IQT QUARTERLY

VOL. 4 NO. 2 FALL 2012

ASYMMETRIC MANUFACTURING

IQT IN-Q-TEL

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IQT Quarterly, published by In-Q-Tel, Inc.

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Design by Lomangino Studio, Inc.

Printed in the United States of America

IQT QUARTERLY

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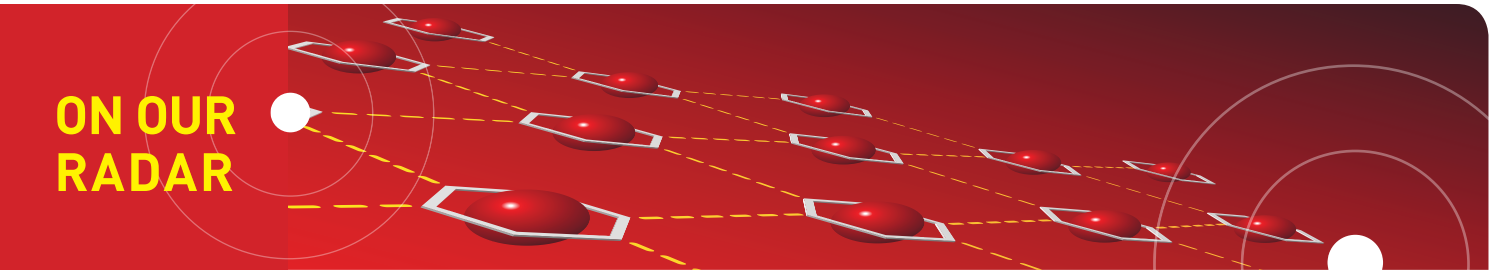


THE MAKER MOVEMENT AND ADVANCED MANUFACTURING

By Megan J. Anderson

Imagine a man driving through the Central Valley of California. Suddenly the familiar sound of a broken fan belt indicates his car is overheating. Pulling over to the side of the road, many miles from a mechanic, he calmly investigates the problem under the hood. Shrugging, he walks to the trunk and pulls out a small briefcase from the roadside kit. Within minutes, the man has downloaded the fan belt design from the dealership and tiny nozzles are depositing rubber and plastic, forming a perfect replacement.

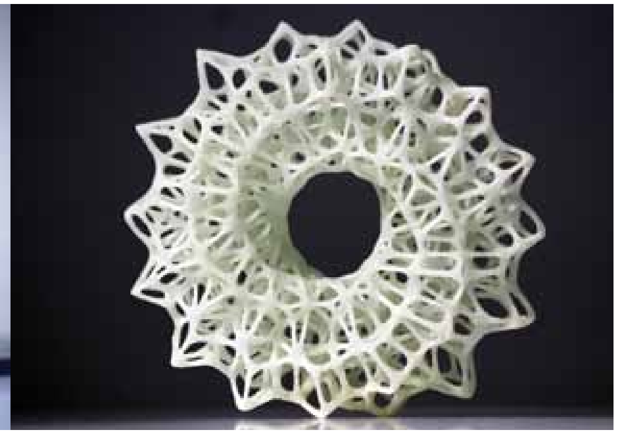
Thousands of miles away, a similar situation unfolds on Highway 80 in Iraq as an Army convoy comes to a standstill. Sand and rocks have taken their toll on the drive sprocket of a M1A1. Soldiers rest in the shade as they watch tiny lasers etch a perfect titanium replica of the gear selected from a complete library of every piece of mechanical equipment in the field.

Meanwhile, in a warehouse in New York City, a group of people at a "Maker" convention are showing a 16-year-old boy and his mother how to use a 3D laser scanner to upload measurements of common household items — a shower curtain ring, a light switch panel, a cupboard knob, a custom video game controller. These items are being simultaneously printed in a small enclosed cube on the demonstration table below. While only the last of these scenes is common today, the rapid advance of 3D printing and digital manufacturing, driven by both the private and government sectors, will soon enable all three.

In this edition of the *IQT Quarterly*, we focus on the opportunities created by the rise of the "Maker Movement" and the proliferation of low-cost 3D printers with easy-to-use open source software design tools. IQT believes that this rapidly growing technology space is enabling a new "asymmetric manufacturing" capability that must be understood, monitored, and leveraged by our Intelligence Community partners. Asymmetric manufacturing technologies have the power to turn any innovative mind into "Q," the James Bond character — and IQT namesake — who produced numerous gadgets for Bond. As such, it is important that we cultivate our understanding of the Maker Movement and track these trends not only in the rapidly evolving commercial market, but at the individual hobbyist level as well. As the articles in this issue illustrate, the stage has been set for the digital manufacturing revolution.

3D printers have been used to generate R&D prototypes in the auto and aerospace industries for more than 25 years. Large industrial systems can cost upwards of $1 million and print plastic, metal, glass, and ceramics to very high precision. As these systems become more robust, companies are beginning to use them for more than just prototyping parts. For example, Boeing currently uses a variety of 3D printed

Designed by macouno. 3D printed by Shapeways.
Photo courtesy of Shapeways.



Designed by Bathsheba Grossman. 3D printed by Shapeways.
Photo courtesy of Shapeways.

parts in its F/A-18 Hornet. Small-scale 3D printing is also on the rise as system cost comes down. These efforts are largely driven by hobbyists and creative individuals who share their designs and creations online. Small manufacturing lines that approximate Star Trek's "replicator" can now be set up in a garage for a few thousand dollars. Software has improved to the point that pictures, drawings, or computer-aided designs can now be sent overseas to be printed in individual quantities. A quick search on the Shapways website shows 3D printed products from jewelry, art, and iPad cases to advanced heat exchangers and even an astrolabe. An engineering research group at the University of Southampton designed and printed their own unmanned aerial vehicle using a 3D printer that cost only a few thousand dollars.

We are experiencing a new era of manufacturing that no longer requires expensive equipment, skilled labor, large inventories, or long timelines. Hardware and software are being developed in tandem, with an emphasis on open source sharing that is driving innovation. Digital printing techniques are enabling a global asymmetric manufacturing capability that is inexpensive, social, rapidly evolving, and bounded only by imagination. 3D printers from MakerBot are delivered as a kit with raw materials, a printer head, and instructions describing how the system will print itself into existence, reminiscent of the lathe from Richard Feynman's "There's Plenty of Room at the Bottom" lecture. How-to videos are instantly available on YouTube and designs can be downloaded from websites such as instructables.com using Autodesk 123D or Google SketchUp software. The unique crowdsourced development of this technology has pushed information into the public domain, where it can be quickly adapted by anyone for anything.

Clearly this represents an opportunity to develop tailored products for government-specific applications that take advantage of the innovations of the Maker Movement. Traditional capital equipment requirements have been eliminated. Mission needs can now be transformed from idea, to prototype, to fielded solution using low-cost in-house equipment. Consumers can be more actively involved in the design and production of critical components. This will result in a shift away from traditional large-scale manufacturing; from "what's available" to "what's needed".

Manufacturing as the world has come to know it over the past two centuries is at an inflection point. No longer is there a need to spend extended amounts of time and large sums of money to create a secure, reliable, global supply chain. The manufacturing paradigm is being transformed, by industry leaders and hobbyists alike, into an at-home endeavor, where the creation of any product you desire is possible in your own garage. These new design and manufacturing platforms are providing citizens, industries, and governments with an asymmetric manufacturing capability that will change the world. Q

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A LOOK INSIDE: ASYMMETRIC MANUFACTURING

When IQT set out to put together a *Quarterly* discussing 3D printing, the Maker Movement, and the advent of the digital manufacturing age, we purposefully chose to group these themes under the title "Asymmetric Manufacturing". We want to call attention to the fact that these ideas and tools can (and will) quickly permeate the globe. There are currently no guidelines or regulations regarding purchase of "hobbyist" 3D printers (MakerBot, RepRap, 3D Systems), circuit boards (Arduino, RaspberryPi), or design software (Autodesk 123D, SketchUp). We must be aware of current capabilities in these areas to continue to stay ahead of the new threats that asymmetric manufacturing will enable.

The issue's first contributor, Joe Dinardo, introduces additive manufacturing and compares its rise to the invention of the personal computer. The author explains how additive manufacturing is different from traditional subtractive manufacturing processes, which remove material from a solid block to achieve the desired product, and the potential economic implications of the proliferation of this new form of manufacturing.

In the next article, Eugene Giller, Frank Azzolino, and Tom Davidson look at the different types of additive manufacturing techniques that are currently available and explain why a particular technique, which combines Fused Deposition Modeling and piezoelectric printing, is the most advantageous method. The authors also discuss some of the markets and challenges for 3D printing, including those for the Intelligence Community.

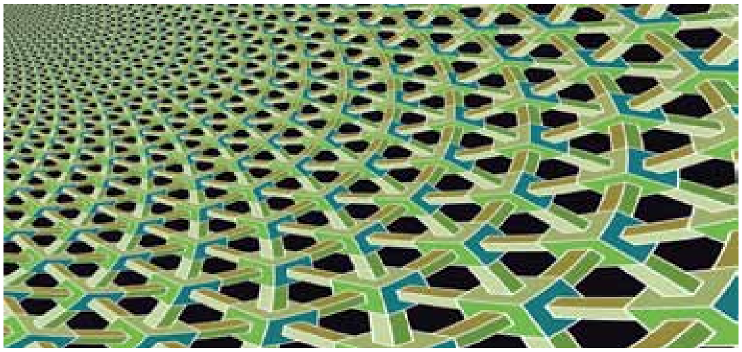
Lt. Col. Nathan Wiedenman follows with a description of DARPA's Adaptive Vehicle Make (AVM) programs, which aim to shorten development timelines of complex defense systems by raising the level of abstraction in the design process, decoupling design and fabrication, and utilizing foundry-style manufacturing. LTC Wiedenman also details the three research components of AVM that DARPA will test in award-based design challenges.

Next, Matt Johnson describes the success of one innovative company in the context of the Maker Movement. The Maker Movement is a creative community of people collaboratively working on projects and sharing knowledge. Starting as a student project that responded to direct feedback from customers within the Maker Movement, Johnson's company Bare Conductive has created a unique product with a range of applications.

In a feature piece about TechShop, Mark Hatch discusses how democratizing access to tools such as mills, 3D printers, and laser cutters is a revolution that enables innovators to develop next-generation technologies and products. Hatch tells success stories of companies that have grown out of TechShop and offers numerous examples of standout, one-of-a-kind technologies created in their workshops.

Finally, Carine Carmy talks about the return to an artisanal culture that is encouraged and perpetuated by 3D printing, the Maker Movement, and platforms to create and sell handmade goods, like Etsy. 3D printing in particular allows for experimentation and customization, with near zero costs and the ability to translate an idea into a product in as little as one day. Carmy discusses this concept through the lens of Shapeways, a 3D printing marketplace and community.

The Fall 2012 issue of the *IQT Quarterly* highlights the most exciting advancements being made in manufacturing right now. Startups, small-to-medium sized enterprises, and — most of all — hobbyists are recognizing the potential of 3D printing and are embracing the opportunities presented by the Maker Movement. Understanding potential applications within the Intelligence Community early on will be crucial in advancing the manufacturing of tools and systems for national security. Q



An Evolution in Industry: The Rise of Additive Manufacturing

By Joe Dinardo

Now is an interesting time in the manufacturing world. We may be witnessing an evolution in technology that could flip the traditional ideology of the manufacturing industry on its head. This change, of course, is at the heart of the world's economy. For many, the rise of additive manufacturing is akin to that of the invention of the personal computer, a development as empowering as the spread of the Internet itself.

Very few technologies have had such a profound effect on the way we live our lives than that of manufacturing methods. Improvements and developments made in the techniques used to manufacture goods have made it possible for quality products to reach the masses. Large-scale production techniques and the infusion of computer control technology have reduced costs and transformed the manufacturing landscape. Centralized production facilities coupled with complex international supply chains lead the way.

A promising new concept in the way we manufacture goods is beginning to emerge. Also referred to as 3D printing, interest in additive manufacturing (AM) has never been higher. Research and development is taking place on a global scale, while many in industry are turning to AM for innovative solutions and novel product designs. Some believe AM could considerably affect the trajectory of geopolitical trends as it may trigger a fundamental shift in the global economy. Countries poised to take advantage of this shift may experience a revitalization in manufacturing innovation and an economic boost, as they may become less dependent on exporting countries like China. It is therefore critical that those involved with influencing the course of strategic U.S. policy become familiar with this technology.

