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# 3D Printing for the Rapid Prototyping of Structural Electronics

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**ABSTRACT** In new product development, time to market (TTM) is critical for the success and profitability of next generation products. When these products include sophisticated electronics encased in 3D packaging with complex geometries and intricate detail, TTM can be compromised—resulting in lost opportunity. 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 stereolithography 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.

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

## I. INTRODUCTION

A new product typically undergoes several transformations before becoming available for sale to the general public. A new device idea is initially prototyped in order to evaluate the fit and finish of the final part as well as to optimize the fabrication process to identify difficulties in manufacture. These steps can be time-consuming and expensive, creating a significant obstacle for new product introductions especially for startups that may not have the appropriate, usually expensive, machining equipment required for prototyping.

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 traditional 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 limitations of the AM technologies – in which compromises were made in terms of material choices, surface finish and dimensional accuracies. For instance, stereolithography (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 fit 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, fit, aesthetics and functionality were explored by 3D printing several versions of electronic devices as rapid, high-fidelity 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. 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 fit and form of a product within a few hours of completing the CAD design [1]. However due to the limitations resulting from the distinct material requirements for AM processing, the designer was unable to fabricate the prototype in the material required for the end-use final product [2]. AM has also been used to improve TTM through rapid tooling in which molds could be fabricated more quickly and then subsequently used in a traditional manufacturing process [3] – in this case, proving vital in cost and time-savings for the development process. 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 [4]. However, in the context of prototyping electronic circuits, which are increasingly encased in 3D forms, rapid prototyping only provided fit 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.

Recently, these deficiencies have begun to be addressed through enhanced 3D printing, such as SL or FDM, in combination with both conductor embedding and robotic pick-and-place. The AM technology can fabricate a dielectric substrate in any arbitrary form, while either micro-dispensing or wire embedding can be used to deposit electrical interconnects through the precise printing of conductive inks or wires to realize traces between components. With this integrated manufacturing capability along with the insertion of electronic components (i.e. chips, passives, batteries, antennas, sensors, etc.) fully functional 3D structural electronic devices can be achieved [5]–[13].

The seminal concept of printing multi-functionality can be traced back at least two decades to the experiments described in [14], where a two-part polyurethane foam was cast to form a preferred packaging for existing electronic components. This process was patented in 1994 [15] and in 1996 with funding from the Defense Advanced Research Projects Agency (DARPA) and demonstrated the repackaging of the components of a personal computer for divers into a case conformal to the leg of a diver and waterproof to 100 feet [16]. Subsequently, the research led to the creation of improved algorithms for optimization of these integrated processes [17].

In 2004, [18]–[20] developed a dual process that included the high accuracy capabilities of SL with the material dispensing capabilities and precision of Direct Write technologies to deposit silver loaded inks, which provided the electrical interconnects between components to enable true electronic functionality. This methodology was patented in 2008 [21]. The research was further enhanced with the creation of a custom-built machine that integrated an SL system with a dispensing pump to automate the process. Fabrication of complex, intricately detailed dielectric substrates created with multiple layers of components and interconnect was now possible. An example included a functional circuit with a 555-timer oscillator and thermistor in order to illuminate a Light-emitting diode (LED) at a rate based on the measured temperature [22].

In 2007 [23] utilized a tabletop AM system - the Fab@Home - to create simple, yet functional circuits. Utilizing a conductive silicone to form the electrical interconnects, a 555 flashing circuit in both two and three dimensions, a flashlight and a toy character with eyes that illuminated upon pressing the belly were fabricated. Printing vertical interconnects was identified as a challenge. A similar LM555 timer circuit was independently demonstrated by [24] on a polythermide substrate using a different process called laser direct write (LDW) in which a laser was used for micromachining (subtractive) as well as controlling the amount of conductive material transferred to the substrate (additive). In other work, the Direct Write approach was integrated with Ultrasonic Consolidation (UC) technology and FDM to fabricate embedded electronic components within solid metal structures. The process required subtractive technologies to carve out a cavity to house the electronic components, the deposition of a layer of thermoset insulator to prevent the base metal from shorting the circuit, and the careful application of ultrasonic energy to prevent the horn from damaging the electronic components, but was ultimately successful in building a functional circuit in a metal protective housing [25]. In order for any of these hybrid systems to become functionalized, significant work is necessary in terms of process planning [26] and material development [27]. All of these collective efforts have led to the fabrication of ever more intricate devices up to and including the research presented in this paper - possibly the most complicated example of 3D printed electronics. Each serves as a testament to the importance and interest in the capability to in-situ embed electronics and electrical interconnect within AM structures during fabrication for - at a minimum - prototyping purposes as described in this paper, but eventually for the manufacturing of final, end-use, high-value, customized 3D products.

