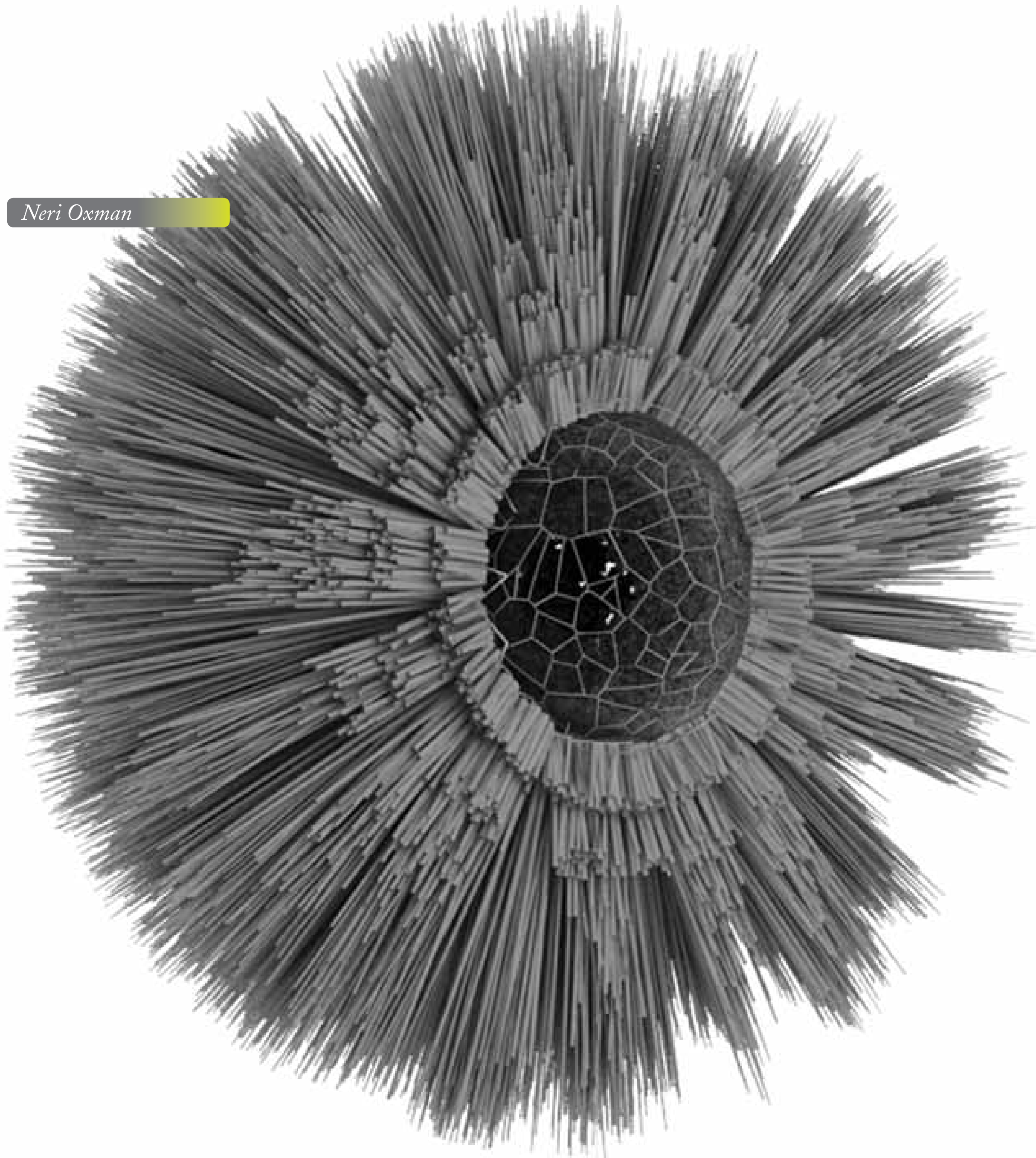
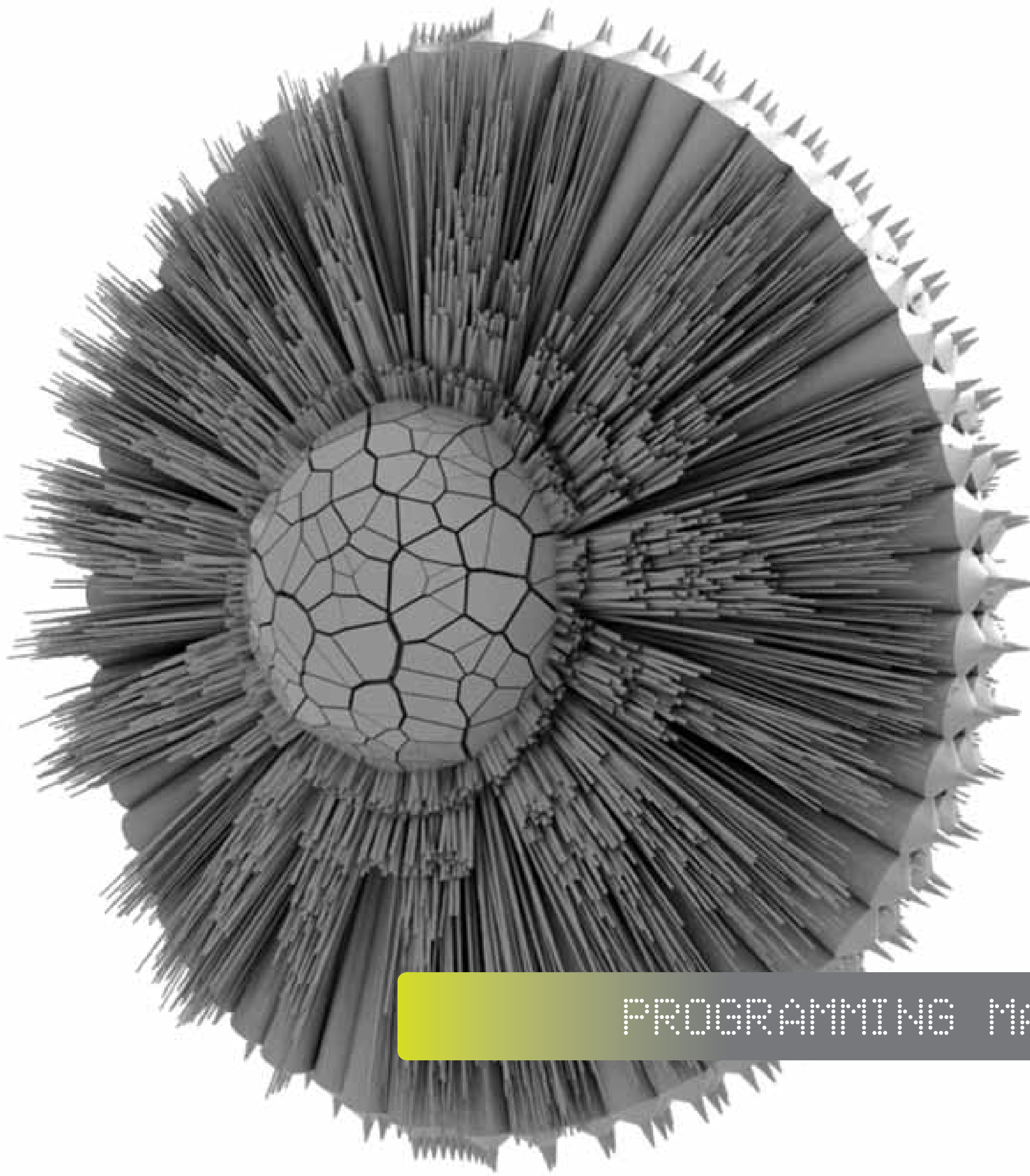
