technologyforecast

2014
Issue 2

The future of 3-D printing: Moving beyond prototyping to finished products

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Contents

2014
Issue 2

Features

Related interviews

Andrew Boggeri

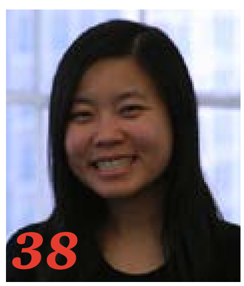
Lead engineer at FSL3D on the rise of 3-D marketplaces

Dr. Joshua M. Pearce

Professor at Michigan Technological University on rapid innovation cycles defining the future for 3-D printers

Gonzalo Martinez

Director of strategic research at Autodesk on going beyond topology information

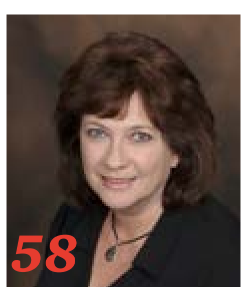


Nancy Liang

Co-founder of Mixee Labs on making 3-D printing accessible

Dr. Eric Duoss

Materials scientist at Lawrence Livermore National Laboratory on fabricating materials that have new properties



Christine M. Furstoss

Global technology director at GE's global research center on seizing competitive advantage with 3-D printing

The road ahead for 3-D printers

By Alan Earls and
Vinod Baya

As 3-D printers become faster, easier to use, handle multiple materials, and print active components or systems, they will find use beyond rapid prototyping.

Technology for 3-D printing will advance through loosely coordinated development in three areas: printers and printing methods, software to design and print, and materials used in printing.

The technology for 3-D printing, also known as additive manufacturing, has existed in some form since the 1980s. However, the technology has not been capable enough or cost-effective for most end-product or high-volume commercial manufacturing. Expectations are running high that these shortcomings are about to change.

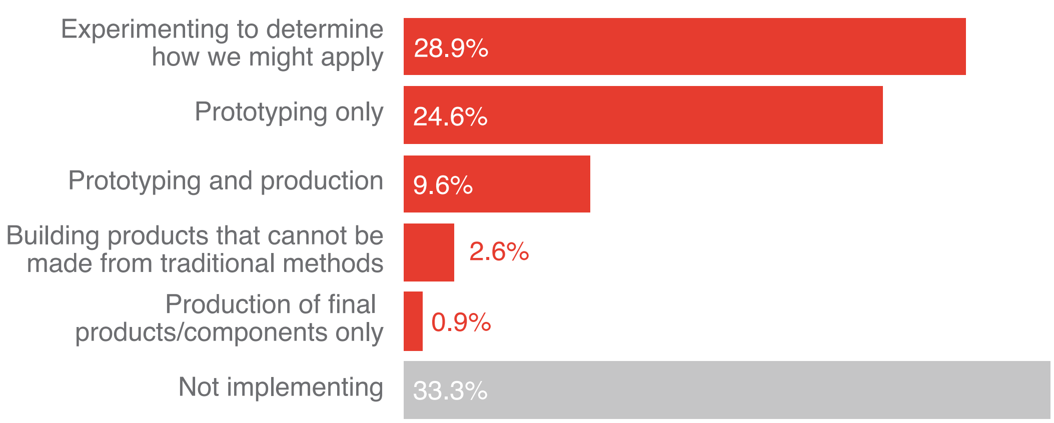
Several technology trends are feeding these expectations. An emerging class of mid-level 3-D printers is starting to offer many high-end system features in a desktop form factor at lower price points. Printer speeds are increasing across the product spectrum; at least one high-end system under development could print up to 500 times faster than today's top machines. And key patents are about to expire, a development likely to hasten the pace of innovation.

In a recent PwC survey of more than 100 industrial manufacturers, two-thirds were already using 3-D printing. (See Figure 1.) Most were just experimenting or using it only for rapid prototyping, which has been 3-D printing's center of gravity for most of its history. Canalys, a market research firm, anticipates changes ahead and predicts the global market for 3-D printers and services will grow from $2.5 billion in 2013 to $16.2 billion in 2018, a CAGR of 45.7 percent.[1]

Despite these trends, the 3-D printing industry faces challenges. Rapid prototyping will remain important but is not the game-changer that will expand the technology into high-volume use cases. The industry should pivot to printing more fully functional and finished products or components in volumes that greatly outnumber the volumes of prototypes produced. For example, some makers of hearing aids and dental braces have adopted the technology for finished products. In addition, 3-D printing should supplement or supplant products and components manufactured traditionally and create items that can be manufactured in no other way.

Figure 1: Prototyping has driven the adoption of 3-D printing so far. Future opportunities include production of final products or components.

How is your company currently using 3-D printing technology?



Source: PwC and ZPryme survey and analysis, conducted in February 2014

1 Canalys, "3D printing market to grow to US$16.2 billion in 2018," news release, March 31, 2014, http://www.canalys.com/newsroom/3d-printing-market-grow-us162-billion-2018#sthash.jovzItNE.dpuf.

Table 1: Emerging uses of 3-D printing in different industry sectors

Industry sector	Some emerging and near-term future uses of 3-D printing
Automotive and industrial manufacturing	• Consolidate many components into a single complex part • Create production tooling • Produce spare parts and components • Speed up the product development cycle with rapid prototyping, form and fit testing
Aerospace	• Create complex geometry parts not possible with traditional manufacturing • Control density, stiffness, and other material properties of a part; also grade such properties over a part • Create lighter parts
Pharma/ Healthcare	• Plan surgery using precise anatomical models based on CT scan or MRI • Develop custom orthopedic implants and prosthetics • Use 3-D printed cadavers for medical training • Bioprint live tissues for testing during drug development
Retail	• Create custom toys, jewelry, games, home decorations, and other products • Print spare or replacement parts for auto or home repair, for example
Sports	• Create complex geometry and shape not possible with traditional manufacturing • Create custom protective gear for better fit and safety • Create custom spike plates for soccer shoes based on biomechanical data • Create multi-color and multi-material prototypes for product testing

To evolve their design and manufacturing strategies, many industry sectors are using 3-D printing solutions already in the market. (See Table 1.) Technology for 3-D printing will advance through loosely coordinated development in three areas: printers and printing methods, software to design and print, and materials used in printing. This issue of the PwC *Technology Forecast* examines each of these areas. This article assesses 3-D printer and printing method trends in performance, the management of multiple materials, and capabilities for producing finished products. Future articles will examine the software and the materials themselves.

The emerging shape of the 3-D printer industry

In 3-D printing, hundreds or thousands of layers of material are "printed" layer upon layer using various materials, or "inks,"[2] most commonly plastic polymers and metals. The many different printing technologies are generally material dependent. (See the sidebar "3-D printing technologies.") For instance, fused filament fabrication (FFF) is used with plastics, stereolithography with photosensitive polymers, laser sintering with metals, and so on.

2 The term *inks* refers to all material in 3-D printing that is either extruded or jetted out of a nozzle. The term is not limited to inkjet-based printing methods.

3-D printing technologies

- **Stereolithography (SLA):** This 3-D printing technology uses an ultraviolet beam to harden liquid resin, bonding each successive layer.
- **Fused filament fabrication (FFF):** A stream of melted thermoplastic material is extruded from a nozzle to create layers, with each layer bonding to the previous layer. Common inks include ABS (acrylonitrile butadiene styrene) and polyactic acid polymers.
- **Selective laser sintering (SLS):** SLS uses powdered materials (such as nylon, titanium, aluminum, polystyrene, and glass) instead of the liquid polymers used in FFF. Powder is jetted from many nozzles onto the print surface, much like an inkjet printer. Laser is used to sinter or fuse the powder, layer by layer.
- **Selective laser melting (SLM):** SLM is similar to SLS, but rather than fusing the powdered material, the powder is melted at very high temperatures.
- **Electron beam melting (EBM):** EBM is similar to SLS, but EBM employs an electron beam as its power source.
- **Laminated object manufacturing (LOM):** In this additive process, laminates of materials (such as metals, plastics, or paper) are bonded in successive layers and then cut into shapes. In some cases, the shapes are worked on further (for example, through machining or drilling) to finalize the product.

The printers must be improved in three areas to seize the opportunities that exist beyond today's predominant use case of rapid prototyping:

- **Performance:** Improve key performance characteristics, such as speed, resolution, autonomous operation, ease of use, reliability, and repeatability.
- **Multi-material capability and diversity:** Incorporate multiple types of materials, including the ability to mix materials while printing a single object.
- **Finished products:** Provide the ability to print fully functional and active systems that incorporate many modules, such as embedded sensors, batteries, electronics, microelectromechanical systems (MEMS), and others.

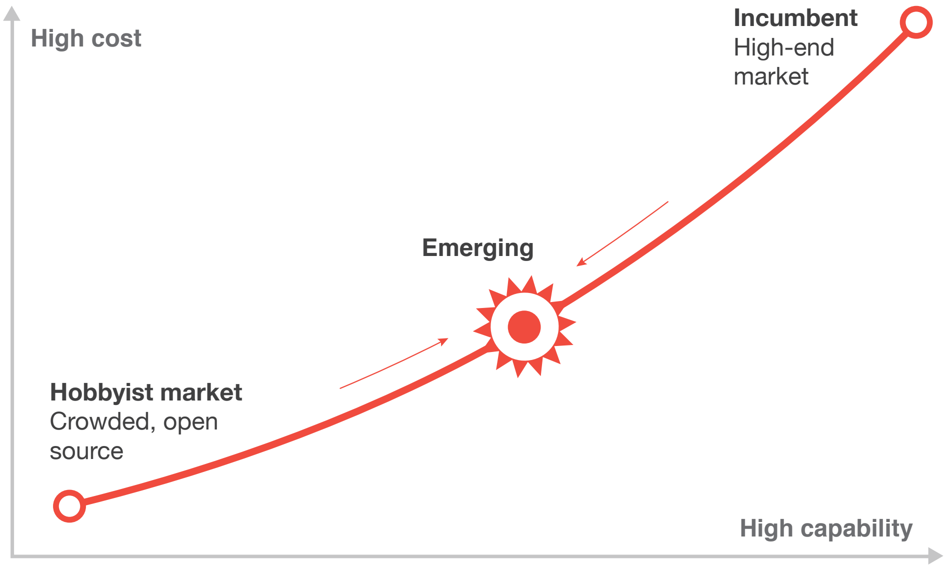
Today's 3-D printers are concentrated at two ends of a spectrum: high cost–high capability and low cost–low capability. (See Figure 2.) High-end printers are generally targeted at enterprises and 3-D printing service bureaus; low-end printers, which are often derivatives of open source RepRap[3] printers, are targeted at consumers and hobbyists.

During the past year, a new class of printers in the middle has emerged. These printers from new entrants and established vendors have many of the higher-end capabilities at lower prices. For example, printers from FSL3D and Formlabs deliver higher resolution and smaller size using stereolithography technology and are priced at a few thousand dollars. Printers from MarkForged offer the ability to print using carbon fiber composites in a desktop form factor for less than $5,000. CubeJet from 3D Systems is priced under $5,000, can print in multiple colors, and brings professional features to a lower price point.[4]

3 RepRap was one of the first desktop 3-D printers. The RepRap concept applies to any machine that can replicate itself, which the RepRap 3-D printer can do. For more details, see http://reprap.org/wiki/RepRap.

4 Brian Heater, "The CubeJet promises pro-level 3D printing in a consumer form factor for under $5,000," *Engadget*, January 7, 2014, http://www.engadget.com/2014/01/07/cubejet/.

Figure 2: The emerging market for printers is defining a new category that has high capability at lower cost.



Source: PwC

While many characteristics define a printer's performance, the key challenges are speed and ease of use.

Gartner predicts that 3-D printers with the value (capabilities and performance) that is demanded by businesses and other organizations will be available for less than $1,000 by 2016.[5] It is fair to expect that printer improvements will accelerate in the next few years, although the degree and nature of these changes will vary considerably across printing technologies and vendors.

Emerging trends in 3-D printer performance

While many characteristics define a printer's performance, the key challenges are speed and ease of use.

Printers can be expected to get faster

Even for simple products, 3-D printing still takes too long—usually hours and sometimes days. Incremental improvements as well as new methods that have the potential for an order of magnitude change will help printers meet the challenge for greater speed. "There are lots of ways to improve speed by using higher-quality components and by optimizing the designs and movement of the lasers," says Andrew Boggeri, lead engineer at FSL3D, a provider of desktop stereolithography printers. For instance, Form 1+, a stereolithography printer from Formlabs, uses lasers that are four times more powerful to print up to 50 percent faster than the previous generation printer Form 1.[6]

Most of today's printers use a single printhead to deposit material. Adding more printheads that print at the same time can increase speed by depositing material faster while incorporating multiple materials or multiple colors of the same material. Multiple heads can also make many copies of the same design in the time it takes to print one. With such innovation, print speed can increase more or less linearly as the number of heads increases. At the hobbyist end, Robox sells a dual nozzle printer that the company says can print three times faster than single nozzle printers.

5 Pete Basiliere, *How 3-D Printing Disrupts Business and Creates New Opportunities*, Gartner G00249922, April 2014.

6 Signe Brewster, "Formlabs reveals the Form 1+, a faster and more reliable SLA 3D printer," *Gigaom*, June 10, 2014, http://gigaom.com/2014/06/10/formlabs-reveals-the-form-1-a-faster-and-more-reliable-sla-3d-printer/.

"These [hobbyist 3-D] printers all need considerably more personal upkeep than people are accustomed to with appliances."

—Professor Joshua Pearce, Michigan Technological University

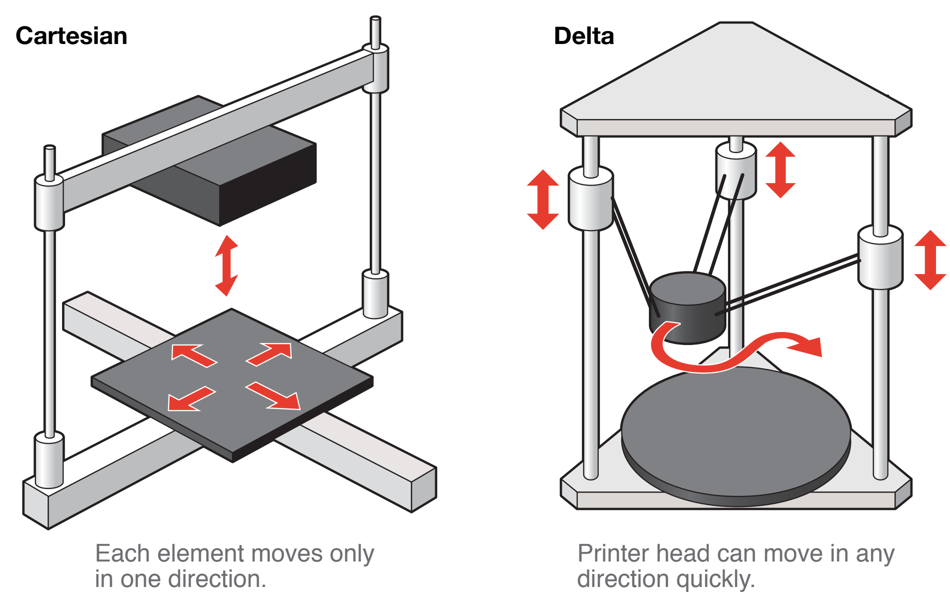
Speed is especially a challenge when printing larger objects. Large objects require more material to be pushed through the printer nozzle, which generally has a set rate for processing material. A partnership between Oak Ridge National Laboratory and Cincinnati Incorporated, a machine tool manufacturer, is addressing this challenge.[7] The organizations are developing a large-scale additive manufacturing system. Their design will combine larger nozzles for faster polymer deposition, high-speed laser cutters that handle work areas in feet rather than inches, and high-speed motors to accelerate the pace at which printer heads are moved into position. The result will be a system capable of printing polymer components as much as 10 times larger, and at speeds 200 to 500 times faster than existing additive machines.

To control the movement of the printer head, 3-D printers use different approaches or architectures. Cartesian printers, which move a printhead in two dimensions on a plane, are the popular configuration today. Deltabot printers, also called Delta robot printers, use parallelograms in the arms like a robot. (See Figure 3.) "The Delta printers will basically take over all the Cartesian printers, because they have some significant benefits, one of which is speed," predicts Joshua Pearce, associate professor at Michigan Technological University (MTU) and an active developer of open source 3-D printers. Delta configuration allows for higher speed, because the printheads are lighter and they use shorter paths from one point to another.

Printers will become more automated and easier to use

Existing 3-D printers perform many tasks autonomously. However, some printers at the hobbyist end require that printheads be cleaned periodically, that beds be properly leveled, and that a human tinker and supervise to minimize errors. "These printers all need considerably more personal upkeep than people are accustomed to with appliances," Pearce says. The potential to reduce or eliminate this human element is real and will be a key area of innovation over the next few years.

Figure 3: Cartesian and Delta configuration in printers



Source: PwC

7 Oak Ridge National Laboratory, "ORNL, CINCINNATI partner to develop commercial large-scale additive manufacturing system," news release, February 17, 2014, http://www.ornl.gov/ornl/news/news-releases/2014/ornl-cincinnati-partner-to-develop-commercial-large-scale-additive-manufacturing-system--.

> *"For multi-material printing, inkjet-like technology such as Voxeljet is the present and the future."*
>
> *—Andrew Boggeri, FSL3D*

Automating the features that cause many of the common errors and reliability concerns, such as support structure generation, part orientation, and others, will likely advance the ease of use in hobbyist printers. For instance, a print run can be wasted if the build platform is not level. Many printers, such as those from Robox, XYZprinting, and MakerBot, include auto-leveling where the printer calibrates itself to the platform. Expected in the future is a feedback system that provides real-time monitoring of the printing process, that detects defects or deviation from the design (as specified in a 3-D model generated by a CAD [computer-aided design] tool), and that allows appropriate intervention. Together, such features will likely improve the reliability and repeatability of the printing process.

Emerging trends in how 3-D printers deal with materials

Most printers work with only one type of material—plastic, metal, ceramic, wood, or a biological material. To create more useful products and expand the market, 3-D printers will need to process multiple material types within a single build cycle. Various factors, mostly related to materials themselves, make this requirement challenging. For example, most processes are built around an ideal material that responds to a narrow range of temperature inputs or light frequency. Using heat or light, printers often liquefy or solidify substances to manipulate the material into specific forms. The characteristics that make this manipulation work exclude many other potential materials—at least at the current level of sophistication.

The pursuit of multi-material capability will favor certain printing methods over others. FFF printing has high potential to accommodate multiple materials without greatly extending the existing technology, because printing heads can be added to handle other polymers. Multi-head printers are available from Hyrel 3D, XYZprinting, and MakerBot for less than a few thousand dollars.

