3D Printed Antennas for Wireless Communication

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ABSTRACT

This paper describes the details of design and critical analysis of the process of 3D printing antennas for wireless communications applications. The subjective testing methods utilized were chosen specifically based on project scope and researcher capability. Our results indicate that more work is necessary in this field but that the basic idea is feasible.

Keywords: 3D Printing, Antenna, Extrusion,

1. INTRODUCTION

We strove to develop a process that utilizes a commercial 3D printer to print functioning antennae that operate in the normal frequency range (from .9 to 26 gigahertz.) As the project proceeded, we defined a robust, consistent process by which we will print conductive material without melting the underlying polymer layers. Our goal is to explore alternative designs in the printing process and hopefully succeed in the printing of conductive materials along with polymers in the same process. If we complete this process, we will then print a functioning 3D antenna. By doing so, we hope to demonstrate the feasibility of printing conductive materials with polymers and open the gateway to more applications of 3D printing. Note that this project does not include a specific design of the hardware or software as the 3D printer is already given and the software is included. This project consists of research into the methodology of printing conductive materials. Since this is our goal, we are not focusing on the design of a new antenna, but the process to print said antenna.

From an operational standpoint, the procedure will be as follows. The user will draw a 3D model using a program that outputs OBJ and/or STL files. This model is fed into MakerBot software, a slicing software which generates g-code, which is read by the 3D printer and used for printing. The product that our process ultimately delivered is just a proof of concept, a way to show that our process works. In developing a repeatable process, we hope to make the actual act of printing an antenna fully using a 3D printer to be a rather trivial process.

2. System Requirements

Early on, we decided to mainly focus on the printing process, rather than the antenna design itself. In order to stay consistent with the goal, we modified the original requirements and added some additional requirements related to the process of 3D printing, as well as our final design. For functional requirements, our printed antenna should meet the most basic requirement that it should both receive and send data. For the Technology Requirement, one of our main concerns stems from the differing properties of the metallic and insulating materials. The metal part of the antenna may melt the polymer layer due to the higher melting point of the metal. So we need to develop a consistent process for printing conductive materials without melting the polymer layer. The lowest conductivity for the conductive material should reach 5% of copper's conductivity, which is 10^6 Siemens/meter. The metal portions of antenna must be twice the resolution of the nozzle-head. The decision we made after the initial project definition to focus on the process rather than the actual antenna designs because a repeatable process is a much more valuable result than delivering a single, one off antenna.   We will take advantage of a 3D printer to accomplish this task. We chose metal extrusion as the most feasible process, given the limited resources and time available to us. Inherent in extruding metal, there is a possibility that the melted solder wire will clog the nozzle head. We don't want to see that happen at all in the printing process. However, clogging problems cannot be prevented even when printing polymers, it is an inherent issue with 3D printing. The Utilization requirement is that the total budget should be within $3500. The requirement matrix is shown below.

Requirements Worksheet: 3D Printed Antennas for Wireless Communication		
9/15/2015		
Number	Type	Description
1	Functional	The antenna should both receive and send data
101	Technology	Conductive material printed out must have conductivity of 10^6 siemens/meter.
102	Technology	The solder must not melt polymer layers
301	Utilization	Total budget should be with in $3500

Table 1: The final Requirements Matrix

3. Metal Extrusion

Metal extrusion involves using a dual-nozzle 3D printer to fabricate an ABS plastic base with an embedded trench. Solder is then deposited into the trench from the other extrusion nozzle. The next layer of the mold is deposited, beginning with the ABS and followed by the solder. The antenna and casing are built up layer by layer in this fashion until a final product is completed.

