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3D Printed Electronics with Multi Jet Fusion

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Abstract

3D printed electronics (3DPE) is an enabling technology that has the potential to allow for the advanced track and traceability of every 3D or additively manufactured (AM) part; enable communication and sensing by an individual part; and remove geometrical limitations for electrically active devices which can directly take on the final product form factor. Additionally, AE solutions attempt to allow for faster prototyping for conventional circuit designs. HP's Multi Jet Fusion (MJF) technology is a powder-based 3D printing technology that enables the production of high mechanical performance polymer parts at high speeds and reduced costs. At HP Labs, the advanced capabilities of the MJF platform have been researched. We have developed a process for 3D printed electronics. This allows an ink-jettable conductive agent (CA) to be utilized with the MJF process to build conductive traces, vias, and contacts anywhere within or on a printed part during the 3D printing process.

Introduction

3D printed electronics (3DPE) is an enabling technology that has the potential to allow for the advanced track and traceability of every 3D manufactured or additive manufacturing (AM) part; enable communication and sensing by an individual part; and remove geometrical limitations for electrically active devices which can directly take on the final product form factor. Additionally, 3D printed electronics solutions attempt to allow for faster prototyping for conventional circuit designs. Many attempts into the 3D printed electronics space require a hybrid solution that relies on conventional 3D print technologies (FDM, PRJ, SLA, etc.) coupled with a direct write solution to extrude out conductive pastes. These hybrid solutions add complexity, cost, and production time to the process and make it difficult to dislodge the incumbent manufacturing techniques.

HP's Multi Jet Fusion (MJF) technology is a powder-based AM technology that enables the production of high mechanical performance polymer parts at high speeds and reduced costs. The MJF process utilizes inkjet technology to deposit various agents onto a powder bed to selectively define part regions and potentially create desired properties at a voxel (volumetric pixel) level. For 3DPE, researched and developed at HP labs, an ink-jettable conductive agent (CA) has been utilized to build conductive traces, vias, and contacts anywhere within or on the printed part during MJF 3D printing process.

Within this work we will present the vision of MJF 3D printed electronics to enable smart parts. Here we see the path of using the CA to generate both internal and external conductive traces in an AM part. Internal traces can allow for conductive interconnects through a part, internal heaters, and simple sensors such as load cells. External traces can be plated with additional metal to give highly conductive finishes. Moreover, simple electronic components such as printed resistors can be constructed directly into the part. When using printed electrical components does not make sense, lumped components can be placed in 3D printed sockets on the part after printing. Additionally, antennas can be built into AM parts to enable part identity and communication. Overall, the MJF 3D print process can be a versatile solution with the potential to incorporate 3DPE without sacrificing print speed, resolution, or the mechanical performance of AM parts.

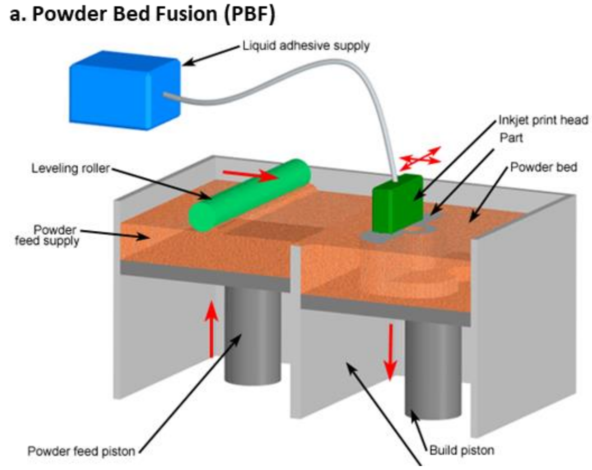
Background on 3D Print Methods

3D printing or AM has generated much interest over the past few decades and more recently has been evolving to incorporate additional functionalities to the materials. Selectively controlling the electrical properties of the part as it is being generated is of high interest. This field of 3DPE could make electronics more cost and time effective, eliminate manufacturing steps, and allow for the electrical and mechanical form to be that of the final product form factor.

