Digital Anisotropy: A Variable Elasticity Rapid Prototyping Platform

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Abstract

Functional anisotropic material gradients on multiple length scales and locations are omnipresent in natural systems. However, the vast majority of industrially fabricated objects, even those designed to augment, coexist and interact with natural systems, are homogenous or discrete in material composition. This paper presents an exploration into rapid fabrication with material gradients in the form of a variable property printing platform. A Digital Anisotropy approach and a variable-elasticity fabrication platform demonstrating the approach are presented. Prototype development methods and processes are presented and discussed in the context of its design applications. Current and future technological implications for functionally graded rapid prototyping across micro, meso, and macro scales are reviewed and future directions discussed.

Keywords: anisotropy, digital anisotropy, 3D printing, rapid prototyping, material gradients, functionally graded materials, variable property design

1. Introduction

Direct rapid prototyping technologies typically lack the ability to generate gradients of variable properties in the materials they work with (Oxman 2011). Material properties are typically assigned discretely to predefined regions during both the design and fabrication process (Sheng *et al.* 2003). Generally, the design of shapes and forms is determined prior to, and separately from, the assignment of discrete material properties, with limited recursive optimization of materials and form (Oxman and Rosenberg 2009). This is mostly due to computational limitations in CAD/E packages currently available for the designer.

In the biological world, however, all matter is anisotropic. Defined as the property of having different values when measured in different directions, anisotropy is central to determining how natural objects are shaped relative to their function and behavior. While most materials exhibit anisotropic behavior such as the dependence of Young's modulus on the direction of load, nearly all rapid prototyping technologies that exist today operate on isotropic materials, lacking the possibility of controlling the material's directional dependence of a physical property (Oxman, 2010). Any observed bulk anisotropy in the end product are typically artifacts of the manufacturing process (i.e. fused deposition modeling or selective laser sintering) rather than results of deliberate design (Ahn *et al* 2002 and Cooke *et al* 2011). Given the significance of controlled anisotropy - specifically with regards to fiber composites characterized by being much stronger along the grain and fiber than across it – the ability to design, control and modulate fiber density and organization appears to be most significant for the future of digital rapid fabrication

Digital Anisotropy is a term coined by the authors to denote the ability of the designer to strategically control the density and directionality of material substance in the generation of form. In this approach, material precedes shape and it is the structuring of material properties as a function of environmental performance requirements that precedes, and furthermore, anticipates their form.

Material gradations with spatially varying compositions, properties, or microstructures are ubiquitous in multiple lengths scales and occur across a wide array of biological systems (Oxman 2011). Both lateral and longitudinal cross sections of cancellous bone, for example, reveal gradient density distributions corresponding to dynamic loading patterns (Gibson 1985). Human skin contains elasticity and stiffness gradients to allow for optimal movement and environmental protection (Agache *et al.* 1980). At tissue interfaces (e.g. bone-cartilage), chemical and material gradients exist in the form of varying cell distributions and extracellular molecule concentrations (Du *et al.* 2010).

In contrast to the heterogeneity observed in natural materials, industrially produced items are often homogenous or composed of homogenously defined forms and parts (Oxman, 2010). While such designs are readily compatible with existing manufacturing platforms and design tools, they may sacrifice certain improvements in strength, weight, functionality, and performance. Orthotics for example, are often homogenous in compositions yet are designed to be situated along limbs and torsos, which are heterogeneous in stiffness and flexibility (Oxman, 2010).

Variable property gradient printing allows for prototyping and fabrication of graduated material properties inspired by naturally functionally graded materials (Oxman 2011). The rapid prototyping platform introduced in this paper seeks to produce digital anisotropy by way of controlled gradients of stiffness and elasticity using a robotic gantry system. The ability to create such gradients allows for the rapid fabrication of products designed to interact with natural systems in a way that complements and enhances their material properties. Beyond mere mimicry, this platform also enables the potential to tailor intricate material responses through the fabrication of 'programmable anisotropy'.

2. Background

Direct rapid prototyping technologies can be distinguished in part by the scale at which they are used to fabricate materials and products (Melchels *et al.* 2010). The scales at which these technologies are implemented determine the specific design considerations inherent in the platforms. At very small scales, emphasis lies in precise positioning of components and specialized materials and printing strategies (Heule *et al.* 2003). Product-scale rapid prototyping encompasses most current commercial 3D printers where the focus is largely on material robustness, printing efficiency and price with various specialized processes for different applications (Kai *et al.* 2010). At architectural scales, a different set of strategies is required in order to create very large structures within practical time and material parameters (Buswell *et al.* 2008).

Generally, anisotropy with rapid prototyping can be obtained in three ways: inherent material anisotropy, deposition (printing) directionality and spatial gradients of material properties (spatial non-uniformity). A pronounced example of inherent anisotropy is fiber composites, which are characterized by being much stronger along the fiber than across it. The ability to design, control and modulate the organization of fiber and fiber-like materials -i.e. in patterns imitating plant microstructures (Gibson 2012) - appears to be most significant for the future of digital rapid fabrication.

