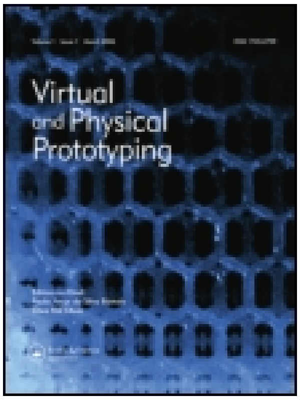

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Variable property rapid prototyping

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Variable property rapid prototyping

Inspired by nature, where form is characterized by heterogeneous compositions, the paper presents a novel approach to layered manufacturing entitled variable property rapid prototyping

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Additive prototyping technologies have become an efficient and common means to deliver geometrically precise functional prototypes in relatively short periods of time. Most such technologies, however, remain limited to producing single-material, constant-property prototypes from a restricted range of materials. Inspired by Nature, where form is characterized by heterogeneous compositions, the paper presents a novel approach to layered manufacturing entitled variable property rapid prototyping. VPRP introduces the ability to dynamically mix, grade and vary the ratios of material properties to produce functional components with continuous gradients, highly optimized to fit their performance with efficient use of materials, reduction of waste and production of highly customizable features with added functionalities. A novel software approach entitled Variable Property Modelling is presented allowing designers to create structural components defined by their desired material behaviour. Research methods are presented and design applications demonstrated. Current technological limitations and future directions are discussed and their implications reviewed.

Keywords: additive manufacturing; variable property fabrication; rapid prototyping; performance-based design; bio-inspired fabrication.

Introduction

The problem with current approaches to virtual and physical prototyping

The use of additive manufacturing technologies for rapid prototyping takes as input virtual computer aided designed models and transforms them into thin, horizontal and successive cross-sections in the creation of physical three-dimensional objects (Sachs *et al.* 1993). These processes assume, however, that such objects are geometrically defined without necessarily considering their material makeup and composition (Oxman 2009a,b). The basic strategy behind additive manufacturing is typically to assign a constant material property to pre-shaped structural components defined as solids or closed surface polygons. Furthermore, both computer-aided design tools as well as rapid prototyping processes are not set up to represent graduation and variation of properties within solids such as varied density or elasticity. As a result, the design process is constrained to the assignment of discrete and homogeneous material properties to a given shape. It is also characterised by a methodological partition between virtual modelling and physical prototyping (Chua *et al.* 1999). Overall, current approaches to virtual and physical prototyping lack the ability to model and fabricate continuously varying material properties as part of the modelling and production phases respectively, resulting in material waste and structurally non-efficient prototypes.

Towards a bio-inspired fabrication approach to virtual and physical prototyping

Natural structures possess a high level of seamless integration and precision with which they serve their functions. A

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key distinguishing trait of nature's designs is its capability in the biological world to generate complex structures of organic, or inorganic, multifunctional composites such as shells, pearls, corals, teeth, wood, silk, horn, collagen, and muscle fibres (Benyus 1997). Combined with extracellular matrices, these structural biomaterials form microstructures engineered to adapt to prearranged external constraints (Benyus 1997, Vincent 1982). Such constraints generally include combinations of structural, environmental and corporeal performance criteria. Since many biological materials are made of fibrous heterogeneous compositions, their multi-functionality is typically achieved by mapping performance requirements to strategies of material structuring and allocation. The shape of matter is therefore directly linked to the influences of force acting upon it (Vogel 2003). Material is concentrated in regions of high strength and dispersed in areas where stiffness is not required. It is a well-known fact that in nature shape is cheaper than material, yet material is cheap because it is effectively shaped, heterogeneously distributed, and efficiently structured.

Nature's ability to gradually distribute material properties by way of locally optimizing regions of varied external requirements, such as the bone's ability to remodel under altering mechanical loads or the wood's capacity to modify its shape by way of containing moisture is facilitated fundamentally by its ability to simultaneously model, simulate and fabricate material structures (Figure 1). The structural properties of wood, for instance, not unlike most biological materials, can widely vary when measured with the growth grain or against it such that its hardness and strength may differ for a given sample as measured in different orientations (Figures 2–4).

Compared to manmade materials, many natural materials, particularly in the plant kingdom, mechanically outperform some of the most common materials used by engineers and architects. Woods have strength per unit weight comparable with that of the strongest steels; shell, bone, and antler have toughness an order of magnitude greater than engineering ceramics; and mature bamboo stalks have slenderness ratios which are remarkable even by the standards of modern engineering (Ashby *et al.* 1995). Yet Nature's materials are less than half as dense as many of these artificial materials and are characterized by very low weight and are functional for the plant to sustain (Niklas 1992). What are the attributes that make natural materials so effective?

In *The Mechanical Properties of Natural Materials,* Gibson explores various classes of natural materials in examining the relation between their composite microstructures and their exceptionally high values of mechanical performance (Gibson *et al.* 1995). The function of these natural materials exploits their exceptional structural properties: woods and palms resist bending and buckling, silk stores elastic strain energy, muscle stores and releases elastic strain energy during locomotion, and so on. Such relations have significant implications for the design of mechanically efficient engineering materials: when considering beams and plates of a given stiffness or strength, or columns of a given buckling resistance, woods, palms and bamboo are among the most efficient materials available (Gibson and Ashby 1982, Gibson *et al.* 1995). Gibson reviews four classes of natural materials: woods, palm and bamboo, stems and quills. The results of the analyses suggest novel microstructures for mechanically efficient engineering materials for bending stiffness and elastic buckling resistance achieved by optimizing micro-structural organization to fit performance requirements such that the cellular structure can enhance performance for loading parallel to the grain (Gibson *et al.* 1995).

Common to all these examples are the exceptional properties of natural materials arising mainly through novel cellular microstructures that make for efficient engineering materials (Figures 5 and 6). Nature's building blocks are therefore not as unique as their structuring in that it is not so much the material properties of the components as their arrangement within the natural composites, which give rise to such a vast range of properties. Thus we may postulate that *Material Structure* is an important design property of natural design as well as a significant body of design knowledge.

A bio-inspired fabrication approach calls for a shift from shape-centric virtual and physical prototyping to material-centric fabrication processes. In this approach, not unlike he bones' remodelling process (Figure 7), the distribution of material properties is informed by structural and environmental performance criteria acting upon the component, and contributes to its internal physical makeup. It thus requires a set of virtual and physical prototyping tools and methods that support a variable-fabrication approach, not unlike Nature's.

Aims and objectives

The paper aims at introducing the variable property modeling (VPM) process as a general approach to the design of building components with graduated properties. In addition, the work will demonstrate a novel deposition technology, coined by the author variable property rapid prototyping (VPRP), which offers gradation control of materials within one 3D print with the aim of increasing mechanical efficiency and reducing energy input.

Novel software environment for variable property modelling (VPM)

The mechanical response of materials designed and engineered with spatial gradients in composition and structure

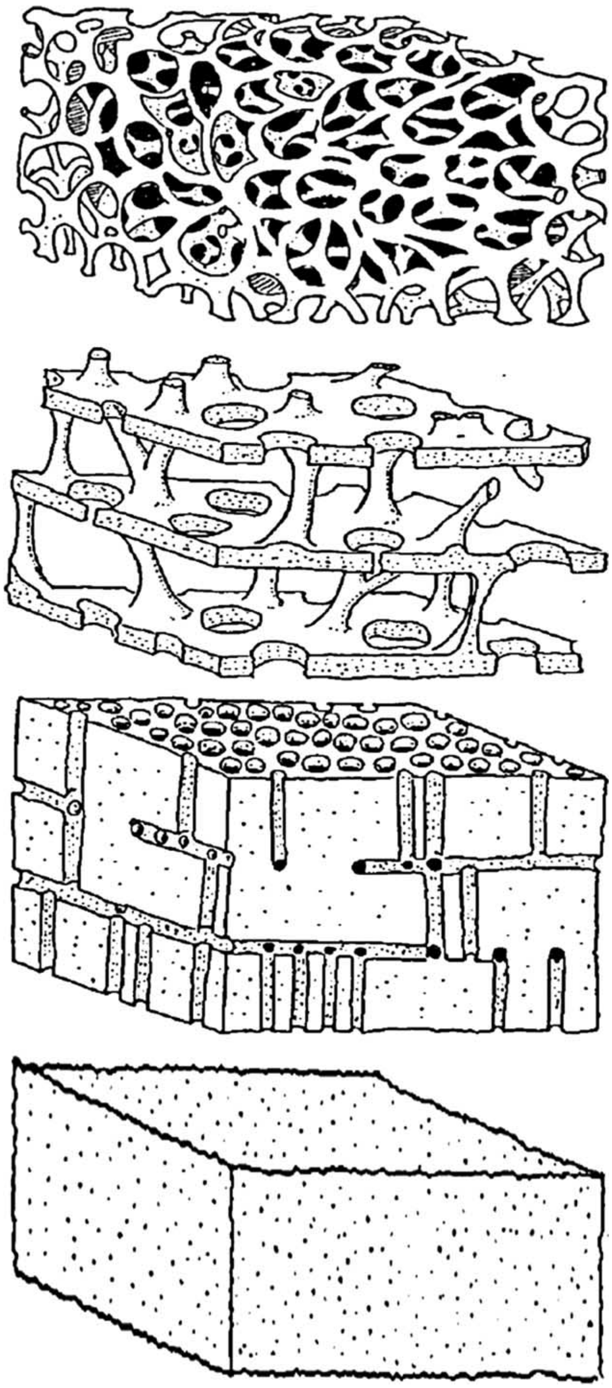


Figure 1. Schematics of various microstructures found in the tests and spines of sea urchins (*Echinodermata*). Organizational principle from top to bottom: labyrinthic, microperforate, imperforate (Smith 1980; Carnevali *et al.* 1991).

is of considerable significance in disciplines as diverse as biomechanics, fracture mechanics, optoelectronics, geology, tribology, nanotechnology, product engineering and even architectural design. Recently, much relevant research in the field of tissue engineering has focused on generating complex polyhedral scaffold structures with such spatial gradients (Cheah *et al.* 2003a, b, 2004, Yeong *et al.* 2010). Indeed, damage and failure resistance of surfaces to normal and sliding contact or impact can be substantially controlled and modified through such gradients. Graded materials than, hold a profound place in the future of material engineering: the ability to synthetically engineer

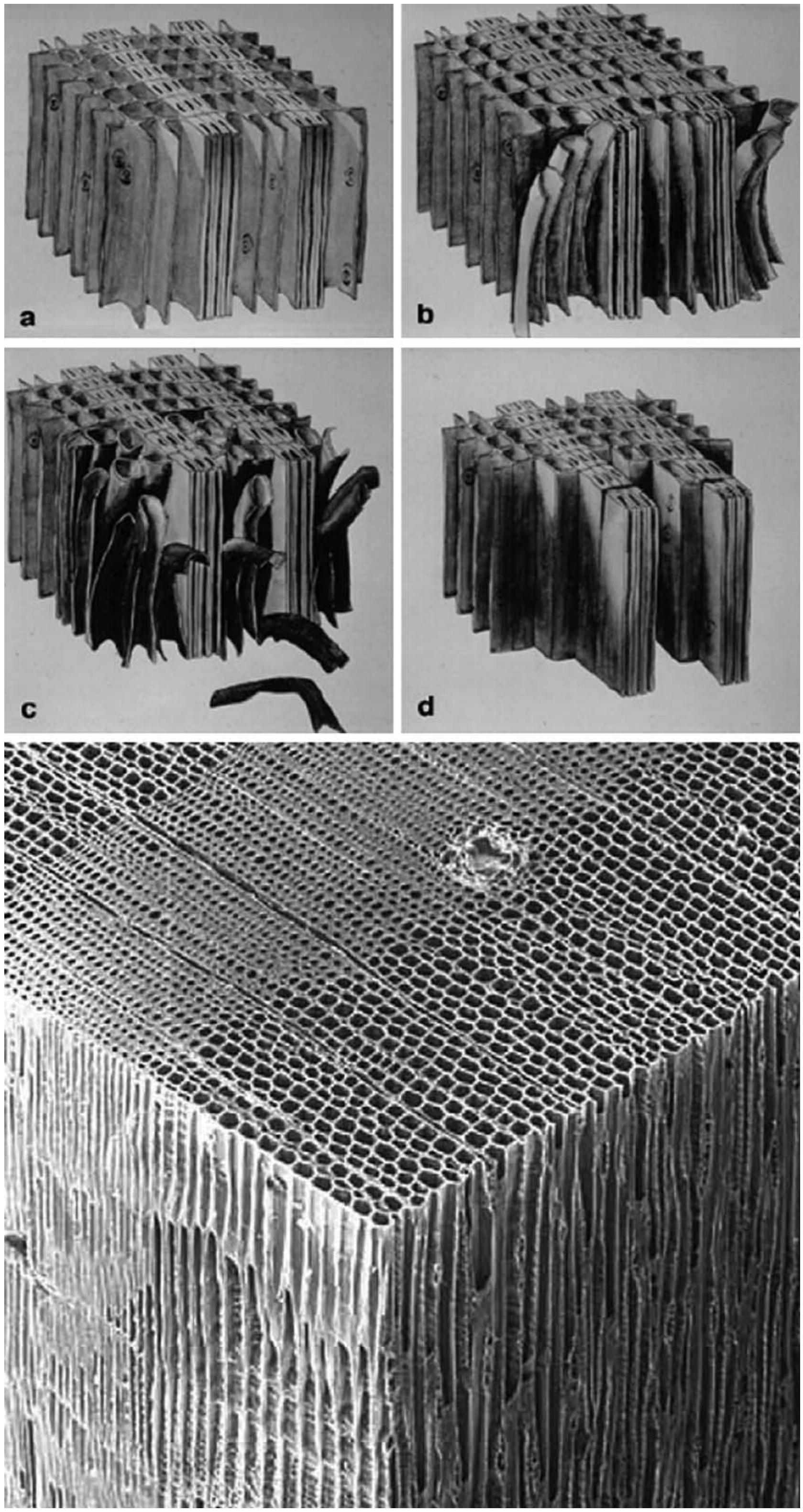


Figure 2. Wood fibers give the wood its anisotropic nature. By controlling fiber density and direction, material performance can be significantly modulated.Source: http://www.woodmagic.vt.edu/Images/activities/BigFiber.jpg