## III. 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 prototypes, these types of parts have been exclusively made to test appearance and fit 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. However, in products outside of the consumer markets, such as in the aerospace or biomedical industries, reliability may stand as the only significant barrier between the prototype becoming an end-use final product or not. Improvements in the area of reliability are inevitable with substantial research in materials and AM processing already in progress. Until these end-use requirements can be fulfilled, the proposed hybrid AM process can fabricate prototypes that will enable at least a comprehensive evaluation of the final design, not only for form and appearance, but also for electronics functionality - simultaneously.

### 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 interconnects 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 SolidWorks without the inherent features for electronics functionality. This lack of software support has relegated 3D printing of electronic devices to relatively simple circuits as routing and placement has been done by hand; however, the circuit designs that have been completed have achieved greater utilization of the available volume given the fabrication freedom offered by the manufacturing technology – with complex geometries easily fabricated in 3D. 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. The original device was a signal conditioning circuit – the schematic of which was provided by engineers at NASA's Johnson Space Center as a benchmark circuit in order to demonstrate the volumetric efficiencies of 3D printed electronics. The circuit volume was reduced to a volume of 0.5'' by 0.5'' by 0.125'' as shown with a component and trace density of 27% significantly reduced from the original design.

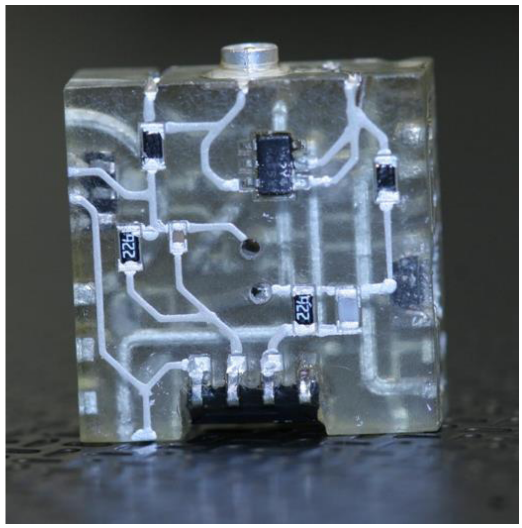

FIGURE 1. 3D printed signal conditioning circuit.

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 flat 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). Mechanical CAD software can later ''deform'' 2D circuits generated from electrical CAD software with curved and folded edges. However, limiting routing to 2D planes foregoes the capability of realizing interconnects between layers - relegating the circuits to simple networks without the use of cross-over points. Utilizing more than one surface as well as connections between multiple surfaces (similar to vias in PCBs) are necessary to provide complex circuit networks regardless of the underlying deformation geometry.

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.

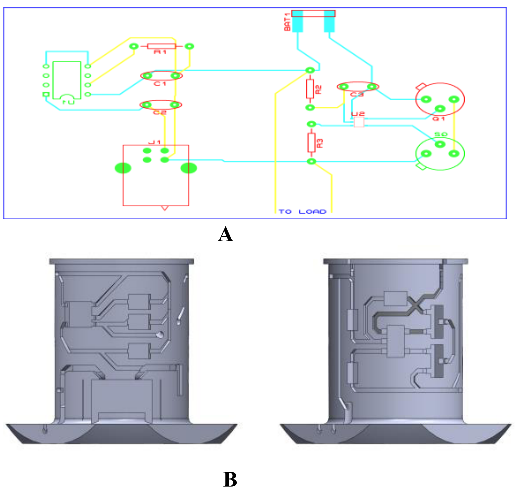


**FIGURE 2. A) Battery charging circuit to be deformed and B) both sides of the final mechanical representation.**

Fig. 3 illustrates a more complex design with a microcontroller and accelerometer in surface mount packaging technology that provides fine pin pitch (0.56 mm) and miniaturized footprints. Although the design included circuits on flat 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.

