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DESIGNING THE OCEAN PAVILION: Biomaterial Templating of Structural, Manufacturing, and Environmental Performance

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Abstract

Driven by novel biomaterials design and natural aqueous formation, this research offers a new structural design perspective combining a crustacean-derived biopolymer with robotic fabrication to shape constructs that interact with the environment utilizing graded material properties for hydration-guided formation. We establish structural, manufacturing, and environmental design templating strategies informing the design of the constructs and their material makeup. We present a biomaterial-driven design process resulting in a novel structural system and a custom robotic manufacturing platform designed to deposit water-based composites unveiling novel functional, mechanical, and optical gradients across length scales. Components are form-found through evaporation patterns informed by the geometrical arrangement of structural members and the hierarchical distribution of material properties. Each component is designed to take shape upon contact with air and dissolve upon contact with water. We present the principles and method applied as a unique case demonstrating the material ecology design approach through additive manufacturing of lightweight, biocompatible and materially heterogeneous structures. Initial results demonstrate a wide range of structural behaviors that represent a novel approach to material-informed biodegradable structure formation by design and hold great promise for the future of sustainable manufacturing.

Keywords: material ecology, biomaterial structures, material-informed design, robotic additive manufacturing, environmental templating, structural templating, manufacturing templating, water-based materials.

1. INTRODUCTION: Motivation and Related work on Structural, Manufacturing and Environmental Design of Water-Based materials

1.1. Background on Natural Structure Formation of Water-based materials

In the biological world, structures are shaped according to the principles of minimum inventory for maximum diversity (Pearce [19]). Organisms use freely available energy, simple molecular chemistry, mild chemicals, and abundant resources to build complex medium-, and large-scale structures, such as bird's nests or termite mounts (Pearce [19], Vincent [24]). Biological structures are locally attuned and responsive, resilient to disturbances, and fully recyclable (Vincent [24]). Most biomaterial structures are generated at ambient conditions with low energy and water (Vincent [24], Mogas et al. [14]). Water is a major constituent of all natural materially heterogeneous structures such as insect cuticles (Fernandez and Ingber [7]). For instance, in the formation of the dragonfly wings, water-based graded materials interact with internal and external forces (Donoughe et al. [4]) to provide for both flexibility and tensile strength along the structure (Fernandez and Ingber [7], Jongerius and Lentink [10]). We derive the principles of natural aqueous formation and implement an integrated design-to-fabrication system. The resulting large-scale, lightweight, biodegradable, and multifunctional structures designed and constructed for the Ocean Pavilion embody both an architectural and an environmental motivation (**Figure 1**).

1.2 Background on Direct Digital Manufacturing of Water-based materials

In industrial applications such as tissue engineering, the manufacturing of water-based gels has rapidly evolved in the last ten years towards producing nano-featured biocompatible tissue scaffolds (Li et al. [11], Gutowska et al. [9], Melchels et al. [9]). There are mainly three different bio fabrication techniques to manufacture hydrogel-networked structures: laser-based techniques, robotic dispensing, and inkjet printing, all operating at the micro scale (Billiet et al. [2], Malda et al. [12]). The fabrication of hydrogel structures requires mild processing conditions such as room temperature and soft chemicals. Therefore, typical additive-manufacturing techniques such as fused deposition modeling (FDM) or selective laser sintering (SLS) cannot be used as they generally involve harsh processes such as high temperatures and abrasive chemicals. However, recent developments use conventional manufacturing methods such as injection molding to produce polysaccharide-based fully compostable cups and egg storing containers (Fernandez and Ingber [7], [8], Rinaudo [20]). By dramatically increasing the scale at which biomaterials are manufactured and used today, we design and implement a customized manufacturing platform using regenerated biomaterial composites.

