EXPANDING RAPID PROTOTYPING FOR ELECTRONIC SYSTEMS INTEGRATION OF ARBITRARY FORM

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Abstract

An innovative method for rapid prototyping (RP) of electronic circuits with components characteristic of typical electronics applications was demonstrated using an enhanced version of a previously developed hybrid stereolithography (SL) and direct write (DW) system, where an existing SL machine was integrated with a three-axis DW fluid dispensing system for combined arbitrary form electronic systems manufacturing. This paper presents initial efforts at embedding functional electronic circuits using the hybrid SL/DW system. A simple temperature-sensitive circuit was selected, which oscillated an LED at a frequency proportional to the temperature sensed by the thermistor. The circuit was designed to incorporate all the required electronic components within a 2.5” x 2” x 0.5” SL part. Electrical interconnects between electronic components were deposited on the SL part with a DW system using silver conductive ink lines. Several inks were deposited, cured, and tested on a variety of SL resin substrates, and the E 1660 ink (Ercon Inc, Wareham, MA) was selected due to its measured lowest average resistivity on the SL substrates. The finished circuit was compared with Printed Circuit Board (PCB) technology for functionality. The electronic components used here include a low voltage battery, LM 555 timer chip, resistors, a thermistor, capacitors, and Light Emitting Diodes (LEDs). This circuit was selected because it (1) represented a simple circuit combining many typically used electronic components and thus provided a useful demonstration for integrated electronic systems manufacturing applicable to a wide variety of devices, and (2) provided an indication of the parasitic resistances and capacitances introduced by the fabrication process due to its sensitivity to manufacturing variation. The hybrid technology can help achieve significant size reductions, enable systems integration in atypical forms, a natural resistance to reverse engineering and possibly increase maximum operating temperatures of electronic circuits as compared to the traditional PCB process. This research demonstrates the ability of the hybrid SL/DW technology for fabricating combined electronic systems for unique electronics applications in which arbitrary form is a requirement and traditional PCB technology cannot be used.

Keywords: rapid prototyping; stereolithography; direct-write; hybrid manufacturing; functional integrated layered manufacturing

Introduction

With recent advances in Rapid Prototyping of High Density Circuitry (RPHDC) research and specifically the development of a hybrid stereolithography (SL) and direct-write (DW) system, three-dimensional (3D) structures can be fabricated with high-resolution electricallyconductive media (Wicker *et al.*, 2005). Consequently, electronic components can be tightly integrated together in a rugged, light-weight structure of arbitrary form. To date, the capabilities of this new RP technology have not been explored in the context of fabricating and prototyping complex electronics applications in which conformal shape, rugged and light-weight integration and a natural resistance to reverse engineering are all of paramount importance. Examples of applications currently being explored include:

- unattended / wireless sensors
- combined electrical and structural components in unmanned aerial vehicles
- soldier-borne electronics
- pavement instrumentation
- implantable bio-electronics

This paper describes initial efforts at evaluating the effectiveness of the hybrid SL/DW system for embedding a simple parametrically-sensitive system into a SL matrix. The natural progression of this work includes the fabrication of electronics with more sophisticated semiconductor devices (i.e. microcontrollers, field programmable gate arrays, memories, sensors, etc.) for a wide range of applications.

Solid freeform fabrication (SFF), layered manufacturing (LM), and other similar rapid prototyping (RP) technologies enable the fabrication of complex three-dimensional (3D) parts. Stereolithography (SL) is one of the most widely used RP technologies to manufacture highly complex and accurate 3D prototypes due to its high build resolution. The materials development for SL and other RP technologies, focused on improving the mechanical strength, durability, and thermal property characteristics of RP materials, has generated great interest in many areas of research such as rapid manufacturing of fully functional embedded electronic devices. The flexibility of placing components within complex 3D designs and the possibility of layering components instead of placing them side-by-side can lead to a reduction in size of the overall circuit. The overall strength of the circuit can be increased and components are protected from outside hazards as compared to its equivalent PCB design. These were some of the unique features and motivating factors that led to this research.