4. Top Level Design

The final design uses a 0.062” solid core SnPb 63/37 solder wire as the conductive material to print the antenna base using the Makerbot. Using HFSS, an antenna design and simulation software, the shape and performance of the antenna can be designed and studied. Solidworks is then used to build two models, one for polymer and another for the metal antenna trace portions. The included Makerbot software, Makerware, cannot read the file output by Solidworks directly. Thus the file must be convert to the OBJ file format, and online resource was utilized for this step. Once the files are converted and readable by Makerware, we must insert the files and align them according to our design specifications to allow for two layer printing. Our Makerbot Replicator 2X can be used to print two different materials using its two nozzle heads alternately. For the metal extrusion method, we use one nozzle head to print polymer and feed the other one solder wire. Using Makerwate to assign the polymer part and the metal part to each nozzle head. Makerware allows for custom print settings to be applied to each printhead, allowing for more control over the printing process. Careful detail will be taken with regards to the 2nd print head as the metal extrusion requires wholly different settings than normal ABS filament printing. Regarding the hardware, the stepper motor associate with the gantry system can tell the print head where to go. In the print head, there are thermal cores that melt the polymer into an amorphous state and the metal into a liquid. Once the settings of temperature, feed rate, and procedure are correct, the antenna will be printed layer by layer.

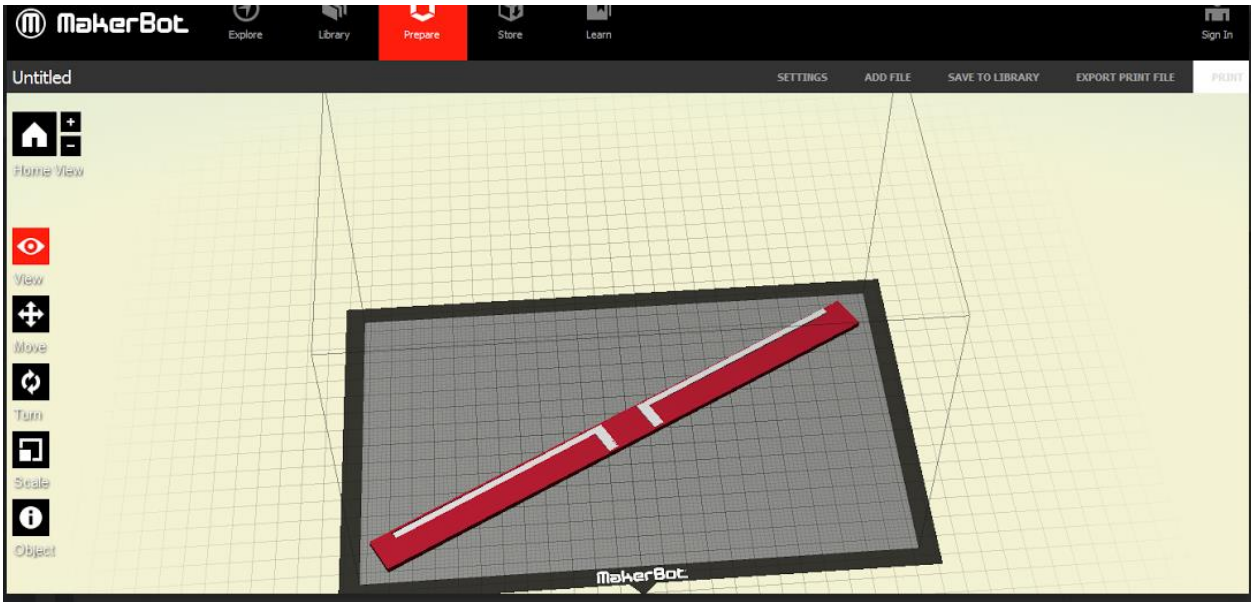

Figure 1: An image that shows the two files are combined. The red color is the polymer base and the silver is the conductive element of the antenna