An Introduction to Additive Manufacturing

As the name implies, AM starts by using raw materials and involves manufacturing products by additively building up these materials to form a fully functioning or near net shape part. AM uses various processes to "grow" a physical product that was modeled using computer-aided design (CAD) software. Three-dimensional model data is fed into specialized software that then slices this model into thin layers

Figure 1 | General additive manufacturing process

to be successively built on an AM platform. Typically, some magnitude of post-processing is then involved in order to finish the product. This process is opposed to traditional subtractive methods of manufacturing, which use cutting tools and multiple steps to remove material from a billet in order to achieve the desired shape.

Through AM techniques, virtually any shape can be created no matter how geometrically complex the design may be. In many applications, freedom within design is now wide open, meaning that engineers can start designing products thinking strictly about the end use and are not limited by what the manufacturing machine tool is capable of producing. An example of this is within the medical field, where titanium implants and hearing aids are being custom made to fit the recipient.[1]

A multitude of AM processes now exist for various types of materials such as plastics, metals, ceramics, and wax. To establish consistency, the American Society for Testing and Materials (ASTM) has formed a committee to develop the standards to which AM will be held to in the future.

Advantages Offered Through AM

In the right application, AM can offer tremendous advantages over traditional manufacturing methods. Many of the following examples also lead to improved economics, which inherently is the largest driver for the adoption of AM.

Less Waste Material Due to the nature of AM, there is very little scrap material that is discarded at the end of a build cycle. By using AM, essentially only the material that is needed to actually make the part is used. With traditional subtractive manufacturing, the end product is machined out of a solid block

Figure 2 | Miniature turbine manufactured using Direct Metal Laser Sintering

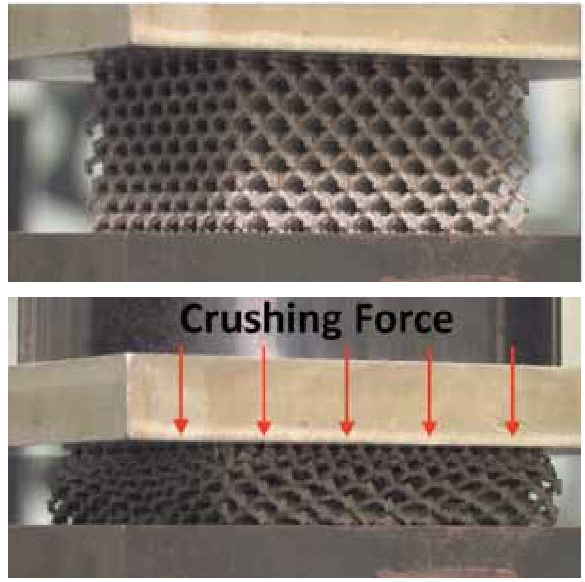


Figure 3 | Crush testing a metallic lattice structure

of material. In many cases this can result in more material being lost in the waste stream than is actually used.

Complex Designs AM allows for very complex designs to be built with little to no increase in cost. Subtractive manufacturing may require multiple processes on a variety of machines. In contrast, the AM build sequence is a single step process no matter the intricacy of the end product. Additionally, due to the fact that material is being selectively placed, it now becomes possible to make shapes not achievable through any other means.

Digital Manufacturing Approach Other than post-processing operations, all of the information that is required to build a part may be contained in a digital format and through the 3D CAD model. This eases communication lines between the designer and machine operator and can significantly reduce the amount of human interaction or expertise needed to produce a functional part.

Mass Customization Due to the fact that AM uses digital files, it becomes relatively simple to quickly modify an existing design for the intended use.

Streamlined Design Iterations For the designer there may be no better tool to assess his or her design than through the tactile experience provided by prototypes. AM provides a means to quickly and economically manufacture prototypes for evaluation. This streamlines the design process, resulting in quicker turnaround from concept to delivery.

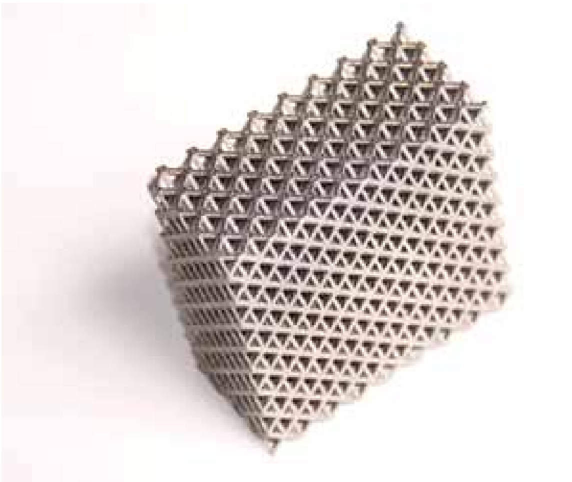


Figure 4 | Example of lightweight titanium lattice structure made using electron beam melting

A Disruptive Technology

Although the concept of AM has been around for quite some time, recently it has been receiving a large amount of attention. There are now a number of very low-cost AM systems designed for personal home use that are being used by hobbyists and enthusiasts all over the world. 2011 saw an explosion of this category of AM systems growing by an estimated 289.2 percent with 23,265 units being placed.[2] Although this accounts for only a small portion of the billion dollar AM industry, it indicates that the idea of personalizing products and manufacturing them close to home is resonating.

The current AM market, estimated at a value of $1.7 billion, is expected to reach $3.7 billion by 2015 and to surpass $6.5 billion by 2019. Some experts in the field very conservatively estimate that today's market only represents eight percent of its potential.[2] A 2011 Gartner Report on emerging technologies estimates an even lower market penetration at only one to five percent, meaning that a total value of $34.3 to $171.4 billion could be realized with current applications.[3] This same report also gives AM the highest technology benefit rating as "transformational" and places it in the "Technology Trigger" phase within the Hype Cycle. In other words, AM technology is forecasted to be five to ten years from mass adoption and to potentially have a very serious impact on industry.[3,4]

Part of the reason for the sudden increase in interest is due to the advancements being made in metal-based AM. The ability to reliably create objects out of materials with significant strength has opened AM to a whole new realm of possibilities. The aerospace industry is arguably one of the most difficult fields to introduce new technologies into as those technologies must be very robust and proven. That being said, there are aerospace companies currently flying components fabricated with AM technology. These companies are investing in the future by taking serious steps towards analyzing what is possible with metal-based AM. General Electric has identified parts of their turbine engines that could be produced using AM and is planning production runs for as early as 2016.[2]

Potentially the most disruptive aspect of AM is the direct from digital approach. The digital representation of a physical object could include not only the geometric definitions but also the parameters for the machine to use. In this manner, human interaction during the build process is very limited. This could significantly lower the barriers associated with manufacturing, allowing the less technically savvy to become both the producers and sellers of goods.

One of the advantages of AM is the ability to manufacture a variety of products without having large amounts of specialized equipment or tools for each different shape. Leveraging this could lead to a more globalized production scheme where a string of strategically located small production plants are used to manufacture goods close to those that need them. Costs associated with distribution could be drastically lowered, as it is the digital files that are transferred at a global scale and the actual product is manufactured and shipped locally. AM digital files sent to machines could be used to alter product lines at a moment's notice, making companies more agile. The volume of stockpiled spare parts could be significantly lowered as on-demand printing becomes available. This production scheme is contrary to most business models, which rely on a small number of large manufacturing plants that ship products internationally.

The global sharing of designs will become more prevalent in the future. With the rise of online social platforms, it is expected that the Internet will continue to be used to build communities where designers can upload files to either sell, trade, or freely give out. This may allow for new markets and professions to form as anyone with CAD software experience can share digital representation of ideas.

AM becomes even more powerful when coupled with another complementary rising technology. 3D scanning offers an alternate means for supplying AM systems with the 3D data it needs. Handheld devices are being used to scan existing items and capture point clouds that are then fed into specialized software that form CAD data useful for AM production. This in turn could bring about many new challenges related to copyrights, patents, trademarks, and liability.[5]

Summary

Although AM can prove to be advantageous, there are current limitations of the technology that must first be overcome for it to become more practical in other applications. Improvements in surface finish and precision are needed for items which require a high degree of dimensional accuracy. Expanding the materials that are available for metal-based AM and increasing the robustness of the processes being used will open new opportunities.

Current build speeds and work volumes limit AM to somewhat smaller parts on the order of one cubic foot. Scaling these processes to much larger sizes will be desirable. Prices for the high-end equipment need to come down and quality control standards need to be developed. Software and simulation packages also need to be written or improved.

AM is currently not in a position to compete with the large-scale mass production of identical items. Physical limitations prevent plastics AM from achieving the quantities that injection molding techniques are capable of. However, we have already seen that AM has become the ideal choice for making custom parts and for low-volume manufacturing.

From an economics viewpoint, AM may still lose the one-for-one comparison when dealing with products designed for the capabilities of traditional manufacturing. In order to take full advantage of the abilities of AM, it will require a paradigm shift in the way engineers think about design. The techniques taught in training regarding design for manufacturing and assembly no longer hold true in the realm of AM. For instance, the use of nuts, bolts, and other fasteners could be partially or even completely eliminated as an entire assembly may be printed as one piece.

Fortunately, all of the aforementioned limitations of AM are being investigated on at least some level. The AM industry is ripe with opportunity and will continue to grow at an accelerated rate. Basic and applied research is being performed within a large number of academia, government, and commercial entities. The U.S. government is taking steps to ensure its role in the future by investing $30 million (not including cost sharing) into a National Network for Manufacturing Innovation (NNMI) pilot institute, which is focused on advancements in AM technology. The concept of making items in an additive fashion will continue to penetrate other areas such as nanotechnology, biology, and electronics.

There is no doubt that AM has arrived, is here to stay, and will grow in the near future. The question remains on just how much of an effect AM will have, and what exactly it will be used for. As with all emerging technologies, it becomes difficult to fully answer this question. It is doubtful that anyone could have fully comprehended the consequences related to the spread of the personal computer. What is clear, however, is that AM will inspire novel products and the reinvention of existing designs, and will bring new solutions to existing problems. Q

Joe Dinardo *is an engineer for the Department of Energy's National Secure Manufacturing Center (NSMC). He graduated from the University of Missouri in 2008 with a B.S. in Mechanical Engineering and a minor in Mathematics. Joe received a M.S. in Mechanical Engineering while researching nonlinear vibration analysis. He currently works on projects involving national security within a range of topics, including mechanical design, additive manufacturing, and numerical modeling using finite difference techniques and hydrodynamic code.*

REFERENCES

1 D. Smock. "High-Tech Implants." DesignNews.com, 2011. http://www.designnews.com/document.asp?doc_id=230500&dfpPParams=ind_183,aid_230500&dfpLayout=article.
2 T. Wohlers. "Wohlers Report 2012." Wohlers Associates, Inc., Fort Collins, Colorado USA.
3 J. Fenn, H. LeHong. "Hype Cycle for Emerging Technologies, 2011." July, 2011. www.Gartner.com.
4 T. Campbell, C. Willimas, O. Ivanova, B. Garrett. "Could 3D Printing Change the World? Technologies , Potential, and Implications of Additive Manufacturing." Atlantic Council Strategic Foresight Report, October 2011.
5 M. Weinberg, (November 2010), "It Will be Awesome if They Don't Screw it Up: 3D Printing, intellectual property, and the fight over the next great disruptive technology," Public Knowledge, http://www.publicknowledge.org/it-will-be-awesome-if-they-dont-screw-it-up, accessed June 2011.

3D PRINTING: OPPORTUNITIES AND CHALLENGES

By Eugene Giller, Frank Azzolino, and Tom Davidson

The development of 3D solid modeling over the last three decades has facilitated the development of 3D printing, also called additive manufacturing (AM), to replace traditional subtractive and molding manufacturing processes for prototyping. 3D printing has become an integral part of the product development process. This technology has drastically reduced prototyping costs and development time. 3D printing enables engineers and designers to have a physical, and often fully functional, mechanical prototype a few hours after completion of the design. 3D printing also vastly improves the development process by enabling rapid design iterations.

Recently, 3D printers have found multiple applications in the manufacture of customized products. For example, almost all in-the-ear hearing aids and invisible orthodonture are produced using 3D printers.

