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Structural Electronics Based on 3D Printing

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ABSTRACT

The use of advanced 3D printing technology enhanced with component placement and electrical interconnect deposition can provide electronic prototypes that now can be rapidly fabricated in comparable time frames as traditional 2D bread-boarded prototypes; however, these 3D prototypes include the advantage of being embedded within more appropriate shapes in order to authentically prototype products earlier in the development cycle. The fabrication freedom offered by 3D printing techniques, such as stereo lithography and fused deposition modeling have recently been explored in the context of 3D electronics integration referred to as 3D structural electronics or 3D printed electronics. Enhanced 3D printing may eventually be employed to manufacture end-use parts and thus offer unit-level customization with local manufacturing; however, until the materials and dimensional accuracies improve (an eventuality), 3D printing technologies can be employed to reduce development times by providing advanced geometrically appropriate electronic prototypes. This paper describes the development process used to design a novelty six-sided gaming die. The die includes a microprocessor and accelerometer, which together detect motion and upon halting, identify the top surface through gravity and illuminate light-emitting diodes for a striking effect. By applying 3D printing of structural electronics to expedite prototyping, the development cycle was reduced from weeks to hours.

Keywords: 3D printed electronics, additive manufacturing, direct-print, electronic gaming die, hybrid manufacturing, rapid prototyping, structural electronics, three-dimensional electronics.

I. INTRODUCTION

Additive Manufacturing (AM) was introduced in the late 1980's in order to rapidly prototype structures and allow manufacturers to circumvent the lengthy process of tra-ditional prototyping by providing either a scaled-down or full-scale mechanical replica of the designed product. These devices were typically only conceptual models due to lim-itations of the AM technologies in which compromises were made in terms of material choices, surface finish and dimensional accuracies. For instance, stereo lithography (SL) provided high-accuracy and superior surface finish but with photo-curable materials that suffer from poor mechanical strength or durability and degrade or discolor with prolonged UV exposure, or alternatively, with fused deposition modeling (FDM) which offers robust thermoplastic materials but at the expense of reduced spatial resolution and anisotropic mechanical strength with a loss of performance in the build direction. While AM technology continues to advance in terms of material properties and minimum features sizes, the technology until recently has remained best suited for manufacturing prototypes for conceptual modeling relegated to only satisfying the need for evaluation of form and t of the device casing or structural features. Until now, no option has existed for validation of both form and functionality simultaneously where functionality includes electronics, energy sources, sensors and displays all of which require additional lead times for bread-boarding, debugging and integration. This paper describes a project showcasing an enhanced 3D printing technology that dramatically reduced the full design cycle of an example electronic device: a novelty six-sided gaming die. The process - from concept, through prototyping, to the final manufactured part - is described noting the significant advantages of employing AM. In this example, form, t, aesthetics and functionality were explored by 3D printing several versions of electronic devices as rapid, high duality prototypes prior to committing to traditional production. The eventual goal is for 3D printing to become the preferred manufacturing method for industries where the use of AM structures provides a real advantage, such as in the production of novelty toys, unmanned aerial vehicles (UAVs), satellites, and other low volume high value applications.

II. METHODS AND MATERIAL

2.1 Previous Work

AM techniques, since inception, have been extensively used for successful rapid prototyping of mechanical structures. These technologies were exceptionally well suited for the fabrication of complex geometries, which allowed designers to verify the t and form of a product within a few hours of completing the CAD design. Further, AM technologies have also been used to produce end-use parts in low volumes through rapid manufacturing techniques that proved to be economic because there was no need for tooling and logistics costs were decreased . However, in the context of prototyping electronic circuits, which are increasingly encased in 3D forms, rapid prototyping only provided t and form verification of the housing. In order to verify functionality, a separate bread boarding activity was required that did not integrate the verification of form with function two separate activities.

