

3D Printed Electronics: Role of Materials and Processes



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1 Introduction

As technology grows in rapid phases, the process of developing electronic components is also expanding. 3D printing has made it easier to fabricate electronics and also plays a major role in innovation. The global electronics components market is expected to rise continuously by 7.7% as a result of the current electronics boom, from 5.41 million US dollars in 2017 to 7.86 million US dollars in 2022 [1]. The most common method for producing printed electronics is to use printing processes frequently used in the graphics sector to impart functional inks to plates (screen, ink-jet, flexo, gravure, etc.) [2]. There are several methods of 3D printing electronic components or circuits. They may be contact type or noncontact type. Majorly, the 3D printing techniques are noncontact in nature. The materials used are widely pursued since they offer numerous advantages in terms of ease of processing, good compatibility with a variety of substrates, and a great opportunity for structural modification [3]. In recent years, various printing technologies have been developed in the areas of screen printing, inkjet printing, and microcontact printing. Most of the work has been for the development of an inkjet solution capable of processing conductive material. The biggest potential benefit for high-density, high-speed, miniature innovative packaging is offered by nanomaterials, composites, and hybrids. These structures are incredibly unique materials with a wide range of potential uses due to their small dimensions, strength, and remarkable physical and electrical properties. With the utilization of 3D printing for electronic components, the application area is enlarged

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[4]. There have been efforts to develop post-processing procedures for 3D printed parts to give them the appropriate electronic properties to get around the high cost and constraints of specific 3D printed electronic systems employing surface direct write technologies. The most well-known of these is probably electroplating plastic components, which is done after a preliminary metallization by electroless deposition or conductive paint [2]. The application area of 3D printed electronics covers stretchable electronics, radio frequency antennae, and 3D structural electronics [5–23]. The present paper discusses the recent advances in 3D printing techniques for printed electronics. Moreover, the materials required for electronics applications are also discussed along with the applications areas of 3D printed technology.

2 Techniques for Printed Electronics

2.1 *Conventional Techniques for Printed Electronics*

There is direct contact between the print head and the intended substrate when using conventional electronic fabrication techniques known as contact printing to transfer the required inked patterns. The functional ink is normally transferred to the target substrate by contact printing procedures using a single sheet or engraved roll. However, the benefits and drawbacks of various contact printing methods could differ based on the printing principles used, therefore critical to carefully compare how each contact printing method operates. There are two steps in the printing process for gravure printing. During the first stage, an ink fountain's inks are collected by a gravure roller, and the amount of ink that is applied is controlled by a blade. Similarly, an ink-blocking stencil prevents an unwanted part of the substrate from touching the functional ink.

Rotary Screen printing uses pressure from an impression roller to imprint predetermined patterns on the substrate. Flexographic printing (also known as offset printing), in contrast to gravure printing and rotary screen printing, uses a soft plate roller to transport a controlled measure of ink. The pattern is indirectly imprinted on the substrate and the screen-printing technique variation known as flatbed screen printing recently allured a lot of attention.

2.2 *Screen Printing*

Screen printing can be applied in many ways, including Roll-to-Roll (R2R) production with an optimum solution and printing settings. Using an optimal approach and the same process constraints, screen printing can be done again and again with identical results [24].

