FORM FOLLOWS FLOW: A MATERIAL-DRIVEN COMPUTATIONAL WORKFLOW FOR DIGITAL FABRICATION OF LARGE-SCALE HIERARCHICALLY STRUCTURED OBJECTS

Laia Mogas Soldevila
(First co-author)
Massachusetts Institute of Technology,
Dept. of Architecture and Urban Planning
Media Lab, Mediated Matter Group

Jorge Duro Royo
(First co-author)
Massachusetts Institute of Technology,
Dept. of Architecture and Urban Planning
Media Lab, Mediated Matter Group

Neri Oxman
(Corresponding author)
Massachusetts Institute of Technology,
Dept. of Architecture and Urban Planning
Media Lab, Mediated Matter Group

ABSTRACT

In the natural world shape and matter are structured through growth and adaptation, resulting in highly tunable and hierarchically structured constructs, which exhibit excellent mechanical properties. Conventional digital design tools and processes, however, display little integration between shape formation and materialization resulting in the disassociation between shape and matter. This paper proposes a framework and an application for the integration of shape and matter by implementing a novel material-driven manufacturing platform and computational workflow to derive large-scale hierarchically structured objects. The workflow is comprised of material-driven methods and techniques such as environmentally informed property variation, material-based hierarchical structuring, and hydration-guided shape formation. The platform is composed of a custom multi-barrel deposition head attached to a robotic positioning system. Components are physically form-found by digitally distributing natural polymer gels with functionally graded properties informed by desired structural and environmental performance. In this approach, properties such as material viscosity, deposition velocity, and nozzle pressure drive the printing of two-dimensional patterns induced into three-dimensional shapes by natural evaporation. The workflow associates material, environmental and manufacturing considerations with virtual design modeling tools, challenging traditional design workflows, prioritizing process over product and *flow over form*.

1 INTRODUCTION: BEYOND DIGITAL MORPHOGENESIS

In the natural world shape results from bottom-up material organization, sophisticated property gradation and functional hierarchies developed over time within single material systems (Vincent 2006; Vincent et al. 2012). As a result, natural structures such as bamboo, silk, or bone, display extraordinary properties. Gaining deeper insight into, and a better understanding of, the formation processes associated with these natural phenomena would greatly benefit the design of digital fabrication tools and technologies (Gibson and Ashby 1999; Mogas, Duro and Oxman 2014). Furthermore, current design practice is characterized by the domination of shape over matter. Consequently, virtual shape-defining parameters are typically prioritized over physical material and fabrication constraints, which are often considered only in hindsight, following a geometric-centric design phase (Menges 2007; Oxman 2011; Marenko 2014). Recent advances in direct digital manufacturing are enabling a shift from a geometry-centric to a material-centric design practice (Oxman 2011; Sabin 2013; Duro et al. 2014b). Today, designers have access to highly sophisticated computer-aided fabrication hardware that is contributing to the development of new material-driven design processes (Nicholas and Tamke 2012; Cabrinha 2013; Kreig and Menges 2013; Duro et al. 2014b). As the two domains—the physical and the digital—interact during the early stages of form generation, new and unexpected structural and morphological potentials may emerge that approach natural morphogenesis increasing efficiency and augmenting performance (Menges 2007; Thomsen 2012; Marenko 2014).

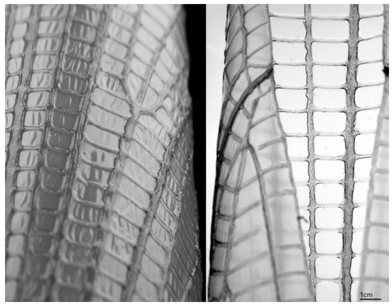

Figure 1
Close-up back and front images of a 3m-long hierarchically structured bio-plastic column form fabricated using a material-driven computational workflow integrating digital design with a novel robotic additive manufacturing platform.