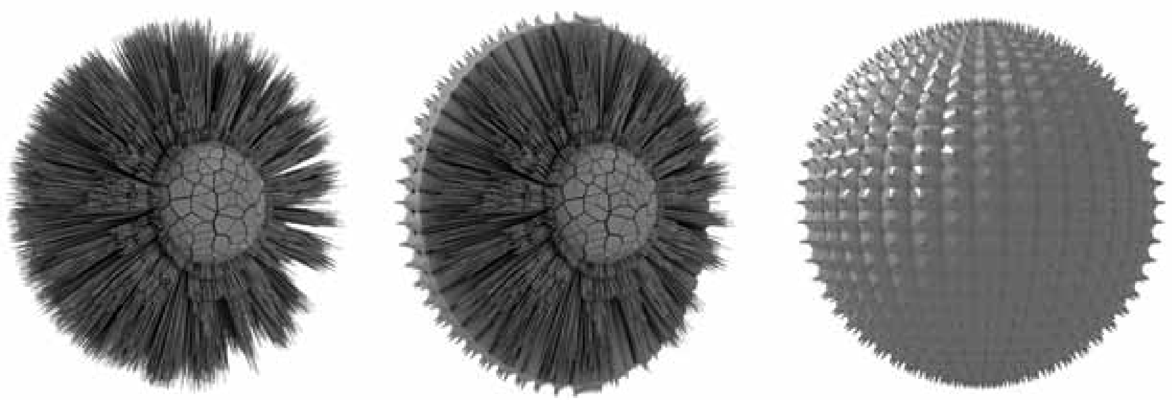
Neri Oxman