In this article we look at the direction of 3D printing technology and specific applications that will benefit the U.S. Intelligence Community.

Major 3D Printing Technologies

Additive manufacturing processes create 3D patterns identical to the model generated with CAD software by printing one layer at a time. The current commercial technologies used in additive manufacturing can be divided into two categories.

Reactive Material Technologies

The first group of technologies uses reactive materials cured by various energy sources in order to create the desired physical shape. The oldest and most commonly used method is Stereolithography (SLA), in which UV-visible lasers cure light-sensitive resin (photopolymer). The laser traces a cross-section of the model, causing instant solidification of the liquid photopolymer. Next, a platform supporting the part descends into a vat of resin to deposit additional uncured photopolymer on the platform (Figure 1). The process continues layer by layer until the part is complete.

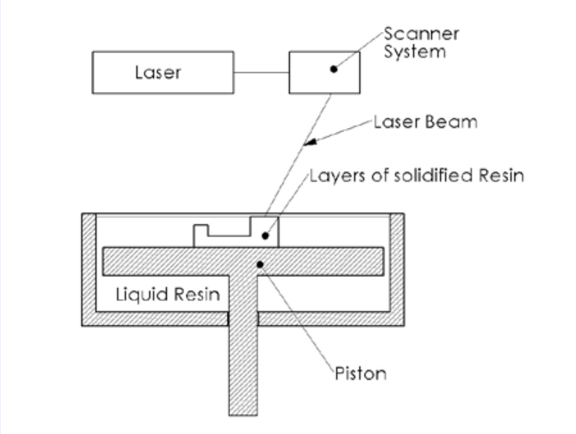


Figure 1 | Schematic of the SLA process

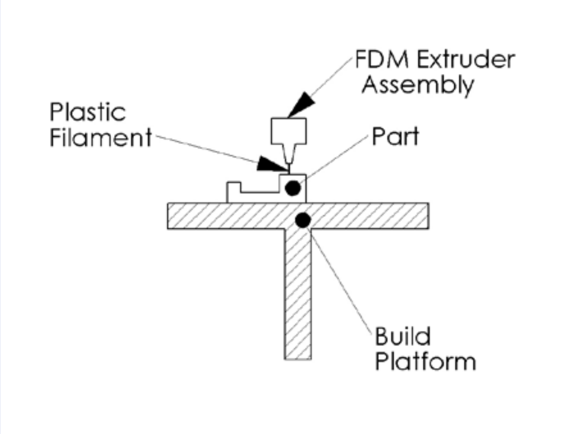


Figure 2 | Schematic of the FDM process

Completed parts must be cleaned with solvent to remove hazardous unreacted material. A support structure is necessary in this process and is created from the same resin material. The support structure is removed using mechanical means after the part is complete, which can damage the finished part.

Digital Light Processing (DLP) Lithography is a process similar to SLA, except a DLP projector is used to cure each layer of photopolymer. While DLP reduces build time compared to SLA, the acrylate-based material set used in DLP is more susceptible to shrinkage than the hybrid epoxy-acrylate resins used in the SLA process.

In another process, liquid photopolymer is jetted through a piezoelectric print head. At the same time, water soluble support material jets from a second print head. Each layer is solidified by exposure to UV light. After the entire build is printed the support structure is removed in a water bath. Parts with variable physical properties can be produced by depositing different materials through separate print heads. However, the heat distortion temperature is extremely low (33-46°C) and the parts produced by this method age quickly and lose their properties within a few weeks.

Fused Material Technologies

Fused Deposition Modeling (FDM) is the most widely used additive process, accounting for 38 percent of installed AM units. In the FDM process, thermoplastic filament passes through an extruder nozzle and solidifies after contact with the cold part or the build platform (Figure 2). Parts are built in a layer-by-layer fashion. The surface finish for an FDM part is relatively poor, and the part quality depends on the diameter of the filament and extrusion temperature. FDM requires a support structure and its removal affects the surface quality of the parts. FDM works only with hard plastics and is not capable of joining dissimilar materials.

Selective Laser Sintering (SLS) uses high energy lasers to sinter powdered polymeric materials or metals. In this process, powder from a feed canister is spread by a roller over the build platform. SLS uses powder with a particle size of 50-150 microns. Next, a laser scans the layer, sintering and solidifying particulate matter. Fresh powder is spread over the previous layer and the process is repeated until the entire part is constructed (Figure 3).

The main advantage of SLS is that support structures are not necessary. Another advantage is a relatively high feature resolution of 0.6 mm and minimum wall thickness of 1.5 mm. However, SLS machines are quite expensive and can operate only in industrial environments due to highly controlled process parameters.

The newest technology, in fact the only new 3D printing technology of the past 15 years, combines FDM with piezoelectric printing (Figure 4). This process, developed by File2Part, can produce accurate, full color parts with excellent surface finish. File2Part's technology makes support structure removal easy. Furthermore, the technology allows the user to produce parts with different material properties (hardness, flexibility, surface finish) at different locations within one part.

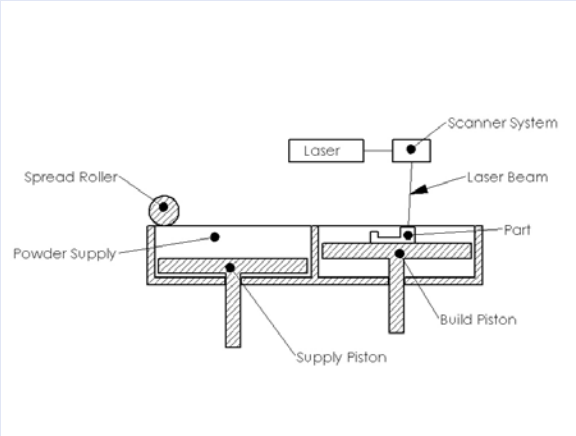


Figure 3 | Schematic of the SLS process

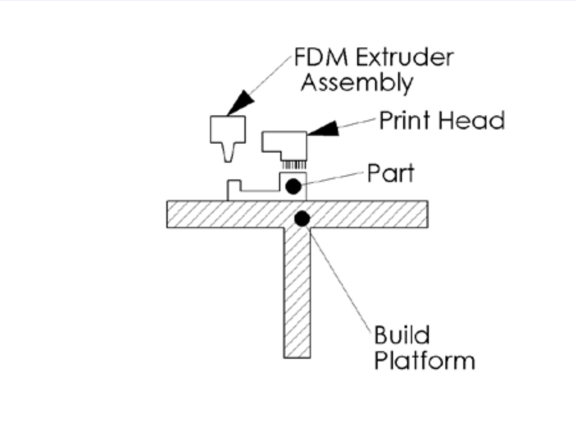


Figure 4 | Schematic of the File2Part process

Markets and Technology Challenges for 3D Printing

In the next several years we foresee continued expansion into industrial, manufacturing, and engineering segments. The largest consumers of printers priced over $5,000 will be service bureaus and manufacturing companies. Significant growth is also expected in the hobbyist market through smaller, cheaper, less capable products leveraging online and community distribution. Despite obvious advantages such as accuracy, the ability to create complex geometries that cannot be produced by other techniques, and the relatively low cost of customized objects, current 3D printing technology does not provide all of the functionality necessary to penetrate the mass market. These shortcomings include limited material selection, limited quality of printed objects, 'ease-of-use,' and safety of the materials and processes. Solving these problems must become a major industry focus. Unfortunately, due to recent consolidation in the industry, expiration of key patents, and low barriers to entry for new and often inexperienced players, the major trend is cutting costs for new models of 3D printing equipment based on existing technology. Lower costs are achieved by sacrificing quality, capability, reliability, and safety.

Demand Creation and Ease-of-Use

Market expansion of 3D printers requires the existence of and access to a large and diverse population of 'things to print.' There were two primary drivers in the creation of 'things to print' in the explosion of 2D printing at home. The first was wide-scale adoption of the PC and software applications that allowed consumers to easily create documents that were printable: word processing, spreadsheets, and presentation graphics. Microsoft Office and similar software products allowed consumers to create documents that needed to be printed. The second was digital photography, which created a seemingly infinite collection of 'things to print'.

The availability and ease of use of new CAD products intended for the masses (e.g., Autodesk 123D and SketchUp, as opposed to products from SolidWorks, Pro/Engineer and Catia targeted at the engineering and manufacturing world) will allow users to create models of three-dimensional 'things to print'. The universe of 'things to print' will be increased as commercial companies and online communities offer models for download, either free or for purchase. The ability to reproduce existing objects by scanning or using "photograph to 3D model" software will also increase the available 'things to print'. These can be spare parts, toys, and novelty items, or other small items appropriate for home printing.

The ability to understand and print model attributes such as color, material, hardness, surface finish, and texture maps (for example, a high resolution photo on the exterior of a part) add additional requirements to the 3D printer driver. File2Part's printer software supports all of these features.

Quality and Characteristics of Printed Objects

Today's consumers have high expectations for 2D printing quality as characterized by high resolution

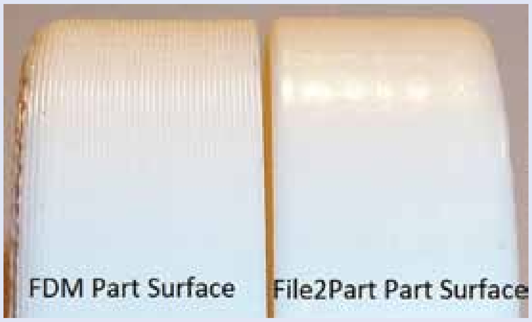


Figure 5 | Comparison of surface finish in parts produced during the same build

color photography. They will quickly extend their expectations to 3D printing. The quality of the printed part must approach the quality of traditional manufacturing methods. Even an inexperienced user will distinguish 3D printed parts from parts produced by traditional methods. Due to the layered manufacturing process, each vertical surface is represented by a lattice structure artifact.

This artifact is often removed by post-processing such as sanding, tumbling parts in drums filled with abrasives, or by solvent vapor smoothing. All of these techniques require a high degree of user interaction, investment in additional equipment, and may restrict use to industrial environments. File2Part has developed a proprietary process to produce plastic parts with surface finish that resembles injection molded parts without post-processing (Figure 5).

The market will not fully accept 3D printing until printers support multiple materials with physical properties that allow them to print a wide variety of items. Unfortunately, most of the existing 3D printers use only one material. Recently commercialized, Objet's PolyJet Matrix™ technology can produce a combination of soft and hard materials in the same part. However, these parts have low thermal stability, low tear strength, and are prone to rapid aging.

Safety

The single most important requirement for the adoption of 3D printing by the mass market is safety. The industry has enjoyed significant leeway on material safety issues in comparison to other industries. This is related to the low penetration of the consumer market because the vast majority of equipment is used in industrial environments and prototypes often do not leave the lab.

As the 3D printer journeys toward the home and retail markets, it will cease to be an industrial device. Rather, it will be a home appliance. All build materials (polymers) and specialty agents (chemicals) must be child-safe and home-safe. All plastics must be food grade and fully cured (no free radicals) at the completion of the build. Inks and other agents must be non-hazardous and disposable as standard household waste. Operation of the device, including maintenance and changing cartridges, must be without vapors, persistent odors, or leakage. The technology File2Part is developing is the only one which meets all these requirements.

Specific Applications of 3D Printing for the U.S. Intelligence Community

The previous discussion relates to the general application of 3D printing. The combination of 3D printing with other technologies allows the creation of unique products. We will discuss a few applications that may address the needs of the U.S. Intelligence Community.

Embedded 3D Electronics

Existing technology allows printing of a variety of conductive materials on plastics with resolution down to 30 microns. Combining this process with 3D printing enables production of antennas, sensors and other electronic components embedded in the polymeric artifact. By combining piezoelectric printing with FDM extrusion technology, File2Part has developed a 3D printing process capable of producing 3D electronics.

Security Features

The ability of 3D printers to produce multi-layer articles can significantly enhance the strength of security features. Each 3D printed artifact can have an individualized electromagnetic or optical sensor signature. In addition, it will be possible to create non-reproducible holographic patterns.

Anti-Tampering Features

Unlike conventional manufacturing, 3D printing can produce any shape. For example, it is relatively easy to completely embed or encapsulate any object. This means that no one will be able to reach inside without breaking the object.