Moreover, even for isotropic printing materials, the stiffness and damage thresholds along the deposition direction are often higher than those across the transverse directions (Dikovsky 2012). The deposition itself can therefore mimic the functionality of fiber anisotropy without the need of inherently anisotropic materials or chemical modifications *in situ*. Spatial non-uniformity introduces anisotropy through gradients of physical properties or material composition. This is currently the most accessible approach, as exemplified and discussed in the following sections.

Previous work has explored functional gradient rapid prototyping inspired by variations in local structure and density evident in cancellous bone and palm tree stems. The work focused on the optimization of cellular material distributions in response to given structural constraints on architectural scales using cement-based materials (Oxman *et al* 2011). Current work focuses on gradients of elasticity and stiffness fabricated in product and smaller scale applications. Inspired by human skin and tissues, it explores variable property polymer printing in parallel with the addition of limited dynamic responses.

2.1 Background Examples

Inspired by the multi-material printing platform, developed by Objet Ltd., here we explore single-nozzle variable-property fabrication, resulting in continuously varying elastic properties across multiple scales. Included in the background work of this research, are two examples of multi-material prints exploring concepts of Digital Anisotropy, fabricated by Objet Ltd.

2.1.1 Helmet Design

The helmet is designed as a protective shock absorbent helmet able to flex and deform in order to provide comfort and high levels of mechanical compliance (see Fig. 1). The head shield introduces variable thickness in the shell, informed by anatomical and physiological data derived from real human skull data (Fig. 1, bottom right). Medical scan data of a human head is selected from an open repository. Two sets of data are created and trimmed from the scan using medical imagining software simulating the hard tissue (skull) and the soft tissue (skin and muscle).

Combined, these two data sets make up the bone-to-skin threshold informing helmet thickness and material composition according to its biological counterpart such that bony perturbations in the skull are shielded with soft lamellas designed as spatial sutures. Digital Anisotropy is achieved by the controlled variation of geometrical and material patterns of varying elastic moduli parameters.

Figure 1. **Top:** Full (**left**) and detailed (**right**) view of a helmet design, 3-D printed by Objet Ltd. (Connex500) exploring digital anisotropy printing. The helmet is composed of soft and stiff material combinations gradually varying properties as a function of the helmet's desired performance. **Bottom left**: The helmet is designed as a composition of soft and stiff materials, where soft tissue makes up the internal structure providing for comfort and stiff tissue functions as the exterior protective shell. Elastic moduli is calculated in 700DPI using a high-resolution printer (16 microns), allowing the designer to pre-calculate the overall digital anisotropy profiles across the surface area of the entire helmet. **Bottom right:** The design is informed by CT scan data of a human skull, such that stiff materials are distributed around soft tissues as a protective shell and soft materials are distributed around hard tissue providing for comfort. Created by Neri Oxman in collaboration with Prof. Craig Carter (MIT), Joe Hicklin (The Mathworks) and Turlif Vilbrandt (Symvol, Uformia). Fabricated by Objet Ltd. Photos: Yoram Reshef. In the permanent collection at the Centre Georges Pompidou, Paris, France.

2.1.2 Armor Design

The challenge of accommodating multiple functions in the natural world is most often overcome by growing structural patterns in multiple scales to provide for various functions. The spongy bone, for instance, is designed as a cellular solid at the mesoscale and as a fibrous composite at the microscale. Combined, cellular structures and fiber textures provide for high weight to volume ratios while maintaining very strong structures. The armor design in Fig. 2 combines a cellular structural pattern with a dotted geometrical pattern accommodating the integration of seemingly contradictory functions: the cellular spongy structure provides for a lightweight shock-absorbent protective armor, while the dotted pattern distinguishes between soft and hard tissue. Regions of higher stiffness follow the outer boundary of the cellular structure, maintaining its structural integrity, while soft tissue is located within.

The 3-D print was fabricated as a multi-material model in 16 micron, high-resolution print layer accuracy (600 DPI X&Y resolution). The dotted pattern allowed for controlled anisotropic behavior in 16 micron voxel resolution.

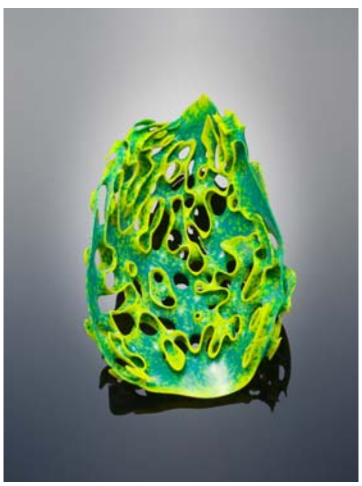



Figure 2. The armor design combines a cellular spongy structure providing lightweight shock-absorbent protection with a dotted geometric pattern distinguishing between hard and soft tissue. Regions of stiffer tissue are found along the outer boundary of the cellular structure while regions of softer tissue are located within. Created by Neri Oxman in collaboration with Prof. Craig Carter (MIT) and Joe Hicklin (The Mathworks). Fabricated by Objet, Ltd. Photos: Yoram Reshef. In the permanent collection at the Centre Georges Pompidou, Paris, France.

