Solid Freeform Fabrication 2018: Proceedings of the 29th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

3D PRINTED ELECTRONICS

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ABSTRACT

Additive manufacturing is revolutionizing the way we build and produce a plethora of products spanning many industries. It 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 efficiencies in various applications including electronic systems and devices manufacturing. Electronic systems and sub-systems are built using a variety of material and processes, which require a large carbon footprint, significant waste material and high production time. 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. The integration of these separate processes into a single high efficiency additive manufacturing process will yield significant savings in energy use, carbon footprint, waste product and production time and cost.

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 [1]. 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 [2]. 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 these 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 [3].

This manuscript will introduce and serve as a guide that showcases the application of 3D printing technology to support advanced 3D manufacturing of integrated electronic devices using conductive polymer. 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. When you integrate this capability with 3D automation of component placement and enclosure construction, we believe this research could revolutionizing the way electronic devices like cell phones, TVs, and automotive systems are designed, manufactured, and distributed. All this while saving energy, reducing time from concept to product, reducing carbon footprint and the cost of manufacturing consumer electronic products.

MATERIALS AND METHODS

Two 3D printers, the Series Pro 1 and Ultimaker, were selected to perform the necessary prints for the proposed circuits. The Series Pro 1 has single extrusion while the Ultimaker has dual extrusion, making for more efficient printing. Despite the difference in extrusion heads both printers have played an integral role in the printing process.

With the printers selected, the conductive filaments that were available to us were evaluated and tested. These filaments consisted of four conductive polymers of which two were Acrylonitrile Butadiene Styrene (ABS) and other two Polylactide (PLA) filaments. The two PLA, a Composite PLA - Electrically Conductive Graphite (ECG) filament from Proto-Pasta and a Conductive Graphene PLA Filament from Black Magic 3D were tested to have the least resistance and were therefore selected for further evaluation. The composite PLA had the following product specification of volume resistivity; 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 (this is a reference to build direction) [4]. And the Conductive Graphene PLA had a product specification with a volume resistivity of 0.6 Ω-cm [5]. Given that resistivity specifications were incomplete due to the fact that the cross-section areas of the materials were not specified, further analysis had to be done.

Figure 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 2 show a 3D printed 3 x 3 mm analysis model.