Conclusions

The evolution of 3D printing technology is at an exciting juncture. The introduction into and adoption by the mass market of 3D printing will be driven by demand for the production of highly customized products in low volumes. This demand will increase the volume of 3D printers, which will drive costs and prices down to levels appropriate for mass consumers. Meeting this demand will require advancements and inventions that are not currently available or commercialized.

New 3D printing technology being developed by File2Part will add critical capabilities essential for meeting the high expectations of the consumer market while vastly improving the safety of the materials used. These new capabilities will allow smaller and specialty markets to be addressed. We have identified a few of these specialty applications which may be of interest to the U.S. Intelligence Community and we believe our technology is uniquely situated to address these and other applications. Q

Eugene Giller *has extensive experience in developing new technologies, materials, and applications for Rapid Prototyping, electronics, and optics. Prior to founding File2Part, Inc. he worked for Z Corporation developing new inkjet technology-based approaches for Rapid Manufacturing and Rapid Prototyping. Previously Eugene developed and commercialized a number of formulations used in the electrical and electronic industries. Head-mounted displays produced with materials and processes developed by Eugene were successfully tested by the U.S. Army on the battlefield and also helped people with low vision syndrome. Eugene holds MS degrees in Chemistry from University of Manitoba and Chemical Engineering from Moscow's Academy of Fine Chemical Technology.*

Frank Azzolino *has had an accomplished career as an executive in software, engineering, manufacturing, and CAD industries. He has held CEO and board-level positions at a number of "concept–to-company" startups, with successful exits including board member at T-Splines, EVP of Agile Software (acquired by Oracle), CEO of Eigner PLM (acquired by Agile Software), CEO at NetSuite (acquired by Visionael), VP and GM at PTC (~10 years), and previous engineering experience at General Dynamics and the U.S. Navy (civilian). Frank holds a BSCE in Structural Engineering from Tufts University as well as an MBA from Babson College Franklin W. Olin Graduate School of Business.*

Tom Davidson *has launched more than two dozen successful products in several industries over the course of his career. He has 21 years of experience developing and launching 2D and 3D printers at leading companies in the industry, including Hewlett-Packard and Z Corporation. During that time he has lead several successful multi-disciplinary teams of various sizes. He holds eight important patents in the field of 3D printing with seven more applied for but not yet issued. The team he led at Z Corporation was responsible for more than two dozen patents in the field and developed the technology on all of Z Corporation's current products. Tom obtained his BS in Mechanical Engineering from Rensselaer Polytechnic Institute and his MS (Honors) from Kansas University.*

REFERENCES

[1] T. Wohlers. "Additive Manufacturing. State of the industry." Wohlers Associates, 2011.

[2] David L. Bourell, Ming C. Leu, David W. Rosen. "Roadmap for Additive Manufacturing. Identifying the Future of Freeform Processing" The University of Texas, 2009.

[3] PEI, E., CAMPBELL, R.I. and DE BEER, D.J., 2011. Entry level RP machines: how well can they cope with geometric complexity? Assembly Automation, 31 (2), pp. 153 – 160.

[4] Hiller J., Lipson H., (2008) "Tunable Digital Material Properties for 3D Voxel Printers," Proceedings of the 19th Solid Freeform Fabrication Symposium, Austin TX, Aug 2008.

[5] Philip Reeves, "Applications of Rapid Manufacturing." Professional Engineering, v.22, Number 1, 2009.

[6] Hiller, J., Lipson, H. (2009) "STL 2.0: A Proposal for a Universal Multi-Material Additive Manufacturing File Format" Solid Freeform Fabrication Symposium (SFF'09), Aug 3-5 2009, Austin, TX, USA.

[7] W. Eberhardt, T. Gerhäußer, M. Giousouf, H. Kück, R. Mohr. D. Warkentin: Innovative concept for the fabrication of micromechanical sensor and actuator devices using selectively metalized polymers; Sensors and Actuators A 97-98 (2002), 473-477.

[7] Marinov V. and Y. Atanasov. "Improved Direct Write Technology for High Frequency Interconnects on Flexible Substrates." Proceedings of IMAPS 2006, 39th International Symposium on Microelectronics, San Diego, California, October 8-12, 2006.

REVOLUTIONIZING DESIGN: Crowdsourcing the Fast, Adaptable, Next-Generation Ground Vehicle

By LTC Nathan Wiedenman

At DARPA, we say that *to innovate, we must make* and *to protect, we must produce*. The importance of our nation's ability to make things is known by every American worker all the way to the highest levels of government. President Barack Obama, while addressing this topic at Carnegie Mellon University last year, stated, "The concept of advanced manufacturing is not complicated. It means how we do things better, faster, cheaper to design and manufacture superior products that allow us to compete all over the world."

Because of the importance of a robust manufacturing capability to both our economic security and our national defense, DARPA embarked upon a five-year, $1 billion investment in advanced manufacturing initiatives beginning in 2009 (a portfolio of programs called Adaptive Vehicle Make (AVM), discussed in detail later in this article, represents the largest piece of this investment). In domain after domain, it is taking increasingly longer to develop products essential to the warfighter, limiting our ability to adapt to the rapidly changing threat environment. We firmly believe that *controlling for time* is the key to adaptability, enabling adaptation to new geopolitical realities, facilitating the rapid insertion of new technologies, and invigorating innovation. To that end, we have set the goal of dramatically shortening development timelines in a variety of product domains by raising the level of abstraction in the design process, decoupling design and fabrication, and utilizing foundry-style manufacturing. Our nation has already successfully applied this paradigm to making everything from pharmaceuticals and vaccines, to synthetic biology, to optics and sensors.

Few would disagree that it would be beneficial if we could also extend this paradigm to the development of complex defense systems. It currently takes too long and costs too much money to bring a new system online, whether it is a fighter jet, a ship, or a ground vehicle. Worse yet, many programs end up being cancelled due to excessive cost overruns before they produce anything at all. This is of little use to the warfighter.

The single biggest factor driving the rapid increase in cost has been schedule growth, and the principal cause of schedule growth is increasing complexity. Military aerospace systems, for example, have sustained an increase of approximately three to four orders of magnitude in complexity over the past half century. Consequently, their development timelines have grown from an average of three to four years to 12 to 15 years. Next-generation systems will have one to two additional orders of magnitude in complexity growth, and development timelines could potentially reach two decades. Norm Augustine, in his "Final Law of Economic Disarmament," plots aircraft unit costs versus time since the advent of aviation. Projecting this into the future, his trend suggests that by the year 2054, the entire U.S. defense budget will purchase just one aircraft. These trends are clearly unsustainable.

AVM's explicit goal is to develop a complex defense system — specifically an amphibious infantry fighting vehicle — using a foundry-style manufacturing approach, while compressing the development timeline by at least a factor of five. At the same time, we want democratize the design process, allowing many more people to participate in the development of a complex defense system than have ever been able to do so before. If we can give people access to the tools they need to participate, we could potentially allow thousands of new innovators to contribute to the design process. This could allow new, revolutionary ideas to bubble to the surface, which we would never have been aware of otherwise.

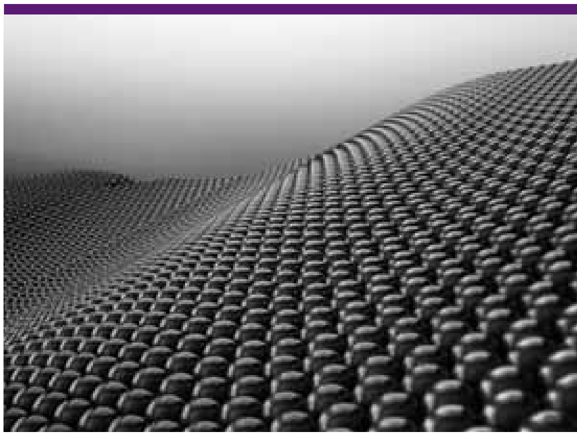
The first step is to reduce one of the biggest barriers to entry for individual innovators and small companies alike: the significant capital requirements of a traditional fabrication facility to support integration, prototyping, testing, and the resulting design iteration. Currently, only the large companies that design defense systems have this capability; eliminating the need for it holds the promise of moving the defense industry from dozens of innovators to perhaps thousands or even tens of thousands. If we essentially decouple design and manufacturing by giving individuals or teams of innovators access to design tools that would enable designs to be correct by construction, we could eliminate the need for expensive prototyping and allow more people to participate than ever before.

To further open the aperture for innovation, DARPA has embarked upon several recent crowdsourcing experiments, including Foldit and last year's Experimental Crowd-derived Combat-support Vehicle (XC2V). Foldit is an online game that challenges users to solve the incredibly complex problem of protein folding. How proteins fold is a computationally intense (in some cases intractable) problem. It turns out that some players without any formal training in biopharmacology turned out to be very good at folding proteins. Through the Foldit crowdsourcing challenge, we reached out to a larger pool of people who previously didn't have access — or didn't even know they had a specific expertise — and gave them an opportunity they would not have otherwise had.

DARPA's crowdsourcing experiments have also focused on solving problems more closely related to the development of complex defense systems. Last year, we conducted a more defense-focused crowdsourcing experiment, the Experimental Crowd-derived Combat-support Vehicle (XC2V) Design Challenge. This was a competition offered to a social network of automotive enthusiasts for the best design of a vehicle body for combat reconnaissance, combat resupply, and evacuation missions. The social network was equipped with a simple collaboration environment that enabled designers to receive feedback from the crowd and leverage each other's ideas and concepts. The contest yielded more than 150 viable designs in a span of six weeks, of which several dozen were deemed innovative by experts from the user community. The XC2V experiment demonstrated the applicability of crowdsourcing techniques to the design of military systems, the potential for significant timeline compression, and the value of heterogeneity in the innovation talent pool.

These are exactly the problems we're addressing within AVM. The portfolio is made up of three research components — META, iFAB, and VehicleFORGE — which provide the three pillars of foundry-style infrastructure — design tools, reconfigurable fabrication, and a collaboration infrastructure. These will be tested at scale in a series of three increasingly complex prize-based design challenges that will result in the design of the Fast, Adaptable, Next-Generation Ground Vehicle, or FANG. The winning ground vehicle design will be manufactured and evaluated against the Marine Corps' Amphibious Combat Vehicle (ACV) prototype in side-by-side operational testing.

Let's look at each of the programs within the AVM portfolio, beginning with META.



If we can give people access to the tools they need to participate, we could potentially allow thousands of new innovators to contribute to the design process. This could allow new, revolutionary ideas to bubble to the surface.

META is all about creating design tools and a design environment that allows us to develop complex systems that are correct by construction. That is, the first time we build it, the system is a production model, not a prototype. META is developing an approach for formal semantic integration across existing domain-specific modeling languages, a set of design tools and metrics for performing design trade-space exploration, and a set of verification tools. These tools will be embodied in an open source research tool chain, an easy-to-use web-based tool with access to cloud-based, high-performance computing capabilities aimed at a mass market, and a high-end tool suite based on state-of-the-art commercial product lifecycle management capabilities. The META environment, once complete, promises to:

- Raise the level of abstraction so that the designer doesn't need to manipulate the design at the lowest numbered part level, but rather can operate at varying levels of abstraction and model fidelity;
- Develop practical and observable metrics of complexity to augment size, weight, power, and performance in informing design decisions;
- Enable rapid exploration of the design trade-space for high-fidelity requirements trade-offs;
- Yield detailed system designs that are "correct-by-construction," meaning they are probabilistically verified for consistency, multi-mode interactions, and first-order performance characteristics across all the relevant physics domains, including embedded software; and
- Provide portable design representations usable by a foundry-style digitally programmable manufacturing facility.

Once a design is developed and verified, iFAB, which stands for Instant Foundry Adaptive through Bits, will take the design and turn it into a physical object. It will take the formal META design representation and automatically configure a digitally programmable manufacturing facility, including the selection of participating manufacturing facilities and equipment, the sequencing of the product flow and production steps, and the generation of CNC machine instruction sets, as well as human instructions and training modules. Essentially, iFAB seeks to eliminate the learning curve in large-scale manufacturing in quantities of one.

Though we term iFAB a "foundry" — mostly to differentiate it from a conventional factory that, at least in the defense world, tends to be a custom facility tailored to produce thousands of one specific product — in actuality iFAB is mostly an information architecture. Only the final assembly capability needs to be co-located under a single roof in anything resembling a conventional factory; the rest of iFAB can be geographically distributed and can extend across corporate and industrial boundaries, united only by a common model architecture and certain rules of behavior and business practices. For AVM, the final assembly node for the FANG vehicle will be at the Joint Manufacturing and Technology Center at the Rock Island Arsenal in Illinois.

