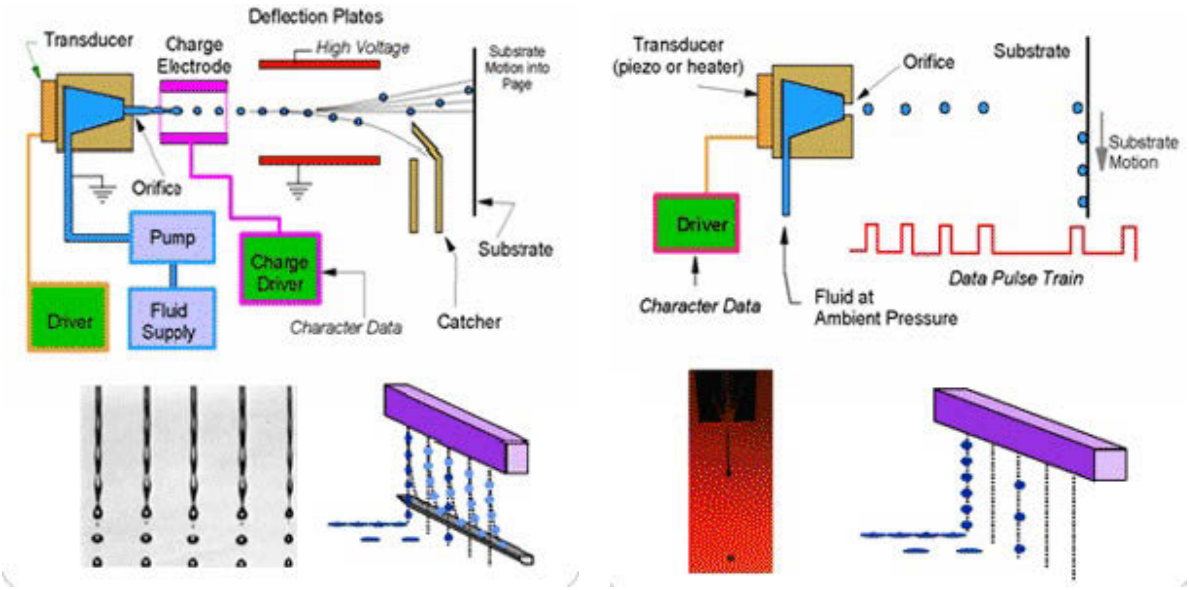


Figure 2.4: Left: CIJ Technology , Right: DOD Technology [27].

Continuous inkjet printing technology tends to be the most expensive due to printing head cost and restrictive inkjet properties [27]. It does however print high frequency [27]. Drop-on-demand inkjet printing technology has a cheaper head and better control of properties, adding to the simplicity and compactness [27]. It also provides smaller droplets which aides many electronic applications, thus making it a superior choice to CIJ technology [27].

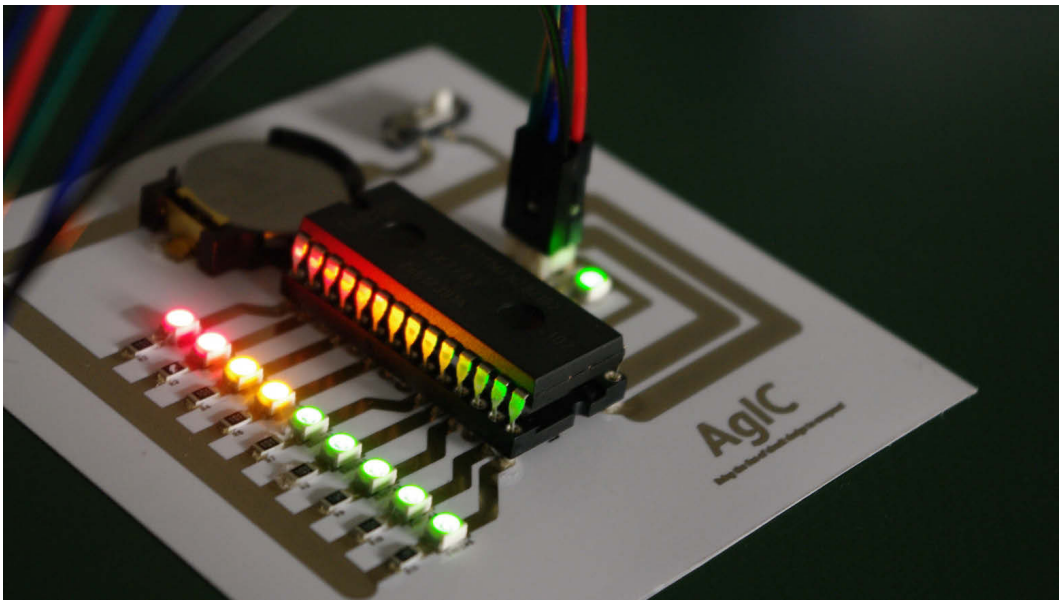


Figure 2.5: AgIC Inkjet Printed Circuit [1]

Figure 2.5 gives an example of an inkjet printed circuit by AgIC. AgIC uses water based, non-toxic, high conductive silver nanoparticle ink to print the shown circuit traces [1].

Though inkjet printing has its positive and promising aspects to further integrate into electronics it does have challenges. Low ink viscosities are preferable. Ink stability must be considered to avoid instances such as particle agglomeration [9, 15]. Exposure to moisture or oxygen can affect material shelf life, wettability properties such as surface tension have to be considered, curing or ink drying has to adhere to ink and substrate thermal tolerances, which also affects duration of process, and of course, cost of ink such as silver is high [9, 15].

Table 2.1 helps us see the challenges that lie in both traditional circuit printing and inkjet printing, which have just been discussed. This brings us back to the argument of pursuing this thesis objective of energy, cost efficient and reduced time to market 3D printed electronic products, including circuit boards and enclosures.

Table 2.1: Challenges with Traditional and Inkjet Printing

Traditional Printing	**Inkjet printing**
High Cost	Ink Costs
High production Time	Ink stability and Viscosity
Large Caron Footprint	Curing Time

Chapter 3

3D Printer

This chapter contains information about how a 3D printer was selected; working to meet the desired goal. A brief history and a function description is also included. Our approach is to use Autodesk Fusion 360 as the design software to model the prints and Cura to prepare the print for the printer, it was imperative to work with a printer that was compatible with both environments [4, 26].

3.1 Series 1 Pro

Initially the Series 1 Pro, shown in figure 3.1, was chosen in the effort of printing the 3D circuits. Features include: 1.75mm extrusion head with 300 °C maximum extruder temperature, a build volume of 305 x 305 x 305 mm, on-board camera, Wi-Fi and Ethernet capabilities, layer resolution range of 50-300 μm and free Cura for Type A machines [18]. In spite of all these ideal features the Series 1 Pro possesses, the single head extruder would make it impossible to print with two materials at the same time. This is a key requirement when printing products with multiple materials, which includes conductive and non-conductive. It was however used in the initial material analysis, which will be further discussed in chapter 4.