2.2 3D Printed Electronics Prototyping

Though typical methodologies like clay models, one-off samples handmade by skilled craftsmen, and more recently AM technologies have largely addressed the need for proto-types, these types of parts have been exclusively made to test appearance and t of the completed part. When the device included sophisticated electronics, these methodologies could not address the need for prototyping a fully functional part. When required, the traditional procedure to prototype electronics was to implement bread board prototypes and to accept the inherent delays that come with the normal process of electronics manufacturing, possibly weeks or even months. A newly developed 3D printing process of fabricating structural electronics provides an appealing alternative. This novel manufacturing, a hybrid of AM complemented with component placement robotics and embedding of conductors can create prototypes that can perform practically the same function within the same form as the final product although possibly not fulfilling some of the other end-use characteristics such as reliability, surface finish, color, or texture.

A. 3D Printed Electronics Challenges

Although this new manufacturing technology allows for more complete evaluations with high fidelity prototypes, substantial challenges remain. The area of electronics design (e.g. schematic capture, simulation, and physical implementation of printed circuit boards PCBs) includes mature, commercially available software packages that allow for component placement and routing of wires to create electrical interconnect on a PCB. These programs however, operate under the assumption of the workspace being a predefined, two-dimensional surface for the circuit based on traditional PCB manufacturing. As a result, the component placement and routing for 3D printed designs has been done manually in 3D space using mechanical engineering CAD software like Solid Works without the inherent features for electronics functionality. As an example, Fig. 1 shows a circuit design that utilizes all available surfaces of a pre-defined volume to accomplish layout of components. The routing has likewise utilized all available surfaces as well as the internal volume of the device.

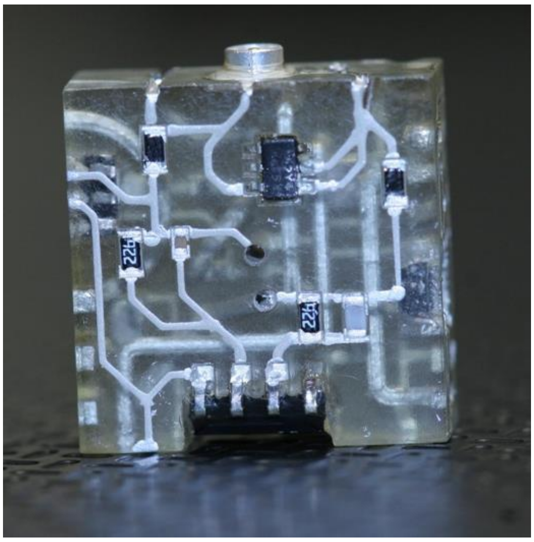
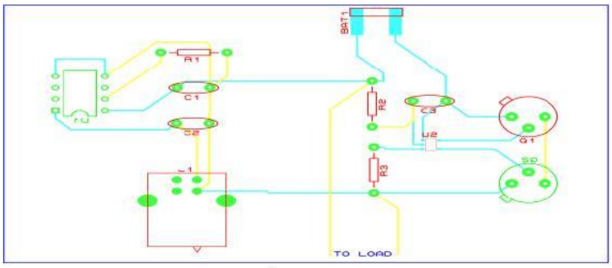


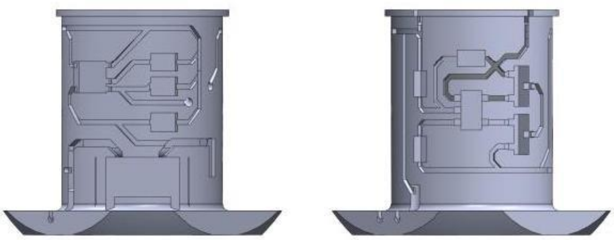
Figure 1: 3D Printed Signal Conditioning Circuit

The use of existing electronics CAD design software for layout and routing of 3D printed electronic devices is possible when the 3D shape can be represented initially as a at 2D surface and then ‘’deformed" to a final intended 3D shape; such cases include a volume that can be represented as an ``unfolded" outer surface (e.g. six sides of a cube) or a curved surface that has been “wrapped" about an axis of revolution (curved side of a cylinder).

