Functionally Graded Rapid Prototyping

Neri Oxman, Steven Keating and Elizabeth Tsai
Mediated Matter Group, MIT Media Lab

ABSTRACT: Functionally Graded Rapid Prototyping (FGRP) is a novel design approach and technological framework enabling the controlled spatial variation of material properties through continuous gradients in functional components. Such variations are traditionally achieved as discrete delineations in physical behavior by fabricating multiple parts comprised of different materials, and assembling them only after the fabrication process has been completed. Recent advances in Computational Topology Design (CTD) and Solid Free-Form Fabrication (SFF) are promoting the creation of building components with controlled micro-, and macro-architectural features. The FGRP approach combines a novel software environment with a mechanical output tool designed as a 3-D printer to allow computer control of material distribution within a monolithic structure. Inspired by the integration of material, structure and form found in natural systems, this biologically inspired design approach allows for physical prototyping of graduated properties in product and architectural design scales. FGRP introduces the potential to dynamically mix, grade and vary the ratios of different materials, resulting in continuous gradients, and structurally optimized designs with efficient use of materials, reductions in waste and production of highly customizable features. The paper presents the FGRP technology as part of an overall integrated design approach to functionally gradient design fabrication. Two work-in-progress explorations of FGRP implementation are presented: a robotic arm able to 3-D print concrete with controllable density and a 3-D printer for UV-curable polymers exploring variable elasticity. Research methods and processes devised for its development are presented and design applications demonstrated. Current technological limitations and future directions are discussed and their implications reviewed.

1 INTRODUCTION

1.1 Background

Current rapid prototyping technologies, specifically additive manufacturing platforms, are limited in their capacity to represent graduated material properties. Their basic strategy is typically to assign material properties to pre-shaped building components such as concrete columns or fiberglass panels (Sachs et al. 1993). Within the design process, this translates into assigning a material property to predefined solids or closed surface polygons (Sheng et al. 2003). Both computer-aided design (CAD) tools and industrial fabrication processes are thus not set up to represent graduation and variation of properties within solids such as varied density in concrete, varied elasticity in rubber, or varied translucency in glass (Oxman 2011). As a result, the design process is constrained to the assignment of discrete and homogeneous material properties to a given shape (Oxman 2011).

The paper introduces a data-driven fabrication approach for designing and prototyping materials with graduated properties inspired by functionally graded materials found in nature.

1.2 Problem Definition

Functionally graded materials, which are materials with spatially varying composition or microstructure, are omnipresent in nature. A typical cross-section of a palm tree will reveal radial density gradients corresponding to the bending stiffness instantiated across its height (Rich 1987, Gibson et al. 2010); cancellous bone exhibits sponge-like cellular tissue with dynamic distributions corresponding to loading patterns (Gibson 1985, Keaveny et al. 1993). Such natural materials offer material and structural efficiencies at various length scales (Ortiz &Boyce 2008).

In contrast to natural materials and biological tissues, industrially fabricated constructions, such as concrete pillars, are typically volumetrically homogenous. While the use and application of homogenous materials allow for ease of production, many qualities - such as improvements in strength, weight, material usage, and functionality - could be obtained by the development and application of functionally graded materials at the product and architectural scales.

2 AIMS & OBJECTIVES

2.1 Developing a New Fabrication Approach

The mechanical response of materials designed and engineered with spatial gradients in composition and structure is of considerable significance in diverse disciplines such as biomechanics, fracture mechanics, optoelectronics, geology, tribology, nanotechnology, product engineering and even architectural design (Miyamoto 1999). Damage and failure resistance of surfaces to normal and sliding contact or impact can be substantially controlled and modified through such gradients. Graded materials hold a profound place in the future of material engineering; the ability to synthetically engineer and fabricate products with material gradients using additive fabrication offers improvements in structural and environmental performance, enhances material efficiency, promotes material economy and optimizes material distribution (Markworth et al. 1995). These processes however, are known to exist predominantly at the micro scale, and are well known in fields such as tissue engineering (Fan et al. 2000, Yang et al. 2002, Yeong et al. 2004).