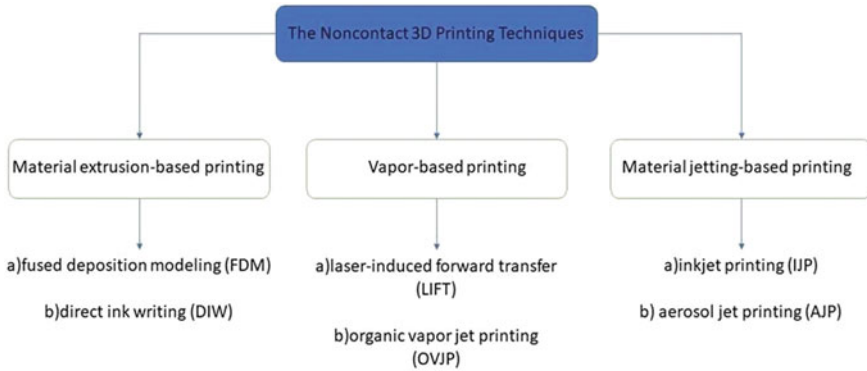


Fig. 1 Classification of noncontact type printing

For screen printing, typically, flatbed screen printing involves coating the screen with a printable solution, coating the mesh on the stencil with ink using a squeegee, and then pressure applied in a controlled manner. High-speed production is made possible by rotary system screens, but they are costly and need frequent cleaning owing to material clogging. However, several factors, including the geometry of the squeegee angle, the mesh size, the solution viscosity, and the snap-off between the screen and the substrate, have an impact on the quality of screen printing.

2.3 3D Printing Techniques for Printed Electronics

Regardless of the various benefits, the printing quality and setup costs of contact printing limit its application for the fabrication of electronics. Noncontact 3D printing helps to create adaptable and affordable electronic device applications. The noncontact 3D printing method, in contrast, printing may generate less waste and reach a greater resolution. As a result, it has received considerable interest in several areas.

The noncontact 3D printing techniques are further categorized into three types as illustrated in Fig. 1.

2.4 Material Extrusion-Based Printing

In this material extrusion-based printing, the filament is fabricated using the hot extruder head and the filament is made of thermoplastic material shown in Fig. 3a. In the working principle of the fused deposition modeling (FDM) technique, the melted filament is extruded through a nozzle. Though fused deposition modeling is used in printed electronics, the application of the printed electronics is very confined because of resolution and printing quality. Direct ink writing (DIW) is similar to

the fused deposition modeling (FDM) technique, the difference is that DIW uses functional ink instead of filament, and the ink is stored in the barrel. The ink is deposited in the substrate by extruding out from a nozzle shown in Fig. 3b. The ink should be considered low-viscosity ink and shear-thinning ink are two different types of functional inks that can be used with DIW. Low-viscosity ink runs down the nozzle without any difficulty, whereas shear-thinning ink needs a much stronger pushing effort. A curing system must be employed when using low-viscosity ink to guarantee that the extruded filament material fixes promptly and maintains its 3D structure. The result functional material is often combined with additional binding material in functional inks, which might reduce the functional material's electrical performance. Dispensing techniques come in a variety of forms, including pneumatic, piston, and screw. To guarantee, the printed filament creates a steady structure; it is essential to apply the right printing parameters and conditions.

2.5 Vapor-Based Printing

The modified technique of laser direct-writing (LDW) known as laser-induced forward transfer (LIFT) has been used to deposit materials to use for electronic applications. This method concentrated laser pulse with high intensity as employed to deliver energy enough to heat the thin film interface. High-quality electrical designs can be created by vaporizing metal from the melted solid film interface and depositing it on a target substrate because of energy accumulation. Organic vapor jet printing (OVJP) method utilizes heated cells that house the molecular organic source material to create saturated source vapor that is carried by a hot inert carrier gas. After expanding, the gas mixture impinges on the substrate creating a high-resolution line.

2.6 Material Jetting-Based Printing

There is growing engrossment in adopting material jetting-based printing for manufacturing electronics, because of the benefits of higher precision and less waste. Inkjet printing (IJP) can be divided into two categories based on different operating principles: continuous inkjet (CIJ) printing systems and drop-on-demand (DoD) printing systems. The printed pattern is produced by the uncharged drops while the charged ones are reused. In systems based on DoD, the droplets are ejected. An innovative noncontact ink writing method called AJP is used to create electronic circuits instead of IJP. Using a carrier gas flow, the functional ink is first atomized into droplets (2–5 μm) and then transferred to the print head. AJP has the potential to print with highly viscous inks and even on curved surfaces maintain a good resolution.

