**REVIEW SUMMARY**

**ADDITIVE MANUFACTURE**

Multiprocess 3D printing for increasing component functionality

Eric MacDonald* and Ryan Wicker*

**BACKGROUND:** Three-dimensional (3D) printing, known more formally as additive manufacturing, has become the focus of media and public attention in recent years as the decades-old technology has at last approached the performance necessary for direct production of end-use devices. The most popular forms of standard 3D printing include vat photopolymerization, powder bed fusion, material extrusion, sheet lamination, directed energy deposition, material jetting, and binder jetting, each creating parts layer by layer and offering different options in terms of cost, feature detail, and materials. Whereas traditional manufacturing technologies, such as casting, forging, machining, and injection molding, are well suited for mass production of identical commodity items, 3D printing allows for the creation of complex geometric shapes that can be mass-customized, because no die or mold is required and design concepts are translated into products through direct digital manufacturing. Furthermore, the additively layered approach enables the merging of multiple components into a single piece, which removes the requirement for subsequent assembly operations. Recently, the patents for the original 3D printing processes have begun to expire, which is resulting in a burgeoning number of low-cost desktop systems that provide increased accessibility to society at large. Industry has recognized the manufacturing advantages of these technologies and is investing in production systems to make complex components for jet engines, customized bodies for cars, and even pharmaceuticals. Although standard 3D printing technologies have advanced so that it is now possible to print in a wide range of materials including metals, ceramics, and polymers, the resulting structures are generally limited to a single material, or, at best, a limited number of compatible materials.

**ADVANCES:** For the technology to become more widely adopted in mainstream manufacturing, 3D printing must provide end-use products by fabricating more than just simple structures with sufficient mechanical strength to retain shape. Recently, research has resulted in the capability to use new materials with commercial 3D printers, and customized printers have been enhanced with complementary traditional manufacturing processes, an approach known as multiprocess or hybrid 3D printing. Collectively, these advancements are leading to fabrications that are not only geometrically complex, but functionally complex as well. By introducing the robotic placement of components, micromachining for intricate detail, embedding of wires, and dispensing of functional inks, complex structures can be constructed with additional electronic, electromagnetic, optical, thermodynamic, chemical, and electromechanical content.

**OUTLOOK:** Multiprocess 3D printing is a nascent area of research in which basic 3D printing is augmented to fabricate structures with multifunctionality. Progress will lead to local manufacturing with customized 3D spatial control of material, geometry, and placement of subcomponents. This next generation of printers will allow for the fabrication of arbitrarily shaped end-use devices, leading to direct and distributed manufacturing of products ranging from human organs to satellites. The ramifications are substantial, given that 3D printing will enable the fabrication of customer-specific products locally and on demand, improving personalization and reducing shipping costs and delays. Examples could include replacement components for grain-milling equipment in a remote village in the developing world, biomedical devices created specifically for a patient in a hospital before surgery, and satellite components printed in orbit, thus avoiding the delays and costs associated with launch operations. The automotive, aerospace, defense, pharmaceutical, biomedical, and consumer industries, among others, will benefit from the new design and manufacturing freedom made possible by multiprocess 3D printing.

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**ADDITION MANUFACTURE**

**Multiprocess 3D printing for increasing component functionality**

Eric MacDonald* and Ryan Wicker*

Layer-by-layer deposition of materials to manufacture parts—better known as three-dimensional (3D) printing or additive manufacturing—has been flourishing as a fabrication process in the past several years and now can create complex geometries for use as models, assembly fixtures, and production molds. Increasing interest has focused on the use of this technology for direct manufacturing of production parts; however, it remains generally limited to single-material fabrication, which can limit the end-use functionality of the fabricated structures. The next generation of 3D printing will entail not only the integration of dissimilar materials but the embedding of active components in order to deliver functionality that was not possible previously. Examples could include arbitrarily shaped electronics with integrated microfluidic thermal management and intelligent prostheses custom-fit to the anatomy of a specific patient. We review the state of the art in multiprocess (or hybrid) 3D printing, in which complementary processes, both novel and traditional, are combined to advance the future of manufacturing.