"For multi-material printing, inkjet-like technology such as Voxeljet is the present and the future," Boggeri predicts. Methods such as selective laser sintering and others use inkjet technology. This technology can handle multiple materials within a range that can be delivered as a powdered "base," because it already uses multiple printheads. As a result, parts or assemblies made from different materials can be printed in a single print run. Today this technology is accessible at the high end from Voxeljet, Stratasys, 3D Systems, and others.

Inkjet printing for 2-D printers has been around since the 1970s, but was adopted for 3-D printing only about seven years ago by Objet (now part of Stratasys) in a process the company calls PolyJet. By jetting two or more base materials in varying combinations, this technology allows the creation of new material properties that span from rigid plastic to rubber-like and from opaque to transparent. More recently, the technology also allows the printing of multiple colors. For example, the Stratasys Objet500 Connex3 printer supports multi-material and multi-color 3-D printing. A printed part can have as many as 14 distinct material properties and 10 color palettes.[8]

8 Stratasys, Objet500 Connex3, *How to Maximize Multi-Material and Color Possibilities*, 2013.

Figure 4: The prototype handspring in this picture combines soft and hard polymer material of different colors. The prototype set of headphones combines multiple materials in multiple colors.

Source: Stratasys

Today, multi-material printers work for a single family of materials—polymers, for instance—and are largely used for prototyping so designers can check form, function, fit, and feel. Figure 4 shows multi-material prototypes of a handspring and headphones made by the Connex3 printer.

Advances are still needed to combine different families of materials, such as metals and plastics, in a single print cycle.

Advances are still needed to combine different families of materials, such as metals and plastics, in a single print cycle. Developments on this front are in very early stages in research labs,[9] and it will likely be more than five years before products are offered.

Emerging trends in printing complete systems

Farther out is the ability to print complete systems or subsystems. Emerging multi-material capabilities will help, since most finished products are made from more than one material. However, challenges extend to the ability to embed components such as sensors, electronics, and batteries, so everything can be printed in one build. R&D efforts are under way in a number of areas, including materials, printing methods, and combining additive and traditional methods of manufacturing.

The key materials science challenge is to develop inks that can be the basis for printing different types of products, be they sensors, electronics, or batteries. For example, Xerox PARC is developing inks so circuits, antennas, and RFID tags can be printed and applied directly to a product.[10] Similarly, Professor Jennifer A. Lewis at the Harvard School of Engineering and Applied Sciences has developed the basic building block of tiny lithium-ion batteries as inks that can be printed.[11]

The future of additive manufacturing is not limited to inanimate objects. Lewis's team has developed bio-inks to make living tissues. The team uses multiple printheads and the customized inks to create complex living tissues, complete with tiny blood vessels.[12] Some pharmaceutical companies are already using 3-D printed tissue for testing drugs.

9 Michael Molitch-Hou, "Metal-Plastic Voxel 3D Printing Pursued by Arizona State University," *3D Printing Industry*, April 2, 2014, http://3dprintingindustry.com/2014/04/02/3d-printing-metal-plastic-voxel-arzona-state-university/.

10 "Print me a phone," *The Economist* (US), July 28, 2012, http://www.economist.com/node/21559593.

11 Mike Orcutt, "Printing Batteries," *MIT Technology Review,* November 25, 2013, http://www.technologyreview.com/demo/521956/printing-batteries/.

12 The Wyss Institute for Biologically Inspired Engineering at Harvard University, "An essential step toward printing living tissues," news release, February 19, 2014, http://wyss.harvard.edu/viewpressrelease/141/.

Bio-printing typically uses two inks. One is the biological material and the other is hydrogel that provides the environment where the tissue and cells grow. The breakthrough to add blood vessels was the development of a third ink that has an unusual property: it melts as it cools, not as it warms. This property allowed scientists to print an interconnected network of filaments and then melt them by chilling the material. The liquid is siphoned out to create a network of hollow tubes, or vessels, inside the tissue. Such creations are possible only with 3-D printing, generating new possibilities beyond traditional manufacturing.

The printing of complete systems is not limited to a nano or microscopic scale. Working with Aurora Flight Sciences and Stratasys, Optomec has printed complete airplane wings, including electronics and sensors, for small drones.[13] Each wing was printed with a Stratasys FFF printer. The sensors and circuitry were printed directly onto the wing using Optomec's aerosol jet system. Whereas the inkjet process prints on a flat surface, depositing tiny drops of ink from a printhead less than a millimeter away, the aerosol jet process atomizes the nanoparticle-based print material into tiny droplets and focuses them via a nozzle on a print surface that can be curved or an irregular shape. The print surface can be kept 5 millimeters or more away. This capability enables the printing of electronic features smaller than a hundredth of a millimeter.

Some approaches may combine 3-D printing with other manufacturing methods. For example, iRobot has filed a patent for a fully automated robotic 3-D printer, including multiple manipulators and milling, drilling, and other processes to make final products.[14]

Can CIOs be a catalyst for taking advantage of 3-D printing?

At this time, the impact of 3-D printing may seem limited to product development, manufacturing, and supply chain functions. However, taking advantage of the full potential of 3-D printing necessitates that CIOs and the IT function be close collaborators. There are many reasons for this need for collaboration, such as:

- CIOs can evaluate 3-D printing for disruptive potential by engaging other C-suite peers in discussions about the possibilities, linking the technology to business goals.
- 3-D printers and any associated accessories, such as scanners and cameras, are all new devices that need to be connected to networks, secured, and administered.
- 3-D printing will generate new product development, manufacturing, and related data that should be captured, secured, analyzed, and integrated with operations to create business advantage.
- Certain transactional systems will need to be modified to accommodate changes in manufacturing and the supply chain processes.
- 3-D printing will create particular challenges related to intellectual property theft, because others might use digital files to create exact replicas of products.

The 3-D printing revolution will be information rich and require wide-ranging changes to business operations. The use of 3-D printers at any enterprise is certain to rise. CIOs should think through the opportunities and challenges that 3-D printing creates for their departments and get ahead of the trend, so they can be a catalyst for the business to take full advantage of 3-D printing.

Pace of innovation suggests high expectations will be met

The 3-D printer market is transforming rapidly. Robust innovation at established vendors and among entrepreneurs and hobbyists is providing a test ground for filling the market with more midrange systems that bring enterprise-class capabilities at much lower prices.

Another key factor that will likely change soon is the control that patent holders have had over specific techniques. When key patents for FFF expired five years ago, the open source community rapidly incorporated the techniques in low-cost printers, triggering improvements in speed, quality, resolution, and ease of use.

13 "Revolutionary 'Smart Wing' Created for UAV Model Demonstrates Groundbreaking Technology," Optomec, 2006, http://www.optomec.com/revolutionary-smart-wing-created-for-uav-model-demonstrates-groundbreaking-technology/.

14 Cabe Atwell, "iRobot Takes Humans out of 3-D Printing Equation," *Design News*, March 13, 2013.

Likewise, many laser-sintering patents are set to expire in 2014. "I would expect rapid innovation to occur in 3-D printers that use laser sintering, sort of what happened with the RepRap and FFF method," Pearce says. Communities such as Metalbot and OpenSLS already have open source efforts to create desktop-based laser-sintering printers. If the pace of innovation is as rapid as it was with FFF printers, then less-expensive desktop metal printers may appear within a few years.

Today's market for 3-D printers and services is still largely bifurcated—at the low end are limited-function offerings of interest to hobbyists. At the high end are expensive printers that have a limited total available market. The key for market growth is the continuing development of printers in the middle price range to achieve advances in performance, in multi-material capability, and in printing complete systems. PwC expects these continuing developments to open the door to a disruptive expansion in the market.

The rise of 3-D printing marketplaces

Andrew Boggeri of FSL3D discusses the future of 3-D printers and predicts the rise of marketplaces bringing together designers and buyers.

Interview conducted by Vinod Baya and Bo Parker

Andrew Boggeri

Andrew Boggeri is a lead engineer at FSL3D, which manufactures high-quality consumer desktop 3-D printers featuring laser-based stereolithography technology.

PwC: Andrew, can you please tell us about your company and how you got into 3-D printers?

AB: Sure. FSL3D is a division of Full Spectrum Laser, which began in our founder's garage in 2010. Full Spectrum Laser started out reselling laser cutters from China. Our founder realized that although the mechanics of those systems were OK, the electronics were not well engineered and the software was almost impossible to use. So we developed our own high-power embedded circuit board to control the lasers, and we developed our own software front end. We also sell custom-designed, high-end metal marking lasers.

In doing so, we gained valuable experience in creating a control system for galvanometers, also called *galvos*. Galvos are devices for steering laser beams. Each one is essentially a DC motor with built-in feedback that has a very light shaft attached to a very small mirror. The system has minimal rotor inertia and so can be used to steer a beam at very high speed with excellent accuracy. A tiny deflection of the mirror will produce a very fast movement over a great distance.

“On a longer time scale, beyond five years, the bigger trend will be the rise of midsize companies that do not need to own their own manufacturing base.”

We saw that 3-D printers were really popular, but all the desktop ones were using FFF [fused filament fabrication] technology. We’ve owned several different types of 3-D printers, and we have used 3-D printing often during prototyping. Most of our experiences were neutral at best. Given our deep experience with lasers, we saw an opportunity to create a laser-based desktop 3-D printer. We launched a Kickstarter campaign to raise $100,000. We raised more than $819,000 in 33 days. Pegasus Touch is our desktop stereolithography [SLA] printer.

PwC: What made it possible to create a laser-based desktop 3-D printer at the price range you are offering, which is around $2,000?

AB: A big portion of the cost for laser 3-D printers is the laser modules. The tremendous change recently has been the proliferation of Blu-ray players, which brought down the cost of laser modules. Blu-ray diodes are now available at a lower cost, making it possible to engineer a desktop system at the price points we are targeting.

We originally looked at DLP [Digital Light Processing] projection technology; the technical term is MIP stereolithography, or mask image projection. With MIP, instead of moving a beam around, a full image of the layer is projected so the whole layer can be cured at once. We found this approach very slow, however. Because the technology uses a light bulb and the light is greatly diffused, it takes several seconds per layer to cure the resin. We had built a prototype, but we shelved the project in favor of using lasers.

PwC: How does the performance of your printer compare with the high-end printers?

AB: First, price is a big difference. Where we excel against the high-end printers is in the speed and the ease of use, and we are comparable and often better in terms of quality. The high-end printers use a different class of resins that have entirely different chemistry and require a lot more expensive laser diodes to cure the resin. The tradeoff is that you can build totally transparent lenses with the high-end printers. You will also get high fidelity and some better properties out of those resins. We searched very hard for improved optics and now have a system that is comparable with products that cost more than 10 times as much.

PwC: Most printers in use today work with only a single material. What would it take to make them multi-material printers?

AB: This is a difficult problem for 3-D printing. Our particular technology, SLA, is a single-material technology. Conceivably, it could be turned into a multi-material technology by adding more types of resin and lasers. Such additions would make the printer very complex, and there would be a lot of operational tradeoffs.

FDM [fused deposition modeling] printers will be more advantageous for multi-material printing, because more heads can be added at much lower cost and complexity. However, the multi-material printers getting the most play are using Voxeljet technology. It’s similar to an inkjet printing head with drops of material. For multi-material printing, I think that is the present and the future.

“There are lots of ways to improve speed by using higher-quality components and optimizing the designs and movement of the lasers.”

PwC: When will we see desktop printers that print with metal? We have heard of the ones that use arc welding to print with metal.

AB: I don’t think we will see a desktop-size metal printer that uses the direct metal laser sintering [DMLS] method. These printers use fine metal powder that is bonded with a laser. Two big barriers are stopping DMLS metal printing from coming down in price. First, the lasers needed to melt metal are typically high-powered fiber lasers. Today the least expensive of these lasers cost $15,000 to $20,000 for an entry-level model, and the entry-level models are not powerful enough for DMLS. Second, the cost of the raw material—the fine metal powder that the printers need—runs anywhere from $600 per kilogram and up. However, DMLS can produce very small features, and therefore complex geometries are possible.

For now, the downside of a welding-based desktop printer is that the bead of a weld is on the order of millimeters rather than a few microns. So it’s suitable for products that don’t need high resolution.

PwC: One barrier often cited is the slow speed of 3-D printers. A print cycle can take hours. What are the prospects for printers becoming faster in the future? Are we anywhere near the physical limits of what is possible?

AB: There are lots of ways to improve speed by using higher-quality components and optimizing the designs and movement of the lasers. Of the laser desktop printers, we’re among the fastest right now. With our control electronics, we can pulse the laser at 500 Hz while printing at 3,000 millimeters per second.

The slow part of the SLA process is the release and recoating cycle. One must either withdraw or tilt the head to get the resin to release and then recoat the next thin layer of resin that will be cured. We’re researching some special release coatings that the resin adheres to much less than our current coatings, so we can perhaps double—maybe triple—the speed of this cycle and still maintain the quality.

The other factor that impacts speed is how fast the resin is cured. We could drive our lasers faster and cure this resin at a very, very fast speed—probably 10 or 20 meters per second, rather than 3 meters per second like we’re doing now. The chemical reaction proceeds much faster than we’re able to drive our lasers.

"As 3-D printing tools become better and more automated, I can imagine a day where people buy just a circuit board for their new phone and print the rest at home or at the nearest 3-D printing center, customized to their needs."

In the filament printers [FDM], speed is influenced by the particulars of plastic melt rheology. Today, a fast printer is moving about 300 millimeters per second while it's pushing plastic out. If you try to move faster, you will end up with a bunch of Hershey's Kisses on the ground. So there are likely physical limits to how fast you can move the head.

The technology that has good headroom for speed improvements is inkjet-based printers. You can deploy a lot of heads to work in parallel on a given layer. It's really a matter of cost and complexity that rises as the number of heads increases.

PwC: Are you seeing any challenges to adoption that the industry needs to address?

AB: The 3-D printing ecosystem depends on digital files that represent the designs that would be printed. The problem that still exists is how do people buy or sell these designs? Today consumers can buy an STL [STereoLithography file format] file from several online libraries, and it is not uncommon for designs to cost $40 or $50 or more. High-end sculptures cost even more, perhaps $600 for a print or $2,000 for the design. Today the designers do not have any protections, as there is no built-in way to protect an STL file from being copied and reused. This lack of protection is reflected in the high prices of designs. That is not the future.

What is needed is a marketplace like Apple iTunes, where 99-cent impulse purchases are available. At these price points, customers can try designs. That's what we're doing, and soon I think everybody will. We have the touch screen on the printer, so the design library store will run on a printer without the need for a PC. This store is going to work like a combination of Amazon and iTunes.

A marketplace will connect design creators and design buyers. Our printers will have built-in digital rights management [DRM], and every printer is encrypted to an individual serial number. This software model will be available like an app, in that a designer can sell a copy of this model to anyone who has this printer and the model works only on that individual's printer.

Without the threat of designs being stolen and copied indefinitely between printers, design owners can price them much more affordably, such as 99 cents or $5. Lower prices should increase adoption by more designers participating in the ecosystem.

PwC: What do you expect to see in the future that is not here today?

AB: I expect the rise of distributed peer-to-peer buying and selling. There are digital crafts and digital artisans—people who are creating digital things using modern technology. The 3-D printers are the manufacturing base for these things and will enable folk manufacturing. In small ways it is already happening, and it will accelerate as the price drops.

On a longer time scale, beyond five years, the bigger trend will be the rise of midsize companies that do not need to own their own manufacturing base. As 3-D printing tools become better and more automated, I can imagine a day where people buy just a circuit board for their new phone and print the rest at home or at the nearest 3-D printing center, customized to their needs.

Toy companies especially are starting to catch on to the possibilities of 3-D printing, as they no longer need to set up $500,000 worth of tooling and months and months of engineering time to launch a new toy line. Now they could just sell a digital design file for $5 or $10 that took them maybe a month or two to design. This scenario is a rapid time to market at much lower risk.

PwC: What are the prospects of printing integrated systems, particularly in the next five years?

AB: I'm not truly sure. Optomec has a very interesting technology, but it's not widely used yet. It would allow for a 3-D printed part with embedded electronic traces, but someone still needs to solder the parts. I think initially it will be confined to higher-end products or high-performance products. It's also a somewhat complicated system, so it won't be on the desktop anytime soon. Will an integrated system printer be in every Joe's house within five years? No, I don't think so. But, I think in five years people will be aware of these things and trends.

Rapid innovation cycles define the future for 3-D printers

Joshua Pearce of Michigan Technological University shares the developments making 3-D printers less expensive and easier to use.

Interview conducted by Vinod Baya and Bo Parker

Dr. Joshua M. Pearce

Dr. Joshua M. Pearce is an associate professor at Michigan Technological University. He heads the Michigan Tech Open Sustainability Technology Lab and is the author of *Open-Source Lab: How to Build Your Own Hardware and Reduce Scientific Research Costs.*

PwC: Joshua, can you please describe your market positioning in the 3-D printing ecosystem?

JP: Sure. My group and our work represent the open source trends in 3-D printing. We're coming at it from the low-cost side and using global collaboration to drive innovation. Our printers in general cost less than $500, and either they are put together from kits or they print themselves. It's called RepRap, short for self-replicating rapid prototype—a technology that was originally developed in Britain but has now spread around the world.

PwC: Do you think the low-cost printers will be in every home in the future?

JP: Yes, most homes. We've done some initial studies on the economics of using a 3-D printer at home. We looked at 20 household products that can be printed in fewer than 25 hours—so shorter than a weekend. Our analysis concluded that if the quality of the product was good enough, then owning a printer could offset the costs of purchasing equivalent products by somewhere between $300 to $2,000, depending on the objects and the amount of usage. Since 3-D printing allows a person to customize objects, I think we can go with the higher end of that range. There are now hundreds of thousands of similar open source designs of printable objects.

"There is clearly room for improvement from where we are today, even without going to fundamentally different physical processes."

The economics get even better if we take into account some recycling. We developed RecycleBot, which can recycle some of the plastic waste as feedstock for an FFF [fused filament fabrication] printer. The RecycleBot takes milk jugs and other household plastic waste and turns them into feedstock for the 3-D printer. Commercial filament today is at least $35 per kilogram. If a person uses recycled plastic containers, not counting labor, the material cost is about 10 cents per kilogram, so basically free. This option is a win-win economically and environmentally.

A typical household can easily recover the cost of a printer in less than a year and also have a positive impact on the environment. These are all strong incentives for owning a 3-D printer.

PwC: What are the challenges to overcome before we see these in every home?

JP: There's a long list of challenges. Currently, I'll say that all the low-end printers—they don't just work. That is, you need to have some technical competency. You don't need an engineering degree, but you need to be able to tinker and work with tools and bolts and so on. These printers all need considerably more personal upkeep than people are accustomed to with appliances. The devices require constant tweaking to maintain the sweet spot for printing good-quality parts. That requirement is one of the reasons the popularity of 3-D printers is limited mostly to hobbyists and engineers today.