5. Results

After attempting to print several bases, we observed that during the solder extrusing step, the melted solder tended to stick to the exterior surface of the nozzle head after being extruded, this made the solder hard to print continuously. Non continuous metal means the circuit will act as an open loop, this is not acceptable in our design. The standard extrusion nozzles were fabricated from brass, which has significant affinity for the solder we have chosen. The materials interaction between brass and solder leads to wetting of the extrusion nozzle, which is to say that the solder adheres to the nozzle's surface. This phenomena can lead to problems such as clogging and wicking of the solder up the outer surface of the nozzle. Both of these issues prevent the consistent deposition of solder from the nozzle. In order to alleviate this problem, we choose several metals containing aluminum or chromium to test for more favorable properties. These particular metals were of interest because of the tough oxide layer which forms a passivation layer on the surface. Due to the ionic nature of bonding, molten solder will be much less likely to adhere to this surface. Another parameter which could inhibit proper extrusion is the temperature. The temperature must be high enough to keep the solder in the molten state as it leaves the extrusion nozzle. This is to prevent nucleation of the liquid solder before it reaches the target surface, as this would lead to clogging and inconsistent solder deposition. Because of the clogging problems we encountered and time constraints, we were forced to deposit the solder by hand.

The next hurdle we needed to overcome is the lack of interaction between the polymer base and the solder. The solder does not want to stick to the polymer, making it very difficult to form a continuous antenna trace. To overcome this, we “painted” the antenna trace first with liquid flux, this did not yield any favorable results. We next leverage conductive silver ink, we again “painted” the antenna trace with the conductive silver ink, this resulted in the solder being much more attracted to the antenna trace, even when the ink dried, allowing for the completion of the conductive element of our antenna.

Figure 2: An antenna with one of the traces filled and the painted with conductive ink

Requirement 101 can be evaluated by measuring the conductivity of the material. This can be accomplished by measuring the resistance. We can then convert the resistance to conductivity by solving for the following equation $R = \frac{Length}{Cross\ Sectional\ Area*Conductivity}$ or $R = L/AC$. We should note that because we are measuring highly conductive materials, a simple ohmmeter measurement would not be effective as the leads of an ohmmeter could greatly skew our measurement. An alternative would be to use 4- wire measurement.

	Left Trace Resistance Values (Ω)	Right Trace Resistance Values (Ω)
Regular Result	.11	.06
4 Sense	.053	.01

	Left Trace Conductance Values (σ)	Right Trace Conductance Values (σ)
Regular Result	4.5*10^5 S/m	.83*10^6 S/m
4 Sense	.94*10^5 S/m	5*10^6 S/m

For analysis sake, we kept the standard two wire measurement as a "regular result" and we note that, in fact, the testing leads did impact our measurement. One can note that by testing our conductive traces with the simple resistance test, our values were skewed sometimes to one order of magnitude. Based on our results, we can say that we have achieved our goals for conductivity. The right trace far exceeded our limit. The left trace fell a bit short; however because we manually filled the trench, we could determine that the lower conductance values could be imparted to human error which may have caused solder crystallization thus lowering our overall conductance value. Since a machine would be used to deposit solder, we can assume that a machine will be more precise and less crystallization will form which should grant us a conductive trace with values closer to the Right trace. Because of this, we can warrant that our antenna and method of depositing solder would fully satisfy our conductivity requirement.

Requirement 1 was tested using a Vector Network Analyzer. Our primary measurement, which we would make using a VNA, would be how much power is reflected from the antenna. This is known as parameter S11, also known as return loss. Ideally, this number should be as low as possible meaning that most of the power should radiate out from the antenna.

