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Augmenting Computer-Aided Design Software With Multi-Functional Capabilities to Automate Multi-Process Additive Manufacturing

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ABSTRACT The ability to access individual layers of a part as they are being printed has allowed additive manufacturing (AM) researchers to experiment with the *in situ* placement of components, thereby creating multi-process parts with additional functionality, such as customized printed electronics. As AM has evolved to become an established method for creating end-use parts, this interest in multi-process printing has increased. Although progress has been made in developing multi-process hardware, which can combine AM with other technologies, holistic design software, capable of readily integrating these processes, is developing at a slower rate. In this paper, an integrated software solution capable of supporting multi-process 3D printing from design through manufacture is described, featuring the integration of electronic components and circuits interconnected by copper wires. This solution features automated generation of the cavities that accommodate electronic components as well as toolpath generation for a multi-process 3D printer capable of automated wire embedding. As a case study of the developed technology, a hexagonal 3D printed body, which included a microcontroller, four LEDs, a USB connector, two resistors, and a Zener diode, all interconnected by embedded copper wires, was fabricated within a short cycle time: 5.75 h from design to fabricated part. Short cycle times allow multiple design iterations to be realized and printed within the same day.

INDEX TERMS 3D printing, additive manufacturing, automation, CADCAM, component placement, printed circuits, three-dimensional integrated circuits, wire embedding.

I. INTRODUCTION

Additive Manufacturing (AM) technology is becoming increasingly ubiquitous, with sales of AM units increasing, on average, by 18.5% per year from 2012 – 2015 [1]. As the popularity of AM increases, innovators have sought to combine AM with other technologies to produce a hybrid AM process that can create multi-functional parts, such as 3D printed parts exhibiting structural functionality that contain additional utility, provided by embedded electronics. In literature, there are several additively manufactured device demonstrations that contain electrically conductive materials and/or electronic components including capacitive sensors/buttons [2], [3], antennas [4], [5], gaming die [6], magnetic flux sensors [7], [8], CubeSat modules [9], and a 3-phase DC motor [10]. Multi-functional parts often require more than one process to manufacture: this can include embedding of electronics or components, dispensing of inks or embedding copper wires, or machining to produce the feature resolution required by the final application [9]. Copper wires may be chosen over conductive inks because wires have higher current-carrying capacity and lower resistivity ($1.7 \times 10 - 8\ \Omega$ m for copper wire vs 11.8 10-8 Ω m for Dupont Ink CB028 silver-based ink). In addition, incomplete sintering of inks can result in self-heating that can lead to reduced reliability [9]. While the processes to create additively-manufactured parts are well-established, the integration and automation of hybrid AM technologies requires the development of new, non-existing software design tools, especially when wires are used for conductive traces.

The lack of integrated design tools for hybrid AM is limiting the wider adoption of AM systems that produce multi-material and multi-functional parts [6], [11], such as those with integrated circuitry that may require additional technologies beyond additive manufacturing. While complex multi-functional designs, such as 3D printed electrical motors, are attainable via a manual step-wise process [10], such an approach is inherently labor-intensive and prone to human error. The machine instructions for these processes can be created using existing sophisticated design tools, such as slicers for 3D printing and PCB design software for electronic design. However, one potential outcome of using these tools in isolation is erroneous, manually-generated G-code that may result in the collision of tools with either the work piece or surrounding structural components. Despite the risk of erroneous G-code, there is still benefit from using these well-engineered design tools, if they can be successfully integrated, preferably in an automated fashion.

Similar challenges have been resolved by enabling interoperability between software designed with specialized functionality. In 2002, NASA started to implement a standard for information exchange between software packages (intended for computer-aided design, manufacturing, and engineering) during the design phase of a product [12]. This allowed users to utilize multiple design tools without having to worry about translation of information between each software package. Because of the interoperability, any software tool in the design process could extract and use the information required for specific tasks without having to rework or repeat the design process. Work on interoperability between CAD tools continues [13], [14]. Likewise, micro-electromechanical computer-aided design software links to databases and other numerical programs allowing users to analyze both the mechanical and electrical aspects of the parts [15], [16]. The interoperability approach has been widely adopted in commercial design software and should be used as a model for creating integrated design software for hybrid AM.

In response to the need for process integration, a small number of attempts have been made to improve the design environment and automatic generation of toolpaths for hybrid AM. An automated software solution for multi-process AM can enable rapid iteration response in the CAD environment, when compared to manually combining stand-alone software packages. Recently, other companies and researchers have become interested in developing software for creating 3D printed electronics. The reported efforts are mostly based on the material extrusion AM technology paired with conductive inks for interconnects between components. Voxel8 (Somerville, MA), a startup from Harvard, has developed a desktop AM machine that dispenses plastic and creates conductive interconnects using a conductive ink [17]. Voxel8 partnered with Autodesk to create Project Wire, a program in which the initial CAD model is imported and interconnects can be subsequently introduced as well as electrical components [18]. Similarly, Wasserfall [19] and Ahlers [20] developed software for 3D printed electronics produced with material extrusion AM and conductive inks. The software allows users to introduce electronic components and interconnects during the slicing procedure. One disadvantage of the approach used by Voxel8 and Wasserfall *et al.* is that electrical features are being implemented during the slicing phase, which limits the design accuracy because placement of components and traces is manual or freehand (i.e., not driven by exact dimensions). In addition, the multi-functional part cannot be readily exported back into the manufacturing CAD (MCAD) environment, which limits the potential to utilize the MCAD environment's simulation tools.

