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3D opportunity for electronics

Additive manufacturing powers up

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Introduction

ADDITIVE manufacturing (AM) has come a long way in the last 30 years. The industry revenue for all AM products and services stood at $5.2 billion in 2015, with a compounded annual growth rate (CAGR) of 31 percent in the last five years.[1] Such rapid growth in the industry's revenue could be attributed to a variety of factors, including improvements in AM processes and technologies, a wider choice of materials, and increasing applications beyond prototyping and low-volume production.[2]

While still at an early stage, the applications for 3D-printed electronics seem promising. For example, engineers are experimenting with conformal electronics—stretchable electronics that can be embedded in fitness trackers, smart apparel, and skin patches—as well as applications in complex supply chains that require on-demand manufacturing and mass customization.[3] In the near term, developments such as printing electronics in nanoscale and using newer materials such as graphene could lead to additional possibilities in product design.[4]

Revenue from 3D-printed electronics and consumer products accounted for 13 percent of the larger AM industry, or $681 million, in 2015.[5] The growth for this segment is expected to remain strong; AM industry analysts predict that 3D-printed electronics is likely to be the next high-growth application for product innovation, with its market size forecasted to reach $1 billion by 2025.[6]

This paper closely examines how AM can be used in manufacturing fully functional electromechanical parts as well as the circuitry within a single production cycle. The latter process could create several challenges, which we'll also address in this paper. Finally, we'll evaluate select applications where AM surpasses traditional manufacturing for electronics.

THE ADDITIVE MANUFACTURING FRAMEWORK

AM's roots go back nearly three decades. Its importance is derived from its ability to break existing performance trade-offs in two fundamental ways. First, AM reduces the capital required to achieve economies of scale. Second, it increases flexibility and reduces the capital required to achieve scope.

Capital versus scale: Considerations of minimum efficient scale can shape supply chains. AM has the potential to reduce the capital required to reach minimum efficient scale for production, thus lowering the manufacturing barriers to entry for a given location.

Capital versus scope: Economies of scope influence how and what products can be made. The flexibility of AM facilitates an increase in the variety of products a unit of capital can produce, reducing the costs associated with production changeovers and customization and, thus, the overall amount of required capital.

Changing the capital versus scale relationship has the potential to impact how supply chains are configured, and changing the capital versus scope relationship has the potential to impact product designs. These impacts present companies with choices on how to deploy AM across their businesses.

THE ADDITIVE MANUFACTURING FRAMEWORK CONT.

Companies pursuing AM capabilities choose between divergent paths (figure 1):

Path I: Companies do not seek radical alterations in either supply chains or products, but they may explore AM technologies to improve value delivery for current products within existing supply chains.

Path II: Companies take advantage of scale economics offered by AM as a potential enabler of supply chain transformation for the products they offer.

Path III: Companies take advantage of the scope economics offered by AM technologies to achieve new levels of performance or innovation in the products they offer.

Path IV: Companies alter both supply chains and products in pursuit of new business models.

Figure 1. Framework for understanding AM paths and value

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Building electronics additively

WHILE research has long focused on how AM uses now-standard materials such as thermoplastics, metals, and ceramics to build the exterior of a product, focus is now turning inward, toward materials that can build a part's internal circuity. These materials include conductive inks: toners loaded with charged particles that build live circuity as they are laid down on a product with high precision.[8]

The process of additively producing electronic objects can go by multiple names: 3D-printed electronics, direct wire, conformal electronics, and others.[9] In this paper, we will use the term "3D-printed electronics."

At its simplest level, a typical 3D printer fabricating 3D-printed electronics utilizes two material sources: the base material for the product construct, and conductive material for the circuitry. By using conductive inks in combination with base materials, printers can 3D-print electronic objects as a single, continuous part, effectively creating fully functional electronics that require little or no assembly. In this way, AM can be used to manufacture a variety of sensors, circuits, circuit boards, antennae, batteries, and microelectromechanical systems, among other electronic parts.

The next section discusses key benefits of creating electromechanical parts through additive manufacturing.

By using conductive inks in combination with base materials, printers can 3D-print electronic objects as a single, continuous part, effectively creating fully functional electronics that require little or no assembly.