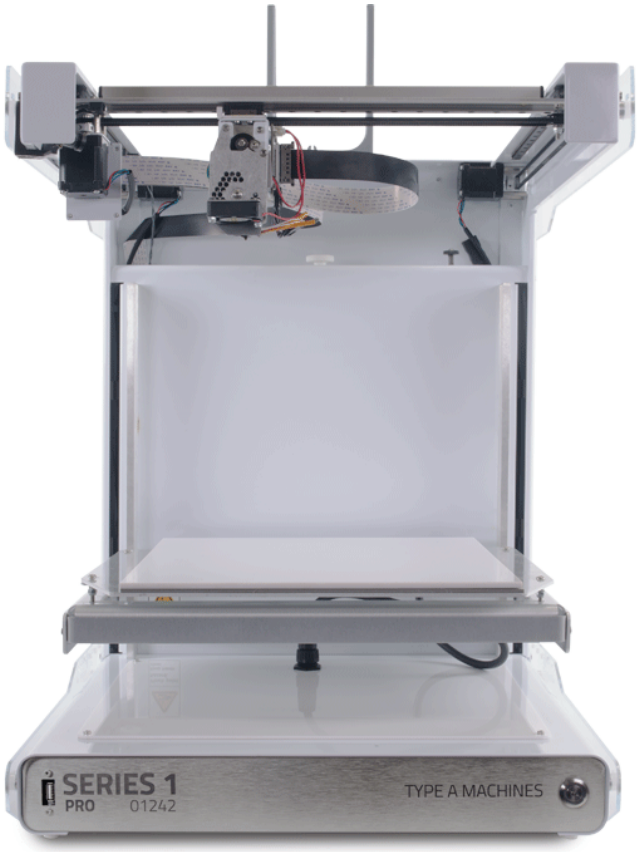


Figure 3.1: The Series 1 Pro Printer [18]

3.2 Ultimaker 3

After some research, the following are the printers that were considered: the LulzBot TAZ 6, the Carvey, the Nomad 883 Pro and the Ultimaker 3 [17, 14, 7, 25]. While these were all viable options, the Carvey and the Nomad 883 Pro did not offer the desired dual extrusion capabilities. And though the LulzBot TAZ 6 had additional tool heads, for purchase, which could support dual extrusion, the Ultimaker 3 shown in figure 3.2, was selected because of the integrated dual extrusion print head. It's printing features include a layer resolution of 0.40 mm nozzle, X, Y and Z accuracy of 12.5, 12.5, 2.5 μm, respectively, active leveling of build plate, swappable print cores, and nozzle temperature of 180 to 280 °C [25]. Its dual extrusion print head allows for two materials to be loaded and used simultaneously in the print process (e.g. with conductive and non-conductive filament).

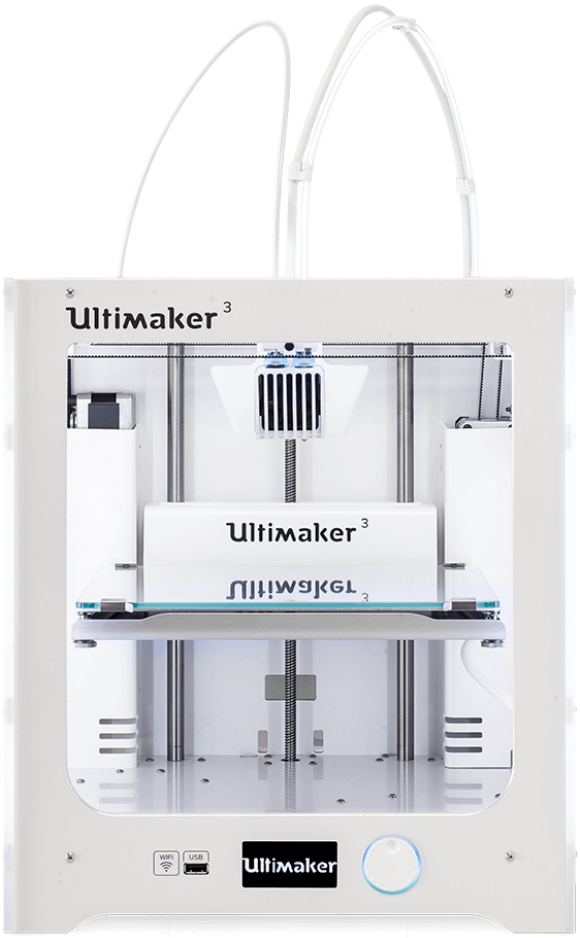


Figure 3.2: The Ultimaker 3 [25]

Chapter 4

Conductive Material

In this chapter, the conductive polymer filament evaluated for the research goals will be introduces and discussed.

Additive manufacturing utilizes materials/filament such as metal and plastic as its building block. These materials include (but not limited to) silver, aluminum, steel, paper, acrylonitrile butadiene styrene (ABS), nylon, polylactide (PLA) and polyvinyl alcohol (PVA) [28]. For this research, two types of polymer filaments were evaluated for use, ABS and PLA.

4.1 Acrylonitrile Butadiene Styrene (ABS)

ABS is an opaque, strong, somewhat flexible, and low cost thermoplastic [28, 16]. It can be used for personal projects, concept and functional models, tooling, as well as general manufacturing [16]. Conductive options of ABS were explored from various manufacturers and distributors.

4.1.1 Conductive ABS

Two distributors were identified to supply conductive ABS , Robotshop and Alchement. The Robotshop conductive ABS did not have any resistivity specification listed [22]. The Alchement Conductive ABS volume resistivity specification was listed as 128 Ω-cm with printing temperatures of 230 °C to 250 °C [2].

4.2 Polyactide (PLA)

Polyactide (PLA) is derived from fermented plant starch and thus biodegradable. This also makes it a cost efficient thermoplastic, with applications similar to ABS, from do-it-yourself projects to general manufacturing [8, 28].

4.2.1 Conductive PLA

Proto-Pasta and Black Magic 3D are manufacturers we identified for their conductive PLA. Proto-Pasta had a Composite PLA - Electrically Conductive Graphite (ECG) filament. Their product specification had the following volume resistivity; 15 Ω-cm pre- 3D printed resin, 30 Ω-cm 3D printed parts along layers in the X, Y dimension and 115 Ω-cm 3D printed parts against layers in Z dimension [21]. The recommended printing temperatures were listed from 190 - 200 °C. Black Magic 3D had a Conductive Graphene PLA Filament with a volume resistivity of 0.6 Ω-cm and printing temperature of 195 - 220 °C [6]. Table 4.1 below shows a volume resistivity and printing temperatures of the materials discussed.

Table 4.1: Material Properties (* Specifications are incomplete given the cross- section areas are not provided)

	Composite PLA Filament	**Conductive Graphene PLA Filament**	**Conductive ABS Filament (Alchement)**	**Conductive ABS Filament (Robot-shop)**
Volume resistivity *	30 Ω-cm	0.6 Ω-cm	128 Ω-cm	-
Extruder Temperature	190 - 200 °C	195 - 220 °C	230 - 250 °C	-

Predicting that resistivity would change contingent with the type of print that was needed for this research. Also given that resistivity specifications were incomplete for the cross-section areas of the materials, further analysis had to be done. The next chapter will discuss filament analysis done to attain electronic properties for each materials.

Chapter 5

Printed Filament Analysis

In this chapter, discussed is the process of determining which of the chosen filaments would be most suitable to perform the task of 3D printing a functioning circuit.

5.1 Resistance Analysis

5.1.1 Filament Model

Figure 5.1 was the model used to further analyze the resistances. The Y represents the 3 different cross-sectional area (width and height), 1.5 x 1.5 mm, 3 x 3 mm, 6 x 6 mm, that were used to determine how the resistance is affected by surface area and volume. Figure 5.2 show a 3D printed 3 x 3 mm analysis model.

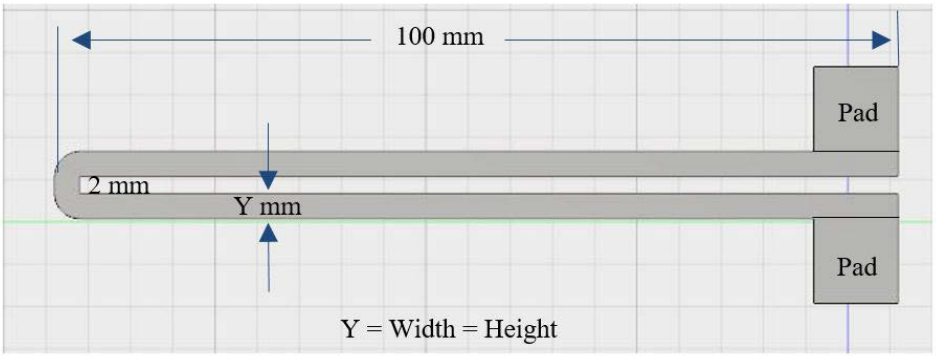


Figure 5.1: Filament Analysis Model



Figure 5.2: 3D Printed Analysis Model

5.1.2 Measured Resistance

The first model printed was the 3x3 mm for all four materials, the composite PLA filament, conductive graphene PLA filament and the two conductive ABS filament - Alchement and Robotshop.