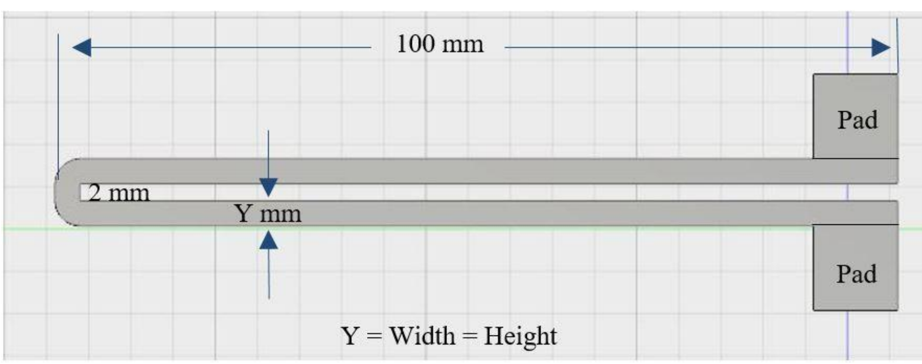

Figure 1: Filament Analysis Model

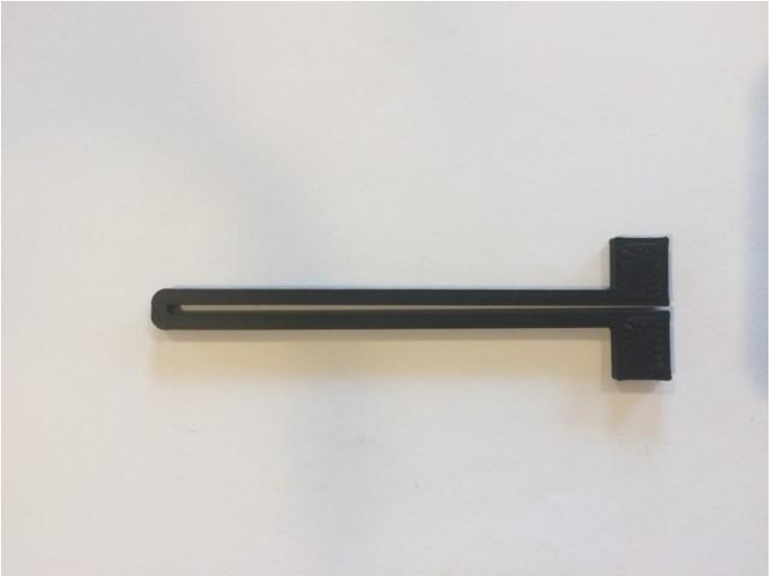

Figure 2: 3D Printed Analysis Model

Measured Resistance

The first model printed was the 3x3 mm the composite PLA filament, conductive graphene PLA filament.

Table 1: Filament Analysis Results for the Conductive PLA

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

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 conductive graphene PLA filament. These measurements helped us better understand how resistance varies with the different widths and heights of the models. Table 2 below, shows a comparison of the resistances measured for all of the three models of the conductive PLA filaments.

Table 2: Filament Analysis Results for the Conductive PLA

	Composite PLA Filament	**Conductive Graphene PLA Filament**
Cross-Sectional Area (width 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.

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. Using the 6x6 mm model as reference, a resistance surface area and resistance volume was calculated. Comparing the calculated resistances above with that of table 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 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 3: Filament Analysis Results for the Conductive 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**

We can observe the volume resistance calculations in table 3 that the conductive graphene PLA filament shows better correlation between volume and resistance 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. It's possible this accuracy can be further improved by increasing the model dimension's width and heights.

The Circuit Printing Process

With the eventual goal of implementing both an analog and digital circuit, we focused on a digital circuit. With reference from a concept, the digital circuit was modeled in Autodesk Fusion 360. Figure 3 shows a top view of the 3D circuit design with the electrical components placements specified: a Common Cathode 7 Segment Display, Seven 4.7 kΩ Series Resistors, Four Switches, Four 1.5 kΩ Pull-Up Resistors, 74LS48 BCD to 7 Segment Decoder.

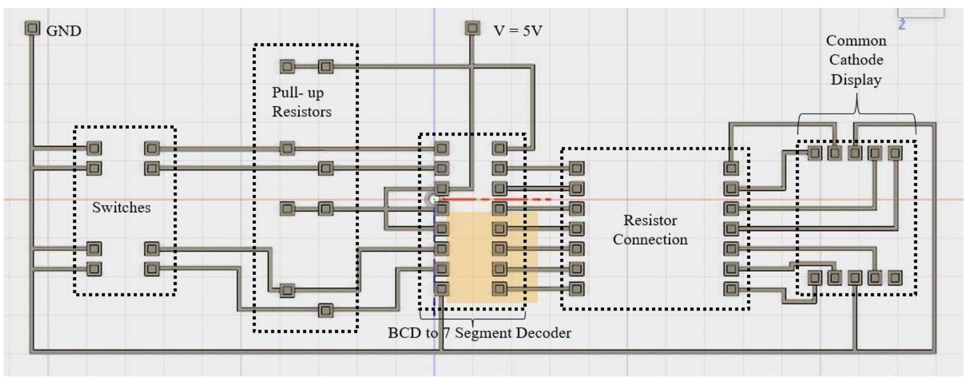

Figure 3: The Digital Circuit Layout Design

With the circuit 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 nonconductive PLA filament was used as the non-conductive base of all the circuit boards. Figure 4 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.