2.2 Micro and Nanoscale Printing

Rapid prototyping at very small scales introduces different various challenges requiring a unique set of strategies. At such small scales, adequate representation of microstructures with existing CAD platforms may become problematic (Hague *et al.* 2003). Precise positioning and high feature resolutions are particularly important for fabricating both micro and nanoscale objects as well as larger objects with deliberate micro and nanoscale structures (Cima *et al.* 1992). In the case of top-down fabrication approaches, methods are typically based on miniaturizing conventional product scale fabrication methods. Substantially below micron scales however, such conventional methods are often impractical and are replaced or complemented by bottom-up approaches (Heule *et al.* 2003).

Microscale top-down fabrication processes include direct writing methods, direct mechanical processing, and photopolymerization/stereolithography. In direct writing methods, automated translation stages are used to position and move a writing device – an ink-jet head, laser writing optics, or a small extrusion nozzle (Heule *et al.* 2003). 2D material structures are then generated in successive layers to create a desired 3D structure. Feature resolutions in the tens of microns can be generated using these methods (Heule *et al.* 2003).

Mechanical processing methods include the low-temperature co-fired ceramic process, in which thin (100-400um) layers of ceramic green tapes are cut, stacked, and sintered to create ceramic structures – a process similar to laminated object manufacturing of adhesive coated paper, plastic, or metal laminates (Heule *et al.* 2003). Feature sizes ranging from 25-100um have been demonstrated using this technique. Lithography-based microfabrication processes are also similar to product scale photopolymerization rapid prototyping processes. In order to achieve the smaller feature sizes required, advanced optics and smaller wavelength excitation rays are used (Heule *et al.* 2003). In multiphoton polymerization, 3D structures with feature sizes under 100nm can be traced out of blocks of gel using the nonlinear nature of photoexcitation (Li and Fourkas 2007).

Bottom-up fabrication processes are often used when further miniaturizing product scale printing techniques become unfeasible. A variety of self-assembling inks and building blocks with inherent metrology have been developed to assist in achieving the precision and resolutions needed (Fernandez and Khademhosseini 2010). In Fan et al (2000) a self-assembling ink is used with three rapid printing procedures to form functional, hierarchically organized nanostructures.

The ability of rapid fabrication to create controlled 3D structures with very small feature resolutions has also been exploited to work with biological materials such as cells, extracellular matrix molecules, chemical factors, and cell scaffolds (Mirkin *et al.* 2007 and Singh *et al.* 2008). The level of control afforded by automated additive manufacturing techniques has allowed complex scaffold microstructures to be produced, some with cell-laden ink capsules (Melchels *et al.* 2011 and Hoque *et al.* 2012).

2.3 Product Scale Fabrication

There are a variety of established direct manufacturing technologies commonly used to produce product scale objects. These can be broadly grouped into three methods: molten polymer deposition (e.g. fused deposition modeling), granular material binding (e.g. selective laser sintering, electron beam melting, and inkjet binder printing), and photopolymerization (e.g.

stereolithography). With the exception of specialized methods such as multiphoton photopolymerization, 3D parts are produced by reducing the form to 2D layers (White 2001).

The range of materials and applications that these processes can work with is relatively large. Fused deposition modeling technologies for example utilize several thermoplastics and can be strengthened with the addition of metal wicking (Wu *et al.* 2002). Granular material binding technologies such as selective laser sintering can use metals as well as polymers. Fully dense and void free metal parts can be created with electron beam melting platforms (add citation). Photopolymerization platforms are capable of producing objects from a large library of polymeric materials (Yan and Gu 1997). More recently, technologies have also been developed for printing with wax, composite, and ceramic materials (Vorndran *et al.* 2009, Cheah *et al.* 2005, Kumar and Kruth 2009).

Implemented in product scale, these technologies are used in a wide range of applications from prototyping to medical models, art, and production-quality parts. Rapid prototyping on this scale removes certain manufacturing limitations and greatly expands the different geometries and complexities available to designers (Hague *et al.* 2003). .

2.4 Construction-scale Rapid Fabrication

At very large scales, additional considerations must be taken into account with regard to material usage, platform structure, and fabrication speed (Oxman 2010 – thesis, Khoshnevis 2004). Materials must be sufficiently structural as to accommodate larger dead loads; the platform infrastructure must be able to travel at the larger distance scales required; and materials must be additively deposited at practical rates and resolutions (Ryder *et al.* 2002, Buswell *et al.* 2007).

At present, there are three architectural scale additive manufacturing platforms in the public domain, all of which are based on curing processes: D-shape, Contour Crafting, and Concrete Printing. D-Shape and Concrete Printing are built on gantry platforms while Contour Crafting is crane mounted (Khoshnevis 2004). D-Shape utilizes a powder deposition process where layers of sand are successively laid down and hardened into a marble-like material with the selective deposition of a binder (Enrico). Contour Crafting and Concrete Printing are both based on the extrusion of cement-based materials. Contour Crafting emphasizes high speed automation and minimal material usage while Concrete Printing has a smaller resolution, greater control of geometries and the option of using a second support material (Li and Fourkas, 2011).

A significant amount of work has been done in exploring the materials for construction-scale rapid fabrication (Khoshnevis 2004 and Boswell *et al.* 2007). Concrete and cement material mixtures used for printing must balance extrudability and buildability which are related to workability and open time (Le *et al.* 2011). At the same time, since material deposition must occur at relatively high rates in order for mega-scale printing to be practical, the balance of material deposition rate and required resolution must also be considered. Given the unique artificial marble material that D-shape works with, it has been estimated to be four times faster than traditional building methods (Enrico).