The substantial time advantage which stands to be gained from META and iFAB relies on the existence of detailed models of components, of the environment, and of manufacturing equipment and processes. This requires significantly more information than exists in most present-day component models, which are typically little more than performance curves and interface specifications. For the purpose of the FANG vehicle, DARPA has embarked upon the construction of model libraries through sponsored research, and in the long run we envision the development of an industry consortium to promote and incentivize model development.

The third and final research component within AVM, VehicleFORGE, is an open source collaboration environment to enable crowdsourcing of military vehicle designs. VehicleFORGE is structured much like open source software collaboration (or "forge") sites such as *sourceforge.net*. Such collaboration approaches, however, have not been previously applied to the design of physical systems due to the impossibility of change propagation across design elements and the challenge of rapidly predicting the impact of design changes on performance.

META, iFAB, and VehicleFORGE will be tested at scale in the FANG challenges, which are set to kick off in early 2013. The first challenge will focus on mobility and drivetrain subsystems, and will feature a $1 million prize for the winning design. The second challenge, scheduled to take place in late 2013, will focus on chassis and survivability subsystems and will also feature a $1 million prize. The third challenge, with a prize of $2 million for the winning team, will feature a full vehicle design and will take place in 2014.

The use of prize challenges is DARPA's attempt to move closer to a make-before-buy paradigm for the procurement of defense systems, as well as to open the aperture to nontraditional offerors such as loosely-aggregated networks of businesses or individuals. In the interest of providing a significant incentive beyond the modest prize award to the design community, the ACV program will incorporate the winning vehicle in its selection of an ACV design for full-rate production.

The success of AVM will mean the possibility of revolutionary changes to the way we design and build complex defense systems of all types. However, this success ultimately depends upon the participation of innovative individuals and companies who may have never considered participating in a military project before. The potential payoff for our country is clear: decreased costs, increased innovation, and delivery of new technologies to the warfighter when they need them, which ultimately saves lives. We invite you to join us as we transform the paradigm for the development of our nation's defense systems for the next generation and beyond. Q

Lieutenant Colonel Nathan S. Wiedenman *is currently assigned as a Program Manager in the Tactical Technology Office of the Defense Advanced Research Projects Agency. He is serving as the Program Manager for the Adaptive Vehicle Make (AVM) portfolio programs. LTC Wiedenman received his commission in 1993 as a second lieutenant in Armor following graduation from Harvey Mudd College, where he earned a Bachelor's degree in Engineering. He earned a Master's degree in Mechanical Engineering from the University of California at Berkeley, and a doctorate in Mechanical Engineering from MIT. His military education includes Airborne School, the Armor Officer Basic and Advanced Courses, the Acquisition Basic Course, and Command and General Staff College. LTC Wiedenman can be reached at nathan.wiedenman@darpa.mil.*

BARE CONDUCTIVE AND THE MAKER MOVEMENT: A PATH TO INNOVATION

By Matt Johnson

Bare Conductive Ltd. is a London-based startup producing a unique electrically conductive paint that can be used to turn almost any surface into a point of electronic interaction. Bare is riding at the brow of a growing wave known as the "Maker Movement" (also referred to as the "Maker Community"). This movement consists of a global network of hobbyists, enthusiasts, engineers, designers, and students working on projects, rapidly sharing ideas, and fermenting fundamental innovations. Within this dynamic community, projects are turning into products and companies are being born upon the foundation of an open and global R&D platform.

The term Maker Movement was coined for its cross-disciplinary participants ("Makers"). A recent study conducted by *Make Magazine* and Intel found that Makers use on average four terms to describe themselves, with "hobbyist," "tinkerer," "engineer," and "builder" at the top of the list. Makers range from students to NASA scientists, all with a desire to pass on their enthusiasm and experience.[1]

Makers work with a wide array of hardware and place the highest value on the collaborative mentality of their community.[2] As Bre Pettis, chief executive of MakerBot said, "If you're not sharing your designs you're doing it wrong."[3] Collaboration is nurtured through print publications like *Make Magazine,* influential websites like instructables.com, and social media services such as Twitter. All provide a solid foundation for quantifiable innovation. Nowhere are these inventions more tangible than at a series of annual events known as Maker Faires.

In May 2012, the four inventors of Bare Conductive flew from London to set up a stand at the Bay Area Maker Faire, a two-day event organized by *Make Magazine*.

The company found itself placed between Atmel processors, a HAM radio club, and an LED-lit lounge. From student projects to high-level corporate innovation, every imaginable technology was on display for a rapidly growing audience. The 2012 Bay Area Maker Faire attendance unquestionably eclipsed the 2011 audience of 100,000. Every year there are three major Maker Faires in the U.S. and more than 50 "Mini Maker Faires" at other locations around the world, giving participants a chance to trade ideas, sell their products, and catalyze collaboration.

Many Makers use these faires as an opportunity to sell their ideas. This entrepreneurial spirit is seeing significant success. Over 200,000 Arduino boards were sold by an Italian company of the same name in 2011.[4] Startups like Makey-Makey present their products to the public, helping to raise over $500,000, eclipsing the company's $25,000 goal on kickstarter.com.[5] At the 2011 New York Maker Faire, MakerBot dominated the 3D printer village with its popular machines, fresh off the back of a $10 million round of fundraising.[6] Makers are identifying and approaching sizeable markets, but it is clear that large firms see the value in this community as well.

Since its first event in 2006, the Maker Faire has involved an increasing number of corporate sponsors who are beginning to recognize the community's potential for producing innovations, as Dale Dougherty, co-founder of Maker Faire and *Make Magazine,* described in 2011.[7] "Makers can play in niches that big firms ignore — though they are watching the Maker Movement and will borrow ideas from it."[8]

The presence of Intel, Microsoft, and General Electric at the 2012 Bay Area Maker Faire was proof that even Fortune 500 companies see the value in the Maker Movement.[9] The juxtaposition of individual entrepreneurs and large firms all occupying the same space suggests that everyone can find value in this diverse group.

A few years ago it would have been easy to dismiss this movement as just a group of enthusiasts, but they have grown into a global community that is full of technological and entrepreneurial opportunity. Prolific use of the Internet makes it possible for Makers to collaborate and inspire each other across continents. Companies like Bare Conductive have grown from within it, developing products based on direct feedback from customers, while also keeping an eye towards focusing these innovations into specific application areas outside of the Maker Community.

Bare Conductive in the Maker Community

Founded as the result of a student project, Bare Conductive was born into the nascent Maker Movement of 2009. The community was just beginning to gain momentum, but it was clear that there was a solid foundation upon which to build a business. With seed funding secured, Bare was ready to produce a proof of concept. As had been demonstrated with a few products before, the Maker Community presented a route to cash flow as well as an opportunity to get instant feedback about new ideas. Two years in, Bare is still finding this to be true. The Maker Community gives the ability to quickly translate ideas into products, and provides the cash flow to pursue more sophisticated applications that otherwise may not have been immediately released.

Bare Conductive and its inventors are rooted deep within the Maker Community, relying on the community as a customer base as well as an open R&D platform. Bare currently sells a range of products built around its electrically conductive paint. The material can be applied to a variety of surfaces to form an electrical circuit and presents a radically tangible way to interact with electronics.

Figure 1 | Bare Conductive's electrically conductive paint, Bare Paint

Figure 2 | A workshop using Bare Paint to create light-up greeting cards

The scope of applications is wide, from painting a circuit onto a piece of paper, prototyping a circuit board, printing interactive posters, or using it to teach the fundamentals of electronics. The size and diversity of the community compels Bare to speak to a breadth of skills and interests. This diversity is the major opportunity for any company working within the Maker Community. From its foundation, Bare has worked to make the most of this unique environment.

As with most companies operating within the Maker Community, the primary connection to Bare's customers has been through the company's website. Bareconductive.com acts as a platform to test new ideas, share users' work, and keep interested parties up to date on new developments. The website is split into three sections: products for sale (testing), work produced internally (sharing), and work produced by our user community (collaboration). Like many Maker sites, Bare is heavily interlinked with other Maker sites and benefits from coverage on the hubs of the Maker Community like makezine.com, hackaday.com, or instructables.com.

Thanks to initial seed funding and an enthusiastic community of users, Bare has had a strong foundation upon which to build a company. Now Bare is ready to look beyond the borders of the Maker Community with a set of ideas originally developed by users, which have been refined, focused, and protected.

Beyond the Maker Community

Bare's work beyond the Maker Community has focused on the idea that its materials can create ubiquitous and often discrete interactions. Any surface can become a sensor, any document can have an electrical signature, and any object can become a conduit for information. Thanks to its roots in the Maker Community, Bare presents a unique mix of design-led thinking underlain by a technical capability. This mixture allows the company to envision and quickly capitalize on applications that may reveal an unexpected opportunity. One such example is the use of the paint as a capacitance sensor.

Capacitance sensing is certainly not new, but the nature of Bare's materials reveals the ability to imagine applications that might otherwise not be appropriate for capacitive technology. In 2011 Bare decided to follow the model of other successful Makers in producing a series of video tutorials explaining the various ways to use the products. These tutorials have been extremely popular and have been a very effective way to generate new ideas and feedback from the user community. The most popular tutorial was (and still is) a video explaining how the paint could be applied to a surface and used to detect proximity or touch. Users quickly adopted this simple setup and began applying it to their own work, creating interfaces on a variety of surfaces to control light, movement, and sound.

While fostering a thriving community of projects, Bare saw that the ability to detect a person from a distance could have a range of significant applications. Recognizing this potential, Bare has refined these ideas (both conceptually and technically), exploring the large-scale implications this application might have. Bare has focused these ideas by developing proprietary hardware that enables accurate, reliable, and comprehensive proximity or touch detection. Reaching back into the Maker Community for components, insights, and manufacturing, Bare has been able to develop and produce complete prototypes in record time.

Thanks to internal hardware development, coverage generated from users' projects, and the subsequent interest of third party firms, Bare has decided to approach a few focused markets, including security and product packaging. The company has also worked to explore the potential of a sensing technology that is discreet, applicable to a wide range of scenarios, and technically flexible. One example is large-scale capacitive sensing that allows the system to generate a map of a three-dimensional space, indicating the presence and location of a person. The first public display of this work will be at GovSec 2013, where Bare will be demonstrating a sensing prototype that promises to revolutionize area sensing. The nature of the material combined with propriety hardware gives a wholly unique way of mapping a space and tracking those within it.

Though the technology showcased at GovSec 2013 will look unlike anything that Bare has done before in the Maker Community, it is in fact all intimately connected. The system that will be presented at GovSec 2013 stands as a testament to the way in which new technology and ideas can be born from a community of users, matured into a business, and then can survive the rigors of the market to spawn even further innovations. The future is bright for both Bare Conductive and the Maker Community. Bare is growing quickly and will be seeking expansion capital soon, and there are more Makers than ever. The pace of innovation is clearly accelerating. Some Makers will stay as Makers and some projects will always be projects, but when we look back in 20 years we will undoubtedly find many Makers who became business leaders and even more projects that became world-changing innovations.

Figure 3 | An interactive invitation using screen-printed Bare Paint as a capacitive sensor. Touching the various images triggers and modulates sounds.

__Matt Johnson__ founded Bare Conductive with three colleagues after earning a dual Master's in Industrial Design Engineering from The Royal College of Art and Imperial College in London, UK. Matt is active in the Maker Community and is currently leading Bare Conductive's technical research into areas such as capacitive sensing, product packaging, and security.

REFERENCES

[1] *Make Magazine.* "Maker Market Study: An In-depth Profile of Makers at the Forefront of Hardware Innovation." Survey. May 2012.
[2] According to a recent study conducted by Make Magazine and Intel, more Makers are involved in projects using hardware than any other category listed. Other categories included electronics, fun projects, building, gardening, and learning/discovery (not a complete list).
[3] "More Than Just Digital Quilting." *The Economist.* 3 December 2011.
[4] A popular reprogrammable component known as a microcontroller. www.arduino.cc
[5] http://www.kickstarter.com/projects/joylabs/makey-makey-an-invention-kit-for-everyone
[6] http://www.makerbot.com/blog/2011/08/23/all-star-lineup-invests-in-makerbot/
[7] The first Maker Faire was held in San Mateo, California with only 100 Makers in attendance.
[8] "More Than Just Digital Quilting." *The Economist.* 3 December 2011.
[9] http://money.cnn.com/magazines/fortune/fortune500/2012/full_list/

THE MAKER REVOLUTION: DE OPPRESSO LIBER

By Mark Hatch

Innovation just went asymmetrical, and it's a good thing...mostly.