PwC: You talked about RepRap printers that use plastic as feedstock. What about metal printing on the desktop—are we there yet?

JP: There have been metal welding robots for some time. Last year we developed a RepRap that could print steel when attached to a MIG [metal inert gas] welder. The design source is the same: a geometrical STL [STereoLithography] data file. We are shooting current back and forth between a metal tip and a grounded metal print bed. The tip is melting and dropping small drops of metal many times a second as it builds the layer. Then we move the build platform in the vertical direction and repeat to create a 3-D metal object.

PwC: Today, printers take hours to print an object of any complexity and size. Is that likely to change in the future? Are we close to any physical limits?

JP: I don't know over the long term, but I can talk about near-term potential. The Deltabot printers are at least twice as fast as the Cartesian printers,[1] because they have much lighter heads. Right now, only a couple of Delta-style printers are on the market. I predict that won't be true much longer. The Delta printers will basically take over all the Cartesian printers, because they have some significant benefits, one of which is speed.

1 Cartesian printers use the three dimensions of x, y, and z. The printhead moves in the xy horizontal plane, and the build platform moves in vertical dimension z. Delta printers use parallelograms in the arms, so the printhead moves in all three dimensions—like the end of a pick-and-place robot.

“I would expect rapid innovation to occur in 3-D printers that use laser sintering, sort of what happened with the RepRap and FFF method. As soon as the patents expired and the open source community got their hands on the FFF method, the innovation accelerated substantially.”

Also, as the low-end printers mature, they get features already in the high-end professional printers that can speed up performance. For example, the printers no longer need to decelerate around curves, because designers can take that into account in the software. I’m not sure what the absolute physical limits are, but there is clearly room for improvement from where we are today, even without going to fundamentally different physical processes.

PwC: What other features of high-end printers should we see in low-end printers in the near future?

JP: The high-end printers have feedback control, and we should see that in low-end printers soon. They also use a different process to print metal—laser sintering—and the patents on that process are running out. So I would expect rapid innovation to occur in 3-D printers that use laser sintering, sort of what happened with the RepRap and FFF method. As soon as the patents expired and the open source community got their hands on the FFF method, the innovation accelerated substantially.

Another feature is self-calibration. We want the printers to self-calibrate, rather than users calibrating the printers by hand, which I think is beyond what normal users are willing to do. If a user can just press a button and the printer knows where it is, that starts to move low-end 3-D printing into the realm of realistic large-scale deployment.

Innovation will also occur on the cost front, the simplicity of use, the ease of building the printer, and so on. Right now we can’t print in the micron resolution on high-end sintering machines, but that doesn’t mean that two years from now, I won’t have a powder or liquid printer on the desktop in my lab to do just that.

PwC: A key limitation facing the industry is the ability to print with multiple materials. What are the future prospects on this front?

JP: I think that journey is just starting. In the low-cost printers using the FFF method, the printers have multiple heads, so those printers can use two colors or two materials—like a flexible plastic and a stiff plastic. The development on this front is also being held back by patents. For example, I know one 3-D printer company that uses two heads and faces the challenge that printhead two smears the work of printhead one, spoiling the product. The obvious solution to that problem is to have one of the heads move out of the way, or even have both moveable on the vertical axis (z-axis) independently. Despite this solution being obvious, my understanding is that such features are all covered by patents, which are in various stages of expiring. As these expire, we would start to see little lever arms or other mechanisms that move multiple heads and we will see many more materials used.

"The lack of standards is a significant issue that should be addressed so the industry can move forward."

PwC: It seems that there are not many standards to provide confidence in the performance of materials?

JP: Indeed, the lack of standards is a significant issue that should be addressed so the industry can move forward. We did one of the first 3-D printing mechanical test studies—a study on the tensile strength of a RepRap-style printer. We asked a group of RepRap users to print with a standard and send us a print of the design of a dog bone. We used our printers and printed the same designs, too. Then we tested them all for strength characteristics.

Our tests indicated that different systems produced different outcomes even though they used the same material and design. So there is a third variable that must be accounted for: it's not just the structure that someone is making or the material that someone is using, but also the particular printer that is used and how it is used. There is much more complexity than a machinist just using a laser to cut some raw material.

The good news is that a lot can be governed by software. I think there will be a feedback loop soon on even the low-end printers. So, for instance, it will ensure that the actual temperature of the plastic coming out is hot enough to get the type of curing wanted. I think this feedback loop will arrive in the next two years.

PwC: Another area of great interest is printing complete systems. You have a project to print electronics and conductive material. What are you trying to make?

JP: My big goal is to be able to print an Arduino [a microcontroller board], which is the brain behind the 3-D printers and basically behind all the scientific equipment we use in the lab—our open source lab.

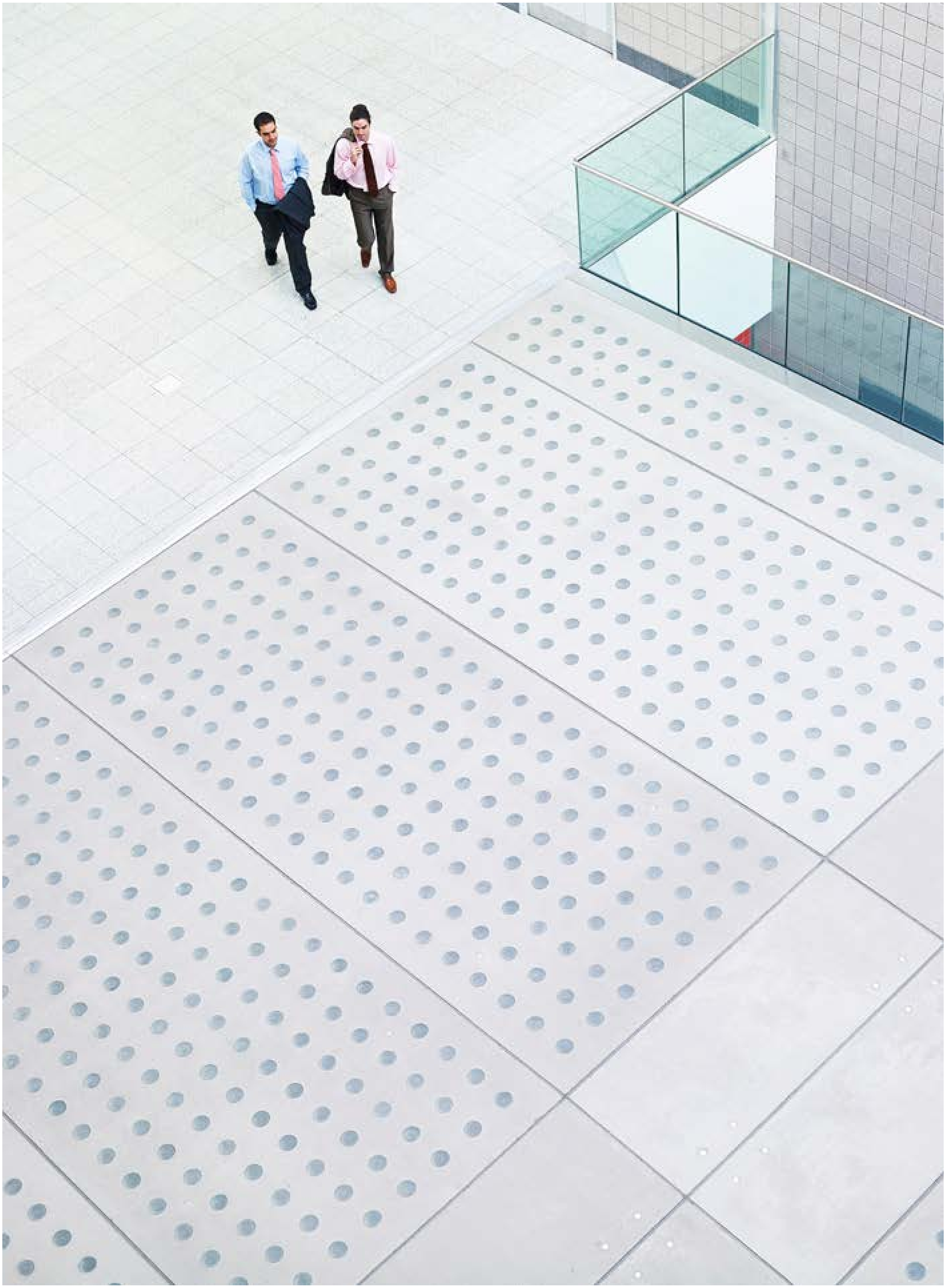
For example, we have a handheld water tester, and right now we're still buying a $20 Arduino and simple circuitry to control it. If we could print the Arduino board in the case of the tester itself, we could make the whole setup a lot smaller. Also, we could customize and take away parts of the Arduino board we don't need. We could make a simplified Arduino-compatible electronic microcontroller for ourselves and then just drop in the chips. Already our open-source water tester replaces a $2,000 tool with a $50 printed one. When we are done, the overall cost will be less than $20 for a scientific device that can replace several different $2,000 to $5,000 proprietary tools.

PwC: As you know, Moore's law was a great way to understand and predict the growth of the computer industry. Is there something similar for the 3-D printing industry?

JP: I think one of the best examples of a catalyst for 3-D printing is the exponential growth of free and open source digital designs. Right now, a major limiting factor for normal consumers is that they don't know CAD [computer-aided design]. Many companies are working on simple and easy-to-use software tools to create designs. In reality, for most things customers want something really well done and professionally designed.

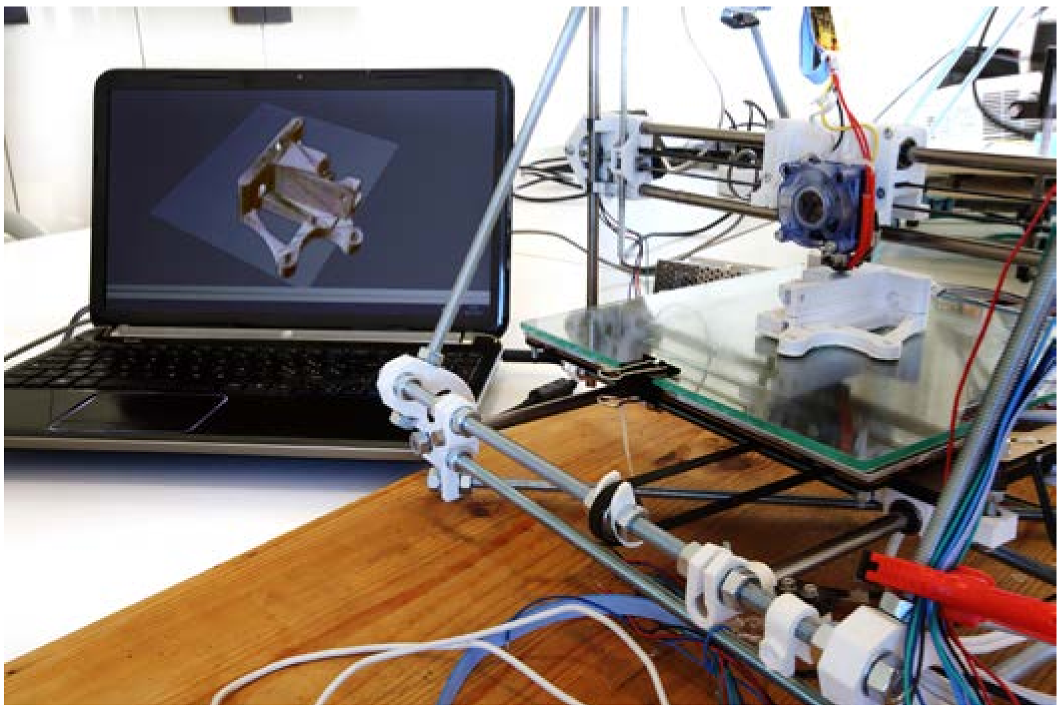
Hundreds or maybe thousands of these professional people are sharing their designs. We tracked the number of designs that are available for free, and they are growing exponentially. There are already several hundred thousand designs that any user can download and print, and we are surely headed to millions. Whether a person owns a printer, has one at school, or rents time on one, there is a good chance that what someone wants to print is already designed or close to it. They can then customize and make it personal or better, but the basic starting point already brings them very far.

Every new design adds more value to owning or having access to a 3-D printer—so it is pretty clear we are just at the start of a fundamental shift in the way production works.



Software innovations: Simplifying the 3-D printing experience

By Alan Earls and Vinod Baya



As the experience of sourcing, creating, optimizing, and printing 3-D models becomes simpler and robust, 3-D printing will find uses beyond prototyping.

This article is the second in a series on the future of 3-D printing. The first article covers the emerging technologies within printers themselves. This article covers the role of software in advancing 3-D printing. A third article will explore advances in materials that position 3-D printing for growth.

Software for 3-D printing is evolving along several paths that complement and accelerate advances in 3-D printers themselves. Innovations focus on providing 3-D designs that are ready to make or modify, developing easier-to-use and less costly design tools, and turning smartphones into 3-D scanners that start the design process—to name a few.

With innovations like these, software lies at the heart of the evolution of 3-D printing. It spans the entire 3-D printing lifecycle—from sourcing ideas and designing in three dimensions to delivering formatted data to 3-D printers, and then monitoring and managing the printing process. Software defines and enables interfaces between computers and printers, drives automation, captures intelligence, and integrates processes that make the whole ecosystem hum and move forward.

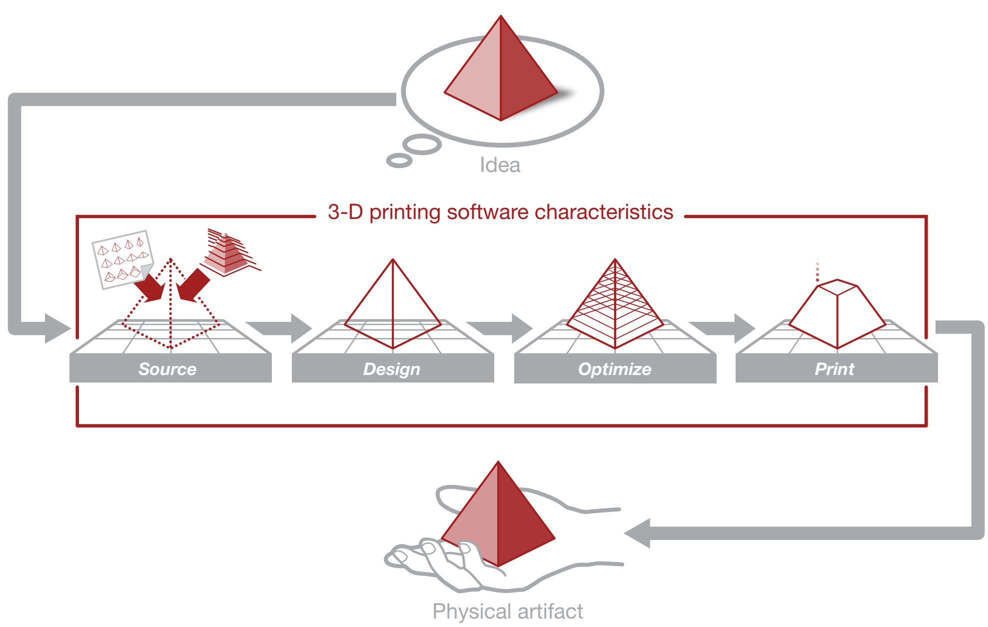
As discussed in the article "The road ahead for 3-D printers,"[1] expectations run high for 3-D printing, also known as additive manufacturing. Meeting those expectations depends on the industry's ability to pivot from rapid prototyping to printing finished products and components. Software innovation, examined in this article, is central to this pivot: manufacturing finished products demands a higher degree of automation, reliability, and repeatability. A future article will explore advances in print materials.

Software roles in 3-D printing

As noted, the role of software spans the entire 3-D-printing lifecycle, starting with the designer's idea and ending with a physical artifact. Figure 1 illustrates that software solutions are concentrated in four phases of this lifecycle:

- **Source:** Software that allows access to existing 3-D models or the creation of 3-D models from existing artifacts; this software includes emerging libraries of 3-D models and scanning solutions
- **Design:** Software used to create a 3-D model that is a digital representation of a physical product; this software includes established computer-aided design (CAD) solutions and newer methods for creating a 3-D model
- **Optimize:** Software that refines 3-D models so they can be printed with accuracy, higher quality, and better results while taking into account cost, speed, materials, and other issues
- **Print:** Software that takes the result of optimization and prepares the model for printing, and that enables the printing process so the print runs are successful

Figure 1: In the journey from idea to artifact, 3-D printing software is concentrated in four phases.



1 "The road ahead for 3-D printers," PwC *Technology Forecast* 2014, Issue 2, http://www.pwc.com/en_US/us/technology-forecast/2014/issue2/features/future-3d-printing.jhtml.

Commercial and open-source [design] libraries are providing ready-made 3-D models that users can further develop or customize.

Where software can make a difference

Software is ideally placed to address many challenges facing the 3-D printing industry. Among these:

- **Creating 3-D models is hard:** Most CAD solutions remain the province of highly trained design professionals. Even they often must acquire additional skills to work successfully with 3-D printers and 3-D printing software.

- **Printers are difficult to use:** Some 3-D print processes can be fussy and unpredictable, requiring considerable tinkering to get the right result. Achieving consistent results on the same printer or across different printers is also difficult.

- **Yield, quality, and cost-effectiveness can be poor:** Existing technology sometimes yields output that might have defects or does not match expectations, wasting material and increasing costs.

- **Software and standards do not capture and transmit complex and functional system details:** The technology for 3-D printing is evolving to be capable of printing complete systems that include multiple materials, integrated sensors, circuits, batteries, and so on. Most modeling software presently does not seamlessly capture and transmit all this information to printers.

The following sections describe emerging techniques meant to address each of these challenges.

Creating finished products with 3-D printing: The role of standards

As with any emerging technology, the right standards will be instrumental to the adoption of 3-D printing, its ease of use, and its success. While the industry pivots toward creating finished products and components, standards are evolving in two key areas. One is standard file formats for exchanging product information among different categories of software and printers. The second area is standards related to the performance of materials and printers.

STL (STereoLithography) is the long-standing format for sharing design information among various CAD programs and printers. STL describes the surface geometry or the topology of the object. It does not include material or color information. To overcome these shortcomings, a new open format called Additive Manufacturing File Format (AMF) has been created. AMF has native support for color, material, lattice, and other attributes. It is an official ASTM standard designed to allow any CAD software to describe the topology and composition of any 3-D product for fabrication on any 3-D printer.

In late 2013, the National Institute of Standards and Technology (an agency of the US Department of Commerce) issued two grants to advance standards in 3-D printing. One grant is to develop a suite of integrated tools for process control and 3-D printed part qualification. The second grant is to ensure that parts produced using 3-D printing are of high quality and are certified for use. Standards that certify the performance of materials and processes will allow designers to select 3-D printing with confidence for uses beyond prototyping.