Table 5.1: Filament Analysis Results for the Conductive ABS and PLA

	Composite PLA Filament	**Conductive Graphene PLA Filament**	**Conductive ABS Filament (Alchement)**	**Conductive ABS Filament (Robotshop)**
Cross-Sectional Area (weight x height)	3x3 mm	3x3 mm	3x3 mm	3x3 mm
Resistance (pad to pad)	**4.3 kΩ**	**0.13 kΩ**	770 kΩ	15 kΩ

From these initial resistance measurements in table 5.1, it can be seen that the two conductive ABS filaments from Alchement and Robotshop have higher resistances. Therefore, concluding that the two PLA filaments from Proto-Pasta and Black Magic 3D

would be the ideal choice for further analysis, owing to their lower resistances. With this information, printing and measurements with the other models (1.5x1.5 mm and 6x6 mm) were conducted for both the composite PLA filament and conductice graphene PLA filament. These measurements helped us better understand how resistance varies with the different widths and heights of the models. Table 5.2 below, shows a comparison of the resistances measured for all of the three models of the conductive PLA filaments.

Table 5.2: Filament Analysis Results for the Conductive PLA

	Composite PLA Filament	**Conductive Graphene PLA Filament**
Cross-Sectional Area (weight x height)	Resistance (pad to pad)	
1.5 x 1.5 mm	13 kΩ	0.48 kΩ
3 x 3 mm	4.3 kΩ	0.13 kΩ
6 x 6 mm	1.1 kΩ	0.04 kΩ

As shown above, as the widths and heights increase, the resistance decreases. Though this new knowledge gave us some insight, we had to further analyze whether resistance varied with volume or surface area.

5.1.3 Volume(Vol) and Surface Area(S.A.) in relation to Resistance

Below are surface area and volume calculations of the analysis model with the three different widths and heights of 1.5 x 1.5 mm , 3 x 3 mm and 6 x 6 mm. The models length is held constant at approximately 202 mm.

1.5 x 1.5 mm Calculations

$$S.A. = 4 \times 1.5 \times 202 = 1212mm^2 \tag{5.1}$$

$$Vol = 1.5 \times 1.5 \times 202 = 454.5mm^3 \tag{5.2}$$

3 x 3 mm Calculations

$$S.A. = 4 \times 3 \times 202 = 2424mm^2 \tag{5.3}$$

$$Vol = 3 \times 3 \times 202 = 1818mm^3 \tag{5.4}$$

6 x 6 mm Calculations

$$S.A. = 4 \times 6 \times 202 = 4848mm^2 \tag{5.5}$$

$$Vol = 6 \times 6 \times 202 = 7272mm^3 \tag{5.6}$$

Using the 6x6 mm model as reference, a resistance surface area and resistance volume was calculated. This was achieved by multiplying the measured resistances from both conductive PLAs of the 6 x 6 mm model with its corresponding volume and surface area as seen in equations 5.7, 5.10, 5.13 and 5.16. Then using the resulting surface area and volume resistance factors divided by the 1.5 x 1.5 mm and 3 x 3 mm surface areas and volumes (equations: 5.8, 5.9, 5.11, 5.12, 5.14, 5.15, 5.17, and 5.18), calculations were done to determine if there was a strong relationship between the resistance and surface area or volume.

6 x 6 mm Conductive Graphene PLA Resistance Volume

$$0.04k\Omega \times 7272mm^3 = 290.9k\Omega.mm^3 \tag{5.7}$$

Using this volume resistance factor of the 6x6 mm model and dividing it with the volumes of the 1.5 x 1.5 mm and 3 x 3 mm to determine a calculated resistance comparison to the measured values of the models.

$$R(3x3) = 290.9k\Omega.mm^3/1818mm^3 = 0.16k\Omega \tag{5.8}$$

$$R(1.5x1.5) = 290.9k\Omega.mm^3/454.5mm^3 = 0.64k\Omega \tag{5.9}$$

6 x 6 mm Conductive Graphene PLA Resistance Surface Area

$$0.04k\Omega \times 4848mm^2 = 193.9k\Omega.mm^2 \tag{5.10}$$

Using this surface area resistance factor of the 6x6 mm model and dividing it with the surface areas of the 1.5 x 1.5 mm and 3 x 3 mm to determine a calculated resistance comparison to the measured values of the models.

$$R(3x3) = 193.9k\Omega.mm^3/2424mm^2 = 0.08k\Omega \tag{5.11}$$

$$R(1.5x1.5) = 290.9k\Omega.mm^3/1212mm^2 = 0.16k\Omega \tag{5.12}$$

6 x 6 mm Composite PLA Resistance Volume

$$1.1k\Omega \times 7272mm^3 = 7999k\Omega.mm^3 \tag{5.13}$$

Using this volume resistance factor of the composite PLA 6x6 mm model and dividing it with the volumes of the 1.5 x 1.5 mm and 3 x 3 mm to determine a calculated resistance comparison to the measured values of the models.

$$R(3x3) = 7999k\Omega.mm^3/1818mm^3 = 4.4k\Omega \tag{5.14}$$

$$R(1.5x1.5) = 7999k\Omega.mm^3/454.5mm^3 = 17.6k\Omega \tag{5.15}$$

6 x 6 mm Composite PLA Resistance Surface Area

$$1.1K\Omega \times 4848mm^2 = 5333k\Omega.mm^2 \tag{5.16}$$

Using this surface area resistance factor of the composite PLA 6x6 mm model and dividing it with the surface areas of the 1.5 x 1.5 mm and 3 x 3 mm to determine a calculated resistance comparison to the measured values of the models.

$$R(3x3) = 5333k\Omega.mm^3/2424mm^2 = 2.2k\Omega \tag{5.17}$$

$$R(1.5x1.5) = 5333k\Omega.mm^3/1212mm^2 = 4.4k\Omega \tag{5.18}$$

Measured Resistance Analysis Conclusion

Comparing the calculated resistances above with that of table 5.2, it is observed that the volume resistance factor yielded relatively close resistances to the measured values, compared to that of the surface area resistance factor. Additionally, observing table 5.3 below (by the colored text), provides that the volume has a stronger relationship with the resistance and it was therefore concluded that resistance is affected by the volume of the material conducting through the body of the material and not just the surface.

Table 5.3: Filament Analysis Results for the Conductive ABS and PLA

	Composite PLA Filament			Conductive Graphene PLA Filament		
Cross-Sectional Area (width x height (mm))	1.5x1.5	3x3	6x6	1.5x1.5	3x3	6x6
S.A.(mm^2)	1212	2424	4848	1212	2424	4848
kΩ.(mm^2)	15756	9454	5333	581.8	315.1	193.9
Vol (mm^3)	454.5	1818	7272	454.5	1818	7272
kΩ.(mm^3)	**5909**	**7090**	**7999**	**218.2**	**236.3**	**290.9**

Even though there is a strong relationship between the resistance and the volume, we must note that the measurements did not give more accurate results. We can also see this in the volume resistance calculations in table 5.3. Furthermore, it can be observed that the conductive graphene PLA filament shows better accuracy than the composite PLA filament. This could all be attributed to multiple reasons, which could include; lack of accuracy with the material due to consistency of distribution of conductive particles during and after the printing process, variations caused by print temperature and cooling, size/density of conductive particles in the material, and capacitive load. Its possible this accuracy can be further improved by increasing the model dimension's width and heights.

Chapter 6

The Circuit Printing Process

In this chapter, the process of 3D printing the chosen circuit concepts is discussed and the challenges encountered.

6.1 Concept Circuits

Two circuits were selected to implement the proposed 3D printing technology. The analog and digital circuits in figure 6.1 are the concept circuits.