Many existing AM technologies have been applied towards 3DPE in various ways. The main AM methods that have had success towards 3DPE are powder bed fusion (PBF), fused deposition modeling (FDM), photocurable resin jetting (PRJ), and stereo lithography (SLA) (Figure 1). These methods are often coupled with direct write (DW) to apply highly conductive pastes (mainly silver based) to the surface of the parts as they are being printed.[1-8]

PBF is the category of AM that MJF falls into. This technology comprises of spreading thin layers of a powdered polymeric material and selectively fusing with either a laser or the combined inkjet printing of a fusing agent (3D ink) and a light source (Figure 1a).[9, 10] For 3DPE, a CA can be used to selectively create conductive features within a fused polymer material. This technology benefits from high mechanical properties, high build rates (>25 mm/hr), moderate resolution (~100 microns), no need for supports, and the printing of multiple parts at a time.

a. Powder Bed Fusion (PBF)



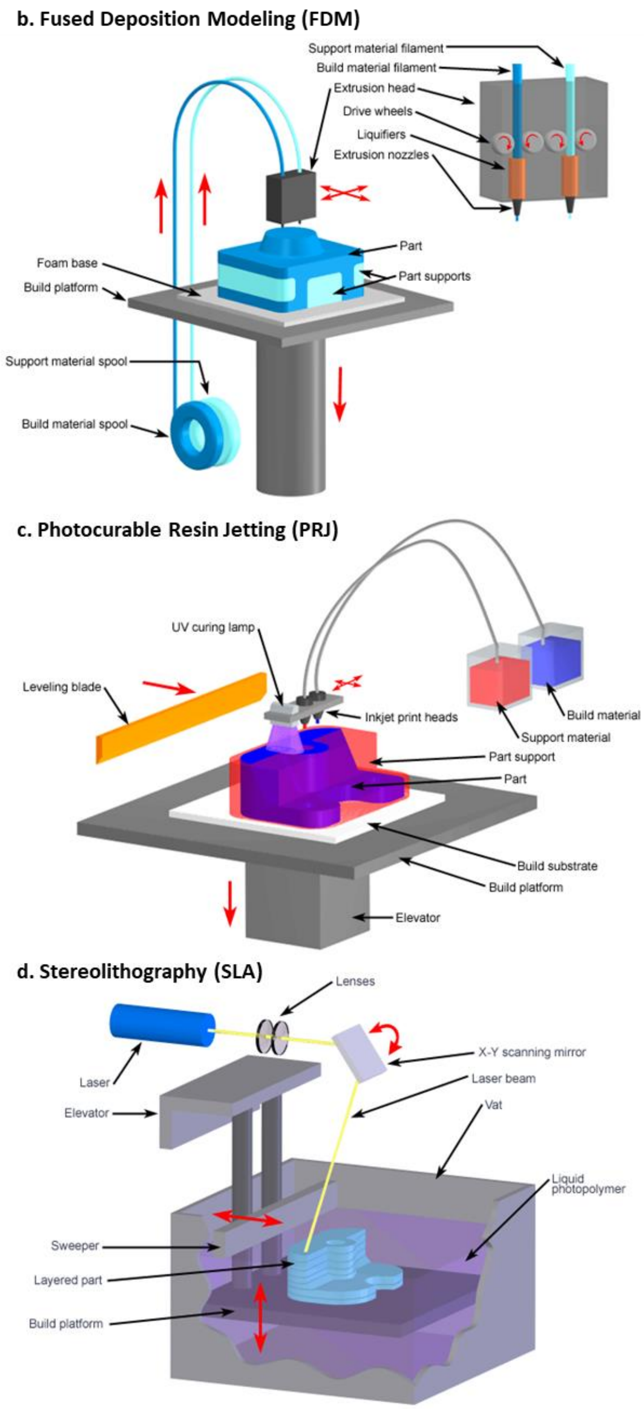


Figure 1. Depicts various AM processes. A shows powder bed fusion (PBF), B shows Fused deposition modeling (FDM), c shows photocurable resin jetting (PRJ), and d shows stereolithography (SLA).[11]

The FDM process consists of melting and extruding one or more polymeric-based filament materials to draw out a part in a layer-based approach. With multiple filament materials different areas of the part can be selectively constructed with a particular material. (Figure 1b) For 3DPE, one of the materials is loaded with a highly conductive composite (graphene or metal flake-filled polymer) for the selective deposition of conductive features.[12] Alternatively, DW can be incorporated to FDM and highly conductive pastes extruded during the FDM print.[13] FDM benefits include a high mechanical properties and multi-material printing, with detriments being build speed (<10 mm/hr typical), low resolution (>100 microns typical), support materials being required, and singular parts being built at a time.