As a former Green Beret, I know that asymmetry challenges organizations and institutions in ways that require preparation, thought, strategy, and action. As the CEO and co-founder of TechShop, I've discovered that the same principles apply to the challenges that come from innovation asymmetry.

Imagine a world where anyone with $100 and access to materials could make anything they wanted. Better yet, don't imagine it. TechShop has made this a reality.

TechShop is a hackerspace on steroids. Each TechShop is 15,000 to 20,000 square feet of space filled with all of the tools needed to make anything imaginable. Bill Ford, Chairman of Ford Motor Company, recently described TechShop as the place where Henry Ford "probably would have started," if it had existed in his day.[1] TechShop has tools for working with metals, plastics, electronics, wood, and textiles. An array of equipment including mills, lathes, ovens, scopes, laser cutters, 3D printers, water-jets (which can cut through five inches of steel, granite, glass, or ceramic), computers, and software are all available to TechShop's members for the cost of a membership and a class on how to use the machine. With memberships starting at around $100 per month and classes starting at $50, TechShop has thousands of members spread across its five locations. Using TechShop, some members have already changed the world in tangible ways. For instance, Square, the company that developed the device that turns smartphones into credit card readers, now has a $3.25 billion valuation.[2] TechShop's industrial and government partners include Autodesk, Ford, DARPA, the Veterans Administration, and General Electric.

TechShop democratizes access to the tools of the industrial revolution for the first time in history. The result: The rise of irregular armies of innovators.

Tools: Cheap, Powerful, and Easy to Use

What once required enormous amounts of capital is now available for the cost of a morning cappuccino. More than $1 million in hardware and software are available for use at each TechShop location. Setting up this type of operation might have cost $5 to $10 million just a couple of decades ago, if the technologies were available at all.

TechShop purchases CNC mills for around $20,000 and lathes with digital readouts for well under $8,000. These are the tools of the industrial revolution. They became too expensive for skilled labor to own back in the 1700s and were moved out of workshops and onto manufacturing floors. For 250 years, these tools have almost exclusively been available to companies, universities, and government organizations. Revolutions were fought over access to these tools.

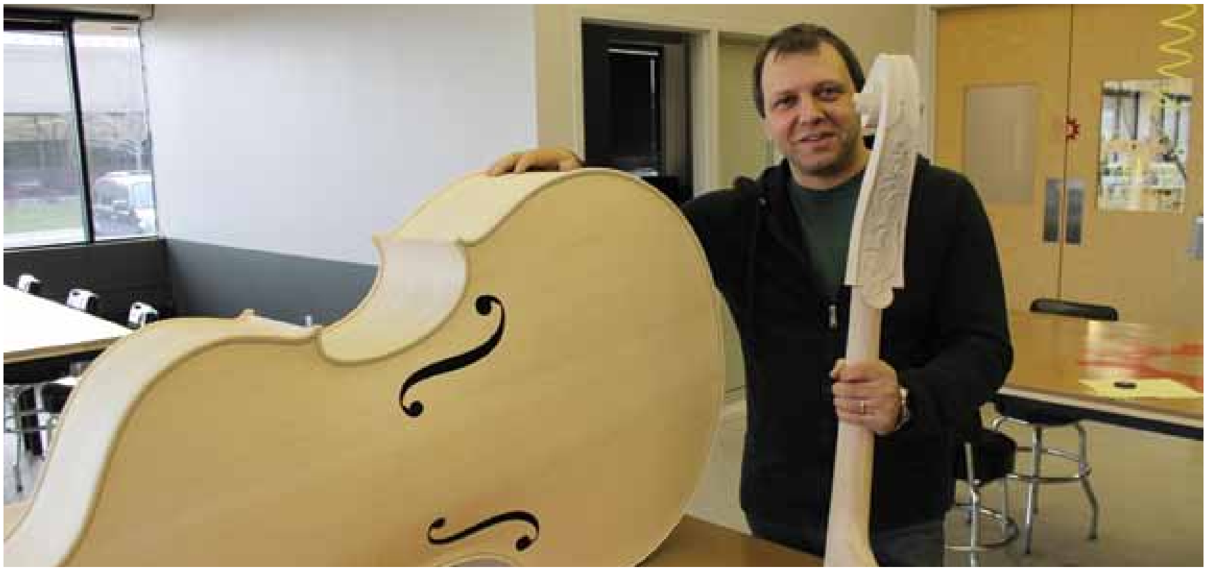
Clearly, cheap access to tools is only one part of the story. These tools are also more powerful and easier to use than ever before. One of TechShop's partners, Autodesk, provides a software tool set for product design that would have made design engineers weep just a decade ago. TechShop trains novices on how to use this software in ever-shortening training sessions as Autodesk continues to make it easier to use. The company recently launched a free consumer product with the same code base as the professional alternative. This enables children to play around with three-dimensional parametric models on their parents' iPads.[3] Autodesk is also leveraging Cloud computing to run massively complex computational algorithms in parallel, thus enabling a consumer to scan a 3D object with a cell phone camera and upload it for modeling. TechShop can then take those models and print, mill, or cut them out. One can't produce Earl Grey tea yet, but some bright irregular is likely going to start working on that problem soon. They are already working on automatic burrito[4] and hamburger robots.[5]

One does not need to learn how to code in the esoteric "g-code" or dedicate months or years to become a master of a mill. TechShop will train users to mill something useful this month, if not this week — or even today.

Democratization

Consider how writers would feel if at the end of each workday they had to return every pencil and pen to the proverbial tool chest, lock up all of their paper, and turn off their computers. And imagine these "tools of production" were so expensive that they didn't have access to them at home. Every day they would ply their trade, but only on the projects their institution chose. At 5 p.m. each day they would be told to leave the premises and, because of the costs associated with their chosen trade, they could not write until the next morning. Few independent freelance writers would exist. Literary innovation would be the exclusive territory of companies, government, and educational institutions. What a sad world it would be. I dare say revolutions would be fought over the mere threat of that world developing.

Yet, almost no one owns his or her own CNC mill or lathe. Revolutions *were* fought over this fact. Capitalism won out. Self-determination, the invisible hand, and financial markets turn out to be better



market organizing mechanisms than central planning. But the skilled professionals still lost personal, direct access to their tools.

The TechShop mission is to help drive global innovation by putting a TechShop in every community in the U.S. and across the world. We figure if we don't, someone else will.

Radical Innovation from Irregulars

Often when the Maker Movement is discussed, and when TechShop in particular is discussed, there is push back. Hobbies are fun and interesting, but the tools TechShop provides aren't rare, so surely no "real" innovations could come out of a lab equipped like that or from a movement of pro-ams. Right?

Wrong.

Irregular armies can become a big threat overnight. IBM and Emerson had never heard of TechShop members Phillip Hughes and Robert Lipp's company Clustered Systems until their $20,000 investment beat everyone (including IBM) in a head-to-head competition designed by the U.S. Department of Energy to find out which data cooling system was most efficient. These large corporations were upended by a small irregular army after $20,000 and two years at TechShop. Emerson now licenses the Clustered Systems technology.

No one in the financial industry would ever have imagined a glass blower building a financial transaction-processing platform using a dongle on an iPhone. The glass blower, Jim McKelvey, built his company in less than three years (with his former intern, Jack Dorsey, just as improbably, the co-founder of Twitter). McKelvey and Dorsey's company, Square, is now running at an annualized rate of $6 billion in transactions while opening up the merchant banking system to anyone with a bank account and a smartphone.[6] Visa, American Express, and MasterCard were all upended by Square, a prototype originally developed at TechShop.

Here is a short list of other standout technologies developed within the walls of TechShop over the last few years:

- The world's fastest electric motorcycle (Lightening Motors)
- The world's cheapest drip irrigation system (DripTech)
- The world's first GPS-enabled fertilizer detection system (Solum)
- A phase changing polymer-based baby blanket designed to save premature infants from death (Embrace)
- A DNA sequencer
- A functional jet pack
- The world's first desktop diamond manufacturing device
- Brain probes
- Homemade electric cars, motorcycles, bicycles, and one two-wheeled, self-balancing, electric barstool
- Scuba rebreathers
- Open source, remote controlled, underwater vehicle platform

- Dozens of crowd-funded startups (Kickstarter, Indiegogo)
- X Prize lunar lander
- Nanosat
- Lunar mining robots
- Remote controlled, video conference, tele-presence, ambulatory robot
- Infrared animal warming device
- An iPad case company that counts President Barack Obama among its customers

As of Q2 2012, TechShop has 4,000 members and is growing at about 100 percent each year. TechShop's members come from a wide range of backgrounds and from every field. What they have in common is a desire to make things. Routinely, people are seen working on projects for their institutions. Places like NASA, SRI, Xerox PARC, Ford, Stanford, and Mercedes-Benz have TechShop members. All of these institutions have better R&D facilities than TechShop, but their facilities are not open access. One doesn't need permission, a business plan, or even relevant domain knowledge to work at TechShop. One doesn't have to work in R&D or manufacturing or have a relevant degree. TechShop doesn't require three bids or a boss or committee's approval. All that's required is an idea, motivation, and $100.

TechShop is arming an unlikely band of irregulars with the tools they need to change the world for the better. Eric von Hippel's book, *Democratizing Innovation,* shows that over 60 percent of successful innovations come from outside of the organization.[7] The Kauffman Foundation recently showed that all the real growth in an economy came from small firms.[8] Imagine what will happen when the world regains access to the tools of the industrial revolution. Q

***Mark Hatch** is the CEO and co-founder of TechShop. He is a former Green Beret and has held executive positions focused on innovation, disruptive technology, and entrepreneurship at large and small firms, including Avery Dennison, Kinko's, and Health Net. A leader in the Maker and Open Innovation Movements, Mark holds an MBA from the Drucker Center at the Claremont Graduate University and a BA in Economics from the University of California at Irvine.*

REFERENCES

[1] http://www.youtube.com/watch?v=2dyMCrnsQKk Minute 1:11:12. "Driving Innovation: Detroit Comes to Silicon Valley – An Evening with Bill Ford.

[2] http://in.reuters.com/article/2012/07/25/us-square-venture-idINBRE86O01O20120725 Sarah McBride and Gerry Shih, Square wins new backer at $3.25 billion valuation: source.

[3] http://www.businesswire.com/news/home/20120509005648/en/Autodesk-123D-Catch-iPad-Turns-Photos-3D, Autodesk 123D Catch for iPad Turns your Photos Into 3D Models.

[4] http://inhabitat.com/marko-manriquez's-burritob0t-is-a-3d-burrito-printer-that-explores-our-fascination-with-fast-food/, Marko Manriquez' Buritob0t is a 3D Burrito Printer That Explores Our Fascination With Fast Food.

[5] http://food-management.com/news-amp-trends/will-burger-making-robot-change-food-service-industry, "Will This Making Robot Change the Food Service Industry?" *Food Management,* May 4 2012.

[6] http://tech.fortune.cnn.com/2012/07/09/dorsey-square-death-cash/, "The death of cash" by Miguel Helft. July 9, 2012.