3. Methods

Structures in nature are capable of transitioning seamlessly between different material compositions, properties, and microstructures. This printing platform aims to mimic these systems by developing a 3D printer that is capable not only of producing multi-material structures with an incredibly wide range of mechanical properties but also of stretching the current boundaries of human design and product manufacturing. The end products have the potential to be aesthetically pleasing through the incorporation of customizable color gradients as well as structurally superior and environmentally efficient.

3.1 Overview

A printing platform capable of mixing and extruding gradients of two materials was built as an exploration into rapid fabrication with material gradients. A material extrusion head comprising a nozzle and mixing area was attached to the z-axis of a 3-axis gantry robot and a compressed-air driven system was used to control the amount of each material dispensed from its reservoir to the mixing area. Several mixing strategies were explored including diffusive, static, and active mixing.

The platform was designed to extrude materials, which remain liquid at room temperatures prior to mixing and extrusion, and solidify after deposition, i.e. certain epoxies, UV-cure polymers, drying adhesives, and thixotropic fluids. Use of these materials instead of thermoplastics as used in fused deposition modeling printers allows for a larger range of compatible materials. In particular, since the printing process does not require heating the material significantly, the platform is potentially compatible with temperature-sensitive compounds and biological molecules.

3.2 Gantry System

The printing platform was built around a three-axis gantry robot composed of two ball screw linear actuators for the x and y axis and a lead screw linear actuator for the z axis (Fig. 3). The z-axis actuator was attached to the back of the frame and a horizontal rod was attached to the z-axis to facilitate positioning of the extruder head. Each actuator is powered by a stepper motor. A re-purposed 3-axis CNC motor driver controller with a spindle output is used to control the gantry.

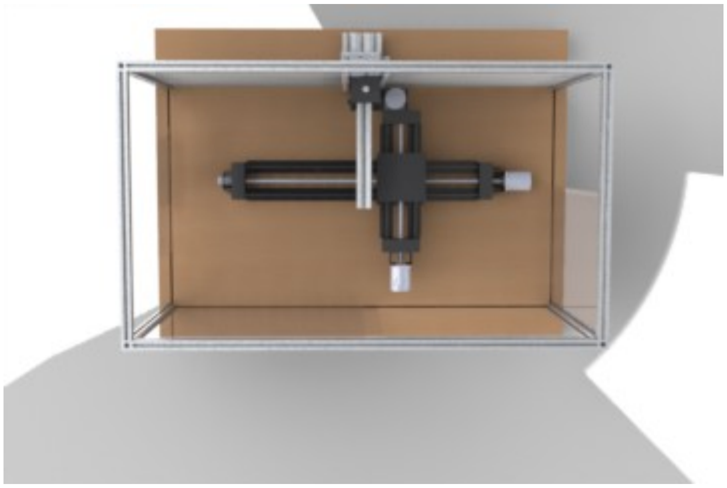


Figure 3. Top view of gantry system model with attached x-y motion stages for actuating the build platform and a separate z-axis with attachment points for the mixer and extruder

3.3 Extrusion and Mixing

The extrusion and mixing system is comprised of material reservoirs connected to pressure sources, a mixing area, and a nozzle (Fig. 4). Solenoid valves either switched manually or automatically, were used to control the pressure in the reservoirs and hence the flow rate of material dispensed. From the reservoirs, the materials are then fed via tubing to a mixing system before being extruded from the nozzle

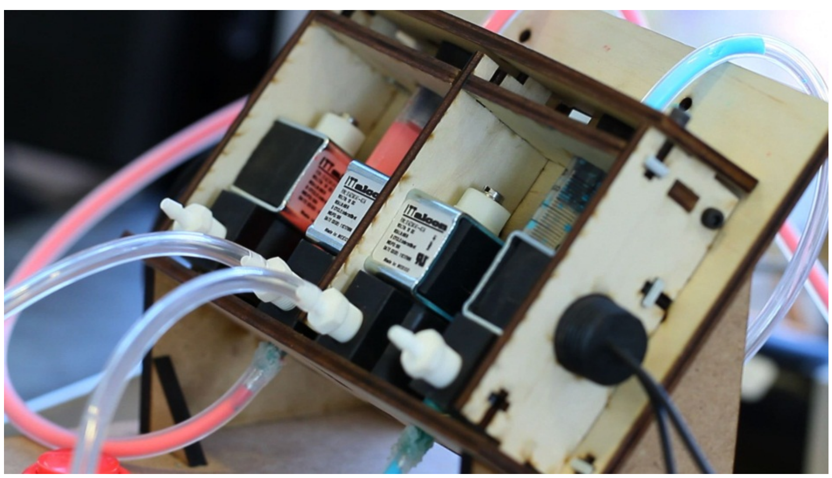
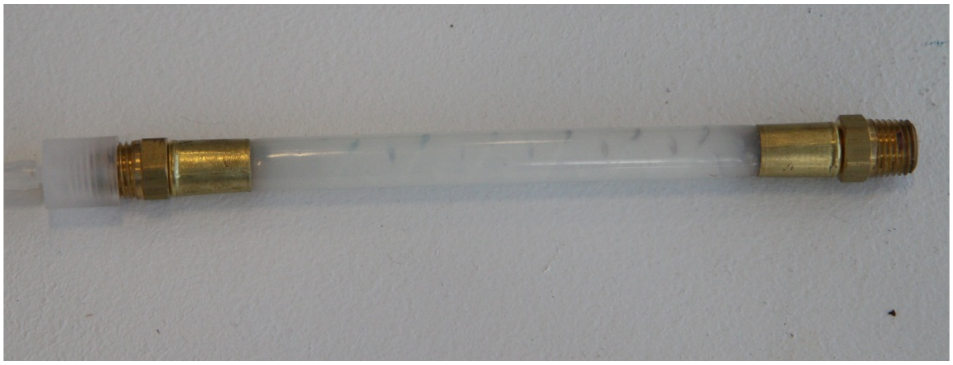