Researchers at the UTEP W.M. Keck Border Biomedical Manufacturing and Engineering Laboratory and Sandia National Laboratories have developed a hybrid manufacturing setup to assist in expanding the markets for RP into rapid manufacturing of such unique functional devices. In this integrated manufacturing environment, SL is employed in conjunction with direct write (DW) fluid dispensing technology to capitalize on each of the individual process capabilities for developing unique electromechanical devices. In recent years, researchers have developed systems for automatic dispensing of conductive, thermally curable media, such as DW inks for maskless patterning of electronics. Palmer *et al.* (2004) proposed a new manufacturing process to integrate SL and DW technologies for the fabrication of 3D, high-density circuitry. Medina *et al.* (2005) utilized this hybrid SL/DW system to demonstrate an SL part with embedded circuitry and 3D connectivity. The electronics industry, where huge performance improvements in each generation of new products are accompanied by the need to continuously reduce costs, is under continuous pressure from consumers to come up with product and design innovations. A number of these innovations need to be applied to satisfy the increasing pressure on the interconnect industry (Mosses and Brackenridge, 2003). The most commonly used interconnects in electronic circuitry is the PCB, where high volume manufacturing can be expensive and wasteful in spite of being suitable for many applications. Embedding electrical components using RP technology provides fewer process steps enabling reduced manufacturing costs (Begaye *et al.*, 2003). RP also increases design flexibility and almost completely eliminates waste due to its additive process. Passive components such as inductors and capacitors are key technology for highly integrated electronic circuits, but typically require two-thirds of the space of a conventional PCB (Waffenschmidt *et al.*, 2005). Investigating the feasibility of embedded sensors or functional components in a layered structure will reduce surface area which could lead to total assembly cost reductions. RP electrical interconnect prototypes could find uses in pre-production testing and three-dimensional circuitry can lead to full departure from conventional circuit PCB boards (Ocampo *et al.*, 2003).

The current effort represents the continuing evolution of the Functional Integrated Layered Manufacturing (FILM) concept introduced in the work of Medina *et al.* (2005) where RP is employed in conjunction with automated access to a toolbox of additional manufacturing technologies to capitalize on individual process capabilities for developing unique functional devices. As the next step in this development, this work presents a hybrid SL/DW machine setup for manufacturing embedded electronic components in a semi-automated environment with DW interconnects. The hybrid system provides a method for automated deposition of fluid media during the SL build (by stopping the SL build but not removing the part from the SL machine). The DW system employed a three-axis translation mechanism, using precision linear positioning stages, that was integrated with the commercial SL machine. The current system allows for easy exchange between SL and DW in order to manufacture fully functional 3D electrical circuits and structures in a semi-automated environment. To demonstrate the manufacturing capabilities, the hybrid setup was used to make a simple multi-layer SL part with embedded electronic components with DW interconnects. The following describes the design and demonstration of the semi-automated hybrid SL/DW machine for manufacturing embedded electronic components.

Hybrid stereolithography/direct-write machine setup

As depicted in Figure 1, an integrated RP system comprising a traditional SL apparatus and a DW fluid dispensing system were used in the hybrid SL/DW manufacturing setup. Many of the details described in this section are also found in Medina *et al.* (2005). However, this section provides several upgrades to the previously described system and represents the latest developments for the hybrid SL/DW manufacturing system. The SL 250/50 machine manufactured by 3D systems was used with a 355 nm solid-state laser upgrade (Series 3500-SMPS, DPSS Lasers Inc., Santa Clara, CA). Due to its ability to withstand heat deflection temperatures (HDTs) up to 126 ˚C and relatively low viscosity (550 centipoise, cp, at 30 ˚C) (DSM Somos®, New Castle, Delaware) DSM Somos® ProtoTherm™ 12120 was selected as the resin for this work. The low material viscosity of ProtoTherm™ facilitated improved handling, building without sweeping, and cleaning prior to DW deposits. This was one of the issues encountered in the work of Palmer *et al.* (2004) where it was challenging to handle and build parts out of ProtoTool™ due to the high value of viscosity (2500 cps).

The DW setup was placed on a custom-made, adjustable height table, which consisted of a stainless steel top and an adjustable-height hand-crank two legged mobile workbench (Part # 9054T113 and Part # 3517T82, respectively, McMaster-Carr Supply Company, Chicago, IL). Two support plates were welded to the stainless steel table top which was then bolted to the workbench base using standard fasteners. The DW setup was aligned to the SLA 250/50 using two identical dowel pins and the support plate on the SLA 250/50 frame until both pins touched the rim thus arranging the X stage parallel to the rim of the SL machine.

The 3-axis movement was achieved by precision linear positioning stages with direct drive precision ground screw drives and built-in 0.1 µm resolution linear encoders. The X-axis motion was provided by a 400mm travel LM150D-0400 model, while the Y and Z axis motion was provided by the LM100D-0100 model (Parker Hannifin Corporation, Electromechanical Automation Division, Rohnert Park, California) with 350mm and 100mm travel, respectively. The X axis was attached to a standard Newport honeycomb breadboard (Newport Corporation, Mountain View, CA) using an aligning plate provided by Parker Hannifin Corporation. The X, Y and Z axes were aligned perpendicular to each other using support brackets as shown in Figure 2b. The 3-axis traverse stages of the DW system facilitated movement of the fluid dispensing system, enabling precise fluid placement without intermediate calibration or removal of the SL part.