2.7 Inkjet Printing

Using a nozzle to deposit drops which may be coupled to a basin of liquid material, inkjet printing is a type of digital printing. The resolution level is determined by the droplet's volume and area covered as it leaves the nozzle. Additionally, it is reliant on how the substrate wets. When it comes to reducing floor space, the initial investment, and the commissioning time, inkjet or digital printing facilities are a preferred option among other printing equipment. A production line can be scaled up to produce electronic prototypes using simultaneous printing on a large number of printers.

Due to their superior conductivity and endurance (several thousands of operating hours), inorganic/metal inks are most frequently utilized for inkjet printing. The affordable materials can be utilized for single-use applications like radio frequency identification (RFID) antennas, which are often employed as distinguishing tags for inventory control in retail outlets or to expedite payment processes. Continuous inkjet (CIJ) and drop-on-demand (DOD) printing techniques are the two primary inkjet printing subcategories (Figs. 2 and 3).

2.8 Aerosol Jet Printing

Aerosol jet printing (AJP) provides a rapid way to create miniature features on the substrate material. The technique does not require a mask, therefore, sometimes referred to as maskless material deposition. Various electronic components and devices can be printed with this technique. Moreover, many materials can be used in this process such as materials required for the fabrication of dielectric and conductive traces. In contrast to conventional electronics production or commonly used direct-write technologies, a key component of AJP facilitates the development of a wide range of devices with higher geometric complexity.

The technique can be used for fabricating intricate features and even solar cells and screens. A wide range of material viscosities can be used in AJP and printing can be done on even nonplanar surfaces. The gas flow that results from atomization or ultrasonication produces a spray of tiny droplets that power the aerosol printing process. Because it can handle, AJP is regarded as the most intriguing technology among other contact-less printing methods since it can print on various materials with greater resolution designs. Figure 3 illustrates the comparison of printing techniques.



1) Continuous Inkjet			A stream of ink is continuously ejected by a nozzle, and charged droplets are deflected and positioned using an electric field. Remaining Droplets are collected by gutter and recycled.
2) Drop on Demand Inkjet			Droplets are ejected on demand. It is a simpler system compared to continuous inkjet
2a	Thermal		The ink is heated by a heating element and ejected as droplets through the nozzle.
2b	Piezo		A piezoelectric transducer is applied with a voltage pulse which creates an acoustic wave propagation in the ink and droplets are ejected through the nozzle.
2c	Electrostatic		The droplet formation involves a complex interaction of surface tension ratio between ink and nozzle and electric field. The signal fed to the printhead balances forces to create ink droplets.

Fig. 2 Categorization of inkjet printing

3 Material for 3D Printed Electronics

Printing conductive materials has gained the most interest among these methods for the manufacture of complex 3D electronics due to the durability, affordability, and development of new printers. Printing enables the construction of intricate electrical circuits in a 3D way, in contrast to conventional microfabrication techniques that often produce flat devices. When using different 3D printing methods for electronics manufacture, knowledge of the spectrum of materials and accendibility, or from prototype to manufacturing, are crucial factors to take into account. Understanding the characteristics of the existing materials for electronic manufacturing and the technologies employed is essential to comprehending the future function of 3D printing processes. These fundamental electronic parts are constructed from functional materials including metal, semiconductors, dielectrics, and polymers that may be connected, printed, or physically positioned on a variety of substrates using

Main types	Fabrication process	Fabrication techniques	Material types
• Gravure printing	• Contact printing	• Roll-to-Roll printing	• Ink-based
• Flexographic printing	• Contact printing	• Roll-to-Roll printing	• Ink-based
• Offset printing	• Contact printing	• Roll-to-Roll printing	• Ink-based
• Rotary screen printing	• Contact printing	• Roll-to-Roll printing	• Ink-based
• Flatbed screen printing	• Contact printing	• Sheet based printing	• Ink-based
• Fused deposition modeling	• Noncontact printing	• 3D printing	• Filament-based
• Direct ink writing	• Noncontact printing	• 3D printing	• Filament-based
• Organic vapor jet printing	• Noncontact printing	• Vapor deposition	• Vapor-based
• Laser-induced forward transfer	• Noncontact printing	• Laser direct write	• Vapor-based
• Aerosol jet printing	• Noncontact ink writing	• 3D printing	• Ink-based
• Inkjet printing	• Noncontact ink writing	• 3D printing	• Ink-based
• Hybrid printing	• Noncontact printing	• 3D printing	• Multi-material based

Fig. 3 Comparison of printing techniques for printed electronics [25]

various printing and patterning methods. The materials for 3D printed electronics can be solids, inks, pastes, etc.