Energizing products and supply chains

The underlying benefits of AM

ADDITIVE manufacturing enables companies to build nonstandard electronics, complex assemblies, and intricate or curvilinear shapes. In this way, AM designers are free to design innovative electronic objects that could not have been produced through conventional means, and they can optimize product designs for functionality with fewer manufacturing constraints.

Electronics and parts manufacturers can benefit from underlying benefits of AM such as:[10]

Printability on nonflat surfaces. 3D printing eliminates the need for flat circuit boards, which can create opportunities for innovative new designs and shapes, or designs optimized for function. Some examples of parts with complex and customized sizes and designs are glucose testing strips, solar panels, antennae and sensors on flexible surfaces, electronic prosthetics and wearables, and batteries (figure 2).[11] Indeed, 3D-printed batteries can outperform conventional batteries, in part because their shapes and dimensions can be adjusted to fit a particular product, optimizing design for functionality, not manufacturability.[12]

There are challenges associated with this advantage, however. For example, if the part has nonuniform surfaces, conductive ink may pool in the gaps, leading to the possibility of short circuits or discontinuities. One way of resolving the issue is to use a layer of dielectric (nonconductive) material as a buffer to fill the gaps before conductive ink is laid down (figure 3).[13]

Mass customization. AM allows greater flexibility for unit-level customization for not only mechanical parts but also electronic and electromechanical parts, thus adapting product functionality, not just aesthetics, to customer preferences.

Figure 2. An example of a printed circuit board with flexible connections

Source: Nano Dimension Ltd., "Nano Dimension targets IoT market—Technological breakthrough: 3D printing of rigid PCB series combined with flexible conductive connectors in a single print," January 12, 2017, http://www.nano-di.com/hubfs/Electronica_Media_Kit/High_Quality_Images/3D_printed_PCB_prototype_was_created_with_a_Nano_Dimension_3D_printer._Photo_Nano_Dimension.jpg?t=1492505623596

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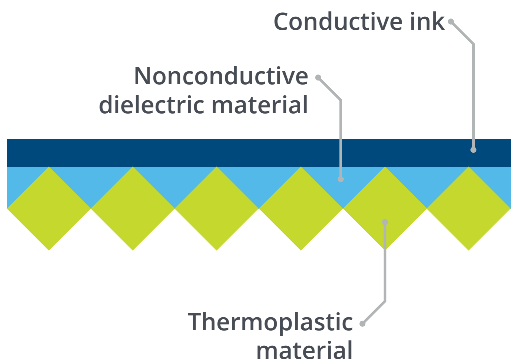
Lower material wastage and part weight. There is empirical evidence to suggest that material wastage may be lower using an additive process (laying down material just where it is required) than using a subtractive process (removing material where it is not required).[14] In addition, part weight

Figure 3. Conductive ink deposited on an object along with a dielectric intermediate material



Source: K. B. Perez and C. B. Williams, "Combining additive manufacturing and direct write for integrated electronics—a review," presented at 24th International Solid Freeform Fabrication Symposium, August 12, 2013.

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can be reduced through eliminating separate circuit boards, cables, and wiring.[15]

Absence of harmful chemicals. Traditional processes for electronics manufacturing involve using chemicals to remove excess material in a process known as "etching." AM eliminates the need for such chemicals, as the material is laid down only where it is required.[16]

Simplified assembly. The traditional, or subtractive, approach to electronics manufacturing involves several steps, such as film deposition, lithography, etching, and packaging. In contrast, AM incorporates all these activities into a single build process. This single-build sequence for the part's exterior body as well as the internal circuity simplifies its assembly.[17]

Reduced product size. In AM, external packaging for protruding parts is not required. For example, antennae in smartphones can be directly printed onto the phone case, which reduces the size of the device.[18]

Protection from external damage. Rather than adding a circuit to the product post-production as in traditional manufacturing, an additively built circuit is encapsulated within the part. This can cushion and protect the circuit from damage.