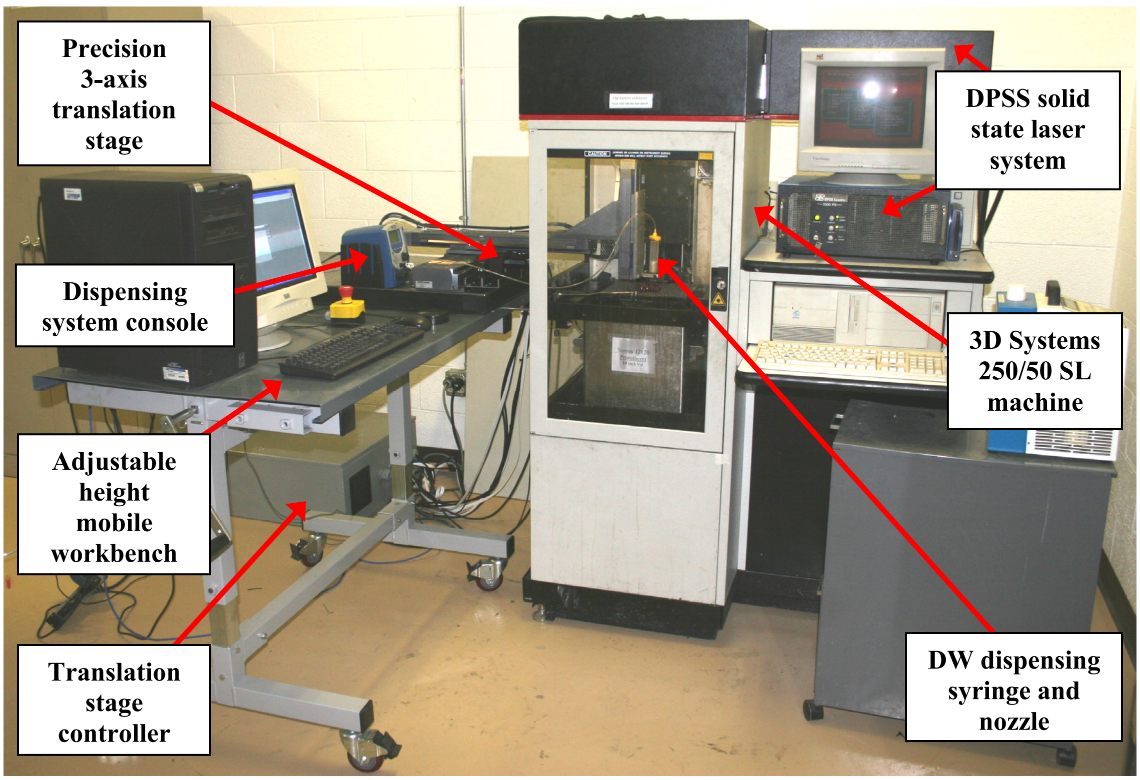


Figure 1. The hybrid SL/DW machine setup.

The 2405 Ultra Dispensing System (EFD Inc., East Providence, Rhode Island) shown in Figure 2a was integrated with the SL machine and adapted to deposit fluid such as conductive ink on the part manufactured by the SL machine. The dispensing system as described previously obtains an externally supplied inlet air pressure (up to 100 psi) and regulates the outlet pressure (from 0 – 5 psi), which is then supplied to the dispensing tip (Medina *et al.*, 2005). The ink can be dispensed manually or controlled using LabVIEW® to draw given circuit profiles and adapted to dispense a variety of fluids.

For this work, a conductive ink (E1660-136, Ercon, Wareham, MA) was dispensed on laser cured ProtoTherm™ 12120 resin (DSM Somos®, New Castle, Delaware). The ink used here was selected based on its low curing temperature (138 ˚C for 15 minutes), and lowest measured resistivity (0.011 Ω/square/mil) based on ink dispensing experiments. The traverses as well as the dispensing system were controlled using LabVIEW®.

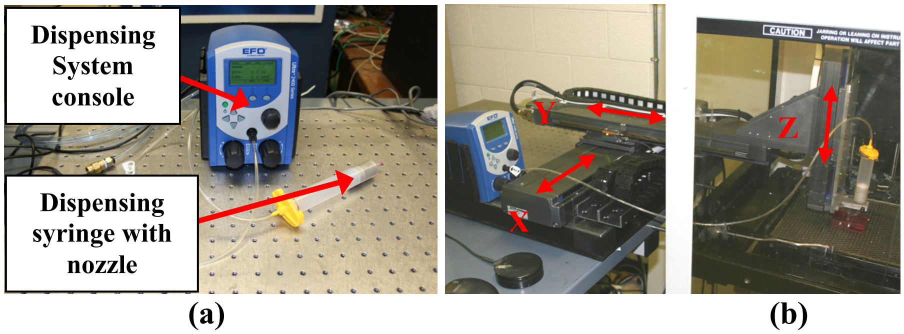


Figure 2. (a) The DW Ultra Dispensing System; b) The 3-axis traverse system.