PRJ constructs its parts through UV curing layers of jetted UV curable resin (Figure 1c). This process can allow for various materials to be dispersed in the UV curable resins. For 3DPE, the photo-resin can be loaded with a conductive material (silver NP or graphene) to selectively define conductive regions of the part.[14] PRJ benefits from high feature resolution (<20 microns typical) and good surface finish, but it is hindered by a slow build speed (<5 mm/hr) and difficulties in creating wide build beds.

The SLA process uses a photocurable resin that is selectively cured with a laser to create a layer of the part, subsequently more photo-resin is deposited for each layer and the process is repeated (Figure 1d). This process has the advantage of easily stopping and restarting the build. Due to this, researchers have taken advantage of this print pause capability to combine the SLA process with DW of silver pastes for conductive traces.[1, 13, 15] SLA has a high build rate (>15 mm/hr) and good surface finish but suffers with the need for supports and incompatibility with multiple materials.

Introduction to Multi Jet Fusion (MJF)

As mentioned previously, MJF falls into the PBF category of AM. Therefore, the core of the technology is the deposition of powder layers followed by selectively fusing certain areas of the bed by jetting a fusing agent. MJF technologies leverage HP's deep knowledge of 2D printing to allow for the high-speed production of many parts in a large build volume.[10]

The MJF technology is demonstrated in Figure 2. The process can be broken into 6 key stages. The first being shown in Figure 2a where the material is recoated (~100 µm) over the previous build layer or a blank layer if the process is just beginning. Next, energy is deposited onto the bed to get the fresh powder layer to the correct thermal environment to continue (Figure 2b). After that a variety of different agents can be deposited with the key agents being shown in Figure 2 c and d. The fusing agent and detailing agent work together to deliver an accurate recreation of the part design. Next the fusing lamps will irradiate the build bed and cause the areas where the fusing agent were deposited to melt and coalesce together to define that layer's part geometry (Figure 2e). Finally, the heat delivered from the fusing step allows the melted region of the top most layer to fuse to the layer beneath it generating a cohesive part (Figure 2f). This process is repeated until the build job has been completed.

Like traditional 2D digital printing where a pixel can be defined to have a state (black, white, colored, etc.), MJF 3D printing allows for similar control over the voxel (volumetric pixel). At the basic level the voxel can be directed to either fuse or not, thus defining the part geometry. However, with various transforming agents many more voxel states can be selected which can lead to a digital control of many more material properties aside from only defining a part. These transforming agents could eventually give voxel control of surface roughness, texture, and friction coefficient; tensile strength, elasticity, hardness, and other material properties; color: embedded and at the surface; opacity or translucency in plastics; and electrical and thermal conductivity.

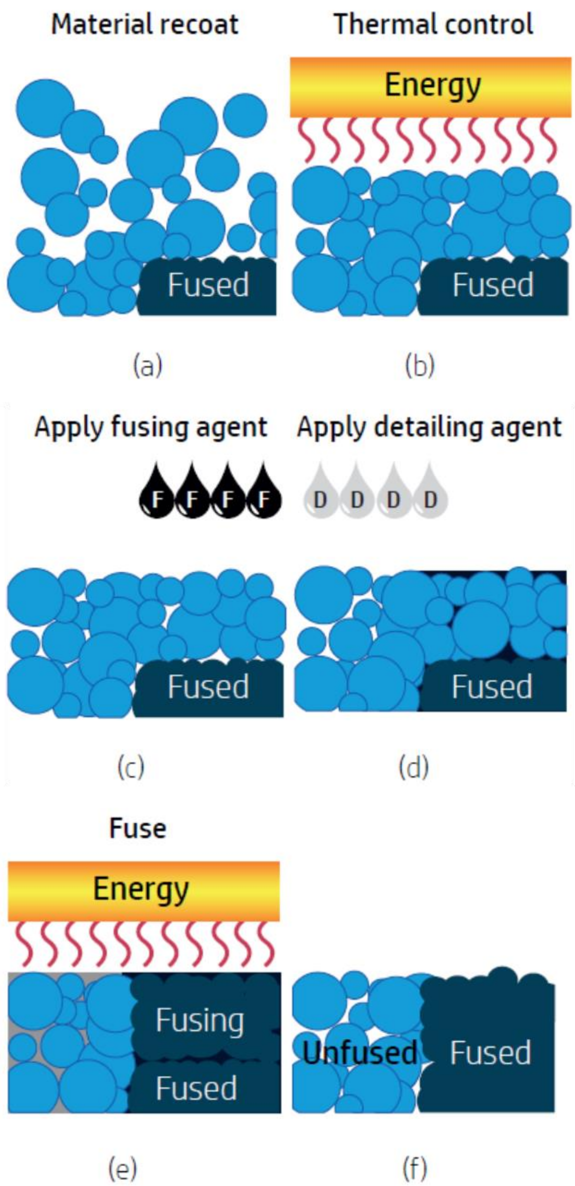


Figure 2. Details the step by step process of MJF printing.[10]