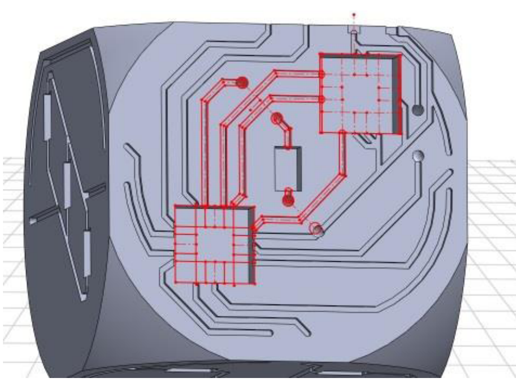

**FIGURE 3. Electronic circuit mechanically designed into substrate.**

### *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 electronic 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 viability 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. After the circuit was finalized, the number of components increased to 25 (Table 1) and the layout and routing was implemented manually using mechanical CAD software.

**TABLE 1. List of required components.**

| Qty. | Description |
|---|---|
| 1 | 8bit Micro-controller QFN package |
| 1 | 3-Axis MEMS accelerometer |
| 2 | 1.5V silver oxide or alkaline batteries |
| 21 | LEDs to supplant dots on die faces |

For the first version, cost and component availability did not carry a high priority as the initial devices served as prototypes, and consequently higher cost was considered acceptable. 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


**FIGURE 4.** Design of prototype version 1.

**FIGURE 5.** Design of prototype version 2.

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 rechargeable 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.

### 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 corresponding micro-controller I/O port; instead, there were up to two groups per face that would flash separately. This modification 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.

However, the modification also necessitated a safety and a charging circuit inside the device and a special methodology to be developed to charge the batteries. An induction charge system was developed to allow non-contact charging.

Finally, ease of manufacturability due to conductive trace spacing was also improved by switching to an overall dice dimension of 19mm per side. Simultaneously, the overall volume increase allowed for a physical design change, the introduction of significant rounding of the dice corners provide the dice with less inhibited rolling. A power module was designed to include a lithium polymer cell and the required safety and charging circuits. A cap was used to seal the assembly.

Though this iteration was a significant improvement over the previous version, shortcomings were also identified in this device: The need for a custom made charging station, which would require additional external components and likewise would introduce further complexity and cost. The induction charging system was subsequently abandoned.

### 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.

## IV. 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. Limited success has been achieved by layering planar circuit boards and interconnecting the boards through flat ribbon cables or through