Multi-process 3D printing offers great potential for expanding the functionality of traditional 3D printed parts. However, there remains a lack of design software to automate the integration of disparate processes into a single CAD environment. The research described in this manuscript demonstrated a multi-process design solution, capable of automatically generating toolpaths to support next-generation hybrid AM, wherein the user can specify part dimensions, electronic component placement, and wire routing from within a single CAD environment, enhancing the efficiency with which engineers can design multi-functional parts and eliminating errors arising from improper manual integration of the requisite processes. The next section details how, through the use of SolidWorks CAD software and Visual Basic macros as well as post processing, a single CAD environment can create designs that support material deposition, automated cavity creation for electronic components, and conductor tracing, resulting in fully-defined and integrated hybrid AM tasks.

II. METHODOLOGY

Before the specifics of a software solution could be determined, the requirements and constraints that the solution should fulfill were defined. The requirements for the software solution were that it

- generate machine-parsable code to control material extrusion AM and wire embedding tools,
- fully define all automated steps of a multi-process print job, and
- be expandable to control additional processes, as well as adaptable to variations in code syntax on different machines.

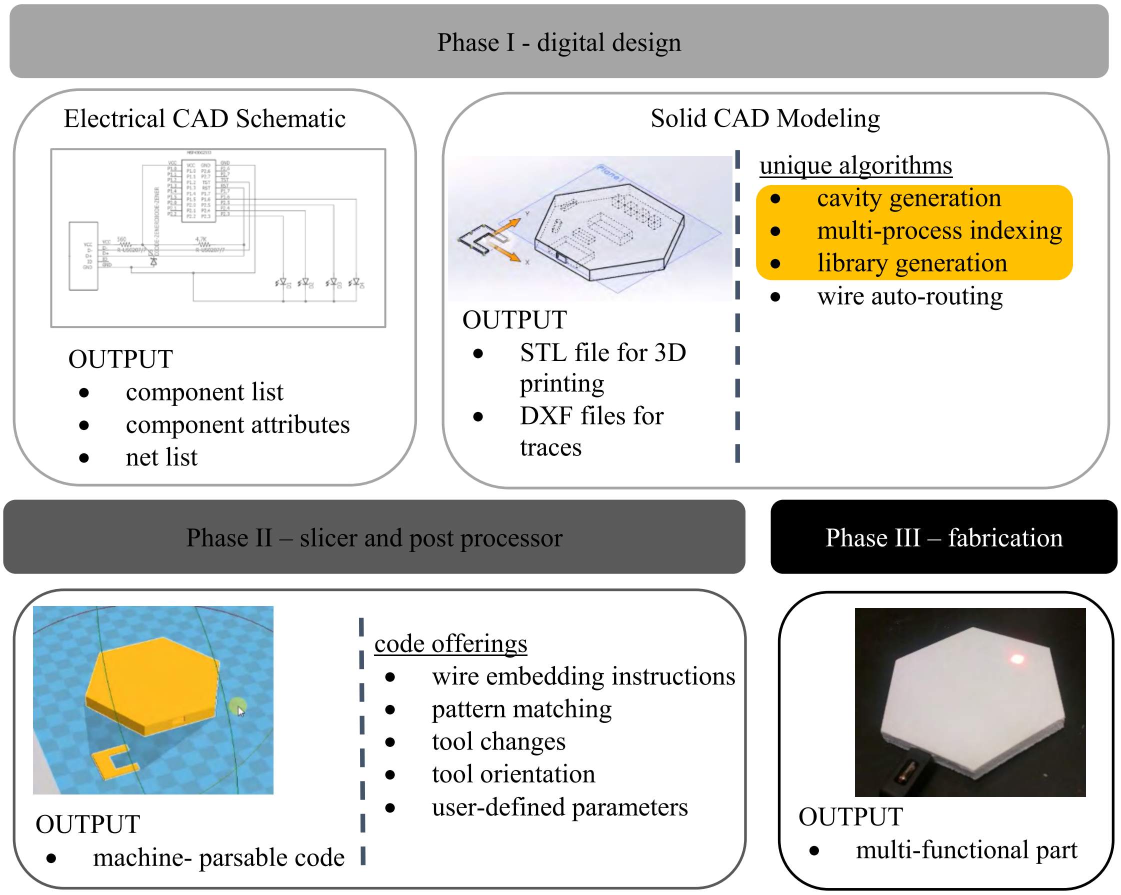


FIGURE 1. **Process chain for designing and 3D printing multi-functional devices. Note that Solid CAD modeling includes unique algorithms that have completed development (highlighted in yellow) and future capabilities yet to be completed.**