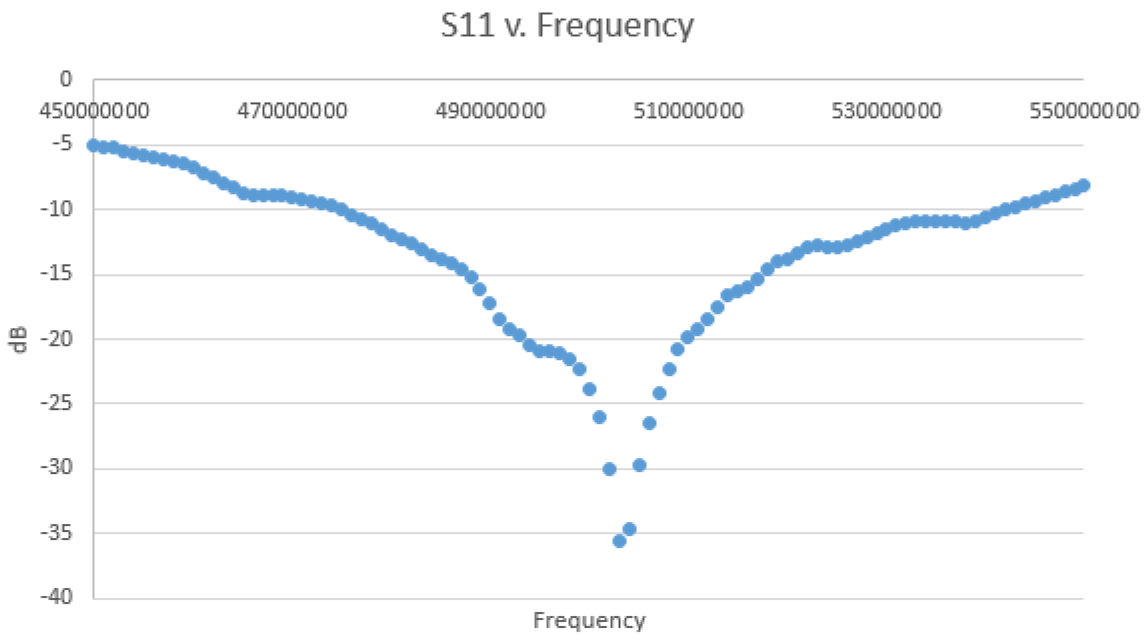

Figure 3: Actual S11 Results

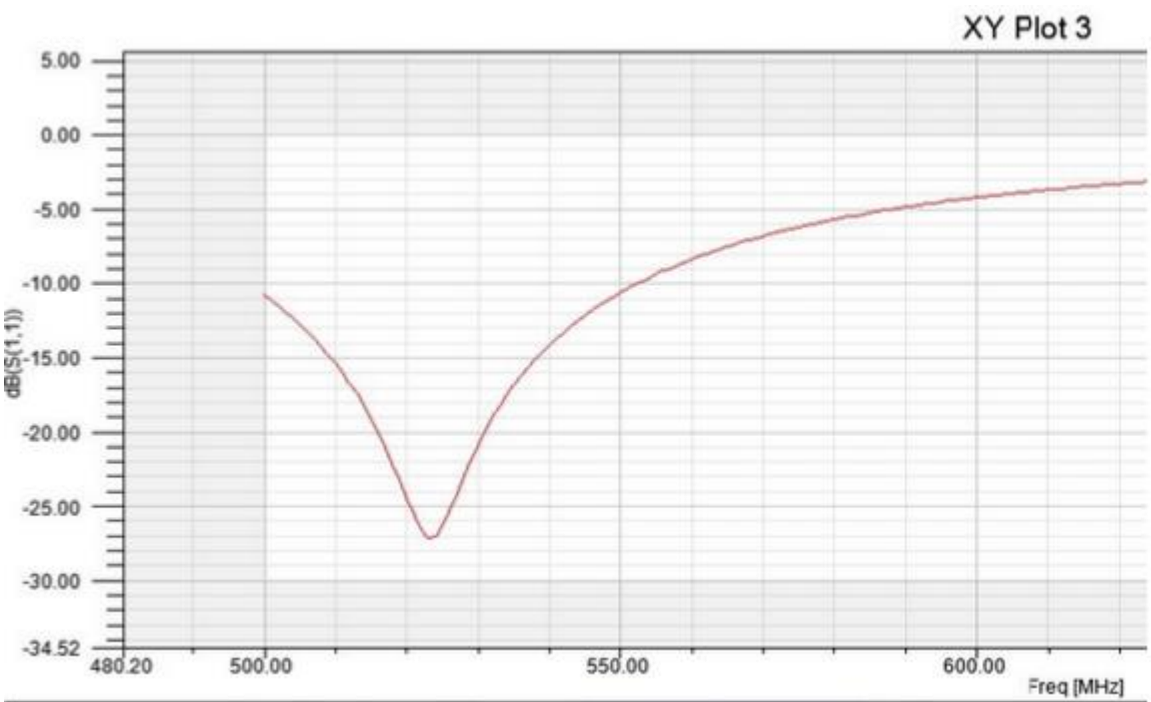

Figure 4: Simulated S11 using HFSS

One can note there are differences between our simulated and actual results. However, we did surpass our -10dB requirement which does mean that we are optimistic about using solder extrusion as a technique. How do we account for the differences then? In our actual results, our antenna had the best performance at around 504 MHz. In our simulation, it was about 525 MHz.

We also note that our actual antenna had a better performance than our simulation. This may be because of the conductive values. In the simulation, it probably had an average value of 10^6 Siemens/meter and used that for analysis. Our antenna had up to five times that value for one of our traces which probably enhanced the performance. Even though it seems our frequency values are not matched, we should note that we are only off by 4% in frequency which should be accounted for given that the plastic base may not have been modeled completely in the simulation software.

Requirement 102 will be evaluated using SEM with EDS, to confirm that the polymer has not been destroyed by the application of molten solder. The specimen will be cross sectioned and sputtered with a platinum coating to prevent charging effects from obscuring the image. A perfectly segregated boundary with no mixing would be the ideal result. The goal of performing this analysis is to provide as much information as possible regarding the microdynamics of the solder deposition process.