3D printed electronics can be made using various materials such as:

1. **Conductive Filaments:** filaments that contain conductive materials such as metals or carbon-based composites.
2. **Resins:** photopolymer resins that contain conductive materials or nanoparticles.
3. **Metal Powders:** metal powders such as copper or nickel that can be sintered or fused using a laser or other heat source to create conductive paths within a 3D printed structure.
4. **Graphene and Carbon Nanotubes:** These materials can be added to resins or filaments to enhance their conductive properties.
5. **Silicone Rubber:** silicone rubber for flexible and stretchable electronics.

The choice of material depends on the specific requirements of the 3D printed electronics such as flexibility, conductivity, and resistance to heat or chemicals. To be processed in the same layer as other functional, dielectric, and photo-imageable materials, printable materials must be physically stable toward them. Devices and packages must maintain their structural and electrical integrity and be sturdy to provide a longer service life. Since organic and polymeric materials have several benefits, such as processing under low temperatures, durability, and a large possibility for change in structure, organic materials have been extensively sought for these uses. Nanomaterials are also a great choice for 3D printed electronics because of the biggest potential advantage for high speed, miniature innovative bundling that is offered by nanomaterials, composites, and hybrids. These structures are extremely

unusual materials with a wide range of intriguing uses because of their tiny dimensions, strength, and exceptional physical and electrical characteristics. Functional polymer, composite, and hybrid-based semiconductor devices are regarded as good choices for applications involving electronics, where they completely use printable polymer technologies and various fillers may be added to a functional polymer system. Advanced packaging uses have been described for several nanocomposites. There is room for improvement in the current materials, allowing for the development of low processing temperature, adaptable, and affordable printable processes, as well as materials for mass production, even though some of the nanocomposites used to advance semiconductor packaging technology are not always printable.

3.1 Conductive Polymer Filaments

Over the past two decades, conductive inks have attracted a growing amount of interest and are transforming the industry. Mainly because of their qualities including conductivity, appropriateness for printing substrates, ease of processing, and mechanical flexibility, as well as for their capacity to impart new traits, prowess, and intricate functions.

For use in electronics, a wide range of materials, including organic and inorganic materials as well as conductors and semiconductors, have been investigated. Water, oil, or solvent-based inks are the most popular varieties. The ink's basic composition consists of various substances both in solid and liquid-based materials, each with unique properties that are tailored to the characteristics of printing technology, allowing the ink to be applied to a wide range of applications with ease. Because conductive nanoscale particles are included in the mix, conductive inks are electrically conductive. Metallic nanoparticles are frequently stabilized in ink solutions by organic ligand shells or capping agents. This creates a uniform and stable dispersion and prevents particles from sticking to one another [25].

3.2 Semiconductors

Semiconductors adjust their electrical characteristics in reaction to environmental factors such as electric fields, mechanical strains, and chemical adsorptions. However, under electrical control, they can also change their physical properties. Semiconductors are necessary for many different electronic devices, including transistors and sensors, because of these characteristics. Even though silicon- or oxide-based inorganic semiconductor materials have traditionally been used in high-performance electronics by the photolithography-based subtractive fabrication process, organic semiconductor materials have been actively researched as 3D printable inks due to their easy deformability and solubility to various organic solvents [26].

In general, inorganic semiconductors perform better and are more stable than organic semiconductors. As a result, research was done on creating printable ink using inorganic semiconductor materials. Dynamic 3D structures are made possible by semiconducting inks' manipulation of viscosity.