1.3. Background on Environmental Performance of Water-based materials

Today's industrial manufacturing processes are generally characterized as wasteful and their products often highly difficult to recycle (Oxman [18]). Specifically, man-made plastics are the most energy intensive materials to degrade (US MSW [23]) posing global health and resource issues as plastic pollution increases and fuel availability decreases (Blacksmith Inst. et al. [3], US MSW [23]). However, water-based material structures are naturally degradable (Vincent [24], Rinaudo [20]) while displaying exceptional and diverse mechanical properties (Fernandez and Ingber [8], Ashby et al. [1]). Our research focuses on low-energy and mild-condition deposition systems for polysaccharide gels in order to design large-scale functionally graded structures with environmental capabilities for applications in architectural and product design (**Figure 1**).

Figure 1: Perspective view of a typical structural assembly and research exhibit focusing on water-based additive fabrication and biological design at the MIT Media Lab.

2. RESEARCH AIMS: Material-informed Structural, Manufacturing, and Environmental Design

With biological material formation characteristics in mind, we present a novel material-driven process and technology for the production of architectural-scale structures that are not only derived from structural patterns in nature, but also manufactured from biological materials such that they highly interact with the environment as they take shape and ultimately biodegrade (Mogas and Oxman [15]). Future implementations of the process can build upon the material system's biocompatibility to encapsulate living cells and incorporate biofuel production into architectural structures. Such integration of matter, fabrication, and environment into digital-design-to-fabrication processes results in emergent material behavior tailored by computational design (Mogas et al. [16]), and aligns with our field of research termed *Material Ecology* (Oxman [17]).

3. BASIC RESEARCH: Bottom-up Material, Manufacturing, and Structural Design

Driven by aqueous material formation, we develop a novel robotically controlled system to deposit natural water-based organic structures at ambient conditions, using mild chemicals and low amounts of energy (Duro et al. [5], Mogas and Oxman [15]). We additively manufacture biodegradable and lightweight composite constructs with functional, mechanical, and optical gradients across length scales (Duro et al. [5], Mogas et al. [14]) (**Figure 1**).

3.1 Bottom–up Chemical Design and Characterization of Structural Water-based Composites

Our bottom-up biomaterial design exploration focuses on chitosan, the second most abundant natural polymer on earth. Chitosan is a polysaccharide derived from chitin (Fernandez and Ingber [7]). Chitin's chemical structure is similar to cellulose and can be found in exoskeletons of insects and crustaceans as well as in some fungi (Vincent [24]). The non-toxicity, solubility, capacity for swelling, and chemical versatility of chitosan allow for the development of functionalized materials that can be used in multiple scales such as drug delivery, tissue scaffolding, consumer products or architectural parts (Mogas et al. [14], Fernandez and Ingber [7], Billiet et al. [2], Malda et al. [12]). For the purpose of our research, chitosan powder 85% de-acetylated and acetic acid are purchased from Sigma-Aldrich. Chitosan powder is processed into gel at 3%, 6%, 9%, and 12% w/v concentrations using 4% w/v acetic acid in aqueous solution. A concentration of 3% has a translucent appearance and displays similar consistency to watery honey. A concentration of 12% has an opaque appearance and displays the consistency of natural rubber. The materials are characterized using a 200cc syringe with a 40mm inner diameter, and a 4 and 2mm nozzle inner diameter under an AR-G2 TA Instruments viscometer and an Instron mechanical tester with a 9071.85kg reversible load cell. Extensive empirical testing results demonstrate that a maximum axial load of 75N and maximum linear plunger motion of 50mm/s present a consistent flow rate with the different gel viscosities (Mogas et al. [14], Mogas and Oxman [15]). Such material-driven parameters are used to dimension and design the presented enabling technology for large-scale digital fabrication of chitosan gels (Section 3.2).

Preliminary testing of deposited materials shows promising 40MPa UTS (Ultimate Tensile Strength) comparable to other 3D-printing filament materials such as Nylon, ABS (Acrylonitrile Butadiene Styrene) or PLA (Polylactic Acid). To perform UTS testing, deposited chitosan materials in different concentrations (3%, 4% and 6% w/v in 4% acetic acid in aqueous solution) and sourced from different manufacturers (Sigma Aldrich and Primex) are dried overnight into 0.5mm thick films and laser cut into dog-bones that are tested under an Instron machine (**Figure 2**). Further research is being conducted in chitosan-based composites incorporating glycerin plasticizers for increased flexibility, as well as fibrous and granular fillers in order to generate components with compression and bending capabilities (Mogas and Oxman [15]).