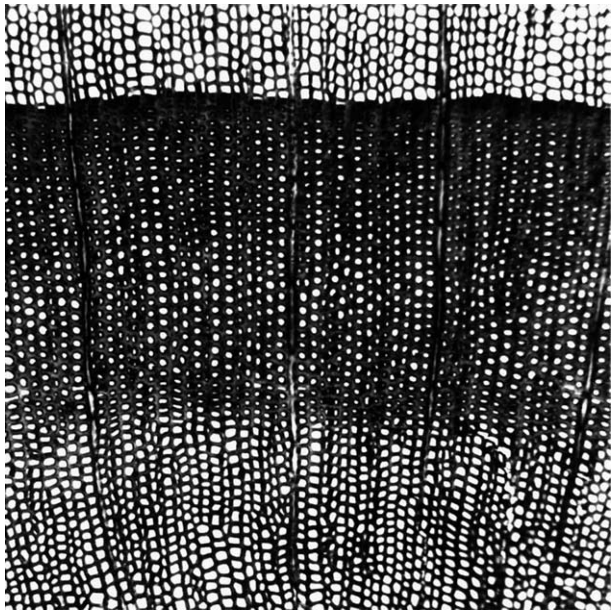


Figure 3. Density variation in compression wood from Juniperus spec. Source: http://www.wsl.ch/staff/jan.esper/pics/anatomy5_high.jpg

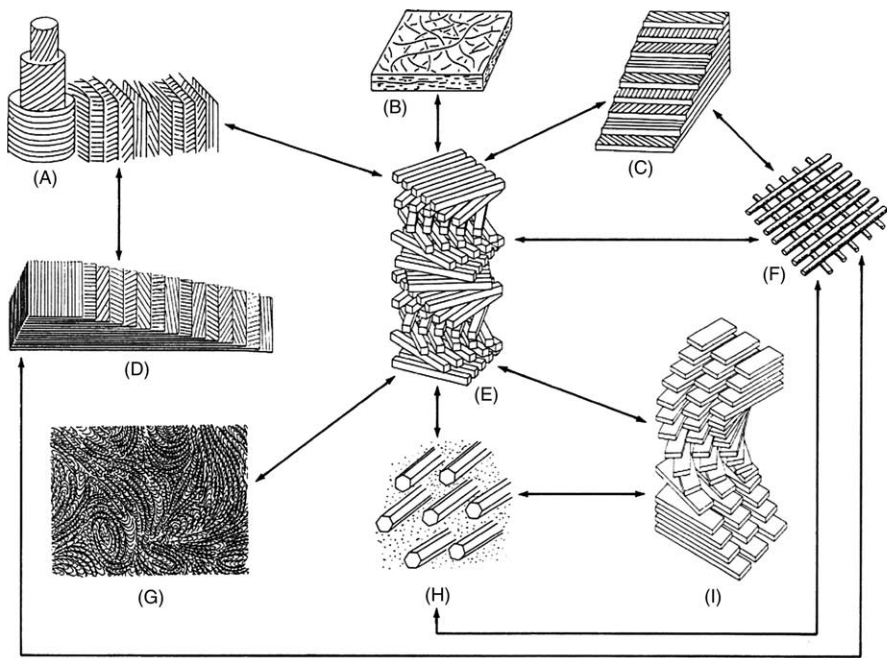


Figure 4. Evidence for a common origin of the diversity of fibrous composite architectures. (A) Cylindrical helicoidal (double twist) grading into planar helicoidal (single twist). Example: bone haversian system. (B) Planar random layer. Examples: parts of some plant cell walls. (C) 45 degrees helicoids. Example: dogfish eggcase. (D) Twisted orthogonal. Examples: fish scales. (E) Monodomain helicoidal (small rotation angle). Example: insect cuticles. (F) Orthogonal. Example: cuticles of cylindrical animals. (G) Polydomain helicoid. Example: mantis eggcase proteins. (H) Parallel (unidirectional). Example: tendons in arthropods. (I) Pseudo-orthogonal. Example: wood tracheids (Neville 1993).

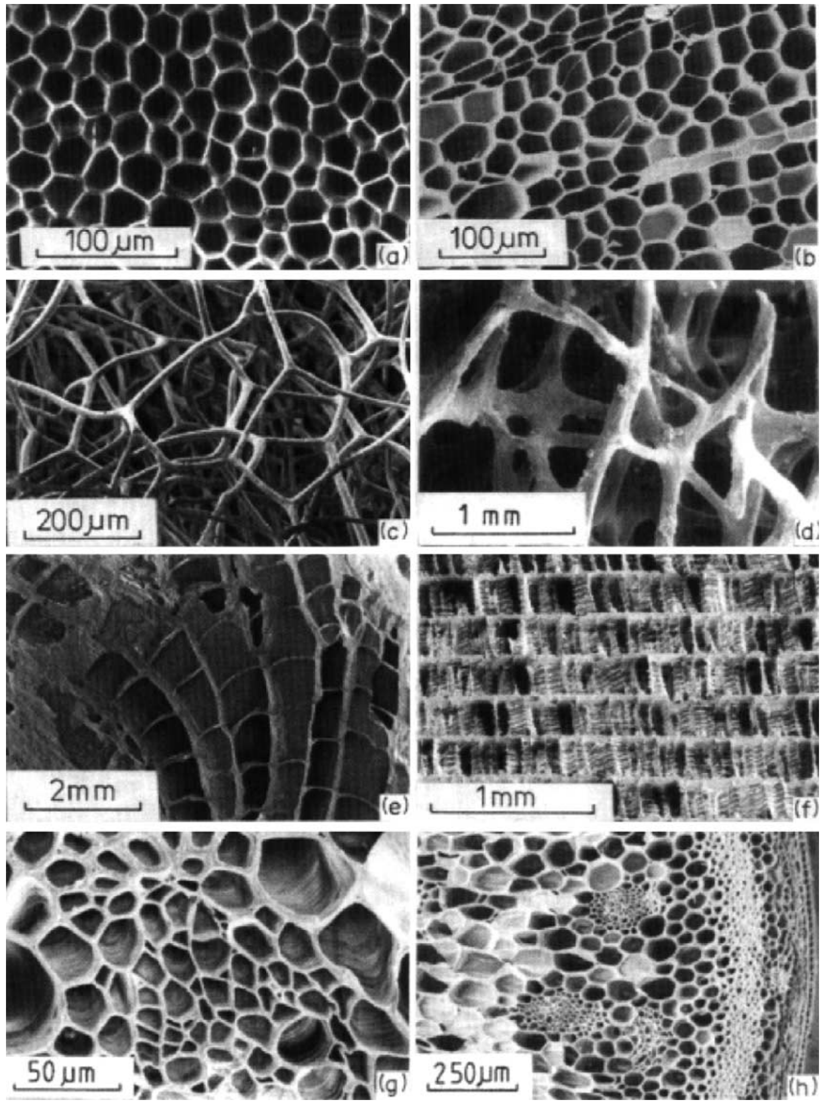


Figure 5. Natural cellular materials including (from left to right, top to bottom): (a) cork; (b) balsa wood; (c) sponge; (d) trabecular bone; (e) coral; (f) cuttlefish bone; (g) iris leaf; and (h) stalk of a plant (Gibson and Ashby 1997).

and fabricate them using additive fabrication is incredibly promising as it increases the product's structural and environmental performance, enhances material efficiency, promotes material economy and optimizes material distribution.

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 the development of a modeling and a fabrication environment for products of industrial applications and architectural scale.

Variable property design (VPM) is a design approach and a methodological framework by which to model, simulate and fabricate material assemblies with gradient properties designed to correspond with multiple and continuously varied functional constraints. Such capability has been termed by the author *Synthetic Anisotropy* and is characterized by the ability to strategically control the density and directionality of material substance in the generation of form (Oxman 2010a, Oxman 2010b). In this approach, material precedes shape, and it is the structuring of material properties as a function of performance that anticipates their form.

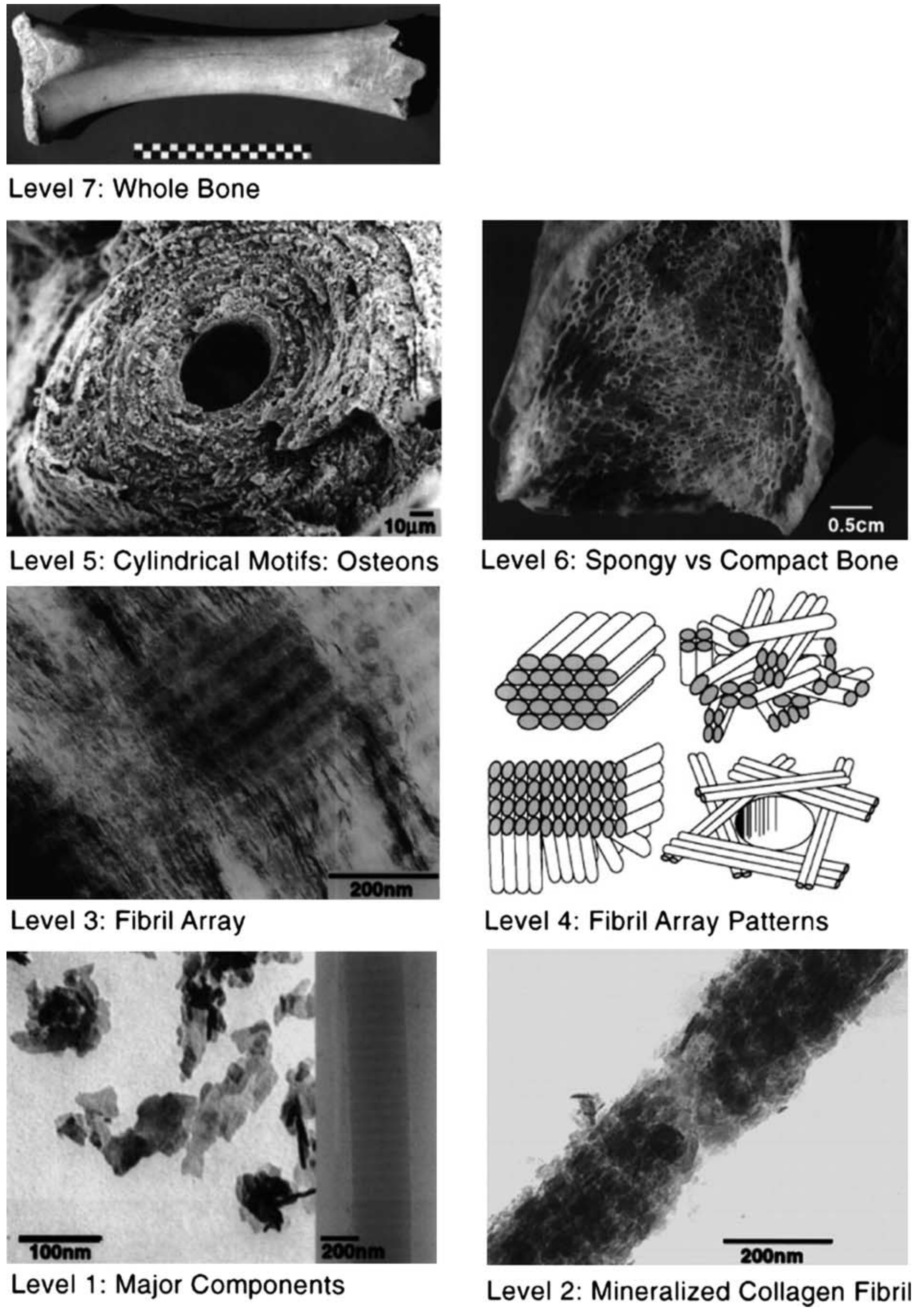


Figure 6. The seven hierarchical levels of organization of the bone family of materials from. Level 1: isolated calcium phosphate mineral hydroxyapatite from human bone (left side) and part of an un-mineralized and unstained collagen fibril from turkey tendon observed in vitreous ice in the TEM (right side). Level 2: TEM micrograph of a mineralized collagen fibril from turkey tendon. Level 3: TEM micrograph of a thin section of mineralized turkey tendon. Level 4: Four fibril array patterns of organization found in the bone family of materials. Level 5: SEM micrograph of a single osteon from human bone. Level 6: Light micrograph of a fractured section through a fossilized (about 5500 years old) human femur. Level 7: Whole bovine bone (scale: 10 cm) (Weiner and Addadi 1997, Weiner and Wagner 1998).

