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Beyond 3D Printing: The New Dimensions of Additive Fabrication

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Additive fabrication, often referred to as 3D printing, is the construction of objects by adding material. This stands in contrast to subtractive methods, which involve removing material by means of milling or cutting. Although additive fabrication and 3D printing are thought of as synonymous, additive fabrication encompasses a far broader range of construction, and new dimensions are on the horizon, inspiring innovation across scales and applications. For instance, can you print a full-scale building? How can we structurally engineer color and alter on the nanoscale? If trees grow additively, can biology be designed for fabrication?

What are these new dimensions for 3D printing? How are they defined? The future areas for additive fabrication span along *spatial* (how the material is laid out in space/geometry), *material* (how new materials can be used and integrated with other constituents), and *temporal* (how materials/geometry can change through time) dimensions, and discussions in this chapter along with examples from our research will highlight novel design potentials in these areas.

MIT and the Mediated Matter Group: Previous and Current Additive Fabrication Research

In our lab, the Mediated Matter Group at the MIT Media Lab (led by Dr. Neri), we explore how these new additive dimensions can push the future of design. Our research focuses on digital fabrication and its intersection with biology, both for inspiration and for production. We strongly believe the next revolution lies in digital biology and how to control the processes across scales—both from the top down and from the bottom up. This can range from new material printers, combining manufacturing techniques (for example, 3D printing combined with milling), and looking beyond 3D printing as we currently understand it for the next generation of additive methods for enhanced speed, efficiency, and resolution. My doctoral work on these topics has resulted in one of the world's largest mobile digital construction platforms (with a robotic reach of over 80 feet diametrically), research into some of the smallest 3D printing systems (nanoscale, 2-photon printers), and development of biological fabrication using growth systems of synthetically designed cells.

Using these newly developed techniques, the expanding limits of additive fabrication are beginning to be explored, and the hints at novel approaches for design are becoming apparent. Biology offers a glimpse into the possibilities for the future: in self-propagating algorithms, responsiveness, integration, and material sourcing. Biology can benefit from additive fabrication for generation of custom tools such as novel microfluidics. In addition, we can design biology as the tool itself. As synthetic biology begins to establish itself, we are excited by the new additive potentials for biologically tuned materials, integrated growth structures, and even living products.

The Dimensions of Additive Fabrication

Additive techniques hold the main benefits of shape complexity (internal feature geometry and spatial property distribution), digital control (the ability to repeatedly produce, edit, and tune via a computer), and distributed fabrication (single-machine factories hold the potential for fabrication on-site). However, the three areas often viewed as problematic in 3D printing provide a good analysis framework—with the main focus on the spatial dimension:

Spatial dimension limitations
: Can printed objects scale to construction scales and nanometer scales?

Material dimension issues
: Will printed objects accommodate multifunctional material properties?

Temporal considerations

How can additive fabrication techniques scale in responsiveness, speed, and sourcing?

Through the exploration of these additive fabrication dimensions, the current benefits and problems surrounding 3D printing will be viewed in a design light. In addition, these directions in additive research will detail the fascinating design potential for users, both new and current. From printing buildings, to making nanoscale machines on your desk, to growing the next synthetically designed biological products—the future is looking strong for additive techniques.

SPATIAL DIMENSIONS

In the past decade, the field of additive manufacturing, specifically 3D printing, has grown significantly in industry usage, technological developments, and consumer popularity. Although the first patents for 3D printing date back to the early 1980s,[1] increases in computer-aided design (CAD) software, availability of lower-cost fabrication systems, and new material options have recently spurred the field into new applications.

However, 3D printing has been limited to a small product footprint, with the typical 3D print volume limited to under a few cubic feet. This size limitation is due to the difficulty of making a large machine function at scale, printing time (small objects often take up to a day to print), and material considerations (cure mechanisms and stability). However, this dimension limitation is not permanent. Both on the macro and micro level, new additive techniques are poised to disrupt existing industrial techniques for construction and micromechanical fabrication through novel features, material integration, and customizability.

Macro-scale dimension

Since Henry Ford's automobile assembly line, inventors and futurists have proposed different ways to automate large-scale construction techniques. Residential construction is a challenging task to automate due to its considerable scale, one-off designs, and varying environmental conditions and requirements. The first significant attempt occurred in

1 Hull, C. Apparatus for production of three-dimensional objects by stereolithography. Patent No. 4575330, 1984.

1917 with Thomas Edison's patent on single-pour concrete housing.[2] Edison proposed a novel system by which a large single reusable metal mold could be used to cast concrete houses, including furniture, indoor accessories, and even pianos all made with concrete. However, the prototype molds proved to be far too complex with expensive molds consisting of over 2,300 pieces and the project became a well-documented failure.

Current modern research efforts into large-scale 3D printing have resulted in several projects such as Contour Crafting and 3D Concrete Printing.[3] These projects use direct extrusion of cementitious material using a gantry mechanism (a mechanical framework support system) to move the extruder along to print walls. Even though these projects have successfully printed large objects, full building-scale structures have not yet been achieved, due to several challenges, particularly due to the material limitations of direct concrete extrusion. These limitations, including integration, geometrical restrictions on production (limited to curvature only in the horizontal plane), and layer strength, have garnered significant attention and focus over time, and as a result, the future has become brighter for such large-scale digital fabrication.

Digital construction platform

A new approach we are currently pursuing involves building a mobile digital platform capable of on-site design, sensing, and fabrication of large-scale structures. The system combines a large hydraulic boom arm and a smaller electric robotic arm, as illustrated in Figure 18-1. Through the control of both arms, the system enables digital fabrication processes at architectural scales capable of spanning buildings. As a result, the system, referred to as a Digital Construction Platform (DCP), opens up new opportunities for on-site sensing, design, and fabrication research.