Sourcing designs

Until recently, users needed to create designs from scratch; now, the rise of CAD design libraries and 3-D scanning methods means designs, or digital models, can be sourced from existing digital or physical versions of a model.

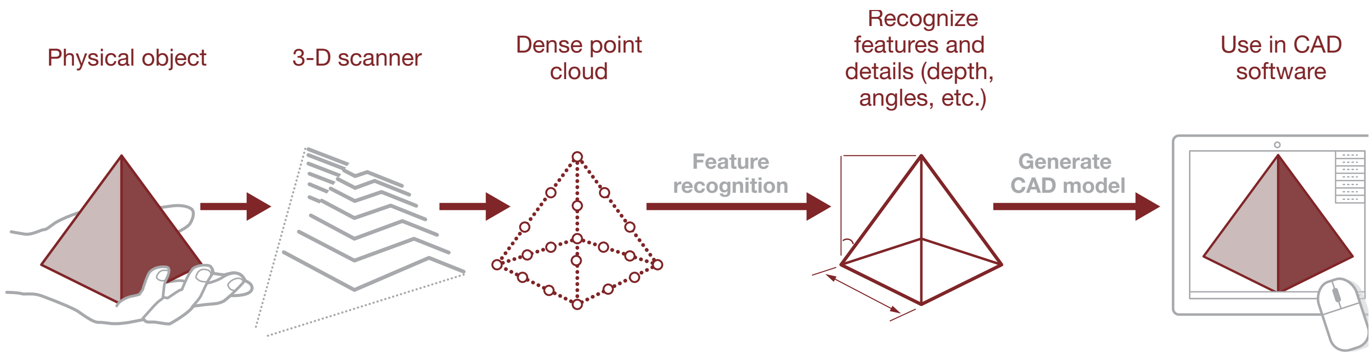
Design libraries

Commercial and open-source libraries are providing ready-made 3-D models that users can further develop or customize. These libraries enable users to experience 3-D printing without requiring them to learn sophisticated design software. Thingiverse, launched by MakerBot (a subsidiary of Stratasys), offers thousands of freely shareable designs to download and print—as is or modified—allowing design activity without a well-developed skill set.[2] The Cubify service from 3D Systems maintains a library where designers can upload, share, download, collaborate on, and eventually print designs.

Autodesk, maker of AutoCAD software, is partnering with GrabCAD, an online community of 700,000 design engineers. GrabCAD recently introduced a web-based collaboration environment called GrabCAD Workbench, which supports design sharing, viewing, and annotation—allowing designers to leverage existing designs. GrabCAD Workbench works natively with AutoCAD 360 and Fusion 360—Autodesk's online design solutions.

2 Andy Greenburg, "Inside Thingiverse, The Radically Open Website Powering The 3D Printing Movement," *Forbes*, December 10, 2012.

Figure 2: Today's 3-D scanning solutions generate a CAD model of a physical object so it can be used in any CAD software.



Most of the 3-D printing service bureaus, such as Shapeways, Sculpteo, Materialise, and Ponoko, maintain growing libraries of designs so anyone can easily select, configure, and print 3-D designs.

Scan an existing object

Users often have a physical artifact they would like to re-create, modify, or refine. In such cases, 3-D scanners can be used to generate a 3-D model. Figure 2 illustrates the steps involved.

"[With 3-D printing], it is no longer enough to communicate just topology information."

—Gonzalo Martinez, Autodesk

The 3-D scanners use different methods and technologies—including lasers, x-rays, and various colors of lights—depending on whether they work at close, medium, or long range from the object and with small or large objects. They all generate a dense point cloud, which is the collection of x, y, and z coordinates that detail the object's external surface. This raw data is further analyzed in the software to identify physical features and their parameters, such as radius, length, angle, and depth.

Complete systems are emerging that combine hardware and software to make generating a CAD model a seamless task, supporting the full cycle shown in Figure 2. For instance, the Matterform 3-D scanner combines an HD camera, dual lasers, a rotating platform, and analytic software to generate 3-D models. An object is placed on a rotating platform and scanned from all angles, capturing details as small as 0.43 mm. The company says it is working to enhance its software to deliver 3-D color scans for more sophisticated requirements.[3] Similar systems are Go!SCAN 3D and HandySCAN 3D from Creaform, HDI from LMI Technologies, MakerBot Digitizer from Stratasys, and Sense from 3D Systems.

Not all solutions require a 3-D scanner. Some take advantage of the ubiquity of digital cameras and generate CAD models from several 2-D photos of the object. Autodesk offers 123D Catch, a smartphone and tablet app that shoots 20 or more photographs of a person, place, or thing from every angle; the photos are then processed to generate a 3-D model.[4]

Design software: Creating 3-D models

For more than three decades, CAD software has been the conventional approach to creating 3-D designs, or models, of products. Leading CAD software vendors have their roots in 2-D drafting. Over time, 3-D capabilities became common, allowing the design, simulation, and visualization of 3-D objects and the support for subtractive manufacturing, such as computer numerical control (CNC) machining. Vendors offering CAD solutions include Autodesk, Dassault Systèmes, Siemens, and PTC. Generally at the high end of sophistication and functionality, these solutions are tailored for engineers and other professionals. They offer wide-ranging command options and functionality appropriate to the design of complex systems and devices.

3 "Color Scanning with Matterform," *Matter and Form* (blog), October 8, 2013, https://matterandform.net/blog/Color-Scanning-with-Matterform.

4 Autodesk 123D Catch, http://www.123Dapp.com/catch.

Engineers may require years of training and practice to become proficient with traditional CAD software. To engage nonprofessionals, innovators are focused on CAD solutions that are far simpler and easier to use and that cost much less. Delivering good-enough functionality in accessible packages could engage a larger pool of users in design and manufacturing and could seed a larger market of hobbyists.

Web browser support for 3-D manipulation and interaction has become a turning point. Initially, 3-D manipulation support in browsers required downloading a plug-in, a step too far for many users. That requirement is changing thanks to the popularity of WebGL (Web Graphics Library) for rendering interactive 3-D graphics, now an integral part of most browsers. Emerging vendors such as Mixee Labs and Dreamforge are taking advantage of WebGL to bring traditional desktop CAD functionality to the browser. In 2013, Autodesk revived cloud-based 3-D modeling software called Tinkercad[5] for casual users. Tinkercad is a browser-based 3-D solid modeling tool that has a comparatively simple interface.

"Not everyone can start from scratch. Giving them templates for product categories, such as figurines, is much better for their purposes than having them create the model on a blank canvas."

—Nancy Liang, Mixee Labs

The attempt to simplify also involves giving users a better starting point than a blank canvas. "Not everyone can start from scratch. Giving them templates for product categories, such as figurines, is much better for their purposes than having them create the model on a blank canvas," says Nancy Liang, co-founder of startup Mixee Labs. The Mixee Labs approach starts with a set of design parameters. Through a browser interface, a user participates in the design process, tweaking within the parameters. The company is also building design libraries and working with third-party designers who can use the Mixee Labs platform to deliver 3-D designs and products to customers.

To improve usability, some innovators are rethinking the interface for creating and interacting with 3-D models. Startup ZeroUI—the name suggests its minimalist intentions—focuses on people's innate abilities to design physical objects by letting them move and gesture in front of a camera. "We're not trying to meet the current tools head on," says CEO Raja Jasti. "We're offering an alternative way for all users to express their creativity and take advantage of 3-D printing."

Innovation such as that from ZeroUI is possible due to the growing ubiquity of 3-D sensors. Apple's acquisition of 3-D sensor company PrimeSense,[6] Intel's recent RealSense technology announcements,[7] and Google's Project Tango[8] suggest that 3-D sensing and depth capability will become commonplace in laptops, smartphones, and tablets, laying the foundation for some radical innovations in interfaces.

To 3-D print complete products or components means contending with materials, colors, and other details beyond basic shape and topology. A key arc of innovation in design software is to include details of complete systems. "Since 3-D printing can allow electronics or sensors to be embedded during the fabrication process, the design tools should accommodate that capability and integrate those details in information communicated to the printer. It is no longer enough to communicate just topology information," says Gonzalo Martinez, director of strategic research at Autodesk.

For instance, the Stratasys Objet Studio software lets users separate a multi-material 3-D design into discrete shells and assign a material or color for each. Users can choose among three base resins; the software calculates the resulting material options and provides a drop-down palette each time the user clicks on a shell.[9]

Tissue Structure Information Modeling (TSIM) software from Advanced Solutions brings together the ability to design, visualize, collaborate on, simulate, and analyze 3-D digital models of tissue structures. Doctors use the software to model much more than a shape; they also can model the arrangement of cell layers, cell types, viscosity, and other details so the complex tissue can be 3-D printed as a complete system.

5 Rakesh Sharma, "The Problems With Reinventing CAD Software," *Forbes*, August 9, 2013, http://www.forbes.com/sites/rakeshsharma/2013/08/09/the-problems-with-reinventing-cad-software/.

6 Chris Velazco, "Done Deal: Apple Confirms It Acquired Israeli 3D Sensor Company PrimeSense," *TechCrunch*, November 24, 2013, http://techcrunch.com/2013/11/24/apple-primesense-acquisition-confirmed/.

7 Will Findlater, "Intel's RealSense camera: gesture control and 3D scanning built into your next PC," *Stuff*, January 16, 2014, http://www.stuff.tv/intel/intel-reveals-realsense-tiny-kinect-camera-thatll-be-built-your-next-tablet-laptop-and-all-one.

8 Rich McCormick, "Google reportedly building Project Tango tablets that can see the world around them," *The Verge,* May 23, 2014, http://www.theverge.com/2014/5/23/5744060/google-making-project-tango-tablets-for-io-conference.

9 "Using Objet500 Connex3 for Prototyping," Stratasys, http://www.stratasys.com/3d-printers/design-series/precision/objet500-connex3.

"We're not trying to meet the current [CAD] tools head on. We're offering an alternative way for all users to express their creativity and take advantage of 3-D printing."

—Raja Jasti, ZeroUI

Optimizing designs for 3-D printing

CAD software is a generic modeling tool for designing in three dimensions, including uses not related to 3-D printing. That means not all designs created by CAD software are ready for 3-D printing and will print successfully. New software solutions help to modify designs without sacrificing functionality, akin to the "design for manufacturability" concept in the traditional manufacturing discipline.

The "design for 3-D printing" concept addresses a range of challenges. For example, thin sections or elements cantilevered from a vertical section can collapse or deform under their own weight during 3-D printing unless additional supports are built. Software can make the changes to add temporary supports that are removed after printing. Software can also determine if a 3-D model is watertight. Being watertight means there are no holes, cracks, or missing features that will prevent the printer from knowing what is inside the object (which is to be printed) and what is outside the object. Another important feature is to hollow out designs, so less material is used and less expense is incurred during printing.

To optimize 3-D printing, the 3-D printing service bureau Shapeways offers its Mesh Medic service. Powered by netfabb, which sometimes calls its service a "spell checker for 3-D printing," Mesh Medic takes files uploaded to Shapeways and examines them for defects that some 3-D design software may not be able to prevent, such as holes in surfaces. netfabb reports that this automated tool repairs 95 percent of these holes, greatly enhancing yields.[10] Similar capabilities are available from Materialise and CADspan.

Another class of software recognizes that a default printing approach will print an object as a solid—simple and strong, to be sure, but costly in time and material. Optimization software creates an internal lattice structure that optimizes both material use and print time. (See Figure 3.) The objective is to use the least amount of material that will meet the design needs for strength, stiffness, and other requirements.

Within Technologies, a design consultancy, offers optimization tools such as Within Enhance. The tool will take as inputs different parameters, including desired weight, maximum displacement, and stiffness. It will then custom design an optimized internal 3-D lattice and outer skin to achieve those goals—and output the information to a third-party printer. The netfabb Selective Space Structures software also turns solid structures into lattice structures.

Another service from Within Technologies uses the same techniques to let engineers and surgeons design and remotely print 3-D titanium orthopedic medical implants. The company provides free, downloadable software to help design the implant and send the file to a third-party manufacturer.[11]

Figure 3: This aerospace component is designed with a lattice structure that makes it lighter while ensuring it is strong enough for the uses it is designed for.

Source: Laser Institute of America (LIA)

10 "Shapeways Mesh Medic—a netfabb Cloud Solution Success Story," netfabb, http://www.netfabb.com/casestudies/shapeways.php.

11 Ann R. Thryft, "Design & 3D Print Custom Metal Implants," *Design News*, December 9, 2013, http://www.designnews.com/author.asp?section_id=1392&doc_id=270238.

3-D printing software should evolve to work with existing enterprise systems

In any enterprise, 3-D printing will not be and should not be an island by itself. "If 3-D printing is going to transition from interesting novelty to legitimate manufacturing technology, then it will need to interface with companies' traditional product and manufacturing data management systems," forecasts Mark Thut, principal in PwC's industrial products practice.

With 3-D printing, products can go directly from engineering and design to manufacturing and production. This direct path suggests that integrating 3-D printing with an enterprise's supply chain, enterprise resource planning (ERP), and product lifecycle management (PLM) systems will unlock a greater proportion of its promised value, rather than being just another production technology.

Over the longer term, 3-D printing is likely to compress the idea-to-realization cycle. (See Figure A.) The long cycle from marketing to realization could conceivably collapse, as many of the intermediary functions are automated, reconfigured or transformed, or deemed unnecessary. For instance, simulations using 3-D models could carry out testing for many use cases.

Undoubtedly, a shorter cycle will have an impact on the enterprise architecture and systems. The marketing, design, manufacturing, and supply chain functions have their own systems, and today they are integrated to share data across these departments. As the compressed cycle of realization takes hold, fewer systems and a simpler process will likely span the full cycle, all while capturing the necessary data to maintain compliance and to run the business.

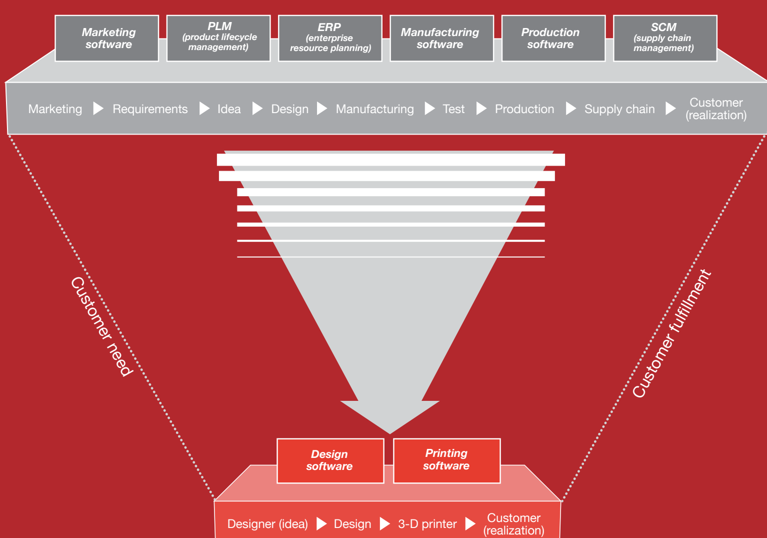


Figure A: The option to use 3-D printing will compress the idea-to-realization process and will impact the architecture and the scope of the systems that support the various functions in the chain.

Software to print successfully

Most 3-D printers require time- and labor-intensive setup before they can be used, and they require regular supervision during printing projects. Software is emerging and maturing to address these usability issues. Areas of focus include preparing the model for printing (slicing), directing the printhead, self-leveling, self-configuration, and feedback for quality checking.

Before a model can be printed, it must be sliced (virtually) into thin layers, and the path of the printer head as it deposits the material must be defined. The way slicing is performed can depend on the material used, the printing method, and the printer type.

Slicing software divides a 3-D design into printable layers and helps plan the path of the printhead or tool, matching the design files to the capabilities of the printer. Many solutions on the market address this need, including low-cost or no-cost options. For instance, Slic3r, an open-source, cross-platform offering, has grown in popularity partly because it is considered easier to use than earlier products. KISSlicer, a closed-source product, provides support for multiple extruders and auto-packing—a process for efficiently printing multiple parts in a single build cycle.[12]

There are also promising developments in automation, particularly at the hobbyist end of the market. For example, the build platform must be level, which is crucial for achieving output quality and repeatability. Self-leveling is now included in new units from Printrbot.[13]

Similarly, software is also central to using real-time feedback to improve quality. Stratasys and the US Department of Energy at Oak Ridge National Laboratory, focusing on carbon composite additive manufacturing improvements, are collaborating to develop in-process inspection methods. In-process inspection identifies manufacturing defects in real time and provides feedback upstream to initiate corrective action. The multiyear program aims to supplant or replace post-process inspection with in-process analysis and correction.[14]

12 Craig Couden, "Know Your Slicing and Control Software for 3D Printers," *Make:*, November 19, 2013, http://makezine.com/magazine/guide-to-3-D-printing-2014/know-your-slicing-and-control-software-for-3D-printers/.

13 Cabe Atwell, "Printrbot Unveils All-Metal 3D Printer," *Design News*, April 17, 2014, http://www.designnews.com/author.asp?section_id=1386&doc_id=272794.

14 Leslie Langnau, "Turning FDM into a mainstream manufacturing process," *Make Parts Fast*, July 2, 2012, http://www.makepartsfast.com/2012/07/3941/turning-fdm-into-a-mainstream-manufacturing-process/.

Sigma Labs has also introduced an in-process inspection technology called PrintRite3D, a suite of software and hardware products to support higher-quality 3-D printing of metal parts.

These kinds of innovations will ensure that the completion of the idea-to-artifact journey increasingly will result in high-quality, cost-effectively printed products.

Conclusion

Software will figure prominently in the evolution of 3-D printing; it is the glue that holds together the entire ecosystem. Printers and the materials they use are subject to relatively slow and costly innovations, and they face limits based on physics. Software offers tremendous potential to greatly enhance functionality and improve the economics.

Concentrated in sourcing, designing, optimizing, and printing, software innovation promises to simplify the experience of engaging with 3-D printing technologies and to make 3-D printing more broadly accessible. By extending support to multiple materials, multiple colors, and complete systems, the software complements similar advancements in printers and materials. Together, they form the foundation for the industry to move beyond prototyping and pivot toward printing finished products and components.

Software will make printers smarter, more capable, and more autonomous, requiring less skill and labor to operate. Software is poised to push the state of the art in 3-D printing substantially in the coming years.

Going beyond topology information

Gonzalo Martinez of Autodesk shares the advancements in 3-D printing software that will power the evolution of additive manufacturing.

Interview conducted by Vinod Baya and Bo Parker

Gonzalo Martinez

Gonzalo Martinez is the director of strategic research for the office of the chief technology officer at Autodesk.