The objectives of the VPD approach are to enhance component optimization of material properties relative to their structural performance as well as to enhance the relation between modeling, analysis and fabrication protocols across media by providing a more efficient and integrated workflow.

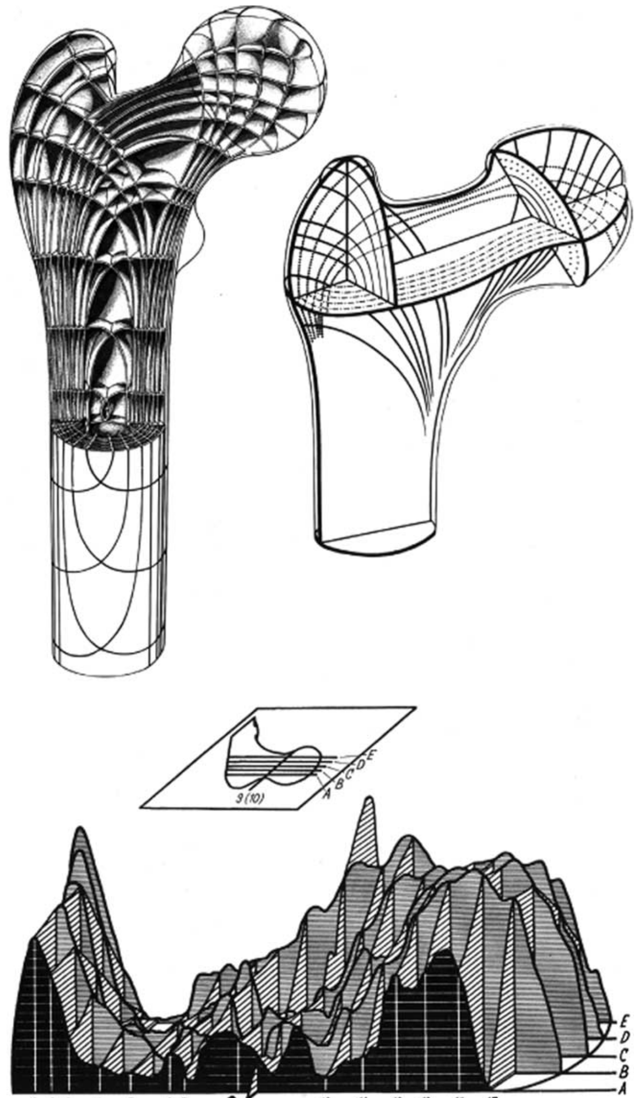


Figure 7. The mountain range technique was invented to illustrate calcium distribution in the bone as a function of the load applied. The top image represents the internal bone structure informed by load paths across the bone. The bottom image represents material distribution relative to the anatomical section examined (Otto *et al.* 1990).

Novel hardware environment for variable property rapid prototyping (VPRP)

Variable property rapid prototyping (VPRP) is a novel method designed to dynamically mix and vary the ratios of different materials in order to produce a continuous gradient (Oxman, N, inventor; 2010 Oct. 5. *Methods and Apparatus for Variable Property Rapid Prototyping*; United States Patent Pending US 61/248,555). Inspired by nature, this ability expands the po-tential of prototyping, since the varying of properties allows for the optimization of material properties relative to their structural performance and for more accurate evaluations of the intended final product, such as stress testing. Dynamic gradients could also contribute to efficient conservation of material usage.

The objectives of the VPRP technology are to enable the 3D modeling of building components with graduated properties corresponding to variable performance criteria as well as to enable the fabrication of building components with graduated properties corresponding to variable performance criteria.

State of the art

Virtual prototyping

Layered manufacturing technologies work hand in hand with computer-aided design (CAD) software to allow engineers and designers to fabricate their designs. The process begins with a design or a sketch with set geometric parameters. Structural and behavioral characteristics of the design are taken into account by the geometry of the design from analysis and testing. Before the layered manufactured product is prototyped, however, the design must be reproduced in CAD software with all accompanying dimensional constraints to be sent out for fabrication. Traditional CAD software acts as a translator, converting a design on paper into a design understandable by a computer. The software application in this project, on the other hand, offers features that act as a platform for creative and structural design by allowing users to generate organic forms by mapping the distribution of various material properties across the expanse of the form. Designs are driven by its properties and material behaviors as opposed to its geometry.

Layered manufacturing technologies have revolutionized the process of prototyping geometrically complex designs. And yet, the geometric modeling and CAD tools employed for such technologies have remained fairly traditional (Chandru *et al.* 1995). Current limitations lie in the developments of structural materials for fabrication; however, beyond such anticipated improvements, and in light of reported advancements in material engineering, major opportunities lie in the designer's ability – within the fabrication process – to control the variation of material properties as a function of external constraints (Pratt 2000, Shin and Dutta 2001). This requires the re-appropriation of computational tools for modeling, simulation and fabrication. The VPM approach, coupled with the VPRP technology, makes use of voxel-based graphics methodologies as an alternative template for variable property rapid prototyping.

Various advantages of this approach such as elimination of the artificial.STL format, easy accomplishments of tasks like estimation of errors in the physical parameters of the fabricated objects, tolerancing, interference detection etc. have been reviewed in the literature (Chandru *et al.* 1995).

This paper demonstrates an integrated approach to design and manufacturing promoting a direct link between virtual performance-based design and physical prototyping. In the following section we introduce some definitions considered essential to understanding the VPM approach and its corresponding VPRP technology, currently under development at MIT (Oxman 2009a, b, 2010a, b).

Current CAD applications do not support the descriptions of internal material composition. However, some options exist which employ digital entities capable of describing micro-scale physical properties of materials and internal composition.

Such entities include:

Voxels

Voxels are digital volume elements that represent analogous to 2D pixels whose position is defined by their proximity to other voxels. Voxels are thus good at representing regularly sampled spaces that are non-homogeneously filled and are used in the visualization and analysis of medical and scientific data but have yet to be implemented in the context of form-generation.

Finite-elements (FEM/FEA)

The finite element method (FEM) is a numerical technique for solving partial differential or integral equations over complex domains (such as cars, pipelines, and complex building skins). The aim is to simulate physical behavior under structural and/or environmental loading cases. The method operates by applying a mesh discretization of a continuous domain into a set of discrete sub-domains, usually called elements. Elements are predominantly small triangular features comprising the surface area of the simulated domain and can be individually analyzed.

Particle system elements

A particle system is a computer graphics technique to simulate physical fuzzy phenomena that are almost impossible to reproduce using conventional rendering techniques (such as the simulation of some, moving water, dust and hair). Emitters typically control particles, which acts as the particle's source and determines it location and motion in 3D space. The emitter has attached to it a set of particle behavior parameters including spawning rates (determining how many particles are generated per time unit), its initial velocity vector (emittance direction upon creation), lifetime, color and more.

Vague discrete modeling elements (VDM)

Vague discrete modeling is a technique, which supports the modeling of features, functions and methods of geometrical objects in associative modeling environments such that every feature is defined as a rule, capable of modifying its representation. The technique is *vague* in the sense that multiple objects are represented by one interval model, and that multiple shape instances can be generated based on certain instantiation rules. This allows the definition of an object's global shape while remaining the possibility to modify the shape in relation to constructive, functional, ergonomic or aesthetic constraints. The model is represented by 3D points representing its geometrical boundaries as sets of instances of object clusters. The outcome is a nominal discrete shape that is defined in terms of its typology, but its geometry is transformable depending on parameters defined by the user.

The common denominator for these four methods is the representation of physical behavior and/or material properties by assigning properties to discrete features comprising the model, weather by using voxels, elements, particles or point-sets.

One major disadvantage of all entities mentioned above is their consumption of computational power in calculations. Also, the editing of such formats is made difficult by the lack of a robust method to relate between them in order to combine and integrate modeling and analysis routines.

Physical prototyping

Layered manufacturing describes a method of manufacturing that uses information from CAD files to dissect a design into numerous thin layers and produce the item by successively depositing or bonding material to form these unique layers. Layered manufacturing is also known as rapid prototyping as produce time is short and objects of varying complexity can be formed without the design and production of a manufacturing system specifically for the object. Some examples of layered manufacturing include stereolithography (SLA), selective laser sintering (SLS), fused deposition modeling (FDM), laminated object manufacturing (LOM), 3D printing, and electron beam melting (EBM). Since materials in layered manufacturing are limited and vary with the method used, objects produced from layered manufacturing usually undergo various secondary processes.

Rapid fabrication (RF) and rapid manufacturing (RM) technologies have emerged, since the mid 1980s, as promising platforms for building construction automation (Jacobs 1992). VPRP defers profoundly from such similar fabrication technologies in that it aims to produce material organizations of varied properties. Generally classified by the material phase used in their extrusion – whether liquid-based (i.e. stereolithography), powder-based (i.e. selective-laser sintering), or solid-based processes (i.e. fused deposition modeling), consistent to all such technologies is the use of materials with homogeneous properties for prototyping and fabrication purposes. We review two technologies that are of relevance to the comparison with VPRP: the PolyJet Matrix technology, extruding multiple photopolymers simultaneously, and the FDM technology, an alternative solid-based fabrication process.

While conventional layered manufacturing technologies have given us the opportunity to create complex works-like and looks-like models in relatively short periods of time, the technology is also very limiting, often reducing material selection to an array of highly brittle, inelastic materials. Objet Geometries, an international 3D printing company, recently introduced their Connex Series, a line of 3D printers that use Polyjet MatrixTM Technology to allow the creation of dual material prototypes. This technology has also allowed the generation of composite material prototypes of varying stiffness. However, single material, varying property layered manufacturing technology has yet to be developed.

OBJET Geometries™ PolyJet Matrix technology, currently applied to their Connex500™ 3-D printer, operates by using ink jet heads with two or more photopolymer model materials; OBJET's process is a dual-, or multiple-jet process which can combine materials in several ways, enabling the simultaneous use of two different rigid materials, two flexible materials, one of each type, or any combination with transparent material. Each material is funneled to a dedicated liquid system connected to the PolyJet Matrix block, which contains eight printing heads. Each material is designated two synchronized printing-heads, including support material. Every printer head includes 96 nozzles. Preset composites of model materials are ink-jetted from designated nozzles according to location and model type, providing full control of the structure of the jetted material and hence of its mechanical properties. This enables each composite material, also known as a 'Digital Material', to provide specific values for tensile strength, elongation to break, heat deflection temperature, and even shore values. The materials are extruded in 16-μm thick layers onto a build tray, layer by layer, until the part is completed. Each photopolymer layer is cured by UV light immediately after it is extruded. The gel-like support material designed to support complicated geometries, is easily removed by hand and water jetting. However, OBJET's materials are extruded by preset combinations; they are distinct and cannot be mixed to generate gradient transitions (Jacobs 1992, Sachs *et al.* 1993, Chang 2004, Bartolo *et al.* 2009, Udroiu and Mihail 2009).

Startasis' fused deposition technology (FDM) operates by laying down a soluble thermoplastic polymer for support in parallel to the extrusion of the build material. Parts are created by extruding material through a nozzle that traverses in X and Y to create each 2D layer. In each layer, separate nozzles extrude and deposit material that forms the parts, and material that form supports where required. Another interesting and relevant FDM technology is Contour Crafting (CC), invented at the University of Southern California by Professor Behrokh Khoshnevis (Khoshnevis 2004). This technology exploits the surface-forming capability of toweling to create freeform planar surfaces out of construction ceramics and concrete. The extrusion nozzle has a side trowel, the traversal side of which creates smooth outer and top surfaces on the layer, as material is being extruded. This side trowel can be deflected to create non-orthogonal surfaces. However, both FDM technologies presented above use only one material at a time such that variation in properties can only be achieved by fabricating multiple parts and assembling them post the printing process (Wasa and Hayakawa 1992, Zein *et al.* 2002).

Most of today's additive fabrication technologies for the building industry serve as prototyping technologies; In other words, the output usually serves as a model representing the geometrical form of the component and is generally made from non-structural materials that are not robust enough to satisfy structural performance criteria. Furthermore, most such prototypes generally display plastic deformation over relatively short periods of time. Given their role as visual prototypes, such components are traditionally made from homogeneous materials, unified in their properties and behavior. Furthermore, certain additive manufacturing technologies are designed to support full-scale construction. Such for instance is the contour-crafting technology, which is designed to 3-D print habitable constructions made of concrete in relatively short periods of time (Khoshnevis 2004). However, such systems too are limited to using only one material per print – whether structural (as is the case with RM technologies) or non structural (as is the case with RP technologies) – without varying its internal compositional properties.

The advantages of printing material with varied properties such as density or stiffness variation are most significant as they can potentially enhance the mechanical performance of a given component while reducing the overall amount of material required for its production. Accompanying an increased motivation in the production of structural and highly functional graded parts using additive technologies, and inspired by pioneering research into 3D fabrication of scaffolds for tissue engineering (Sun *et al.* 2004), the VPM approach aims to combine 3D printing with recant advancements achieved in material science and tissue engineering (Chua *et al.* 1999, Freyman *et al.* 2001, Cheah *et al.* 2003a,b, 2004). The distribution of material properties as a function of their performance requirements at micro structural scale is elegantly exemplified with the development and application of functional gradient materials (FGMs).

Functionally gradient materials

The term *Functionally Graded Materials* was developed in the mid 1980s in Japan in the design of a hypersonic space plane project where a particular combination of materials used would be required to serve the purpose of a thermal barrier capable of withstanding a surface temperature of 2000 K and a temperature gradient of 1000 K across a 10-mm section.