Traditional manufacturing is well optimized for mass production of identical parts but can involve complex assembly steps, result in material waste, and incur substantial expense for low-volume production. Three-dimensional (3D) printing, a technology receiving considerable attention recently for direct part production, allows the creation of complex geometric shapes that can be mass-customized without a need for part-specific tooling such as dies or molds. Originally referred to by terms such as rapid prototyping, solid freeform fabrication, and others, this layer-by-layer fabrication methodology converts a precursor material in a spatially controlled manner to create a complex shape. As the technology has developed over the past three decades, both the spatial resolution and the diversity of usable materials have improved. These advancements have led to an increase in end-use production of consumer, aerospace, and biomedical devices as industry has recognized the potential opportunities offered by 3D printing for improving designs, reducing assembly requirements through part consolidation, and optimizing the manufacturing supply chain through point-of-use manufacturing. General Electric’s chief executive officer, Jeff Immelt, has recently stated that by 2020, the corporation plans to produce over 100,000 3D-printed parts for jet engines, and to meet these goals, General Electric plans a $3.5 billion investment in 3D printing (1). Simultaneously, as 3D printing patents are expiring, the costs of these systems are decreasing dramatically, and they now are becoming accessible to the general public. Collectively, these trends are leading to a democratization of manufacturing (2). 3D printing, now often referred to as additive manufacturing to emphasize production rather than prototyping (3), is evolving. Figure 1 illustrates the potential for fabricating end-use structures with embedded fluidic control printed from a traditional single-material 3D printer (powder bed fusion of electron beam-melted titanium) (4).

One potentially disruptive step in the evolution of 3D printing will be to increase the functionality of the manufactured components. The 3D printing process can be started and stopped to incorporate complementary fabrication processes or embed subcomponents manufactured using traditional methods; however, until recently, 3D printing has been generally relegated to the prototyping of single-material structures for form and fit evaluation (5). The next generation of 3D printers will enable products with multifunctional capabilities, including combinations of features not possible with a single print material, produced within a unified, tooling-free, multiprocess printing environment. In this context, multiprocess (or hybrid) 3D printing is defined as additive manufacturing enhanced with complementary processes. These complementary processes can include traditional manufacturing such as machining, cutting, dispensing, robotic placement, and more. This new approach represents a paradigm shift in which the goal is to fabricate, in a nonassembly process, multifunctional end-use devices, potentially combining electronic, electromagnetic, optical, fluidic, actuation, chemical, and thermal features simultaneously—all with the inherent geometric benefits of 3D printing. Moreover, without tooling requirements, these advanced 3D printing technologies continue to leverage mass customization (6), through which, for instance, sophisticated biomedical devices can now be fabricated for the specific anatomy of a patient. Figure 2 illustrates two examples of multifunctional devices that highlight the possibilities of using multiprocess 3D printing systems: (i) a gaming die that includes a processor, an accelerometer, and light-emitting diodes (LEDs) to enhance the outcome of a roll by illuminating the top surface (7) (Fig. 2A) and (ii) a periodic spiral antenna that allows for physical patterns of conductors and dielectrics with unprecedented geometries, which will inevitably provide new levels of performance in next-generation antennas (Fig. 2B).

In this Review, we provide an overview of current 3D printing technologies, discuss advances and limitations in multiprocess 3D printing specifically with respect to multifunctionality, and describe a number of functionalities that have been investigated and enabled by 3D printing. Limited only by the readers’ imaginations, the innumerable design opportunities provided by this manufacturing technology cannot effectively be covered in this Review for all applications of multifunctional printing (such as organ printing), and the included examples only serve to highlight the potential and motivate further advances.