File-to-factory integration efforts aim to link between the fields of Computer-Aided Design (CAD), Computer-Aided Engineering (CAE) and Computer-Aided Manufacturing (CAM) (Oosterhuis 2004; Oosterhuis et al. 2007; Sheil 2013). These efforts tend to focus predominantly on the creation of direct and seamless data transmission across media. To a lesser extent they address the potential incorporation into and integration of material-, and fabrication-driven design parameters. Given that conventional CAD software enables geometric and topologic manipulations but lacks robust means to design with material information, new workflows to support such processes are required that offer cross-domain integration (Michalatos and Payne 2013; Duro et al. 2014b). We present a data-driven computational workflow for the design and fabrication of geometrically and materially complex functional designs *(Figure 1)*. Building on our previous work in the field of Material Ecology (Oxman et al. 2015), this research responds to our interests in Fabrication Information Modeling (FIM), a methodology focusing on the integration of (1) multi-scale geometric representations; (2) fabrication and material properties, and; (3) trans-disciplinary data sets (Duro and Oxman 2015).

2 METHODS: TOWARDS INTEGRATION OF DIGITAL DESIGN AND FABRICATION

The computational workflow presented herein aims to integrate digital design and fabrication processes in a single virtual and physical platform. As case in point shown here, the customized design of both novel hardware and software is driven by force fields and property gradients of soft aqueous matter *(Figure 2a)*. We have designed a pneumatic extrusion system attached to the end-effector of an existing 6-axis robotic arm employed as a positioning platform (Mogas and Oxman 2015) *(Figure 2b)*. Specifically, the system is designed to extrude water-based polysaccharide gels and natural composites based on chitosan—a derivative of chitin as well as a biopolymer abundantly produced by crustaceans and insects (Mogas, Duro and Oxman 2014). Traditionally, chitosan-based hydrogels have been used at the micro-scale for tissue scaffolding and drug delivery; this is the first time that such biocompatible and biodegradable materials are used in structured additive manufacturing of architectural scale products (Mogas, Duro and Oxman 2014; Mogas and Oxman 2015). In order to structure the deposited constructs we implement design and control software that integrates between material, design and fabrication parameters.

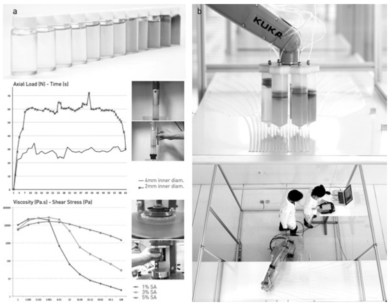

Figure 2
(a) Hydrogel material gradients vary from 1% to 12% concentration of biopolymer in water. Material characterizations such as axial load and shear rate are used to inform hardware design and software implementation. (b) The hardware platform is composed of a custom multi-barrel deposition system and a positioning robotic arm.

2.1 IMPLEMENTATION DETAILS

Materials: Base biopolymer materials used are tuned with mild chemicals and water. They exhibit visco-elastic and visco-plastic behavior when contained within airtight barrels, and undergo extrusion as well as natural curing at room temperature with relatively low use of energy. We employ natural gels generated from shrimp shell waste—a source of chitin—in different concentrations of polysaccharide and mild acidic solutions to generate a gradient of materials with varying degrees of stiffness, viscosity and opacity (Duro, Mogas and Oxman 2015; Mogas and Oxman 2015). Specifically, we mix chitosan in a mild acid aqueous solution to obtain a graded-by-design viscosities, opacities, and stiffness. Analyzed results inform the hardware assembly and in turn provide the ability to tune material properties with high levels of digital control *(Figure 2a)*. For additional information on material characterization review related scientific journal articles (Mogas, Duro and Oxman 2014; Duro, Mogas and Oxman 2015; Mogas and Oxman 2015).

Hardware: The pneumatic assembly is designed to additively fabricate large-scale structures made of water-based materials. It is composed of six large-capacity clear plastic barrels containing hydrogels of different viscosities and is attached to the end-effector of an existing 6-axis robotic arm, connected to a positive and negative air pressure system. Both pneumatic assembly and robotic arm are digitally controlled to tune pressure and speed on-the-fly based on desired extrusion geometries and material properties *(Figure 2b)*.

Software: An integrated design workflow is implemented in the C# language within the Rhinoceros3D platform; in C++ language as a stand-alone applet for mechanical synchronization of deposition and positioning platforms; and as custom firmware loaded into the deposition electronic assembly. Instructions generated by the software are implemented to achieve full synchronization of deposition and positioning, including the incorporation of material metadata with direct feedback to and from hardware.

2.2 A MATERIAL-DRIVEN COMPUTATIONAL WORKFLOW

The computational workflow is designed to integrate physical parameters associated with material and hardware constraints, to compute relationships between these parameters based on material viscosity, extrusion pressure, and deposition speed; and to encode these relationships through customized instructions in the forms of metadata that is communicated to the fabrication platform (Duro, Mogas and Oxman 2015).