Given the significant potential of the ability to design and fabricate building components with varied properties (i.e. density, elasticity, translucency, etc.) supporting the integration of functions (i.e. load-bearing, natural ventilation, etc.), this work seeks to develop modeling and fabrication environments for functionally graded products of industrial application and architectural scale.

The paper aims to introduce the Functionally Graded Fabrication (FGF) process as a general approach to the design of structural components with graduated properties. In addition, the work will demonstrate a novel deposition technology, coined by the authors Functionally Graded Rapid Prototyping (FGRP). This technological framework offers gradation control of materials within one 3-D print with the aim of increasing mechanical efficiency and reducing energy input in the product's generation and lifespan.

We introduce the application of this approach in two material contexts – polymers and concrete – with the aim of enabling 3-D rapid prototyping of structural components with variable properties corresponding to structural, functional, and environmental conditions.

2.2 Developing Novel Design and Fabrication Processes Using FGRP

The aim is to produce an automated tool able to dynamically mix and vary the ratios of different component materials in order to produce complex continuous gradients in monolithic structures. Two separate examples of FGRP-based processes are being developed: a variable-density concrete system and a variable-elasticity polymer system. We report upon work-in-progress for the utilization of this approach in product-design scales, and speculate on its further development and automation.

3 STATE OF THE ART

3.1 Comparison to Existing RP Technologies and Prior Arts

Rapid Fabrication (RF) and Rapid Manufacturing (RM) technologies have emerged, since the mid 1980's, as promising platforms for building construction automation (Jacobs 1992). The FGF approach and potential technologies defer profoundly from current additive fabrication technologies in that they aim to produce material organizations of varied properties. Generally classified by the material phase used in their extrusion – whether liquid-based (e.g. stereolithography), powder-based (e.g. selective-laser sintering), or solid-based processes (e.g. fused deposition modeling) – consistent to all such technologies is the use of materials with homogeneous properties for prototyping and fabrication purposes (Jacobs 1992, Gibson &Shi 1997, Weiss et al. 1997). An expanded review of prior arts is provided in (Oxman 2011).

3.2 Functionally Graded Materials

The general idea of structural gradients was initially proposed for composites and polymeric materials in 1972 (Miyamoto et al. 1999), but it was not until the 1980's that actual models investigating the design, fabrication and evaluation of graded structures were proposed.

Functionally Graded Materials (FGMs) are characterized by the gradual variation in composition and structure over their volume, resulting in corresponding changes in material properties. Such materials can be designed and engineered for a specific set of functions and applications. Various approaches based on particulate processing, preform processing, layer processing and melt processing are used to fabricate FGMs.

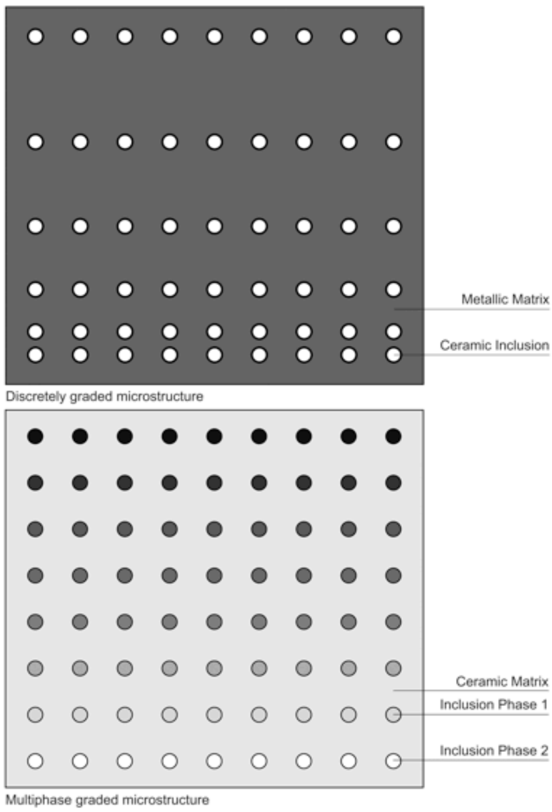

Figure 1. Graphic illustrations of discretely graded (top) and multiphase graded (bottom) microstructures of functionally graded materials. Within FGMs, the different micro-structural phases have different functions; the overall FGMs attain their multifunctional status from their property gradation, thus enabling various multifunctional tasks by virtue of spatially tailored microstructures.