Figure 3 summarizes the results of the ink dispensing experiments. The substrates used for this experiment consisted of a standard FR-4 board along with SL samples, which were simple 3” X 3” X 0.25” parts fabricated on the SL 250/50 machine using the ProtoTherm™ 12120, NanoForm™ 15120, and ProtoTool™ 20L (DSM Somos®, New Castle, Delaware) resins. The SL parts were cleaned using Isopropyl Alcohol and post-cured in a UV oven prior to the DW process. A set of five one inch DW lines using a variety of inks were deposited on these substrates and cured at the recommended curing conditions. A dispensing pressure of 4 psi and Z gap of 4 mils between the dispensing tip and the SL substrate were chosen for this experiment based on previous research and gave the most consistent DW line (Medina *et al.,* 2005).

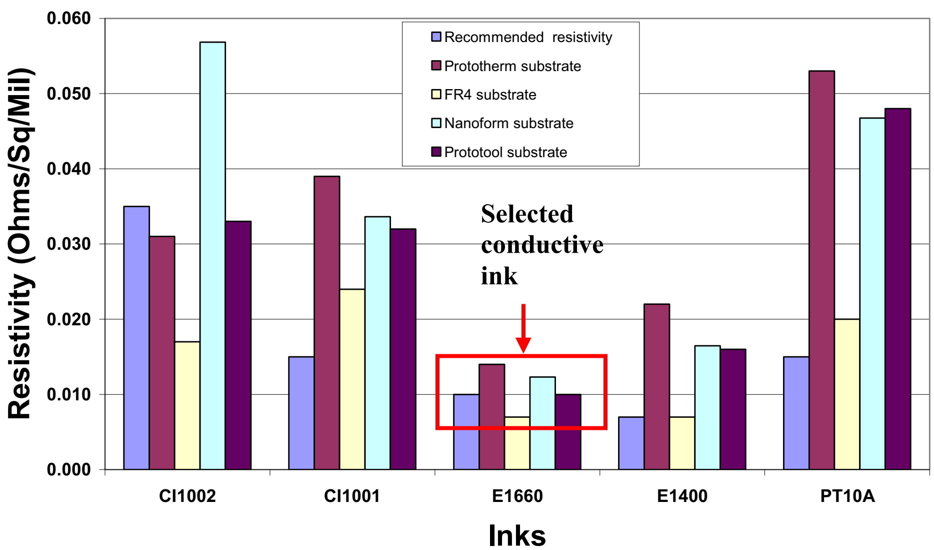


Figure 3. Comparison of average resistivity of various inks on different substrates.

The results indicate that the E 1660 silver conductive ink gave the lowest average resistivity after thermal cure on all the substrates as compared to the other inks and was thus selected for creating the electrical interconnects between the electronic components. Future research will include experimentation with smaller dispensing tips at various dispensing speeds to get the narrowest consistent DW interconnect line at the fastest speed. The newly acquired precision linear positioning stages will enable this experimentation.

Hybrid SL/DW machine operation overview and L555 timer circuit design review

Figure 4 provides an operation overview of the LM 555 timer circuits with embedded electrical components and DW interconnection between the components. This figure is intended to provide a general description of the fabrication process using the hybrid SL/DW system for embedding electronic components within SL parts. The figure represents separate STL files for inserting as well as embedding the electronic components using different SL parts, and DW electrical traces for connection between the electronic components.