3.2 Bottom–up Mechanical Design of a Material-informed Additive Manufacturing Platform

Figure 3 illustrates the designed manufacturing platform with fully synchronized fabrication parameters for position, speed and extrusion via material property constraints (Duro et al. [5]). The platform is composed of an existing 6-axis robotic arm (Kuka KR 10 R1100) as a positioning system operated via Ethernet instructions (**Figure 3(1)**); a customized pneumatic deposition platform operated via serial instructions carrying 6 barrels of different structural capacity hydrogels (**Figure 3(2)**); a security envelope for operation of the robotic system (**Figure 3(3)**); a 1m-wide and unlimited length print bed (**Figure 3(4)**); a computer-controlled evaporation system (Section 3.1.3) (**Figure 3(5)**); and finally a 10m-long workspace and storage cabinet (**Figure 3(6)**). The water locked within the polymeric materials allows for total self-bonding as well as self-repair of layers and sections of the print. Consequently, structures span a sliding print bed with virtually-infinite longitude allowing for structural construct generation beyond the robotic arm reach, which overcomes the gantry size limitation of current additive manufacturing technologies (Oxman [18]). In previous implementations of the extrusion platform we achieve static mixing on the fly of different gel viscosities, and parallel, coaxial as well as sub-millimeter nozzle extrusion of gels and colloids (Mogas et al. [14]).

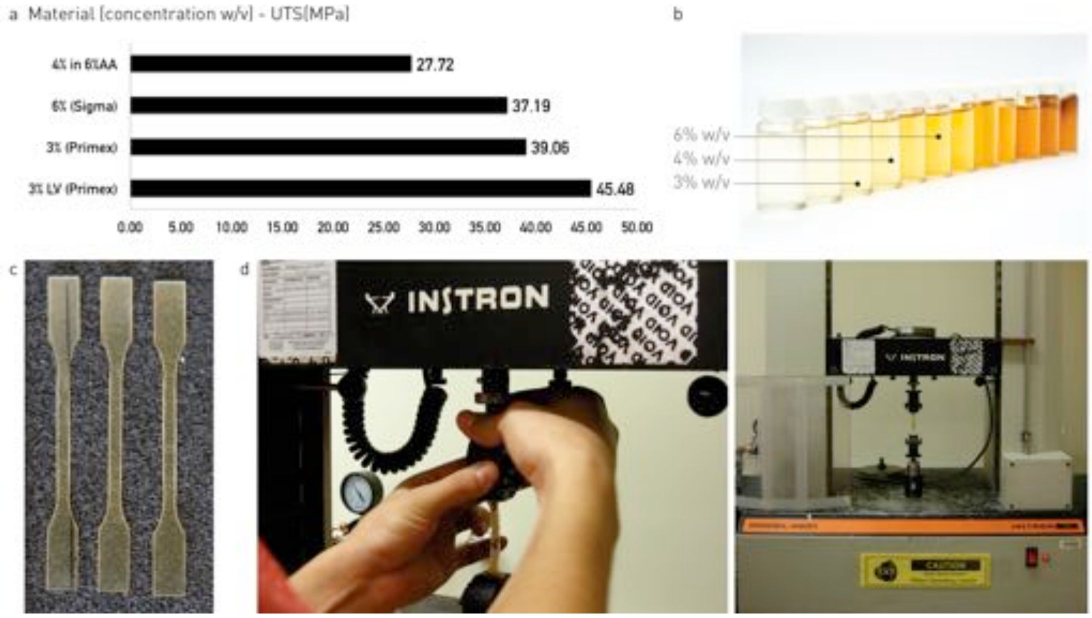

Figure 2: (a) Ultimate Tensile Strength (UTS) testing results of chitosan film dogbones in different concentrations and purchased from different companies (b) Chitosan concentrations in gel state (c) 3D printed and laser cut dogbones before being tested (d) Instron mechanical tester with a 9071.85kg reversible load cell.