The constraints of the software solution denoted that

- the primary design environment should be a single interface, wherein both physical and electronic components could be specified with fully-defined dimensions, locations, and electrical interconnects,
- the software should be able to utilize sophisticated electronic computer-aided design (ECAD) software to specify electrical interconnections and, once defined, import that data into a mechanical CAD environment to use as the primary design space, and
- the output machine code needs to meet the specific syntax requirements of the current multi-process material extrusion AM and wire embedding printer, a modified Lulzbot TAZ 5.

To satisfy the requirements in the context of the constraints, three phases (Fig. 1) were identified. During digital design (Phase I), the electrical schematic file was created followed by the solid model CAD. While in the solid CAD modeling environment, data from the electrical schematic was imported and used to automatically create cavities that would house components. The output of Phase I was a project folder that contained an STL file for 3D printing and DXF files that describe the traces of each circuit. Data from the library was then processed in Phase II by a slicer and a custom post processor to produce machine instructions, which were used during Phase III to fabricate a multi-functional device. Further description of each phase is provided in the following sections.

A. PHASE I – DIGITAL DESIGN

With the use of the SolidWorks (Dassault Systémes, Waltham, MA) application program interface (API), a macro was created capable of importing ECAD schematic data from Autodesk's software EAGLE (San Rafael, CA), thereby fulfilling the constraint that the software be able to integrate with ECAD software. The macro included a graphical user interface (GUI), as depicted in Fig. 2, which allowed for importing electronic components and automatically generating cavities that conformed to the components' dimensions. The GUI also enabled the creation of a reference shape, which was used for registration. The reference shape was needed because the circuit DXF file and the model STL file data were exported separately from SolidWorks. Therefore, both the model and the circuit lost their origin and were no longer spatially related. In addition, when the user imported the shape into the slicer, the user was allowed to move and rotate the part, further modifying the origin of each model and circuit. The reference shape, since it was contained in

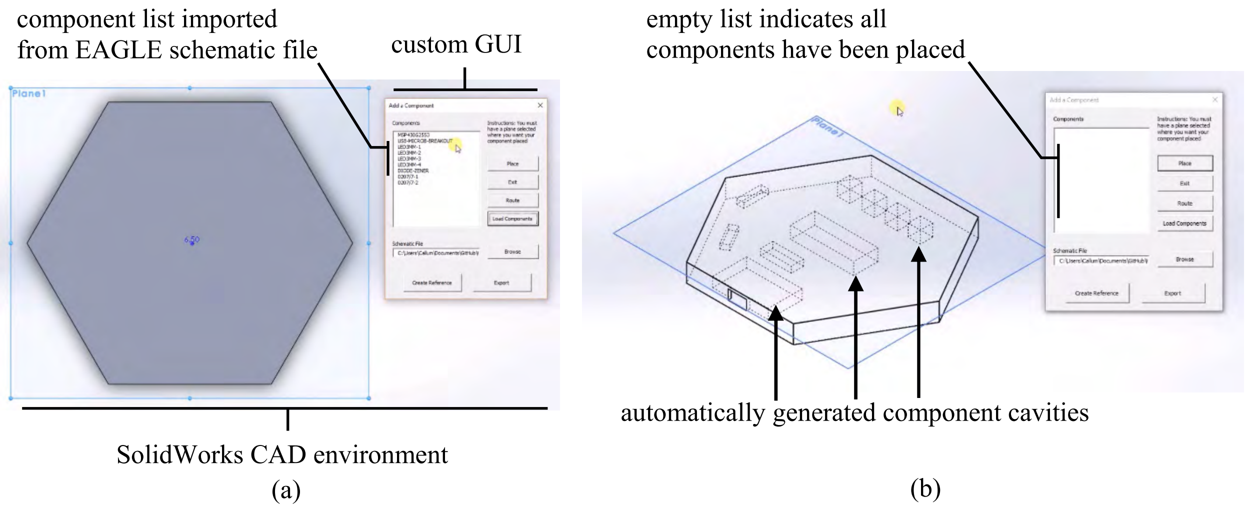


FIGURE 2. SolidWorks CAD environment with invoked macro that imports data from EAGLE schematic and enables automatically generated electronic component cavities.

both the model and circuit, aided in spatially relating the separate files. The output of the SolidWorks macro was an STL file for material extrusion AM and a DXF file for wire embedding.