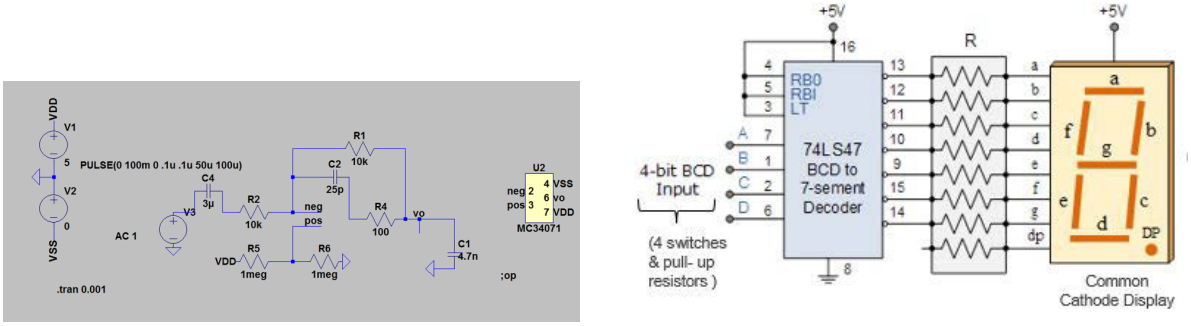


Figure 6.1: Left: The Analog Circuit Concept , Right: The Digital Circuit Concept [11].

6.2 Material Analysis for Print Process

With the circuits chosen, it was decided to first concentrate on the digital circuit, given it would be less susceptible to resistance in the traces. Therefore printing analysis of the

material to execute suitable pin holes for the components of the digital circuit was done. White non-conductive PLA filament was used as the non-conductive base of all the circuit boards. Figure 6.2 shows the AutoDesk Fusion 360 3D model for the pin hole analysis. The pin holes had a height of 5mm, outer width of 1.8mm, outer length of 1.9mm, inner width of 0.8 mm and inner length of 0.9mm.

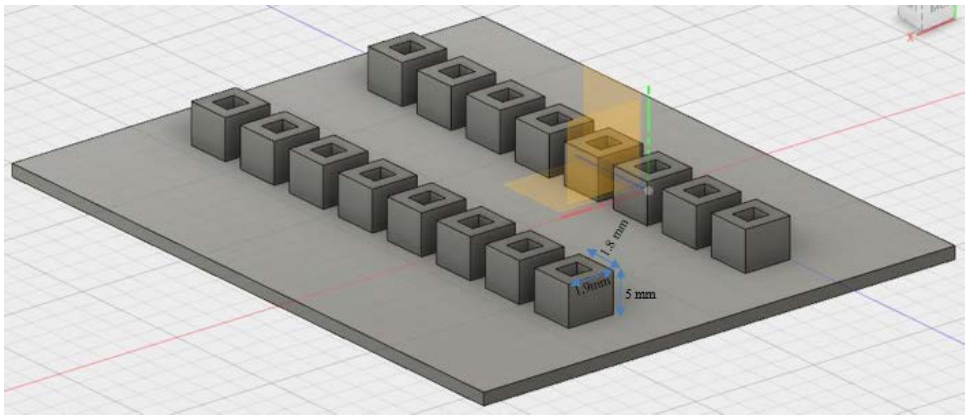


Figure 6.2: Pin Holes Analysis

6.2.1 Printing Challenges

The composite PLA filament did not offer as many challenges in the printing process as the conductive graphene PLA filament did. Initially both materials deposited extra material at the start of the print as can be seen in figures 6.3 and 6.6. To resolve the extra material deposition at the start of the print (e.g. on the top right corner), a small square pad as well as non-conductive material line traces in between the pin holes were added to the print, as shown in figure 6.4 and 6.7. This was done to try and force the extra material to be deposited before the print of the pin holes and to avoid bleeding in between the pin holes. This however did not solve the problem. Several adjustments to the temperature and columns were tested to achieve better prints. For the composite PLA filament the print temperature was increased slightly above the manufacturers/distributors recommended maximum temperature to 205°C. As for the conductive graphene PLA filament, it was found that the suitable printing temperature was 215°C. We must also note that the conductive graphene PLA filament material texture caused a slight expansion to the nozzle of the

printer from wear, which we had to switch out (detachable nozzles) when we printed with the composite PLA filament. This affected the print resolution for the conductive graphene PLA filament.

Though the printing temperatures helped to a certain degree with the above mentioned challenges, we still had to take further measures to ensure that the pin holes would print according to the 3D model design. The the bottoms of the pin holes were beveled 0.5 - 1 mm, figure 6.8 shows the resulting print with the beveling. A line trace was added for extra measure. With this result, we were more confident to proceed with printing the digital circuit.



Figure 6.3: Conductive Graphene PLA Filament Pin Holes challenges 1



Figure 6.4: Conductive Graphene PLA Filament Pin Holes challenges 2

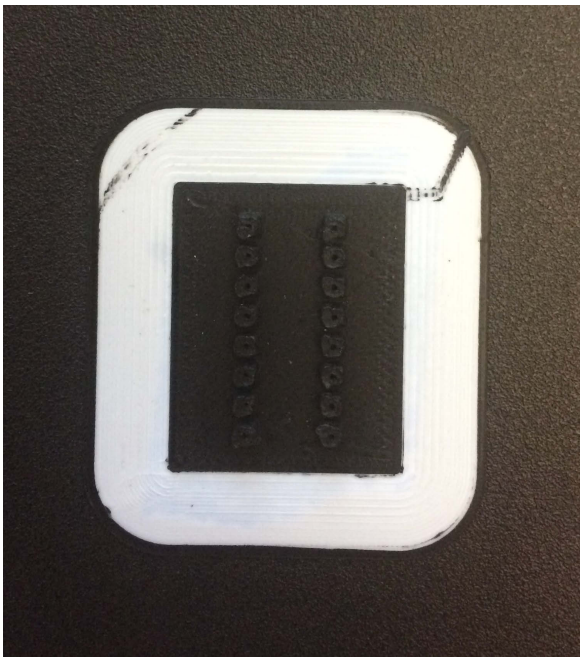


Figure 6.5: Conductive Graphene PLA Filament Pin Holes adjustments(with graphene base)



Figure 6.6: Composite PLA Filament Pin Holes challenges 1

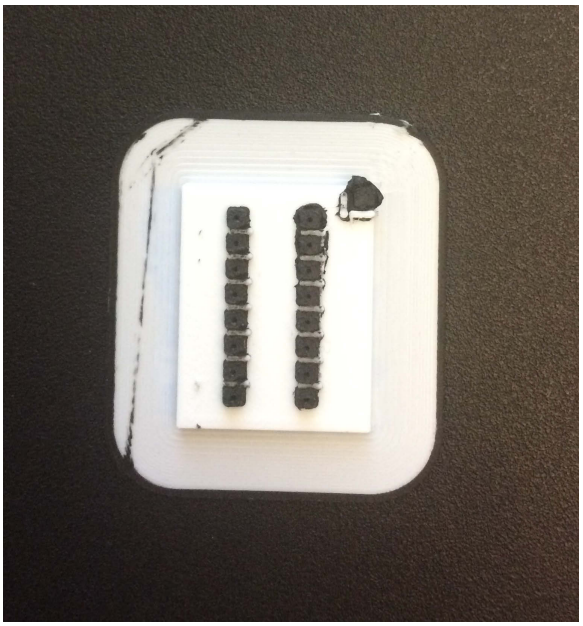


Figure 6.7: Composite PLA Filament Pin Holes challenges 2

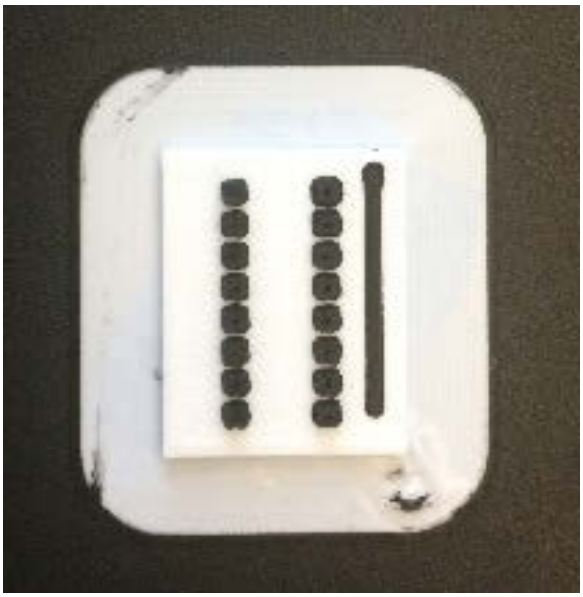


Figure 6.8: Composite PLA Filament Pin Holes adjustments

Chapter 7

Circuit Analysis and Tests

In chapter 7, discussed are the results of printing digital circuit in both the composite PLA and the conductive graphene PLA filaments. Analysis is also done to determine conductivity.