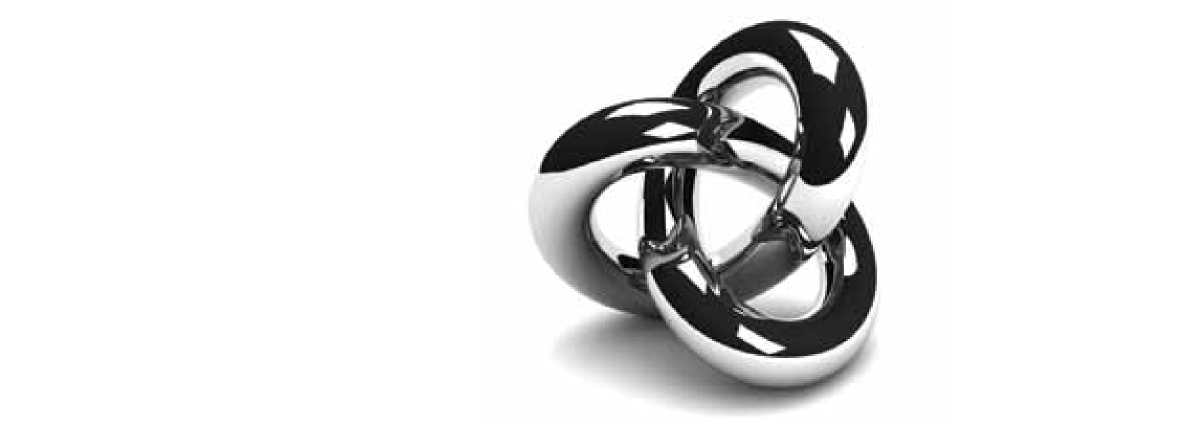
[7] http://www.people.hbs.edu/cbaldwin/DR2/BHVRODEOKayakHBSWPv2.pdf, "How User Innovation Commercial Products: A Theoretical Investigation and Case Study." Carliss Baldwin, Christoph Hienerth, Eric von Hippel. March 2006.

[8] http://www.kauffman.org/uploadedfiles/high-growth-firms-study.pdf, "High-Growth Firms and the Future of the American Economy." Dane Stangler. Ewing Marion Kauffman Foundation. March 2010. Page 5.

THE RISE OF CREATIVE COMMERCE

How 3D Printing and the Maker Movement are Bringing About the Next Industrial Revolution

By Carine Carmy



Online retail is experiencing double-digit growth in the United States, with potential to become a $300 billion market by 2015.[1] However, we shouldn't expect the continued proliferation of click and buy culture. Unlike the passive connotations associated with consumer society, the future of e-commerce in the United States will be creative, collaborative, and revolutionary. 3D printing is transforming the way we make, buy, and sell just about anything from cottage industry products to electronics.[2]

3D printing has been around for decades, used for rapid prototyping in commercial settings such as airplane parts and architectural models. Within the last several years, the technology has been democratized such that individuals of all technical backgrounds can turn their ideas into physical products. Shapeways.com, the leading 3D printing marketplace and community, has been driving down costs of 3D printing and increasing access to cutting edge materials.[3] As such, the typical barriers to entry for product design and development are withering away. The result? Everyone can be a creator.

Yin and Yang: Mass Manufacturing and Mass Customization

Most products we buy online or in stores are made with mass manufacturing. The typical product development lifecycle goes something like this: large corporations identify a market need. Typically, they conduct extensive market research in order to isolate the need, the target market, the types of solutions that could address that need, and the dollar amount an individual consumer would spend to solve their need. A budget is created that takes the consumer value at point of sale and backtracks how much can be spent on manufacturing.

Enter the designer, who is given a set of parameters: develop a product that directly addresses the market need, will be culturally relevant within the target market, and fits the cost criteria. Once a set of products is developed, those are vetted and tested with focus groups, refined through prototyping, and the winner is sent off for mass manufacturing. In order to meet the economies of scale, a minimum of 10,000 products are made, though usually the runs surpass 100,000 or a million. The products are finally brought to market using complex distribution networks. They arrive at stores and, fingers crossed, they end up in the hands of happy customers.

The product is destined to be a "hit," using Chris Anderson's nomenclature from *The Long Tail*.[4] It caters to the lowest common denominator and has seemingly broad appeal. The winners sell out of stock, and the losers collect dust on store shelves and warehouses until they meet their next fate.

Traditional manufacturing is a slow, inefficient process. It can take a year in a best-case scenario, and it's fraught with complexity and costs that hinder many ideas from being realized.

One popular alternative to mass manufacturing is the return to an artisanal culture in which things are made by hand. With roots in the Maker Movement and popularized by platforms like Etsy, millions of people are choosing to buy products that are handmade and local. By way of example, over three million handmade products were sold on Etsy in March 2012 alone, accounting for $62.8 million of goods.[5] Handmade has its limits, naturally, particularly for those trying to scale their businesses.

With 3D printing on the market and available to the masses, Makers can tap into the ethos of handmade (local, green, custom) with far more efficiency and a much smaller toolbox — namely, a computer. You can make one unique product, thousands of that product, or a template for unique products, in which individuals without traditional making skills manipulate several parameters and hence become involved in the product development process.

3D printing starts with the individual and the product unravels from their unique needs. It enables mass customization, or the ability for anyone to make a product that suits his or her individual needs. Compared to mass manufacturing and making things by hand, the process is relatively simple: come up with an idea, develop a 3D design using CAD software (or hire a designer to help), send the product for 3D printing in the material of your choosing, and hold it in

Figure 1 | Octocup by Shapeways designer Cunicode

your hands. Using Shapeways, individuals can also make their products available for sale on-demand, which enables infinite inventory and zero capital costs aside from sweat equity. Shapeways currently has over 6,000 independent designers selling their work on Shapeways.com.

The contrast is stark. The time it takes to go from idea to product is as little as one day, as one Shapeways designer proved by designing and producing 30 cups in 30 days.[6] He wanted to test whether you could reduce the time it takes to go from idea to market in 24 hours. Shapeways had recently launched 3D printed food-safe ceramics at the time, so he used the new material for his experiment. He successfully designed 30 cups in 30 days, almost all of which pass the tests of gravity and can be ordered by customers all over the world.

The startup costs are minimal, namely time to design or funds to pay a designer. Colleen Jordan, a recent university graduate based in Atlanta, Georgia, is

Figure 2 | Wearable planter by Shapeways designer Colleen Jordan

Figure 3 | Bicycle Cufflinks by Shapeways designer GothamSmith

supporting herself by making wearable planters on demand using Shapeways.[7] She has customers all over the world who are buying these planters as necklaces and bike accessories; what started as a twist on her senior thesis has blossomed into a full-fledged business.

The risk is near zero as well, as individuals no longer have to concern themselves with market viability before the product is on the market — they can have the market prove demand and produce inventory accordingly. Products are made to order on demand, extending just-in-time manufacturing into real-time. If the idea is a success, an individual can have a hefty passive income that shows up in their PayPal account in the morning, and if it's a failure, the only loss is time. As Shapeways community member GothamSmith explained, bringing a product to market costs less than a few bad dates.[8]

Everyone is a Creator

With low startup costs and negligible risk, the only barrier to entry is imagination. What has happened to many other forms of art and "creation" (e.g., blogging, music, video) as a result of digital media is now happening to product design. Shapeways is democratizing access to the tools of creation — from ideation through manufacturing through sales — and as a result, we're seeing the rise of "creative commerce" (c-commerce), or the shift from a two-sided marketplace (buy and sell) to a dynamic Makerplace (create, buy, and sell).[9] The growing Maker Movement[10] and the trend toward participatory design[11] were early signs of the shift to creative commerce enabled by 3D printing. Crowdsourcing of designs is already quite common, and there are lightweight customization platforms that allow consumers to give t-shirts or sports gear a personalized design, for example, using platforms like Threadless, CafePress, and NikeID. Some of the most successful products of the past decade used community insights to drive product innovation, such as the revival of LEGO Mindstorms.[12]

When Etsy closed its latest round of funding, Doreen Lorenzo, President of Frog Innovation, wrote, "It's easy to see that many consumers are increasingly seeing themselves as creators, too...But it's not just about simple crowdsourcing for ideas by asking people to suggesting how to improve or create products via online brainstorming sites, as was the rage in the mid-2000s. Today, consumers want to participate in forming and promoting their concepts in a very personal way, with themselves in the spotlight."[13]

Custom does not have to be couture. 3D printing enables you to make something — on demand — that fits your needs exactly. And unlike the days of couture, the costs and quality of making one thing "just right" rival products that you can buy off the shelf. Mineways helped users of the popular game Minecraft convert their in-game models into 3D printed products.[14] Shapeways partnered with SoundCloud, the social sound platform, to help people turn their favorite sound into a custom iPhone case.[15] A college-aged Shapeways user printed his custom wedding ring on Shapeways for under $100.[16]

Figure 4 | The Vibe by Shapeways, an iPhone case you can fully customize with your favorite sound from SoundCloud

Creative commerce has existed for some time in a host of offline capacities — custom tailoring, craft workshops, farm-to-table. Its rise, however, is fueled by a combination of timely factors: open source, the accessibility of 3D printing, and the increasing connectedness of the Internet and the ease with which you can find your niche. Because of Shapeways and 3D printing, anyone can come up with and make unique products on demand.

What's Next?

Shapeways started by focusing its efforts on supporting 3D modelers; today, the tools are that much better, so that anyone can be involved in creating the objects that populate their lives, whether it's a custom gift or a tool for their hobby. For the modelers, the design freedom the technology offers is exponential. For years, designers have been trained to think within the limits of "technically possible," with the rules set by mass manufacturing. CEO and co-founder of Shapeways Peter Weijmarshausen notes:

"What's happening with the democratization of production is game changing. With this at your fingertips, the world is a different place. Having access to this kind of technology will change the way products are consumed and developed. Think of the fact that you can mix materials on an almost molecular level. Next, you'll be able to create new materials that we've never had before. You can mix strong and soft materials. You can engineer how a product will break if you put too much stress on it. Mix electronics into it, and we'll see things you can't even imagine now...With 3D printing you can get feedback and improve design after producing just one object. Your minimum run is one. So products can evolve much quicker. Mix this with the opening up of design — what open source did for software, 3D printing can do for product design. I don't know what we're going to create, but it will be amazing."[17]

As the tools for creation improve and the materials for 3D printing increase in scope and quality, more and more people of all technical backgrounds will be involved in the creative process of defining the objects that populate their lives. If the burgeoning Shapeways community is a microcosm for what's to come, we can expect a very different future for manufacturing, design, and creativity. Q

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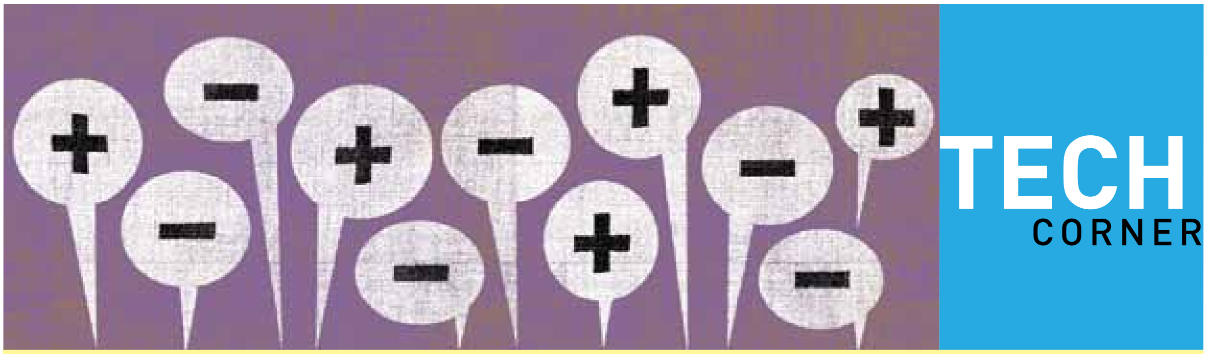
REFERENCES

[1] http://www.forrester.com/US+Online+Retail+Forecast+2010+To+2015/fulltext/-/E-RES58596?objectid=RES58596
[2] http://www.economist.com/node/21559593
[3] http://bits.blogs.nytimes.com/2012/06/19/shapeways-prints-1-million-objects-anda-secures-more-funding/
[4] The Long Tail
[5] http://www.etsy.com/blog/news/2012/etsy-statistics-march-2012-weather-report/
[6] http://cunicode.com/one-coffee-cup-a-day/
[7] http://www.wearableplanter.com/
[8] http://money.cnn.com/video/technology/2011/10/20/t-ts-shapeways.cnnmoney/
[9] http://www.forbes.com/sites/techonomy/2012/06/11/the-next-wave-of-e-commerce-innovation/
[10] http://www.forbes.com/sites/tjmccue/2011/10/26/moving-the-economy-the-future-of-the-maker-movement/
[11] http://www.ted.com/talks/tim_brown_urges_designers_to_think_big.html
[12] http://mindstorms.lego.com/en-us/Default.aspx
[13] http://tech.fortune.cnn.com/2012/05/10/etsy/?iid=HP_LN
[14] http://www.shapeways.com/blog/archives/1149-Mineways-3D-Print-your-Minecraft-Model.html
[15] http://www.businessweek.com/articles/2012-03-10/turn-your-babys-cry-into-an-iphone-case
[16] http://www.shapeways.com/blog/archives/1310-True-love-3D-printing-your-wedding-ring.html
[17] http://www.forbes.com/sites/techonomy/2011/10/10/mass-production-for-the-masses-shapeways-ceo-peter-weijmarshausen-on-the-rise-of-personal-manufacturing/2/



To supplement the ***IQT Quarterly***'s focus on technology trends, *Tech Corner* provides a practitioner's point of view of a current challenge in the field and insight into an effective response.