The Conductive Voxel

The transformation agent that allows for modifying the conductivity of a voxel is known as the CA. The current CA is a metal nanoparticle dispersion that has been formulated to work with thermal inkjet (TIJ) pens. When using the CA, the overall MJF process shown in Figure 2 is modified with the addition of the CA shown in Figure 3. Here it can be seen that the CA is selectively applied to the intended voxels as described by the part's design file. Then during the fusing step, the CA forms conductive pathways throughout the melting powder to form a conductive composite in the voxel. By continuing this process conductive elements can be generated at any orientation or geometry within the part. This voxel process is scalable allowing for small traces to be placed throughout the part, to large area ground planes, and even the entire part being constructed out of the CA.

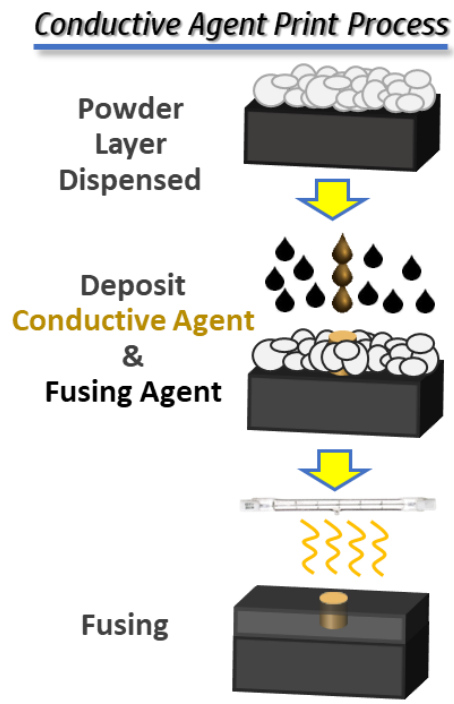


Figure 3. Shows the process variations between the 3DPE version of MJF. Here the steps shown in Figure2 b through e are appended with the CA print process.

One major benefit of the MJF 3D printed electronics process is the freedom to utilize conductors at voxel level. As seen in Figure 4 the use of conductors inside of a part can allow for the placement of traces at any orientation inside of a part. This can allow for the piezoresistive properties of composite conductors to be utilized to construct simple sensors such as strain gauge or load cells. Additionally, by carefully controlling the designed geometry as well as incorporating additional electronic agents, internal printed components could be actualized. Externally printed conductors can be used to selectively electro/electroless-plate the surface of the plastic with additional metals. Also, external traces can be used for surface mounted or socket mounted lumped components.

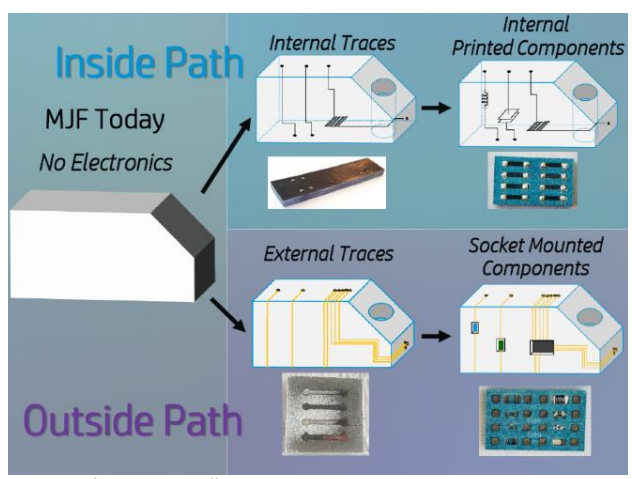


Figure 4. Outlines the different vectors that 3DPE can be utilized with 3D printed electronics with MJF technology.