3.3 Dielectric

Electrically insulating materials have been made easier to use as dielectric materials for transistors and capacitors, or as substrates on which other electronics may be built. Electronics' structural variety and integrity have recently been shown to increase with the use of 3D printing for insulating materials. Electrically insulating materials have been made easier to use as dielectric materials for transistors and capacitors, or as substrates. Electronics' structural variety and integrity have recently been shown to increase with the use of 3D printing for insulating materials. Despite having a lower dielectric constant than inorganic materials, polymers have been intensively explored as 3D printed inks because of their low processing temperature properties. Particularly, the brittleness of inorganic materials can become a restriction in flexible/soft electronics, while organic materials can get around this problem. The use of hybrid ink made of organic–inorganic substances has recently been described in investigations for 3D printable dielectric layers.

3.4 Metallic Nanoparticle

They have unique physical, chemical, and biological properties that make them promising materials for 3D printed electronics. For example, nanoparticles can be used as conductive inks in 3D printing to create electronic devices with high conductivity and improved mechanical properties. Additionally, nanoparticles can be used in the development of 3D printed sensors, actuators, and energy storage devices. Nanoparticle-based 3D printing has the potential to revolutionize the way electronics are manufactured and enable the creation of new and innovative devices. The individual metallic nanoparticles in metallic nanoparticle inks are enclosed in a layer of insulating organic additives and stabilizing agents and suspended in liquid media. In addition to preventing the metallic nanoparticles from agglomerating, the organic additives and stabilizing agents also obstruct the passage of electrons from the particles to the surface [27]. Figure 4 shows some of the applications of nanocomposite in 3D printed electronics.

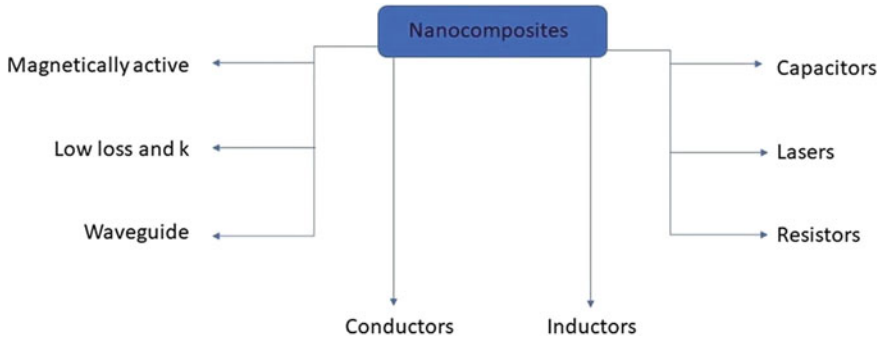


Fig. 4 Overview of some of the potential applications of nanocomposite in 3D printed electronics [27]

3.5 Carbon Nanotubes and Graphene

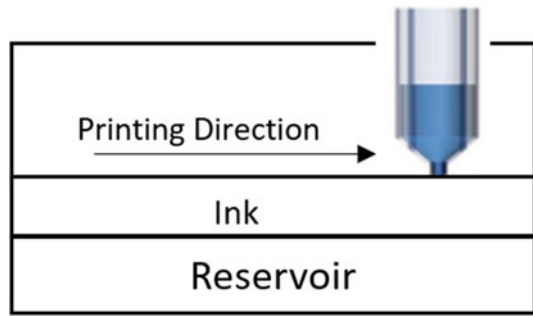
Because of their unique traits, carbon nanotubes (CNTs) are still one of the most researched materials in use today. They find use in wearable electronics, energy storage and harvesting devices, optoelectronics, chemical sensors, and water filters. Conductive inks and an accumulation process make use of several printing methods, including screen printing, transfer printing, and contact printing, creating conductive patterns on flexible substrates like carbon nanotubes. The conductive inks used in printing techniques are mainly based on volatile solutions containing conducting or semiconducting micro- and nanoscale materials, such as carbon nanotubes (CNTs), graphene, conducting polymer nanoparticles, metallic nanorods, or a mix of this material [3]. Because of exceptional mechanical qualities, particularly electrical conductivity, CNT-based inks in particular have become an attractive contender for the construction of malleable electronics utilizing printing technology. Additionally, the adaptability of CNTs has made it possible to print a variety of devices, including flexible actuators, supercapacitors, sensors, and transistors.