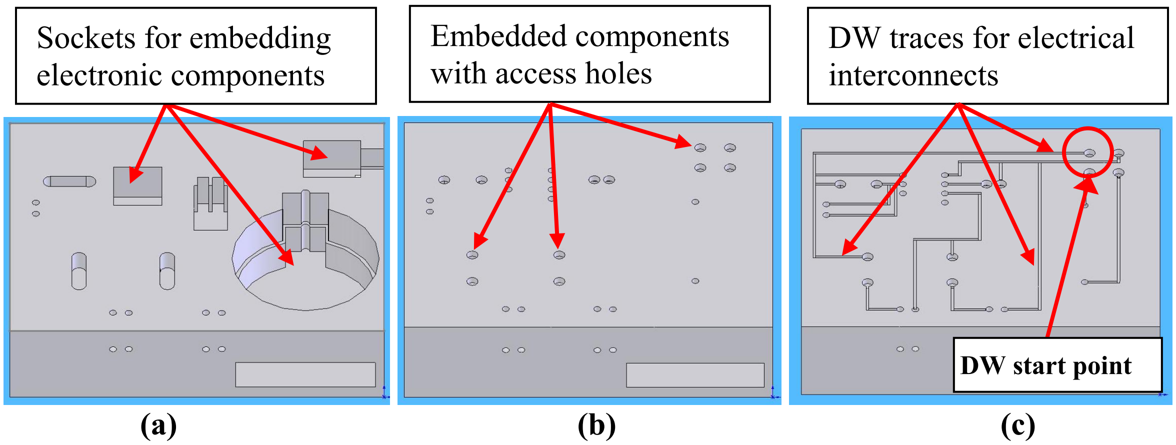


Figure 4. (a) SL part with sockets for embedding electronic components, (b) Embedded components with access holes for DW, (c) DW traces for electrical interconnects.

The ability to accurately register the DW trace with the SL part and providing precise electrical interconnections using the DW system are some of the key elements of successful SL/DW integration. The registration issue is solved by locating the dispensing tip to a predetermined reference point, which is a simple cylindrical hole on the SL part, as shown in Figure 4c. A vertical gap of 4 mils is maintained between the DW ink dispensing nozzle and the SL part to achieve a consistent DW line based on previous research (Medina *et al.*, 2005). The SL vat is lowered to allow access to the sockets and vias for inserting the electronic components and during the DW process while the platform remains at the same z-height. This procedure eliminates the geometric differences between the elevator positions before and after the DW process. These features summarize the necessary elements for successful hybrid SL/DW operation. Additional details of the operation are provided below in the description of part manufacture illustrated in Figure 4.

Figure 4 represents a simple part with embedded electronic components to be manufactured using the hybrid SL/DW setup. Manufacturing issues like part re-registration, continuous cleaning, and curing between part builds, as mentioned in Medina *et al.* (2005) are addressed using the hybrid setup. SolidWorks modeling software or similar CAD packages can be used to generate the individual part designs, and converted into STL file format as required. 3D Systems proprietary slicing software, 3D Lightyear™ 1.4, is used to convert the STL files generated during the part preparation and design stages into the build file format required for the operation of the SL 250/50.

The entire build process is designed in the form of an assembly using SolidWorks CAD design software. The assembly is first saved as a part file and then converted into an STL file. The final STL file is divided into three distinct parts, as shown in Figure 4, to facilitate the

SL/DW integration. The first STL part is the SL base into which the electronics components are embedded (Figure 4a). The electronic components that are embedded in the SL part include a battery holder, LM 555 timer chip, three resistors, a thermistor, a capacitor, a switch and two LEDs.

The 555 timer is one of the most popular and versatile integrated circuits and can be configured as either a monostable multivibrator or as an astable multivibrator (oscillator). It includes 23 transistors, 2 diodes and 16 resistors on a silicon chip installed in an 8-pin mini dual-in-line package. The 555 timer circuit is based on the sequential charging and discharging of the external capacitor and can be used with any power supply in the range of 5-15 volts making it useful in many analog circuits. The simple temperature-sensitive circuit oscillated the LED at a frequency proportional to the temperature sensed by the thermistor. This circuit was selected because it (1) represented a simple circuit combining many typically used electronic components and thus provided a useful demonstration for integrated electronic systems manufacturing applicable to a wide variety of devices, and (2) provided an indication of the parasitic resistances and capacitances introduced by the fabrication process due to its sensitivity to manufacturing variation.

In the hybrid operation, traditional SL part building was performed layer by layer with planned interruptions to incorporate the electronic components. The vat was lowered while keeping the build platform location constant to provide access to the sockets and vias for embedding the electronic components. Once the components were manually inserted into their respective sockets and their leads were aligned perpendicular to the SL part surface, the vat was re-leveled to the last built layer, thus filling up the sockets and embedding the components with the SL resin. The second STL file was used to cure the resin in the sockets and embed the components followed by a few more build layers to create a flat top surface with matching holes to provide access to the connector pins of the embedded electronic components as shown in Figure 4b. The DW system was used to dispense the conductive ink in the required profile and the connector pin holes are filled with ink to complete the interconnections as shown in Figure 4c. The ink can be cured using either the SL laser or standard heat convection oven at the recommended curing conditions. Since this was a preliminary study for embedding functional electronic components and circuits using RP technologies, the heat convection oven curing method was used to cure the ink. However, Medina *et al.*, (2005) previously demonstrated successful curing of the DW ink using the SL laser. In order to enable vertical integration of the electronic components and systems and justify the advantages of this research, optimum laser curing of the ink is the next natural progression in this research for truly automatic fabrication of multi-layer 3D circuitry.

