Increasing component functionality via multi-process additive manufacturing

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ABSTRACT

Additively manufactured components, although extensively customizable, are often limited in functionality. Multi-process additive manufacturing (AM) grants the ability to increase the functionality of components via subtractive manufacturing, wire embedding, foil embedding and pick and place. These processes are scalable to include several platforms ranging from desktop to large area printers. The Multi^{3D} System is highlighted, possessing the capability to perform the above mentioned processes, all while transferring a fabricated component with a robotic arm. Work was conducted to fabricate a patent inspired, printed missile seeker. The seeker demonstrated the advantage of multi-process AM via introduction of the pick and place process. Wire embedding was also explored, with the successful interconnect of two layers of embedded wires in different planes. A final demonstration of a printed contour bracket, served to show the reduction of surface roughness on a printed part is 87.5% when subtractive manufacturing is implemented in tandem with AM. Functionality of the components on all the cases was improved. Results included optical components embedded within the printed housing, wires embedded with interconnection, and reduced surface roughness. These results highlight the improved functionality of components through multi-process AM, specifically through work conducted with the Multi^{3D} System.

Keywords: multi-process, additive manufacturing, robotic arm, wire embedding

1. INTRODUCTION

Disrupting traditional manufacturing methods, Additive Manufacturing (AM), commonly referred to as 3D printing, has developed into an industry valued at $5.16 billion[1]. The novelty of AM arises from granting the user greater design freedom and mass customization[2]. While traditional manufacturing, including injection molding and machining, allows for optimized, low-cost mass production, AM benefits from rapid design iteration and the absence of tooling costs. This process, which consists of joining material layer upon layer to create a three-dimensional object, can be classified into seven technology process categories as defined by ASTM F42: binder jetting, directed energy deposition, vat photopolymerization, material jetting, material extrusion, powder bed fusion and sheet lamination[3]. As the seven process categories have matured, advances in AM have exponentially grown. The growth can also be attributed to the numerous patents for AM that are expiring, allowing for new creativity and innovation[4].

Although a plethora of applications for AM exists, the established technologies are still limited. The final product of most printing processes, as intricate and complex as the object may be, has little more than structural functionality. Envisioning an evolution for AM, the ensuing step involves improvement of the functionality of AM components via multi-process additive manufacturing or 3D printing. Multi-process AM in this context refers to amalgamating available AM technologies with processes such as machining, wire embedding and the robotic placement of electronics. The ability to create end use products that contain complete circuits, sensors, optics, and other components autonomously without sacrificing the geometric benefits of AM parts is groundbreaking. Some demonstrations of this already exist in literature such as a 3D printed gaming die that includes a processor, accelerometer, and light-emitting diodes (LEDs)[5], antennas with embedded copper wire or conductive traces[6,7] and a 3-phase DC motor that includes 18 components, including electromagnets and an electronic speed controller[8]. In November 2013, a CubeSat Trailblazer was launched into low earth orbit. Manufactured with stereolithography and Fused Deposition Modeling (FDM) substrates, the CubeSat contained conductive silver ink traces that served to connect the electronic components within the structure[9]. Keating and Oxman[10] repurposed a 6-axis robotic arm that integrates milling, additive manufacturing and a clay sculpting platform to perform “compound fabrication”, a concept similar to multi-process AM.

Research conducted in the W.M. Keck Center for 3D Innovation at the University of Texas at El Paso (UTEP) explores multi-process AM, also referred to as hybrid manufacturing, with methods applied to a range of platforms, from desktop to large area 3D printers. Multi-process AM case studies will be presented in this paper, where component functionality was increased. Though commercial multi-process AM systems exist on the market, such as Voxel8’s printer, that in addition to creating thermoplastic parts, dispenses conductive ink for connecting electronic components[11], UTEP’s own Multi^{3D} System shown in Figure 1 is featured in the sections that follow along with its capabilities.