2 Edison. Apparatus for the production of concrete structures. Patent No. 1326854, 1917.

3 Khoshnevis, 2004; Lim, Buswell, Le, Austin, Gibb, & Thorpe, 2012.

Figure 18-1. The Digital Construction Platform comprises a six-axis KUKA robotic arm mounted to a five-axis Altec hydraulic boom arm

The DCP utilizes a mobile system capable of a large physical reach and high load capacity that enables new modes of in situ construction. The platform design was motivated by the need to generate a flexible system capable of implementing various kinds of large-scale digital fabrication approaches including additive, subtractive, and assembly techniques. An extended stationary reach and large hydraulic arm make large load capacities possible; the smaller electric arm affords high degrees of access and accuracy. Furthermore, a mobile system allows for fast setup times and ease of repositioning.

Compared with existing construction platforms, hydraulic boom arms are much more flexible to digitally manipulate from a stationary position. However, these boom arm systems typically lack the precision required for automated fabrication techniques. The DCP is designed around a hydraulic boom arm with an added robotic arm effector for the spatial compensation of temporal oscillations to achieve increased precision and ease of access.

Informed fabrication

The current system we have built utilizes a truck platform, an Altec boom arm, and a KUKA robotic arm to provide a lift capacity of 1,500 lbs (boom-arm mount) with a manipulation capacity of 20 lbs (small arm). The six-axis KUKA robotic arm is mounted on the end of a two-axis hydraulic jib on the three-axis boom arm, as demonstrated in Figure 18-2. The system uses a KUKA arm controlled via a custom Python script package, enabling real-time control via the Robot Sensor Interface (RSI) package.

Figure 18-2. The range of motions for the DCP large (five-axis boom) and small (six-axis KUKA robot) arms are shown through long-exposure photography

With real-time sensing and actuation, new design possibilities can be achieved based on environmental conditions, process data, and material goals. For the DCP, this ability is critical to operation to integrate site conditions into the system. The controls system is designed as a feedback loop based on current data from magnetostrictive sensors, rotary encoders, and inertial measurement units. The coupling of input and output fabrication capabilities of a robotic arm allows for a system capable of producing objects that incorporate environmental data. This use of environmental feedback to directly inform and influence fabrication holds many potential new avenues for design and manufacturing. We use the term *informed fabrication* to refer to this combination of environmental sensing and fabrication (Keating and Oxman, 2012).

To enable the variation of material properties with any castable material while providing enhanced speed, we created a new technique based on formwork (see Figure 18-3). Akin to a mold, formwork makes it possible for any castable material to be poured inside, providing benefits of wide material selection, fast production, and monolithic cast strength. Similar to insulated concrete forms, leave-in-place insulating formwork can be 3D printed for castable structures. By using a fast-curing BASF polyurethane material, layers of foam can be printed into formwork and also provide thermal insulation to the final structure. The process, termed *Print-in-Place construction*, is designed for on-site fabrication of formwork for castable structures, such as concrete exterior walls and civil infrastructure (Keating and Oxman, 2013). The process can also be rapidly integrated into current building strategies and regulations because the Print-in-Place construction method aligns directly with the traditional mold-based insulated concrete form (ICF) technology. After the mold is printed, conventional methods and regulations that apply to ICF construction can also be applied to the Print-in-Place process.

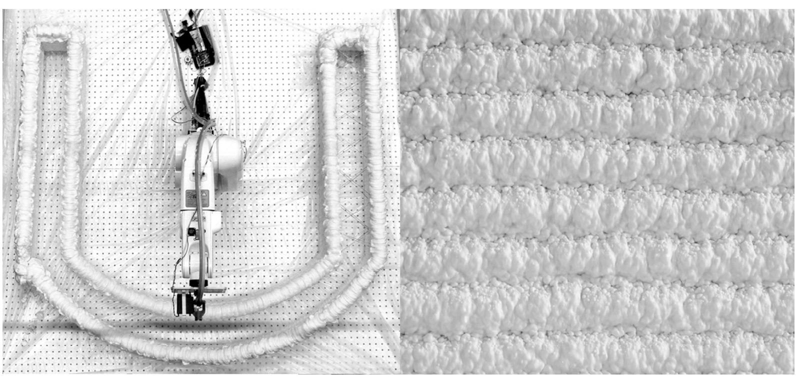

Figure 18-3. Additive fabrication tests using polyurethane spray foam with a KUKA six-axis arm (left) produced test insulative formwork samples with consistent and tunable layer heights (right)

In addition to additive printing, Print-in-Place utilizes secondary milling techniques to improve surface finish and reduce manufacturing time. The resulting resolution from a cast structure inside a printed and milled mold is shown in Figure 18-4. Furthermore, subtractive processes, combined with embedding objects (such as rebar or tie structures) in the printing process, enable creation of complex details such as windows, wiring areas, and embedded sensor integrations.

Figure 18-4. Combining additive and subtractive processes in a compound end effector (right) facilitates fast build times and high resolutions, as seen in the cast structure produced from a printed and milled mold

The proposed method will have comparable energy, strength, and durability benefits over insulated concrete formwork construction. Importantly, it also aims to tackle the safety, design, speed, environmental, energy, and financial issues currently plaguing the residential construction industry.

Benefits of digital construction

A compelling benefit of digital construction is its potential to significantly decrease the number of injuries and deaths in the construction industry by eliminating many of the dangerous and laborious tasks of manufacturing a building. Traditional construction methods are unsafe, slow, labor intensive, costly, and damaging to the environment. According to the United States Bureau of Labor Statistics, 4 out of 100 full-time American workers in 2010 were injured or contracted a work-related illness, and 802 total annual American fatalities were reported. This is the largest number of deaths in any sector, making construction one of the most dangerous professions in the country. The significant decrease in building time and labor proposed here through the use of automated methods is expected to greatly reduce costs and improve safety in an otherwise inefficient and hazardous field.