PwC: Gonzalo, can you please describe the efforts under way in 3-D printing at Autodesk?

GM: Sure. We started looking at 3-D printing about five years ago. We experimented with almost every 3-D printer that was available then. We experimented with small objects, big objects, multiple materials, and so on. The goal was to understand what we needed to do strategically in terms of software partnership with companies creating and using 3-D printers.

3-D printing is very strategic to Autodesk, as it enables a different way to manufacture things. It's not that 3-D printing will replace traditional manufacturing; rather, there will be collaboration between 3-D printing and traditional manufacturing, so businesses can have the best of both worlds.

Autodesk has a rich history of providing tools for design, visualization, and simulation. We are entering a new area that we call fabrication. In fabrication, we look at what we're doing with 3-D printing, traditional manufacturing, CNC [computer numerical control], and robotics, and we evolve our products to a vision around how these four pieces work together.

“Our vision is to provide the software solutions of choice for subtractive manufacturing, additive manufacturing, and robotics and how they interact.”

PwC: What is that vision?

GM: We don’t believe that additive manufacturing is a replacement of traditional manufacturing. They are in fact complementary and will need to work together. Our vision is to provide the software solutions of choice for subtractive manufacturing, additive manufacturing, and robotics and how they interact.

There are already machines that combine additive and subtractive manufacturing for complex geometries, such as the multi-axis milling machines with laser deposition welding. The first operation may be subtractive manufacturing on a milling machine to remove material. Then the head changes on the fly to use laser deposition welding to do additive manufacturing, depositing metal over metal. After that the machine can come back to a subtractive tool to remove a minimal amount to keep the surface in perfect tolerance.

PwC: How are you executing against that vision?

GM: While in the past we largely catered to professionals, today Autodesk caters to three distinct groups: professionals, hobbyists—also called prosumers, and consumers. In these three segments, we are building software that touches all of 3-D printing.

We are developing many software innovations to aid the ecosystem we serve. A key area of focus is to make our solutions easy to use and access. For example, we are offering our solutions via the cloud, as we have done with our product Fusion 360 for the professionals. This web-based 3-D modeling tool is very user friendly while supporting complex designs. You don’t need to own the application; you can rent it and pay for usage only. It can be very affordable depending on how you rent and use. For consumers we have solutions such as Tinkercad and 123D, which are even simpler and can be accessed from a web browser.

To help make 3-D printing more accessible, Autodesk is also developing Spark, an open and free software platform that will improve the information exchange between design software and the 3-D printer. For example, software can make automated fixes and optimizations to the design before production begins. We are also including APIs [application programming interfaces] with Spark to enable a broad group—from materials science companies to crowdfunded startups—to access and innovate with 3-D printing.

We believe that tightly integrated hardware, software, and materials will be critical to accelerating innovation in 3-D printing. Therefore, we will also be releasing a 3-D printer as a reference implementation that demonstrates the power of the Spark platform and exemplifies emerging 3-D printing user experiences.

PwC: Why is simplification such a big focus?

GM: We know that traditional methods of manufacturing require a lot of training to operate the software and the machinery, involving significant time and investment. Such requirements were fine for engineers and trained professionals.

But 3-D printing is different. If you have access to a printer, you can produce complex things very, very fast with minimal manipulation between the user and 3-D printer. The 3-D printer will ask you a few questions, which you answer, and in less than a minute, your 3-D printing experience already started.

“The simpler we make the process, the more users can take advantage of 3-D printing technology.”

We saw the opportunity and the need to simplify a lot of customization and fabrication. We conducted some experiments inside Autodesk and realized that 3-D printing is very much about the overall experience. It is almost like playing a game—a game of designing and making, all very affordably. The software should facilitate this experience and make it seamless. The experience spans design, visualization, and fabrication. Fabrication can be on a connected printer or at a service bureau. The simpler we make the process, the more users can take advantage of 3-D printing technology.

PwC: How is that different from traditional manufacturing?

GM: In traditional manufacturing, the typical scenario starts with a blank canvas on which engineers create their designs. We saw the opportunity to do something more interesting by giving users a starting point based on a product or object they had. Today, everyone has the capability to take photos with their smartphones and such. What if you take pictures from different angles of the physical object and ask, “Can you build me a three-dimensional model from these pictures?” The Autodesk 123D Catch app builds 3-D models from pictures. You can then manipulate the model or send it to a printer.

PwC: A key trend in 3-D printing is to move toward multiple materials and colors in a single print. How does software handle this capability?

GM: This issue is less about the design software and more about the communications formats or standards. That aspect is completely broken today. The information from CAD [computer-aided design] software to a printer is transmitted in STL [STereoLithography] file format. The STL file format is basically the shape or the form of the product and is very simplistic. It does not understand multiple materials or colors.

There is movement to go beyond STL to AMF [Additive Manufacturing File Format], and there’s something even beyond AMF that the hardware manufacturer and the software manufacturer are looking at.

When design software communicates multi-material or multi-color information, then in printer software a person must assign what materials and what colors will take part in that process, and that assignment can be tedious. We are working to simplify this communication.

We must solve this issue for the full ecosystem to make finished products and not just prototypes using 3-D printers. Once you start making finished products, the material choices will go far beyond the 150 or so that are in use today.

“It is no longer enough to communicate just topology information.”

PwC: Given the history of Autodesk, it is natural that you would create design software for 3-D printing. What other types of software are you investing in?

GM: Today, if you want to 3-D print a part from titanium or stainless steel and you try to compete with traditional manufacturing, 3-D printing would cost more. On the other hand, you could hollow out the part and keep material just where you need it for strength and other requirements. So you could have a part that is one-tenth the weight but as strong as the part made by using traditional methods. For certain applications, this approach would make business sense—in aircraft or cars, there will be tremendous savings on fuel over the life of the product.

The challenge is how you make things lighter using software. At a microscopic level, you might use a lattice-like structure or honeycomb-like construction. Such challenges are ripe for software applications. You can build honeycomb structure in between the walls of a product to make it lighter and stronger and easy to produce using 3-D printing, but building that structure would be close to impossible using traditional methods.

PwC: It sounds like software has a role in optimizing the design, such as for weight in the example you used. Are there other areas?

GM: Yes, optimizing designs for key performance characteristics, be it weight or thermal performance or others.

In the other areas, the optimization has to do with printing. One issue has been the reliability of the print. Some designs print OK; others do not. Designs might lack the appropriate orientation or support structure during printing. The printer might give error messages on open gaps and so on.

In some cases, we are improving solutions already out there. For example, some automated support-generation solutions use a lot of additional material. We developed the algorithm that can reduce by 90 percent the amount of support material used and still provide the necessary support structure to build that complex geometry.

Along these lines, we are doing a tremendous amount of work to make sure that our core products—such as AutoCAD, Inventor, Fusion, and others—would generate 100 percent proof STL files that are ready to be printed reliably.

Also, on our research side, we are investigating how to accommodate multiple materials, since the STL format communicates only the shape and topology and no information about materials or colors.

PwC: Already, 3-D printing has the capability to print a complete system and not just a component. How will software support that capability?

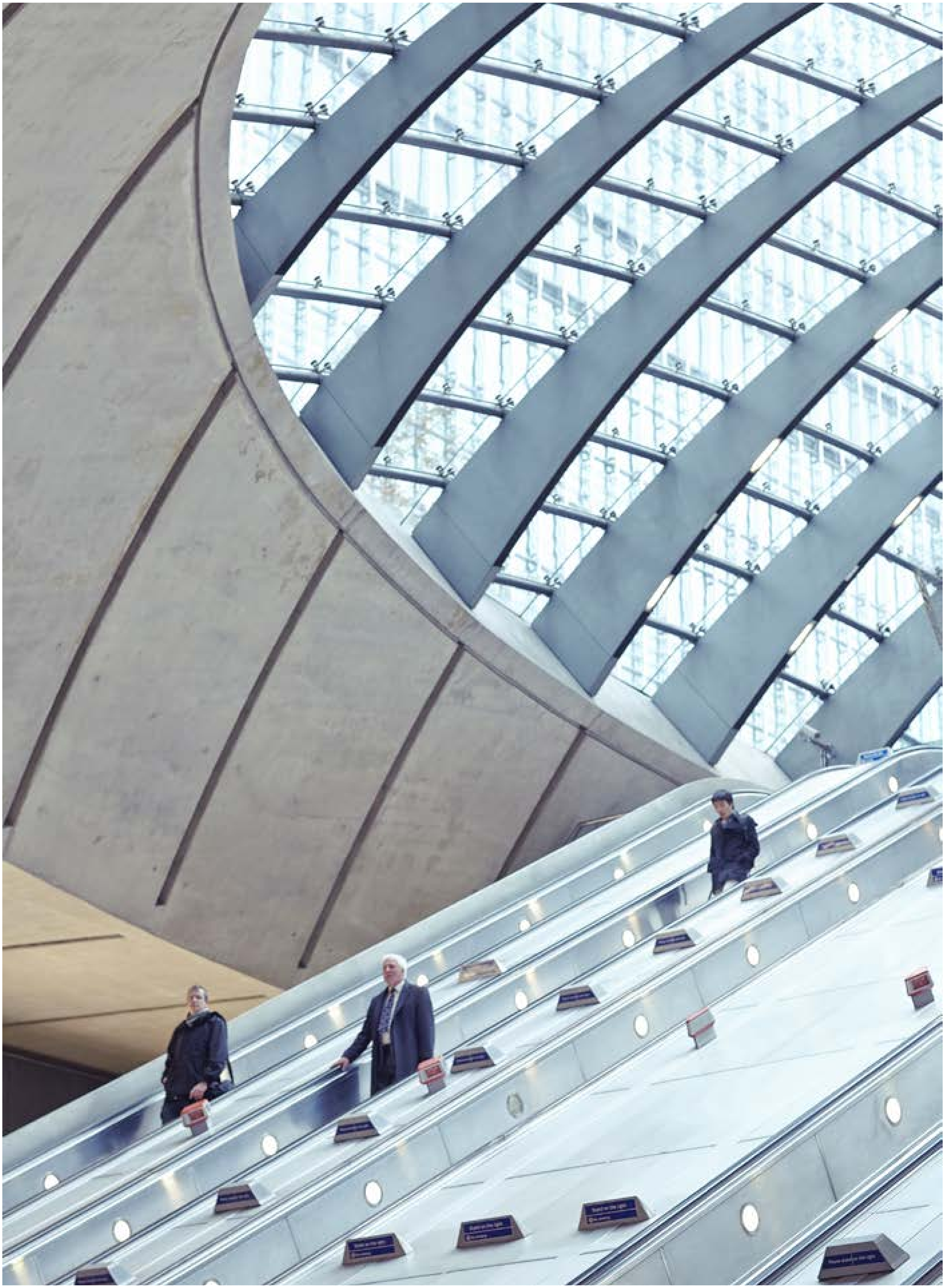
GM: Yes, indeed, 3-D printing can print complete complex systems. We are thinking beyond that, as engineering of the future will be different from the way it is today. Since 3-D printing can allow electronics or sensors to be embedded during the fabrication process, the design tools should accommodate that capability and integrate those details in information communicated to the printer. It is no longer enough to communicate just topology information.

For example, any product with embedded sensors and electronics will use multiple materials. So we need to communicate what material goes where during fabrication in a single process. Today CAD software doesn't do that. If there's a particular way the printer will fuse the metals at a certain point on the metal sintering devices, you should be able to specify it.

Today, the CAD software provides the shape and then the 3-D printing software will help you to indicate what material and color you want and so on.

PwC: So there's a shift here from communicating only topology to communicating a lot more than topology.

GM: Yes. It's communicating materials, circuits, sensors, and other aspects of any complex system.



Making 3-D printing accessible

Nancy Liang of Mixee Labs forecasts which products will spur 3-D printing adoption.

Interview conducted by Vinod Baya and Bo Parker

Nancy Liang

Nancy Liang is the co-founder and the design and business lead for Mixee Labs.

PwC: Nancy, can you please tell us what inspired you to start Mixee Labs?

NL: Sure. Before I started Mixee Labs, I was working at Shapeways, a 3-D printing service bureau. One of the things I realized is that a lot of people are interested in 3-D printing, but most don't have a particular idea that they want to print or they don't know how to model their idea. We saw a big gap on the content generation side of things. How can we let people make their own customized items?

At Mixee Labs, we are creating a platform that makes it easy for people to customize their own products and for designers to publish their designs—but in a way so other people can tweak certain parameters and styles to customize it to their taste—all without knowing how to use CAD [computer-aided design] software or what that is.

PwC: What functionality does your software provide?

NL: Much of what we do is work with designers to verify that their idea is a good product that can be 3-D printed economically, so it's not too expensive for consumers to purchase.

For example, we take into consideration manufacturing costs. With 3-D printing, you pay by the amount of material used, not by the complexity of the product you print. Printer time and material usage relates to build volume, so the pricing structure is called volumetric pricing. This pricing can be strange. If you double the height of an object from 2 inches to 4 inches, for instance, you will increase the amount of material by eight times and hence the cost by eight times.

"The challenge for us was how to give [users]a good starting point and still allow enough freedom for them to make the design their own."

A lot of people don't take that into consideration. Or they don't understand that if you don't hollow something out, for example, then you're using a lot of material that can lead to the print being very expensive.

We work to educate the designers: How to design for 3-D printing, how to enable customization, how to price appropriately, the pros and cons of different material options, and how to use the available choices of materials.

PwC: What technologies are you using to build your platform?

NL: We are using some of the common web framework, including Ruby on Rails and JavaScript. A lot of our 3-D rendering is done using WebGL [Web Graphics Library], which is a 3-D framework for the browser. We are really taking advantage of the growing popularity of WebGL. With WebGL, you don't need to wait for the server to respond. The user interaction is completely on the client side, so the display and interaction with 3-D designs is fluid and responsive.

We feel our bet on WebGL is paying off. When we started, Internet Explorer didn't support WebGL; now IE version 11 supports it. There is a promising future of 3-D software in web browsers.

PwC: What does WebGL make possible that was not there before?

NL: WebGL is sort of a JavaScript API [application programming interface] for rendering graphics in a web browser. Before, if someone wanted to render 3-D graphics, a Java or Flash plug-in was needed. That's a barrier to usability, and it takes up a lot of processing power.

Another paradigm for 3-D was to set a few parameters and send any interaction to the server. The server would process and generate a new file and send it back to the browser, which would render it. Those steps are really slow and not ideal.

WebGL comes packaged with a browser. It allows the browser to access the graphics processor on the display device directly. This approach speeds things up. That's why we can support interaction with and the display of 3-D animations in real time.

PwC: What are you learning?

NL: In our research, we talked with potential users ranging from designers to casual users interested in this technology but who don't have a design background. We found that many people don't have a specific idea of what they want to make. So even if the CAD program was very simple, they are not sure where to start or what the goal is.

Not everyone can start from scratch. Giving them templates for product categories, such as figurines, is much better for their purposes than having them create the model on a blank canvas.

The challenge for us was how to give them a good starting point and still allow enough freedom for them to make the design their own. So we have parameterized the design. They can manipulate the parameters to change the design. And designers must decide which aspects of a design they parameterize and which they do not.

“Ultimately it is about the product and not about the manufacturing process.”

Through much iteration, we learned to optimize our designs for 3-D printing. We believe having templates that are pre-optimized for 3-D printing removes some hassle and cost from the experience. The experience is also transparent. A person knows the cost up front, knows what the item looks like, and has assurance that the item will be printed.

PwC: Who are your customers?

NL: Our main commercial audience consists of consumers shopping for customized designs that they can 3-D print and designers who create the designs and are interested in accessing a market.

PwC: What are some of the challenges you are seeing?

NL: One key challenge today is cost. For example, 3-D printing a coffee mug at a service bureau could be about $40 to $50. Then you must add on charges for the designer. It can get quite expensive, which I think a lot of designers or consumers do not understand. To get more consumers to use this technology, we must keep the prices low while providing the benefits of the technology.

We are sensitive to cost in our designs. The figurines on our website, for example, are modeled in a manner so they are also less expensive to produce, which is why we can have the $25 price point. On the other hand, if you sit down with a modeler who does not understand 3-D printing, then a figurine like this could be much more expensive and potentially not even printable.

PwC: What have you learned about products that have greater adoption with 3-D printing than others? Is there an equivalent of a killer app or a killer product for 3-D printing?

NL: We think about it as a framework: What can be solved by 3-D printing that cannot be solved by any traditional means? But a lot of people don’t think about it that way. Many designers fall in the trap of thinking only from a technology perspective: What can I make with a 3-D printer? But just because you can make it with a 3-D printer doesn’t mean it’s better or something that consumers want.

Customers don’t care whether their figurine is 3-D printed or mass manufactured. It is just a detail—a really cool detail, but just a detail. Ultimately it is about the product and not about the manufacturing process.

We created figurines as a category because figurines are something that can’t be produced using mass manufacturing methods. Also, it’s a use case that most people can relate to. Everybody has friends and families and coworkers they can make these little figurines for.

I think one very promising area is the use of 3-D printing to serve the small independent designers. There is a huge movement in DIY [do it yourself]. People want to make stuff themselves or buy from local designers. Now, 3-D printing really makes that possible. It removes the barrier to entry for designers to test their markets and bring things to market quicker.

One exciting segment is jewelry. For instance, to make a ring you probably need to have many different styles and sizes. That is very expensive if they're mass manufactured. With 3-D printing, it's possible to have a whole jewelry line with custom sizing because you're making things one at a time.

PwC: So 3-D printing for personalization purposes should be designed into traditional manufacturing processes, correct? That way, everything a person owns has some custom elements, whether for vanity or other reasons.

NL: Yes. I think there are two factors. One is the vanity as you mention, so a person feels they have something unique, something others do not have. The simplest example is monograms.

Second, if you look at the maker movement, it represents the appetite people have for making their own things. It's not about vanity or being somewhat different, but totally new. It's the reason people knit their own sweaters or knit for their kids, make their own beanie hats, or create scrapbooks. You could go and buy an album from a store, but there is something more personal about making your own scrapbooks.

It is the same kind of innate desire that drives the crafting market, and it is a huge market. Now 3-D printing greatly expands what can be crafted, so there is a lot of potential there.