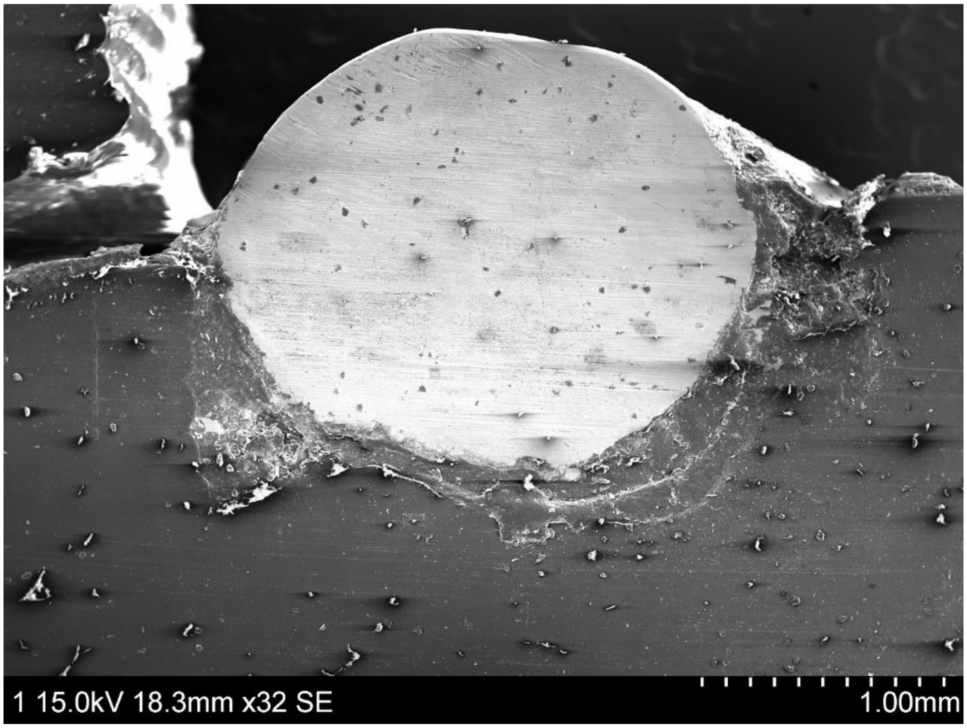

Figure 5: SE image or cross-section at 15x

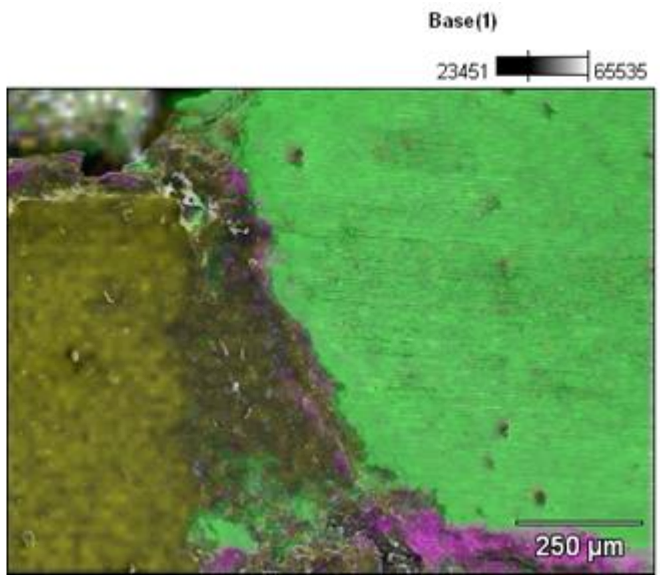

Figure 6:EDS elemental analysis showing separation between various materials

In order to perform SEM testing, the sample was first cross sectioned with a diamond blade and mounted on a chuck. The uncoated sample was difficult to image and had significant charging effects. The sample was sputter coated with platinum in order to avoid the buildup of static charge on the polymer sample. A piece of carbon tape was affixed to the sample to provide a conductive path to ground. The SEM showed striations on the solder trace. These were produced as an effect of the diamond blade. Small black pits are also noticeable along the cross-section of the solder trace. Elemental analysis showed that these were not impurities in the solder but were instead either small voids intrinsic to the solder trace or pits introduced by the cross-sectioning process. Clearly visible in the false color EDS image is the plastic base. This section maintained a clear rectangular groove. The oxygen content is highlighted in yellow, and due to the high levels of oxygen in the polymer, clearly indicates where the plastic is located in the sample. The bright green section indicates tin content and clearly shows the solder filament. The multicolored region between the solder and the plastic is the conductive silver ink and flux. The phase separation within the deposited ink was noticeable due to the concentration of silver (colored in purple) near the solder-ink interface. Below the silver ink is the flux layer. The image shows that none of these layers showed significant mixing which meets our 102 requirement. The flux and conductive ink may have had a protective effect in shielding the plastic from the solder. This may have helped to prevent mixing between the solder and plastic layers.

6. Conclusions

Our testing results showed that the process passes all requirements which have been evaluated. The antenna performed above benchmarks in the S11 parameter. The requirement was a 10 dB loss and our antenna exceeded 30 dB of loss. This is an important result which shows that the antenna would be able to receive signals. The conductance test showed that we were able to print a solder trace which meets the conductance requirement of 10^6 Siemens. There was an inconsistency in the conductance between the left and right solder traces. This inconsistency can be attributed to the fact that the solder was deposited manually instead of by automation. Due to this fact, the solder had a large variation in the width of the solder traces. With the added ability to print solder we believe that we could achieve a much more uniform and consistent antenna.

Finally, we believe machining an extrusion nozzle using a carefully selected metal is the only barrier to being able to fully 3D print a functional antenna. In doing so, the main hurdle, nozzle clogging/wetting will be overcome, allowing for further innovation using 3D printers.