After the reference shape was placed, the schematic file that represented the circuit to be embedded into the part was selected. The ''Load Components'' button parsed the schematic to populate the ''Components'' list. Since Visual Basic for Applications (VBA) for SolidWorks did not support XML parsing, the parsing was performed via an external Python script. The information extracted included the component names and their dimensions, which were exported as a simple text file that was easily parsed with VBA in the SolidWorks API. Once the list was populated, a plane was selected and parts were chosen to import from the components list. Clicking the ''Place'' button created a perimeter and performed an extruded-cut operation with the correct height to create a component cavity within the SolidWorks part. The sketch representing the part was then allowed to be translated or rotated to its final position. The component list contained an auto-refresh feature that removed parts that had already been placed from the list. If an electrical component was deleted from the 3D model, clicking on load components again repopulated the list with the deleted components. Once the components were positioned, the electrical routing was created. This routing was defined in SolidWorks as a ''3D sketch'' which fully defined a contour in X, Y, and Z. The height (Z) information was programmatically extracted by renaming the 3D sketch to a standardized name ''circuit#'' where ''#'' was replaced with a corresponding number that defined each distinct ''circuit'' or conductive routing pattern. This name standardization allowed a VBA macro to identify and export the Z height for each routing pattern, which it saved in a simple text file, as well as a DXF file, which defined the contours of the routing pattern. These files were placed inside a project folder, which was created as a subdirectory within the directory where the SolidWorks part was saved.

Other modifications required to enable the creation of multi-functional 3D printed parts were the modifications of EAGLE libraries. The existing libraries lacked the information to define the 3D cavity required to accommodate each component. In response, a modification for components used in 3D printed parts was created. This modification included adding an extra layer labeled ''Perimeter'' and an attribute ''H'' that defined a footprint and a height, respectively. The parser described earlier extracted this dimensional information, allowing the macro to implement the dimensions in the SolidWorks model, creating accurate cavities based on the modified EAGLE library.

TABLE 1. Functions executed by the custom add-in program integrated into the Cura slicer.

Function	Description
tool orientation	calculates the rotation angle based on X- and Y-coordinates to appropriately orient the C-axis of the wire embedding tool
pattern matching	Procrustes analysis to determine the location and orientation of the material extrusion G-code and the wire embedding G-code
wire embedding instructions	writes commands (standard G-code and custom M-code) specific to the wire embedding sub-processes (e.g., stake wire, supply coolant, cut wire)
post processor	ensured the final G-code file contained the format and syntax required by the TAZ 5

B. PHASE II – SLICER AND POST PROCESSOR

A custom plugin for Cura, a slicing program originally developed by Ultimaker (Geldermalsen, Netherlands), was written using the Python programming language. The plugin's functions are described in Table 1. Cura was also used in its conventional manner as an STL slicer to generate G-code for the