Material-driven Property Variation: The system encodes an array of independent parameters associated with basic mechanical and chemical material properties, as well as platform-dependent constraints given by the fabrication system such as viscosities; shear rates, barrel types, hardware response times, and/or envelope size. These parameters are then combined with design-specific variants such as nozzle type, material composition, as well as time-dependent pressure maps. Resulting calculations output necessary flow-rates, barrel refill patterns and positioning speeds. Finally, custom fabrication instructions are generated as output, encoding motion and extrusion commands to the pneumatic deposition and robotic positioning systems respectively. Computer-controlled negative pressure is achieved via a vacuum pump (v), positive pressure via a compressed air tank (c) and a digital PSI regulator (r). Synchronized instructions given by both deposition and positioning platforms are represented by the "home position" in 3D space (H), motion (M), extrusion initiation values based on material properties (E), partial and final position targets including time delays (T) and barrel refill pattern (R) *(Figure 3a left)*.

Material-driven Hierarchical Structuring: Hierarchical structuring of printed components is obtained across three levels of resolution associated with the additive manufacturing process *(Figure 3a, right, Figure 3b)*: At the first level of resolution, material is distributed locally through varying layering strategies and stiffness gradients. At the second level of resolution, material is extruded in longitudinal regions with variable extrusion height and width associated with pressure data given by the deposition platform and the nozzle *(Figure 3b)*. Finally, at the third level of resolution, global topologic effects are obtained across the entire construct through geometrically patterning the overall shape *(Figure 3a, right)*. It is important to note that local layering, regional extrusion gradients, and global geometric patterning are designed and fabricated in 2-dimensions (2D). Specifically, designs are not modeled in 3D; rather, they are composed of 2D extrusions that are associated with, and informed by, material properties, robotic arm speed and nozzle speed. Depositions of material hierarchies with varying stiffness are extruded flat on a two-dimensional substrate.

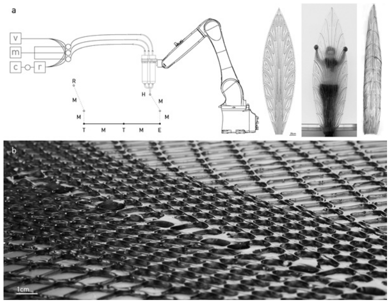

Figure 3
(a) Motion-extrusion instructions schema: a pneumatic assembly for material deposition is designed as a multi-chamber nozzle and attached to the end-effector of an existing positioning platform (Kuka KR AGILUS robotic arm; model KR 10 R1100 SIXX WP). (b) Close-up image of a hierarchically structured chitosan-based deposited construct.

Material-driven Shape Formation: Hydration guided shape formation is informed by both intrinsic constraints (relating to material properties, e.g. elastic modulus) and extrinsic constraints (relating to the environment, e.g. thermal maps). Designed and digitally fabricated constructs are left to dry flat, overnight, while positioned under a tunable fan array. Figure 3a (right) displays a two-dimensional (2D) digital drawing, its fabrication protocol including structural hierarchies on three levels of resolution, and the final three-dimensional (3D) structure; a self-assembled column formed during drying. During the drying process, internal evaporation-induced stresses accumulate within the printed structures of the flat material *(Figure 4a)*. Once removed, the constructs undergo folding as remaining moist content evaporates from their surface. Shape is therefore found or formed based on computationally templated material and environmental effects incorporated into the workflow. Figure 4b displays 2D-to-3D formation induced by digitally patterning material properties in a medium-scale structured grid removed from its substrate at an intermediate hydration stage. Additional research on predictive modeling of 3D shaping is currently under way to further advance the digital design tool by incorporating immediate simulation of 2D hierarchical designs.

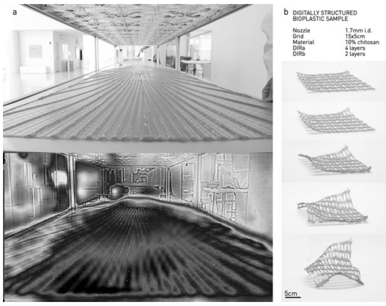

Figure 4
(a) Internal stresses generated by natural evaporation contribute to the shaping of each structural component. (b) 2D-to-3D shaping stages of an additively manufactured structured chitosan grid removed from the substrate at an intermediate state of curing (left to dry and form-found within 12 hours).