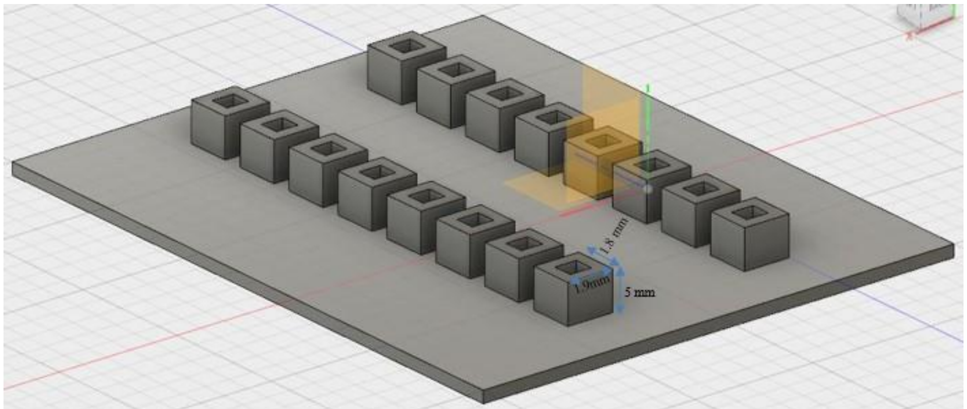

Figure 4: Pin Holes Analysis

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 5 and 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 nonconductive material line traces in between the pin holes were added to the print, as shown in figure 6 and 9. 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 bottoms of the pin holes were beveled 0.5 1 mm, figure 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.