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Fig. 1. Example of 3D-printed multifunctionality achieved with commercially available 3D printing technology. Shown is a pneumatically controlled prosthetic hand fabricated in titanium by using a powder bed fusion 3D printing technology known as electron beam melting (4). [Photo courtesy of Oak Ridge National Laboratory]
Multifunctional fabrication processes

The cornerstone of 3D printing is the layer-by-layer fabrication methodology, which allows manufacturing flexibility with the provision of interrupting the process to leverage complementary processes. The ASTM (American Society for Testing and Materials) F42 subcommittee was established in 2009 (8) to provide standards for common terminology, testing methods, and file formats, among other concepts for additive manufacturing, and has identified a taxonomy of seven basic 3D printing processes.

1) Vat photopolymerization is a process involving a vat of liquid photo-curable polymer that is selectively cured with an energy source, such as a laser beam or a lamp with a projection system. The fabricated part is typically created layer by layer on a platform that descends after selectively curing each layer.

2) Material extrusion is a process in which material is selectively dispensed through an extrusion nozzle. The most common materials used are thermoplastics requiring heated extrusion. The process generally includes layer-by-layer fabrication with a movable platform and/or extruder.

3) Powder bed fusion involves selectively fusing regions of powder in a bed using a thermal energy source such as a laser or electron beam. A platform supporting the bed descends by a layer thickness, and a rake or roller dispenses additional powder to create the next layer.

4) Binder jetting selectively dispenses a binder to join powder feedstock in a bed supported by a platform. As in powder bed fusion, the platform descends by a layer thickness, and a rake or roller dispenses additional powder. Most parts require postprocessing with an infiltrant and a furnace cycle.

5) Material jetting selectively deposits droplets of the build material, which are typically photo-cured. Deposition and curing are repeated for all layers.

6) Sheet lamination is a process in which individual sheets of material are bonded together to form a structure, typically requiring machining or cutting between layers to accurately form the 2D shape for each particular layer.

7) Directed energy deposition directs both a material deposition (typically wire or powder) and an energy source (typically a laser or an electron beam) at the surface being built.

Each of these processes stands to benefit from enhancements enabling the printing of structures with increased functionality. The earliest reported research in the 1990s leveraged the layered technique of 3D printing by interrupting the process to integrate functional components and conductive traces within a structure (9). Kataria and Rosen enhanced vat photopolymerization with inserts (10), and Lopes et al. dispensed conductive inks to manufacture electronics with antennas built directly into solid polymer structures (11). Ultrasonic consolidation, a sheet lamination process, creates metal components by ultrasonically bonding a sheet of metal foil to a previously deposited sheet. A machining process using an end mill renders the required geometry and follows the bonding. Thus, 2D sheets are essentially stacked together to provide a 3D part fabricated with two processes—an early example of multiprocess 3D printing. Robinson et al. interrupted the ultrasonic consolidation process to insert simple circuits through the combination of material extrusion with both thermoplastic and conductive ink (12). Using the material extrusion 3D printing technique, Malone et al. demonstrated a circuit and clever electromechanical applications by using an open-source fabrication system that dispensed multiple materials, including conductors and dielectrics (13). Navarrete et al. described enhancements to a vat photopolymerization process that introduced microchannels into the substrate to guide and contain curable conductive fluid, which was microdispensed to leverage the minimum feature size of the laser-curing process (14). Conductive trace spacing was thus controlled by the precision of the laser beam, rather than the secondary dispensing process, illustrating the symbiotic benefit of a compound process over either process acting alone.