Fig. 2(a) shows the application of the above-described methodology for a battery charge protection circuit that can be implemented on a 2D surface without cross-over points and thus only required a single surface of interconnect. The circuit was first placed and routed in electrical CAD software and subsequently imported into mechanical CAD software to be “deformed" around a cylinder, which in this example contains a lithium polymer battery. Fig. 2(b) illustrates the final representation from both sides. Cavities are formed to place components and UV curable material is used as adhesive to hold the devices in place. Each interconnect trace was designed into the surface with a trench to allow for depositing ink without the concern of the conductive inks spreading and resulting in electrical shorts prior to thermal curing. With the trenches, the SL process dictates the routing density based on the laser resolution rather than the resolution of the micro-dispensing system or the viscosity of the inks. In this example, line pitches (e.g. center to center minimum distances) were 560 microns.



A



B

Figure 2: A) Battery Charging Circuit to be deformed and B) Both Sides of the Final Mechanical Representation.

Fig. 3 illustrates a more complex design with a microcontroller and accelerometer in surface mount packaging technology that provides little pin pitch (0.56 mm) and miniaturized foot prints.

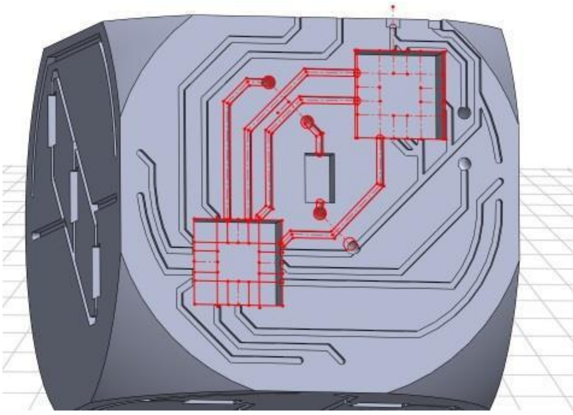


Figure 3: Electronic Circuit Mechanically Designed into Substrate.

Although the design included circuits on at 2D planes, two additional challenges were present: (1) the planes were connected with 90 degree connections around the corners which needed to be physically protected and (2) the 2D circuits required several cross-over points due to the complexity of the circuit network. These can be seen as tubular channels that tunnel underneath other traces to avoid shorting. This base design represents the outer shell of the gaming dice, which housed the cylindrical battery circuit shown in Fig. 2.

B. Gaming Die Versions

The concept to be prototyped in both form and function was a typical gaming die in terms of size with additional elec-tronic functionality that provided for (1) the determination of the die coming to rest after a roll; (2) detection of final orientation; and (3) flashing of the LEDs on the top surface. The design underwent three prototype optimization versions, each of which was quickly implemented, improved and iterated owing to the availability of the enhanced AM process. A final prototype version was implemented using traditional manufacturing techniques for commercial viabil-ity analysis and used for cost and manufacturing time comparison.

1) Version 1: Non-Rechargeable Batteries

The first prototype was made to test the feasibility of the concept; the overall design began by defining the functional requirements. The electronic circuit was developed to provide the stated operation. The constraints of cost, functionality, and availability were evaluated in turn. The major priority was given to the availability of components that would allow for the fabrication of a dice within normal physical dimensions, (17mm or 19mm per side based on a measured commercial die), while still providing the desired functionality.

Fig. 4 shows the design of the dice constructed from two parts, to allow access to a cavity where two silver oxide batteries would be placed connected in series. The cavities for each of the components were designed into the volume of the die itself. The channels, to provide interconnects between each of the components, were likewise mechanically built into the design of the dice. This prototype demonstrated the feasibility of the concept as well as the availability of components sufficiently small to allow for the desired operation within the target volume. The first version prototype also revealed shortcomings that would be addressed in future iterations of the design: (1) the use of disposable, replaceable batteries was seen as an undesirable complication. These would be later replaced with recharge-able batteries to avoid requiring a structure that could be opened repeatedly. (2) The use of individual LED control was also deemed unnecessary. Instead, LEDs for each side could be grouped together for simplicity, allowing for the reduction of I/O ports used on the microcontroller and providing smaller overall dimensions of the largest chip component

Figure 4: Design of prototype version 1.