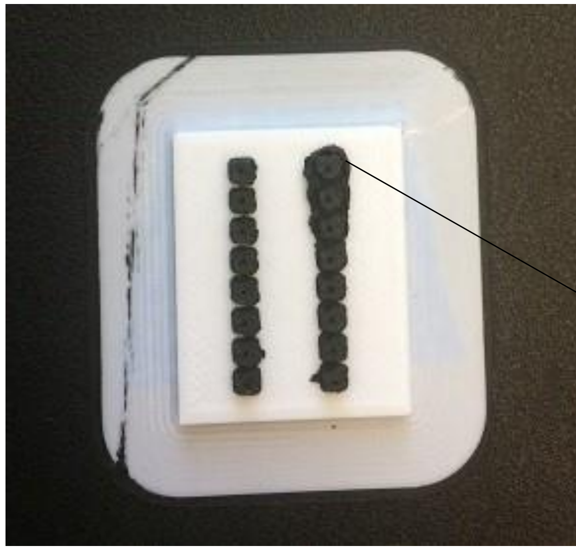

Figure 5 : Conductive Graphene PLA Filament Pin Holes challenges 1

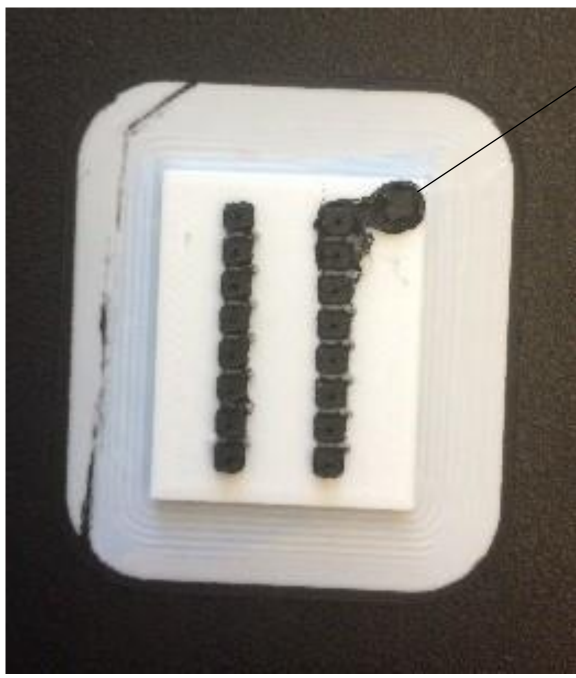

Figure 6: Conductive Graphene PLA Filament Pin Holes challenges 2

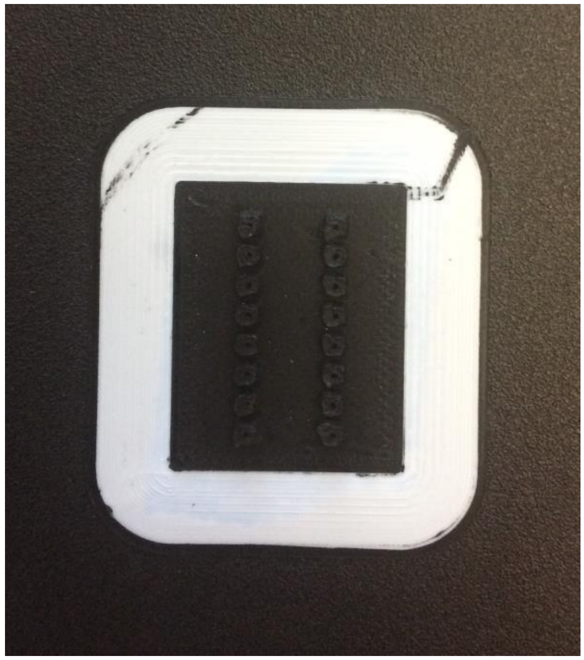

Figure 7: Conductive Graphene PLA Filament Pin Holes adjustments (with graphene base)