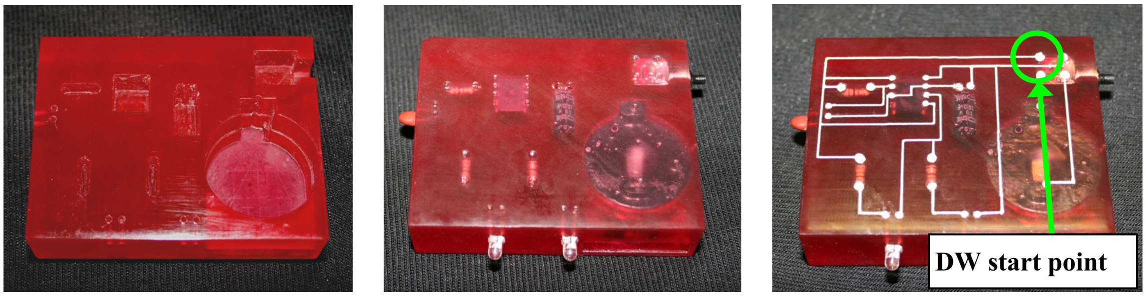
The precision 3-axis stages were controlled using LabVIEW®. Registration between the DW tip and the SL part were achieved by locating the dispensing tip on top of the previously described reference point using the stages. The dispensing nozzle was controlled using the Z-stage traverse, accurately positioned over the registration point via a digital position readout using the linear encoders on the stages. The Z-axis traverse was adjusted to 4-mils vertical distance so that the required gap between the dispensing tip and the SL part was obtained. These dispensing conditions were chosen based on previous research which provided the optimum dispensing pressure and z distance between the dispensing tip and the SL part for consistent DW traces. After the initial calibration and accurate positioning of the dispensing tip was complete, the DW process was performed using LabVIEW®. Once the traverse sequence (which a set of simple motion commands) was activated using LabVIEW®, the dispensing could be controlled to start and stop as and when necessary to complete the entire DW process in one step.

After the DW process was complete, the part was then cured in the convection oven to complete the ink curing process. The effect of curing was investigated by testing the resistivity using a MeTex® multimeter (Model # M–3850D). The curing process was repeated until the required resistivity was achieved. The ink was considered cured when the resistivity was within 3% of the previous measurement after each curing cycle. The SL part was then allowed to cool to room temperature before inserting the battery.

Fabrication demonstration

The complete LM 555 timer circuit was manufactured using DSM Somos® ProtoTherm™ resin and the E 1660-136 conductive ink and the hybrid SL/DW system. Figure 5 represents the SL/DW procedure used to manufacture the functional part with embedded electronics and depicts the part at various stages during the build, while still attached to the build platform. The entire process takes place without removing the part from the SL machine platform until the completion of the DW process and thus provides a continuous manufacturing system without the need for re-registration. The DW stages were controlled using LabVIEW® to replicate the required DW profile and dispense the ink to draw the circuitry. The SL/DW process was initiated by building the SL base with sockets and vias, for inserting the electronic components, using the first set of STL files as shown in Figure 5a. Once the SL part reached a predetermined layer in the STL file, the build was interrupted without raising the platform, the vat was lowered to expose the top surface, and the sockets and vias were cleaned prior to inserting the electronic components. The components were manually inserted into their respective sockets and vias such that the connector pins of the components were slightly below the last built layer and aligned perpendicular to the SL part surface thus allowing the build to continue with regular Zephyr™ blade sweeping. The resin level was re-adjusted and the build was continued to embed the components using the second set of STL files. Here, the components were embedded while providing access to the connector pins of the electronic components via precise holes manufactured during the SL build as seen in Figure 5b. The vat was lowered to expose the top surface of the SL part to begin the DW process. LabVIEW® was used to guide the traverse system as well as control the dispensing for the DW interconnects using the 2405 Ultra Dispensing System. The dispensing syringe was directed from a predetermined home position (which allowed normal SL build without any obstructions) to the starting position for the DW process (shown in Figure 5c) using the precision 3-axis traverse stages. The traverse sequence (which a set of simple motion commands) was initiated, and the dispensing was controlled to start and stop as and when necessary to complete the entire DW circuit in one sequence.

After the ink deposition was complete, the functional part was removed from the machine, and cured using a standard heat convection oven. To test the effectiveness of the ink curing, the resistivity of the functional test piece, placed in a heat convection oven at 138 ˚C, was monitored and recorded at 15 min intervals. The curing process was continued until the resistivity value reached the value recommended by the ink manufacturer (0.01 Ω/square/mil), and it was found that curing at 138 °C produced the required resistivity value. The total time for manufacturing the completed part with embedded components and DW interconnections was approximately three and a half hours. The functional hybrid SL/DW part was further compared to the traditional breadboard LM 555 timer circuit for functionality.