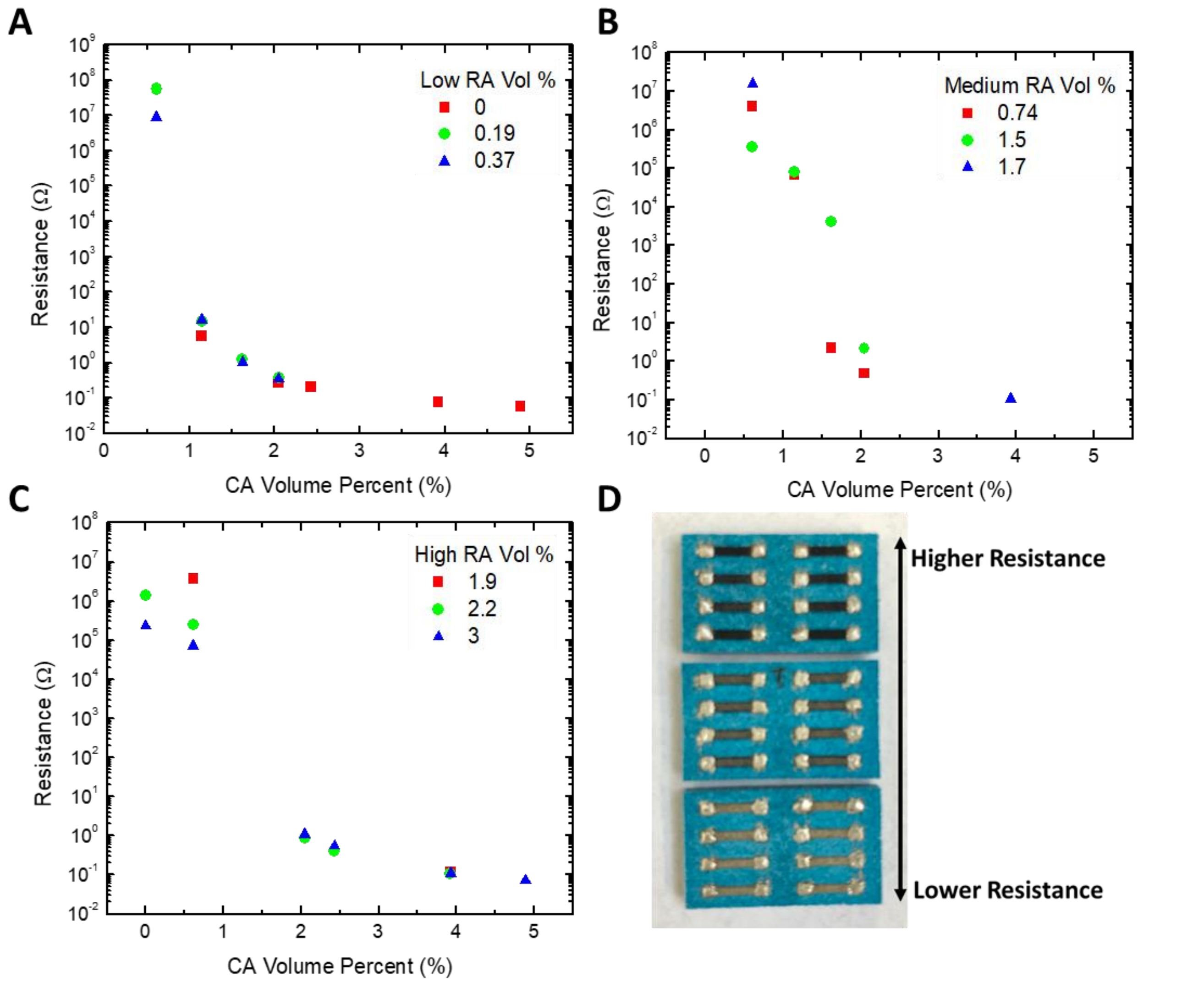


Figure 5. Resistance results from various CA and RA volume percent in the resistors. (a) shows the resistors printed with low loadings of RA, (b) shows moderate amount of RA, and (c) shows a high amount of RA. (d) is a representative image of 3D printed resistors after the contact points were coated in solder paste. The change in color from the black lines on the top part to the more silver lines on the bottom part hint at the overall resistance of the trace.