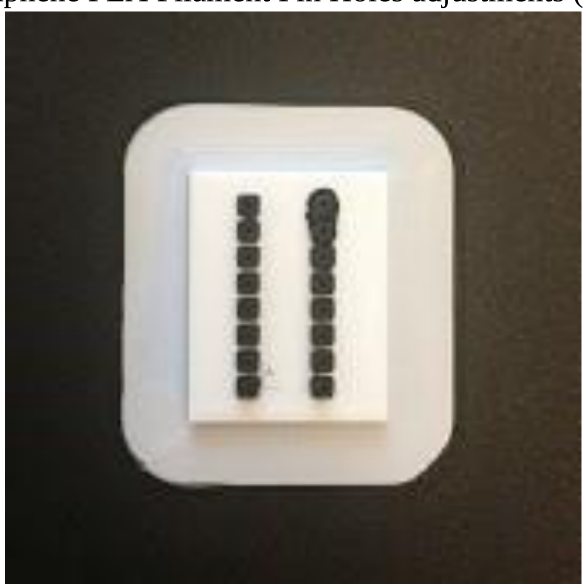

Figure 8: Composite PLA Filament Pin Holes challenges 1

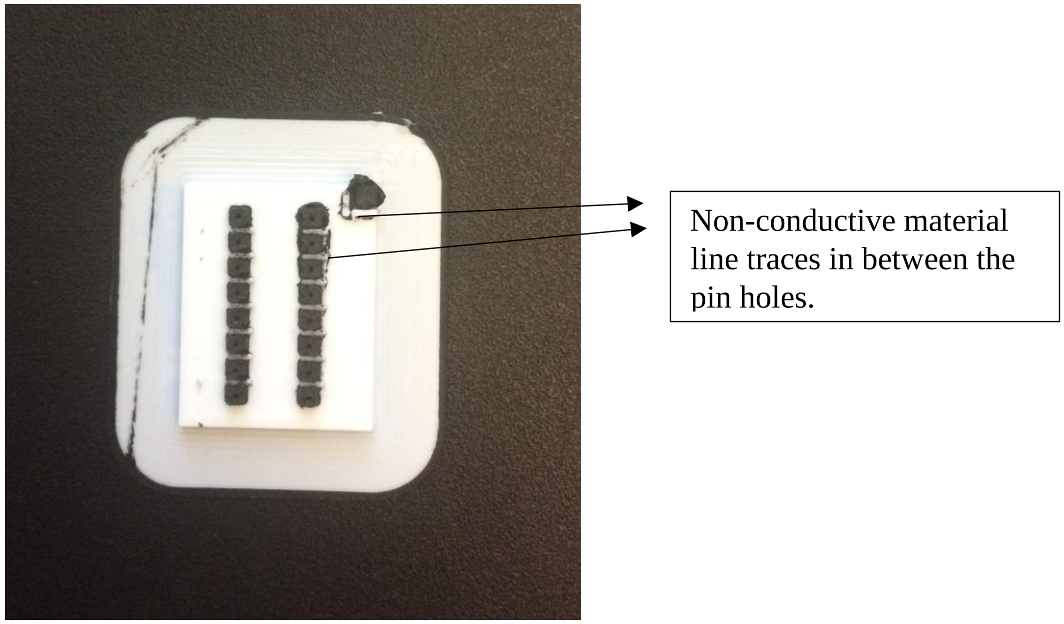

Figure 9: Composite PLA Filament Pin Holes challenges 2

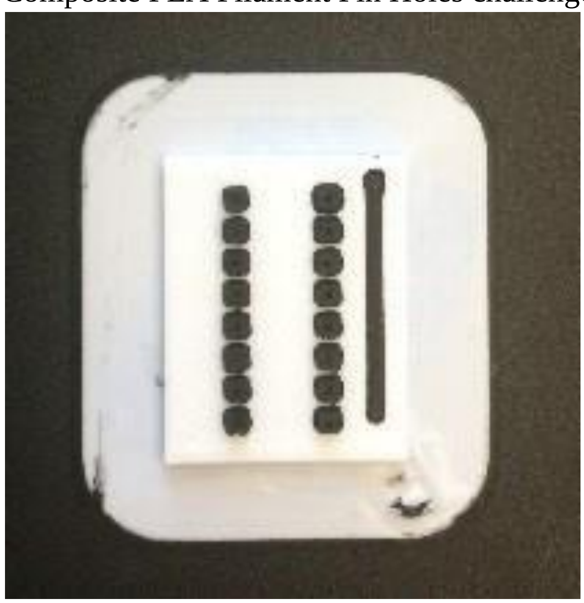

Figure 10: Composite PLA Filament Pin Holes adjustments

RESULTS/DISCUSSION

Implementation with both the composite PLA filament and conductive graphene PLA filament was conducted. To reduce the resistances across the circuit, with the information learned in filament analysis, 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 4. 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.

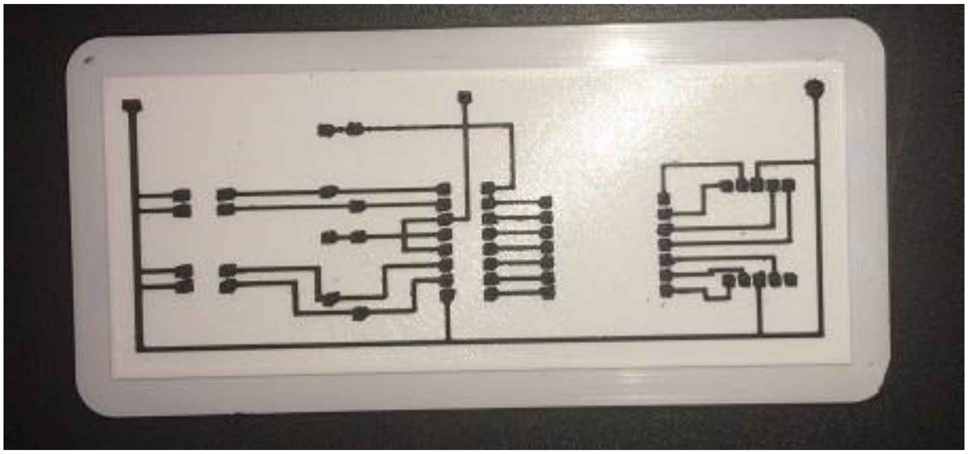

Figure 11: Composite PLA Digital Circuit Print

We experienced no issues with printing the digital circuit with the composite PLA filament. As can be seen in both figures 11. 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.

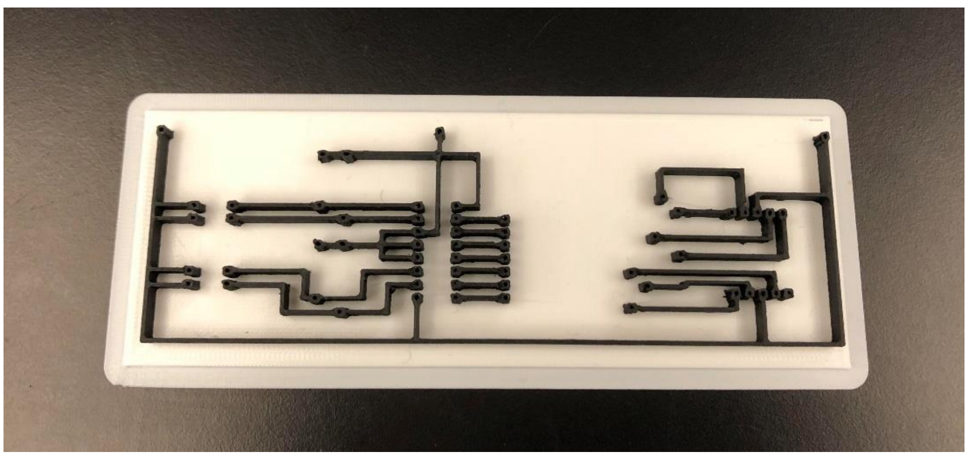

Figure 12: Conductive Graphene PLA Digital Circuit Print

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 4. The digital circuit print for 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.