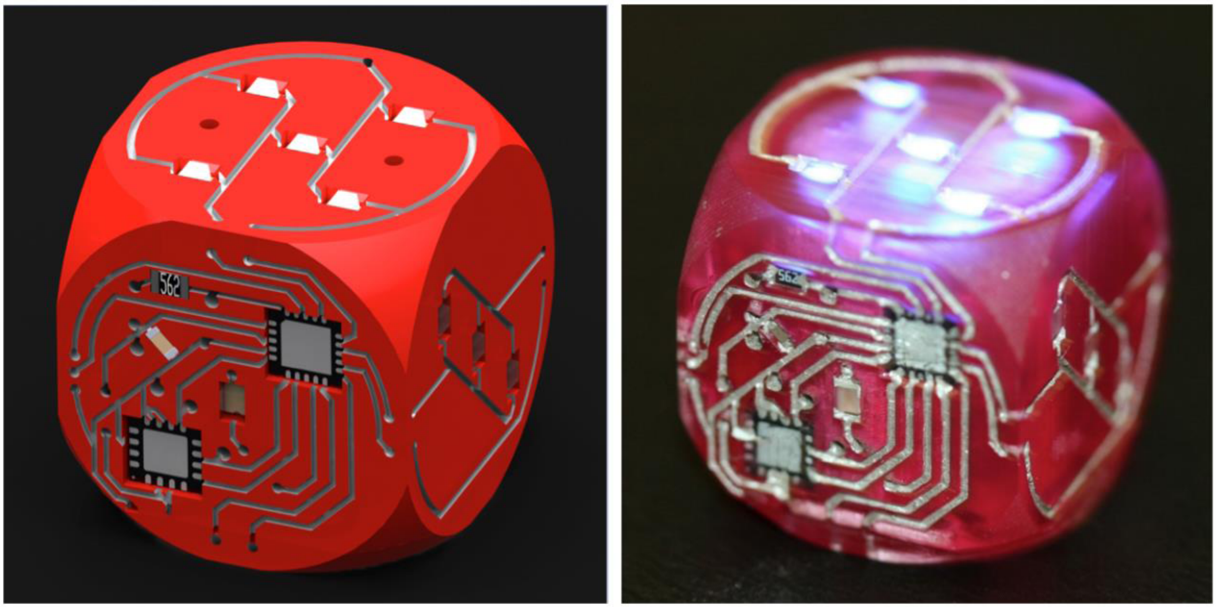


**FIGURE 6.** Version 3 design.

connectors which allow one circuit board to be mounted directly onto another with a motherboard/daughterboard configuration. 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 'flex 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. This step was necessary to advance the device into a more high volume, commercially viable product (for a low-cost novelty toy market, for example – although as will be described later, a higher cost market, say for a Las Vegas casino to provide gifts to its high rollers, may exist for the AM-fabricated die because of its unique touch and feel including the electronics integrated on the surfaces of the die) including full design consideration for (1) the final cost of the end-use product, which is paramount for consumer electronics and (2) product reliability which is compromised with the use of conductive inks for electrical interconnect as used in the 3D printed methodology.

### *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 housing; (2) a flexible circuit board designed as a flat 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. The final physical implementation is shown in Fig. 7. A handful of manual interventions were still required. Any vias 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.

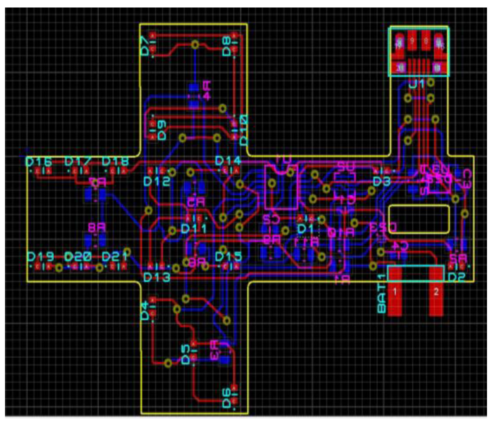


**FIGURE 7.** Automated design for flexible circuit.

### *B. PLASTIC INJECTION MOLDED 3D CASE*

Though the advantages of AM techniques have been discussed 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 damage. Additionally, care must be taken to ensure a smooth path for the plastic material to flow through the cavity to form the part; this is achieved by, as much as possible, keeping wall thickness the same throughout the structure and eliminating sharp corners in the design. As the material cools, regions with greater mass typically cool at a slower rate, and uneven cooling may cause thermal stress in the part. 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. The final design is shown in Fig. 8.