PREVIOUS WORK & APPLICATIONS

4.1 Variable-Property Design Fabrication

Previous work has been carried out setting up the theoretical, methodological, and technical foundations for Variable Property Design Fabrication (Oxman 2010).

A variable-property 3-D printing prototype able to dynamically mix and vary the ratios of different materials in order to produce a continuous gradient in a 3-D printed part was developed. This project establishes a novel nozzle design coupled with a mixing chamber that can produce a continuous gradient, using colors as a substitute for material properties (Oxman 2010, Oxman 2011).

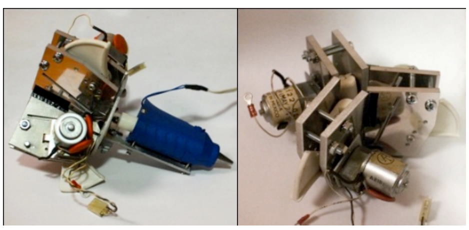

Figure 2. Physical prototype of Variable-Property 3-D printer.

4.2 Design Applications

Potential design applications for Functionally Graded Rapid Prototyping occupy a vast range of possibilities in medical device design, product design, and architectural design (Oxman 2007, Oxman 2009). We present two examples facilitated by the FGF approach: *Beast*, a prototype for a Chaise Lounge, is a 3-D printed chair. It combines structural, environmental and corporeal performance by adapting its thickness, pattern density, stiffness, flexibility and translucency to load, curvature, and skin-pressured areas respectively. A single continuous surface acting both as structure and as skin is locally modulated to cater for structural support on the one hand, and corporeal performance on the other.

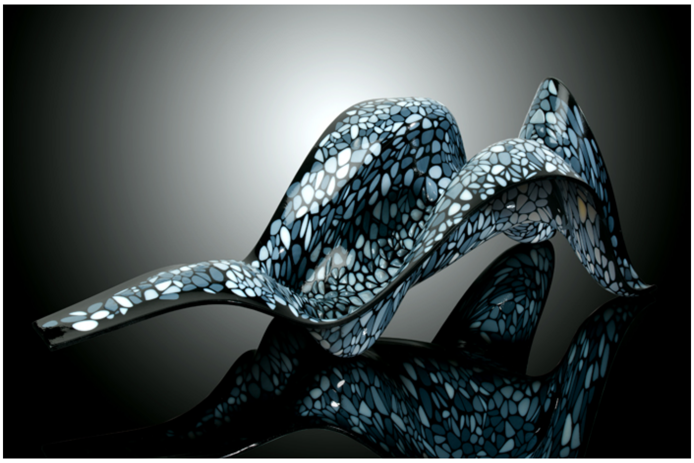

Figure 3. Variable stiffness and elasticity as demonstrated by Beast. Prototype for a Chaise Lounge. 2008. Boston Museum of Science.

Figure 4. Variable thickness and elasticity as demonstrated by Carpal Skin. Prototype for medical splint. 2008. Boston Museum of Science.

Carpal skin is a process by which to map the pain-profile of a particular patient – its intensity and duration - and distribute hard and soft materials to fit the patient's anatomical and physiological requirements limiting movement in a customized fashion.

The formation process involves case-by-case pain registration and material property assignment. The 3-D scan of the patient's hand, including its pain registration, is mapped to a 2-D representation on which the distribution of elastic modulus is applied. This pain-map is then folded back to its 3-D form and 3-D printed using photopolymer composites (Oxman 2010).