Multifunctionality in additive manufacturing can be defined broadly as the introduction of any additional functionality beyond rendering a basic shape. Multiple colors and densities can be graded throughout a structure, for example, which qualifies as multifunctionality (albeit minimally), and these structures can be fabricated with various forms of standard commercial 3D printing. In fact, processes capable of multiple colors have been commercially available for years (15–20). Other examples of multifunctionality with commercial 3D printers include mechanical meta-materials that induce negative stiffness to dampen vibrations and reduce cabin noise (21) or that allow pneumatic actuation, as shown in Fig. 1. Related but not identical to multifunctional 3D printing, multiprocess 3D printing—the collaborative use of multiple processes—often but not necessarily results in multifunctional devices. A counter example is a single-material metal structure printed additively and then machined subtractively within a single gantry for the sole purpose of improving
Microdispensing has been investigated for over a decade with the aim of direct writing (e.g., the ability to print components, wires, batteries, antennas, and other subcomponents). The introduction of electrical and thermal interconnects allows for subsystem communication or the delivery of energy or heat across a structure. Conductive inks and pastes have been used in conjunction with 3D printing, given the manufacturing flexibility and pastes have been used in conjunction with multiple integrated technologies, including the combination of 3D printing with other complementary processes to provide or improve spatial control of material, geometry, and functionality. These additional manufacturing capabilities can embed components, wires, batteries, antennas, and other subcomponents. The introduction of electrical and thermal interconnects allows for subsystem communication or the delivery of energy or heat across a structure. Conductive inks and pastes have been used in conjunction with 3D printing, given the manufacturing flexibility and direct writing (e.g., the ability to print conformally, no tooling required), and the combination has been investigated for over a decade with microdispensing, ink jetting, and aerosol jetting. Generally, the inks have been dispensed onto external surfaces of finished structures, but only a limited number of examples have involved interrupting and re-initiating a 3D printing process to fully embed interconnect capability. Conductive inks have improved over the past two decades but still suffer from high resistance relative to traditional printed circuit boards created with a bulk copper plating process. Higher resistance conductors result in performance reductions with voltage drops and power loss, and reliability remains an additional concern. Low-temperature metal alloys have been printed with modified thermoplastic extrusion heads and through injection into polymeric structures to provide interconnection with improved conductivity relative to inks. Although these alloys tend to have higher conductivity relative to conductive particle-loaded inks, interconnection continues to disappoint in comparison with bulk plated copper used in traditional electronics. The use of laser direct structuring to allow for selective plating on 3D printed substrates has been demonstrated, provides bulk properties, and is an exciting development, but it does require an additional chemical bath process.

A startup company from the Lewis group at Harvard, Voxel8, has announced the first low-cost commercial 3D printer combined with a pneumatic ink dispenser for creating conductive interconnects in 3D printed structures. The ink is printed and cured at room temperature, providing substantial manufacturing benefits and flexibility. Self-supporting, the ink can bridge internal cavities within structures and is dispensable through a 250-μm nozzle, which is well within the spatial precision required by the majority of traditional electronic components. When a printed trace extends to a pin of a chip, an electrical connection forms without the requirement of high-temperature soldering. An example circuit is shown with an x-ray image of a drone copter in Fig. 3A, along with an example of a modern surface mount chip with connections (0.8-mm pin pitch thin quad flat pack) in Fig. 3B. However, the process involves a higher resistance of 5 × 10^6 Ω·cm (as opposed to bulk copper at 168 × 10^6 Ω·cm), but it nevertheless provides the first example of an economical desktop 3D printer specifically for electronics.

The W. M. Keck Center for 3D Innovation at the University of Texas at El Paso has produced 3D-printed electronic circuits since as early as 2004 and was recently named a Satellite Center of America Makes, a federal-public-private partnership focusing on additive manufacturing and based in Youngstown, Ohio. Recently, the 3D devices produced by the group have featured interconnects that can compete directly with traditional electronics in terms of cost and performance, enabled through the use of structurally embedded wires and foils within 3D-printed thermoplastic structures. Metal filament is selectively heated and in situ submerged flush with the top surface of the thermoplastic structure during a print interruption. Because the embedded wires are available in a wide range of diameters ranging from 80 μm or smaller to virtually any larger size, the fabrication of geometrically elaborate structures can incorporate small intricate routing patterns or large high-power circuits. Once the wires are integrated, the substrate remains planar, and subsequent 3D printing can continue uninhibited. Figure 4 shows 36-gauge (127-μm-diameter) wires embedded in a poly carbonate structure that was printed with a material extrusion printer (Stratasys Fortus 400mc). Movie 1 illustrates the hybrid process as two 3D printers collaboratively create a multimaterial structure in combination with a gantry, which provides complementary processes such as wire embedding or micromachining for fine detail. The blue six-axis robot acts as conveyance to transport the build chamber between manufacturing stations and can be used for postprocess assembly if required. The embedded wires originally intended to afford high-performance electrical interconnection also provide the serendipitous benefit of increased mechanical strength, because they make the structure a reinforced composite (like rebar in concrete). This process can render 3D-printed plastic structures that are stronger than those fabricated with traditional injection molding and helps eliminate the anisotropic strength differences that can compromise 3D-printed structures (e.g., weakness between added layers, so-called z-strength weakness in the vertical or z direction).