3D printed buildings would also have structural benefits and could be built more easily than traditional buildings. Although ubiquitous due to their simplicity and low cost, rectilinear buildings are actually weaker and more dangerous due to stress concentrations. Curvature improves structural integrity, but curved shapes are extremely challenging to form using traditional methods. With additive fabrication, creating curved structures is as simple as designing them on a computer, with which architects can create more stable, unique, and versatile structures. Imagine what buildings would look like in the future if the total cost were completely independent of the shape and merely tied to the cost of raw materials. The potential economic impact could range in the billions and all with the ability to digitally back up your house structure, to boot!

Additionally, automation facilitates highly detailed process control, as demonstrated in Figure 18-5—both in building specifications and in scheduling. Parameters such as wall properties and construction time can be controlled and precisely predicted. By removing human error and variation, civil engineering calculations can be much more accurate, allowing for a house to be built to exact structural and thermal specifications. Automation of the building process also eliminates the scheduling difficulties of having multiple contractors on a jobsite at the same time in addition to saving construction time and, consequently, labor costs. Time calculations based on prototype test conditions estimate that the mold for a typical one-story house with 10-foot walls and a perimeter of 170 feet could be printed in approximately 8 hours. Having accurate time prediction is very useful for planning purposes and ensuring a project finishes on time.

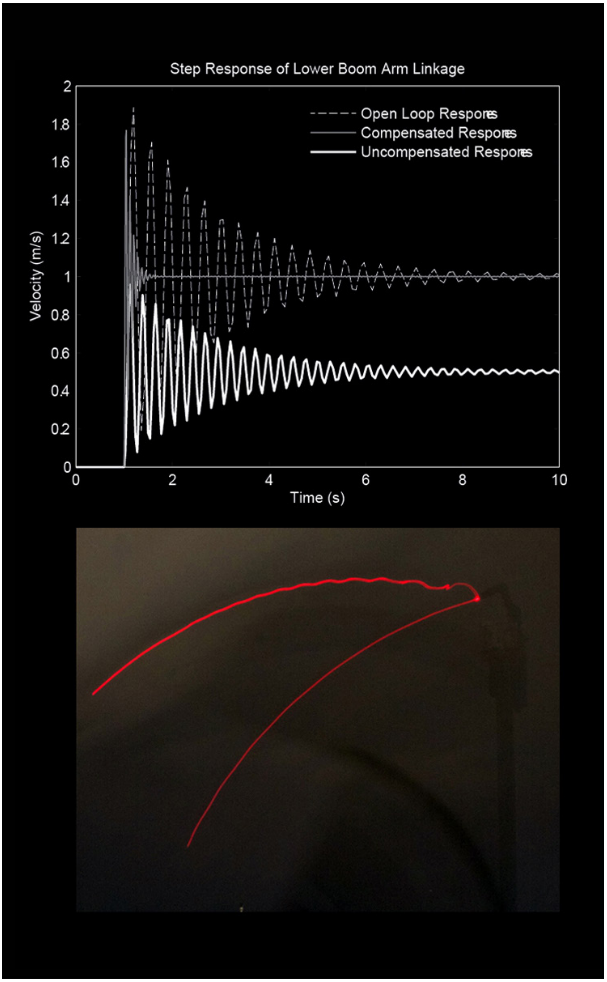

Figure 18-5. The control model (top) for the DCP compensates for robotic arm oscillations (bottom); a simulation of open loop, compensated, and uncompensated response from the control model is demonstrated (top); control model work conducted in collaboration with Nathan Spielberg and Will Bosworth

Future work entails further detailing the mechanical and sensing systems, material testing, and investigations into multiplatform collaboration with swarm construction techniques. Finally, we aim to design and construct a full-scale architectural pavilion using the DCP system in the near future (Figure 18-6). We believe this is a new growth area for 3D printing and look forward to digital fabrication encompassing digital construction.

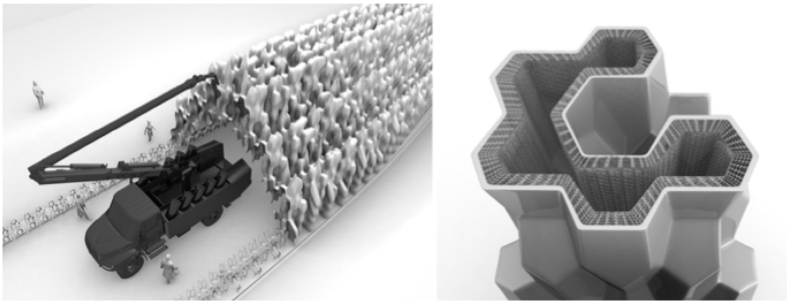

Figure 18-6. Computer renderings of potential uses for the DCP showing on-site fabrication (left) and a sandwich structure for potential future printing (right) (image: John Klein)

Micro-scale dimension

On the other side of the spectrum, micro-scale 3D printing has significant applications in micromechanical devices, optics, and research. However, the current micro-scale limitations include material restrictions, warping and inaccuracy, and speed. Accessible one-photon 3D printing has become a key driver in biological and medical research, including printing tissue scaffolds and microfluidic devices.

Commercial optical 3D printers commonly use stereolithography techniques with z-stage resolutions on the order of 10–100 microns, with x-y minimum feature sizes around 100 microns (for example, Formlabs Form 1, Figure 18-7). These types of printers use one-photon absorption to trigger polymerization of a resin. Positioning of the light source and resin depend on the specifics of the printer and common methods such as galvanometers to steer a laser beam, inkjet deposition of resin, or projection-based systems. Standard one-photon absorption systems usually use UV-curable resins, which require average continuous wave optical power around 100 mW. Typical print times for a 5 x 5 x 5 cm part with these commercial stereolithography printers are around 10 hours, and the current cost can be as low as a few thousand dollars.