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 1980s when actual models investigating the design, fabrication and evaluation of graded structures were proposed.

In Material Science, functionally graded materials (FGMs) are characterized by the gradual variation in composition and structure over their volume, resulting in corresponding changes of the material's properties (Figure 8). Such materials can be designed and engineered for a specific set of functions and applications (Suresh and Mortensen 1998). Various approaches based on particulate processing, perform processing, layer processing and melt processing are used to fabricate FGMs (Figure 8).

Functionally graded materials are a new generation of engineering materials characterized by compositional and structural variation across their volume unit, resulting in property changes in the material such as mechanical shock resistance, thermal insulation, catalytic efficiency and relaxation of thermal stress (Miyamoto *et al.* 1999). Spatial variation is achieved through non-uniform distribution of reinforcement phases (regions of space with unique chemical uniform and physically distinct characteristics). Reinforcements are inserted with different properties, sizes, and shapes, as well as by interchanging the roles of the reinforcement and matrix phases in a continuous manner. The resultant microstructure is characterized by continuously or discretely changing its thermal and mechanical properties at the macroscopic or continuum scale. In this way materials can be designed for specific functions and applications.

Various approaches exist which are used to fabricate FGMs such as perform processing, layer processing and melt processing. The basic structural unit of an FGM resembles biological units such as cell and tissues, and is referred to as an *element* or a *material ingredient*. Bamboo, shell, tooth and bone are all made up of graded structures consisting of chemical, physical, geometrical and biological material ingredients.

The concept of FGMs is revolutionary in the areas of material science and mechanics as it allows one to fully integrate between material and structural considerations in the final design of structural components. (Stoneham and Harding 2009). FGMs are applicable to many fields. In the engineering applications it is applied to cutting tools, machine parts, and engine components. Various combinations of these ordinarily incompatible functions can be applied to create new materials for aerospace, chemical plants, and nuclear energy reactors. However, the application of FGMs in product and architectural design construction scale has not been thoroughly researched and developed.

Functionally graded materials stand out as a special class of materials characterized by the gradual variation in composition and structure over volume, resulting in corresponding structure-property relationships. Unlike any other class of materials, FGMs are 'designed materials', assembled rather than selected for a particular function or application. Given the designer's freedom to define the material microstructure based on its properties, any composite material could be made simply by varying the

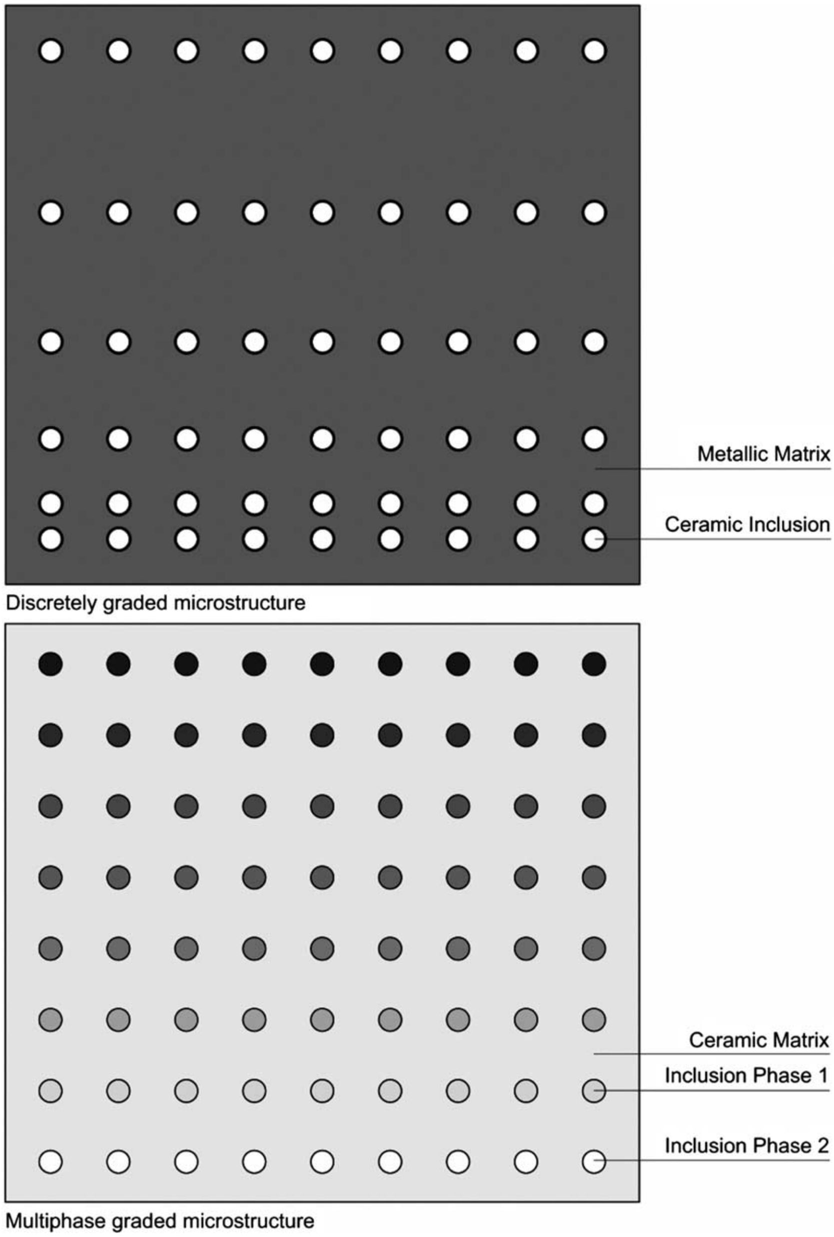


Figure 8. Graphic illustrations of discretely graded (left) and multiphase graded (right) microstructures of functionally gradient materials. Within FGMs, the different microstructural phases have different functions and the overall FGMs attain the multifunctional status from their property gradation enabling various multifunctional tasks by virtue of spatially tailored microstructures.

microstructure from one material to another with a specific gradient. Such processes facilitate the designer with the possibility of combining the ultimate properties of each material into one. Generally approximated by means of a power series, the transition between the two materials is achieved by combining several discrete layers, each containing localized optimal properties. Here, the notion of 'units' is relevant insofar as it defines the micro-structural property of the material relative to its attributed mechanical functions.

The basic unit for FGM representation is the *maxel* (Miyamoto *et al.* 1999). Its attributes include the location and volume fraction of individual material components. The term *maxel* is also used in the context of additive manufacturing processes to describe a physical voxel defining the build resolution of a rapid prototyping or rapid manufacturing process, or the resolution of a design produced by such fabrication means.

Computational definitions

Domains

Freeform design has seen an abundance of software packages supporting complex modeling environments in terms of surface and solid descriptions through BURBS and/or mesh architectures. Predominantly, the challenge in design has been focused around the geometrical description of form as property-less features to which material is assigned homogeneously in the process of fabrication. The VPM modeling environment supports the representation of solids as geometrical features described by their material composition. The distribution functions of properties across the domain are valid, but not exclusive, to that domain.

Properties

The VPM environment distinguishes between two classes of properties: discrete properties and variable properties. Discrete properties (DISC-props) are constant, and are assigned to areas of constant properties across the surface or volume area of the domain. Being independent of each other, discrete properties cannot intersect. For instance, when relating to the extreme cases of strength, a voxel cannot be defined as soft and stiff at the same time. Variable (VAR-props) properties are assigned for advanced property distribution such as the one discussed in the example above. Variable properties describe areas with gradient material composition across the surface or volume area of a domain.

Distribution functions

A distribution function will typically describe the fracture of a given property (i.e. strength, conductivity) as a function of location. The VPM environment distinguishes between absolute and relative distribution functions. An absolute distribution function is defined by a function and the distance to or from a given property. The function computes the relation between the relative distance, given by the user, and the property fracture. For example, the material is X times softer in Y times the distance from the boundary of the model across its length. The relative distribution function is defined by two properties and a function. From any given point, the shortest distance is calculated to the maximum magnitude of both properties.

The structure of a nerve's dendrite for example, schematically represented in Figure 9, nicely illustrates the notion of variable properties across multiple domains: the outer layer of the dendrite is stiffer then its inner substance. Its inner substance displays variation in conductivity depending on the location of the electrical signal. In other words, the nerve displays variation both across its longitudinal section (in the length dimension) and its transversal section (perpendicular

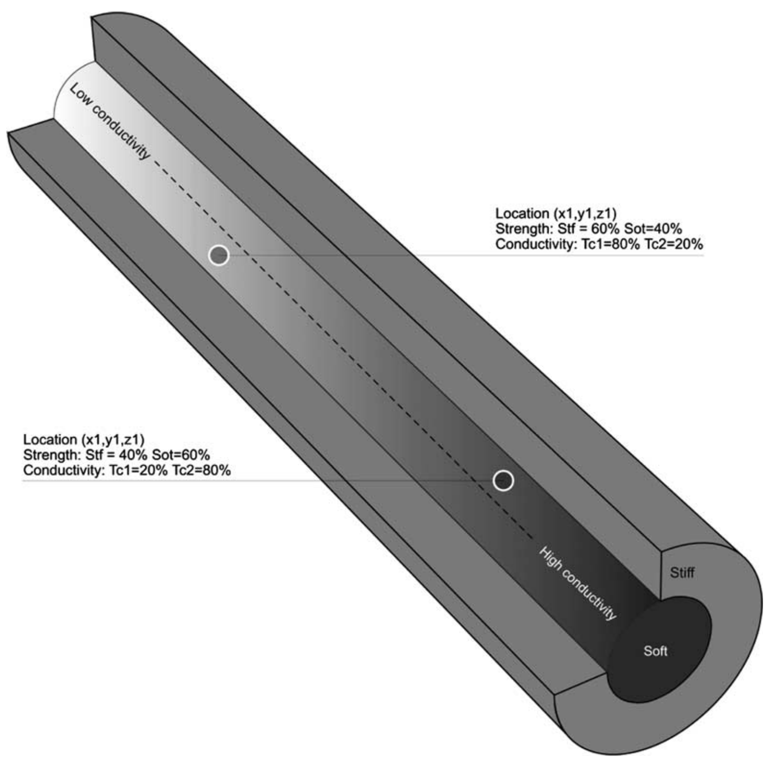


Figure 9. Schematic 3D model illustrating multiple variable property representation.

to the length dimension). Such variation is incredibly difficult and challenging to account for in any 3D modeling software.

In the example shown in Figure 9, the domain contains the geometrical representation of the solid itself, its properties include stiffness and conductivity, and its distribution functions compute the transition from stiff to soft regions and from highly conductive to low-conductive regions within the domain.

Like the example above, many other products and building components require a rethinking of the modeling environment in order to achieve the ability to design and edit graded material compositions as the ones offered by functionally graded materials (FGMs). The limited functionality with current CAD systems is due to conventional fabrication technologies, which do not take graded properties into account.

Methodology

Variable property modelling is investigated as a theoretical and technical framework by which to model, analyze and fabricate objects with graduated properties designed to correspond to multiple and continuously varied functional constraints. In order to implement this approach as a fabrication process, a novel fabrication technology, termed - *variable property rapid prototyping* has been developed, designed and patented. Experimental designs employing suggested theoretical and technical frameworks, methods and techniques are presented, discussed and demonstrated. They support product customization, rapid augmentation and variable property prototyping. Developed as approximations of natural formation processes, these design experiments demonstrate the contribution and the potential future of a new design and research field.

Design case studies and experimentation

The variable property modeling (VPM) design approach was developed in conjunction with the variable property rapid prototyping (VPRP) technology. Given certain of the technical limitations still under development such as automated axes control of material deposition, the approach was developed independently of its complimentary and corresponding technology. The VPM approach is demonstrated and executed using existing software and hardware platforms, with the aim of demonstrating the principles of variable property modeling (VPM) in the design of building components, products and potentially larger constructions. Three design products are presented, each demonstrating the VPM approach in different scales while utilizing different modeling strategies for the control of material properties based on performance constraints. All case study projects are characterized by the ambition to integrate structural and functional performance requirements within one continuous surface. In addition, in all cases material property variation is limited to a pre-assigned range of stiff and soft materials. In this respect, it is the properties of stiffness and elasticity that are being controlled rather than density, as is the case in many natural structures.

Chair design

The chaise 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. Multiple algorithms were generated that correspond to these variables such that stability is mediated with pleasure, and structural integrity – with visual and sensual experience. In this light, the chaise celebrates the negotiation between engineering and experiential performance. It is a method, as much as it is an object of pleasure that promotes material and structural integrity with the physical act of sitting and lying down against a hard–soft surface. The traditional chaise is transformed here to promote lounging of a different kind. It is designed as a three dimensional object that provides for multiple seating positions each promoting a completely different experience. The cellular pattern applied to its entirety is designed to increase the ratio of surface area to volume in occupied areas where the body potentially rests. A pressure map study was conducted that matches the softness and hardness of the cells to cushion and support sensitive and high-pressured areas. By analyzing anatomical structures that cause concentrated pressures, the chaise becomes softer and flexible where pressure needs to be relieved. The relative volume of each cellular cushion is locally informed by pressure data averaged with values representing structural support and flexibility. Its density is informed by global and local mean curvature values such that denser, smaller cells are organized in areas of steeper curvature whereas larger cells are found in areas of shallow curvature. The chaise's natural relation of structural and sense datum is propagated in variable polymer composites offering a wide range of physical properties. Through these algorithms force conditions naturally propagate functionality. Stiffer materials are positioned in surface areas under compression and softer, more flexible materials are placed in surface areas under tension. State of the art technologies are applied here for the first time to cater for a large range of physical properties and behaviours. The surface patches are 3D printed using a new multi-jet matrix technology simultaneously depositing materials of different properties corresponding to structural and skin-pressure mappings.