Another example of robotic multiprocess additive manufacturing has been integrated with this same wire-embedding technology. The system, called the multibot cluster and intended for...
large-area manufacturing, includes two six-axis robots to respectively implement additive and subtractive processes (40) and is enhanced with a tool exchanger to implement thermal wire embedding during print interruptions. One important contribution of the multirobotic cluster is enabling 3D printing of parts larger than the machine itself, exceeding the size constraint imposed by nearly all 3D printing machines to date, as well as enabling conformal 3D printing.

Comparison with traditional manufacturing

With 3D printing as a foundation, multiprocess additive technologies generally suffer from lower throughput when compared with traditional methods. However, new 3D-printed geometries are now possible, and additive manufacturing has its own advantages; for example, the elimination of tooling allows mass customization through which each production part can be personalized, and the amount of labor required is reduced by the nonassembly methodology. The mechanical performance of the structures produced by some of the additive processes struggles in the area of anisotropic strength; however, more recent technologies, and particularly the powder bed fusion of metals by means of lasers or electron beams, provide many equivalent properties of traditional cast and even wrought materials (41), motivating General Electric to use these systems to produce Federal Aviation Administration–approved parts.

Interconnect performance metrics in electronics include routing density, conductivity, dielectric strength, dielectric permittivity, dielectric loss, and general reliability. Ink-based traces on polymer substrates can be fabricated with equivalent routing density relative to traditional printed circuit boards but, at least to date, at the expense of lower conductivity. Routing densities are competitive, with microdispensing of line widths below 10 µm (22), ink jetting widths as low as 25 µm (26), aerosol jetting traces as small as 10 µm (31), laser direct structuring defined by a laser beam width and reported at less than 100 µm (42), and structurally embedded wires as thin as 80 µm (38). All of these approaches have routing densities at or approaching that of the state-of-the-art printed circuit board, which for comparison is typically around 50 µm. A hypothetical example of conductivity highlights the importance of this parameter to electronics. If an ink-jetted trace is required to deliver a typical 100 mA of electric current to a motor through a printed connection with a width of 250 µm, thickness of 10 µm, and length of 100 mm, the total resistance would accumulate to ~16 ohms for an ink with 40 × 10⁻⁸ ohm-m resistivity. The motor would receive a voltage degraded by 1.6 volts, reducing performance. Comparatively, bulk copper (e.g., a similar trace on a printed circuit board, structurally embedded wires, or laser direct structuring) would deliver a resistance less than 1 ohm.

Beyond conductivity, the dielectric performance of 3D-printed substrates, particularly polycarbonate and polyetherimide, are close to the levels of traditional electronics (e.g., FR4 laminates), with reasonable permittivity, loss tangent (43), and dielectric strength (44). Reliability remains relatively unknown for all of these 3D interconnect processes because of the lack of manufacturing history compared with the much older traditional electronics industry.

Printable and embeddable function

For decades, additive processes have been used to achieve complex geometric shapes, which often serve as physical models and prototypes for a range of applications. However, in the past decade, specific features that go beyond simple mechanical functionality have been produced by a growing number of researchers, generally by printing or embedding using multiple processes. Printable functions beyond those provided by basic 3D printing include sensing, transducing, thermal management, electromagnetic, energy storage, and propulsion utility, as described in this section.