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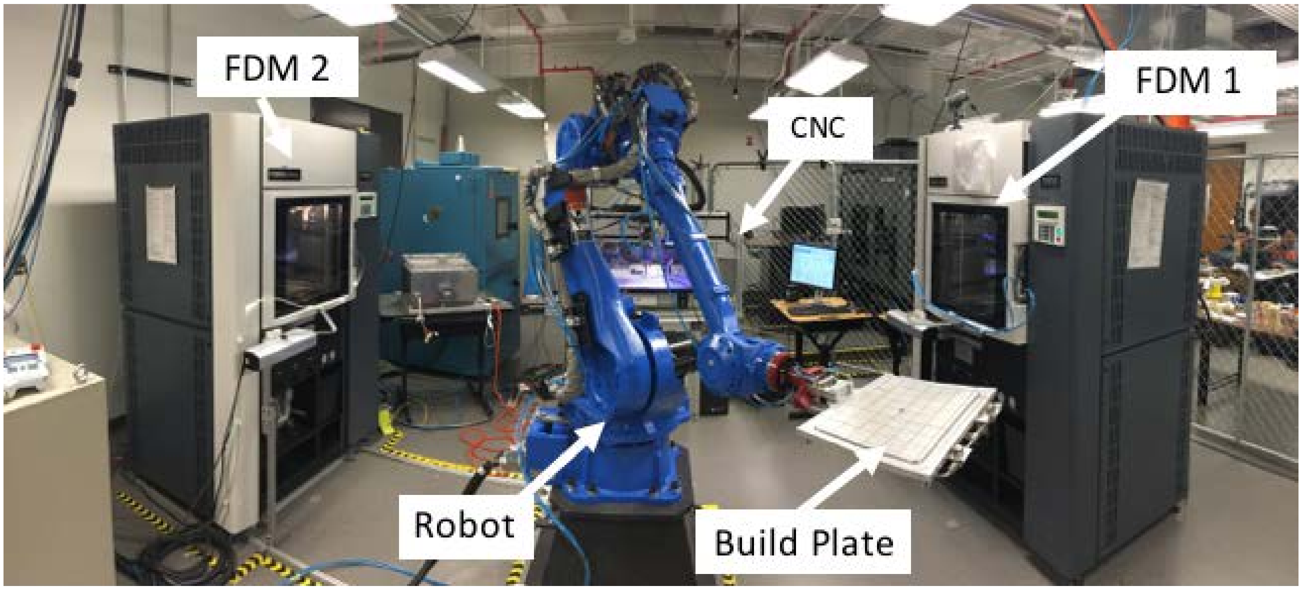

Figure 1. The University of Texas at El Paso's Multi^{3D} System.

2. MULTI-PROCESS ADDITIVE MANUFACTURING

Additive Manufacturing is defined by ASTM as the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining"[3]. A wide variety of materials can be "printed" including polymers, metals, ceramics, organic materials, and more. Applications for AM are often limited to the structural functionality of the parts printed. Multi-process AM allows for improved functionality via subtractive manufacturing, wire embedding, foil embedding, and pick and place; capabilities found on the Multi^{3D} System. The Multi^{3D} System is composed of two Stratasys Fortus 400mc industrial 3D printers, a Techno CNC router, and a Yaskawa MH50 robot. Its processes for increasing component functionality are detailed in this section.

Combining additive manufacturing with subtractive manufacturing may seem counterintuitive. However, many benefits arise when these two methods are used in tandem. Machining, and more notably micromachining, provide a 3D printed part with the ability to have a significantly improved surface finish and more intricate features. Stratasys Ltd. currently defines the finest resolution of their FDM printers as 0.127 mm layer height[12] whereas micromachining technologies have recorded a minimum cut thickness of 1 nm[13]. In multi-process AM systems, subtractive manufacturing is often performed by CNC machining[14]. The Multi^{3D} System possesses a Techno CNC router that has been modified to add not only subtractive manufacturing capabilities, but also embedding, and component pick and place capabilities. Some examples of machining and foil embedding are seen in Figure 2.

When incorporating electrical components into additively manufactured parts, embedding wire to complete circuits has been found to be a desirable solution. Some multi-process AM systems use conductive inks to accomplish this[15]; however, the conductivity of a solid wire is significantly greater, and in many cases, preferred. UTEP has developed the Multi^{3D} System to adapt a wire embedding tool and a foil embedding tool to the CNC router. The embedding toolpaths were programmatically generated to synchronize the deposition of wire or foil, with the motion of the CNC. For wire embedding, the metal filament is heated and deposited onto the printed surface. Due to the heat energy applied to the printed substrate, the wire successfully embeds and lies flush on the substrate's surface. Once complete, the build platform is transferred by the robot to the subsequent manufacturing station, often to have material extruded upon the surface by one of the 3D printers. The foil embedding tool, also adapted to the CNC, was used for application of copper foils. The foils are used to create conductive surfaces for applications such as antennas. By combining foil embedding with the CNC, the ability to mill complex foil patterns onto printed parts is added to the capabilities of the system. The embedding of foils and wires has obvious benefits in terms of conductivity for electronic components. Components are deposited by the final process on the Multi^{3D} System, using pick and place. This capability arises from an assembly that allows the CNC to pick and place components by using vacuum. These components, ranging from circuit card assemblies to optical elements, are installed in predetermined cavities formed on the printed substrate. The Multi^{3D} System is not the only platform where functionality is introduced to printed components, UTEP works with different scale platforms (from desktop to large area printing systems) where these capacities are implemented.