Splint design

Carpal skin is a prototype for a protective glove against carpal tunnel syndrome. The syndrome is a medical condition in which the median nerve is compressed at the wrist, leading to numbness, muscle atrophy and weakness in the hand. Night time wrist splinting is the recommended treatment for most patients before going into carpal tunnel release surgery. *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 customized fashion. The form-generation process is inspired by animal coating patterns where instead of colours we are controlling stiffness variation.

Ballet sneaker shoe sole deign

Similarly to the two previous case studies, the design for a shoe sole explores the possibility of controlling material property variation across the surface area of the shoe supporting the sole. This process entails the layering or compounding of different materials to create a single entity, and is particularly apparent in the construction of performance footwear, where various polymers are strategically inlaid to meet the ergonomic and athletic needs of consumers.

Digital tool development

The VPM *approach* was developed independently, and in parallel to the development of the VPRP *technology.* Illustrated in this paper are two design projects which provided the guiding principles for a variable-property approach to design fabrication. In this context, the projects are considered case-studies for the generation of form, designed and fabricated with variable material properties that integrate and correspond to one, or multiple performance criteria.

Methodologically, the development of the digital environments supporting the generation of these projects focused on the generation of texture-based computational algorithms applied to the surface area of each product (Figure 10). In the case of the first study, *the chaise's*, the digital tool assists the designer in assigning a *voronoi* pattern to the surface area of the product, while in the second case, *Carpal Skin*, the digital tool assists the designer in assigning a *reaction-diffusion* pattern to its surface area. Both surface-based textures promote surface subdivision and assignment of material properties to each element. While in the digital form-generation approach, the assignment of material properties is guided by element size and surface texture, the physical technology is characterized by the assignment of material properties to performance-based gradients classified by color. In the latter case, geometrical patterns are replaced with color gradients further translated into continuous mixtures of materials with varied properties.

Physical tool development

Both design projects used to demonstrate the VPRP approach were 3D printed using OBJET Geometries' Connex500™. The Connex500™ is considered the first 3D printing system able to jet multiple model materials simultaneously. It offers the completely unique ability to print parts and assemblies made of multiple model materials, with different mechanical or physical properties, within a single build, enabling users to create composite materials that have preset combinations of mechanical properties (Figure 11).

Design approach: case studies and demonstration

Chair design

Digital modelling and representation of graduated properties

The traditional chaise is transformed to promote lounging of a different kind. The cellular pattern applied to its entirety is designed to increase the ratio of surface area to

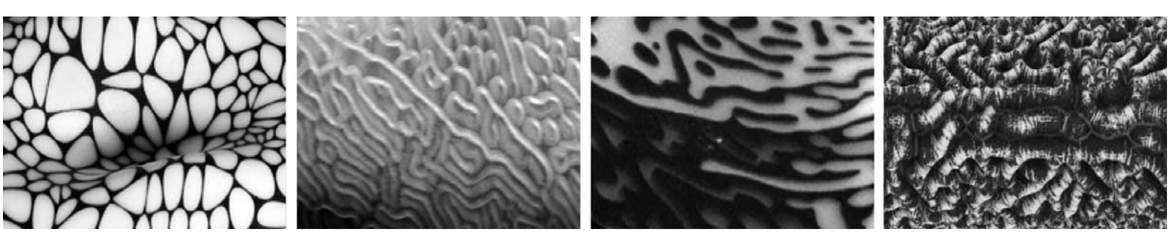


Figure 10. Various methods implemented for texture synthesis defining material 'units' in variable property rapid prototyping. From left to right: (a) material cells are defined by a voronoi algorithm, (b) material units are defined by thickness variation reaction-diffusion algorithm, (c) material units are defined by property variation reaction-diffusion algorithm (d) material units are defined by a composite condition: reaction-diffusion algorithm for macro-scale definition and 1mm voxel sized units for meso-scale definition.

Primary material: VeroWhite **Secondary material**: TangoBlackPlus

RIGID

Property	ASTM	Units	DM_8510	DM_8520	DM_8530
Tensile Strength	D-638-03	MPa	49	44	39
Modulus of Elasticity	D-638-03	MPa	2350	2150	1750
Elongation at Break	D-638-03	%	35-45	50-60	60-70
Flexural Strength	D-790-03	MPa	67	54	48
Flexural Modulus	D-790-03	MPa	2050	1700	1550
HDT at 0.45 MPa	D-648-06	°C	44	41	41
Notched Izod Impact	D-256-06	J/m	25	25	25

Primary material: TangoBlackPlus **Secondary material**: VeroWhite

FLEXIBLE

Property	ASTM	Units	DM_9840	DM_9850	DM_9860	DM_9870	DM_9885	DM_9895
Tensile Strength	D-412	MPa	1	1	3	3	6	20
Elongation at Break	D-412	%	160	140	90	60	55	30
Tensile Tear Resistance	D-624 Die C	N/mm	5	6	8	13	26	46
Hardness Shore A	D-2240		40	50	60	70	85	95

Cartridges: VeroWhite, TangoPlus

Primary material: VeroWhite **Secondary material**: TangoPlus

RIGID

Property	ASTM	Units	DM_8410	DM_8420	DM_8430
Tensile Strength	D-638-03	MPa	49	44	39
Modulus of Elasticity	D-638-03	MPa	2350	2150	1750
Elongation at Break	D-638-03	%	35-45	50-60	60-70
Flexural Strength	D-790-03	MPa	67	54	48
Flexural Modulus	D-790-03	MPa	2050	1700	1550
HDT at 0.45 MPa	D-648-06	°C	44	41	41
Notched Izod Impact	D-256-06	J/m	25	25	25

Primary material: TangoPlus **Secondary material**: VeroWhite

FLEXIBLE

Property	ASTM	Units	DM_9740	DM_9750	DM_9760	DM_9770	DM_9785	DM_9795
Tensile Strength	D-412	MPa	1	1	3	3	6	20
Elongation at Break	D-412	%	160	140	90	60	55	30
Tensile Tear Resistance	D-624 Die C	N/mm	5	6	8	13	26	46
Hardness Shore A	D-2240		40	50	60	70	85	95

Cartridges: VeroWhite, TangoBlack

Primary material: VeroWhite **Secondary material**: TangoBlack

RIGID

Property	ASTM	Units	DM_8110	DM_8120	DM_8130
Tensile Strength	D-638-03	MPa	52	42	30
Modulus of Elasticity	D-638-03	MPa	2690	2400	1800
Elongation at Break	D-638-03	%	17	34	52
Flexural Strength	D-790-03	MPa	77	65	42
Flexural Modulus	D-790-03	MPa	2580	2190	1620
HDT at 0.45 MPa	D-648-06	°C	42	41	39
Notched Izod Impact	D-256-06	J/m	26	26	35

Primary material: TangoBlack **Secondary material**: VeroWhite

FLEXIBLE

Property	ASTM	Units	DM_9110	DM_9120	DM_9130
Tensile Strength	D-412	MPa	3	4	9
Elongation at Break	D-412	%	50	40	39
Tensile Tear Resistance	D-624 Die C	N/mm	8	15	47
Hardness Shore A	D-2240		80	85	95

Cartridges: FullCure720, TangoBlack

Primary material: FullCure720 **Secondary material**: TangoBlack

RIGID

Property	ASTM	Units	DM_7210	DM_7220	DM_7230
Tensile Strength	D-638-03	MPa	56	54	47
Modulus of Elasticity	D-638-04	MPa	2300	2150	1750
Elongation at Break	D-638-05	%	15-25	15-25	15-25
Flexural Strength	D-790-03	MPa	88	84	72
Flexural Modulus	D-790-04	MPa	2500	2450	2350
HDT at 0.45 MPa	D-648-06	°C	50	49	46
Notched Izod Impact	D-256-06	J/m	24	24	24

Primary material: TangoBlack **Secondary material**: FullCure720

FLEXIBLE

Property	ASTM	Units	DM_9410	DM_9420	DM_9430
Tensile Strength	D-412	MPa	3	4	9
Elongation at Break	D-412	%	50	40	39
Tensile Tear Resistance	D-624 Die C	N/mm	8	15	47
Hardness Shore A	D-2240		80	85	95

Figure 11. Pre-set combinations of Connex500™ materials. Currently, multi-material printers such as the Connex500 allow for the 3D printing of building components designed with several material constituents. However, in this case each material is jetted from a discrete jet making it challenging to achieve gradient mixture and micro-scale continuous changes in properties.

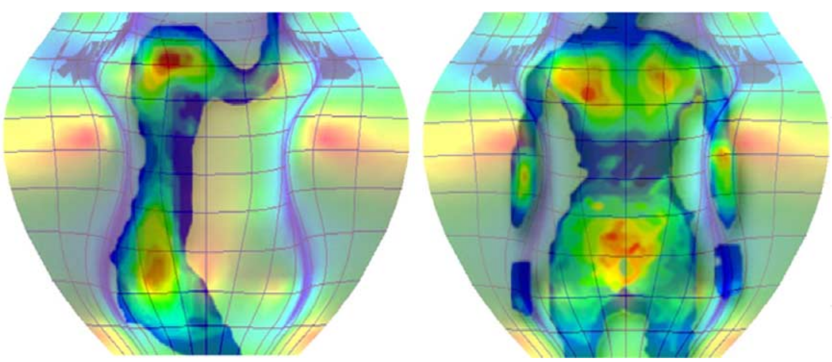


Figure 12. Chaise design informed by material properties assigned to pressure map registration, body form and body weight.

volume in occupied areas where the body potentially rests. A pressure map study was conducted that matches the softness and hardness of the cells to cushion and support sensitive and high-pressured areas (Figure 12).

By analyzing anatomical structures that cause concentrated pressures, the chaise becomes softer and flexible where pressure needs to be relieved. The relative volume of each cellular cushion is locally informed by pressure data averaged with values representing structural support and flexibility. Its density is informed by global and local mean curvature values such that denser, smaller cells are organized in areas of steeper curvature whereas larger cells are found in areas of shallow curvature.

The chaise's natural relation of structural and sense datum is propagated in variable polymer composites offering a wide range of physical properties. Through these algorithms force conditions naturally propagate functionality. Stiffer materials are positioned in surface areas under compression and softer, more flexible materials are placed in surface areas under tension. State of the art technologies are applied here for the first time to cater for a large range of physical properties and behaviours. The surface patches are

Figure 13. Weighted material selection: a stochastic computational process assigns a stiffness ratio corresponding to structural performance.

3D printed using a new multi-jet matrix technology which simultaneously deposits materials of different properties corresponding to structural and skin-pressure mappings.

Physical prototyping

During the initial stages of the design, the texture inherits the geometrical features of the design as defined by the user. Such geometrical features are, in the case of the Chaise, costumed to fit body curvature criteria. The initial distribution of cells corresponds to the type and degree of curvature: smaller and denser cells are located in regions of higher curvature, and larger, sparser cells are located in regions of smoother curvature. Material properties correspond to both structural requirements (self stability with no additional

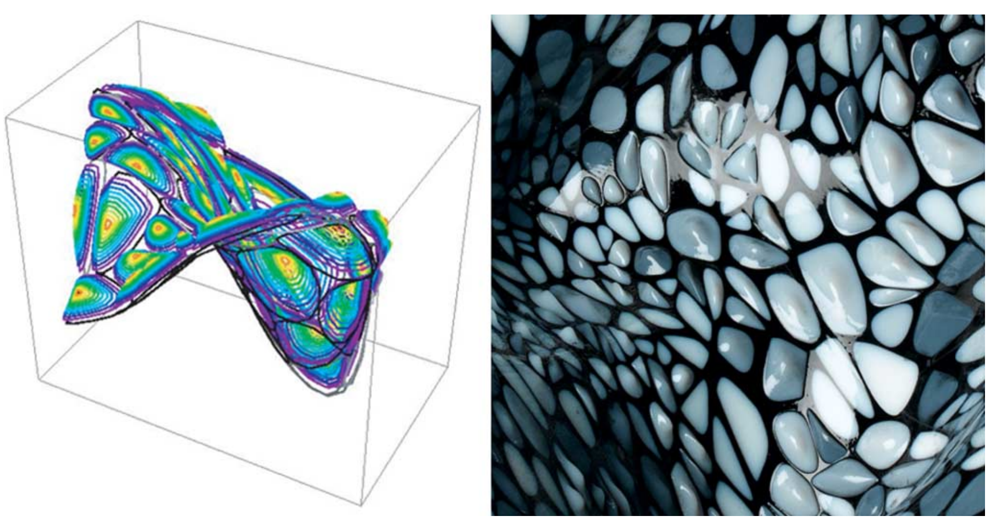


Figure 14. Weighted material selection: a stochastic computational process assigns a stiffness ratio corresponding to environmental performance. The relative height of the soft silicon bumps corresponds to the body pressure mappings.