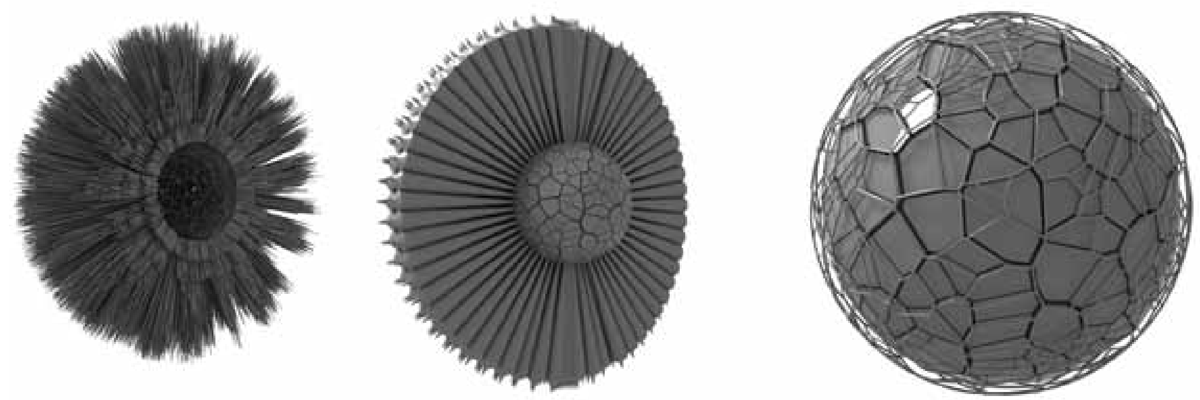




PROGRAMMING MATTER

A direct parallel can be made between the Modernist separation of form, structure and material and the more recent tripartite division in digital processes of modelling, analysis and fabrication, which has resulted in the predominance of geometric-driven form generation. Today, though, design culture is experiencing a shift to a new level of material awareness. Inspired by nature's strategies where form generation is driven by maximal performance with minimal resources through local material property variation, **Neri Oxman** investigates a novel design approach to digital fabrication that offers the potential to program physical matter.