7.1 Digital Circuit on Breadboard

We first built the digital circuit concept shown in figure 7.1, on an actual breadboard with the electronic components that would be used for the printed digital circuits. The electronic components consisted of:

- A Common Cathode 7 Segment Display
- Seven 4.7 kΩ Series Resistors
- Four Switches
- Four 1.5 kΩ Pull-Up Resistors
- A 74LS48 BCD to 7 Segment Decoder

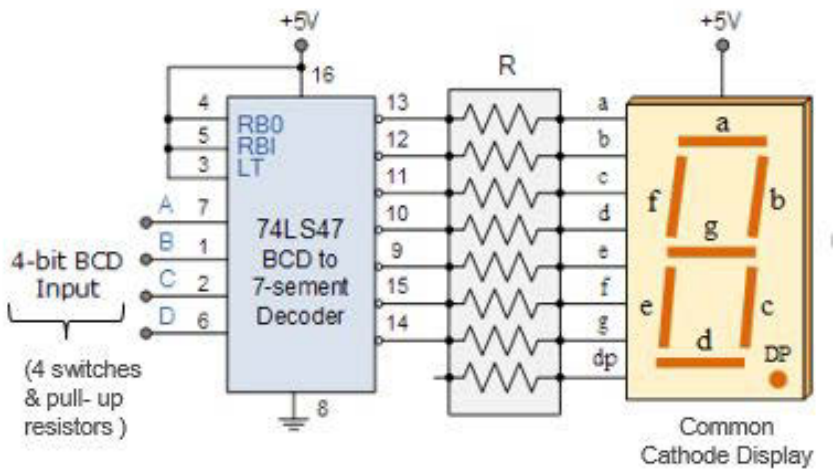


Figure 7.1: The Digital Circuit Concept

Figure 7.2 and 7.3 show the digital circuit built on a breadboard displaying the number '0' with switch inputs '0000' and the number '9' with switch inputs '1001'. Having tested that our circuit worked on a breadboard we could use it as reference.

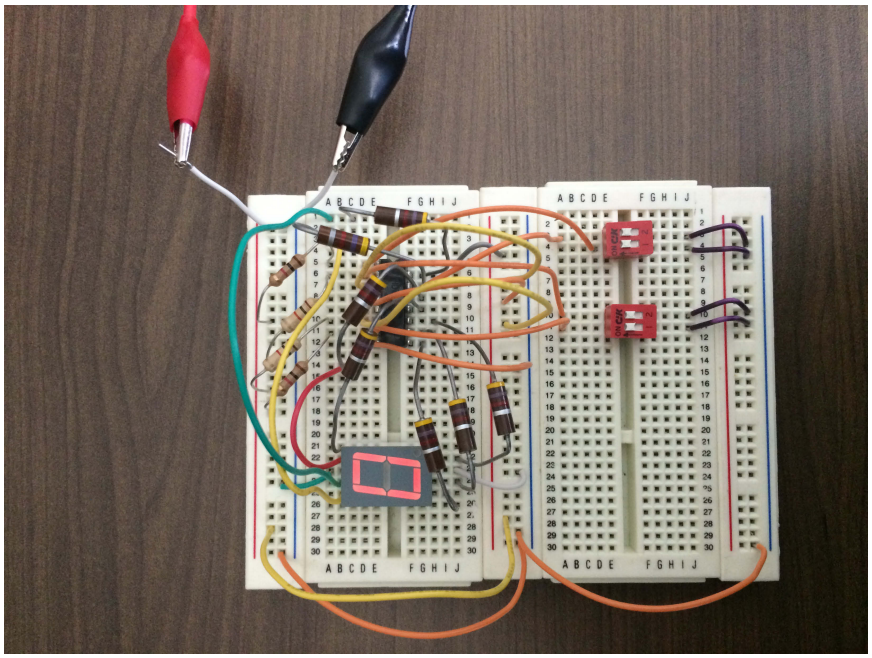


Figure 7.2: The Digital Circuit on a Breadboard, displaying the number '0' with switch inputs '0000'

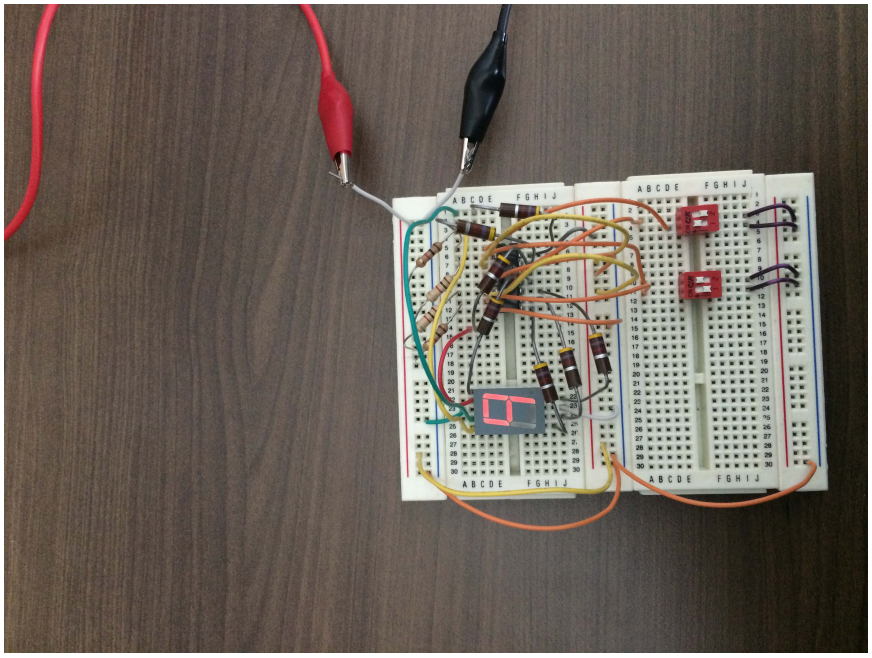


Figure 7.3: The Digital Circuit on a Breadboard, displaying the number '9' with switch inputs '1001'

7.2 Digital Circuit Design

The digital circuit was modeled in Autodesk Fusion 360. Figure 7.4 shows a top view of the 3D circuit design with the electrical components placements specified. A trial circuit print with white and black non-conductive PLA filament was first printed, figure 7.5.