Figure 2. left) 3D printed part with machined paths, right) a part showing embedded foil and micromachined paths.

3. IMPLEMENTATION PLATFORMS

Multi-process AM machines can be made to suit a variety of applications by existing on a selection of platforms. Efforts at The University of Texas at El Paso aim to cover a wide range of these platforms, spanning from small scale to large scale printers. Functionality improvement has been implemented to the smallest of printers, the desktop 3D printer, through the addition of wire embedding. The wire embedding process has since been scaled up to larger area printers, along with the incorporation of other processes.

Preceding the current Multi^{3D} System, an initial version utilized tool changing to create multi-purpose parts through the use of a 3-axis gantry to swap between tools, such as drills and a laser[16]. The purpose was to have a stand-alone gantry system that would extrude filament, mill parts and laser engrave. The current Multi^{3D} System, the robotic handling platform, which has been described in detail in the previous section, uses a material handling robot to transfer the part being fabricated to different manufacturing stations. This allows for the implementation of the foil embedder and pick and place processes. Currently, a low(er)-cost version of the Multi^{3D} System is being fabricated, where the robot arm is eliminated. It is referred to as the tool change platform, as it will have pellet extrusion, machining, wire embedding as exchangeable tools. This system presents the ability to prototype electronics and other multi-functional parts that would be utilized in homes and small businesses.

The final platform in this series of multi-process AM machines, is the Big Area Additive Manufacturing (BAAM) printer. BAAM printing allows for the production of large scale components with structural integrity. As a stand-alone feature, structural integrity suffices for many applications. However, the introduction of wire embedding to this platform would increase the functionality of the components, to include electrical features within the print. The BAAM system with wire embedding functionality is currently under development and future publications are expected to describe this functionality. In this paper, several cases of improved functionality with the Multi^{3D} System are presented in the following.

4. CASE STUDY 1: MISSILE SEEKER

Highlighting the benefits of multi-process AM, and testing the capabilities of the Multi^{3D} system, a missile seeker was 3D printed. The seeker was fabricated using the two modified Fortus 400mc printers, while the Techno LC 3024 CNC router was used to perform component placement. The CNC was equipped with an ATI automatic tool changer, VMECA vacuum generator, as well as VMECA level compensators and suction cups. The end-effector assembly, comprised of the tool plate, level compensators and suction cups, is shown in Figure 3. Modified versions of the end-effectors were utilized for specific component placement, i.e. some were custom designed for handling optics. The missile seeker incorporated six components, placed within the thermoplastic body: a transmissive dome, a spreader, an optical lens, a detector, an analog CCA and a digital CCA as shown in Figure 4. The seeker was printed using black polycarbonate with a layer thickness of 0.254 mm (0.010”) over a period of approximately 4.5 hours.

To fabricate the seeker, the full capabilities of the Multi$_{3D}$ System were utilized. Due to modifications made on what is referred to as “FDM1”, support material was not able to be deposited by that printer. The process began by printing the support material base on what is referred to as “FDM2”. The robotic arm then transferred the build platform to “FDM 1” where the model material base of the seeker was printed. A pause was programmatically inserted at predetermined sections of the build, where a component was to be placed. Once paused, the first component, the digital CCA, was picked up with its complementary end-effector by the CNC. The seeker was then transferred to the modified CNC where the digital CCA was ready to place the component. The seeker was then transferred back into “FDM 1” and the process was repeated until all the components were placed within their respective sections of the seeker housing. Figure 4 shows the completed missile seeker.