Anthony DeVincenzi and Nicholas Wilkes Polanski, Seed Morphologies, Crafted By Nature, MIT Media Lab, Cambridge, Massachusetts, 2011
Digital models of *Plantanus Hybridia* and its structural anisotropy demonstrating (left)
1) Seed core; 2) Fibre fill and (right) 1) Achene head packing; 2) Achene shaft; 3) Achene anchor; 4) Core; 5) Core mesh; 6) Finer fill.

Digital form-finding has been known to support design processes characterised by the control and manipulation of formal elements as a function of the interaction between material and environment. Yet all too often such experiments have resulted in a rather traditional approach to material assignment during processes of fabrication and construction. Indeed, most praxis in the realm of materials in architectural design has centred on questions relating to material selection rather than to material generation. Imagine one could control the spatial distribution of finely grained material elements upon digital fabrication: Can physical matter be made programmable?

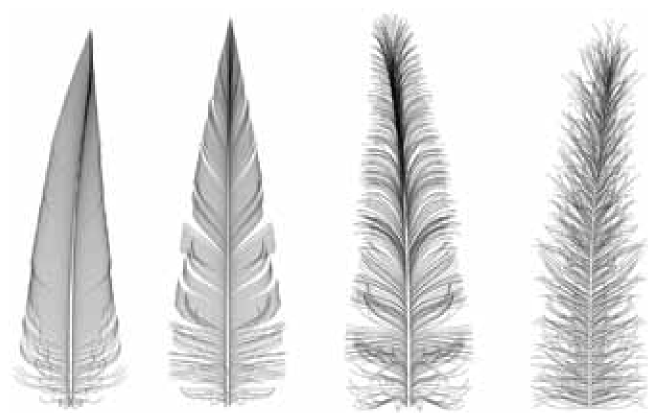
Until recently the function of materials in design processes was persistently treated as secondary to form itself. In the context of design materialisation, materials are traditionally predefined and classified as property pools.[1] This condition has been amplified by digital fabrication processes, which have exacerbated the tendency of the designer to materialise design by liberally accessing materials as a library of consistent and physically homogeneous properties.[2] In the natural world, however, materials are rarely homogeneous in shape and composition across a wide range of scales.[3] This is also the reason for the lack of consistently repetitive components in the landscape of the natural environment, contributing to energy conservation and high levels of mechanical efficiency.[4] What makes up nature's secret and how might such logic be emulated in the fabrication of the artificial?

Digital Anisotropy

Materials are traditionally classified by their various properties, as either structural or functional.[5] Structural materials are mainly exploited for their mechanical properties, while functional materials have some other purpose, in relation to electrical, thermal, optical properties, or combinations of them. In nature, however, it is often quite challenging to distinguish between structural and functional materials, as most biological materials such as wood, sponge and bone can be both structural (supporting the branches of a tree or the body) and functional (pumping water up to the leaves or storing energy), with different scales for these different roles. Nature achieves such integration by varying the material's properties and introducing in it directional (structural) changes relative to the structural, mechanical and environmental functions required. This ability is termed anisotropy. Anisotropy is defined as directional dependency and is expressed as a given difference in a material's physical property[6] when measured along different axes. The directional dependency of a physical property is easily found in most natural materials and is central to the structuring of materials and their behaviours.[7] In the fields of material science and engineering, the concept of anisotropy is tightly linked to a material's microstructure defined by its grain growth patterns and fibre orientation.[8] Beyond these scales, however, anisotropy may be utilised as a design strategy leading away from digital form-finding to trait finding and the potential programming of physical matter. In design, examples vary depending on the type of property being examined and the manufacturing technology applied to manipulate material organisation. Yet the extent to which anisotropy is explored, as a generative means to create form, is still rather limited and unexplored. If one were able to model anisotropy in the digital space – as part of the form-generation process – what would it look like?

Mathew Blackshaw, Philip R Seaton and Yushiro Okamoto, Feather Morphologies, Crafted By Nature, MIT Media Lab, Cambridge, Massachusetts, 2011
Close-up scan of the feather's generic structure. At the bottom left side, barbs have been parted using tweezers following a process of surface formation and self-healing which can be defined as and by geometrical anisotropy.