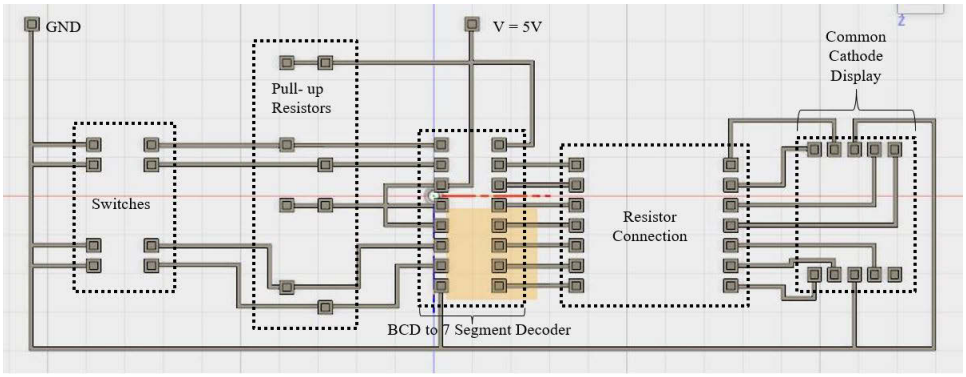


Figure 7.4: The Digital Circuit Layout Design

Seeing that the print was successful, implementation with both the composite PLA filament and conductive graphene PLA filament was conducted. To reduce the resistances

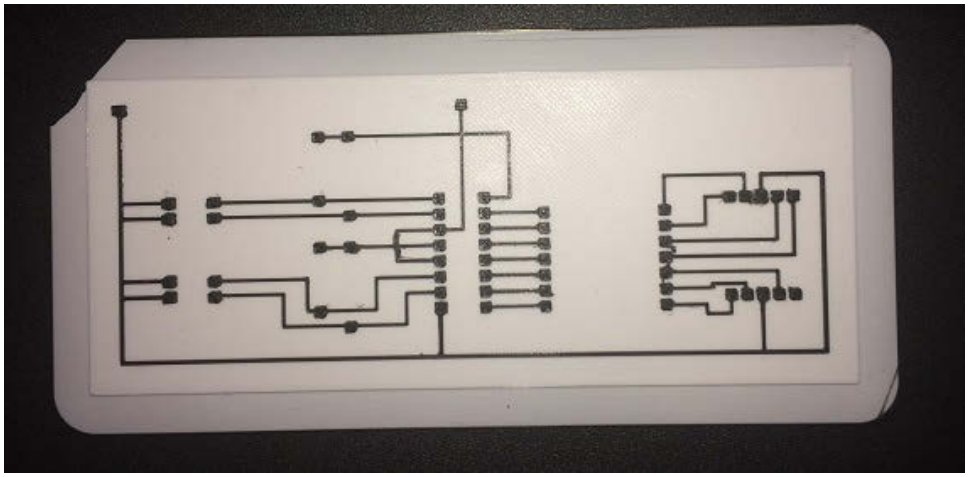


Figure 7.5: Non - Conductive PLA Digital Circuit Print

across the circuit, with the information learned in chapter 5, without compromising the circuit design, the line traces were designed with a height on 4mm and width of 0.5 mm, while the pin holes remained the same dimensions shown in figure 6.2. A height of 5mm, outer width of 1.8mm, outer length of 1.9mm, inner width of 0.8 mm, inner length of 0.9mm, and gaps between the the pin holes was 0.7mm. With the gap between the pin holes being 0.7 mm, we were unable to place any traces in between the pin holes due to the print resolution.

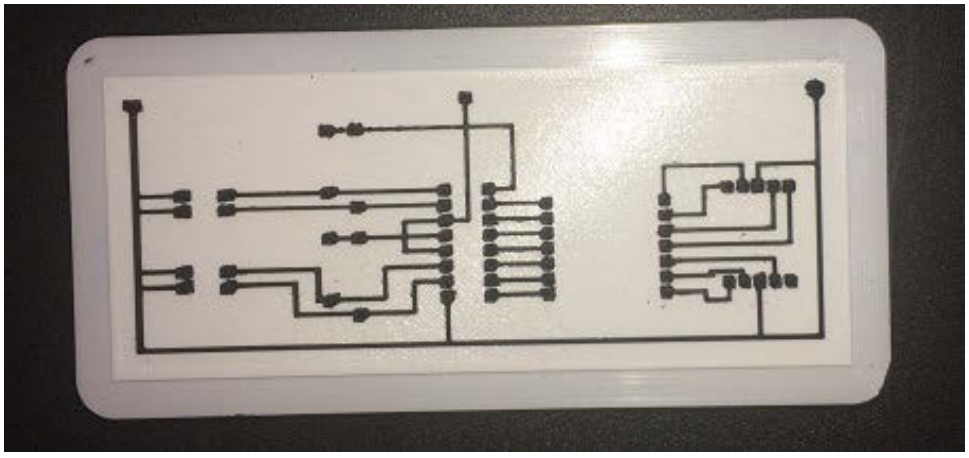


Figure 7.6: Composite PLA Digital Circuit Print

We experienced no issues with printing the digital circuit with the composite PLA filament. As can be seen in both figures 7.6 and 7.7, the design was adjusted to extend

the ground line trace on the right side to create another ground connect in the hopes of further reducing resistance in the ground circuit.

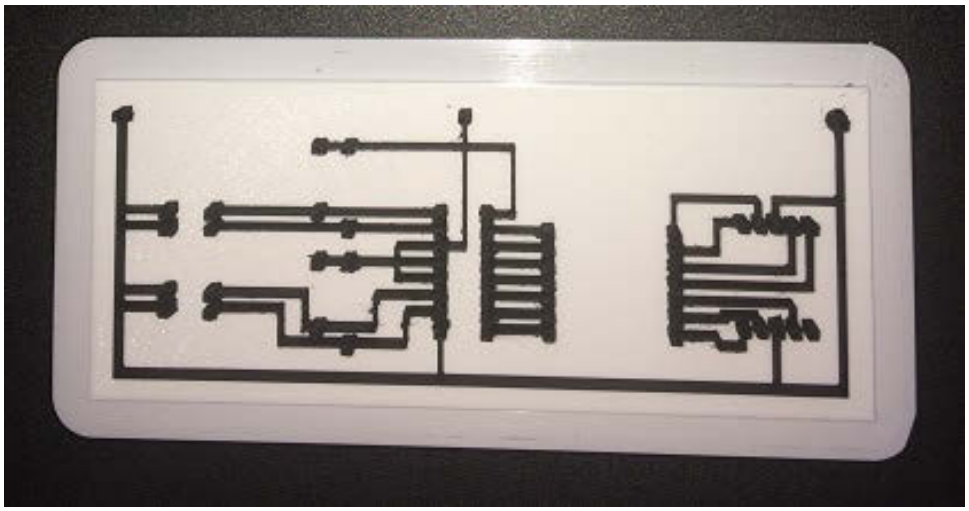


Figure 7.7: Conductive Graphene PLA Digital Circuit Print

The conductive graphene PLA filament line traces were also designed with a height on 4mm, width of 0.5 mm, and the pin holes remained the same dimensions shown in figure 6.2. The digital circuit print for the this filament, as a whole, was relatively good. However two spots in the circuit line trace was ragged in certain layers of the print. This could have been due to clogging and the material did not deposit evenly. We mitigated the issue by thickening the traces 0.5mm or less, which seemed to alleviate the problem.

7.3 Circuit Tests

After the circuits were printed, resistance of the circuit traces were measured to observe resistance across the circuit at various points. Using figure 7.8 as reference and the resistance measurement lists below, R(1-2) represents the measurement between points (1) and (2). R(2-3) represents the measurement between points (2) and (3). R(I.(4)), R(II.(4)), R(III.(4)), R(IV.(4)), R(V.(4)), R(VI.(4)), R(VII.(4)) represents the measurements between the points identified (4) in figure 7.8. R(5-5), R(6-6), and R(7-7) represents the measurement between point (5) and (5), (6) and (6), and (7) and (7), respectively. As displayed by the resistance measurements listed below (from the different points of measurement) that the

conductive graphene PLA filament circuit measured lower resistance than the composite PLA filament circuit. However it was decided to test both circuits with the electronic components embedded.