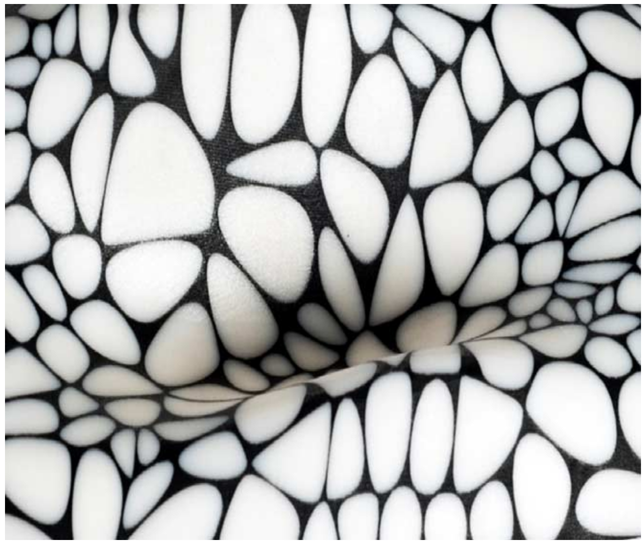


Figure 15. The distribution of shear-stress lines and surface pressure is embodied in the allocation and relative thickness of the stiff vein-like elements built into the skin (black) and the soft (white) cellular components between them.

enforcement members) and environmental requirements (assigned to the body pressure mappings). For the structural performance, a stochastic computational process was developed in which stiffer materials are assigned to vertical regions which work for buckling and softer materials are assigned to horizontal regions that work for bending. The probability of a material being stiffer or smoother depends on the angle defining the level of horizontality in the chaise (Figure 13).

With regards to the environmental requirements, the relative height of each cell is defined by the degree of pressure mapped onto the Chaise such that softer and bigger silicon bumps are located in regions of higher pressure (Figure 14). The Chaise was fabricated using a multi-material 3D printing technology and assembled in 32 parts (Figures 15 and 16).

Splint design

Digital modelling and representation of graduated properties

Nature's engineering expertise in matching material properties to environmental pressures, be it the formation of stiff materials for load bearing functions, or insulating materials as protection from extreme temperature gradients. The

Figure 16. *Chaise performative.* Prototype for a Chaise Lounge, 2008, Boston Museum of Science. The chaise combines structural, environmental and corporeal performance by adapting its thickness, pattern density, stiffness, flexibility and translucency to load, curvature, and skin-pressured areas respectively. It is patterned with five different materials color-coded by elastic moduli. Stiff (darker colored) and soft (lighter colored) materials are distributed according to the user's structural load distribution; Soft silicon 'bumps' are located in regions of higher pressure.

human skin is designed in the same fashion and acts simultaneously as a structural and an environmental filter and barrier. In the very same way that load or temperature can be mapped in order to design structures that are highly optimized for their function, physical pain can also be mapped in the design and production of medical assistive devices such as pain reducing splints.

Since the experience of pain is a very personal one, it is different for each individual. Pain is very difficult to define, and it is one of those conditions that are poorly understood by the western medical sciences. Carpal Skin is a prototype for a protective glove against carpal tunnel syndrome. The syndrome is a medical condition in which the median nerve is compressed at the wrist, leading to numbness muscle atrophy and weakness in the hand. Night-time wrist splinting is the recommended treatment for most patients before going into carpal tunnel release surgery.

The main problem behind immobilized braces is that since they are mass-produced they often are too big, too small or too constricting in terms of mobilization. In this case, as is the case with most muscular and nerve-related syndromes, product mass customization – as opposed to mass-production – is crucial.

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 his or her anatomical and physiological requirements limiting movement in a customized fashion. The formation process involves case-by-case pain registration and material property assignment. The 3D scan of the patient's hand, including its pain registration, is mapped to a 2D representation on which the distribution of stiff and soft materials is applied. This pain-map is then folded back to its 3D form and 3D printed using photopolymer composites.

The mapping of required material properties and their assignment to the surface area of the wrist-splint is guided by a texture synthesis based on the simulation of local nonlinear interaction, called reaction-diffusion, which has been generally proposed as a model of biological pattern formation (Witkin and Kass 1991). In this context, the reaction-diffusion algorithm dictates the desired distribution of material properties (Figure 17). In this design context, the traditional reaction-diffusion systems has been extended to allow anisotropic and spatially non-uniform diffusion of material properties as a function of anticipated pressure on the surface area of the wrist (Oxman 2010a,b).

Physical prototyping

In this particular prototype, stiff materials constrain the lateral bending motion at the wrist, and can be identified by the oblique trajectory of dark and stiff materials. Soft materials allow for ergonomic wrist support and comfort through movement. The local thickness changes correspond

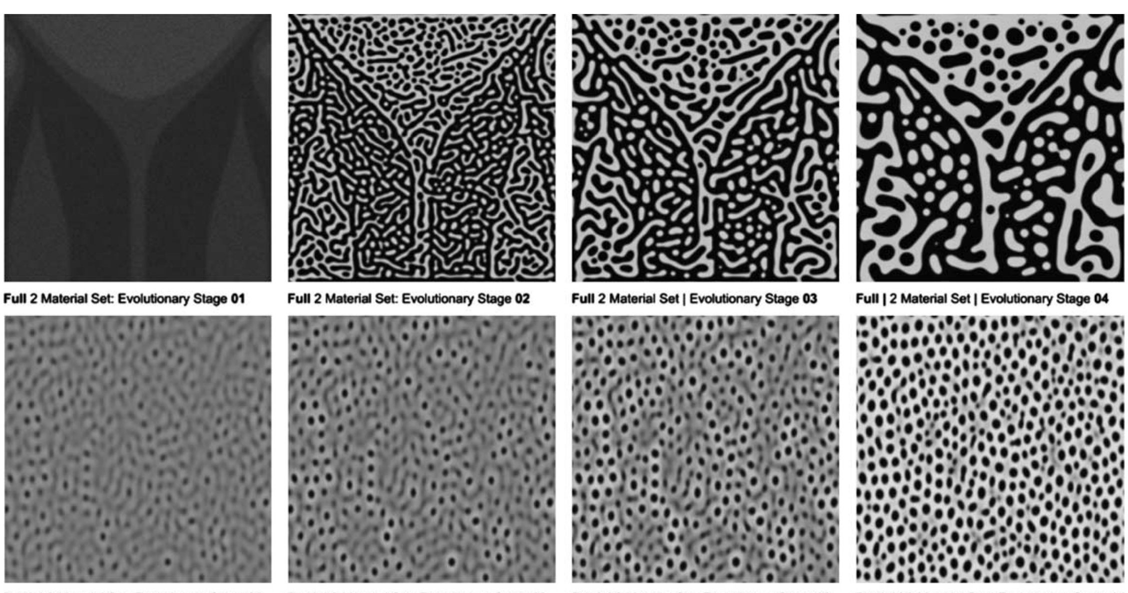


Figure 17. Carpal skin. Prototype for a carpel tunnel syndrome splint, 2008, Boston Museum of Science. Physical model of prototype. Material distribution charts illustrating a range of potential solutions informed by size, scale, direction and ratio between soft and stiff materials. The charts are computed on top of an optimized unfolded representation of the frontal and dorsal planes of the patient's hand and refolded following material assignment to construct the 3D glove.

Figure 18. Carpal skin. Prototype for a carpal tunnel syndrome splint, 2008, Boston Museum of Science. Physical model of prototype. In this particular prototype, stiff materials constrain the lateral bending motion at the wrist, and can be identified by the oblique trajectory of dark and stiff materials. Soft materials allow for ergonomic wrist support and comfort through movement.

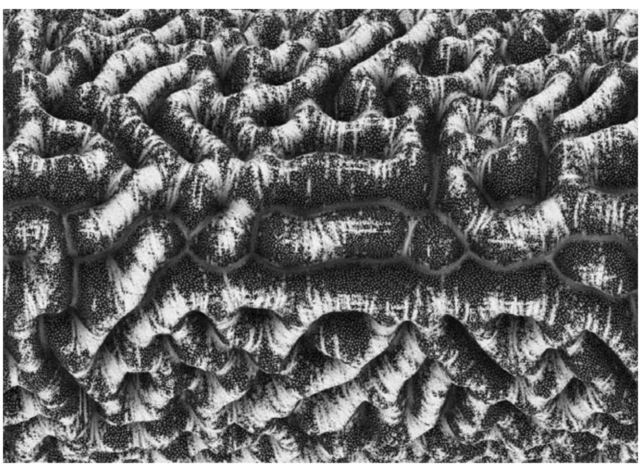


Figure 19. Carpal skin. Prototype for a carpal tunnel syndrome splint, 2008, Boston Museum of Science. Detail illustrating the distribution of material properties as a function of movement constraint and control. The custom-fit property-distribution functions built into the glove allows for passive but consistent pulling and stretching simultaneously.

to strategic areas across the surface area of the wrist in cushioning and protecting the wrist from hard surfaces as well as allowing for a comfortable grip. These thickened bumps also increase flexibility and enhance circulation and relief pressure on the Median Nerve as it acts as a soft tissue reshaping mechanism. The custom-fit property distribution built into the glove allows for passive but consistent pulling and stretching simultaneously (Figures 18 and 19).

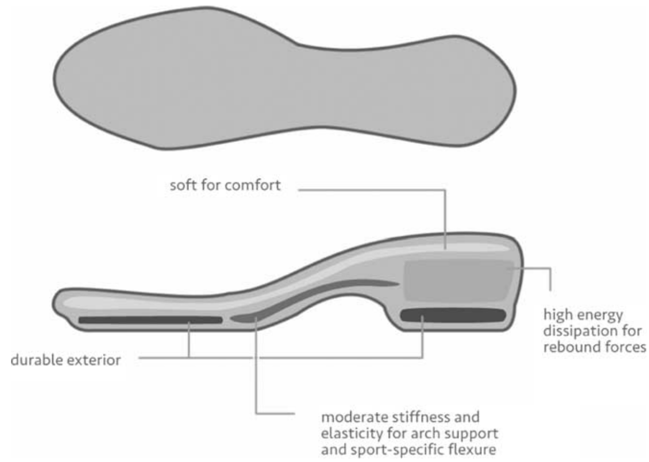


Figure 20. Illustration of design specifications for material property variation within the shoe-sole. Design specifications include stiff durable exterior surfaces in the heel and toe regions. Moderate stiffness and elasticity is required for the arch-support region and performance-specific flexures. High energy dissipation materials are required against rebound forces above the heel. Soft materials are required at the top surface area supporting the dancer's foot. Illustration: Mindy Eng.

Ballet sneaker shoe sole design

Digital modelling and representation of graduated properties

Based on the structural performance requirements of a 'ballet sneaker', a range of stiffness and elasticity parameters was determined allowing the designer to vary these properties across the surface area of the ballet sneaker. This particular shoe requires a unique combination of properties and a relatively rapid change from stiff to soft within the shoe sole. Figure 20 illustrates property variation as a function of design specification.

Unlike the two previous cases, where mathematical algorithms have been implemented as a material-distribution strategy, here the user specifies surface regions characterised by their desired stiffness and elasticity within the framework of a graphic-user-interface allowing for freehand voxel allocation. In other words, the user-interface allows the designer to 'paint' the design with material specifications which will directly inform the fabrication process.

The graphic user interface consists of a 'figure space choice' menu and a 'material choice' menu as illustrated in Figure 21.

The right-hand space is divided into three functional regions including the voxel control region, the material behaviour region, and the design tools region. The voxel control region informs the user with the minimum voxel size for the specific material being used and allows the user to

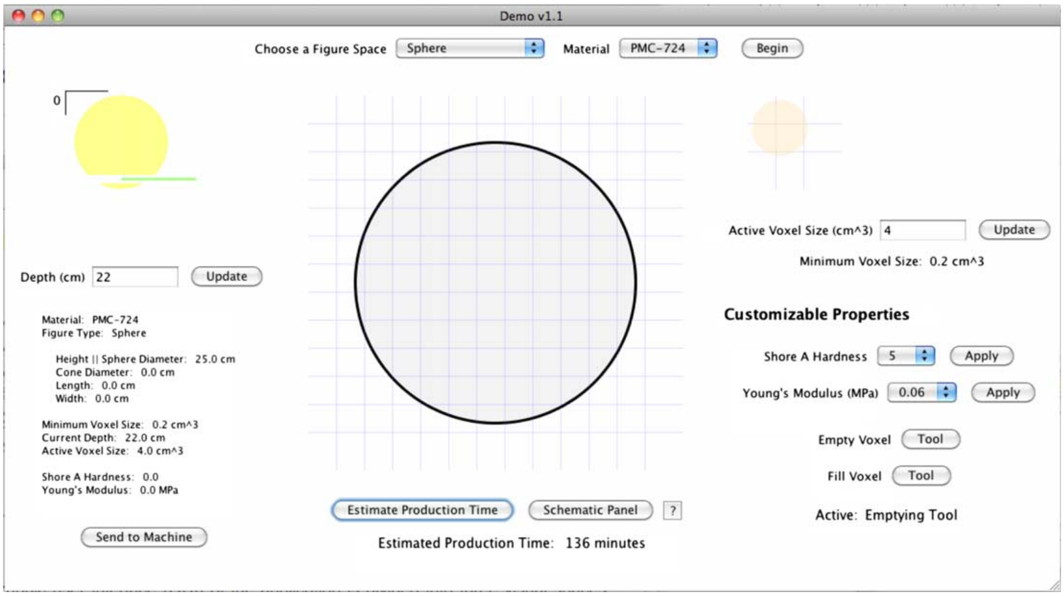


Figure 21. The graphic user interface (GUI) of the application is divided into three visual spaces allowing the designer to 'paint' the design with material specifications which will directly inform the fabrication process. Illustration: Mindy Eng.

control the size of material voxels being deposited. The display indicates the current active voxel size on a scale identical to that of the work area in the central graphic space. The material behaviour region indicates material properties that the user has control of for a given material. Property constraints are stored within the software, and the user is informed if he/she falls out of these constraints. Property constraints vary from material to material. The design tools region displays the tool types that the user can access. The fill voxel tool deposits voxels of material while the empty voxel tool removes voxels of material.