5 METHODOLOGY

5.1 Biologically-inspired Rapid Fabrication

Previous work and current work reported upon in this paper are developed and implemented following research into biological systems and natural formation processes. Rather than a product-oriented approach to fabrication, we devise a process-oriented approach mimicking the formation of tissue and natural material property variation as explored in muscle (i.e. variable elasticity), or bone tissue (i.e. variable density).

Material formation processes found in nature do not operate by the same logic traditionally applied in digital design processes and rapid fabrication platforms, such as additive manufacturing (Sarikaya 1999). Nature constructs solid objects by means of local processes using unformed locally available raw materials (Vincent et al, 2006). Demonstrably sustainable, natural structures possess the highest level of seamless integration and precision with which they serve their functions (Oxman 2010). A key distinguishing trait of nature's designs is the capability in the biological world to generate complex structures of organic or inorganic multifunctional composites designed with variable properties observed, for example, in the way in which fibers are oriented in wood or mechanisms by which calcium is distributed in the bone as illustrated below (Benyus 1997, Gibson & Ashby 1982, Freyman et al. 2001). Combined with extracellular matrices, these structural biomaterials form microstructures engineered to adapt to prearranged external constraints introduced upon them during growth or throughout their life span (Vincent 1982). Such constraints generally include combinations of structural and environmental performance (Gibson & Ashby, 1982, Vincent 1982, Vogel 2003). Since all biological materials are made of fibers, their multi-functionality often occurs at the micro or nano scale and is typically achieved by mapping performance requirements to strategies of material structuring and allocation; material is concentrated in regions of high strength and dispersed in areas where maximal stiffness is not required. The shape of matter is therefore directly linked to the influences of forces acting upon it (Neville 1993, Vogel 2003).

6 3-D PRINTING VARIABLE DENSITY CONCRETE

6.1 Variable Density Concrete Foam Fabrication

Presented in this section is work-in-progress for the rapid fabrication of variable-density cement foams. First prototypes are presented illustrating foams of varying densities using aluminum powder admixtures. The project is motivated by the hypothesis that density gradients in structural building components made of concrete may increase the strength of a structural component while reducing material waste.

6.2 Biological Inspiration

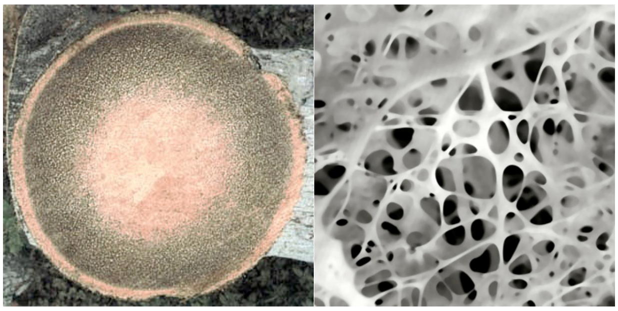

Figure 5. Left: radial density in palm-tree stem; Right: variable density in spongy bone. Palm tree cross-section image from the Food and Agriculture Organization of the United Nations (FAO, 1996).

The work is inspired by load-induced variable densities found in cancellous bone and by radial-gradient densities found in palm tree stems. Palm trees maintain a roughly uniform diameter along their height by thickening the cell walls in certain regions, producing radial density gradients across the surface and volume area of the stem. The density is highest at the peripheries and lowest in the center, for example with densities ranging from 100-1000 kg/m^3 in a single stem of the *Iriartea gigantea* (Rich 1987).

6.3 Variable-Density Graded Fabrication of Concrete and Cement Foams

The aim is to design a novel rapid fabrication apparatus able to dynamically vary cellular materials corresponding to any given structural constraints. The following work focuses on cement and concrete foams where the density is controlled through an admixture of aluminum powder and lime, which react to produce hydrogen gas bubbles.

Compression samples of Type III Portland cement foams with varying density were produced and measurements of material density, pore size, and mechanical properties were taken using mass measurements, micrograph image analysis, and compressive strength testing, respectively. Measured foam data agrees well with existing data on cement foams made with a protein-based foaming agent (Tonyan 1991).