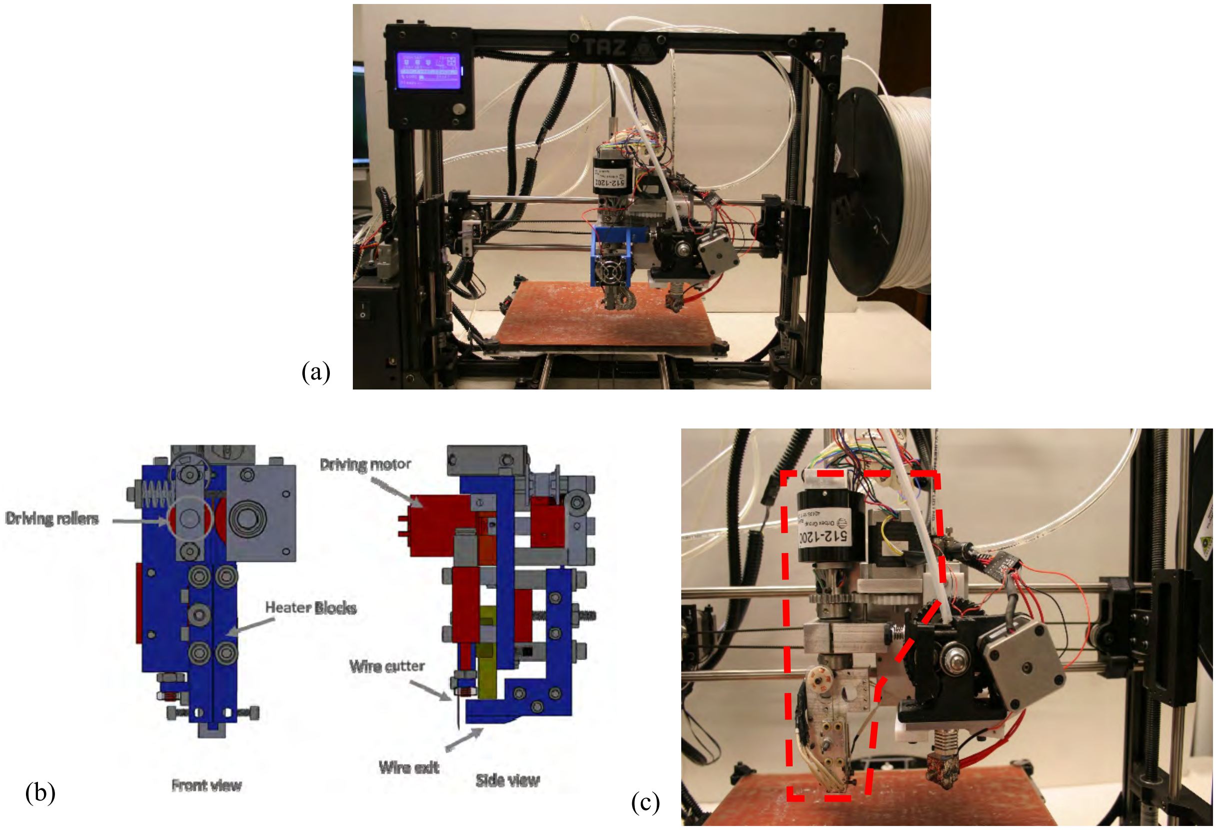


FIGURE 3. Desktop 3D printing and wire embedding machine. a) modified Lulzbot TAZ 5 printer with wire embedding tool, b) CAD of wire embedding tool, c) wire embedding tool (highlighted by red dashed line) and print engine side-by-side.

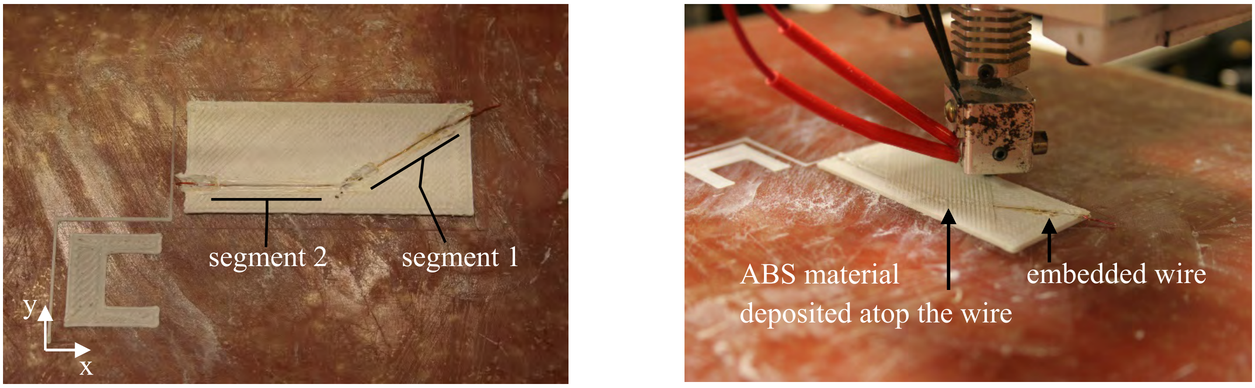


FIGURE 4. Two-segment trace created by embedding a 26 AWG (Ø = 0.405 mm) copper wire into ABS plastic dispensed by a modified Lulzbot TAZ 5 3D printer.

material extrusion AM process. When the material extrusion AM and wire pattern G-code were imported into the custom Cura plugin, the reference shape's motifs were identified and overlaid using a Procrustes analysis, allowing the wire pattern G-code to be rotated and translated to the correct coordinates, which matched those of the material extrusion process. The combined output of Cura and the custom plugin was a G-code file containing machine instructions for material extrusion AM and wire embedding, as present on a modified Lulzbot TAZ 5.

C. PHASE III – FABRICATION

To execute the wire embedding, a Lulzbot TAZ 5 (Aleph Objects, Inc., Loveland, CO) printer was modified (see Fig. 3) so that the custom, patent-pending [21] wire embedding technology was installed beside the original material extrusion tool. Additional hardware modifications to the printer included the relocation of motion limit switches and connecting the embedding tool wiring to the printer's RAMBo motherboard. A homing sequence was added to the Marlin firmware, that properly oriented the C-axis of the wire