The central space includes the user's work area and provides a means of estimating the production time of the current piece as well as access to the a schematic panel. In the work area the user may utilize the design tools required in order to work on an object. The schematic panel brings up a full body view of the entity in a third-angle projection drawing and displays property gradients in the entity through colour variation. Important features in the application include the use of voxels, the opportunity for users to control material behaviour, and voxel size.

In the application, voxels stand for units of volume. All material property values set by the user apply to an active voxel. By controlling the size of the voxel, the user controls both how quickly areas are filled and how intricately smaller features might be developed. The minimum voxel size indicates the small voxel that can be deposited with the device nozzle at a given pressure. The depth navigator allows the user to navigate across the figure space along a single axis while the work area displays the cross section of the figure at the current depth. Work across the span of the figure space is tracked and stored.

The concept of figure spaces in this application offers an alternative to the zooming and grid-scaling functionality that appear in traditional applications. By choosing a figure space and a figure size, the user specifies the canvas size for the design. It is within the figure space that the user then develops the design. Once the dimensions of the figure space are determined, the user is free to access the regions in the applications to designate voxel size and material properties as well as utilize the design tools.

Physical prototyping

The physical prototyping of the shoe sole was executed using a polyurethane elastomer (PMC®-724). This elastomer is comprised of various mixtures of a plasticizer and a filler material. The plasticizer can be added to the elastomer in order to soften the material while the filler can be added to stiffen it without altering its chemical

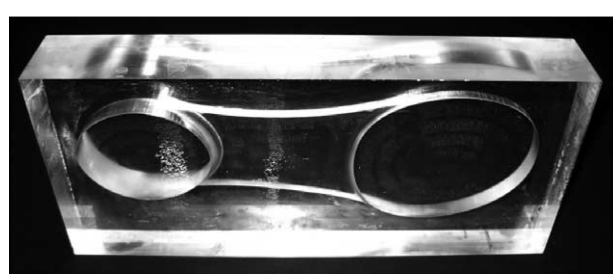


Figure 22. Initial mould prepared for shoe-sole variable material deposition.

Figure 23. Physical model illustrating variable-property material deposition as a function of coloration.

composition. By modifying the ratios between these two composites, hardness and elasticity can be easily controlled. In addition to varying hardness, the material samples also displayed differing elasticity, suggesting material property dependency between hardness and elasticity (Figures 22 and 23).

Design technology demonstration

General technical descriptions

Materials

Uniquely colored resins are used to represent different materials. We melt and remold resin sticks into thirds of a stick so that three may be fed into a heating chamber which accommodates one normal stick. Three modified glue dispensers are arranged radially in a surrogate housing such that they feed these thirds into one heating chamber, acting also as a mixing chamber. The glue dispensers are controlled by 9 V motors. Since we use the same pushing mechanism as commercial handheld glue guns, the mechanism must be reloaded after every push, so deposition is non-continuous, which is compensated for in software. The resins used in this demonstration are resin glues. It is important to note that such materials could easily be replaced by thermo-plastic polymers, silicon rubbers, or other resins. Different materials require different nozzles.

Support materials

In solid-based processes, support materials are necessary to ensure the stability of the part in the process of printing. Support materials removal can be manual, or when water soluble supports are employed, they are removed by simply being dissolved, an advantage when fabricating highly complex 3D forms. The VPRP technology demonstrates the ability to control material mixing in order to achieve different properties using the same nozzle. The technology currently works without extruding support materials, which are materials deposited in negative regions of the 3D prototype in order to support it in the process of building. It is important to note that for more accurate and complex builds of 3D forms, it is possible to incorporate support materials, such as soluble resins, that would be extruded in parallel to the *build* materials. Much like the Stratasys machines, one could also implement extruded polymer support.

Following the logic presented by the VPRP technology, support materials may also be implemented as variable property mixtures using the exact same method. In this way, support materials can vary in stiffness and/or density depending on the complexity of the region being printed. Such an implementation increases speed and efficiency of printing. In the case of density variation, such method would decrease material use in cases where minimum support is needed due to local geometrical simplicity.

Body and mechanism

In order to dispense the trifurcated glue sticks into the same heating chamber, aluminum plates have been machined that function in the same way as the sliding trigger guides in the original housing, but the trigger assemblies are angled so that the glue sticks will all be pushed into the same chamber (they are flexible). These are fastened to a round baseplate with screws. On the bottom side of the baseplate, we have attached a heating chamber. Figures 24–28 illustrates the various components of the entire assembly. Its components include the following:

(1) Trifurcation Bushing

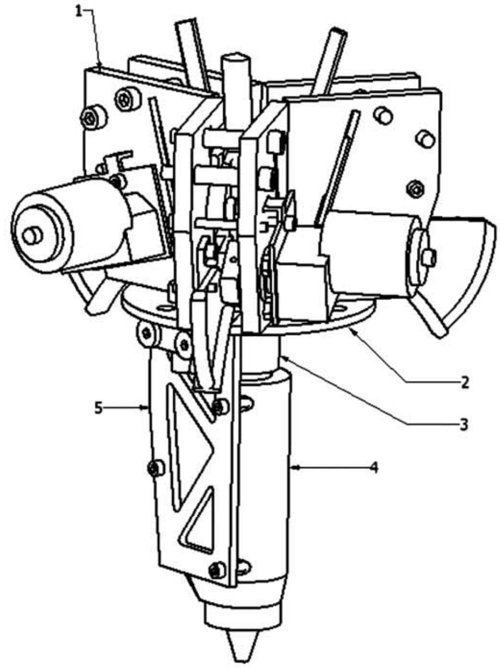
Each plastic trigger is designed to push a whole glue stick via a frictional force angled downward. We insert a bushing, which is a solid cylinder with a third of its arc cut away as shown in Figures 19 and 20, so that the plastic ring guiding the glue stick is reduced to the size of the third.

(2) Guide Plate

The aluminum guide plate is water-jetted from ¼’ thick aluminum. Its primary purpose is to replicate the slot

Prototype assembly

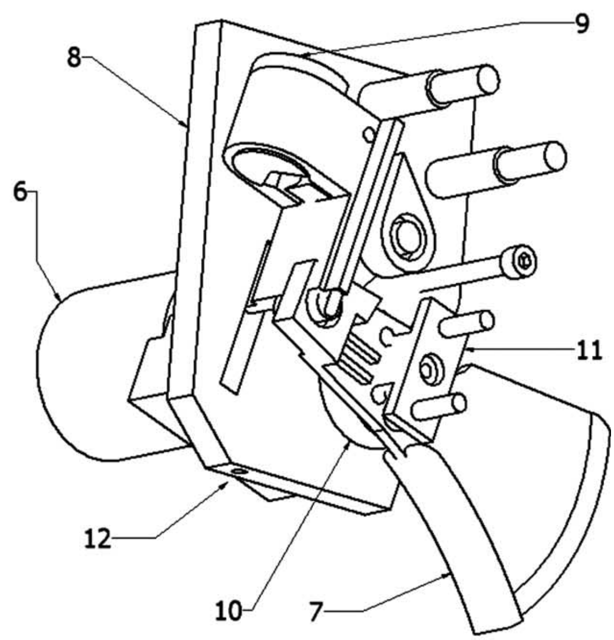
No.	Part name	Description
1	Pusher subassembly	Advances individual stick
2	Baseplate	Structural; waterjetted aluminum
3	Baseplate bushing	Guides glue sticks into heating chamber; 3d-printed plastic
4	Heating chamber	Taken from commercial glue gun
5	Nozzle cradle	Attaches heating chamber to delivery assembly; waterjetted aluminum



0.75:1 scale

Pusher subassembly (1)

No.	Part name	Description
6	Motor	9V
7	Trigger	Taken from a commercial glue gun
8	Side plate	Waterjetted aluminum plate; structural purposes
9	Trifurcation bushing	3d-printed plastic; guides 1/3 glue stick
10	Trigger hub	Constrains trigger movement to motor shaft
11	Axis sleeve	Reinforces trigger-hub connection; waterjetted aluminum
12	Motor bushing	Aligns motor shaft; waterjetted aluminum



1.6:1 scale

Figure 24. Illustration showing prototype and pusher assembly and their components.

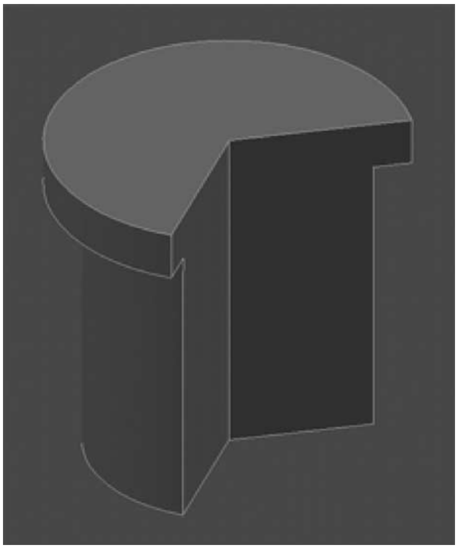


Figure 25. Close up of tri-bushing

that would guide the trigger in the original housing. It also supports the motor in order to ensure proper shaft alignment.

(3) Motor Interface

- Mechanical interface: Each motor is mounted to a guide plate for alignment. Its D-shaft is coupled to the trigger via a setscrew in a hub that is bolted to the trigger.
- Electrical interface: The servomotors are connected to a microcontroller board controlled by the software module (see further descriptions in section 3). On the reuptake (after exceeding the motion range of the trigger), a motor's direction must be reversed in order to reload. The speeds of each motor are independently controllable by varying the voltage feed. For this demonstration we have used V9 motors. Stepper motors allowing more accurate control of material extrusion and mixtures speed and power could replace these motors.

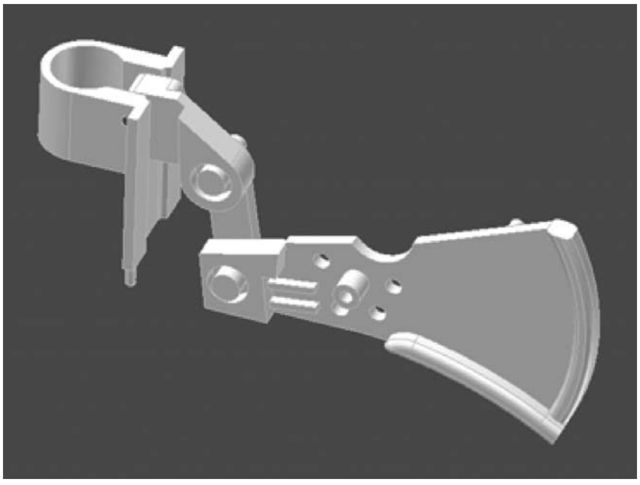


Figure 26. Plastic trigger from glue gun.

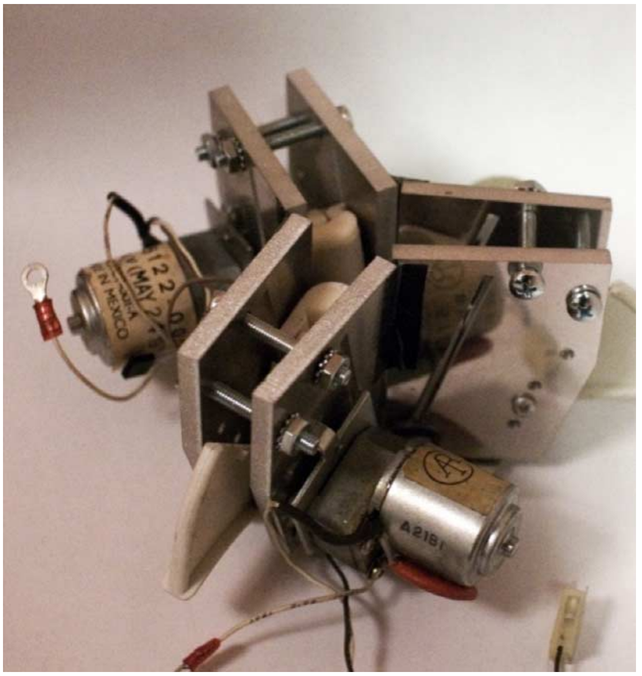


Figure 27. Individual pusher assemblies mounted just to base-plate.