Figure 5: Design of prototype version 2.

2) Version 2: Lithium Polymer Battery with A Wireless Charging System

The second prototype improved on the shortcomings observed on the first iteration and is shown in Fig. 5. In this version, the LEDs were not individually controlled by a cor-responding micro-controller I/O port; instead, there were up to two groups per face that would ash separately. This modi-cation allowed for a physically smaller microcontroller with a smaller pin count.

The disposable batteries were replaced by a lithium polymer cell; meaning that the case could be sealed upon assembly for additional structural robustness.

3) Version 3: Using Rechargeable Lithium Polymer Battery With A Standard USB Charging Port

The third prototype stage addressed the shortcoming identified in version 2. The overall design remained largely unchanged; however the induction charging was eliminated and replaced with a simple micro USB-b charging port. Through this charging port, a simple USB to micro USB-b cable can be utilized to directly charge the lithium polymer battery from any computer USB port. This modification was intended to improve the appeal from a commercial perspective, by providing a simple user interface and reducing the sale price by eliminating the separate charging station. The power module cylinder was modified by merging the power circuit with the sealing cap used in version 2. The final design, both in CAD and actual fabrication, is shown in Fig. 6.

III. RESULTS AND DISCUSSION

Traditional 3D Electronics

The design of traditionally manufactured electronics (e.g. cell phones, laptops, defense and space systems, etc.) has been driven towards better volume utilization without abandoning the flat printed circuit board paradigm. The traditional 3D electronics methodology can be more accurately described as 2D-layered or 2-1/2 D. An alternative approach used in traditional 3D electronics is to implement flexible printed circuit boards or ` ex circuits' that allow some freedom to conform to an irregular volume by bending the circuit into the final volume. The next step in proposed development process of the design of the six-sided gaming die was to leverage the work previously done and to finalize the design using a traditional flexible circuit approach in order to produce a product with as low a cost point as possible.

A. Flexible PCB Design

For this final traditionally manufactured version of the smart dice, three main components included: (1) a hollow plastic cube built from plastic injection molding providing the hous-ing; (2) a flexible circuit board designed as a at unfolded cube and folded into the cube cavity and (3) the battery. The flex circuit was a `cross' shape prior to being folded into the cube was created using layout and routing software. A handful of manual interventions were still required. Any wires connecting the top and bottom layers were manually moved away from the flexing points in the circuit.

The LEDs were manually laid out to match the natural location of the die pips on each of the six sides of the dice and the remaining components were laid out on the opposite side from the LEDs to remain hidden on an internal surface. As required for this methodology, the flexible circuit was then sent to an outside vendor for quote and fabrication.

Plastic Injection Molded 3D Case

Though the advantages of AM techniques have been dis-cussed at length, the current state of development of these technologies still makes them a costly alternative for mass production. Consequently, a more conventional technique for manufacture of the housing was chosen: a plastic injection molded case. In order to produce a plastic case, care must be taken to address some design constraints particular to this technology. While designing a part to be fabricated through injection molding, the ``parting line'', where the two mold halves will meet, must be determined so that once solidified, the part will allow the mold halves to separate and the completed part to be extracted. Likewise each part must be designed with a small draft angle to allow proper separation from the mold. The draft angle ensures that the solidified material is released from the mold without distortion or dam-age. Additionally, care must be taken to ensure a smooth path for the plastic material to flow through the cavity to form This stress can result in deformation and other defects and design guidelines were observed in the construction of the final die housing which would ultimately contain the flex circuit and battery. Final design shown in figure.7.

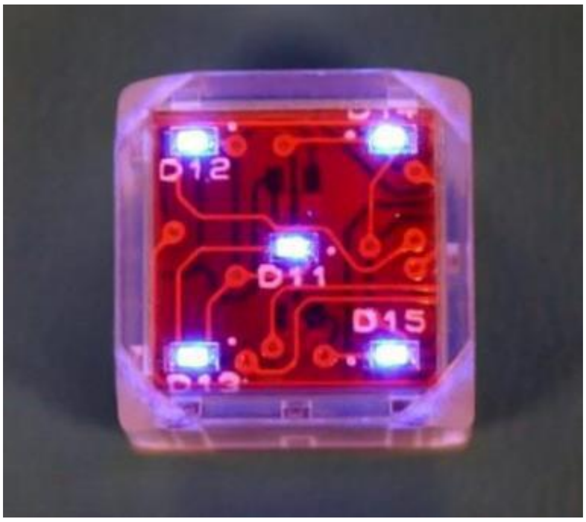


Figure 7: Final Version with Traditional Manufacturing.