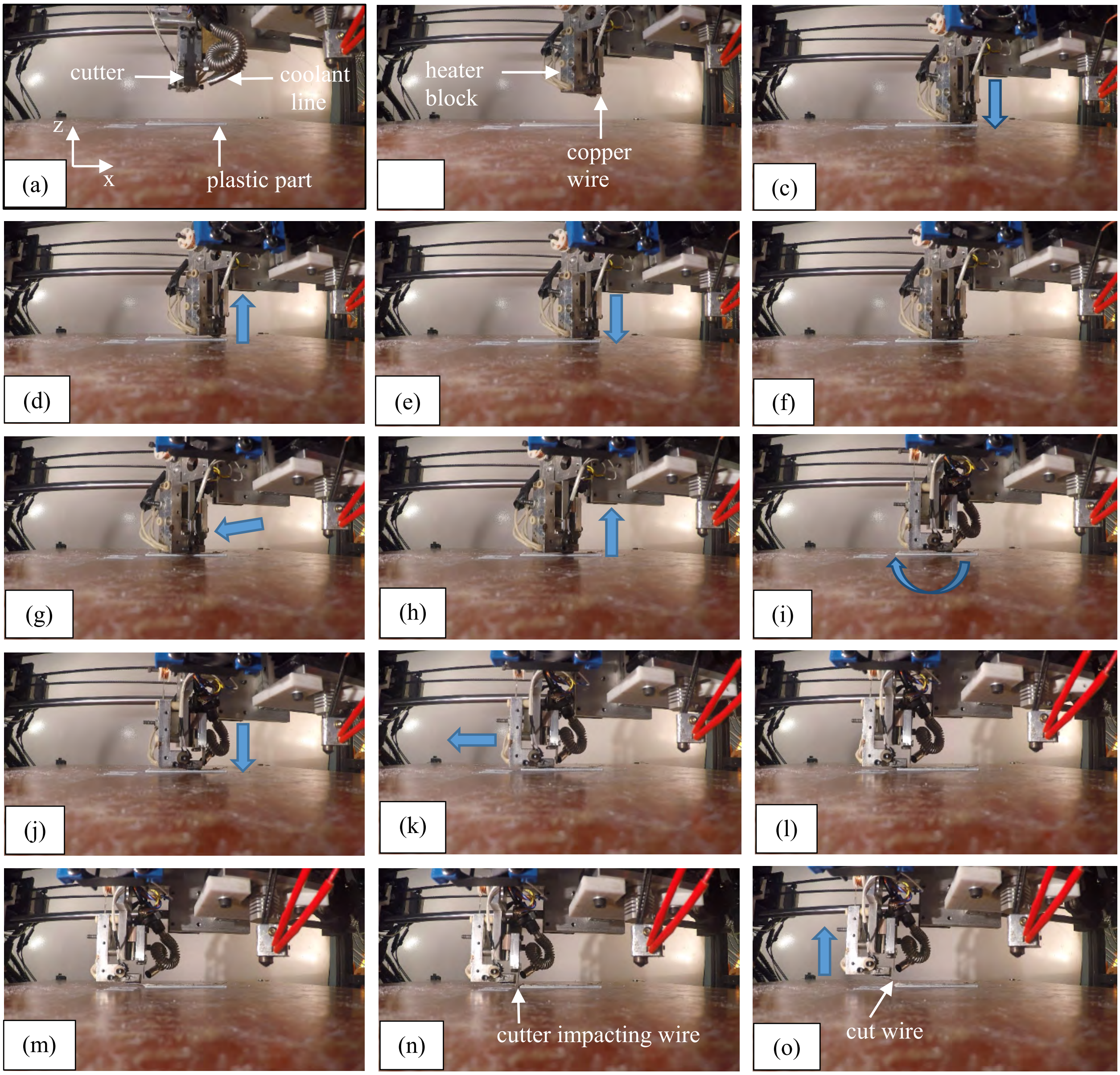
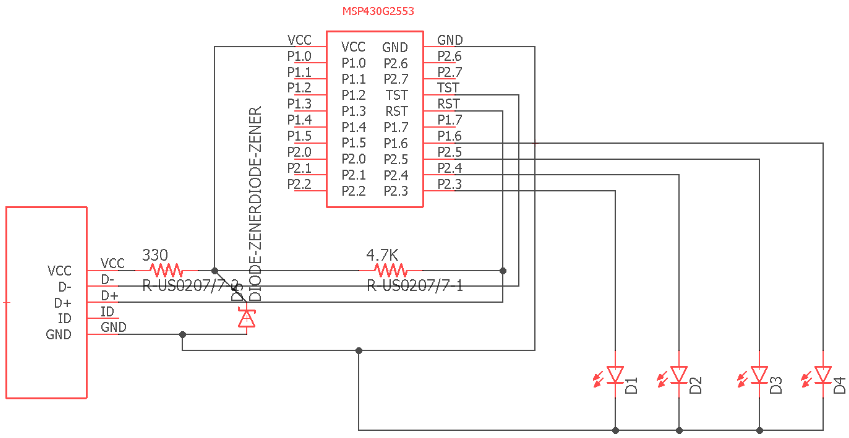


FIGURE 5. Sequence of steps for embedding a two-segment trace with a continuous copper wire into an ABS part; a) tool approaching the part, b) rotating tool, c) staking the wire into the polymer, d) retracting tool and supplying coolant, e) making contact with polymer, f) traversing the tool in the trace direction, g) traversing the tool in the trace direction, h) retracting tool and supplying coolant, i) rotating the tool, j) making contact with the polymer, k) traversing the tool in the trace direction, l) retracting the tool and supplying coolant, m) moving the tool away from cut location, n) cutting the wire, o) retracting the tool.

embedding tool before fabrication, and the printable area was reduced to avoid collision of the larger tool plate that carried the extruder and wire embedding tool. To appreciate the commands that were introduced into the wire embedding G-code, the wire embedding process for a two-segment trace (Fig. 4) is described in the following paragraph.