The ink is suitable for screen printing, dip coating, and traditional printing methods. Additionally, it has two-step 3D printing capabilities, which would make it simple to fabricate patterned conductive structures on a variety of flexible substrates without subjecting them to difficult processing conditions.

4 Applications of 3D Printed Electronics

The innovative technology of 3D printing commonly referred to as additive manufacturing or AM, has been around for quite some time but has recently gained more and more popularity. 3D printed electronics offer great potential for building complex objects with multiple features.

Fig. 5 The e-3DP procedure is illustrated schematically [30]



3D printed electronics have been presented as the next additive frontier. In previous years, a large amount of research and effort related to 3D printed electronics has been carried out by universities and industry. Due to its layer-by-layer or point-by-point properties, 3D printing encourages the integrated assembly and embedding of additional components. Sensors, electronics, and embedded components, among others, are incorporated into 3D printed goods. In printed electronics, metal-based particle-containing solutions or suspensions are used to print contacts and interconnects. Metal nanoparticles, often known as nanoparticle inks, are employed in ink formulations in the suspension form [28, 29].

4.1 Stretchable Electronics

Stretchable electronics are a brand-new class of electronic devices made possible by recent interest in wearable electronics and soft robotics (Fig. 5). e-3DP's invention of incredibly flexible sensors opens up new options for manufacturing soft-functioning gadgets for wearable electronics, soft robotics, and other applications. It makes it possible for electrical devices to have conformance, a lightweight design, and shock-resistant construction, which are difficult to achieve when utilizing rigid substrates like glass plates and semiconductor wafers [30].

4.2 Radio Frequency Antenna

AM has potential use in the construction of RF antennas (Fig. 6). Due to material and processing limitations, conventional antennas are rarely conformal or flexible, but AM makes it possible to create antennas that are more effective, lighter in weight, and smaller in size. Because UAVs are frequently used for high-risk missions and certain UAVs are not designed to be retrieved at all, the advantages of AM in terms of faster fabrication times and lower costs become increasingly alluring for UAV

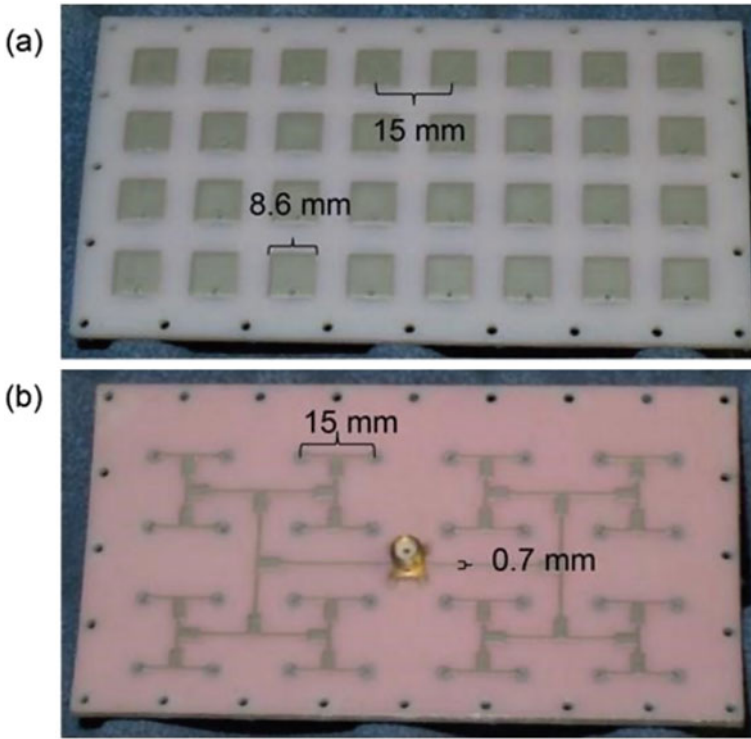


Fig. 6 Antenna radiating patch parts made additively and **b** feed network with SMA connector [31]

antennas. Increased installation sites, reduced weight, smaller size, and lower cost are made possible by this impact of aerodynamics on the airborne platform.