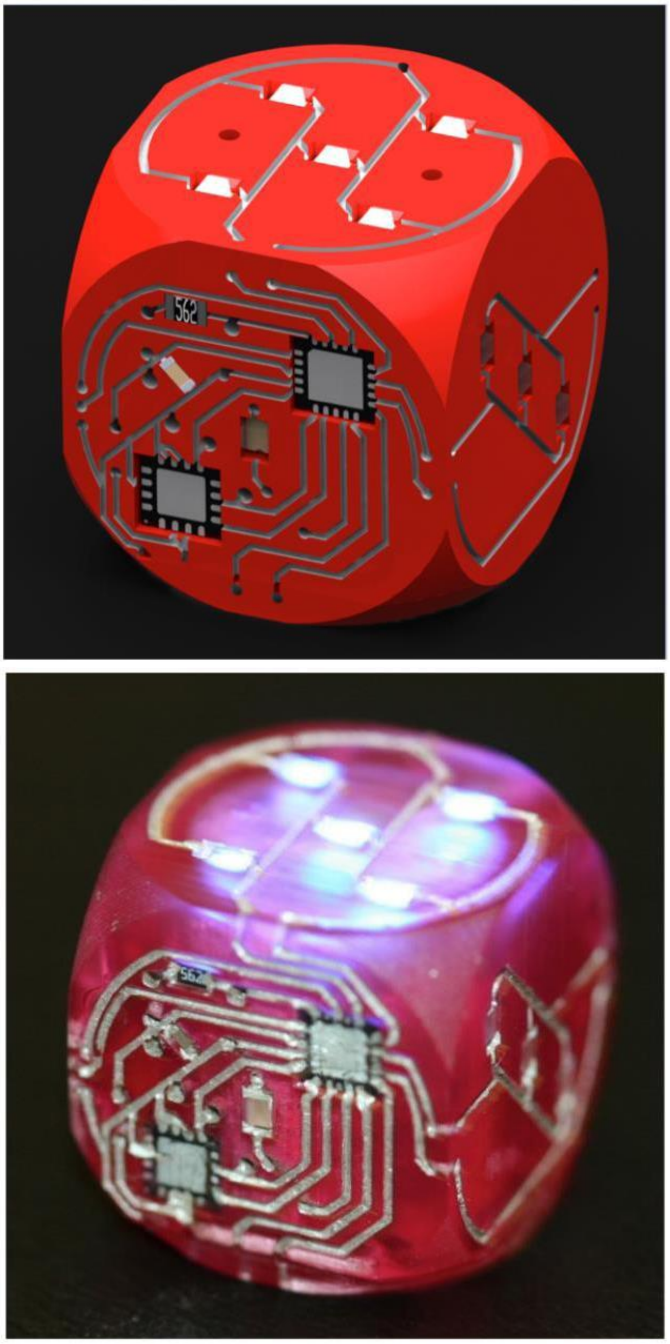


Figure 6: Version 3 Design

IV. CONCLUSION

This paper describes an enhanced 3D printing technology that by printing multifunctional prototypes can dramatically reduce the total time of the design cycle for an electronic device. An example case study is provided of four gen-erations of a novelty electronic gaming die. The process, which includes building dielectric substrates using 3D printing, is enhanced with other complementary manufacturing technologies such as conductor embedding and component pick and place. By interrupting the 3D printing process and integrating electronics functionality into the structure, rapidly-developed, high fidelity prototypes can be fabricated in order to capture and evaluate form, t and functionality simultaneously.

V. ACKNOWLEDGMENT

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