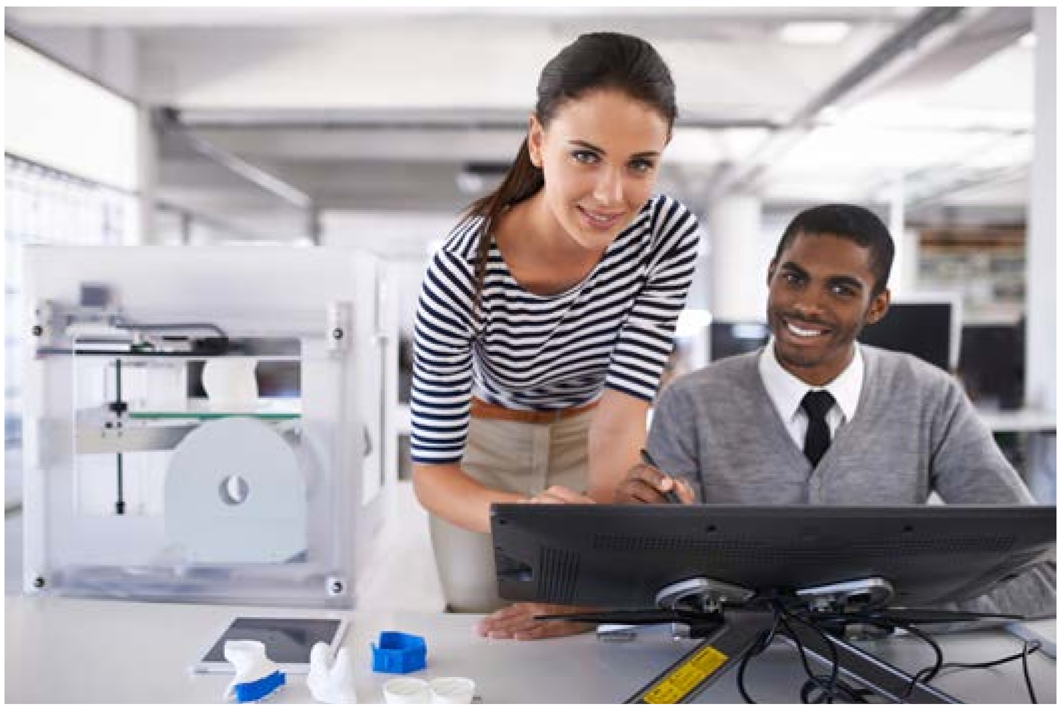
PwC: What about multi-material use in products? Are you using multiple materials in a single product?

NL: Our latest product—the bobblehead—uses two different materials. It uses the kind of gypsum sandstone material for the head and the body. And it uses a nylon printed screen material for the spring, as nylon is more flexible. Right now, the parts are printed with two different printers and then assembled afterward.

More interesting is how to combine 3-D printing—not just materials within 3-D printing—with other technologies, such as combining 3-D printing with mass manufacturing. For example, you could 3-D print the earring but then add on an earring hook that comes in bulk from mass manufacturing. That is a simple example, but things like that.

The role materials play in powering the 3-D printing revolution

By Lamont Wood
and Vinod Baya



As resolutions improve, material choices expand, and methods to control their properties evolve, 3-D printing will find uses beyond rapid prototyping.

This article is the third in a PwC Technology Forecast *series on the future of 3-D printing. The first article discussed emerging technologies in the printers themselves. The second article covered innovations in software for 3-D printing. This article explores advances in materials that position 3-D printing for growth.*

For 3-D printing to move beyond prototyping into fabricating finished products and components, the materials used in printing must undergo several developments. Resolutions must continue to improve. More types of materials must become available and especially include more metals. And materials and printing processes must be optimized so multiple materials can be combined in a single fabrication process; for example, metals combined with plastics to make circuits, batteries, and so on.

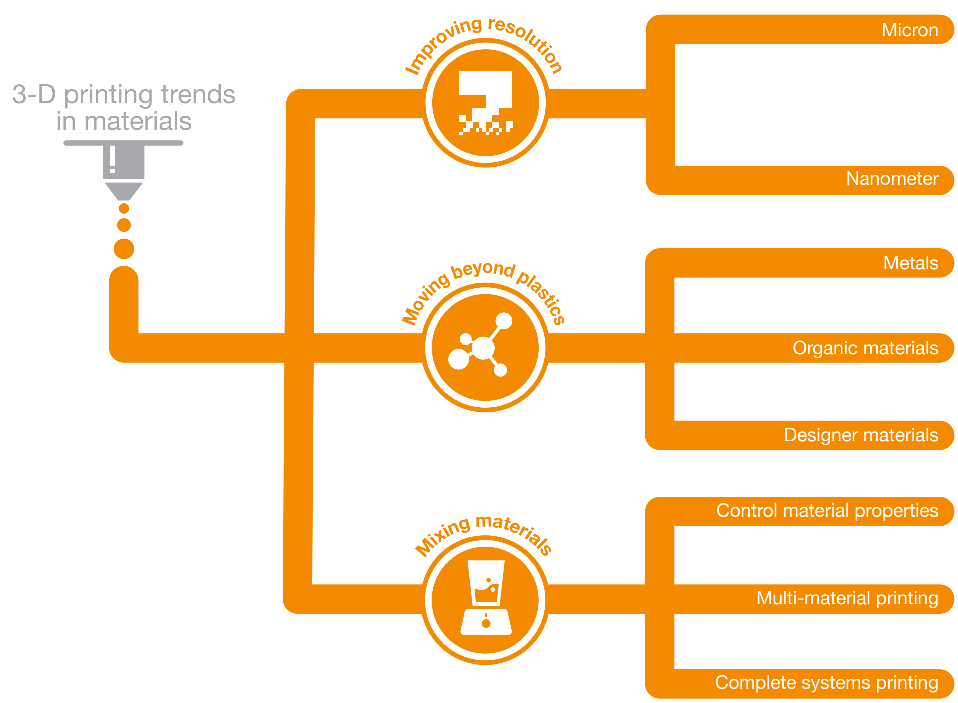
The good news: innovation is happening in all these areas.

The industry is also likely to find ways to customize materials, adding another dimension to the design process. Such customization creates new materials by using chemical recipes to achieve desired mechanical, thermal, electrical, and other properties.

As discussed in the article "The road ahead for 3-D printers," expectations are high for 3-D printing, also known as additive manufacturing.[1] Meeting these expectations depends on the industry's ability to pivot from rapid prototyping to printing finished products and components. Making this pivot depends not only on advances in hardware and software.[2] It also requires innovation in materials. A robust choice of materials and the ability to control and predict their performance are essential to achieve broader use of 3-D printing. This article examines three trends in 3-D printing materials, which are sometimes called *inks*. (See Figure 1.)

- **Improving resolution:** Achieving greater resolutions to print finer details
- **Moving beyond plastics:** Expanding the range of materials used
- **Mixing materials and controlling their properties:** Working with multiple materials to create new combinations that have unique properties and to fabricate complete systems

Figure 1: Trends in materials that are advancing the 3-D printing industry



1 See the article "The road ahead for 3-D printers," PwC *Technology Forecast* 2014, Issue 2, http://www.pwc.com/en_US/us/technology-forecast/2014/issue2/features/future-3d-printing.jhtml, viewed October 30, 2014.

2 For more information, see the article "Software innovations: Simplifying the 3-D printing experience," PwC *Technology Forecast* 2014, Issue 2, http://www.pwc.com/en_US/us/technology-forecast/2014/3d-printing/features/3d-printing-innovation.jhtml, viewed October 30, 2014.

Today's 3-D printers offer resolutions ranging from 100 micrometers for typical desktop printers to 0.1 micrometers for the most advanced machines.

Toward higher-resolution printing

Resolution, which is the fineness of detail during printing, is a function of material and the printing process. In 3-D printing, resolution is measured by the micron (internationally called the *micrometer* and denoted µm), which is one-thousandth of a millimeter. Today's 3-D printers offer resolutions ranging from 100 µm for typical desktop printers to 0.1 µm for the most advanced machines.

A sheet of office paper is about 100 µm thick. An object fabricated with a 100-µm resolution is composed of stacked layers of material, and each layer is 100 µm. Therefore, no feature on the object can have a height smaller than 100 µm, and the height of larger features must be multiples of 100 µm. An object of 100-µm resolution has a layered texture reminiscent of fine plywood. Whether the texture is acceptable without further finishing depends on the application.

When the resolution is smaller than 50 µm, the layered texture is no longer discernible and the results become indistinguishable from objects created by using the injection molding process.

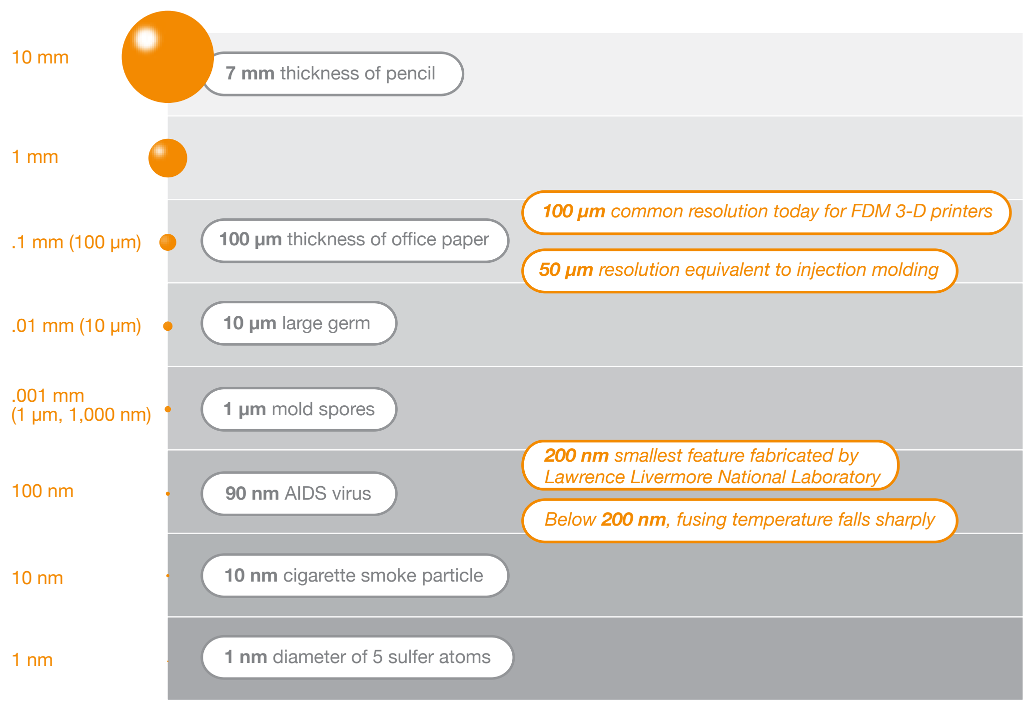
For most 3-D printing processes, the size of each layer is gated by the size of the droplet extruded from the printhead.

A resolution of 16 µm has proven sufficient for making anatomical models realistic enough for use in the operating room to guide surgeons, says Dima Elissa, co-founder and CEO of ProofX. "But I can't say that will be sufficient forever," she adds.

Below the micron scale is nanoscale territory, measured in nanometers (nm) or one-thousandths of a micron. That territory is also being pioneered in research labs. "The smallest nozzles we've printed with are 500 nanometers in diameter. That's pretty small. With post-processing, the finest features we've demonstrated are down to 200 nanometers," says Eric Duoss, a materials scientist at Lawrence Livermore National Laboratory.

Those are germ-sized features. (See Figure 2.) Even smaller particles may be in the offing—and their adoption could revolutionize fabrication. OWL Nano, a desktop stereolithography (SLA) printer, can already print at resolutions of 0.1 µm, or 100 nm.[3]

Figure 2: Logarithmic chart of the dimensions that 3-D printing materials are being asked to achieve or that feedstocks need to attain



Source: PwC, 2014

mm = millimeter µm = micrometer nm = nanometer

3 Cabe Atwell, "Stereolithography down to 1/10 of a micron—Old World Laboratories' Nano 3D printer," *SolidSmack*, September 2, 2014, http://www.solidsmack.com/fabrication/stereolithogrphy-110-micron-old-world-laboratories-nano-3d-printer/, viewed October 30, 2014.

Moving beyond plastics

Currently, 3-D printing is dominated by thermoplastics used in fused filament fabrication (FFF) printers and by photopolymer resins that harden when exposed to certain wavelengths of light and that are used in stereolithography apparatus (SLA) printers. Both materials are undergoing development beyond the previously mentioned resolution issues.

"There is a lot of chemical space to explore to make stronger end products. And if you name a physical metric, there is something better out in chemical space for that metric."

—Lance Pickens, MadeSolid

Thermoplastics are desirable because they soften enough for deposition when heated and then solidify at room temperature. The two most commonly used are acrylonitrile butadiene styrene (ABS) and polylactide acid (PLA). ABS is a structural plastic widely used in products ranging from toy building bricks to crash helmets. PLA is made from organic material, compostable, and biodegradable in a human body over time, which makes it usable for implants.

The problem with ABS is that it tends to shrink and warp when cooling; successful use requires a printer that has a heated fabrication chamber, increasing the cost and complexity of the process. Successful printing is easier with PLA, but the resulting models tend to be brittle. Consequently, the industry is seeking warp-free thermoplastics that have high tensile and impact strength.

The use of thermoplastics involves many tradeoffs, but those tradeoffs also present opportunities for a range of experiments. "There is a lot of chemical space to explore to make stronger end products. And if you name a physical metric, there is something better out in chemical space for that metric," says Lance Pickens, CEO and founder of MadeSolid, a developer of advanced materials for 3-D printers. In this regard, Pickens' company has produced a material called PET+ that has strength comparable to ABS but ease of use like PLA.

Work is also under way in the field of complex fluids and their possible application to FFF. Complex fluids are a mixture of particles and a suspension media, and they are often viscoelastic—that is, they behave like solids under standard conditions but undergo a change to more liquid-like behavior under shear, Duoss explains. A common example is polymer paint, which flows when pressed under a brush but otherwise clings to the wall, where it subsequently cures and hardens.[4] Similarly, these complex fluids would solidify once extruded from a nozzle and maintain their shape at room temperature. Such advancements open up the FFF method to many more materials rather than the subset of thermoplastic materials that it is limited to today.

In time, the availability of lower-cost inert ceramic piezoelectric printheads, which can deposit any suitable liquid without using heat, is also expected to enable FFF printers to accommodate a wider variety of materials, according to Pickens. Today these heads cost about $1,500 each, so the industry concentrates on far cheaper thermal printheads, which are limited to using materials that have a specific range of viscosity and boiling points.

One near-term possibility in the FFF and SLA methods is the fabrication of full-color, photorealistic models. The company OVE has developed ultraviolet-curable color inks and has integrated their use in the FFF and SLA processes. Each 3-D printed layer is followed by a 2-D print layer for color, offering as much color choice as inkjet printing offers.[5]

The slow part of the SLA process is the release and recoating cycle. Resins used for SLA printing likely will be optimized for fabrication speed, specifically to drain from the part faster, says Andrew Boggeri, lead engineer at FSL3D, a 3-D printer vendor.[6] "We can perhaps double—maybe triple—the speed of this [release-recoat] cycle and still maintain the quality," he estimates.

4 "Shear thinning," Wikipedia, http://en.wikipedia.org/wiki/Shear_thinning, viewed October 30, 2014.

5 Eddie Krassenstein, "First Full Color Consumer Level Stereolithography & FDM 3D Printers Coming Soon From OVE," 3DPrint.com, July 17, 2014, http://3dprint.com/9493/ove-full-color-3d-printers/, viewed October 30, 2014.

6 See the PwC interview with Andrew Boggeri, "The rise of 3-D printing marketplaces," http://www.pwc.com/en_US/us/technology-forecast/2014/issue2/interviews/interview-andrew-boggeri-fsl3d.jhtml, viewed October 30, 2014.

Nanoscale technology may be the key, because the temperature at which metal particles will fuse together falls off sharply as the particle sizes become smaller than 50 nm.

Metal fabrication

Far greater use of metals in 3-D printing is expected in the near future. Currently, metal fabrication is achieved primarily on devices that use selective laser sintering (SLS) or similar technology. These are generally large machines that have expensive, powerful lasers, which offer significant advantages in industrial settings. But the use of emerging materials and printer heads that work at nanoscale may soon permit fabrication of metal objects, possibly using desktop FFF printers.

Nanoscale technology may be the key, because the temperature at which metal particles will fuse together falls off sharply as the particle sizes become smaller than 50 nm. This size puts them in the range of cigarette smoke particles and viruses. (See Figure 2.)

For example, copper normally fuses at about 1000°C (1832°F). But 20 nm copper particles will fuse at about 280°C (536°F), which a kitchen oven can reach. Consequently, this little-known physical property opens the possibility of desktop 3-D metal fabrication.

"We believe this will work with steel and other metal alloys" at temperatures specific to them, Pickens says. "All you need to do is apply energy. Nanotechnology is the future of materials in 3-D printing and will turn it from a cottage industry into a widespread manufacturing technology. It will lead to new products we can't foresee."

The widespread adoption of nanoscale technology assumes the availability of industrial quantities of reasonably priced, graded, and consistently sized metallic nanoparticles. There is no natural source of such particles. The search has begun for the necessary industrial-scale manufacturing processes, either by scaling up the processes used to make nanoparticles for films and coatings, or through entirely new proprietary processes.

Nanoparticles will not be a priority for 3-D printers that use metal in workshop settings, because high-temperature equipment is already common in such settings. For industrial applications, such installations may be the norm because fabricating the object is often only the first step in creating a metal part. Additional steps can involve the removal of support structures and surface finishing, both of which need heat treatment that requires a machine shop.

"Generally we will see a step-by-step adoption of metal, starting with aluminum and brass," due to their low melting points, predicts David Alan Grier, a computer science professor at George Washington University. "High-tensile steel may be one of the last things we get to."

Organics and other materials

Printing a body part from living tissue for implantation has already been demonstrated. Doctors can harvest tissue from one area of the patient and use it to print a part the patient needs elsewhere. Such methods have been used to print skin grafts for burn victims[7] and to grow bone replacements.[8]

An expansion of this technique integrates blood vessels into the design and fabrication of the object. At Harvard University, Professor Jennifer A. Lewis has overseen the development of bio-inks that create living tissues with blood vessels. Using multiple printheads, the system lays down an intercell matrix and living material. Another printhead creates 35 µm blood vessels by laying down a material that melts as it cools, rather than as it warms. After being printed as an interconnected network of filaments, the material is melted by cooling and then drained away, leaving hollow tubes to form blood vessels.[9]

7 "Printing Skin Cells on Burn Wounds," Wake Forest School of Medicine, http://www.wakehealth.edu/Research/WFIRM/Research/Military-Applications/Printing-Skin-Cells-On-Burn-Wounds.htm, viewed October 30, 2014.

8 Dan Thomas, "Using 3D-Bioprinting for Artificial Bones," ENGINEERING.com, July 24, 2014, http://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/8134/Using-3D-Bioprinting-for-Artificial-Bones.aspx, viewed October 30, 2014.

9 Susan Young Rojahn, "Artificial Organs May Finally Get a Blood Supply," *MIT Technology Review*, March 6, 2014, http://www.technologyreview.com/news/525161/artificial-organs-may-finally-get-a-blood-supply/, viewed October 30, 2014.