Figure 4: Solenoid valves and material reservoirs. Flow rate of the two materials (shown here in red and blue) were controlled through the actuation of solenoid valves connected to either compressed or atmospheric air. The reservoir and valve assembly may be expanded to accommodate additional materials.

Three different mixing strategies were explored: diffusive, static, and active. The diffusive strategy consisted simply of an additional length of tubing between the nozzle and a "Y" connector joining the material feed tubes (see Fig. 5). The active mixing strategy utilized a small reservoir immediately before the nozzle into which material could be fed. A set of blades driven by a small motor within the reservoir facilitates mixing. The static mixing strategy used inline static pipe mixers inserted between the nozzle and the material feed tubes.



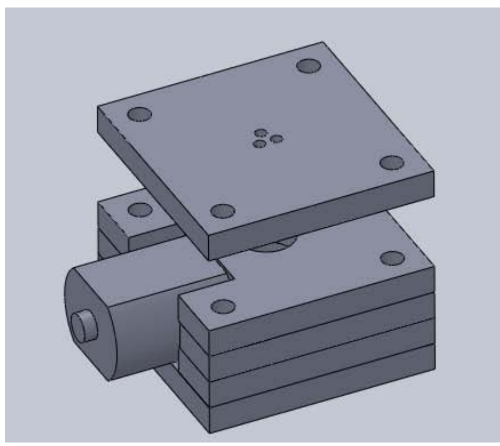


Figure 5: Passive (top) and active (bottom) mixers. Static mixers with varying numbers of blade elements were tested and compared to active mixing schemes accomplished by using motorized mixing blades.

3.4 Frame

An aluminum extrusion frame with sliding acrylic doors was designed to enclose the printing platform to provide structure, safety, and environmental control. Additional supports were added to the back of the frame to allow for attachment of the z-axis actuator. The acrylic doors were added in anticipation of working with UV-curable polymers to provide protection from UV radiation. The enclosure that the frame and doors provide also makes it easier to introduce humidity, temperature, and other environmental controls in case more sensitive materials are used.

3.5 Software

The gantry platform is controlled using Mach3, a PC-based CNC software. For printing, tool paths were generated from 3D STL models or 2D contour models using PyCam, an open-source tool path generator for 3-axis CNC machining. The resulting GCode is sent to Mach3 and used to control the gantry movement. The viscosity and curing time of the materials being printed are taken into account when setting appropriate line widths.

The material extrusion was separately controlled. The reservoir for each of the materials to be mixed was connected to two valves, one leading to unpressurized atmospheric air and the other to a pressure source. Control of the valves and hence relative amount of each material was provided by a programmed Arduino microcontroller with either preprogrammed sequences or manual control buttons.

In this version of the printing platform, control of material mixing and extrusion was provided separately, and coordinated with the tool path movement to produce the specified gradient. In future versions, the spindle output channel may be used to communicate directly with the extrusion system controller.

4. Results and Discussion

In Fig. 6, the platform is shown printing with blue and red glue. The two adhesives are mixed in different ratios to produce varying color gradients. The cast sheet in Fig. 7 demonstrates a similar principle, where a softer blue-colored silicone (Shore 00-10) is mixed with a harder red-colored silicone (Shore 00-50) to produce gradients in both color and durometer. Other combinations of materials tested for potential use on the platform include UV cure silicones and polyurethanes as shown in Fig 8. In the future, ratios of aggregates, foaming agents, or responsive materials may also be introduced.

Figure 6: Color gradients being created on the 3D printed platform by mixing red and blue adhesives in different controlled ratios.

Figure 7: Cast silicone sheet where a softer blue-colored silicone (Shore 00-10) is mixed with a harder red-colored silicone (Shore 00-50) to produce gradients in both color and durometer.