Figure 3: Perspective view of the manufacturing platform installed at the MIT Media Lab composed of (1) a positioning robotic arm (Kuka KR AGILUS robotic arm, model KR 10 R1100); (2) a customized multi-barrel extrusion head for water-based materials; (3) a security envelop for operation of the robotic assembly; (4) a 1m-wide and 5m-long deposition bed; (5) a computer-controlled evaporation system composed of 100 fans; and (6) a 9m-long workspace and storage cabinet.

3.3 Bottom-up Bio-inspired Design of Hierarchical Structural Behavior Experiments

Empirical studies involve the design and fabrication of functional patterns inspired by insect wing and leaf venation geometry, mimicking structure-and-skin graded architectures. In particular, dragonfly wings are passive lightweight structures supporting dynamic loading and employing high corrugation to increase stiffness and strength (Jongerius and Lentink [10]) (**Figure 4a**). It is interesting to note that the Young's modulus of dragonfly wings can vary widely within the structure partly due to hydration patterns induced in the presence of chitin and proteins altering local properties (Donoughe et al. [4], Jongerius and Lentink [10]) and providing for both graded flexibility and graded tensile strength along the wing from the joint to the tip (Fernandez and Ingber [7]). As insect wings, leafs are flat structures that maximize surface-to-volume ratios. Their venations are two-dimensional ramifying structures that tightly relate form and function performing both transportation of mass and energy, and distributing force fields across the surface area of the leaf structure (Roth-Nebelsick et al. [21], Sack and Scoffoni [22]). The highest mechanical stresses in leafs occur along their longitudinal axes; and transversal parallel veins contribute to stabilize bending forces (**Figure 4a**). Both longitudinal and transversal structural systems are lignin-based with a high elastic modulus, which, when combined with hydration and turgor pressure within cells, provides support and allows for high flexibility to reconfigure or fold under mechanical loading (Roth-Nebelsick et al. [21], Sack and Scoffoni [22]). Such support and functional variation strategies, as well as the use of primary and secondary structural systems, are applicable to architectural structural cantilevers, shells and spatial structures.