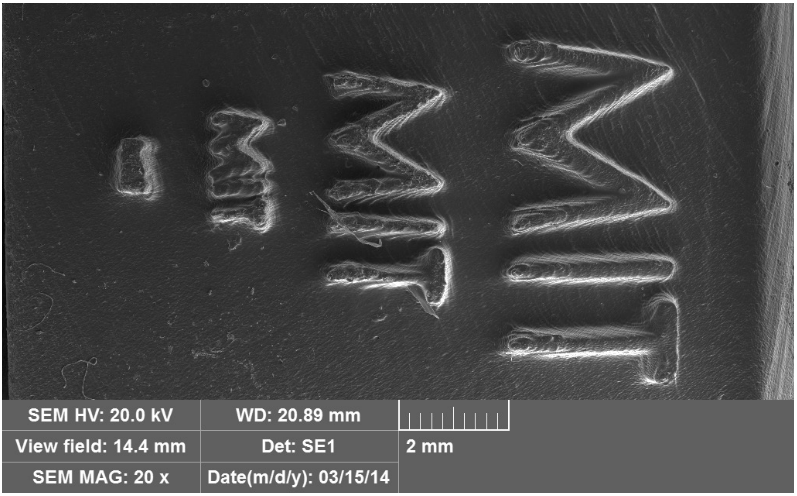

Figure 18-7. Scanning electron microscopy image detailing a resolution test print from a Formlabs Form 1 printer (image: Dr. James Weaver)

Meanwhile, advances in two-photon polymerization have helped realize applications that require high resolution on the nano scale. In contrast to one-photon printers, two-photon polymerization systems function via nonlinear optical absorption to achieve a smaller polymerization voxel unit. Two-photon absorption occurs when two photons are simultaneously absorbed by a molecule to allow an electron to jump to a higher state. This is a third-order process in which higher photon densities are required for two-photon absorption compared to one-photon absorption (linear process). For fabrication, a system typically uses either a pulsed femtosecond or a nanosecond laser operating at double the absorption frequency of the light-curable resin. The latter requires that the laser is tightly focused into a bath of resin, with the focal point being where the two-photon absorption primarily occurs. This generates a small voxel of polymerized resin, typically around 100–500 nm in size. Such systems (such as printers made by NanoScribe) are capable of submicron resolutions, but are limited by speed and positioning capability to under 1 mm object size typically. The print time for a 1 x 1 x 1 mm object on a NanoScribe printer is around 50 hours. In addition to the limitations on speed and size, cost is another barrier; commercial two-photon systems such as these start around $500,000.

Work done in collaboration with Will Patrick and Christian Landeros has focused on the limitations of both one-photon and two-photon printers. Our group has taken steps in developing a combination system to take advantage of the two systems' inherent strengths: fast one-photon polymerization for larger areas and precise two-photon polymerization for small features where needed. We believe the future of 3D printing with this system scales down to the nanometer and will facilitate micromechanical features on product-scale devices, such as structural color, sensing, and actuation mechanisms.

The integrated one- and two-photon polymerization system we designed and built uses an optical setup similar to a fluorescent microscope, as depicted in Figure 18-8. In our configuration, we used two different lasers: a blue diode laser for one-photon polymerization, and a Nd:YAG laser for two-photon polymerization. Early results are promising and show improvements for reliability, measurement data, and the potential to improve resolution based on material monitoring (see Figure 18-9). The work has taken key steps in the direction of coupling the relatively low cost and high speed of one-photon 3D printing with the nano-scale precision of two-photon printing in a combination system. With these advancements, we set the stage for the development of a 3D printing system capable of closing the gap between submicron and centimeter scales. The area of digital fabrication on the small scale continues to push boundaries, allowing for novel structural color fabrication, micromechanical devices, and advances in metamaterials.

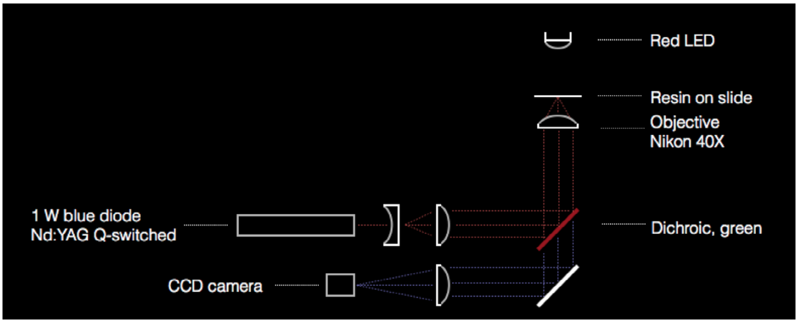

Figure 18-8. Schematic diagram of the combination one- and two-photon 3D printing system; note that the mechanical actuation system, comprised of a stepper motor stage with a piezoelectric stage, is not detailed in this schematic (graphic: Will Patrick)

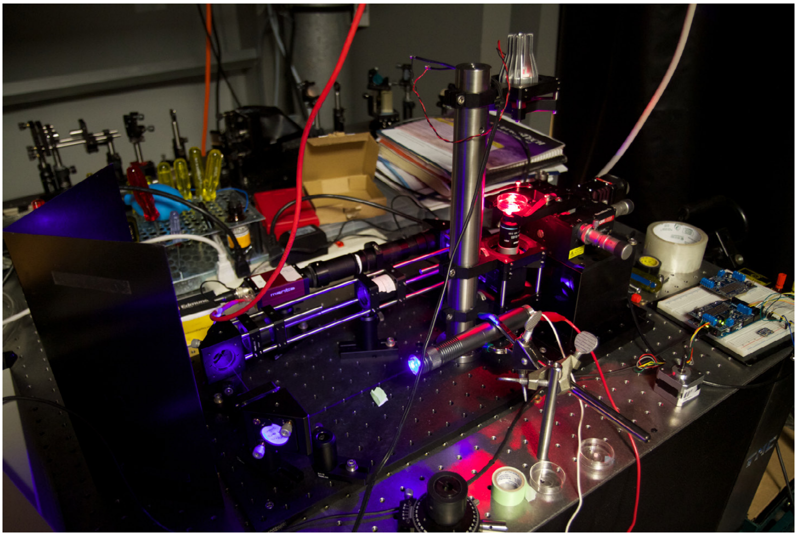

Figure 18-9. Experimental setup showing the combination one- and two-photon printing system with the 1W blue laser in the process of curing material; designed and built in collaboration with Will Patrick and Christian Landeros