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 13 as reference and the resistance measurement lists below, R(1-2) represents the measurement between points (1) and (2). R(23) 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 13. 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.

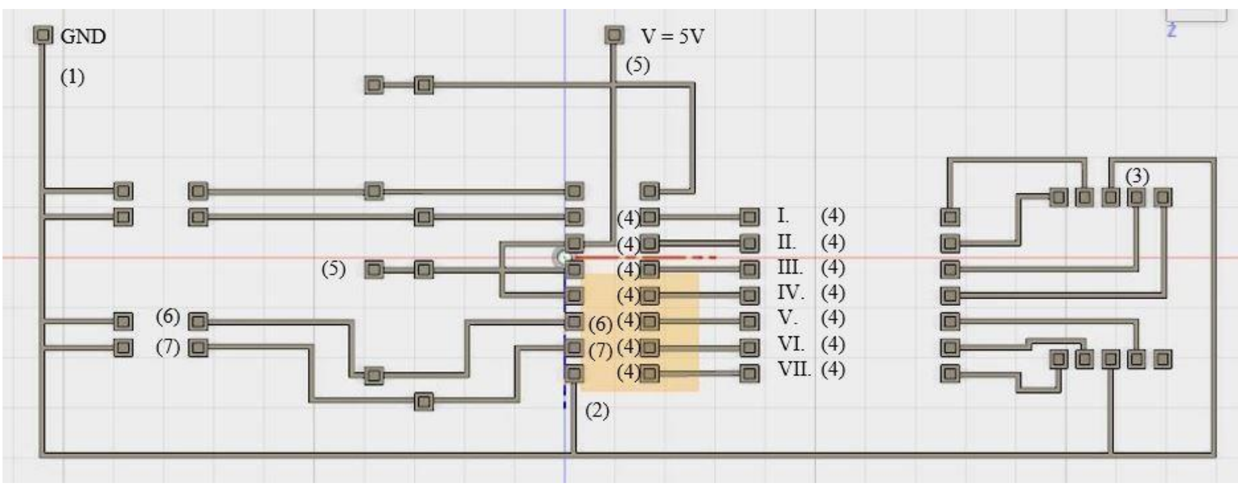

Figure 13: Composite PLA and Conductive Graphene PLA Filament Digital Circuit for Resistance Measurement Points

Table 4: Composite PLA and Conductive Graphene PLA Filament Digital Circuit Resistance Measurement

Composite PLA Filament Circuit Resistance Measurements	**Conductive Graphene PLA filament Circuit Resistance Measurements**
R(1-2) = 5.1 kΩ	R(1-2) = 0.7 kΩ
R(2-3) = 5.5 kΩ	R(2-3) = 1.0 kΩ
R(I.(4)) = 1.0 kΩ	R(I.(4)) = 0.6 kΩ
R(II.(4)) = 1.1 kΩ	R(II.(4)) = 0.3 kΩ
R(III.(4)) = 1.1 kΩ	R(III.(4)) = 0.5 kΩ
R(IV.(4)) = 1.0 kΩ	R(IV.(4)) = 0.3 kΩ
R(V.(4)) = 1.0 kΩ	R(V.(4)) = 0.6 kΩ
R(VI.(4)) = 0.9 kΩ	R(VI.(4)) = 0.5 kΩ
R(VII.(4)) = 1.1 kΩ	R(VII.(4)) = 1.0 kΩ
R(5-5) = 2.3 kΩ	R(5-5) = 0.8 kΩ
R(6-6) = 2.5 kΩ	R(6-6) = 0.6 kΩ
R(7-7) = 3.0 kΩ	R(7-7) = 0.5 kΩ

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 14 and 15. 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.