Early computational models describing geometrical anisotropy in a feather structure exploring four states of hook attachments, from consistently organised to scattered.



Functionally Graded Materials

Functionally graded materials, which are materials with spatially varying composition or microstructure, are omnipresent in nature. A typical cross-section of a palm tree reveals radial density gradients corresponding to the bending stiffness instantiated across its height.[9] Such natural materials offer material and structural efficiencies at various length scales.[10] In contrast to natural materials and biological tissues, industrially fabricated constructions, such as concrete pillars, are typically volumetrically homogeneous. While the use and application of homogeneous 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. Below are a few examples from the natural world, by way of defining three classes of anisotropy.

Functionally Gradient Geometrical Anisotropy
The internal structure of a typical feather exhibits the property of anisotropy relative to the function of self-healing. Self-healing is known as the zipping and unzipping mechanism that allows feathers to easily group and ungroup while interfacing with various external environments such as air or water. A typical feather is made of barbs, barbules and barbule hooks providing the structure by which it can cling to a neighbouring feather substructure. The hooks enable barbs to attach to other barb edges in a way that is both surface forming and self-healing. Differences in the degree of the barbules' length, density and overall spatial arrangement lead to differences in type for the overall feather structure, achieved by an anisotropy that can be geometrically described and demonstrated.

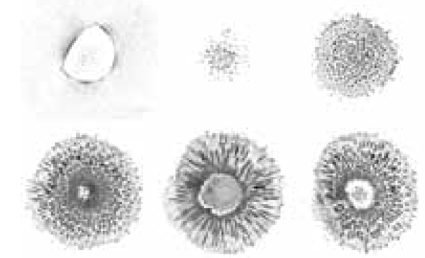
Functionally Gradient Structural Anisotropy
The sycamore seed (*Plantanus hybridia)* is made up of several fibre groups, each structured uniquely to cater for its relative function within the overall structure of the seed. This example illustrates the property of anisotropy that is structurally defined and demonstrated. The seed's matter is homogeneous in property; however, it is the way in which the fibre is distributed, its spatial orientation and material characteristics, that generate multiple, distinctively defined micro- and meso-structures within its functional unit.

Functionally Gradient Material Anisotropy
Abundant among cellular solids and many natural materials, functionally gradient material anisotropy is characterised by spatial heterogeneity. Sponges, like bone tissue, demonstrate such properties. They control the flow of water by various combinations of wholly or partially closing the oscula and ostia – their intake pores – as they correspond with underwater external stimuli. The structure of a typical dried sponge reveals the uneven distribution of holes generating a continuous lightweight tissue with varying degrees of density and porosity. Given the significant potential of the ability to design and fabricate building components with varied properties (density, elasticity, translucency) supporting the integration of functions such as load-bearing and natural ventilation, there is value in developing a modelling and fabrication environment for functionally graded products of industrial application and architectural scale.

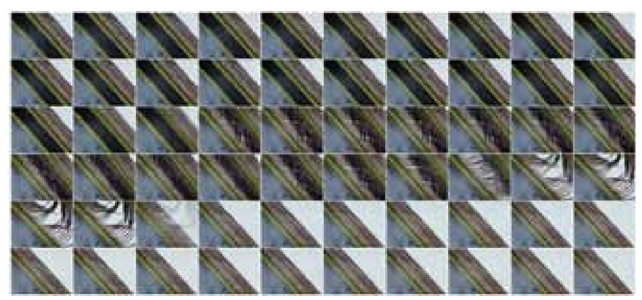
Functionally Graded Digital Fabrication
Current manufacturing and construction technologies,