Microfluidic devices

Our work in micro-scale printing is motivated by exciting opportunities for using optical 3D printing in biological applications. Microfluidic devices are used in chemical and biological applications to perform fluid reactions using internal channels on the order of 1–1000 microns.[4] Typical microfluidic devices are generated by using top-down lithography techniques, but additive manufacturing holds exciting potential in this field for fast turnaround, complex internal features, and multimaterial structures. In particular, we are exploring printers such as the Formlabs Form 1 and the Stratasys Objet500 Connex to create microfluidic devices. We have demonstrated the first 3D printed microfluidic valves made from both single and multiple materials (Figure 18-10).[5] Similar to integrated circuits, microfluidics hold potential for miniaturizing biological and chemical reactions for a variety of medical and product devices.

4 Whitesides, G.M. 2006.

5 In collaboration with Dr. David Kong, Will Patrick, and Maria Isabella Gariboldi.

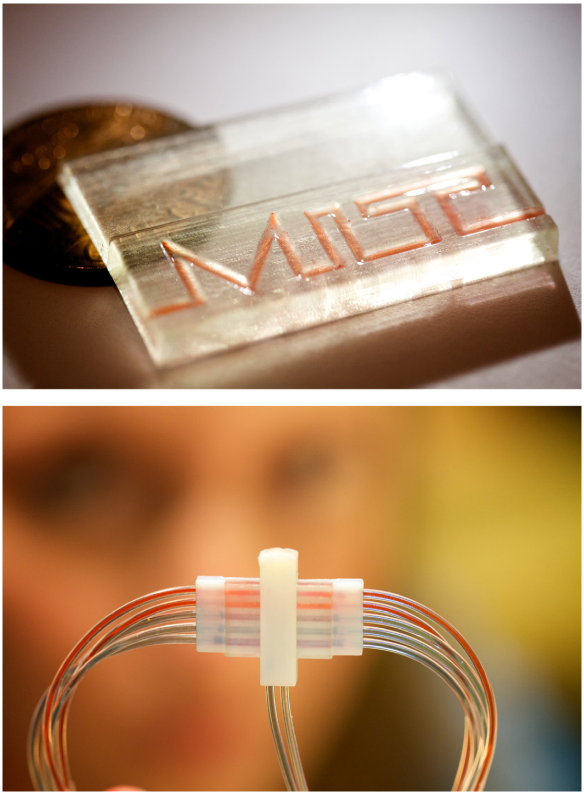

Figure 18-10. Microfluidic devices are additively fabricated using a Stratasys Objet500 Connex printer in both single material (top) and multimaterial modes (bottom)

MATERIAL DIMENSIONS

Another important area in additive fabrication is material selection. Currently, commercial printers exist for a wide variety of materials, ranging from thermoplastics, optical-cured polymers, ceramics, metals, biomaterials, and even food. These printers use a selection of different techniques for solidifying the material, such as thermal, optical, and chemical curing methods.

Multimaterial printing

Currently, most printers still function with a single primary material. In the future, however, multimaterial printers will become the standard rather than the exception that they are today. For commercial printers, the small subset of multimaterial printers are limited to mainly optically cured photopolymers. Stratasys is a leader in this field and its top printer models presently can print using a mixture of three resin types, in addition to support material used for generating overhanging features. These multimaterial machines use inkjet deposition heads and can print mixtures of the three selected resins to allow for gradient material properties. The material gradients can vary in properties such as stiffness, color, and translucency. A relevant example using the Stratasys Objet500 Connex3 printer is a recent chaise lounge designed by Dr. Neri Oxman and Dr. W. Craig Carter, as illustrated in Figure 18-11. It was based on the functional goal of an acoustically quiet orb. As seen in the lower portion of the figure, gradients of color and elasticity were designed to inform the aesthetic and acoustical properties of the chair. The printer uses a 16 µm voxel (volumetric pixel) size to accommodate spatial variations throughout the printed parts. The chaise lounge uses a milled wood back panel for support and is an example of combining both additive and subtractive fabrication modes.

Material tunability

Mass manufacturing commonly assembles single material parts in post-production. In contrast, digital fabrication and multimaterial additive techniques are beginning to introduce specificity, customization, and material integration into product design. This concept, referred to as *tunability*, makes it possible for designs to be adapted to their functional goal or environment. Instead of assembling single materials discretely, 3D printing can produce graded material properties with tunable characteristics such as color, density, and stiffness. In the previous chaise lounge example, the functional goal was acoustical. For the environmental case, we used sensed data alongside design algorithms to create a computational model. Another example is seen in a customized 3D printed helmet for a specific person's head, designed by a team led by Dr. Neri Oxman.[6] As opposed to a mass manufacturing approach based on a generic user, 3D printing enables tailored, highly customized design both in terms of geometry and material property variation. For the helmet, user data from a medical head scan allowed for the external geometry and internal material distribution of the head to be

6 Design team for the Minotaur Head with Lamella included Dr. Neri Oxman in collaboration with Stratasys, Dr. W. Craig Carter (MIT), Joe Hicklin (The Mathworks), and Turlif Vilbrandt (Symvol, Uformia).

mapped, as presented in Figure 18-12. The helmet was designed and 3D printed with variable stiffness properties on a Stratasys Objet500 Connex 3D printer. The helmet model is algorithmically generated to provide a geometrical fit that provides different elastic responses corresponding to the layout of tissue and bone in the user's head.