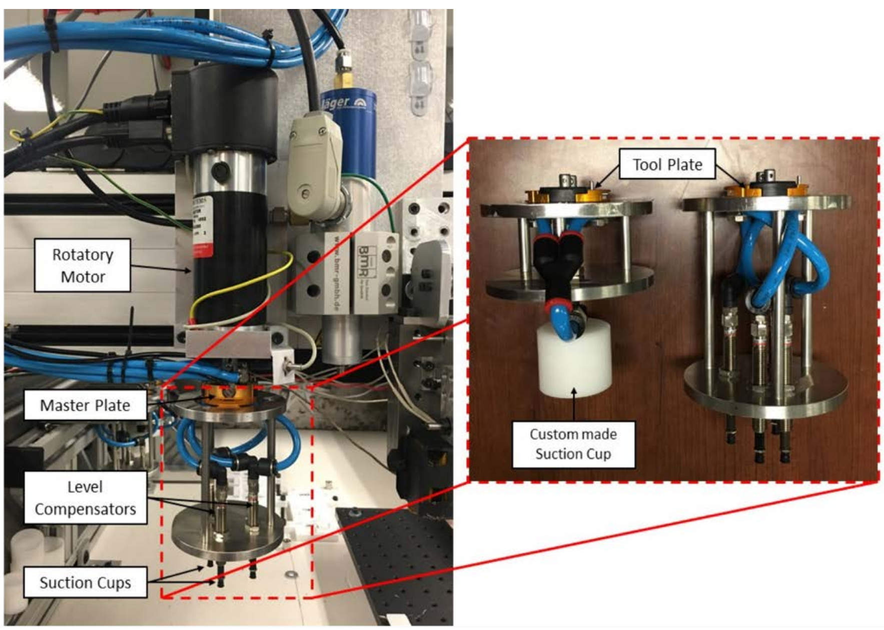

Figure 3. End effector assembly.

Benefits of using this multi-process approach include a reduction in excess cycle time when compared to current supply chain models and an overall shorter lead time. As the Multi^{3D} System is fully automated, multiple missile seeker variants could be built with the same workcell with no touch labor. This approach also boasts an end-to-end digital thread where all machines produce log files with process data with the ability to provide nonconformance tracking. There are also some technical issues to consider when fabricating a missile seeker in this fashion. Generally speaking, FDM-produced parts will have a lower strength than traditionally manufactured parts and the dissipation of heat generated by the electronics could alter the thermoplastics. Polycarbonate, the material used in this demonstration, has a tensile strength in the XZ orientation of ~40 MPa and a heat deflection temperature of ~138°C. Through this case study, the functionality of the component clearly improved over a single material 3D print. Placement of electronics via the pick and place process represents only one of the capabilities of the Multi^{3D} System. Wire embedding will be discussed in the following case study, where conductive paths also add greater functionality to printed components.

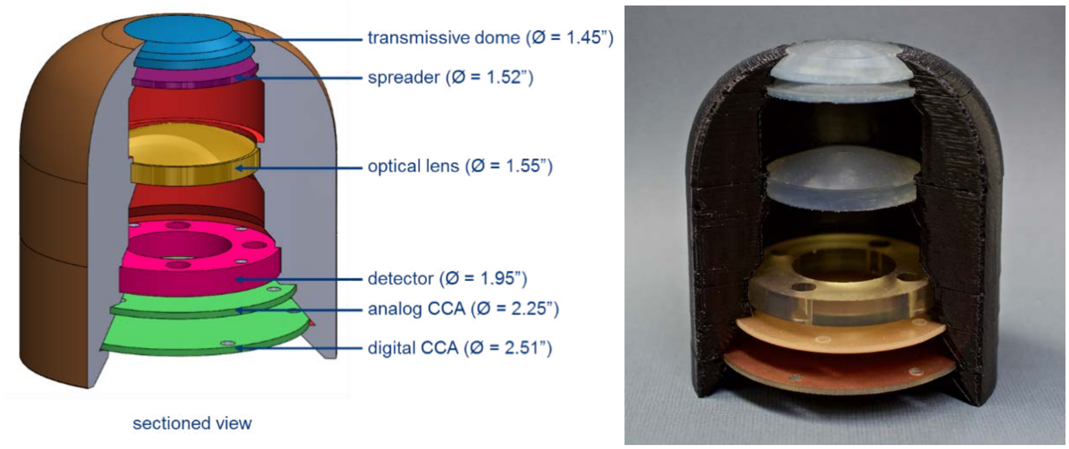

Figure 4. Left) Drawing of missile seeker, and right) completed part.