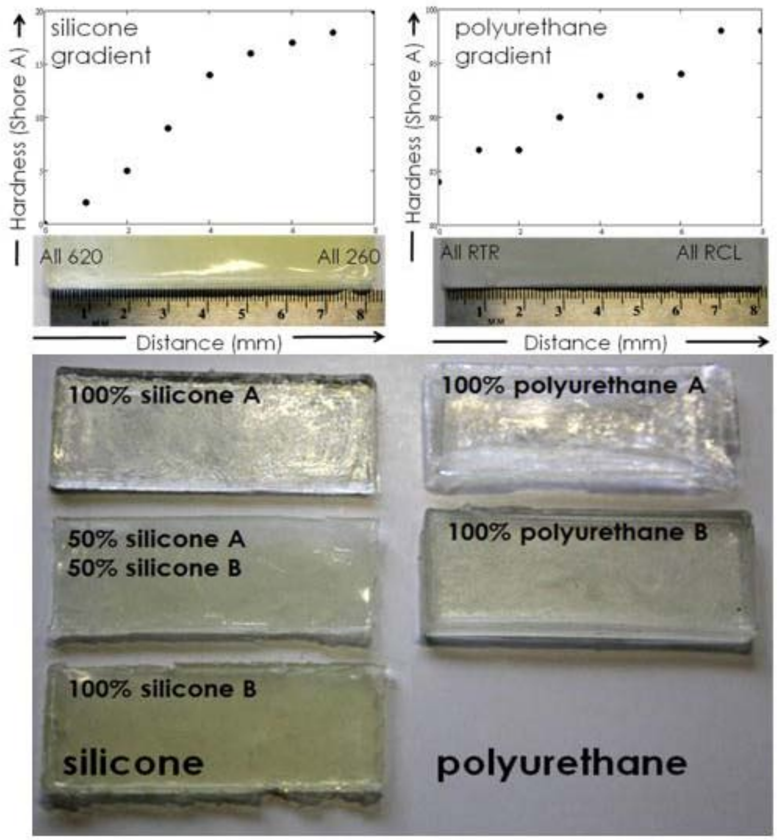


Figure 8: UV cure silicone and polyurethane samples tested. A series of samples were made by combining UV curable silicones and polyurethanes with different shore values in a gradient across each sample.

For the adhesive used in the printer, passive mixing was sufficient to create color gradients. The inline static pipe mixers produced the most complete mixing with the smoothest gradients, however, the fluid flow and fill patterns in the mixers combined with the substantial length of the mixers (0.1905m to 0.2437m) made it difficult to control and change gradients quickly. The diffusive mixing strategy enabled adequate gradient production and rapid changes in gradient composition. The nozzle used in the current prototype was chosen from an assortment of stainless steel dispensing needles ranging from 7 gauge to 14 gauge, depending on the extrusion line thickness desired. For the fairly low viscosity and long drying time of the adhesive used, a 10 gauge needle was used.

While adequate for demonstrating variable property gradient printing, the gradient mixing strategies presented thus far are difficult to control and use a relatively large volume for mixing. In parallel to the development of the printer, several other gradient creation mechanisms are being explored. One method seeks to generate controlled two-dimensional gradients prior to extrusion (Fig. 9) rather than the 1 dimensional gradients produced by the current printer.

Figure 9: Two-dimensional gradients generated in a microfluidic device using red and blue dyes. The geometry of the gradient is controlled by tuning the flow rates and pressures of multiple flow streams

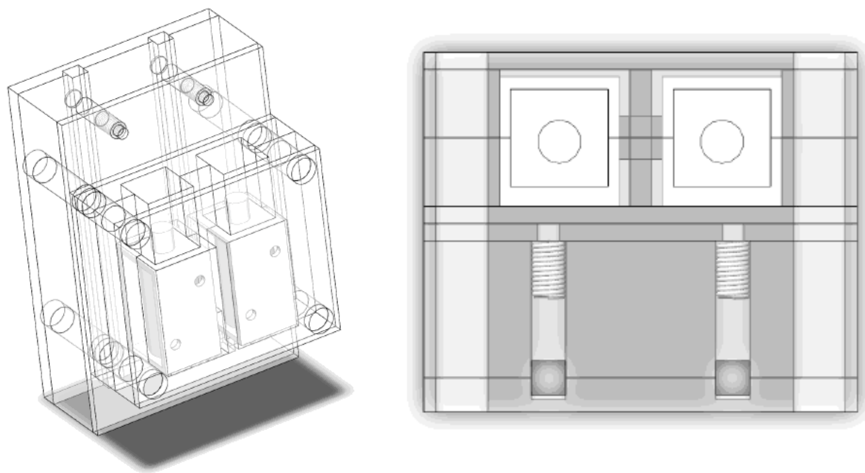


Figure 10: Multiple nozzle design concept where gradients are generated internally in each nozzle reservoir before being extruded in parallel. Combined with controlled two-dimensional gradient generation, this design seeks to increase gradient resolution without sacrificing print speeds.

In cooperation with the development of more precise gradients creation strategies, methods of using two dimensional line nozzles are being explored. Two-dimensional gradients generated prior to extrusion cannot be deposited using conventional round nozzles.

The use of multiple extrusion nozzles in variable property gradient printing raises challenges regarding efficient mixing and fluid handling. One solution currently being explored uses a microfluidic array of peristaltic mixing channels to simultaneously mix tens of output gradient combinations immediately before extrusion.

5. Current and Future Vision

Digital Anisotropy is defined in this paper as an approach for controlled multi-scale material property variation. The research presented here focuses on variable elasticity in micron scale resolution. However, various other experiments are currently under way to explore digital design and control of fiber-based materials and systems.

Potential applications play an important role in the decision to explore specific materials and aggregates to incorporate into the variable property gradient printing platform. These potential applications can be broadly characterized by scale into micro, meso and mega scales.