3 DISCUSSION: MANUFACTURING LARGE-SCALE HIERARCHICALLY STRUCTURED OBJECTS

Biological structures adapt to external stimuli by growth-induced material property variation resulting in hierarchically structured forms. Conventional digital design tools and processes, by contrast, lack in robust integration of computational design tools, digital fabrication environments and the material itself. Preliminary results shown here demonstrate chemical tuning of biomaterials with digitally designed and fabricated structured hierarchies informed by load-responsive arrangements as can be found in the biological world *(Figure2, Figure 3)*. Such case studies have informed our research into form generation and fabrication of optimized load distribution in architectural scale cantilevering components. Hydration guided shape formation studies are currently being conducted in our lab in order to establish informed relationships between shape, material composition, hydration and deformation *(Figure 4b)*. Additional research on structural design criteria can be found in (Mogas, Duro et al. 2015).

4 CONCLUSION: FROM VIRTUAL-CENTRIC TO PHYSICAL-CENTRIC WORKFLOWS

In this paper we have presented a workflow and an enabling technology for large-scale robotic design and fabrication of functionally graded materials and structures (US PPA Num. 17388T, 2014). The system is deigned to additively manufacture hierarchical and multifunctional structures across length scales. Such multi-scale structures embody new processes and application domains for biodegradable and biocompatible natural waste materials that are to date predominantly used in nano-, and micro-scale medical applications (Mogas, Duro and Oxman 2014). New application domains enabled by this work range from robotic construction of architectural facades with tunable translucency to temporary lightweight shading devices or tent-like architectural structures. At the core of this research lies our motivation to advance the invention and practice of novel workflows and tools involving fabrication-informed modeling of variable property structures. We believe that such advancements will enable a shift of both mindset and tools from geometry-centric design processes to material-, and fabrication-centric approaches in digital design and fabrication. Digital design research combining manufacturing data and material-based computation will, in the future, not only contribute to achieving higher overlap between virtual and physical tools increasing manufacturing efficiency and promoting the design of more sustainable products; it will also generate new and potentially interesting formal vocabularies driven by structural efficiency and material logic as exemplified by form follows flow.

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LAIA MOGAS SOLDEVILLA

Laia Mogas Soldevilla is a Research Assistant at the Mediated Matter group, MIT Media Lab, focusing on design and digital fabrication of biologically inspired material systems. She completed her Architectural diploma minoring in Visual Arts at the Polytechnic University of Catalonia, School of Architecture (UPC-ETSAV) where she graduated with honors. In 2010 she completed a post-professional degree in 'Advanced Design and Digital Architecture' at the Pompeu Fabra University (UPF). Since 2008 she co-leads the DumoLab research studio (dumolab.com). In 2010-2011 she was awarded research grants to pursue the 'Architecture, Energy and Environment' program at UPC-ETSAB and the 'Master of Science in Architecture Studies' at the Massachusetts Institute of Technology within the Design Computation Group.

JORGE DURO ROYO

Jorge Duro Royo is a Research Assistant at the Mediated Matter group, MIT Media Lab, where he focuses on novel virtual-to-physical theoretical and applied digital design methods under the umbrella of Fabrication Information Modeling (FIM). He studied Architecture as the Polytechnic University of Catalonia, School of Architecture (UPC-ESTAV) and Mechanical Engineering at the Polytechnic University of Catalonia, School of Industrial and Aeronautic Engineering (UPC-ETSEIAT) where he graduated with honors with a focus on structural design and construction. Since 2010 he has taught introductory hands-on courses on Digital Visualization, Parametric Architecture, and Computational Design, and collaborated with diverse groups at MIT and Harvard.

NERI OXMAN

Neri Oxman is the Sony Corporation Career Development Professor and Associate Professor of Media Arts and Sciences at the MIT Media Lab where she directs the Mediated Matter group. Her group conducts research at the intersection of computational design, digital fabrication, materials science and synthetic biology and applies that knowledge to design across scales from the micro scale to the building scale with a focus on additive manufacturing. Oxman was named to ICONs list of the top 20 most influential architects to shape our future (2009), and was selected as one of the 100 most creative people by FASTCOMPANY (2009). In 2014, she received the Vilcek Prize in Design. Her work is included in the permanent collections of MoMA, Centre Georges Pompidou, the Museum of Science and elsewhere.