5. CASE STUDY 2: AFRL SATELLITE

The case study described in this section demonstrates improved functionality of components with multi-process AM via wire embedding. For implementation on the robotic handling platform, the Multi^{3D} System, a wire-embedding tool was constructed on a Haas Mini Mill 2 where Computer Aided-Design (CAD) changes to the structure of the geometry were made. Through experimentation, wire embedding paths were optimized, and a G-code processing software was developed and scaled for the custom Multi^{3D}. Initially made for processing G-code for wire embedding on a LulzBot desktop system, the software was later tailored to function on the Multi^{3D} System. What is demonstrated in this case study is the capability of fully embedding two layers of copper wire paths in different planes with successful vertical continuity between the planes.

Using SolidWorks 2015-2016, the CAD file for this case study was made and wire embedding paths were created. The file is where the connection between electronic components and interconnections between layers is specified. Once the CAD file is completed, the software for processing a polymer G-code and a circuit G-code create a reference shape. The bottom left corner of this reference is used as the origin for both axes. The reference part can be seen in Figure 5. Within Insight, a slicing software by Stratasys, pauses are inserted at three layers of polymer extrusions. This demonstration contains twelve layers of polymer extrusion, with pauses placed at every four layers, for fully embedded wires. At every pause, the custom build platform was removed from the Fortus 400mc printer with the Yaskawa robot arm and placed into the CNC router where the wire embedding tool was mounted. With the G-code for the wire embedding paths processed, the files were then loaded into the CNC. Zeroing the Z axis to the surface of the substrate was crucial. Experimentation led to the discovery of the most effective Z axis height at which wire paths are fully embedded so that they cannot be removed with the stroke of the extrusion tips when printing resumes. Before wire embedding on the first layer, copper foil was be adhered to the circular cavities printed, shown in Figure 5 a). The foil was cut to size and adhered to the bottom of the cavity. The copper foil application aids with maintaining the solder flush to the surface. Soldering flux was also applied before the solder was applied. Once the wire embedding paths for the first layer were completed, Figure 5 b), solder flux was applied, and the wires soldered to ensure a continuous connection where wires met. The custom build platform was then placed back into the Fortus 400mc for continued printing until the second pause. A similar process is repeated for the second layer of wire embedding, resulting in what is shown in Figure 5 c). The cavities in the figure allowed for the wires to interconnect vertically. Once completed, a multimeter was used to test for continuity between the vertically separate layers of wire embedded paths. Excess wire was removed at that point, and the substrate was returned to the printer so that the final layers may be deposited, fully embedding both layers of wire, as shown Figure 5 d). The final product successfully allowed for two layers of embedded copper wire to interconnect. The demonstration would progress into soldering electronic components and having a fully functional temperature sensor embedded within a structural element.