All of these product and supply chain benefits allow 3D-printed electronics to have applications in a wide range of industries, including sensors and prototypes for aerospace and defense, mobile antennae for telecom, touchscreen displays and transistors for consumer electronics, and solar cells for energy and utilities.[19] Despite all of these possibilities, manufacturers interested in using AM for manufacturing electronics often face the question of where to start and which technology to use.[20] In the next section, we discuss key approaches to building electronics additively.

One process, different technologies

JUST as AM can be used to manufacture parts using different technologies, electronics can be "printed" onto parts using different technologies, which fall into two broad categories.[21]

- Building electronics separate from the part production process
- Building electronics within the part production process

Each approach has its advantages and limitations and can be used for different applications, depending on the objectives for a product and its use.

Building electronics separate from the part production process

AM technologies can be used to manufacture electronics that can later be integrated into parts fabricated via AM or traditional manufacturing techniques. In this approach, electronics are printed onto a surface and later added to the product during assembly. While this approach is easier to implement than the second approach of building electronics within the production process, it requires additional assembly efforts.

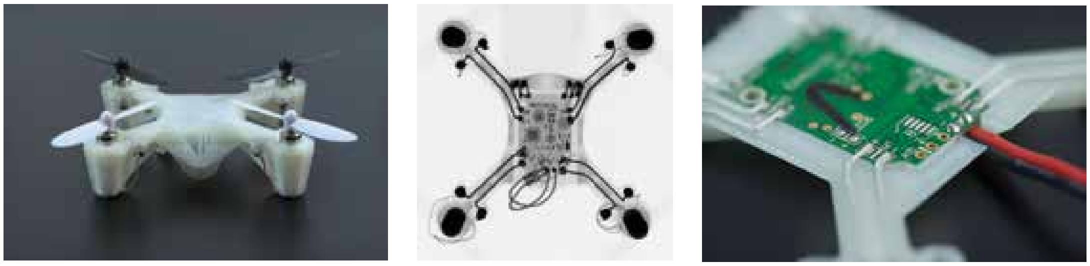
For example, Optomec's Aerosol Jet 3DP technology enables electronics customization for communication devices, personal care, and automotive products. Aerosol Jet technology works by feeding the conductive ink into an atomizer that converts the ink into a mist with material-laden droplets.[22] From the deposition head, the mist is deposited onto the substrate. As the ink is discharged from the nozzle, it is surrounded by a gas, generally dry nitrogen, which helps to keep the ink focused and speeds up the deposition process. Aerosol Jet machines are currently being used to print sensors, antennae, and other functional electronics onto plastic, glass, and ceramic products.[23]

In another example, EoPlex uses AM and multimaterial inks to manufacture a number of electronics.[24] Potential applications include ceramic antennae, camera modules, and lithium batteries. While comparing the costs of additively manufactured products with traditionally manufactured products depends on a number of factors (including design complexity, size, material used, and functionality), the additive approach is better suited to applications where design customization takes precedence over other factors. EoPlex's technology could also have applications in the field of fluidics: the technique of using a fluid to perform analog or digital operations similar to those performed with electronics. Potential applications include fuel cells, microreactors, and emission control sensors. In the field of energy harvesting, the technology can be used to manufacture microstructures that incorporate the space for parts to move, vibrate, and generate energy.[25]

Building electronics within the part production process

The second type of AM-enabled electronics manufacturing represents "one-stop manufacturing" in perhaps its truest sense. Using the desired material, the part is built up until the point at which the electronics parts need to be placed. The part material nozzle is then paused, and the electronic parts are built using another nozzle extruding conductive ink. Once the circuit is complete, the remaining portion of the product is built using the first nozzle. This approach integrates the two production processes in a single build sequence, simplifying assembly efforts. In fact, with companies having some of the existing

Figure 4. A functional quadcopter prototype built additively



Source: Voxel8 Inc., "Case studies: Quadcopter," April 26, 2016, http://store.voxel8.com/case-studies/2016/4/26/quadcopter.