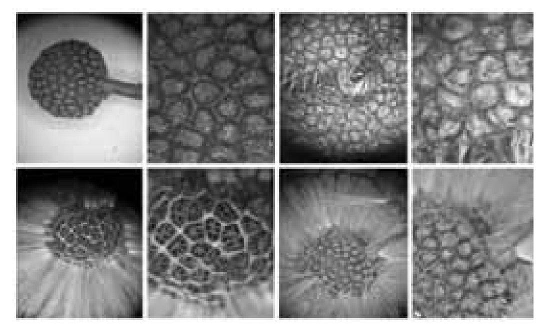
bottom left: Microscopic digital video (shot at approximately 20x and 400x) reveals the self-healing and surface-formation process in feathers, guided by geometric anisotropy. The process involves large numbers of tiny, relatively rigid hooks that are attached to flexible barbules, as they interact with the unhooked barbs on the 'paired' feather strand. When pulling the strands apart, the feather's barbs appear to 'unzip'; while local deformations occur during the unzipping process, the feather readily returns to its more relaxed state, allowing it to 're-hook' when barbs are jostled slightly against their mates. This combination of flexibility and rigidity produces a unique resiliency in the feather at a macroscopic scale.

below: CT scans of *Plantanus Hybridia* illustrating the various cell structures defined by fibre anisotropy that make up the seed.



Anthony DeVincenzi and Nicholas Wilkes Polanski, Seed Morphologies, Crafted By Nature, MIT Media Lab, Cambridge, Massachusetts, 2011
bottom right: Electron-microscopy images of Plantanus Hybridia demonstrating the seed core and mesh structure providing a frame for fibres and spokes. These two distinct structural systems are made from a consistently uniform material, structured uniquely to accommodate for distinctive functions. Image generated and processed by Anthony DeVincenzi and Nicholas Wilkes Polanski.





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 fibreglass panels.[11] Within the design process, this translates into assigning a material property to predefined solids or closed-surface polygons.[12] Both computer-aided design (CAD) tools and industrial fabrication processes (CAM) 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. As a result, the design process is constrained to the assignment of discrete and homogeneous material properties to a given shape.[13]

Functionally graded digital fabrication is a general approach to the design of structural components with graduated properties. The technical platform is comprised of 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 this approach are currently being developed at MIT's Mediated Matter Research Lab: a variable-density concrete system and a variable-elasticity polymer system.[14]

Variable Density Digital Fabrication

The work at MIT 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. The work-in-progress includes the rapid fabrication of variable-density cement foams, with prototypes illustrating foams of varying densities using aluminium powder admixtures. 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. Measured foam data agrees well with existing data on cement foams made with a protein-based foaming agent.[15]

The project also looks into the controlled automation of density gradients in concrete using a robotic platform. Through the use of a dynamic mixing chamber and an extrusion head mounted on a robotic arm, concrete with controllable density can be 3-D printed.[16] The use of a six-axis robotic arm offers complete positional and angular control of the extruder head, generating interesting fabrication possibilities utilising a set-up similar to current fused deposition modelling technologies. Additional material properties, such as aggregate ratios and optical properties, can also be controlled through dynamic mixing.

Variable Elasticity Digital Fabrication

In many biological systems, the physical properties of the materials are determined by the chemical composition and microstructure of the material's matrix. In soft collagenous tissues such as cartilage, the mechanical behaviour of the matrix is determined by the amount and crimp of the collagen it contains.[17] Experimentally, increased ratios of collagen to proteoglycan in the cartilage matrix correspond to higher tensile moduli.[18] The work at MIT uses polymer mixtures that, when combined in different ratios, produce blends with broad ranges of customisable mechanical properties.

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. The current work focuses on automating the controlled mixing and deposition of polymer layers using a six-axis robotic arm, as well as integrating the physical fabrication platform with user design interfaces.