(a) (b) (c)

Figure 5. (a) SL part with sockets; (b) embedded components; (c) DW interconnects.

Results and discussions

The LM 555 circuit manufactured using the hybrid SL/DW machine was analyzed to validate its performance against its equivalent temperature circuit built on a breadboard. The analysis included testing both circuits concurrently at a temperature range of -20°C to 90 °C using a heat convection oven and a freezer. The critical resistances and capacitance values that affected the frequency were measured using a standard multimeter for each circuit. Both circuits were maintained for 5 minutes at the desired temperatures to approximately achieve thermal equilibrium prior to measuring the resistances and capacitances across the components, which affected the frequency of the LEDs. The circuit drew virtually no power so self-heating during operation was negligible. The resistance and capacitance of the thermistor, resistor (1kΩ) and capacitor on the breadboard circuit were measured by placing standard alligator clips on the leads of the components and measured using the multimeter. For measuring the parameters on the RP circuit, standard wire jumpers were wrapped around the alligator clips. The leads of the wire jumpers were inserted into the DW ink lines across the components of the RP circuit, consequently including any parasitic variation that might be induced by the DW ink lines.

Table 1. Comparison between the RP circuit and breadboard circuit.

	Rapid Prototyped Circuit				Breadboard Circuit			
Temp (°C)	Thermistor Resistance (Ω)	Capacitance (F)	Frequency (Hz)	Time (s)	Thermistor Resistance (Ω)	Capacitance (F)	Frequency (Hz)	Time (s)
-20	12552	9.97E-05	0.55	1.807	12525	9.95E-05	0.56	1.80
-10	4823	9.97E-05	1.36	0.737	4813	9.96E-05	1.36	0.73
0	2997	9.97E-05	2.07	0.484	2990	9.96E-05	2.07	0.48
10	1871	9.97E-05	3.05	0.328	1867	9.98E-05	3.05	0.33
20	1233	9.99E-05	4.16	0.240	1231	1.00E-04	4.16	0.24
30	863	1.00E-04	5.28	0.189	863	1.00E-04	5.28	0.19
40	604	1.00E-04	6.52	0.153	604	1.00E-04	6.52	0.15
50	430	1.01E-04	7.67	0.130	431	1.01E-04	7.66	0.13
60	323	1.01E-04	8.66	0.115	324	1.01E-04	8.65	0.12
70	230	1.01E-04	9.77	0.102	231	1.02E-04	9.66	0.10
80	162	1.02E-04	10.66	0.094	163	1.02E-04	10.65	0.09
90	110	1.02E-04	11.57	0.086	111	1.02E-04	11.55	0.09

The slight variation (± 1%) between the measured resistances and capacitances between the components of the two circuits was well within the resistance value allowable differences for the components (± 10%, Jameco Electronics, Catalog 262, May 2006). The thermistor's properties were confirmed in Table 1, which exhibit an increase in its resistance as temperature decreases and vice versa. The capacitance in the temperature circuit is independent of temperature and varied slightly from its selected value, but is required to determine the frequency of oscillation of the output. The calculated time indicates the period of the blinking LEDs and the differences between the circuits are likely dominated by the component variation rather than the DW ink.