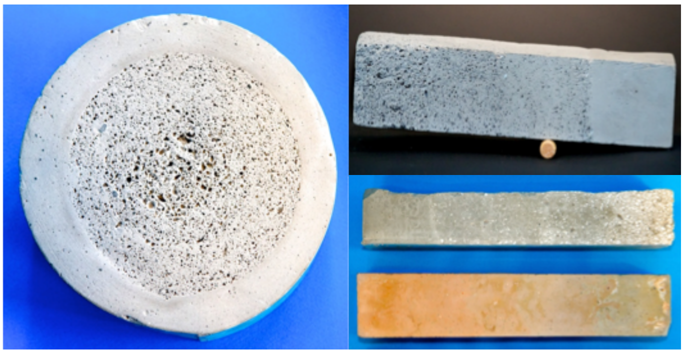

Figure 6. Left: Radial density gradient in a concrete sample produced by varying ratio of foaming agent (aluminum powder). Top right: Linear density gradient in a concrete sample with the center of gravity highlighted by the pivot point. Bottom right: Functional gradients of other various properties such as aggregate ratios (top), color/optical properties (bottom), and other material properties are possible. Samples made using Type III Portland cement and fly ash as the base material and were made with assistance from Timothy Cooke of the Building Technology program at MIT.

The porosity was able to be controlled by the proportion of aluminum in the mixture; past an optimum amount the porosity decreased as the ratio of aluminum to cement increased. The maximum porosity achieved was 40% using a weight ratio of 1.2 g/kg aluminum to dry cement mix. The compressive testing results strongly agree with the exponential ceramic strength model, with a found value of q = 5.4, compared to the q value of 7 found in the literature (Rice 1976). The implications of radial density gradients in concrete foams were explored and theoretical calculations using the experimentally found mechanical properties show that for a cylinder under bending stress, a graded beam can have 9% less mass than a solid cylindrical beam of the same dimensions and support the same load. This is achieved by grading the radial density to set the tensile strength equal to the tensile stress generated by the bending load (while maintaining a shear stress lower than the shear strength to ensure failure in bending). This creates a more efficient use of material by optimizing bending stiffness relative to weight.

6.4 Work-In-Progress: Automating Variable-Density Rapid Fabrication

Current work-in-progress looks into the controlled automation of density gradients in concrete using a robotic platform. Through the use of a dynamic mixing chamber and extrusion head mounted on a robotic arm (a 6-axes KUKA arm), we aim to 3-D print concrete with controllable density. This demonstrate of FGRP will use a rapid-set concrete mixture with either an aluminum foaming admixture or a protein-based foaming agent. The use of a 6-axes robotic arm offers complete positional and angular control of the extruder head, generating interesting fabrication possibilities utilizing a setup similar to current fused deposition modeling technologies. Additional material properties, such as aggregate ratios and optical properties (Figure 6) can also be controlled through dynamic mixing.

7 3-D PRINTING OF U-V CURABLE POLYMERS WITH VARIABLE ELASTICITY

7.1 Variable-Elasticity Fabrication

Presented here is work-in-progress for the rapid fabrication of functionally graded monolithic polymer products. The ability to 3-D print products with controllable gradients in material properties may allow for more optimized designs as well as reductions in the stresses and strains commonly present at the interface between materials of different properties.

7.2 Biological Inspiration

Biological structures are capable of transitioning seamlessly between materials of different compositions, properties, and microstructures. Natural materials such as human cartilage and many types of bird beaks exemplify how spatial variations in density and stiffness can help optimize the response of structures to environmental and mechanical constraints. The goal is to mimic these systems by developing a 3-D 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.

7.3 Biologically-Inspired Variable-Elasticity Graded Fabrication

In many biological systems, the physical properties of the materials are determined by the chemical composition and microstructure of its matrix. In soft collagenous tissues such as cartilage, for example, the mechanical behavior of the matrix is determined by the amount and crimp of the collagen it contains. Experimentally, increased ratios of collagen to proteoglycan in the cartilage matrix correspond to higher tensile moduli (Williamson 2003). We are currently in the process of developing polymer mixtures that, when combined in different ratios, produce blends with broad ranges of customizable mechanical properties. Shown in Figure 7 are examples of silicone and polyurethane samples containing gradients in hardness produced through blended casting.