At the micro scale, the ability to control the microstructural elements of 3D printed components may be achieved by using mixtures of different powder morphologies (Cima *et al.* 1992). The ability to mimic the cellular distribution and chemical gradients found in biological tissues can help accelerate the understanding of biological processes such as cancer metastasis and chemotaxis (Singh *et al.* 2008).

At the meso and product scales, the ability to generate functional and aesthetic gradients have potential applications in improving the robustness of dynamic parts and improving the performance of orthotics and prosthetics (Giannatsis and Dedoussis 2009). In the future, the ability to 3D print with gradients of functional responsive materials will contribute further towards truly customizable and dynamic artifacts.

Advanced properties of functional materials can very often be controlled through the mixing ratio of the active components, additives, or dopants, allowing their gradient printing without necessitating chemistry in-situ. Multishape objects can be designed utilizing gradients of the transition (glass) temperature of memory-shape polymers (Xie and Rousseau 2009), by altering the cross-linker density. In those and other thermally-activated responsive materials, the inclusion of magnetically-active nanoparticles can be used for remote heating (Kumar *et al.* 2010), with their gradients yielding spatially-dependent heating rates. In 2D printing of organic LEDs and its future application in 3D printing, continuous variation of the emitted color can be designed through relative concentration of red-green-blue constituent polymers. In the same class of organic electronics, electrical conductivity is controllable through dopants concentration (Pfeiffer *et al.* 1998), enabling the fabrication of intricate 3D circuit designs embedded within the structure.

Spatially controllable property gradients in large and architectural-scale fabrication allow for material optimization on multiple length scales. The inclusion of gradients of aggregates, optical properties, and perhaps even responsive materials bring further applications in building and sculptural design.

Digital Anisotropy as an approach and an experimental framework provides promising intellectual and technical challenges for the digital fabrication industry at large. The designer's ability to design, control and modulate material property and behavior across spatial and potentially temporal scales, will promote higher efficiencies and more effective additive manufacturing platforms. In emulating Nature's way, Digital Anisotropy may have much promise in expanding the design toolbox available in digital rapid fabrication.

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References

Agache, P.G., Monneur, C., Leveque, J.L. and Rigal, J., 1980. Mechanical Properties and Young's Modulus of Human Skin in Vivo. *Archives of Dermatological Research*, 269 (3), 221-232.

Ahn, S-H., Montero, M. Odell, D., Roundy. S. and Wright P.K., 2002. Anisotropic Material Properties of Fused Deposition Modeling ABS. *Rapid Prototyping Journal*, 8(4), 248-257.

Buswell, R.A., Soar, R.C., Gibb, A.G.F. and Thorpe, A., 2007. Freeform Construction: Mega-scale Rapid Manufacturing. *Automation in Construction*, 16, 224-231.

Buswell, R.A., Thorpe, A., Soar, R.C. and Gibb, A.G.F., 2008. Design, data and process issues for mega-scale rapid manufacturing machines used for construction. *Automation in Construction*, 17, 923-929.

Cheah, C.M., Chua, C.K., Lee, C.W., Feng, C. and Totong, K., 2005. Rapid Prototyping and Tooling Techniques: A Review of Applications for Rapid Investment Casting. *International Journal of Advanced Manufacturing Technology*, 25, 308-320.

Cima, M.J., Lauder, A., Khanuja, S. and Sachs, E., 1992. Microstructural Elements of Components Derived from 3D Printing. *Proceedings Solid Freeform Fabrication Symposium*, 220-227.

Cook, W., Tomlinson, R.A., Burguete, R., Johns, D. and Vanard, G., 2011. Anisotropy, Homogeneity and Ageing in an SLS Polymer. *Rapid Prototyping Journal*, 17(4), 269-279.

Dikovsky, D., 2012. private communication.

Du, Y., Nichol, J.W., Hancock, M.J., Khademhosseini, A. and Cropek, D.M., 2010. Generation of Long-Range Material Gradients for Biomimetic Functions. *27th Army Science Conference.*

Enrico, D. D-Shape. Monolite UK Ltd. Available from: http://www.d-shape.com [Accessed 23 February 2012].

Fan, H., Lu, Y., Stump, A., Reed, S.T., Baer, T., Schunk, R., Perez-Luna, V., Lopez, G.P. and Brinker, C.J., 2000. Rapid Prototyping of Patterned Functional Nanostructures. *Nature*, 405, 56-60.

Fernandez, J.G. and Khademhosseini, A., 2010. Micro-Masonry: Construction of 3D Structures by Microscale Self-Assembly. *Advanced Materials*, 22, 2538-2541.

Giannatsis, J. and Dedoussis, V., 2009. Additive Fabrication Technologies Applied to Medicine and Health Care: A Review. *International Journal of Advanced Manufacturing Technology*, 40 116-127.

Gibson, L. J., 1985. The Mechanical Behaviour of Cancellous Bone. *Journal of Biomechanics* 18(5): 317-328.

Gibson, L. J., 2012. The Hierarchical Structure and Mechanics of Plant Materials. *J. R. Soc. Interface* doi: 10.1098/rsif.2012.0341.

Hague, R.J., Campbell, R.I. and Dickens, P.M., 2003. Implications on Design of Rapid Manufacturing". *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 217(1), 25-30.

Heule, M., Vuillemin, S. and Gauckler, L.J., 2003. Powder-Based Ceramic Meso- and Microscale Fabrication Processes. *Advanced Materials*, 15(15), 1237-1245.