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AM infrastructure, there is an increasing focus on retrofitting existing AM systems to develop capabilities to print electronics. Some companies offer an extruder head that emits conductive ink and that can be plugged into an existing 3D printer to build circuity as part of the production process.[26]

In one example, Voxel8 has developed a fused deposition modeling printer that can print using both thermoplastic and conductive materials. The software developed with Autodesk allows circuit pathways and electronic component bays to be incorporated into the design. Voxel8 built a quadcopter (figure 4) through a multistage process, which started with printing the plastic part of the body along with the spaces for the electronics and circuit pathways. The conductive paste extruder was then used to print the circuitry. At the last stage, the rest of the body was created, and the part was complete.[27]

The second type of AM-enabled electronics manufacturing represents "one-stop manufacturing" in perhaps its truest sense. This approach integrates the two production processes in a single build sequence, simplifying assembly efforts.

Choosing from a limited—but growing—set of materials

In addition to the differences in the process of manufacturing electronics, AM technologies also vary by the type of materials they can use. While a part can be manufactured using standard AM materials such as thermoplastics, metals, and ceramics, electronics must be made using different materials such as conductive silver, copper ink, or newer materials such as graphene. The list of current materials available for 3D-printed electronics is currently somewhat limited, but growing. (See the sidebar "Accelerating intellectual property: A hot area with an increasing number of patents.")

Graphene, a form of graphite, is particularly noteworthy for manufacturing electronics additively. Graphene is transparent, bendable, and offers high electric and thermal conductivity; these properties make it well suited to applications in integrated circuitry.[28] However, the material has challenges: The process for extracting graphene from graphite can be expensive and complex, and supply of high-quality graphene can be inconsistent.[29]

Nanomaterials, materials with particles of materials such as conductive silver or copper in nanoscale dimensions (10^{-9} meters), represent another key development in the field of material sciences. The Aerosol Jet technology discussed in the previous section uses carbon nanotubes to build thin film transistors and nanoparticle silver inks for cellphone antennae.[30] Sicrys I50TM-119, an example of a conductive ink, consists of silver nanoparticles that can be sintered at room temperature.[31] The ink can be used to print electronics on flexible substrates including plastic, fabric, and paper, and enables mass production of antennae printed directly onto phone cases, thereby reducing the cost and size of parts used in smartphone manufacturing.[32]

Developments in traditional and newer materials for electronics could complement 3D printing's broader applications. However, the availability and economic viability of those materials need to be evaluated and improved.

ACCELERATING INTELLECTUAL PROPERTY: A HOT AREA WITH AN INCREASING NUMBER OF PATENTS

As a result of various technology developments, some of which are discussed earlier, activity in the intellectual property (IP) market has heated up in recent years. IP activity typically foreshadows real growth of a new technology and its applications.[33] The total number of AM-related patents issued grew at a CAGR of 20 percent in the last five years to reach 545 patents in 2015. In comparison, the number of 3D-printed electronic/consumer products' patents increased at a 43 percent CAGR to reach 76 patents in 2015—patents for new or improved functionality of electronic products, as well as for the process through which they are made, including materials used.[34]

Avoiding short circuits

Addressing challenges to adoption

FOR all the benefits and opportunities it presents, 3D printing for electronics comes with multiple challenges that can hinder further adoption. These challenges need to be addressed before we see broad applications of AM in electronics manufacturing:

Sophistication of design software. When it comes to designing electronic objects for 3D printing, design software must be able to include electronics in the build sequence of the part itself. In general, design software for 3D-printed electronics is at a nascent stage right now.[35] However, it is reasonable to posit that it will follow the same path as additive manufacturing of parts. There are different estimates of when design software will be ready to support mainstream electronics applications, but it seems probable that the software will become robust over the next couple of years.[36]

Accuracy for microelectronics. Currently available AM systems are capable of printing electronic parts in the scale of a few micrometers; however, integrated circuit chips used in electronic products, popularly known as IC chips, are sized in nanometers.[37] One of the experts we interviewed acknowledged this challenge, but said, “The machines that we have right now, the nozzles are so big, but they can be miniaturized. The challenge is manageable and requires systematic debugging and optimization of the processes over the next couple of years.”[38]

High temperature processing. Most metals used for circuitry require post-processing at a minimum of 100°C to become conductive. However, only a few AM materials such as Duraform (used in AM technologies such as selective laser sintering) and ULTEM (used in fused deposition modeling) can withstand such temperatures.[39] This reduces the combination of materials that can be used to build parts along with electronics. Printing electronics in nanoscale, an area of ongoing research, could provide a solution for temperature processing. Nanoscale particles could be sintered and made conductive at lower temperatures, thus becoming compatible with AM materials that cannot withstand high temperatures.[40]