Such development is part of what Elissa at ProofX calls the trend toward personalized precision medicine. But aside from living material, anything that goes into the operating room must be certifiably able to withstand sterilization in an autoclave, or oven.

Machines that can print with fiber, even ordinary cotton, are being explored, as they would be useful in wound dressings. MarkForged, a 3-D printer vendor, has announced a machine that can lay down carbon fiber filaments to create high-impact parts.[10]

Multi-material road to fabrication of systems

Current 3-D printers build components that can be assembled into systems, such as an individual gear that can be installed in a gearbox or a cylinder that can be filled with chemicals to make a battery. The Holy Grail of 3-D printing is to fabricate an entire gearbox, gaskets and all, or a ready-to-use battery that has the necessary chemicals—in other words, to fabricate complete systems. Obviously that goal would require the printing device to work with multiple materials, especially metal and plastic.

"We are creating materials via microarchitected design that have properties or property combinations that were previously unobtainable."

—Eric Duoss, Lawrence Livermore National Laboratory

Combining metal and plastic fabrication on one machine is a daunting challenge, if only because of differing melting points. However, new approaches are evolving. "For us, something that has worked out very well is to build structures with one process and add some functionality with another process, and then add more functionality again with a third process," explains Duoss of Lawrence Livermore National Laboratory.

He calls that multi-step process *deterministic deposition*, in which material is added to a preexisting 3-D structure. The process requires more sophistication than building on a flat substrate. By using different material in each step, designers can mix materials and embed one material in another.

Desktop alloys and microarchitectures

With 3-D printers that lay down material at micron or nanometer scale, different materials can be combined to create an object that has customized physical properties. By combining materials, designers can add toughness, elasticity, conductivity, and other such characteristics exactly where needed, and the printer can add internal voids—hollowed out spaces inside an object to reduce weight.

Lawrence Livermore and other labs are working at this scale, and designers are tuning coefficients of thermal expansion and other properties by mixing materials and voids. "We are creating materials via microarchitected design that have properties or property combinations that were previously unobtainable," Duoss says. Integral to the process are Ashby charts, which let designers select materials on the basis of their properties. Named for Professor Michael Ashby at the University of Cambridge, such charts compare a range of materials according to selected properties, such as strength versus density, strength versus cost, resistivity versus cost, and so forth. (See Figure 3.) It is likely that future fabrication systems will have the Ashby chart data built in, and establishing the properties of the material will be as integral to the design process as establishing its shape.

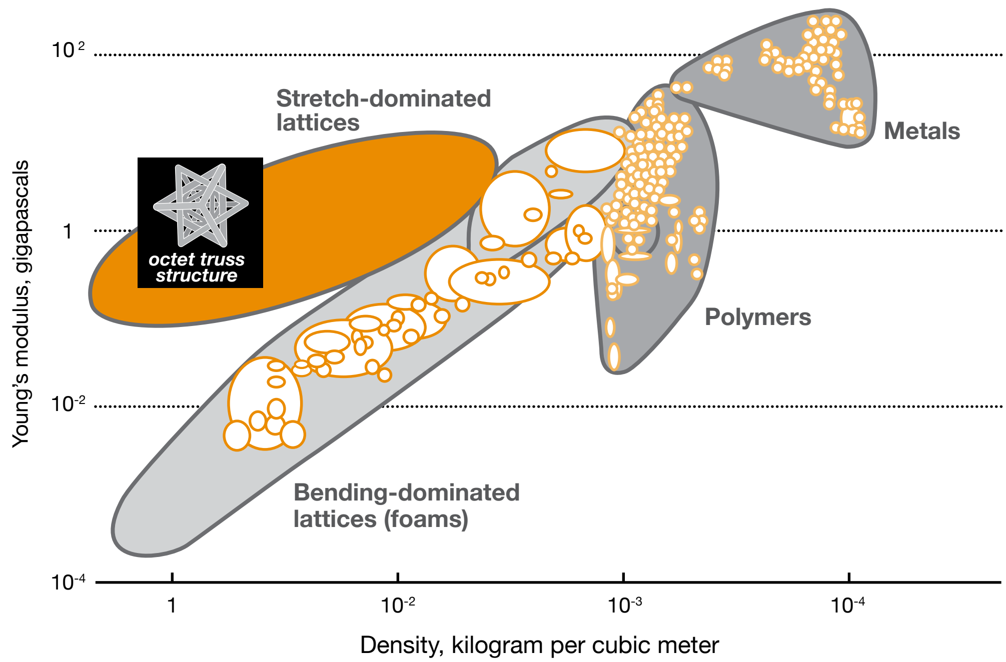
Or going even further, future fabrication systems might decide what material needs to go where in a fabricated object, and then add it. But there is a fundamental difference between fabricating with feedstock from a supplier who warrants its properties and relying on calculated properties from ingredients combined on the fly.

"You must be able to take [an object] out [of the 3-D printer] and be assured it is the right quality, or the technology will have limited appeal for commercial use," Grier warns.

10 Alexandra Chang, "New 3D Printer by MarkForged Can Print With Carbon Fiber," *Popular Mechanics,* January 27, 2014, http://www.popularmechanics.com/technology/gadgets/news/new-3d-printer-by-markforged-can-print-with-carbon-fiber-16428727, viewed October 30, 2014.

Figure 3: This example of an Ashby chart shows the kind of comparative information future designers might use to customize an object's physical properties.

The orange oval for stretch-dominated lattices shows that some materials developed by using microarchitected design populate a previously nonpopulated area of the Ashby material selection chart, signifying new properties that can be designed into materials.



Source: Adapted from Lawrence Livermore National Laboratory

Standards and economics

There are no industry standards to ensure that the same part made on different machines will have the same properties or dimensions. This significant challenge will hinder the industry in moving beyond prototyping to printing finished products. The Additive Manufacturing Consortium, operated by the nonprofit EWI (formerly Edison Welding Institute), is taking initial steps toward setting standards.[11]

Grier says one thing seems certain: The materials that become most widely used will mirror the needs of the industries that adopt 3-D printing with the most enthusiasm. These industries presumably will be those that have costly problems that 3-D printing can solve. Such problems probably include the requirement to stock expensive, specialized, and individual replacement parts and then deliver them immediately to distant points where they are suddenly and unexpectedly needed.

"For airlines, truck fleets, HVAC vendors, and certain medical specialties, needed parts can suddenly be made locally," Grier says. "Everything will flow from the economics of the situation. Those doing it because it's cool will die out."

11 For more information, see Additive Manufacturing Consortium, http://ewi.org/additive-manufacturing-consortium/, viewed October 30, 2014.

The pace of change

Stereolithography, the first form of 3-D printing, was invented in 1984. Since then, the power of computers has increased by a factor of more than 30,000, thanks to the computer industry's adherence to Moore's law, by which the number of transistors in a computer chip doubles about every two years. The result is that millions of people now pursue digital, online lifestyles very different from 1984.

But computers only need to manipulate almost-mass-free electrons. For physical objects, there can be no Moore's law or any exponential rise in functionality. Consequently, the 3-D printing field is still experimenting with materials and probably always will be. No perfect solutions exist for materials, only tradeoffs calculated with ever-increasing precision. Bronze, a copper alloy, was invented at least 6,500 years ago, yet development of new copper alloys continues to this day.

The question is whether the number and resources of the people working on these 3-D materials challenges have reached a critical mass, so solutions can be confidently expected. The answer appears to be yes—resolutions will improve to the germ level; wider repertoires of material, including metal, living tissues, and more plastics, will become routinely available; 3-D printers will be able to fabricate systems rather than parts; 3-D printers will be able to engineer the physical properties of an object as well as its shape; and standards will be encoded to ensure the results are commercially viable.

The only uncertainty is *when* these capabilities will become commonplace and affordable, not *if* they will do so.

Fabricating materials that have new properties

Eric Duoss of Lawrence Livermore National Laboratory explains how advancements in materials science are expanding material choices.

Interview conducted by Vinod Baya

Dr. Eric Duoss

Dr. Eric Duoss is a materials scientist and engineer at Lawrence Livermore National Laboratory, where he conducts research in advanced materials and manufacturing.

PwC: Eric, can you please tell us about your research?

ED: Sure. Our research focuses on developing new materials and methods for additive manufacturing. We are creating novel 3-D printing processes that can achieve feature sizes that are smaller than what most commercially available methods can produce—so microscale and, in some cases, nanoscale feature sizes. The processes we're creating have the ability to incorporate different materials in the same printed part. Also, because of the geometric complexity that additive manufacturing enables, you can tune or control material properties such as density, stiffness, strength, and thermal expansion by designing complex geometries, or microarchitectures. We are creating materials via microarchitected design that have properties or property combinations that were previously unobtainable.

PwC: Is your research focused only on materials, or are you studying the printing processes as well?

ED: It's both, and common between the two is the materials science. We strive to understand structure-process-property-performance relationships. That means understanding how the feedstock materials, printing processes, and post-processing interplay to affect the final part properties and performance. We do this with a combination of experimentation and simulation.

PwC: How do you control material properties?

ED: In the case of architected design, we do that by controlling the arrangement of material at microscale or nanoscale. For example, we have printed microarchitectures that are extremely stiff and strong yet lightweight.

“With post-processing, the finest features we’ve demonstrated are down to 200 nanometers.”

We have also designed architectures with programmed coefficients of thermal expansion [CTE] and Young’s modulus. We do this by precisely placing disparate materials in the same unit cell along with empty space or void. The unit cells are then configured into a lattice that has the programmed CTE. The CTE values can range from positive to negative or can even be neutral. In the case of a negative CTE, the material will actually shrink as you heat it. The common theme for architected materials is that these structures would be difficult or impossible to fabricate via any other way besides additive methods.

PwC: What resolutions are you working with?

ED: The resolution of printing depends upon the specific process. In one process called *direct ink writing* [DIW], we use an extrusion technique where we can employ very small diameter nozzles. The nozzle size sets the ultimate feature size. The smallest nozzles we’ve printed with are 500 nanometers in diameter. That’s pretty small. With post-processing, the finest features we’ve demonstrated are down to 200 nanometers. In practice, we most often work with feature sizes between 1 and 500 micrometers. I should point out that if you’re increasing the resolution, you might also be increasing the build time. Generally there is a tradeoff there.

PwC: How does your research fit within the broader trends in 3-D printing?

ED: In 3-D printing [also known as additive manufacturing] so far, hardware designers and mechanical engineers have developed printers and processes. I see the field expanding its focus to materials. Designers love what they can do with 3-D printing processes and the complex geometries they are able to make. But a continuing challenge is that these designers cannot use the materials they desire or get the properties they want with existing 3-D printing processes. A lot of our work focuses on addressing these challenges. We ask ourselves, what new materials are possible for existing and emerging processes? We try to design new feedstock materials so they’re compatible with existing printing processes and new processes.

We develop probably 10 to 20 new materials for our in-house 3-D printing processes per year. What we create is early stage R&D that’s not necessarily ready for commercialization. Other research efforts at LLNL [Lawrence Livermore National Laboratory] are focused on methods to qualify and certify many of these new materials for manufacturing and application purposes.

PwC: Can you provide an example of a new material for an existing process?

ED: We are designing new feedstocks that are elastomeric, or highly flexible and stretchable materials, for DIW. This method is akin to fused deposition modeling [FDM], the technology in many of the desktop 3-D printers, only it does not use a heated nozzle. Both have an extruder, but in FDM, the filament [the feedstock material] is a thermoplastic. When you heat the plastic, it melts, which allows it to flow. When it exits the nozzle, it rapidly cools and solidifies.

For DIW, we design complex fluids, which we call *inks*, that also can be extruded at room temperature. Complex fluids are a mixture of particles and a suspension media, and they are often viscoelastic—that is, they behave like solids under standard conditions, but undergo a change to more liquid-like behavior under shear.

In the case of DIW, when you flow the ink out of a nozzle, it is designed to be shear thinning—that is, its viscosity [fluid resistance to flow]

"Our long-term hope is that [models] will be predictive, so that during the design of the component, someone could analyze the performance characteristics [of the material] and adjust the design accordingly."

is lowered in the presence of shear. As the fluid exits the nozzle, it essentially will gel or solidify, so it maintains its shape even at room temperature. This is really great, because now extrusion-based printing is opened beyond the subset of thermoplastic materials that FDM was limited to. It opens up a much larger material space, including many of these elastomeric materials that we are currently pursuing. The innovation here is developing the complex fluid to have particular flow properties, or what is also called *rheological* properties.

PwC: You've talked a lot about understanding the flow and microarchitecture and so on. How do you capture and communicate this understanding?

ED: To tackle that challenge, LLNL is developing sophisticated models that capture—at multiple length and time scales—the behavior of materials during printing. For example, LLNL researcher Wayne King is leading an effort to model the laser melting process for metal-based additive manufacturing. The model captures the understanding of how the laser interacts with the material, what thermal gradients form during the printing process, how the microstructure changes during this melting process, the residual stresses that build up from the rapid heating or cooling, and so on.

You can scale up the model to the finished component and really understand how those process conditions affect a component's overall performance. Such multi-scale models, enabled by LLNL's high-performance computing capability, really are an effective way of capturing and communicating our understanding of additive manufacturing processes.

PwC: Could these models be predictive of properties of the final product?

ED: We are in the early days in building and using these models. Our long-term hope is that they will be predictive, so that during the design of the component, someone could analyze the performance characteristics and adjust the design accordingly. We also hope that these models can accelerate qualification and certification of the end products. It's for these reasons that such models have gained a lot of attention. At many of the industry events we attend, manufacturers and end users of these additive manufacturing platforms really want to see these models evolve and become more sophisticated. In many cases, you simply cannot achieve this sophistication without the significant high-performance computing resources available at places like LLNL.

In addition, one of the really exciting aspects of additive manufacturing is that it's a layer-by-layer process, so there is potential to capture data at each step in the build process via in situ [real-time] characterization. This capability starts to become a big data problem and you need to look for ways to make use of all the data that you collect, preferably in real time. For example, we're looking at ways to characterize the material as it is being built up. If you can do it well enough and react quickly, then if a defect occurs during manufacturing, you can discard the item or you can go back and correct that defect on the fly if there is a way to do so. Of course, we are also looking at ways to use the captured data to refine and validate our models and push them to become more predictive.

PwC: How are you able to print fully functional, complete systems?

ED: To build systems, we must deal with multiple materials. For us, something that has worked out very well is to build structures with one process and add some functionality with another process, and then add more functionality again with a third process. Essentially we are combining multiple steps in a fabrication cycle. We call such a multi-step process *deterministic deposition*.

Deterministic deposition is a bit different from traditional 3-D printing, because now you're placing material onto a preexisting 3-D structure. With most 3-D printing technologies, you start from a flat substrate and the part grows layer by layer. Depositing material on a 3-D structure requires a lot more sophistication, accuracy, and referencing.

From what I can tell, 3-D printing onto a 3-D shape is very new. There will be a lot of cases where a customer or an end user will say, "I have this existing device, and it has some form factor. How can I add to it?" In many cases, that device is not a nice rectilinear device. Often it's curvilinear, and it has some complexity. That's one issue we needed to solve before we could combine multiple processes.

We've used this technique to build antennas and different RF [radio frequency] devices. We are also working on things like metamaterials, batteries, electrodes, and resistors. We are building a toolset that in the end could get you to a fully functional, active smart system.

PwC: What are you learning about using multiple materials in your build cycle? What is the future potential here?

ED: As long as you are dealing with materials of the same type—all organic material, for example—this is an easier problem. Some printers already combine hard and soft plastic. If you start talking about multi-material in the sense that you want to put plastic with metal, then that brings more challenges because the materials are so very different.

Using the understanding we are gaining at the micro and nano levels, we have developed a microfluidic control system that allows us to pattern multiple materials in the same part. It's all in the same tool, but it's pretty neat because we can flow one material into our chamber, shoot an image [in the case of a photosensitive resin], cure in selected locations, flow that material out, and flow a second material in. These layers are very thin—they're micron-scale thickness. In some cases, you also could create smooth gradients between materials, depending on how you cure it.

We can accomplish such control because we have good knowledge of the photosensitive resin; understand the way that resin interacts with light; and understand issues like a cure profile, the kinetics, the depth, and how the light is absorbed. We have a process model to help us accelerate from the build process, but also to help us know how to move and change the resin itself.

However, more research and development are required to fully realize the potential of multi-material 3-D printing—basically patterning plastics, metals, and ceramics in the same part using the same process. In the future, you will also see different active systems—sensors, electronics, combined with structural elements and so on—built into the same component using 3-D printing.

Develop the ability to "think 3-D printing"

By Bo Parker

3-D printing could lead to a gradual, long-term transformation of internal and external value chains that span design, manufacturing, use, and service. How will you maintain your competitive advantage?

This article is the fourth in a PwC Technology Forecast *series on the future of 3-D printing. The first article discussed emerging technologies in the printers themselves. The second article covered innovations in software for 3-D printing. The third article explored advances in materials that position 3-D printing for growth. This article examines how enterprises could use 3-D printing for competitive advantage.*

Twelve weeks or so into a pregnancy, many of us get a first glimpse of our children from a live ultrasound video. If you've had more than one child, you may have noticed how much sharper these images have become over the years. In the future, you can thank 3-D printing for the machines that "see inside your body" to produce these ever-better images with greater reliability at lower cost.

GE pioneered the use of 3-D printing in ultrasound probes, first for medical use and now in sectors where noninvasive inspections are important for safety and performance, including aircraft maintenance, oil extraction, and electricity generation.[1] GE's experience underscores a key takeaway from PwC's research on 3-D printing. Much like the Internet, 3-D printing is a general-purpose technology that can transform a product or service in unique ways today, while providing a runway that will extend its impact for a long time in the future.

The capabilities offered through 3-D printing have the potential to transform internal and external value chains that span design, manufacturing, use, and service. Earlier articles in this issue of the PwC *Technology Forecast* explore developments in printers,[2] software,[3] and materials[4] for 3-D printing that are advancing the industry. This concluding article examines how your enterprise could use these developments for competitive advantage.

3-D printing and the Internet: Strange cousins

The Internet started as a channel to disseminate product and other information. Today it is a multifaceted business imperative at the core of an enterprise's digital transformation, impacting customer relationships, service delivery, efficiency, and agility. Many businesses that did not take the Internet seriously early on do not exist today or now struggle to compete.

The impact of 3-D printing could be similar. Although most businesses today consider 3-D printing as a manufacturing technology for prototyping, the longer-term impact will be based on its use for manufacturing finished products and taking advantage of shifts in internal and external value chains that will unfold over a long time, perhaps decades. Ultimately, 3-D printing could carry businesses beyond the purely digital world. "3-D printing is one of the first areas where digital truly meets physical," says Christine M. Furstoss, global technology director of manufacturing and materials technologies at GE's global research center.