Figure 18-11. The Gemini Acoustic Chaise was 3D printed on a Stratasys Objet500 Connex3 3D printer and mounted on a CNC milled wood back (Le Laboratoire). Designed by Dr. Neri Oxman in collaboration with Stratasys and Dr. W. Craig Carter (MIT). Image credit: Michel Figuet (top) and Yoram Reshef (bottom).

Through these gradients of elasticity, the helmet provides improved function and feel. In this sense, 3D printing introduces a new era of customized fit and functionality for individual users and environments. The final helmet is printed on the Stratasys machine and is exhibited as the *Minotaur Head with Lamella*.

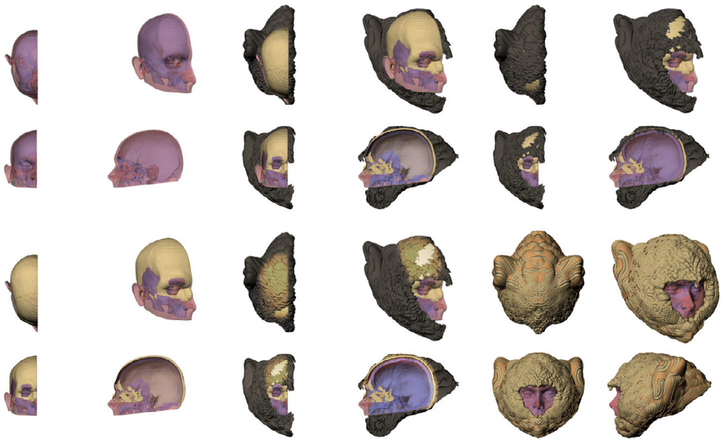

Figure 18-12. Minotaur Head with Lamella. From the Imaginary Being series, Centre Pompidou (Paris). 3D printed by Stratasys with variable stiffness properties on a Objet500 Connex 3D printer. Designed by Dr. Neri Oxman in collaboration with Dr. W. Craig Carter (MIT), Joe Hicklin (The Mathworks), and Turlif Vilbrandt (Uformia). Photo credit: Yoram Reshef.

The future of 3D printing is moving toward increased control of multimaterial printers. In time, additional printing techniques will be developed or converted to output multiple materials. Multimaterial printing control allows for functional gradient properties to accommodate functional goals and environmental data. For now, the field is limited primarily to optically cured polymers. These polymers work well for prototypes, but due to the higher cost, long-term stability issues, and material properties, additional material types is a forthcoming challenge and will be developed in future technologies. We believe multimaterial metal/thermoplastic printers, digital electronics printers, and biological material printers are on the near horizon.

TEMPORAL DIMENSIONS

The final dimension of additive manufacturing is the temporal regime, which affects both the fabrication process and the resulting product behavior. In comparison to mass manufacturing methods, current 3D printing techniques are slow, and build trays often require in excess of a day to finish a single part. In contrast, traditional mass manufacturing techniques such as molding, stamping, and casting are carried out in seconds to minutes. Looking toward the future, we expect the temporal dimension to be exceedingly important in new product development and processes.

Printing processes will become much faster in the future and will begin to challenge mass manufacturing techniques because of its inherent advantage in producing complex geometry, customization, and integration benefits, as discussed in the previous sections of this chapter. To achieve higher print speeds, the serial print process (print head) can move faster, print a larger bead size, and/or utilize parallel processes. Unfortunately, resolution is often inversely proportional to speed due to the total tool path length, thus limiting the 3D printing process to slower speeds for detailed parts at scale. However, biology excels in two areas—scale and adaptation—and growth mechanisms offer possibilities for additive techniques that surpass the conventional limits.

Digital biological fabrication

Turning to the exponential growth and parallelization capacity in biology, we are excited by the potential that biological materials offer for printing. The common *Escherichia coli* cell can replicate itself, along with all its internal complexity and high resolution, in approximately

20 minutes (genetically engineered strains of *E. coli* can approach doubling times much faster, currently down to 11 minutes). The concept of parallelization, in which individual fabrication units fabricate larger systems, is a powerful technique that biology applies to enable speed, robustness, adaption, and responsiveness. Applying the scaling laws, it is easy to imagine the vast potential for biological growth systems to be combined with digital controls and materials. In our work, we are exploring parallelization through large-scale fabrication with biological growth systems and digital controls.

Beginning in 2012, our group started studying silkworms, organisms that produce silk cocoons used for the world's silk supply. Viewing the silkworms (*Bombyx mori*) in a framework akin to miniature 3D multimaterial 3D printers, scaffolding template experiments were conducted by the team led by Dr. Neri Oxman.[7] These experiments revealed silkworm motion patterns and provided scaffolding guidelines to produce flat sheets of silk as opposed to cocoons (the silkworms still metamorphose outside the silk into moths; the cocoon is for protection from predators). Using this data, a digital controls model was developed and a robotically constructed scaffold was produced to provide spatial information to the silkworms. 6,500 silkworms were placed on the scaffold and over the course of two weeks the silkworms layered the scaffold with silk in the geometry constructed by the digital controls model. When the scaffold was removed, the final Silk Pavilion was exhibited in the MIT Media Lab lobby, as shown in Figure 18-13. The Silk Pavilion, with its massive parallelization of additive fabrication, serves as an excellent example of the power-scaling potential for biology. By extension, looking around a common room and noticing the bulk of natural materials (for example, wood, cotton, and food), the potential for controlling biological growth models is very exciting.

Although existing biological organisms are impressive in their capacity to engage spatial and temporal growth and material variation, we are also intrigued by the potential to design biology itself through synthetic biology methods. These methods focus on genetic engineering through designing the gene pathways with logic structures analogous

7 Silk Pavilion team led by Dr. Neri Oxman with Mediated Matter's Markus Kayser, Jared Laucks, Jorge Duro-Royo, and Carlos Gonzales Uribe—in collaboration with Dr. Fiorenzo Omenetto (Tufts University) and Dr. James Weaver (Wyss Institute, Harvard University).

to electrical and computer engineering. Using the biological equivalents (using transcription factors) of logic gates (such as AND, NOT, and OR gates), genetic circuits can be designed and constructed within organisms.