Reshaping Energy Storage for Portable Electronics

A technology overview from IQT portfolio company Imprint Energy

Abstract

The demand for functionality in portable electronic devices is continuously growing, as is the desire to expand design freedom. Manufacturers are challenged with building smaller, thinner, and lighter devices that are also more powerful. There is also growing interest in devices that could conform to the human body and other curved surfaces and that withstand bending and flexing. This article discusses how currently available batteries are limiting the form and function of portable electronics and introduces Imprint Energy's breakthrough Zinc Poly™ battery technology, which utilizes innovative electrochemistry and print-based manufacturing to enable energy dense, thin, and flexible batteries. Zinc Poly batteries combine the energy density and rechargeability of lithium technologies with the cost, stability, and environmental benefits of zinc-based batteries to enhance existing portable electronic devices and enable new devices.

Introduction

The number and diversity of electronic products powered by batteries has required commercial batteries to evolve into a wide range of shapes and sizes. Commercial batteries, however, have been unable to break out of their rigid mold principally due to processing and packaging constraints. Since batteries are often among the largest components in electronic products, their lack of flexibility is a fundamental limitation on device flexibility.

Most commercial battery chemistries require significant amounts of packaging, commonly in the form of hard metal or plastic shells, to control safety risks and maintain performance. Zinc alkaline cells, for example, use a corrosive aqueous electrolyte that is hazardous and that must be kept from leaking or evaporating in order for the battery to function. Lithium-based batteries are well-known for their environmental sensitivity: even trace amounts of moisture will poison the battery, causing rapid degradation. In cells with flammable solvents, this can result in fire or explosion.

There has been some progress in alleviating battery packaging constraints over the last few decades. Breakthroughs in lithium-ion solid electrolytes have resulted in a new class of batteries that have enabled portable electronics to be lighter, more compact, and more pervasive. Lithium polymer (LiPo) batteries replace liquid electrolytes with a solid polymer, enabling them to be packaged in metallic foils ("pouch cells") instead of rigid canisters. The use of pouch cell packaging significantly reduces the volume of the battery dedicated to non-energy-storing packaging and increases the overall volumetric energy density. LiPo batteries, however, are still subject to significant materials sensitivity and safety constraints. The pouch cell packaging must be impermeable to air or water and often requires double encapsulation to ensure the package is not ruptured. This packaging requirement causes a significant drop in energy storage capacity as cells are miniaturized below the size of a smartphone battery (approximately 10 cm^3). For these smaller batteries, the packaging overwhelms the active material volume, causing a sharp decline in volumetric energy density (see Figure 1). Similar declines are seen in other rechargeable battery chemistries, such as nickel-metal hydride (NiMH).

There has also been significant recent work with thin-film lithium ion technology, which can produce cells less than 500 microns thick using semiconductor processing techniques. These are predominantly based on sputtered lithium films that were developed at Oak Ridge National Laboratory. However, these cells suffer from limited energy storage densities, high production costs, and limited flexibility, which can restrict their application to small devices.

Imprint Energy's Zinc Poly Battery Technology

Imprint Energy is reshaping the battery landscape with its proprietary rechargeable battery technology, Zinc Poly. This materials system uses zinc and manganese oxide electrodes that sandwich a high conductivity polymer electrolyte and enable the production of thin, flexible, rechargeable batteries that offer a significant volumetric energy density advantage over other rechargeable battery chemistries. Zinc Poly batteries are inherently safe and can be manufactured at low cost in thin and custom sizes.

Zinc Poly is a compelling materials system due to its inherent safety (zinc and manganese can be found in household vitamins), high capacity, low cost, earth abundance, and considerable North American materials reserves. Imprint Energy's solid polymer electrolyte works through Zn multivalent ion transport and storage and removes longstanding limitations on the rechargeability of zinc batteries through suppression of dendrite formation. This energy storage mechanism is analogous to what is exploited in lithium-ion batteries, but with higher charge transport per ion and less reactive materials. As such, the Zinc Poly chemistry provides a more stable, higher storage capacity materials system that is easier to process and requires less packaging to be used safely.

Imprint Energy is developing its Zinc Poly technology for small portable electronics applications in the consumer space, as well as for military applications. Target areas include compact wireless devices, wearable electronics, health and fitness monitoring, and medical devices. These applications need power supplies that are small, lightweight, energy dense, safe, and cost-effective. Additionally, designers are looking for an energy storage solution that offers customizability, thinness, and flexibility for next-generation products.

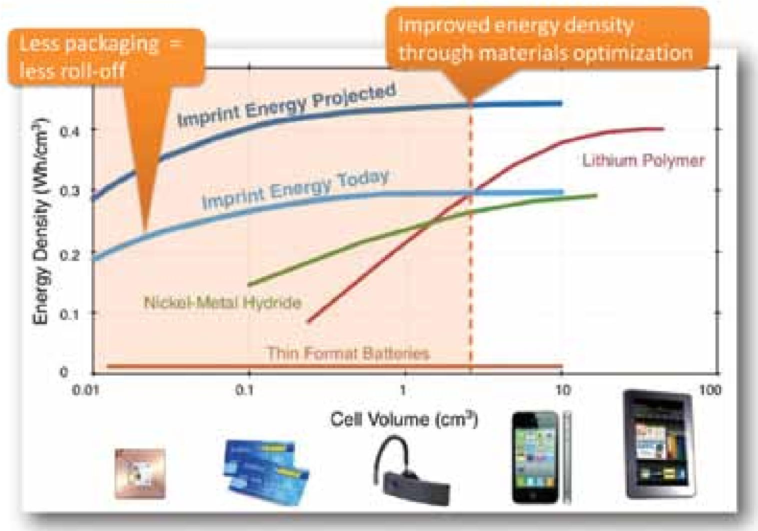


Figure 1 | Plot of volumetric energy density (Wh/cm^3) versus battery cell volume (cm^3) for leading rechargeable battery alternatives

Challenge

To deliver effective, high volumetric energy capacity batteries in rugged, thin, flexible, and customizable form factors for portable electronics, the Zinc Poly technology must deliver on key performance and processing capabilities:

- Volumetric energy densities on par with lithium polymer battery technologies that scale to thin form factors without losing their effective capacity density (to thicknesses less than 400 microns and cell sizes less than 1 cm^3 in total volume)
- Good discharge capability across a wide temperature range with low leakage and high charge retention times
- Performance retention under cycled bending
- Producible at low cost in custom shapes and form factors to enable new space-efficient product designs

Performance

At a volume of less than 5 cm^3 (from portable electronic accessories to printed electronics), there is an overwhelming need for energy dense batteries that can be manufactured in compact and volume-efficient formats. Based on laboratory performance data, Zinc Poly can provide over 0.25 Wh/cm^3 and is projected to exceed that, increasing the market opportunities for Imprint Energy batteries.

Manufacturing

All components of a Zinc Poly battery can be processed as ink, much like acrylic paint, and additively patterned

Figure 2 | A highly flexible, air stable, printed Zinc Poly battery cell

using the same print equipment used for t-shirts and art. This low-cost solution-based processing method is made possible because all of the materials in the Zinc Poly technology can be handled and processed in air. This means that Imprint Energy can leverage the unique abilities of print manufacturing to provide repeatable, high volume output, and low setup and unit production costs. Battery production can be scaled by printing and coating from digitally designed battery shapes, in low or high volume runs, using low-cost, sheet-based, roll-to-roll processing.

Furthermore, by using a process that is substrate-agnostic and additive, batteries can be deposited on a variety of unconventional materials such as paper, plastic, fabric, and glass. Imprint Energy is unique in that it can leverage the inherent versatility of printing to integrate its batteries into devices using a variety of strategies — from providing customers with traditional modules, to selling easily-integrated batteries that can adhere to a surface via an adhesive, to printing a battery directly onto a device surface. Printing also affords cost-effective customization of battery architectures for tailored voltage and capacity output by stacking multiple battery cells or printing custom connections of battery "pixels" in an array. Imprint Energy is able to leverage commercial printing processes that are inherently versatile and the abundant know-how of the domestic printing industry.

Applications

For a large number of portable electronic devices, Imprint Energy's Zinc Poly batteries will provide the following benefits:

- Store more energy in smaller spaces
- Reduce battery thickness and increase flexibility
- Fit application needs with customizable batteries
- Safer, more stable, earth-abundant materials

Imprint Energy will initially target customers whose products could be enabled or significantly enhanced by the use of Zinc Poly battery technology. Customers in the emerging area of printed electronics and micropower devices — including smartcards, sensor cards and labels, active RFID, and cosmetics and pharmaceutical delivery — offer an attractive starting point. Customer needs in this market are not being met by currently available batteries. At the same time, the performance requirements for many of these products in terms of energy storage capacity are less demanding than in larger devices.

Success in the lower capacity applications, combined with scaling of the process technology, will enable Imprint Energy to access its target market of mid-level capacity batteries (less than 1 Wh) for small portable electronics. In this market segment, Imprint Energy will capitalize on the volumetric storage capacity advantage of its batteries over LiPo batteries. The application areas that are serviceable in this range include small wireless devices (e.g., hands-free kits, Bluetooth devices, etc.), wearable electronics (e.g., Nike+ FuelBand, adidas miCoach, and Jawbone Up fitness monitors), toys and games, portable robotics, and wearable medical devices (e.g., Qualcomm Life, Medtronic). These applications can additionally benefit from other advantages of Zinc Poly batteries, including thinness and flexibility, ease of customization, inherent stability, safety, and an approximately 50 percent cost reduction versus lithium-based batteries. Q

Imprint Energy*, an IQT portfolio company, develops low-cost, printable zinc-based polymer battery chemistry for thin, flexible, rechargeable batteries. To learn more, visit www.imprintenergy.com.*

IN THE NEWS

The *IQT Quarterly* examines trends and advances in technology. IQT has made a number of investments in manufacturing and advanced materials technologies, and several companies in the IQT portfolio are garnering attention for their unique solutions.

MedShape

IQT portfolio company MedShape has developed a range of medical devices using novel shape-changing materials. The devices utilize shape-memory alloys and polymers for a variety of orthopedic applications, including reattaching and anchoring connective tissue. MedShape devices are currently approved for a number of common surgeries, including ligament repair in the knee and ankle. The company recently received additional federal grants to expand its device capability. MedShape is headquartered in Atlanta, GA and has been part of the IQT portfolio since September 2010.
www.medshape.com

Semprius

Semprius designs and manufactures solar energy technologies that leverage a micro-transfer printing process to achieve excellent performance at a low cost. These high-concentration photovoltaic (HCPV) modules set a new world record for efficiency in 2012, reaching 33.9 percent. Semprius technology is currently used by a number of utility providers, as well as corporations and government groups. The company was recently named one of MIT's top 10 most important emerging technologies. Semprius joined the IQT portfolio in March 2009 and is headquartered in Durham, NC.
www.semprius.com

QD Vision

QD Vision is a leader in developing quantum dot technology to build a new generation of lighting and displays. QD Vision's technology platform incorporates light-emitting nanocrystals to enhance the appearance of LED-based products, including television and computer screens. Quantum dot technology is quickly gaining traction in the display market thanks to improved visual performance and the promise of low-cost, easy to manufacture hardware. QD Vision is headquartered in Watertown, MA, and has been part of the IQT portfolio since March 2008. **www.qdvision.com**

Cambrios

Cambrios is an IQT portfolio company working in the nanotechnology space to develop transparent conductive materials. The company's flagship product, ClearOhm, is a wet-processable conductive film that contains transparent electrodes for touchscreen and liquid crystal displays. Cambrios recently received a strategic investment from Samsung Ventures to further develop its technology. IQT initially invested in Cambrios in December 2004. The company is headquartered in Sunnyvale, CA.
www.cambrios.com

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