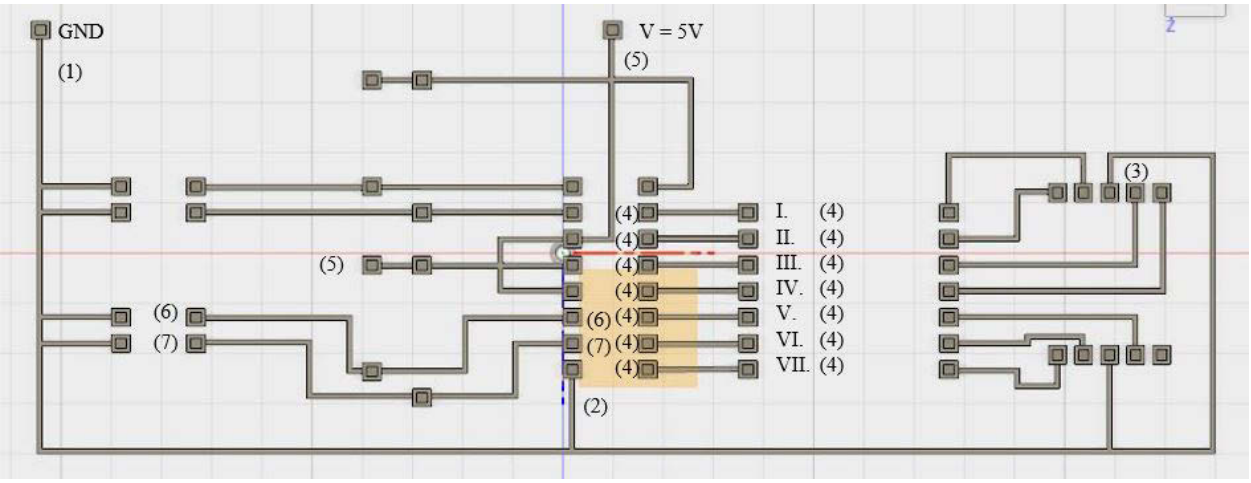


Figure 7.8: Composite PLA and Conductive Graphene PLA Filament Digital Circuit for Resistance Measurement Points

Composite PLA Filament Circuit Resistance Measurements

- R(1-2) = 5.1 kΩ
- R(2-3) = 5.5 kΩ
- R(I.(4)) = 1.0 kΩ
- R(II.(4)) = 1.1 kΩ
- R(III.(4)) = 1.1 kΩ
- R(IV.(4)) = 1.0 kΩ
- R(V.(4)) = 1.0 kΩ
- R(VI.(4)) = 0.9 kΩ
- R(VII.(4)) = 1.1 kΩ

- R(5-5) = 2.3 kΩ
- R(6-6) = 2.5 kΩ
- R(7-7) = 3.0 kΩ

Conductive Graphene PLA filament Circuit Resistance Measurements

- R(1-2) = 0.7 kΩ
- R(2-3) = 1.0 kΩ
- R(I.(4)) = 0.6 kΩ
- R(II.(4)) = 0.3 kΩ
- R(III.(4)) = 0.5 kΩ
- R(IV.(4)) = 0.3 kΩ
- R(V.(4)) = 0.6 kΩ
- R(VI.(4)) = 0.5 kΩ
- R(VII.(4)) = 1.0 kΩ
- R(5-5) = 0.8 kΩ
- R(6-6) = 0.6 kΩ
- R(7-7) = 0.5 kΩ

7.3.1 Implementation

The electronic components were laid for the composite PLA filament and conductive graphene PLA filament, and connected to the 5V power supply. This is displayed in figures 7.9 and 7.10. It can also be seen that there is an obvious response from the circuit, in terms of connectivity, however the display did not switch numbers when prompted by the switches.

Composite PLA

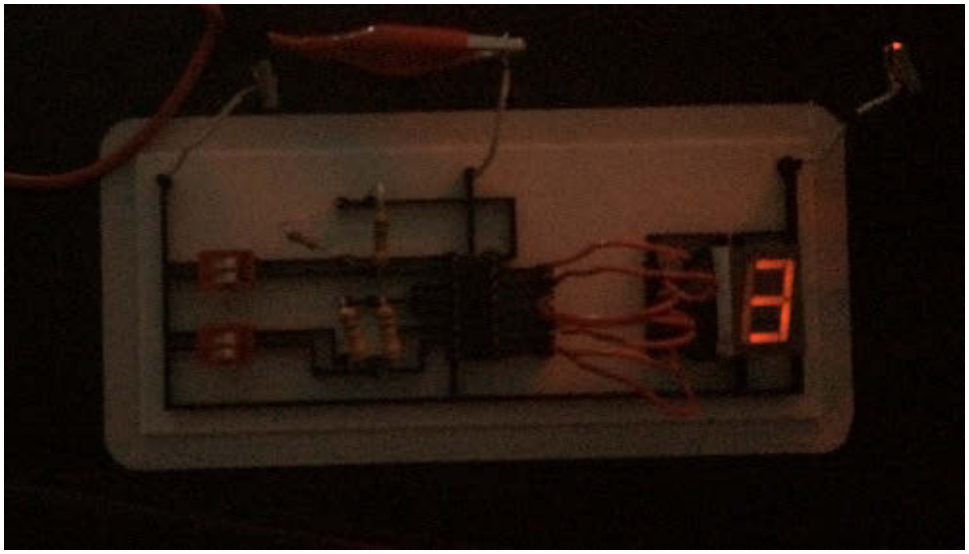


Figure 7.9: Conductive Graphene PLA Digital Circuit Print

Conductive Graphene PLA

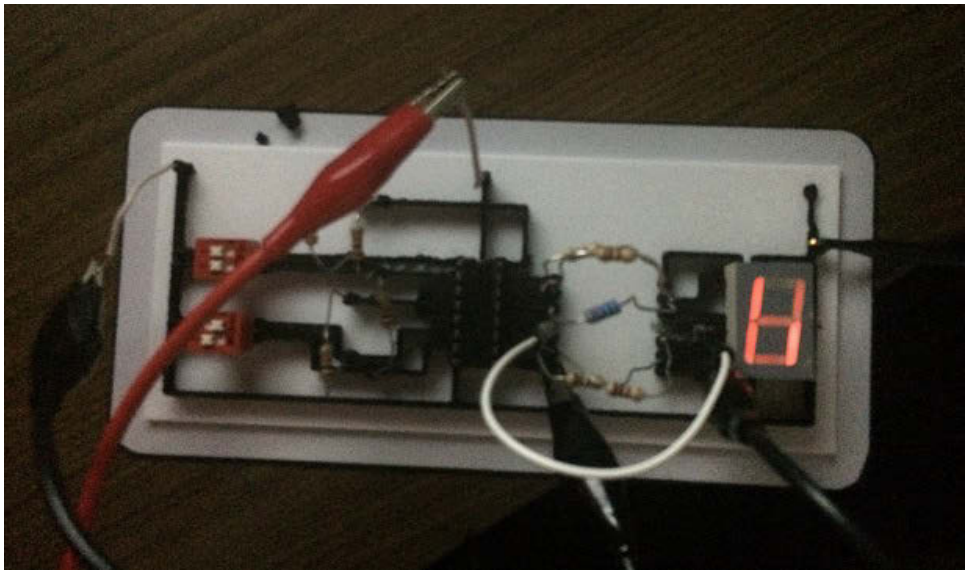


Figure 7.10: Conductive Graphene PLA Digital Circuit Print

There various possible reasons as to why the both circuits, shown in figure 7.9 and 7.10, did not produce any other results when promoted by the switches. It could have been due to different resistance the traces showed as seen in figure 7.8, causing poor conductance in certain areas of the circuit. Furthermore, as we had discussed in section 7.2, the ragged traces seen in the conductive graphene PLA filament print (figure 7.7) definitely created additional resistance. Finally, we have not yet looked into a relationship between the material and its capacitance and/or inductance, but it could have also played a role in impeding the flow of current in some of the line traces.

Chapter 8

Conclusion and Future Work

Additive Manufacturing has proved to be of significant value across many industries. It is continuing to push boundaries in the ways it can be utilized and integrated into various applications. With the capability of cost and energy efficiency, potential benefits to the electronic manufacturing industry is substantial. The thesis research goals were to integrate 3D printing with circuit board printing in the hopes to eventually have a system that reduces time from concept to market. To create one process for the circuit board printing and packaging while reducing the carbon footprint and manufacturing costs.