After printing the acrylonitrile butadiene styrene (ABS) foundation, the wire embedding tool first approached the part (Fig. 5a) and was rotated (Fig. 5b). The copper wire was then staked by bringing the hot end of the wire embedding tool into contact with the plastic surface (Fig. 5c). The simultaneous heating of the wire and plastic allowed the wire to be embedded into the plastic. Subsequently, the hot end was retracted from the surface (Fig. 5d) and compressed air was introduced to the wire-plastic interface to solidify the plastic and mechanically lock the wire in place. Next, the compressed air was turned off, the hot end again touched the surface (Fig. 5e), and the tool traversed in the direction of the desired trajectory (Fig. 5f and 5g). Once the tool reached the end of the first segment, the tool retracted from the plastic surface and compressed air was introduced again to solidify the plastic (Fig. 5h). After rotation (Fig. 5i), the tool



Component List:

- MSP430G2553IN20 MSP430 MICROCONTROLLER
- SparkFun microB USB Breakout
- 1N4728A-ND DIODE ZENER 3.3V 1W
- CF14JT4K70CT-ND RESISTOR 4.7K OHM 1/4W 5% CARBON FILM
- CF14JT330RCT-ND RES 330 OHM 1/4W 5% CARBON FILM
- COM-00533 LED - Basic Red 3mm

FIGURE 6. **Electrical schematic created with Autodesk EAGLE software along with the components used during fabrication.**

was placed in contact with the plastic surface to embed the second segment (Fig. 5j). At the end of the second segment (Fig. 5k), the tool was retracted from the surface (Fig. 5l), compressed air was supplied (Fig. 5m), and the cutter was actuated to cut the wire (Fig. 5n). The tool was retracted one final time (Fig. 5o).

In summary, the described method utilized SolidWorks CAD software to export an STL, DXF, and a text file. These files were used by a combination of open-source slicing software and post-processing algorithms to automatically generate machine-parsable print files for material extrusion AM, component placement, and the wire-embedding multi-process print job. This was all achieved from a single holistic design environment. The G-code was subsequently delivered to the modified desktop printer to perform both material extrusion 3D printing and wire embedding in an automated fashion.

III. CASE STUDY

To test the capabilities of this new methodology, a demonstration part was designed and fabricated. The part was comprised of a hexagonal 3D printed body (44 mm on each side and 7.5 mm thick) that included a microcontroller, four LEDs, a USB connector, two resistors, and a Zener diode. The circuit's schematic is shown in Fig. 6. The circuit utilizes a simple resistor-Zener voltage divider to reduce the 5 V USB voltage to approximately 3.3 V to power the Texas Instruments MSP430G2553 microcontroller. The microcontroller was connected to a pull-up resistor on the reset pin and to four LEDs on its digital I/O ports. Finally, the USB port was also connected to the reset and test pins of the MSP430 microcontroller, allowing the controller to be reprogrammable even after embedding the controller.

The 3D solid model design was created in SolidWorks (Fig. 7a), as described in the methodology section, with electronic components imported from an EAGLE schematic of the design (with volumetric information, defining the required cavity size for each component). The appropriate macros were initialized to export the design to Cura, where the custom Cura plugin was initiated to generate the final G-code. The files were then loaded onto the multi-process Lulzbot TAZ 5 3D printer. The print job began as a conventional additive manufacturing job (Fig. 7b). During the print or thermoplastic deposition, the component cavities were formed (Fig. 7c), followed by a wire-embedding stage (Fig. 7d) when the plane containing the circuit was reached. A pause was set at the end of the wire embedding stage, to allow for manual placement of components into the cavities as well as the manual joining or soldering of wires to component leads (Fig. 7e). Finally, the printing process was resumed to fully embed the components and wires (Fig. 7f). It was noted that even during printing, the circuit was functional when energized. The final device had characteristics of both a structural thermoplastic part as well as an electronic device, yielding a multi-functional 3D printed part. The cycle time (from design to end of fabrication) was 5.75 hours. The time required for each of the process steps within the process chain is listed in Table 2. Note that the time for designing (30 minutes) only constituted 9% of the total cycle time, which is lower than previously experienced when component

TABLE 2. **Time required for each of the steps in the design and fabrication of a multi-functional 3D printed device**

Process Step	Time (min)
Step 1: design and G-code output	30
Step 2: material extrusion AM	180
Step 3: wire embedding	15
Step 4: manual component placement and joining wire to leads	90
Step 5: material extrusion AM	30
Total cycle time	345 (5.75 hours)