Figure 6 shows a conformal AM antenna as an illustration. An existing UAV platform's skin was used in the design of this antenna to ensure a smooth fit. Using a poly jet printer, the substrate material was 3D-produced and had a variety of curvatures throughout the sample. The micro-dispense nozzle is kept evenly spaced from the substrate throughout the printing process thanks to the printer's utilization of the coordinates established by laser mapping. This guarantees that the final print will have the greatest resolution available. This technique was used to print the feed network, the vias linking the two, and the radiating patch elements [31].

4.3 3D Structural Electronics

A P μ SL (projection micro stereolithography) method is one method used to construct 3D structures. Combining hybrid manufacturing and additive manufacturing (AM)

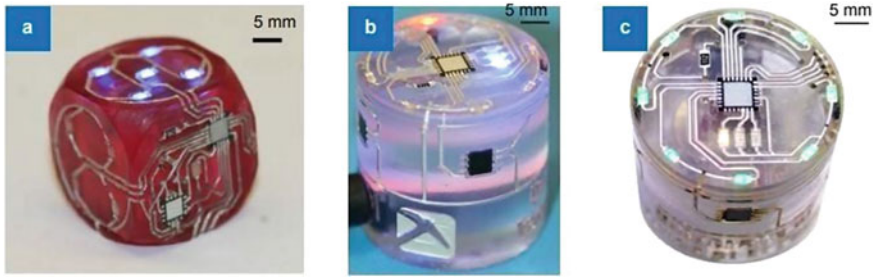


Fig. 7 a A game die with a microcontroller and an accelerometer. b, c A magnetometer system that includes a microcontroller and orthogonal Hall Effect sensors [25]

technologies will enable fully 3D, high-resolution, multi-material, and large-area fabrication. The conductive tracks were created by combining DWC (direct-write/cure) with CNT/polymer nanocomposites, which could pave the way for a new generation of affordable 3D structural electronics in the field of consumer, defense, and medical electronics (Fig. 7). The use of various viscous materials in a single build might cause contamination problems, and there are still difficulties with throughput, limited materials, and conductive inks that can cure at low temperatures [25].

5 Conclusions

3D printed electronics offer great potential for the fabrication of electronic components and devices. Compared to traditional techniques 3D printed techniques offer numerous advantages for printed electronics. Utilizing the benefits of 3D printing techniques has opened new avenues in the field of printed electronics. Moreover, the development of viable materials for the fabrication of electronic components and devices has further paved the way for the utilization of the 3D printing approach for printed electronics. One of the main benefits of 3D printing electronics is the ability to create highly customized and optimized devices. This customization can lead to better performance and efficiency compared to off-the-self-help components. Additionally, not all materials are suitable for electronic components, so careful selection is important. Despite these challenges, 3D printing electronics has the potential to revolutionize the way we design and manufacture electronic devices, especially for small-scale production and prototyping. As the technology continues to improve and mature, we will likely see even more innovative applications of 3D printing in electronics. It can be concluded that 3D printed electronics have revolutionized the way we think about manufacturing and production. It offers numerous benefits over traditional methods, such as speed, customization, and cost-effectiveness. The ability to print complex electronic components and circuits with precision and accuracy has opened new possibilities in various fields, including healthcare, aerospace, and consumer electronics. Additionally, the technology has the potential to reduce

waste and environmental impact by allowing for on-demand production and minimizing the need for excess inventory. While there are still challenges to overcome, such as improving the speed and quality of printing, the future looks bright for 3D electronic printing, and it is sure to continue to transform the manufacturing industry in the years to come.

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