Sensors

In terms of embedding sensing into 3D-printed structures, considerable research has focused on either (i) embedding a sensor directly into printed structures during a process interruption or (ii) printing the entire sensor intrinsically into the structure. The integration of sensing into custom-designed geometries is beneficial for many applications—examples of which could include patient-specific biomedical devices capable of measuring comfort in prosthetics, optimized control of temperature and pressure in elaborate jet turbines, and motion control in tailor-shaped robotics, to name just a few—and may be useful for many more not yet conceived. Sensing tends to be concentrated into four areas: tactile, motion, vision, and hearing. Of these, tactile sensing is well suited for 3D printing and has dominated research efforts. The other three sensing categories tend to be implemented by integrating traditional commercial “off-the-shelf” components into 3D-printed structures through robotic or manual insertion. However, in the case of acoustics, Mannoor et al. printed a functional microphone in the form and feel of a human ear with bio-compatible hydrogels (45), and Van Tien et al. printed an angular accelerometer (46). Other sensors such as cameras, infrared LEDs (47), accelerometers (7), pressure sensors, dust sensors, and bioelectrical sensors (48) have been inserted directly into designated cavities during fabrication.

Optical sensing of motion has been implemented in structures with material jetting at Disney Research (47). Inexpensive infrared diodes can radiate and measure reflections in the translucent 3D-printed walls of an enclosure. Integrating the sensors into the overall structure simplifies sensing and improves volumetric efficiency; however, the proposed optics require a sufficiently transparent structure possible only with liquid-based processes in 3D printing, such as vat photopolymerization or material jetting. Based on photo-curable polymers, these technologies can provide sufficient clarity to serve as light guides but are also constrained by the limitations of photochemistry and the layered fabrication process. The translucence can degrade over time in photo-curable polymers because cross-linking continues after fabrication.

![Fig. 5. 3D-printed tactile sensors. (A) A stretchable touch sensor. (B) A capacitive touch sensor.](http://science.sciencemag.org/).
Actuation

Several forms of mechanical actuation, from simple retraction to fully functional rotational motors, have been demonstrated. Richter and Lipson used vat photopolymerization to create bio-inspired flapping wing insects (53). Several groups have created prosthetic hands with embedded external motion (4, 54, 55). In (56), the ability to produce sound with 3D-printed speakers, including for entertainment, was described. By embedding wires coaxially into extruded dielectric filament, Saari et al. printed coils as the basis for producing speakers with a tight cylindrical configuration that was coaxially isolated (57), providing increased magnetic coupling; however, this isolation limits the applicability for more complex topologies necessary for general interconnection (e.g., multilayered printed circuit boards). Aguilera et al. described the fabrication of a high-power (>25 W) electromechanical device (a rotational motor) through a nonassembly additive build sequence based on a material extrusion printer (58). With high-performance conductors (solid copper wires) embedded directly into the printed substrate, coiled electromagnets were integrated in an external stator. Two bearings introduced at the top and bottom of a rotor created a mechanical circuit with an internal structure that could rotate freely. The typical requirement for water-soluble support material for internal cavities had to be eliminated because this support is incompatible with embedded electronics, given that water-sensitive circuits would be required to be submerged to remove the support. Consequently, design features were limited to inclines of less than 45° from vertical to minimize overhanging structures and allow the two independent mechanical structures to be constructed without intermediary support. Movie 2 is a time-lapse video of the fabrication of an original proof-of-concept print, and although the intervention was manual, this video highlights a potential application of multi-process printing providing multifunctionality. In this 5-hour process (shown in time lapse in under 1 min), component and wire embedding were completed by hand to demonstrate the potential of a fully automated fabrication system under development. With the inclusion of an energy source, the possibility exists of fabricating a motorized robot capable of walking or flying out of the 3D printer on completion.

Thermal management

Given the design freedoms afforded by 3D printing, advanced geometrically complex heat exchangers have been explored by researchers for years. Metal 3D printing systems have been used to fabricate complex large-surface-area structures with high thermal conductivity (59) for applications such as fluidic heat transfer devices (60), 3D-printed plastic injection molds (61), and even thermoelectric reactors (62). As multiprocess 3D printing advances, thermal management applications will as well, including advanced designs with embedded heat pipes and reservoirs of phase change material, leading to improved thermal management in 3D structures.