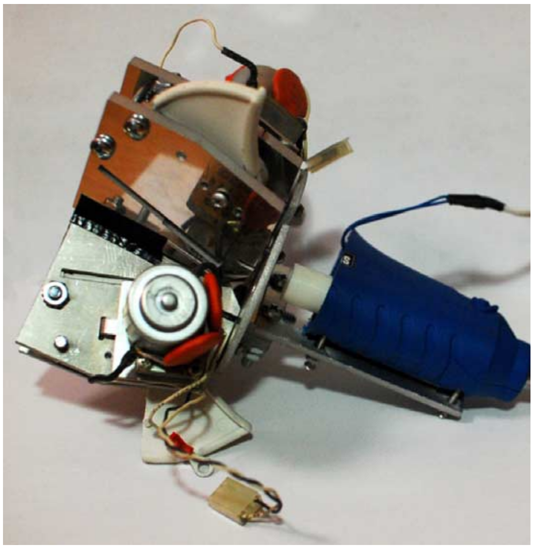


Figure 28. Final assembly (not including a stand or CNC movement).

(4) Nozzle

A truncated glue gun heating chamber/nozzle receives the glue sticks. An aluminum plate is screwed to its side so that it may be attached to the rest of the assembly.

(5) Base-plate

The entire set of guide plates are screwed onto a round water-jetted base-plate, and the nozzle is mounted to the underside. A tapered plastic bushing (3D printed) in the center of the plate guides the angled glue sticks so that they are all forced into the nozzle opening.

Software: variable property modeling (VPM) environment

Beyond its contribution as a novel additive fabrication technology, the implications of VPRP on the CAD industry are most significant and require that we revisit current applications used for the geometrical description of 3D form and structural analysis of prototypes. The VPRP technology us supported by a novel method for form-generation entitled variable property modeling (VPM). Such proposed set-up for a CAD system to design, manipulate and fabricate graded materials.

Given their variation of properties across volume and surface area, FGMs could also be 3D printed by sending the machine a layer-by-layer pixel sheet such that when they are stacked they are represented as voxel clouds. However, functional grading is something to be designed and voxels are traditionally representative physical data scanning. This raises the problem of how to generate voxel-based information in a CAD environment. Given their representation as discrete elements defining a continuous whole, able to carry 3D information (scalars, vectors) as well as physical information (tensors), voxels are ideal entities to design and edit graded functionalities. Volumetric property design is new to CAD and CAM systems and offers an alternative to NURB and STL representations. The diagram below exemplifies the need for a Variable Property Modeling (VPM) paradigm.

Within the VPM modeling environment, the program must translate desired model properties to material properties. The VPM environment gives the value of any property at any point (high or low conductivity / stiff or soft) in order to structure the correct material composition and emulate both its structural and electrical performance. Currently, transition functions that compute gradient property distribution across one or multiple dimensions do not exist in CAD.

The VPM environment is developed in order to cater for such requirements and present physical data and material composition by treating voxels as tensors (geometrical entities containing multiple physical parameters), or by computing transitions between multiple compositional phases as extrapolation functions. Clearly, the distribution of materials must be limited by the boundary of the solid, or, its domain (Figure 29).

The software control module is written in Processing, an open source environment that facilitates data visualization. Mixture ratios may be controlled through sliders, but absolute quantities are controlled so that only the ratio, not the total output amount, changes. Color selection (analogous in the suggested software to material selection) operates according to the schematics shown in Figure 24.

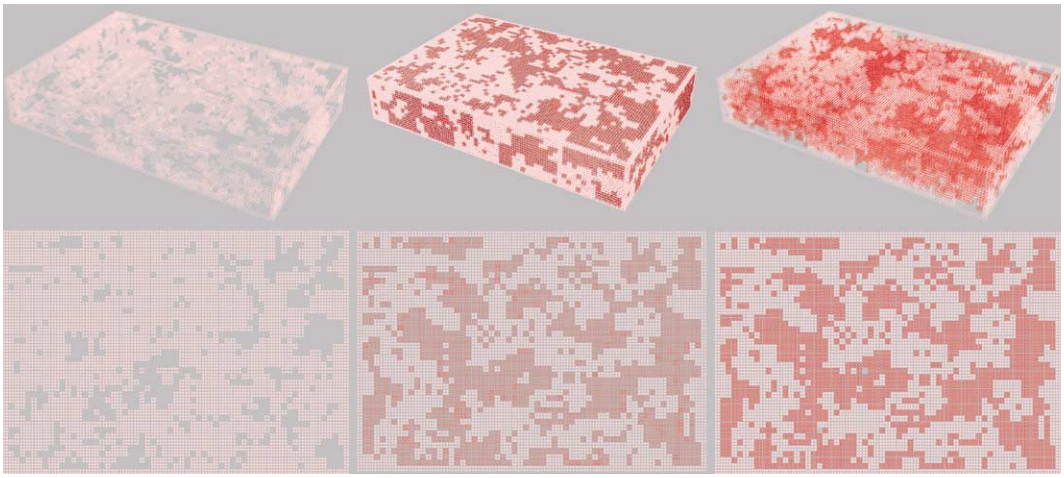


Figure 29. Distribution-driven and property-driven ‘digital anisotropy’ assumes the allocation of pixels as analogous to that of homogeneous physical matter. In this case, every pixel contains equal properties (represented by the color red), however, the heterogeneous organization of pixel-groups on a larger scale, defines its overall performance, depending on the property at hand. In this case, the cube is heterogeneously structured due to the non-homogeneous distribution of ‘pixel units’.

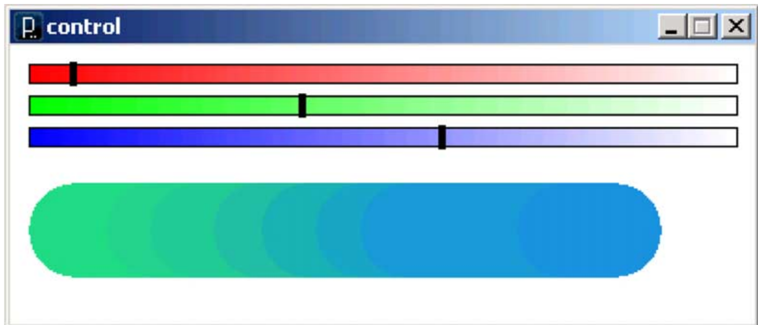


Figure 30. Screen shot of control module developed in the Processing environment

Contributions

Theoretical contributions

Most of today's rapid prototyping technologies create products in a point-by-point fashion. Selective-laser-sintering (SLS) and stereolithography (SLA), for instance, initiate prototype solidification at areas of contact between the stock material and the laser as the laser traverses the X, Y and Z planes. Other layer manufacturing technologies, such as 3D Systems' In Vision machine and Objet Geometries machine, deposit the material point by point. In these systems, the prototype is constructed systems drop by drop using a modified inkjet system. When supplied with one or more extra jets, both systems could build graded material parts, also known as 'functionally graded materials' (FGMs). This type of graded internal structures is only possible when taking an additive approach to manufacturing. However, it is still impossible to represent FGM's in a CAD environment. Most commercial CAD systems are in the category of 'B-rep' modelers. This means that the inside of the 'solids' using these modeling techniques are as empty as the volumes surrounding the solid. Therefore, for most CAD systems, even though they are known as 'solid modelers, they are, in fact just surface representation protocols of the geometry defining the 3-D form. All RP production formats, STL predominantly, are thus numerical representations of those geometries.

The variable printing method (VPM) offers a novel approach to modeling and fabrication of 3D solids as it offers a way to represent the internal structure/composition of the form at individual points within the volume of the part. Currently, this method is explored by using colors as a representation of material properties. In the future, we anticipate that 3D printers will be designed as 'FGM machine' which are provided with information to 'print' the desired graded material distribution.

It is expected that new CAD systems such as the VPM environment could also be applied for the design or Functionally Graded Materials using the same application logic in micro scales. Such developments will most probably occur independently from other developments in CAD for rapid prototyping and manufacturing.

It is also expected that such innovations in rapid prototyping technologies will find their way into rapid manufacturing parallel to the development of more structural materials and an increase in scale. Currently, all developments in rapid manufacturing have been aligned with and dependent upon, traditional CAD environments. However, the VPM environment contributes to a radical shift from contour modeling composition modeling, allowing for new capabilities in performance modeling, with a decrease in material waste and an increase in efficiency.

Finally, the design and fabrication of building components with graduated properties holds great methodological and practical implications to the design disciplines and to architectural construction respectively. The VPRP approach might be considered as an approximation to natural material formation processes. Such processes take in unformed raw materials and operate on them locally; using a single parameterized and digitally controlled process rather than many specialized processes, to produce formed solid objects. In this way, the designer is now able to break free from the rigid logic of industrial supply chains and related CAD systems.

Technical contributions

Variable property rapid prototyping (VPRP) is a novel approach and method introducing the ability to dynamically mix and vary the ratios of different materials in order to produce a continuous gradient in a 3D printed part. This ability expands the potential of prototyping, since the varying properties allows for optimization of material properties relative to their structural performance and for more accurate evaluations of the intended final product, such as stress testing. Dynamic gradients could also contribute to efficient conservation of material usage. This project establishes a novel nozzle that can produce a continuous gradient, using colors as a substitute for material properties

VPRP could potentially be applied to support materials within the printing process: Support materials are designed as temporary deposited structures that allow for a stable build to be prototyped. These structures, for the most part, are removed from the final model by decomposition, melting, heating or mechanical removal. However, such constructions are incredibly wasteful. The ability to 3-D print with variable properties may potentially eliminate the need to extrude support material by varying the relative thickness of the functional part in regions of under cuts and/or geometrical perimeters which require more strength in order to self-stabilize in the build process and also as the part dries out. Moreover, an intermediary step towards the application of such ideas could potentially be applied to existing support materials themselves: by offering variable property support, parts could be excavated with ease as stronger support pieces cling to more fragile areas within the print.

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 3D 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 technology able to design freeform shapes consisting of multiple materials to meet high level functional goals.

Limitations and future work

VPM: general limitations

Geometry

It is important to note that a reciprocal relationship exists between a given material property (i.e. stretch, bend or shear) and the geometrical dimensions of the part (i.e. thickness). For example, a sheet can be made stiffer by either increasing its material stiffness or by increasing its thickness. The VPRP approach was demonstrated in two designed objects in which the variation of properties included both thickness and stiffness distribution, the latter being informed by the former. Currently, few computational tool exist which supports physical-based-form-generation and fabrication by computing relationships between material properties and geometrical manipulations.

Behavior

The VPRP technology currently under development is focused around the controlled variation of properties such as stiffness, strength and elasticity. The VPRP approach at large however, may well be extended to include combinations of various other properties. These may include mechanical, electrical, thermal, chemical, magnetic, optical, acoustical, environmental, sensorial, atomic and even radiological properties. Similar attempts have been previously developed outside the building industry, particularly in the medical fields and within the disciplines of material science and engineering; it is anticipated that the applications of property variation control and manipulation in the building industry hold much promise to the industry as a whole but require further research and development.

Scale

The paper has shown that property variation in nature occurs at the atomic to cellular length scales, as well as the mid-human scale (micro-meter to millimeter). More specifically, the VPRP technology has been implemented and evaluated in mm and cm scales. Limitations in scale still subsist in the technology's current set up. A scale leap of 3 or more orders of magnitude to the meter and even kilometer scale will clearly depend on the combination of material durability (i.e. the search for structural materials in additive manufacturing) as well as the automation set up (i.e. three-axes CNC tray sizes). We expect more research be done as the approach further develops and implemented in construction scales. This also implies that beyond VP component scale, some component delineation is required in the definition of a building element. The question of where does property graduation end, and a new component begin, must be addresses in this context.

VPRP: technical limitations

Material deposition flow control

Certain of the complex individual components used in the design of the VPRP technology, such as the heating chamber, are taken from commercially available glue-guns in order to streamline the construction of the nozzle. As a result, there are certain flow-control limitations that must be addressed in future iterations of this technology.[1] Furthermore, the current mechanism must reload itself frequently and discretely following every deposition. Re-designing, and improving upon the flow automation control unit could potentially overcome such limitation.

Composites and fibers

The first VPRP prototype displayed here makes use of three resin types classified by color. For the software unit, colors

[1]The rest of the components are designed to avoid complex manufacturing and can be easily put together; most pieces are either lathed or require minimal machining beyond a 2D profile.

are used to represent material properties and their various mixtures. For example, if epoxy is used as the deposition material, one would vary the ratios of resin and hardener, but the functional range of the resulting mixture would be limited and must be determined. Other possibilities for future material exploration include fiber composites, which may be varied in hardness by changing fiber orientation, and selective laser sintering, which allows porosity and consequently material strength to be controlled.

Gradient distribution control and material granularity

Most of today's rapid prototyping technologies create products in a point-by-point fashion. Selective-laser-sintering (SLS) and stereolithography (SLA), for instance, initiate prototype solidification at areas of contact between the stock material and the laser as the laser traverses the X, Y and Z planes. Other layer manufacturing technologies, such as 3D Systems' In Vision machine and Objet Geometries machine, deposit the material point by point. In these systems, the prototype is constructed systems drop by drop using a modified inkjet system. When supplied with one or more extra jets, both systems could build graded material parts, also known as *functionally graded materials* (FGMs). This type of graded internal structures is only possible when taking an additive approach to manufacturing. However, it is still impossible to represent FGMs in a CAD environment. Most commercial CAD systems are in the category of 'B-rep' modelers. This means that the inside of the 'solids' using these modeling techniques are as empty as the volumes surrounding the solid. Therefore, for most CAD systems, even though they are known as 'solid modelers, they are, in fact just surface representation protocols of the geometry defining the 3D form. All RP production formats, STL predominantly, are thus numerical representations of those geometries.

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