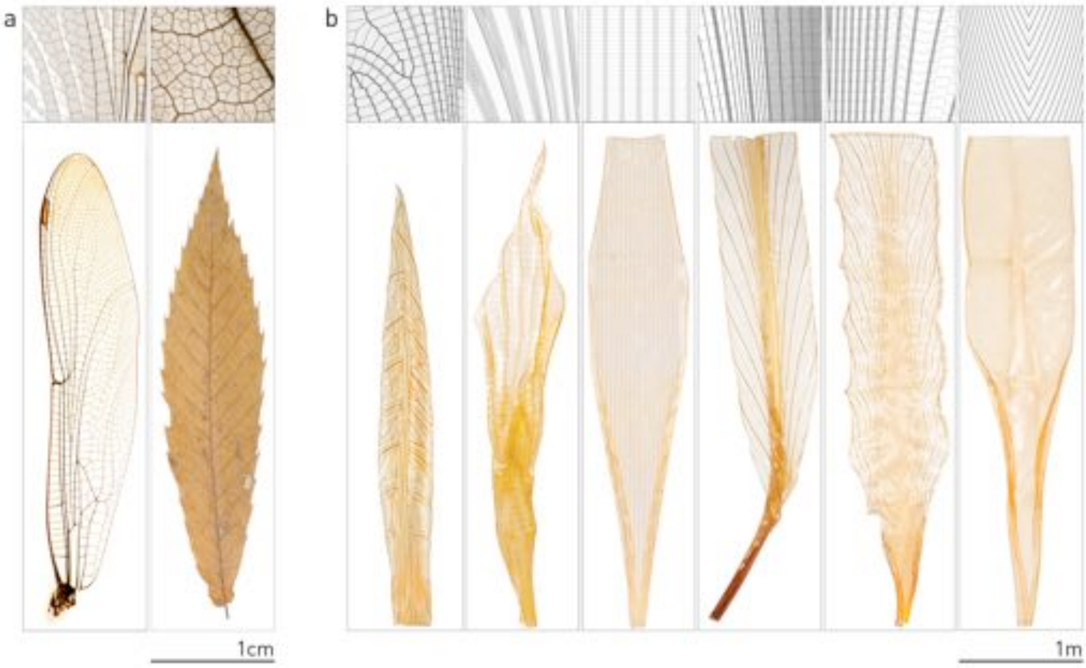

Figure 4: Experiments in hierarchical additive manufacturing strategies. **(a) Top:** close-up image of the structural pattern of a dragonfly wing and of the venation pattern of an Acer leaf (Image credit: CUPAC (Cornell University Plant Anatomy Collection, specimen 366, used with permission). **Bottom**: plan view and detail of a dragonfly wing and a dry leaf. **(b) Top**: detail of geometric trajectories for additive material distribution patterns (the gray shaded background represents film membrane infill). **Bottom**: front view of large-scale structural experiments when dried.

We synthesize structural design patterns combining strategies from both voronoi-based insect wing patterns, and leaf ramifying venations in order to obtain functional and mechanical gradients. Functional gradients, spanning column-like behavior to surface-like behavior, are obtained by negotiating geometrical pattern density and hydration rates (see Section 4.1 and 4.3) (**Figure 4b bottom**). Mechanical gradients are obtained by modulating stiffness, pressure, and layering strategies (see Section 4.1). Finally, we also obtain optical gradients that are directly proportional to structural gradients and are a result of grading material concentration from 3% w/v -translucent- to 12% w/v – opaque - in deposited gels (see Section 2.1 for further detail). The constructs are 1m to 70cm wide and range from 2.5 to 3m tall when dry (**Figure 4b bottom**). In our implementation, as in insect wings and many leaf types (Roth-Nebelsick et al. [21], Sack and Scoffoni [22]), the size of the local diameter of load bearing members with respect to the global size of the structure is key to guaranty self-support and bending stability for cantilevered performance of the constructs.

4. DISCUSSION: Integrated Templating of Structural Design, Robotic Manufacturing, and Environmental Performance

We define design templates as frameworks for data translation that inform and encode material and immaterial performance criteria. For example, an anticipated load map can be used as a template for structural component thickness; whereas a thermal map can be used to template surface thickness and porosity for ventilation purposes. Such templates accommodate property variation in the course of the design process, while ensuring the implementation of the main algorithm. We tailor and integrate structural, manufacturing and environmental design templates relating to multi-scale feature resolution and global structure formation and performance. In order to do so, we implement a seamless computational process encoding virtual design and physical digital fabrication that relates to our ongoing research on multi-dimensional, media and trans-disciplinary data informed design workflows. We have coined this approach Fabrication Information Modeling (FIM). We demonstrate fully biodegradable architectural-scale structures that are additively manufactured, self-supportive, lightweight, and materially heterogeneous. Variable flow rates, differentially distributed material properties, and environmental control inform self-folding by shrinkage of the constructs as water evaporates from the water-based deposited gels (Duro et al. [5], [6], Mogas et al. [14]). Results display a range of structural behavior (**Figure 4b**) and represent a response to some of the planet's distresses related to the construction industry's unsustainable practices.

4.1 Structural Design Templating

In the Ocean Pavilion (work-in progress), we design structural template maps based on hierarchical flow of loads encoded into principal and secondary structure streamlines. The principal structure is longitudinal to the global shape of the construct and provides for stiffness employing thicker diameter members and higher material concentrations as can be observed in leaf venation and insect wing structures. The secondary structure can be semi-parallel or semi-perpendicular to the principal structure and is composed of hierarchical networks of thinner member diameters and lower concentration materials. Parallel secondary structures allow for column-forming structures, and perpendicular secondary structures allow for wall-forming structures. **Figure 5a** shows principal and secondary streamlined structural pattern generation by interpolating 2D vector fields from 3D scalar fields. We model desired 3D surfaces and map their gradient of slope into 2D vector fields that represent local structural behavior. The vector fields are then computed into continuous principal and secondary directions of flow (**Figure 5a**).