The 3D printed digital circuit was successfully implemented using the composite PLA filament and conductive graphene PLA filament. Though there still a few adjustments that need to made to attain optimal functionality, this analysis and initial testing highlights tremendous promise that a digital circuit can in fact be 3D printed with the both filament materials.

Moving forward, a better characterization of the materials needs to be done for consistency. A further look into the material make up, as in what amounts of graphene and graphite are present in the materials and how it relates to the conductivity. This information was not provided by the manufacturers/distributors and further research into the materials must be conducted.

We started with the goal to implement two circuits, a digital circuit and analog circuit. An analog circuit is still yet to implemented and tested. And to do so inductance and capacitance must be considered and evaluated for both materials. This will be crucial to

successfully printing a functioning analog circuit. Resistive precision is needed to adhere to sensitivity that can be experienced with analog circuits. The lines traces will probably have to be kept at minimum lengths and the distance between line traces increased to accommodate sensitivity.

In conclusion, the advancements that have been made are proving to expose very strong potential for integrating 3D printing with conductive polymers into electronic circuit printing and manufacturing. Further opening doors to a world of applications from the automotive industry, consumer electronics industry to the toy industry. This is only the beginning of an electronic manufacturing revolution and evolution.

Bibliography

[1] AgIC (2014). Agic print - printing circuit boards with home printers. [Online]. Available: https://www.kickstarter.com/projects/1597902824/agic-print-printing-circuit-boards-with-home-print. ix, 7

[2] Alchement (2017). [star] alchement - abs conductive series, 3d filament, 1.75mm, 1kg (conductive). [Online]. Available: https://www.amazon.com/STAR-Alchement-Conductive-Filament-1-75mm/dp/B01COH43R2/ref=sr_1_7?s=industrial&ie=UTF8&qid=1472216725&sr=1-7&keywords=conductive+abs+filament. 12

[3] Association, C. T. (2014). Consumer electronics industry revenues to reach all-time high in 2014, projects ceas semi-annual sales and forecasts report. [Online]. Available: https://www.cta.tech/News/Press-Releases/2014/July/Consumer-Electronics-Industry-Revenues-to-Reach-Al.aspx. 1

[4] AutoDesk (2017). Fusion 360. [Online]. Available: https://www.autodesk.com/products/fusion-360/overview. 9

[5] Bensoussan, H. (2016). The history of 3d printing: 3d printing technologies from the 80s to today. [Online]. Available: https://www.sculpteo.com/blog/2016/12/14/the-history-of-3d-printing-3d-printing-technologies-from-the-80s-to-today/. 3

[6] BlackMagic3D (2017). Conductive graphene pla filament 100g. [Online]. Available: https://www.blackmagic3d.com/Conductive-p/grphn-pla.htm. 13

[7] Carbide3D (2017). The nomad 883 pro. [Online]. Available: http://carbide3d.com/nomad/. 11

[8] CreativeMechanisms (2016). Everything you need to know about polylactic acid (pla). [Online]. Available: https://www.creativemechanisms.com/blog/learn-about-polylactic-acid-pla-prototypes. 13

[9] Daniel, J. (2010). Printed electronics:technologies, challenges and applications. [Online]. Available: https://www.parc.com/content/attachments/printed-electronics-technologies.pdf. 6, 7

[10] Dyer, E. (2015). The world's first 3d-printed car is a blast to drive. [Online]. Available: http://www.popularmechanics.com/cars/a16726/local-motors-strati-roadster-test-drive/. ix, 4

[11] ElectronicsTutorials (2017). Bcd counter circuit. [Online]. Available: http://www.electronics-tutorials.ws/counter/bcd-counter-circuit.html. ix, 20

[12] EOS (2017). Additive manufacturing, laser-sintering and industrial 3d printing - benefits and functional principle. [Online]. Available: https://www.eos.info/additive_manufacturing/for_technology_interested. 3

[13] Hooper, T. (2017). The 7 biggest trends and challenges in the electronics manufacturing industry in 2017. [Online]. Available: https://www.pannam.com/blog/top-trends-and-challenges-in-electronics-manufacturing/. 1

[14] Inventables (2017). Carvey. [Online]. Available: https://www.inventables.com/technologies/carvey. 11

[15] Kamyshny, A. and Magdassi, S. (2014). Conductive nanomaterials for printed electronics. *Small*, 10(17):3515–3535. 1, 7

[16] Kulich, D. M., Gaggar, S. K., Lowry, V., and Stepien, R. (2001). Acrylonitrilebutadienestyrene polymers. *Polymers. Encyclopedia of Polymer Science and Technology.* 12

[17] LulzBot (2017). Lulzbot taz 6. [Online]. Available: https://www.lulzbot.com/store/printers/lulzbot-taz-6. 11

[18] Machines, T. A. (2017). Series 1 pro. [Online]. Available: https://www.typeamachines.com/series-1-pro. ix, 9, 10

[19] Manufacturing, A. (2017). What is additive manufacturing. [Online]. Available: http://additivemanufacturing.com/basics/. 3

[20] of Exeter, T. U. (2017). The history of additive layer manufacturing. [Online]. Available: http://emps.exeter.ac.uk/engineering/research/calm/whatis/history/. 3

[21] Proto-Pasta (2017). Composite pla - electrically conductive graphite. [Online]. Available: https://www.proto-pasta.com/products/conductive-pla. 13

[22] RobotShop (2017). conductive abs 250g 175mm filament with spool. [Online]. Available: http://www.robotshop.com/en/conductive-abs-250g-175mm-filament-with-spool.html. 12

[23] Singh, M., Haverinen, H. M., Dhagat, P., and Jabbour, G. E. (2010). Inkjet printingprocess and its applications. *Advanced Materials*, 22:673–685. 6

[24] Sridhar, A., Blaudeck, T., and Baumann, R. (2011). Inkjet printing as a key enabling technology for printed electronics. [Online]. Available: https://www.sigmaaldrich.com/technical-documents/articles/material-matters/inkjet-printing-as.html. 6

[25] Ultimaker (2017). Ulitmaker 3. [Online]. Available: https://ultimaker.com/en/products/ultimaker-3. ix, 11

[26] UltimakerCura (2017). Ultimaker cura software. [Online]. Available: https://ultimaker.com/en/products/ultimaker-cura-software. 9

[27] Unijet (2009). Inkjet technology. [Online]. Available: http://www.unijet.co.kr/eng/main/sub04_01.html. ix, 6, 7

[28] von Ubel, M. (2017). 3d printing materials guide 2017 the complete overview. [Online]. Available: https://all3dp.com/1/3d-printing-materials-guide-3d-printer-material/. 12, 13

[29] Wohlers, T. and Gornet, T. (2014). History of additive manufacturing. Technical report. 3

Vita

Mwamba Bowa was born and raised in Zambia. She moved to Knoxville, TN to attend the University of Tennessee (UT) and pursue a degree in electrical engineering. She graduated with her Bachelor of Science (B.S) in December 2015 and started as a Master's student, in the same field, that following spring. Mwamba works as Graduate Teaching Assistant (GTA) for the senior design courses in the Electrical Engineering and Computer Science (EECS) department while working on 3D printed electronics research. Outside her school and research work, Mwamba is passionate about mentoring minorities and growing the number of Women in STEM (Science, Technology, Engineering and Mathematics) fields, specifically engineering. She served on the board of Systers: Women in EECS as the secretary and a mentor. The mission of Systers is to recruit, mentor, and retain women in the engineering field. She has also taught a one-hour credit seminar book study class on Sheryl Sandbergs Lean In: For Graduates. The class covered crippling professional barriers that exist between women and their professional goals, bridging the cultural gaps, professional development topics and building community. Mwamba has also served as a freshman mentor for the STEAM (Science, Technology, Engineering, Agriculture and Mathematics) minority mentoring program, which is joint a collaboration between the College of Engineering, the College of Agricultural Sciences and Natural Resources, and the Tennessee Louis Stokes Alliance for Minority Participation (TLSAMP). Mwamba is looking forward to join the engineering industry after graduation this fall 2017.