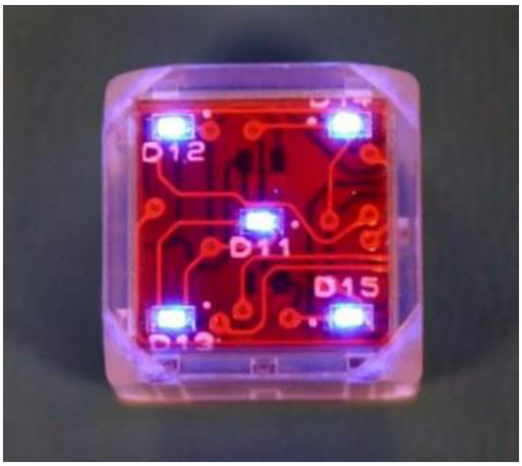


**FIGURE 8.** Final version with traditional manufacturing.

## V. COMPARISON OF MANUFACTURING TECHNIQUES ON TIME TO MARKET (TTM)

Of the various prototype fabrication techniques available for the proposed gaming die, two of which have been discussed at length here: 1) an enhanced 3D printing with the integration of conductor and component embedding, and 2) traditional flexible circuit fabrication embedded within a plastic case fabricated with injection molding. It is important to note that in this application example, bread boarding the circuit was not sufficient to test the functionality as the electronics were required to be rolled (using the six-sided die) to understand the impact of the corresponding settling time before the top surface could be illuminated. Versions 1 through 3 were fabricated using the SL technique which, without requiring tooling, allowed for faster turn-around time and were therefore, better suited for prototyping in early stage development. However, the reduced durability of the conductive inks and photo curable polymers would presumably result in a less reliable final product [9], [28]. Alternatively, version 4 was fabricated using traditional manufacturing, and consequently could be fabricated for significantly less cost per device – better for high volume production - but with the trade-off of extended lead times due to the required tooling and therefore, would not be well suited for the development cycle.

In order to compare and contrast these differences, it is important to note that (1) the research and development of a fully automated 3D printing system with complete integration of the component and conductor embedding technology is currently underway and (2) the work described here included significant amounts of manual intervention. However, realistic assumptions can be made and conclusions can be drawn regarding the time required to fabricate a device of related complexity to the gaming die using a fully automated, integrated 3D printing technique. Furthermore, even with different forms of 3D printing possible (e.g. material extrusion versus vat photo polymerization – used in this example), as well as different forms of embedding conductors (ink-jetting, micro-dispensing, embedding of solid wires, etc.), and a wide range of different materials, the assumptions of fabrication time remain reasonable and can be applied generally to other enhanced AM technologies. In fact, a new system based on FDM, which extrudes production-grade thermoplastics, is the current focus of the research group, and furthermore, this system avoids conductive inks by submerging wires directly into the thermoplastic without disrupting planarization of the substrate to allow for subsequent continuation of the fabrication. The following fabrication time analysis would be similar and applicable to this next generation system as well.

In terms of time from design of part to first part fabrication, version 3 (SL fabricated substrate with electrical components) required 6 hours for the stereolithography and then 24 hours to populate the substrate with components and deposit and cure ink in the channels for a total of 30 hours. Version 4 (plastic injection molded shell with electrical components on a flex PCB) required a minimum of 120 hours to build, which resulted from either of two critical paths: (1) the time to order the injection mold and build the molded shell (which could possibly be equivalent to the time for the previous example if a 3D printed alternative were available), or, more critically, (2) the time to fabricate the flexible printed circuit board and populate the board with electrical components. Many assumptions can be made about the range of time that these two processes can take but a reasonable estimation for either is 5 workdays based on the experience of this project (yielding the minimum 120 hour estimate). For a contract company to build and populate a flex circuit would require that all components were in stock and generally lead times can be much longer than a week without sufficient upfront planning. Based on this simple analysis, the new breadboarding approach using SL with embedded electronics, provided a minimum of 4:1 improvement in time to test the prototype. This translates into significant time savings in time to market.

To compare the two existing cases to a hypothetical automated system, if one were to build the same SL substrate without any of the components, the build time would only be about 6 hours. This provides a base line for an automated system, which would require integrating additional manufacturing activities for the placement and routing of components. The build time would increase by some amount required to integrate the electronics and this time would be design dependent – where designs with complex substrates and simple electronics (e.g. button and LED in a large structure) would spend a larger fraction of time fabricating the dielectric, while other designs that had complex electronics and simple substrates would be reversed. If the first case added 25% to the manufacturing time and the second case tripled the time (300%), then the time to part would range from 7.5 hours to 18 hours depending on the design complexity – significantly less – in either case - than the traditional approach at a minimum of 120 hours.

Finally, as an anecdotal comment, the 3D printed version was overwhelmingly received more favorably than the traditionally manufactured version – possibly due to the color, or the surface finish, or the modern appearance of the electronics flush to the external surface. Without a doubt, 3D printing currently has captured the imagination of popular culture today, and consequently, the 3D printed die version has a more intangible attractive quality (e.g. *je ne sais quoi)*.

## VI. 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 generations 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, fit and functionality simultaneously.

## ACKNOWLEDGMENT

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