These are early days, and the road to adopting and integrating 3-D printing into your products and operations may not be obvious. How 3-D printing applies is likely to be particular to your business, based on your product portfolio, supply chain, business model, and so on. Engaging with 3-D printing will be a journey rather than a product purchase. Therefore, your 3-D printing strategy will evolve over time through discovery, experimentation, and experience. PwC concludes that any company not already engaged with 3-D printing should start this journey of discovery now.

How to get started?

Here are some lessons everyone can draw from GE's experience with ultrasound sensors:

- Identify a critical component that is difficult or expensive to manufacture. GE's ultrasound sensors create and sense sound waves by using many small chambers in a ceramic device. Historically, manufacturing relied on dicing—making millions of tiny cuts in the material. It was time-consuming and prone to failure partway through the slicing process. First and foremost, 3-D printing was a more reliable, less expensive way to make the sensors.

1 "Three-dimensional printing: An image of the future," *The Economist*, May 19, 2011, http://www.economist.com/node/18710080, accessed November 18, 2014.

2 "The road ahead for 3-D printers," PwC *Technology Forecast* 2014, Issue 2, http://www.pwc.com/en_US/us/technology-forecast/2014/3D-printing/features/future-3D-printing.jhtml.

3 "Software innovations: Simplifying the 3-D printing experience," PwC *Technology Forecast* 2014, Issue 2, http://www.pwc.com/en_US/us/technology-forecast/2014/3D-printing/features/3D-printing-innovation.jhtml.

4 "The role materials play in powering the 3-D printing revolution," PwC *Technology Forecast* 2014, Issue 2, http://www.pwc.com/en_US/us/technology-forecast/2014/3d-printing/features/materials-3d-printing-revolution.jhtml.

- Use 3-D printing to extend the performance of the component. Conventional methods of making millions of tiny cuts allowed only straight or rectilinear shapes in the sensor. The use of 3-D printing freed designers to try new patterns, unconstrained by the slicing approach. GE discovered that more complex, random shapes created by 3-D printing processes resulted in better, more refined images.

- Look for new applications of higher-performing components in other sectors. GE found that 3-D printing allowed higher-frequency acoustic processing, ultimately delivering finer resolution than needed in health applications. GE then discovered new uses for this capability in industrial inspection products that require noninvasive, finer-resolution capabilities.

"3-D printing opens new ways of thinking, not only about our products but also about the whole design process."

–Christine Furstoss, GE

GE has also applied 3-D printing to jet engine fuel nozzles, engine brackets, and turbine blades, among others. And it is not just about manufacturing. "3-D printing opens new ways of thinking, not only about our products but also about the whole design process," Furstoss suggests.

From prototyping to finished products

Today's 3-D printing market continues to be dominated by prototyping, which is an important capability but not likely to change the game. PwC expects the 3-D printing market will likely accelerate only when the technology is used in final part production, not just prototyping. "For us, 3-D printing is not just for the engineering validation prototype. That's one of our uses, but it is also a manufacturing technology to create finished products," shares Furstoss.

Today there are a few businesses that use 3-D printing for creating final products. GE is using it to create fuel nozzles for their jet engines.[5] Invisalign manufactures millions of custom dental braces every year.[6] More than 30 parts in the Boeing 787 Dreamliner plane are 3-D printed parts,[7] and Lockheed used finished 3-D printed parts in satellites built for NASA.[8] These companies are early adopters who capably use today's limited 3-D printing offerings.

PwC's research on 3-D printing highlights both the limits of today's printers, supportive software, and materials, as well as the promising developments occurring in the 3-D printing ecosystem. Here's a recap.

Printers

The market for 3-D printers and services is still largely bifurcated. At the low end are limited-function offerings of interest to hobbyists. At the high end are expensive printers that have a limited total available market. Even across the range of printers there are performance limitations. These include the speed of fabrication and the impact of speed on throughput, the ability to print objects using multiple materials, and the ability to print fully functional systems, such as small combinations of computers and sensors.

These limits are being addressed, as described in the PwC *Technology Forecast* article "The road ahead for 3-D printers." The prices of high-end printers are dropping, and service bureaus are much more prevalent. The key for market growth is the continuing development of printers in the middle price range to achieve advances in performance, in multi-material capability, and in printing complete systems.

Software

Software is integral to sourcing or designing 3-D objects from scratch and serves as the interface between designers and users on the one hand, and delivering printable files on the other. Opportunities for software innovation are abundant. Chief among them are to simplify the experience of engaging with 3-D printing technologies, thereby making them more broadly accessible.

5 "Fit to Print: New Plant Will Assemble World's First Passenger Jet Engine With 3D Printed Fuel Nozzles, Next-Gen Materials," *GE Reports*, June 23, 2014, http://www.gereports.com/post/80701924024/fit-to-print, accessed November 18, 2014.

6 Will Drevno, "How 3D Printing is Creating Unique Products," *Inside3DP*, September 3, 2014, http://www.inside3dp.com/3d-printing-creating-unique-products/, accessed November 18, 2014.

7 Shanie Phillips, "Boeing's 3D Printed 787-9 Dreamliner Wows at Airshow," *Inside3DP*, July 24, 2014, http://www.inside3dp.com/boeings-3d-printed-787-9-dreamliner-wows-airshow/, accessed November 18, 2014.

8 Robert L. Mitchell, "3D printing makes its move into production," *Computerworld*, August 13, 2014, http://www.computerworld.com/article/2490930/enterprise-applications/3d-printing-makes-its-move-into-production.html, accessed November 18, 2014.

Today's software functionality echoes the printers and materials: the design options and performance characteristics of the printed object are limited, often to one material and far from entire systems. As materials and printers advance, PwC expects a rapid introduction of management features in software aligned with these developments. Together, they will form the foundation for the industry to move beyond prototyping and pivot toward printing finished products and components.

Materials

For physical matter, there is no Moore's law or exponential rise in functionality. Consequently, 3-D printing is still experimenting with materials and probably always will be. No perfect solutions exist, only tradeoffs calculated with increasing precision. Today, material characteristics limit the resolution at which objects can be printed. Only a few material types are available. And it is still early to predict the final material properties of a 3-D-printed object, especially when considering nanoscale molecular interaction effects. The question is whether the number and resources of the people working on these materials challenges have reached a critical mass, so solutions can be confidently expected.

The answer appears to be yes. The PwC *Technology Forecast* article on materials explored several key developments. Resolutions will improve to the germ level. Wider repertoires of materials, including metal, living tissue, and more plastics, will become routinely available. Eventually, 3-D printers will be able to fabricate systems rather than parts, and they will be able to engineer the physical properties of an object and its shape. Standards will be encoded to ensure the results are commercially viable. The only uncertainty is when—not if—these capabilities will become commonplace and affordable.

Got 3-D printing?

To summarize, 3-D printing is poised to become a force beyond its conventional use in prototyping. The key gating factors are the following:

- The 3-D printers must become faster and easier to use, handle multiple materials, and print active components or systems.
- The processes of sourcing, creating, optimizing, and printing 3-D models must become simpler and more robust.
- Resolutions must improve, material choices must expand, and methods to control their properties must evolve.

But don't wait for perfection. Don't even wait for "enterprise ready." The general applicability of 3-D printing to many future products and services across a number of sectors is a given. But learning to "think 3-D printing" in the design, manufacture, and servicing of products is unlikely to be a current asset in your company. It's time to start learning how.

Why now?

Here are some reasons why enterprises should pay attention to 3-D printing now:

- The impact of 3-D printing will unfold over a long time and will be pervasive across internal and external value chains that span design, manufacturing, use, and service.
- Understanding and integrating 3-D printing methods in current value chains will be a discovery process that evolves through exploration and experimentation. Engaging early is necessary to stay competitive.
- The pace of innovation in 3-D printing is fast and diverse. Internal talent will need to have adequate hands-on experience with 3-D printing to be in a position to take advantage of innovations.
- The capabilities offered through 3-D printing will force businesses to raise their expectations about instrumentation and feedback control used in current methods of manufacturing. Those who engage with 3-D printing will get better at conventional manufacturing as well.

Seizing competitive advantage with 3-D printing

Christine Furstoss of GE shares the breadth and depth of how 3-D printing is transforming manufacturing at GE.

Interview conducted by Vinod Baya and Bo Parker

Christine M. Furstoss

Christine M. Furstoss is the global technology director of manufacturing and materials technologies at GE's global research center.

PwC: Christine, can you please briefly describe your role at GE and your current priorities?

CF: Sure. I lead the manufacturing and materials technology organization at GE's global research center. My role is to work with the supply chain and engineering leaders across all GE business units to assess, set strategy for growth, and implement critical process and material developments for industry-leading products and manufacturing.

Major initiatives that we're working on this year and will continue for the foreseeable future are to invest in new materials and to get higher-efficiency products, better performance, and longer life. That's the core of what we do. I'm very proud that our chairman always says we are a materials company even though we don't sell materials. That's a big part of what differentiates us. Also, we can never talk materials without discussing the manufacturing process. The two go together. So we continue to invest in novel manufacturing technologies and are moving toward what we call *advanced manufacturing*.

PwC: What is advanced manufacturing and how does 3-D printing fit in that vision?

CF: Advanced manufacturing is not any one technology or a different type of factory system. It's the dedication to advance your products, your position in the market, and your competitiveness through new manufacturing technologies. This is where 3-D printing fits in, along with new types of machining—whether that's a new type of material processing, forming, drilling, and others.

“[Advanced manufacturing] is a comprehensive vision to understand how manufacturing is being transformed and disrupted across the value chain from design to service.”

It is a comprehensive vision to understand how manufacturing is being transformed and disrupted across the value chain from design to service. There are four pieces in advanced manufacturing, and 3-D printing fits in many pieces.

The first piece is concept and design, and the prospect that a lot of it can now be accomplished through crowdsourcing. Recently we successfully organized an open competition to design jet engine brackets that radically reduce the bracket weight by taking advantage of 3-D printing. The winning design was 84 percent lighter than the existing bracket. What the project told us is that you can conceive and create things, and you can find people anywhere in the world who can solve your problem. It is concept and design piece getting disrupted.

The next piece is the disruption of machining, tooling, and fabrication. This piece is where 3-D printing has the most application, along with subtractive manufacturing and others, by enabling rapid prototyping, rapid tooling, and so forth.

The third piece is encapsulated in our idea of brilliant factories, which is digitizing and revolutionizing manufacturing. You can run factories smarter, just in time. You can run them in a distributed fashion, have more of them, or place them closer to raw materials or consumption. So factories are disrupted.

The last piece is the disruption of the supply chain. Future supply chains will combine digital and physical distribution in interesting ways to change the economics and efficiencies of the supply chain. Designers will rethink their products to take advantage of these new characteristics.

PwC: Since all stages of the value chain are getting disrupted, how should businesses work across all of them?

CF: I think that after the assembly line in manufacturing, the next big paradigm shift is the brilliant factory concept I mentioned earlier, where we use real-time data to make real-time decisions on the plant floor and closed-loop feedback up and down the value chain. These feedback loops are how businesses can work across the value chain.

You really have two feedback loops. One goes from factory operations to the manufacturing engineering operations. The other goes from service to engineering. We maintain a lot of our products, so in my mind, every maintenance and repair of the product is a failure effects analysis. We can see what went wrong and feed that back into engineering for design improvements.

If you have that feedback based on built data, usage data, and service data, you really have closed-loop feedback across the value chain, and that is where GE is very different from others.

"For us, 3-D printing is not just for the engineering validation prototype. That's one of our uses, but it is also a manufacturing technology to create finished products."

PwC: Where is 3-D printing being used at GE?

CF: For us, 3-D printing is not just for the engineering validation prototype. That's one of our uses, but it is also a manufacturing technology to create finished products.

Today, as we work with 3-D printing, we are learning about a lot of things, such as making a part in days instead of years, or being able to test in a turbine or a locomotive or in a new lighting fixture. We're also learning about making designs out of the right material. Maybe the design isn't perfect, because it is early in the engineering phase and we didn't optimize the process for the material, but we can actually test it and it will last long enough for the test. For example, we can find out whether we can burn fuel 200 degrees hotter, so a product is more efficient and produces fewer emissions.

For us, 3-D printing opens new ways of thinking, not only about our products but also about the whole design process. In addition, 3-D printing is one of the first areas where digital truly meets physical—or you can also say where analytics meets software. It is the integration of software from the process into the design, from the design into the machine, and during the printing of the actual part.

PwC: What are some challenges you've needed to address as you engage with 3-D printing?

CF: We had to overcome many challenges. Everyone needs to change their skill sets, and that is one challenge. The materials engineers and manufacturing engineers need to know software. That's why we're excited about some of the new opportunities, including the newly announced digital manufacturing institute for which GE is one of the industrial partners.

Another challenge that stops many companies from embracing 3-D printing is software-inclusive control. In other words, the whole loop hasn't been closed, as we envision in our brilliant factory concept. A closed loop is essential to make 3-D printing an industrial element, so it is not limited to making two or three parts or just the prototype parts but can be used for making the full part or a large portion of the parts at scale.

PwC: Is 3-D printing making it easier to create and work with new materials?

CF: With regard to materials, 3-D printing offers both an opportunity and a challenge. The opportunity is to create and use new types of materials. The challenge is to introduce new materials into new products, because there are no standards to certify material properties. When I get a forged bar billet, a casting, I know the properties. I can take a little piece off of it and know how strong it is before I ever put a cutting tool to it. The supplier who sent it to me certified it, so I know exactly what I'm getting and I know what to do with it.

“The flexibility 3-D printing gives us to understand activity on the factory floor and during the design, customization, and repair of parts—that’s the power of additive manufacturing.”

With additive manufacturing, if you don’t understand which parameters—laser strength, speed of deposition, powder quality—control the material properties, you need to test every piece and may need to scrap an item after you’ve spent, for example, 72 hours building it. That’s not where we want to be.

Today there are fewer examples where we’re building both geometry and properties at the same time. I don’t think people fully grasp what that really means. By building geometry and properties you have such great potential, but you also have such great responsibility to understand where every single particle is going. I have a responsibility to produce reliable products that meet performance characteristics. How do I ensure that? How do I inspect intricate parts?

PwC: How should enterprises analyze 3-D printing efforts? Should they compare them with conventional methods of manufacturing?

CF: It really depends on what you are doing. In some cases, comparing manufacturing costs alone might be misleading. For example, although 3-D printing could be slower and more expensive than conventional methods in some cases, it could enable you to change the terms of competition and get into a new market.

Let’s say that a fuel nozzle we are developing will be five times more expensive to make using 3-D printing than it would using the current process, where we make the various components and bolt them together. However, as a result of the fuel nozzle being lighter, stronger, and more efficient, you can sell jet engines that have X percent more throughput. That’s not a very complicated equation, but on the surface, a typical engineer might ask, “Why would you do that? The cost using conventional methods is $2,000. The 3-D printed part costs $10,000 and takes twice as long to produce.” But then someone points out that the fuel nozzle is 4 percent lighter, which means it will deliver $100,000 greater productivity over its lifetime. Now that changes the whole equation.

How you get people smart enough to run that equation all the way through is part of what must get figured out in this new world of advanced manufacturing. That’s the nature of disruption that we are trying to understand and take advantage of.

PwC: What are the implications of 3-D printing on other parts of the business?

CF: Additive manufacturing gives us some flexibility to explore new designs and new material systems faster than ever before. I don’t need to wait—I can print it. But you must couple 3-D printing with better analytics. We’re just learning how to control the machines better, so we can also have more flexibility on the process side.

I think 3-D printing has a dramatic implication for research. Not only can 3-D printing be a production tool, or a surrogate for understanding how valuable data is, but it also can be a research tool because you can manipulate quickly and combine different materials without disrupting an existing setup. Today, if I want to melt a different type of steel, I must change all the tooling, otherwise the experiment will contaminate everything. This possibility of using additive technologies as a material discovery and research tool is just emerging.

The capabilities of 3-D printing also represent a new bar that is being set for other manufacturing methods. All the things we talked about—closed feedback loops, better integration, faster turnaround—3-D printing shows they are possible. Now we want to have these capabilities with every machine and every drill bit and every new material. All of these are a learning opportunity as well as a growth opportunity.

PwC: What is the longer-term outlook of 3-D printing at GE?

CF: The outlook is evolving as we learn and understand more. We already are sparking a lot of our growth using 3-D printing in areas that require customization. The oil and gas industry is a big growth business for GE, and we're very proud to be partnering with our customers there. Because every wellhead is different, both in geography as well as gases or oils, that industry requires a certain amount of customization for every project. Power generation products also have been that way. Although we have core units, every customer's configuration is unique. With 3-D printing, we have the flexibility to extend our products quickly to fit each customer's needs.

We expect to use 3-D printing across our value chain of design to service. How far can 3-D printing bring us in tooling? How far can 3-D printing take us in adding features to existing parts? We're stretching and flexing those muscles right now to understand. I often say that additive technologies will touch more than 50 percent of parts we make in the future. I do not mean we will print more than 50 percent, but maybe we make the tooling, maybe we do the repair, maybe it allows us to test this unique configuration and to offer more unique configurations than ever before.

The flexibility 3-D printing gives us in understanding activity on the factory floor during the design, customization, repair of parts—that's the power of additive manufacturing.

Acknowledgments

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Special thanks

James Bono, Lawrence Livermore National Laboratory

Jennifer Gentrup, Autodesk

Lynn Hendrickson, GE Global Research

Ken Ma, Lawrence Livermore National Laboratory

Industry perspectives

During the preparation of this publication, we benefited greatly from interviews and conversations with the following executives:

Stephen Biller
Chief Manufacturing Scientist
GE

Andrew Boggeri
Lead Engineer
FSL3D

Dr. Eric Duoss
Materials Scientist and Engineer
Lawrence Livermore
National Laboratory

Dima Elissa
Co-Founder and CEO
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Christine M. Furstoss
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Glossary

3-D printing, additive manufacturing	A manufacturing method where 3-D objects are printed layer by layer based on a 3-D digital representation. The printing process uses various materials, or *inks*, most commonly plastic polymers and metals.
Prototype	A preliminary physical replica of a product from its 3-D digital model, built to test a concept or process or form-function-fit and to generate feedback for further refinement of the product's design.
Finished product	A final physical creation of a 3-D digital model that is ready to be sold or distributed to end customers or customers in a supply chain. Not a prototype.
Fused filament fabrication (FFF)	A 3-D printing method where a stream of melted thermoplastic material is extruded from a nozzle to create layers, with each layer bonding to the previous layer.
Stereolithography (SLA)	A 3-D printing method that uses an ultraviolet beam to harden liquid resin, bonding each successive layer.
Selective laser sintering (SLS)	A 3-D printing method where powdered material (such as nylon, titanium, aluminum, polystyrene, and glass) is jetted from many nozzles onto the print surface, and laser is used to sinter or fuse the powder, layer by layer.

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