Adhesion between part and conductive materials. For any deposition process, adhesion between the conductive material and part material (substrate) is important because accessing and repairing the circuit later is difficult. Better adhesion can be ensured by analyzing the texture and chemical interaction between the two materials and applying material treatment based on process optimization.[41]

High cost of materials. Cost is a major factor when materials such as conductive silver are used; however, a part of the inflated cost could be offset by reduced material wastage. One case study is Lockheed Martin’s tests on bleed air leak detector brackets for aircraft engines. While the titanium alloy (Ti-6Al-4V) used in the AM process costs more than the wrought Ti-6Al-4V used in the traditional process, the bracket can still be produced at 50 percent of the cost, because material wastage can be reduced from 97 percent to almost zero.[42] Also, development of standard materials in nanoscale, such as Sicrys I50TM-119 made of silver nanoparticles discussed earlier, are likely to bring down production costs.[43]

Overall, challenges associated with the process through which the electronics are made additively as well the cost of materials need to be addressed before the technology could reach mainstream applications.

Where do we start?

SOME of the key questions executives considering 3D-printed electronics ask are, "How do we start, and where do we deploy these?" The first step in using AM for electronics involves companies assessing how ready they are to start using the technology. Companies could follow the natural cycle of experimenting and using AM for tools, functional prototypes, and then finished parts. Making electronics through AM is a complex process; companies that have become proficient in using the technology for end parts are better placed to take the next step toward making a fully functional electromechanical product straight out of an AM system.

One question often seen in popular media is, "Can AM replace traditional silicon chip manufacturing?" The answer is most likely no.[44] Given current issues with quality consistency and limited material choice, AM can complement traditional manufacturing for select applications discussed below. Relevant applications for 3D-printed electronics can be evaluated through the lens of the AM framework broadly in terms of product and supply chain evolution (see figure 1 "The additive manufacturing framework").

Product evolution

Review the product portfolio: Electronics manufacturers could start by evaluating products with complex shapes or electronics on nonflat surfaces in which they would like to invest. They could think through the many opportunities for designing electronics that fit into a product instead of designing a product around the electronics. Furthermore, companies could consider if product weight or size is a concern they would like to address, given many customers' preference for light, compact electronic products with no decrease in functionality.

Identify products subject to harsh external environments: Companies could evaluate the life cycle of their products, including mass-customized products, to identify situations that may involve external damage to components, such as the electronics used on aircraft wings or in mining equipment. This can help them identify opportunities for adding 3D-printed electronics capabilities.

Examine the assembly processes: Companies could also assess whether complex assemblies are limiting their competitive advantage to improve top lines. For example, NASA is building densely populated assemblies using 3D printing for electronic devices.[45] Detector assemblies are especially difficult to assemble traditionally, because they are usually very small with a large number of components. Aerosol Jet technology can print around spheres, bends, and flexible surfaces, which can later be assembled into any desired shape. Such flexibility is typically difficult to achieve through traditional methods. Furthermore, the manufacturing and assembly time for circuit boards can be cut down from a month to one or two days using AM.[46]

Companies that have become proficient in using the technology for end parts are better placed to take the next step toward making a fully functional electromechanical product straight out of an AM system.

Monitor material costs: While growing their revenues through new or improved products, electronics companies could assess where costs or resource outlays are most significant. There may be opportunities to reduce material wastage, especially where expensive materials are being used.

Supply chain evolution

Identify remote or inaccessible locations: Electronics companies may also look for places that are hard to reach via their traditional supply chains or that require production at the point of use. In one such example, the US Department of Defense is evaluating the use of MultiFab, a 3D printer that can use up to 10 materials at once and embed circuits and sensors directly into the product; it can potentially provide spare parts to missiles in the field itself.[47] The printer is relatively cheaper than previously available multimaterial printers and uses machine vision to generate continuous 3D scans and maintain print accuracy; its ability to self-calibrate and correct minimizes the need for operators to fine-tune the print settings.[48]

Electronics companies may also look for places that are hard to reach via their traditional supply chains or that require production at the point of use.