Energy storage

At present, contemporary battery manufacturing can provide custom-shaped lithium ion batteries, which are well suited for providing an energy source in an arbitrary shape to improve volumetric efficiencies in assemblies, but these batteries are confined to high-volume production with expensive molds. Research is ongoing to enable the printing of batteries with programmable shapes, but the energy density is orders of magnitude less than that of contemporary commercial batteries, and the long-term reliability is untested. Several groups have printed batteries with roll-to-roll manufacturing (63–66). The research does not necessarily project to the full 3D geometries; however, sheets may be sufficiently flexible to be rolled or folded. Another option for energy sources in the context of 3D printing is to robotically insert traditional batteries as components during the 3D print, but an obstacle is that many of the printing processes use high-temperature build envelopes. Because most batteries have high energy densities, they have a dangerous sensitivity to temperature, as a result of which they could potentially become unstable (67). Consequently, combining component batteries into 3D-printed structures is often not possible unless confined to post-processing assembly steps or low-temperature 3D printing processes, such as binder jetting or vat photopolymerization. MacDonald et al. included commercial batteries during post-processing (68). Polymer caps were printed to cover the battery after insertion into the structure, and a low-temperature chemical process welded the plastic cap. A micro-USB (universal serial bus) plug and charging circuit were included to allow for the recharging of a test coupon, which was intended for space flight qualification for a project with the NASA Glenn Research Center. Another option is to embed ultra- or supercapacitors into the structure, which are far less sensitive to temperature in comparison with the chemical storage techniques (69).

Malone et al. reported a 3D-printed batteries (Zn-air), providing an early example of the combination of 3D-printed structures and energy storage (69). 3D-printed Li-ion batteries have been preliminarily demonstrated with high-aspect-ratio interdigitated anodes encapsulated within an electrolyte solution, as shown in Fig. 6 (70). The aspect ratios of the patterned microelectrodes were as high as 11 (height to width) for 16-layer electrode walls. The printed array was cured to 600°C to remove binder and sinter the nanoparticles. This temperature would preclude the integration of the process with thermoplastic matrix. Conductive networks were formed inside the polymeric matrix, and external forces deformed the network, increasing contact between nanotubes, and thus the resistance was modulated. Similarly, Muth et al. reported creating highly stretchable sensors by 3D printing of a carbon-based ink within an elastomer structure (60). The stretchability was well suited for strain gauge measurement. The sensor is shown in Fig. 5A. Hossain et al. included high-temperature-tolerant piezoelectric sensors in a metal structure during a pause in the powder bed fusion process, in which the build temperatures are typically above 600°C—a temperature that severely limits the type of components that can survive insertion during fabrication (57).

Capacitive touch sensing has been demonstrated by Shemelya et al. (52). Wire or wire mesh was submerged into 3D-printed thermoplastic structures to act as a single capacitive plate of a touch sensor, in which changes in capacitance could be readily measured indirectly through the frequency of a simple oscillator. A modification in the electric field would indicate the presence of new material in the vicinity (Fig. 5B). The integration of single-sided capacitor plates can be used for custom 3D grip detection, keyboards, and even microfluidic sensors capable of detecting the presence and type of material flowing through structure capillaries.
3D printing; however, batteries could be printed in custom, arbitrary shapes as a separate process and then inserted within a specific 3D-printed structure after sintering. The most difficult challenge for realization is related to energy density, because at present, printed batteries provide orders of magnitude less energy density than traditional batteries.