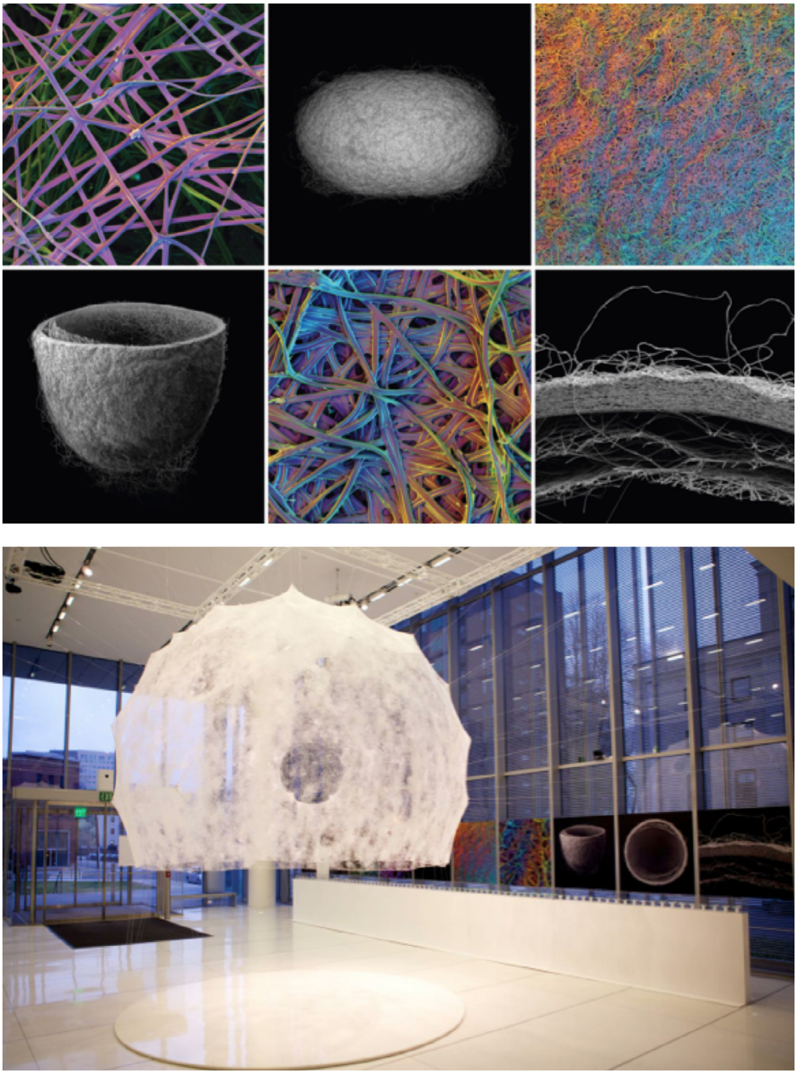

Figure 18-13. Scanning electron microscopy images detail a typical silk cocoon, and the observed spinning patterns are highlighted in false color generated by surface orientation (top); the Silk Pavilion on display in the MIT Media Lab (bottom) (photo: Dr. James Weaver [top], Steven Keating [bottom])

In the future, what would wood look like if it were optimized for structure, color, homogeneity, speed of growth, and so on? Could we have living products? Cell phones that are half-biological and half-digital? Houses that can replicate or materials sourced from the air like plants? The new field of synthetic biology designs genetic biological functions for engineering solutions. Synthetic biology is an exciting area with serious potential to revolutionize not only medicine, but also fabrication and computation. The thoughts seem infinite, although we are just at the beginning of the science, tools, and capabilities to design basic synthetic biological systems.

The beginning building blocks of synthetic biology are emerging, as new science from the last decade has created designs for genetic circuits akin to logic gates. These genetic circuits are designed gene pathways made from materials such as deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) that program certain chemical actions from cellular organisms. From these basic logic gates, the goals of genetic circuits and computation are starting to emerge in scientific research by leading biologists in the field. As a research group, we are just in the first stages of getting our feet wet in the area, but we are enthused and look forward to a future of growth, temporal responsiveness, and hybrid systems with digital components.

Current research in our group in the area focuses on fabrication systems and mechanical means of combining top-down digital controls and bottom-up biological growth. Early work has generated inkjet distribution heads for printing cells, genetically modified cell lines for tunable biofilm growth, and mathematical models for using light to trigger fabrication gene pathways in cell lines for potential 3D printing techniques (see Figure 18-14).[8] In the future, we believe 3D printers will function with biological resins capable of complex parallelized growth with responsive temporal and spatial properties.