Hoque, M.E., CHuan, Y.L. and Pashby, I., 2012. Extrusion Based Rapid Prototyping Technique: An Advanced Platform for Tissue Engineering Scaffold Fabrication. *Biopolymers,* 97(2), 83-93.

Kai, C.C., Leong, K.F. and Lim, C.S., 2010. Rapid Prototyping: Principles and Applications.

Khoshnevis, B., 2004. Automated construction by Contour Crafting—related robotics and information sciences, *Automation in Construction Special Issue: The Best of ISARC 2002*, 13 (1), 5–19

Kumar, U.N., Kratz, K., Wagermaier, W., Behl, M. and Lendlein, A.. 2010. Non-contact Actuation of Triple-Shape Effect in Multiphase Polymer Network Nanocomposites in Alternating Magnetic Field. *J. Mater. Chem*., 20, 3404–3415.

Kumar, S. and Kruth, J.-P., 2009. Composites by Rapid Prototyping Technology. *Materials & Design*, 31(2), 850-856)

Le, T.T., Austin, S.A., Lim, S., Buswell, A., Gibb , A.G.F., Thorpe, T., 2011. Mix Design and Fresh Properties for High-Performance Printing Concrete. *Materials and Structures*.

Li, L. and Fourkas, J.T., 2007. Multiphoton Polymerization. *Materials Today*, 10(6), 30-37.

Lim, S., Buswell, R.A., Le, T.T., Austin, S.A., Gibb, A.G.F., Thorpe, T., 2011. Developments in Construction-Scale Additive Manufacturing Processes. *Automation in Construction*, 21, 262-268.

Melchels, F.P.W., Domingos, M.A.N., Klein, T.J., Malda, J., Bartolo, P.J., and Hutmacher, D.W., 2011. Additive Manufacturing of Tissues and Organs. *Progress in Polymer Science*, 1-26.

Melchels, F.P.W., Feijen, J., Grijpma. D.W., 2010. A Review on Sereolithography and Its Applications in Biomedical Engineering. *Biomaterials*, 31(24), 6121-6130

Mirkin, C.A., Neimeyer, C.M., Khademhosseini, A., Ling, Y., Karp, J.M., Langer, R., 2007. Chapter 18 Micro- and Nanoscale Control of Cellular Environment for Tissue Engineering. *Nanobiotechnology II: More Concepts and Applications.*

Oxman, N., 2010. Material-based Design Computation. PhD Thesis, Massachusetts Institute of Technology. 328 p.

Oxman, N., 2010. Structuring Materiality: Design Fabrication of Heterogeneous Materials. *Architectural Design*, 80(4), 78-85.

Oxman, N., 2011. Variable Property Rapid Prototyping. *Virtual and Physical Prototyping*, 6(1), 3-31.

Oxman, N., Keating, S. and Tsai, E., 2011. Functionally Graded Rapid Prototyping, *Innovative Developments in Virtual and Physical Prototyping: Proceedings of the 5th International Conference on Advanced Research in Virtual and Rapid Prototyping*, Leiria, Portugal, pp. 483-490.

Oxman, N., Rosenberg, J.L., 2009. Material-based Design Computation: An Inquiry into Digital Simulation of Physical Material Properties as Design Generators. International Journal of Architectural Computing, 5(1), 26-44.

Pfeiffer, M., Beyer, A., Fritz, T. and Leo, K., 1998. Controlled Doping of Phthalocyanine Layers by Cosublimation with Acceptor Molecules: ASsystematic Seebeck and Conductivity Study. *Appl. Phys. Lett*., Vol. 73, No. 22, 3202 -3204.

Ryder, G., Ion, B., Green, G., Harrison, D. and Wood, B., 2002. Rapid Design and Manufacture Tools in Architecture. *Automation in Construction*, 11(3), 279-290.

Sheng, W., Xi, N., Chen, H., Chen, Y. and Song, M., 2003. Surface partitioning in automated CAD-guided tool planning for additive manufacturing, *IEEE*, 2, 2072-2077.

Singh, M., Berkland, C. and Detamore, M.S., 2008. Strategies and Applications for Incorporating Physical and Chemical Signal Gradients in Tissue Engineering. *Tissue Engineering Part B*, 14(4), 341-366.

Vorndran, E., Klarner, M., Klammert, L., Grover, M., Patel, S., Barralet, J.E. and Gbureck, U., 2009. 3D Powder Printing of B-Tricalcium Phoshate Ceramics Using Different Strategies. *Advanced Engineering Materials*, 10(12), B67-B71.

White, D., 2001. Rapid Prototyping Processes. Encyclopedia of Materials: Science and Technology, 8003-8009.

Wu, G., Langrana, N.A., Sadanji, R. and Danforth, S., 2002. Solid Freeform Fabrication of Metal Components Using Fused Deposition of Metals. *Materials & Design*, 23 (1), 97-105.

Xie, T. and Rousseau, I.A., 2009. Facile tailoring of thermal transition temperatures of epoxy shape memory polymers. *Polymer*, 50, 1852–1856.

Yan, X. and Gu P., 1997. A Review of Rapid Prototyping Technologies and Systems. *Computer-Aided Design*, 28(4), 307-318.