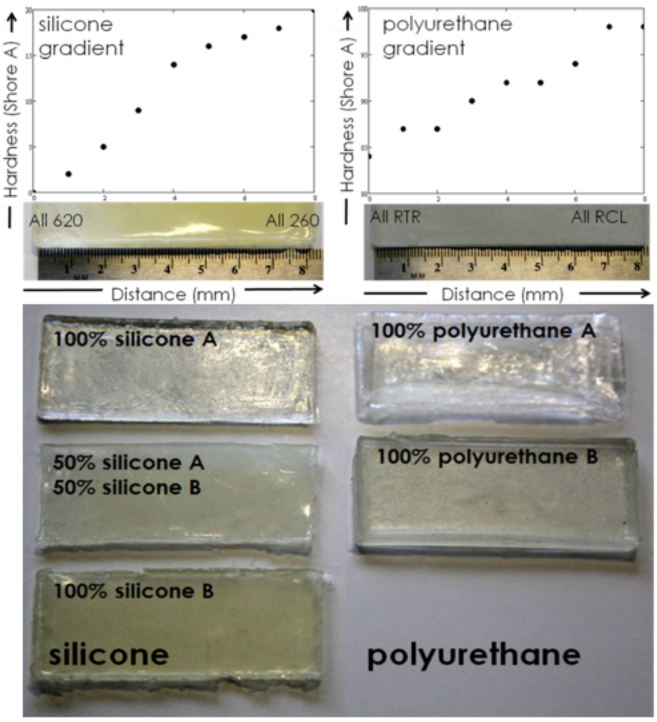

Figure 7. Samples generated by combining UV curable silicones and polyurethanes with various properties in a gradient across each sample.

7.4 Work-In-Progress: Automating Variable-Elasticity Rapid Fabrication

By controlling the ratios in which two or more polymers are mixed immediately prior to deposition and UV curing, monolithic structures with functional gradients can be produced using additive fabrication technologies. Current work-in-progress is focused on automating the controlled mixing and deposition of polymer layers using a 6-axes robotic arm, as well as integrating the physical fabrication platform with user design interfaces.

8 CONTRIBUTIONS

Functionally Graded Rapid Prototyping (FGRP) is a novel approach and method introducing the ability to dynamically mix and vary the ratios of component materials in complex 3-D distributions in order to produce continuous gradients in a 3-D printed part. This ability expands the potential of prototyping, since the varying properties allows for optimization of material properties relative to their structural and functional performance and for more accurate evaluations of the intended final product, such as stress testing. FGRP could also contribute to efficient conservation of material usage, high performance of integrated structures, optimized response to mechanical stimuli, and overall improved product life spans.

Finally, it is expected that in parallel to the emerging capabilities of multi-material, freeform fabrication, materials with a wide range of mechanical, electrical, thermal, and optical properties will soon be seamlessly 3-D printed. Indeed as of today, traditional CAD programs are inadequate in efficiently utilizing this vast design potential. In this research, we have outlined an approach and demonstrated the first steps in the design of a complimentary approach and potential technology acting as an additive digital fabrication platform supporting continuous cellular and elasticity gradients within a structural component to meet high level functional goals.

9 FUTURE WORK

Future work will focus on developing the robotically automated design fabrication platform to achieve numerically controlled variable density and variable elasticity in product scales. In addition, the development of a 6-axes 3-D printing platform (in contrast to conventional 3-axes platforms) will offer opportunities to explore additional avenues of 3-D printing such as automated embedded-part printing and integrating additional fabrication technologies with 3-D printing (i.e. milling, painting, casting, etc.). In parallel, continued exploration and development digital of form-generation environments will support the generation of 3-D forms incorporating material properties and behavior with potentially real-time fabrication feedback.

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