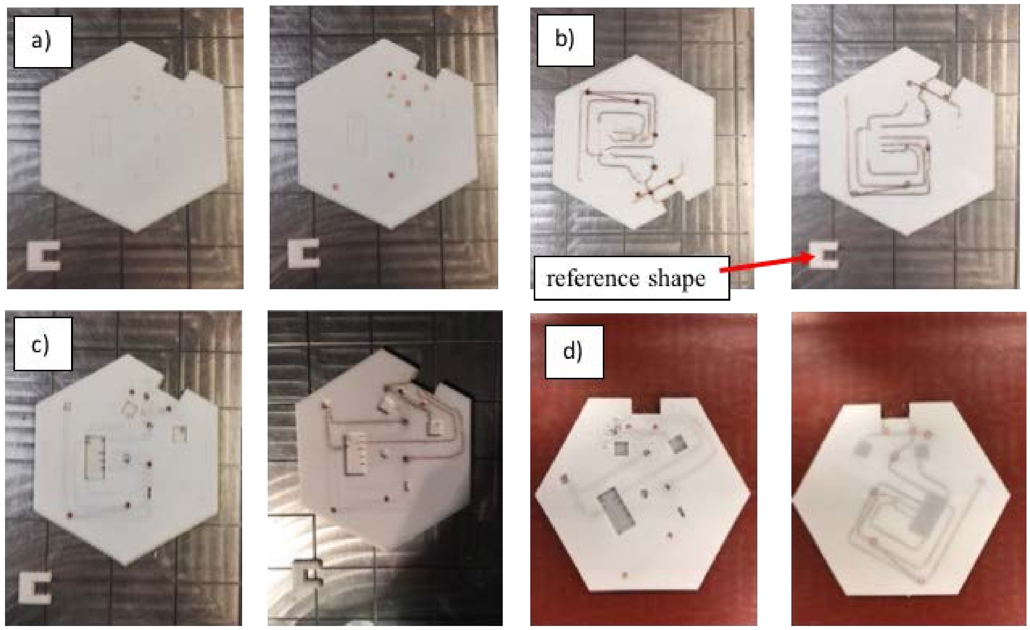

Figure 5. Wire embedding for two layer interconnection

6. CASE STUDY 3: GENERAL BRACKET WITH CONTOUR

Benefitting from multi-process AM, the juxtaposition of additive and subtractive manufacturing allows for fabrication of end-use components with decreased surface roughness (Ra). Due to the layered nature of additive manufacturing, contoured surfaces tend to be fabricated with a rough surface finish. Layered "steps" clearly visible to the eye are a result of the limited resolution of 3D printers, shown in Figure 6. Decreasing surface roughness allows for aesthetically improved final products. One advantage of utilizing subtractive manufacturing in multi-process AM is the ability to machine cavities with precise dimensions required for inserting electrical components. Verification of improved functionality was tested on a bracket that was printed with a contoured, three-dimensional surface and partially machined.

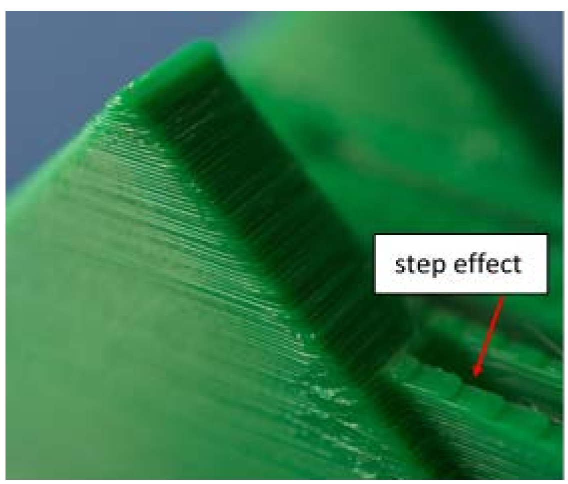

Figure 6. Example of visible layer steps.

The bracket for this case study was created using the Multi^{3D} system. The part was printed on a Fortus 400mc and transferred to the CNC router, where it was machined with a 1.016 mm (0.040") end-mill. The footprint of the bracket was 101.6 x 127 mm (4" x 5") with a maximum height of 19.05 mm (0.75"). For comparison, two identical brackets were created; one was left as-fabricated, and the other was partially machined. The partially machined bracket can be seen in Figure 7 where the machined and as-printed areas are labeled. It is visually evident from the image, that the machined surface has removed the layered "step" effect. To quantify the improvement, both fabricated brackets were measured for surface roughness using a Mitutoyo SJ-201P Surftest Portable Surface Roughness Tester. Each bracket was measured five times, with resulting measurements averaged to characterize the roughness. Table 1 illustrates the values of surface roughness for the machined and as-printed bracket. The decrease in surface roughness introduced via subtractive manufacturing was ~87.2% for this experiment.

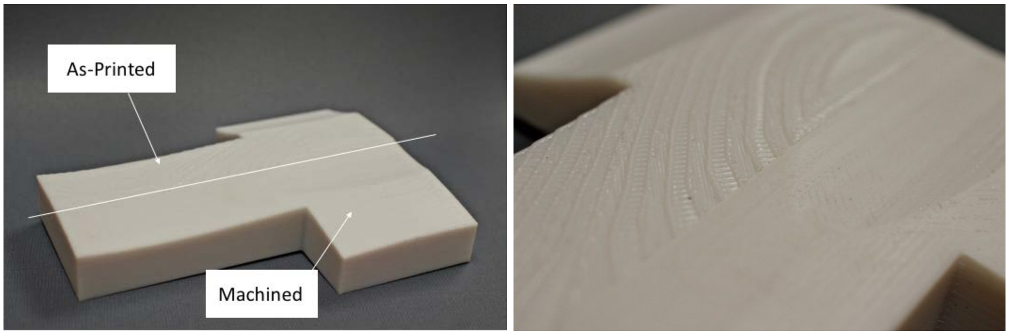

Figure 7. Bracket test print utilizing surface machining.