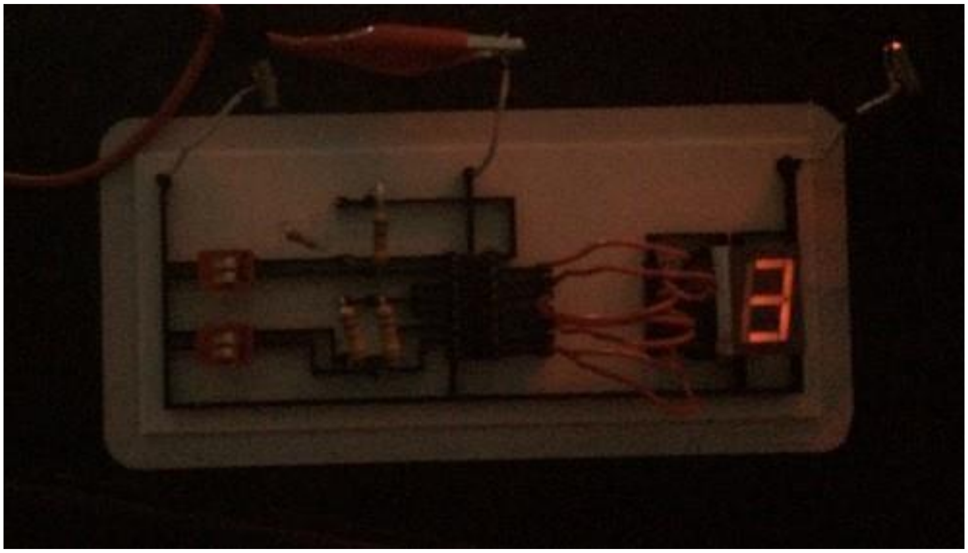

Figure 14: Composite PLA Digital Circuit Print

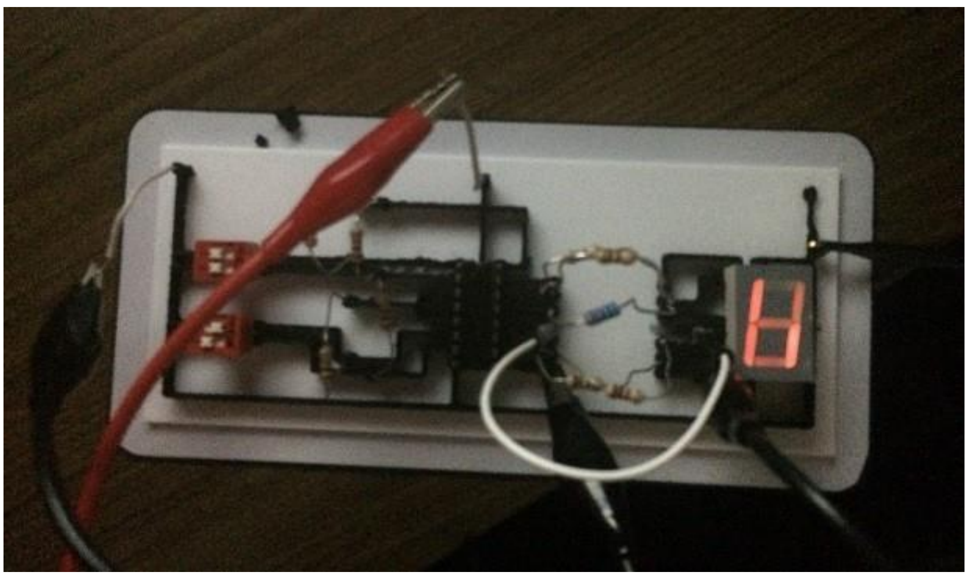

Figure 15: Conductive Graphene PLA Digital Circuit Print

There various possible reasons as to why the both circuits, shown in figure 14 and 15, 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 13, causing poor conductance in certain areas of the circuit. Furthermore, the ragged traces seen in the conductive graphene PLA filament print, 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.

CONCLUSION

From the analysis and initial testing, a 3D printed digital circuit was successfully implemented using the composite PLA filament and conductive graphene PLA filament, as shown in figures 14 and 15. There are still a few adjustments that need to be made to attain optimal functionality, however, 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. In addition to future work, there are plans for implementation and testing of analog circuit with these conductive polymers.

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