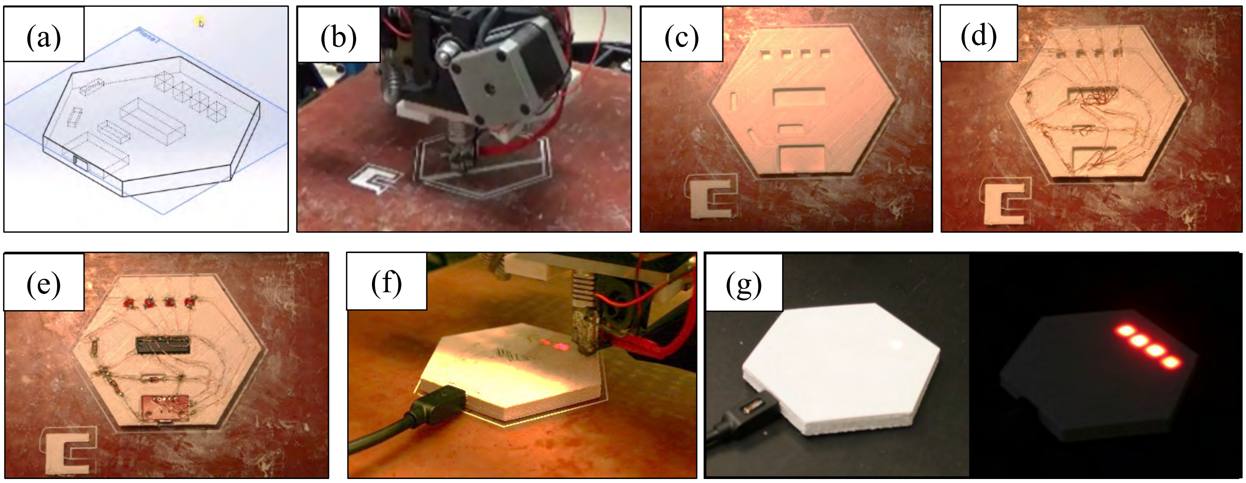


FIGURE 7. Implementation of the software and hardware tool for the fabrication demonstration of an embedded circuit within an ABS part. a) digital design of the part including the creation of machine instructions, b) deposition of thermoplastic for structural functionality, c) fabrication of component cavities, d) embedded wires for interconnect, e) manual placement of components and soldering, f) thermoplastic deposition over components and interconnect (note the functioning circuit even during material deposition as indicated by the energized red LEDs), and g) final multi-functional, energized device.

cavities were designed manually and G-code files were manually concatenated. The previous manual design and G-code output process took 6.5 hours, which was 13 times longer than the 30 minutes consumed when using the new software tools in this method. The shorter cycle time enabled by the new software and hardware tools is promising since design changes can be implemented rapidly to accommodate any of the following:

- electronic components changed in the schematic due to availability,
- functionality changes, such as adding additional integrated circuits or changing the nature of physical or electrical interfaces if the design interacts with other external components,
- different materials (polymers) with different thermal and electrical properties can be tested, and
- rapid iterative design optimization, if analog (dimension-dependent) circuit components are present such as an antenna, or custom-built sensor (capacitive touch or load cell).

IV. CONCLUSION

In this paper, a comprehensive design solution for multi-process or hybrid AM was presented. Software was developed and integrated with commercial software (i.e., SolidWorks and Cura) to respond to the lack of design support for multi-process 3D printing. The software solution enabled the automatic creation of electronic component cavities in a solid CAD model directly from data in EAGLE electrical schematics and electronic component libraries. Introducing the schematic data into the solid CAD environment allowed for accurate control of dimensions and locations of electronic components and traces, as opposed to introducing cavities in the slicing stage. After development, the software was demonstrated by creating a multi-functional part that included a simple analog circuit to adjust input voltage and a microcontroller to control LEDs. It was noted that the new design tools substantially reduced design time from 6.5 hours to 30 minutes. This software solution has bridged mechanical and electrical engineering CAD to greatly improve the efficiency with which multi-functional parts can be designed and executed on the custom multi-process 3D printer and will serve as the foundation to control the next generation of multi-process AM equipment at this facility.

Further development will focus on improving the integration between solid CAD modeling and ECAD, to allow for advanced simulation and testing of multi-material designs with respect to both mechanical and electrical properties. Other enhancements include the ability to embed wires on non-planar geometries; this will require improvements to conventional slicing software to account for geometric dependencies and collision avoidance that occur when printing and embedded wires in non-planar geometries. Additional research is underway to develop software support for 5-axis printing and wire-embedding, allowing for control of next-generation multi-process printers and the realization of more sophisticated designs. There is also ongoing work to investigate utilizing other CAD environments such as Autodesk Fusion 360. In addition, the developed design software will also be used with a large format material extrusion machine (Cincinnati's BAAM) and a custom multi-tool 3D printer with a build envelop size of 355 × 355 × 355 mm.

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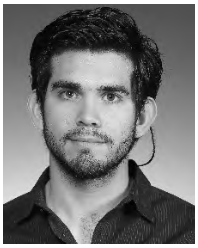

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