Evaluate opportunities for customer involvement and mass customization: Electronics manufacturers could evaluate their supply chains for opportunities to incorporate customer feedback into the product development stage and manufacture mass-customized products. For instance, 3D-printed wearables for the military could include helmet lining that is suited to different weather conditions, antennae with minimal visible signature, and conductive textiles for uniforms.[49]

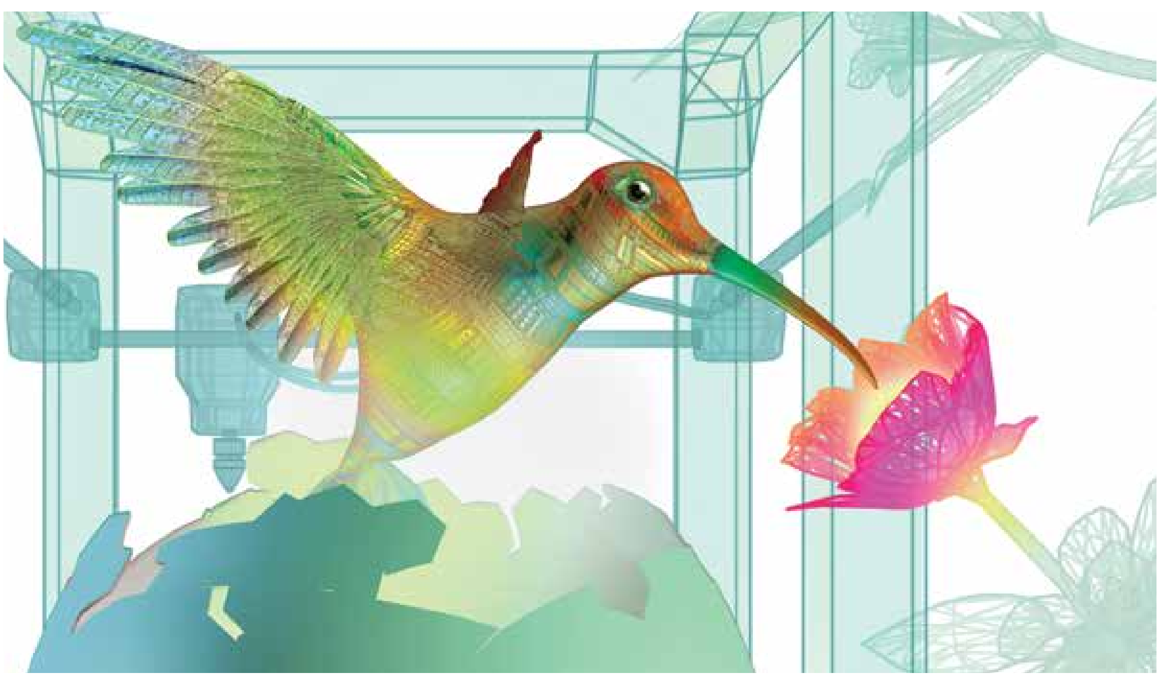
This is just the beginning

THE underlying challenges associated with 3D printing of electronics require systematic debugging and optimizing processes over a period of time. While comparing traditional and additive technologies, it must be noted that traditional processes for manufacturing electronics have been optimized for over 30 years, and AM would require similar fine-tuning to improve its adoption.

Some AM analysts expect 3D-printed electronics to be the next high-growth application for product innovation in the next five years.

By examining the opportunities and underlying challenges of using AM for electronics, executives could make informed decisions about applications where AM surpasses traditional manufacturing to differentiate their products and create a competitive advantage for themselves. As we discussed, AM is relevant for a few specific applications that require complex designing, lower weight, point-of-use manufacturing, and mass customization.

Some AM analysts expect 3D-printed electronics to be the next high-growth application for product innovation in the next five years. This piece should serve as a ready reckoner for readers contemplating the use of AM for manufacturing electronics—and while it is difficult to cover all the aspects related to this fast-growing space, companies could use the technical and strategic aspects covered in this paper as a starting point.



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