Functionally graded digital fabrication is a novel design approach offering the potential to program physical matter. Its technological method enables dynamically mixing and varying the ratios of component materials in complex 3-D distributions in order to produce continuous gradients in 3-D fabricated objects. This expands the potential of prototyping, since the varying of properties allows for optimisation of material properties relative to their structural and functional performance, and for formal expressions directly and materially informed by environmental stimuli.[19]

This approach could potentially contribute to efficient conservation of material usage, high performance of integrated structures, optimised response to mechanical stimuli, and overall improved product lifespans. It is anticipated that in parallel to the emerging capabilities of multi-material, free-form fabrication, materials with a wide range of mechanical, electrical, thermal and optical properties will soon be seamlessly fabricated. Indeed, traditional CAD programs are inadequate in efficiently utilising this vast design potential. The MIT research outlines an approach for programming matter and demonstrates the first steps in rendering physical the digital design substrate. Through a new fabrication approach supporting continuous property gradients within structural form, designers can meet high-level functional goals while creating new expressions in nature's dialect. AD

Notes

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6. Ie absorbance, refractive index, etc.
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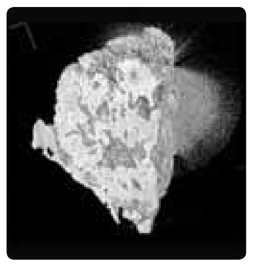
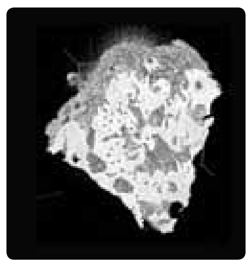
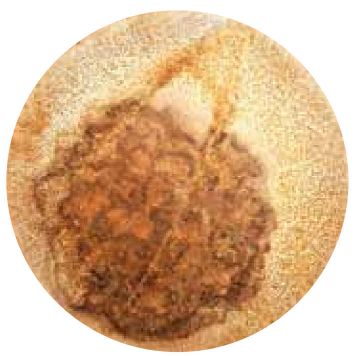
18. N Oxman, 'Variable Property Rapid Prototyping', op cit.





David Lakatos, Cara Liberatore and Marshall Prado, Sponge Morphologies, Crafted By Nature, MIT Media Lab, Cambridge, Massachusetts, 2011
left: CT scan of a typical sponge structure highlighting regions of various densities across the surface and volume area of the scan.

Steven Keating and Timothy Cook, Variable-Density Printing, Mediated Matter Group, MIT Media Lab, Cambridge, Massachusetts, 2011
below: Right: Radial density in palm-tree stem. Left: Variable density in cement.



Material tests for a concrete extruder head capable of dynamic density and aggregate control. Mechanical foaming techniques are automated using a six-axis robotic arm to produce lightweight, floating concrete structures with programmable porosity. The image illustrates a linear density gradient in a concrete sample with the centre of gravity highlighted by the pivot point produced by varying the ratio of foaming agent.

David Lakatos, Cara Liberatore and Marshall Prado, Sponge Morphologies, Crafted By Nature, MIT Media Lab, Cambridge, Massachusetts, 2011
Initial concept models demonstrating geometrical, structural and material anisotropy mimicking the natural sponge. The top image shows the fabrication set-up for the physical modelling of the sponge system which is based on a sealed watertight container into which inflatable units of various volumes are inserted, constricting the sponge's external membrane form. An additional internal distribution set-up of inflatable bodies determines the spatial porosity across the volume area of the system. The bottom image illustrates material density variation across unit cells within the sponge system. Variations in strength, density and elasticity are achieved by programming the spatial distribution of elastic material.

Steven Keating, Variable Density Fabrication, Mediated Matter, MIT Media Lab, Cambridge, Massachusetts, 2011
Image demonstrating the six-axis 3-D printing capabilities of the robotic platform. The code developed for this platform allows the designer to take a 3-D part file, slice it into layers and paths, and convert it into a robotic industrial operating language. The image demonstrates initial results using various test extruder heads such as a silicone extruder and an ABS plastic extruder in 0.3-millimetre layer thickness with an accuracy of 0.02 millimetres.

Image demonstrating the robotic arm platform acting as a six-axis 3-D printer for the digital fabrication of variable elasticity gradients in product design scales.