Results

Much work has gone in to developing our CA to demonstrate the print reliability and conductivity necessary to effectively print conductive traces throughout a part. Any conductive trace printed into a 3D part will fall into two major categories: scan axis traces and build axis traces. Scan axis traces are printed parallel to the carriages scan axis as it moves across the powder bed, where build axis traces are printed normal to the powder bed. In scan axis traces, the conductor is deposited in a single layer and the main conductive pathway is driven based of the sintered particles delivered from one drop to the next. Whereas build axis traces rely on the percolation of the conductor through the voxel into the voxel beneath it. It should be noted that scan axis traces are normally multiple print layers thick and a cohesive conductive path through between layers is important to fully utilize all the conductive material, but it is not the primary mechanism of conductivity. To maintain uniform conductivity of traces throughout the part, it is important to precisely control the process of depositing the CA to allow for good drop to drop coalescence and percolation through the voxel. With our current CA and process control in our testbed printers the scan axis conductive traces and the build axis conductive traces can achieve resistivities of approximately 10^{-6} Ω m. Nominally the difference between the print axis traces and normal axis traces has not been greater than 5x in these studies.

Expanding the process of using a CA to generate a conductive voxel, two different CAs could be blended together to generate an intermediate conductivity. This could allow for resistors to be created within the construction of the part. For this process the secondary CA with a higher resistance will be referred to as the resistive agent (RA). For the experiments, the RA is a high resistance carbon black based ink. By varying the volume percent of the CA and the RA in the final part, over 9 orders of magnitude of resistances can be shown in the 3D printed resistors. Figure 5 separates the various volume percent combinations of the CA and RA in three sections: low, mid, and high loading by volume.

In general, the higher the resistive agents loading is, the more resistive the traces are, and the higher the conductive agents loading is, the more conductive the traces are. Surprisingly, high amounts of conductive agents and any amount of resistive agent leads to almost no change in resistance. The addition of the resistive agent to highly conductive traces or large areas of conductors could be used as a process control agent to raise the temperature of those sections during the print of the part. To achieve a high resistance, varying amounts of resistive agents needs to be used in combination with a low to moderate amount of conductive agent. If not enough of either agent is used, there will be no conductive pathway throughout the trace and an open circuit will be measured. If the loading of the resistive agent is increased, at a certain point the resistance will decrease and approach a value close to that of the bulk RA material. This shows that a resistor can only be reliably printed to a resistance around that of the bulk resistive agent value. To achieve a higher resistance, another material will need to be used. Resistors printed along the z-axis or build axis were also investigated and showed similar results but are still being investigated further.

Overall, 3D printed resistors are one of the first steps in building out the entire capabilities of the 3DPE field with MJF. This process shows the power of being able to digitally apply materials to give functional properties to selected voxels that leads to changes in the macroscopic properties of sections of a part. With this control of resistive functionalization, you can take advantage of the piezo-resistivity to build load cells or strain sensors. This can allow for the seamless integration of mechanical sensing directly into a part. Additionally, the resistors can be constructed to replace lumped components and lessen the number of components that are used in the final electronic assembly. Another application could be to utilize the resistors as heating elements which can be placed in the part free from normal assembly constraints.

Conclusions

In summary, it has been demonstrated that on the MJF platform with the addition of a CA, electronic functionalities can be built into a static physical 3D object. This CA can be applied digitally to any voxel in a part and can, therefore, alter the conductivity of any region of the part. The conductive regions can be used to construct traces that span any geometry throughout the inside and on the surface of the part. This can be utilized to create antenna internally in a part which can allow for the tracking and tracing of AM parts. Additionally, these traces can be utilized to connect sensors throughout the part. This can allow for active monitoring without the need for invasive wiring and additional assembly. Finally, that can be extrapolated into fully electronically active devices where the mechanical and electrical designs are merged into one part that has the entire functionality. With the addition of a RA, the 3DPE process in MJF has been expanded to allow for the digital control of the conductivity of conductors constructed in parts. In the simplest application, this allows for lumped resistor components to be replaced by resistive voxels. Additionally, the piezoresistive properties of flexible resistive traces in the 3D printed parts gives the opportunity to construct strain gauges, load cells, and other piezoresistive based sensors. As research continues with the 3DPE process for MJF, better control over the process will continue to drive the precision of the properties and overall electronic performance as well as introduce new capabilities of the electronic voxels.

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Jarrid Wittkopf is a researcher in HP Lab's 3D Print Lab. There he focuses on investigating opportunities in 3D printed electronics field. Before joining HP, Jarrid graduated with his master's degree in chemical engineering from the University of California, Riverside in 2011 and finished his doctorate in chemical engineering at the University of Delaware in 2017. His PhD focused on oxygen reduction reaction catalysts for hydrogen fuel cells, electrochemistry, and nanomaterial synthesis.