A profile of the height measurements of each bracket was created, spanning the length from base to tip. The laser attachment of the OGP SmartScope Flash 250 was utilized to generate values for the profiles. The results of the as-fabricated bracket and the machined bracket were compared to the dimensions specified in the CAD model of the bracket. Figure 8 shows the profiles, where the leftmost points represent the base of the bracket, and the rightmost points are found at the tip. The "steps" formed on the as-fabricated part are emphasized in the figure, along with the plateaued region that was formed at the minimum point of the parabolic curve. Both these defects were attributed to the limited layer resolution of additive manufacturing processes. The machined contoured bracket most closely resembles the geometry desired from the CAD model. This serves to highlight multi-process AM as an effective means of modifying components for increased functionality.

Table 1. Surface Roughness, Ra (μm), of brackets

	Machined	**As-Printed**
Average	2.50 (μm)	19.61 (μm)
Std Dev	0.57 (μm)	3.98 (μm)

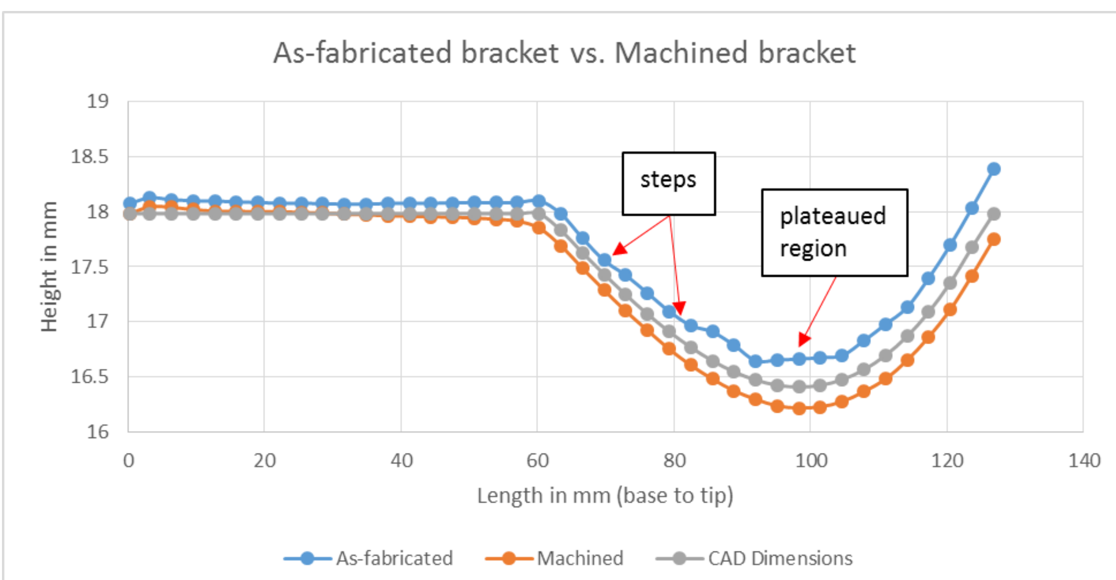

Figure 8. Bracket test print utilizing surface machining.

7. CONCLUSION

Multi-process AM systems may lead to significant improvements in the functionality of 3D printed parts. Traditional printed parts can offer complex geometries but still require human intervention to add electrical components and perform other finishing techniques. The research conducted at the W.M. Keck Center for 3D Innovation at the University of Texas at El Paso (UTEP) has led to the development of the Multi^{3D} System, a multi-process (hybrid) additive manufacturing manufacturing platform. The processes amalgamated in the system include additive manufacturing (3D printing), robotic pick and place, wire embedding, foil embedding and micromachining. As shown in the three case studies presented in this paper, the results of these combined processes, led to the automated fabrication of components with significantly more functionality than would be achieved with simply 3D printing. The automated printing of a seeker with embedded optical and electronic components demonstrated 3D printing with automated pick and place. Automated wire embedding in 3D printed substrates was demonstrated for a small satellite structure, demonstrating a printed piece with conductive wires spanning two different vertical layers. The final case demonstrated the improvement of surface finish and dimensional accuracy on a 3D printed piece. These cases are the first steps to creating automated multi-process 3D printers that produce fully functional, customized, electrical and a variety of other products. As these technologies expand across a variety of platforms (from inexpensive desktop systems to industrial large-scale systems), these machines and technologies will revolutionize not only large scale manufacturing but at-home prototyping and inventing.

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