**Antennas and electromagnetic structures**

The rising interest in 3D printing technology is resulting in rethinking of traditional approaches for the design and manufacture of antennas and electromagnetic devices. Several groups have used multiprocess 3D printing technology to embed conductors such as conductive wires, meshes, and metallic foils in order to provide full spatial control of dielectric and conductive foils in order to provide full spatial process 3D printing technology to Several groups have used multiprocess 3D printing technology to
design and manufacture of antennas and electromagnetic devices. These devices and technologies can be tailored with the inclusion of high-performance RF components and conductors is enabling a new class of 3D-printed antennas that can provide multiple frequency bands or maintain a small physical footprint while potentially outperforming traditional antennas. The dielectric materials used in these processes can have generally reasonable radio frequency (RF) performances with low loss tangents and, in some cases, can be tailored with the inclusion of high-permittivity additives. Furthermore, these antennas can be integrated seamlessly in the overarching mechanical structure in the nose cone of a plane, for instance to save volume, and they provide the serendipitous benefit of improving the mechanical strength of the device by virtue of being a composite structure—demonstrating true multifunctionality. One aspect of 3D printing that has a profound impact on antenna design is the ability to spatially vary the density of a structure with intentional porosity and thus functionally grade the permittivity and permeability. These gradients can enable electromagnetic transitions through material interfaces to minimize reflections or allow for sculpting of RF waves. However, one challenge with 3D-printed electromagnetic devices is the reduction in permittivity resulting from the well-known and unintentional porosity inherent in thermoplastic 3D printing processes.

**Propulsion**

Interest in 3D printing of space vehicles and satellites has grown in the past decade as a result of NASA's encouragement of the use of 3D printing for structures suitable for space and orbit. In addition, the National Academy of Sciences commissioned a committee to study the utility of 3D printing in space. Propulsion is a specialized case of actuation and is particularly relevant to NASA and motion in space. The use of metal printers to fabricate rocket thrusters for spacecraft was reported in. Presently, CubeSats are generally free-floating, low-cost satellites used in inexpensive university space science and often constructed with off-the-shelf components. These satellites often are launched parasitically and can use magnetic torque rods or momentum wheels if attitude control is required, but these generally consume a large fraction of precious space in the volume-limited format of CubeSats. Although various electric propulsion concepts are available, micro-pulsed plasma thrusters (μPPTs) offer tight integration, long shelf life, and survivability in the high fabrication temperatures of 3D printing build chambers. Additionally, because 3D-printed polymers provide appropriate dielectric strength and recently available copper wires have sufficiently low resistance, Marshall et al. were able to demonstrate this form of propulsion by delivering high voltages (over 1000 V) in 3D-printed test coupons that were ignited (82). This example manifests the utility of multiprocess 3D printing with wire and component placement, substantially benefiting the manufacturing of space components and vehicles. Movie 3 shows a series of ignitions in an evacuated bell jar.

**Conclusions and outlook**

Multiprocess (or hybrid) 3D printing, where complementary processes are combined to advance manufacturing by increasing the functionality of fabricated components, has been the focus of this Review. As 3D printing continues to advance, the next generation of printers will fabricate not just dissimilar materials but structures with embedded and interconnected active components to provide functionality that was not possible previously. The progress thus far has illustrated the potential for leveraging multiprocess 3D printing to provide a broad base of capabilities necessary for customized end-use production. For multifunctional additive manufacturing to become an economic reality, however, substantial hurdles must be overcome in a number of areas: (i) material enhancements, including for mechanical performance; (ii) the diversity of materials available in terms of characteristics such as flexibility or thermal and electrical conductivity; (iii) improved material interfacial performance to ensure the reliability of structures composed of multiple materials; (iv) computer-aided design and computer modeling to optimize the complex geometries and performance possible when working with disparate content simultaneously (e.g., mechanical and electrical features fabricated concurrently); (v) processes feedback control, which is widely absent in most contemporary printers and will become even more necessary in the context of multiple interacting processes required for fabrication of aerospace-grade or biomedical devices; and (vi) development of the manufacturing hardware and software necessary for a wide range of complementary technologies to collaborate with 3D printers in order to fabricate fully multifunctional devices. The required investment has begun, notably in the federal public-private initiative on manufacturing and the resulting America Makes program, which is focused on many of the challenges facing 3D printing technologies. Similar investment from industry and government will need to grow in order to fully leverage the advantages made possible by this next generation of manufacturing.

**REFERENCES AND NOTES**

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Editor's Summary

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