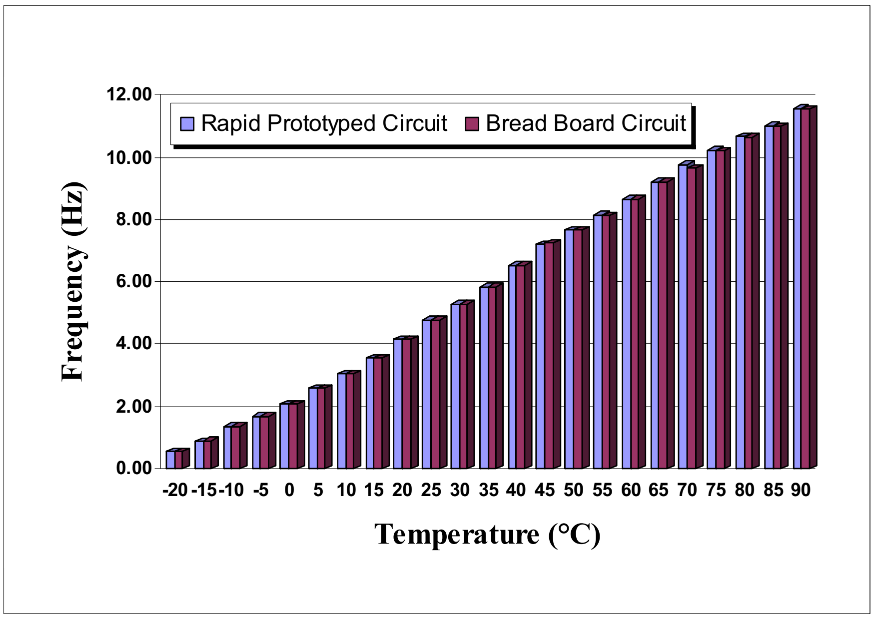


Figure 7. Temperature vs. LED frequency comparison

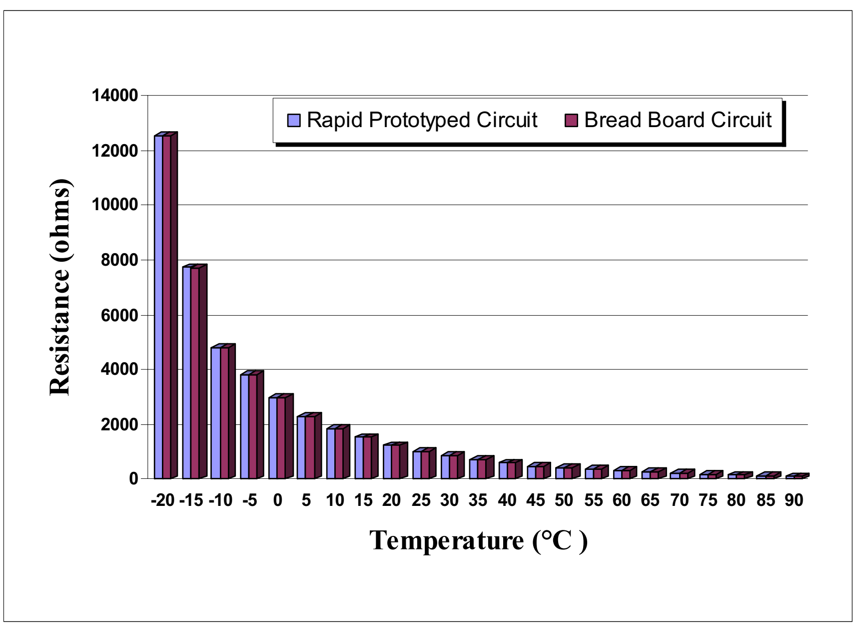


Figure 8. Temperature vs. thermistor resistance comparison

Figure 7 illustrates the comparison of the RP circuit and breadboard circuit under different temperature settings and indicates that temperature is exponentially related to the resistance of the thermistor, as expected.

Figure 8 verifies that the temperature is linearly related to frequency of both the RP circuit and the breadboard circuit as predicted at different temperatures. Results from the temperature test conclude that the RP temperature circuit operates similar to the breadboard circuit as little variation in the resistances and capacitances was measured.

Conclusions and future work

A hybrid SL/DW machine setup was used for manufacturing embedded electronic components in a semi-automated environment with DW interconnects. The modified SL system was incorporated with build interrupts used to stop and start the SL build while embedding electronic components and using DW interconnects to complete the electrical interconnects. The DW system employed a three-axis translation mechanism that was integrated with the commercial SL machine. The 3-axis DW traverse system and the ink dispensing were controlled using LabVIEW® to replicate the required DW profile and dispense the ink to complete the required circuitry. Comparisons of the RP fabricated electronic circuit with a breadboard circuit indicated that the RP circuit operated essentially the same as the traditional breadboard circuit. It should be noted, however, that this circuit consumed very little power (<10mW), and therefore did not generate any appreciable heat. Circuits with higher power consumption may self-heat due to the reduced thermal conductivity of the system based on the complete encapsulation of the components in the SL resin. However, we believe that these challenges can be overcome by embedding novel passive cooling techniques (i.e. heat pipes) and advanced thermal management is the focus of future work.

In summary, RP designed circuits can reduce process planning steps enabling cost reduction with reduced assembly due to effective use of material and minimization of waste and effluent. The use of different materials and the ability to build in arbitrary geometries can enable the design and manufacture of compact and visually appealing 3-D circuits. Improved performance by reducing electrical interference between the components and opting to fabricate in several structured functional layers can reduce circuit size and area. By having components embedded within the design, they are protected from outside hazards and weather which increase the overall strength and reliability of the final product. Some of the manufacturing and design issues that can be foreseen during this work include vertical interconnections between components and multiple circuits based on complexity, temperature control during laser curing of ink and its effect on the electronic components, and heat dissipation when using high speed passive components operating at high frequencies.

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