8 Work performed in collaboration with Will Patrick and Dr. David Kong.

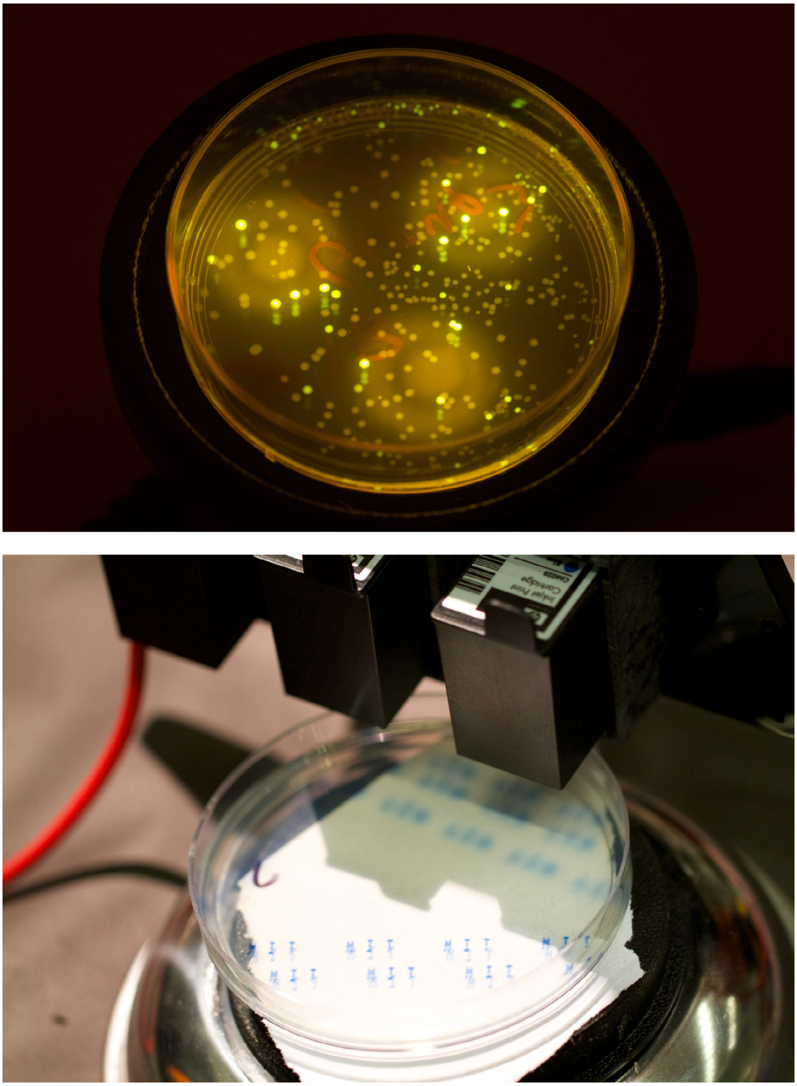

Figure 18-14. Genetically engineered Escherichia coli cells with a fluorescent tag (top); a biological print head using inkjet nozzles to print living cells onto substrates (bottom)

While these are very early predictions, we look forward to the future of printing living materials and believe that the capabilities in all of the dimensions discussed in this chapter—spatial, material, and temporal—hold the future for vast scaling potential, material/energy sourcing, and responsive products, as illustrated in Figure 18-15.

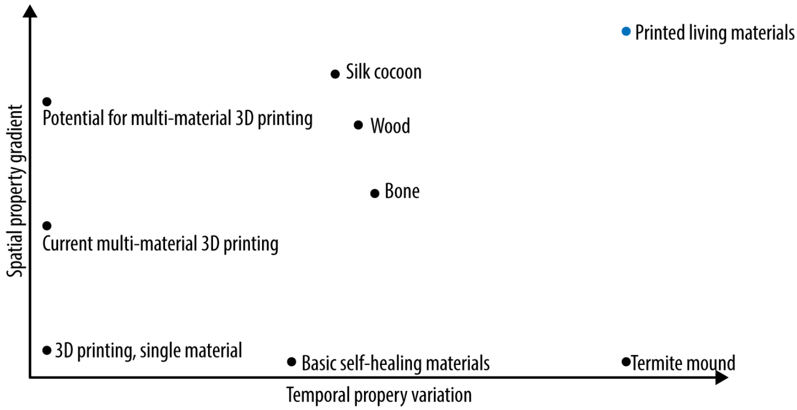

Figure 18-15. An overview chart detailing the spatial and temporal variations possible with different materials systems (work in collaboration with Will Patrick)

Conclusion

The future for new dimensions in additive manufacturing holds promise for novel design processes and industrial applications. Starting with spatial control, the scales of 3D printing are continuing to expand on both the small and large scales. In the coming years, we will see infrastructure made through automated additive techniques. Buildings printed, assembled, and dynamically measured will create responsive architecture. Conversely, the nano-scale will begin to merge with the product-scale through novel printing techniques such as two-photon absorption curing. We will see the development of a multitude of applications empowered by these new nano-scale machines, ranging from structural color, to on-product mechanism arrays, and widespread sensors/interfaces.

Spatial limitations are just one frontier—new printed materials and graded properties hold potential for design to move beyond combining standardized parts. With current optical printers capable of dynamically mixing base materials to print in multiple materials, products can be customized to design environments. Gradients of stiffness, translucency, and density have made possible a new language of monolithic design in which integration offers significant benefits in functionality, efficiency, and ease of fabrication. Moving forward, the research direction of multimaterial printers will progress with more materials such as composites, ceramics, and metals. Research work is pushing the materials dimension toward active electronic properties, such as printable circuit boards, integrated digital sensors, and batteries. For designers, the ability to create complex products is becoming simpler, faster, and accessible. At the moment, this complexity is defined as shape/material sophistication, though it will continue to grow into electronics, at-scale manufacturing, and in the more distant future, biological complexity.

Ending on a biological note, design is often inspired by natural organisms. Current research directions predict a future of design in which organisms themselves can be designed. Although current 3D printing techniques are limited in the temporal dimension (print time) due to speed/resolution/geometric scale, biology has found solutions through growth and adaptability. Turning to synthetic biology, the concept of a digitally controlled (top-down), biologically designed (bottom-up) fabrication system holds mesmerizing potential for fast growth of significantly complex systems. Even though the field of synthetic biology is still in its infancy and there is enormous work to be done, encouraging examples of grown bricks, tunable biofilms, and designed biological calculators hint at the design capabilities. The concept of a biologically grown house, self-healing vascular networks in our products, and integrated electronics with biology are exciting ideas for future focus. Overall, the possibilities of combining digital controls, logic, and memory with the biological power of scaling, resolution, paralleling, and material/energy sourcing are limitless.

We are excitedly enthused by the potential to explore new dimensions of 3D printing in spatial scale (construction-scale and nano-scale), material possibilities (multimaterial gradient properties), and temporal considerations (parallelization and biological combinations). The future for additive techniques is bright and we look forward to continued developments in the field.

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