4.2 Robotic Manufacturing Templating

Once the streamlines for principal and secondary directions are determined, hierarchical material distribution is implemented. There are three ways to determine differentiated material distribution to achieve selective structural capacity; pressure variation can be implemented along selected lines resulting in continuously varying material accumulation (**Figure 5b**); material concentration can be assigned to each trajectory resulting in stiffness gradients from lower to higher concentrations; and, finally, layering onto dry deposited material provides higher degree of reinforcement (Duro et al. [5], Mogas et al. [14]). Such strategies are encoded into position, speed, pressure, and material instructions that are sent in real-time to both positioning and deposition platforms (for further detail on manufacturing instruction generation see Duro et al. [5], [6]).

4.3 Environmental Performance Templating

Hydrogel materials are deposited in geometrical and pressure patterns onto a flat substrate following instruction parameters. As water evaporates, shrinking forces accumulate across the networked gel and induce self-folding once the construct is removed from the substrate. In order to distribute hydration across large-scale depositions, a computerized evaporation control system can be easily implemented composed of 100 variable speed fans with differential control according to desired degrees of final hydration compared against thermal imaging of the deposition (**Figure 5c**) (see Mogas et al. [16] and Duro et al. [5] for additional detail). Hydration control allows for increased final folding in hydrated areas providing for structural interface joints as shown at the foot of the dry structure in **Figure 5c**. If uncoated, the structures will fully biodegrade providing nutrients as they decay in contact with the environment. Such materials can be fully recovered and reused if dissolved in water (Mogas et al. [14]).

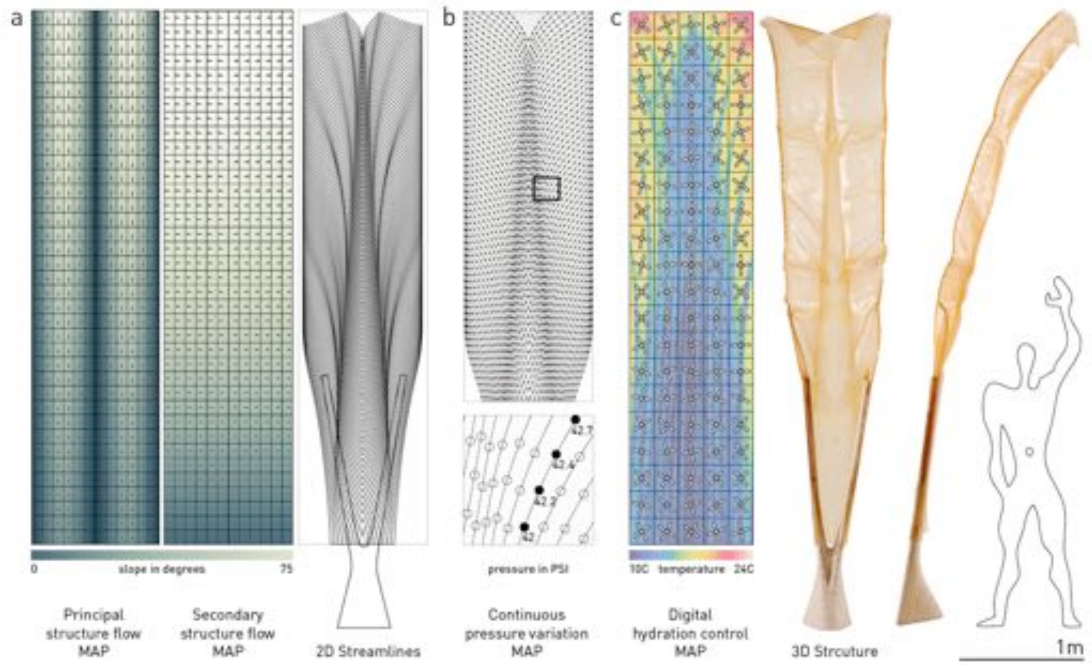

Figure 5: (a) Vector fields encode variation in principal and secondary structure, and are interpolated into streamlines of material deposition trajectories. **(b)** Pressure, speed and material concentration variation along structural streamlines is encoded into real-time instructions sent to the manufacturing platforms. **(c)** Computerized hydration control maps on top of deposited structures provide global evaporation-driven self-folding of the final functional 3D structure.

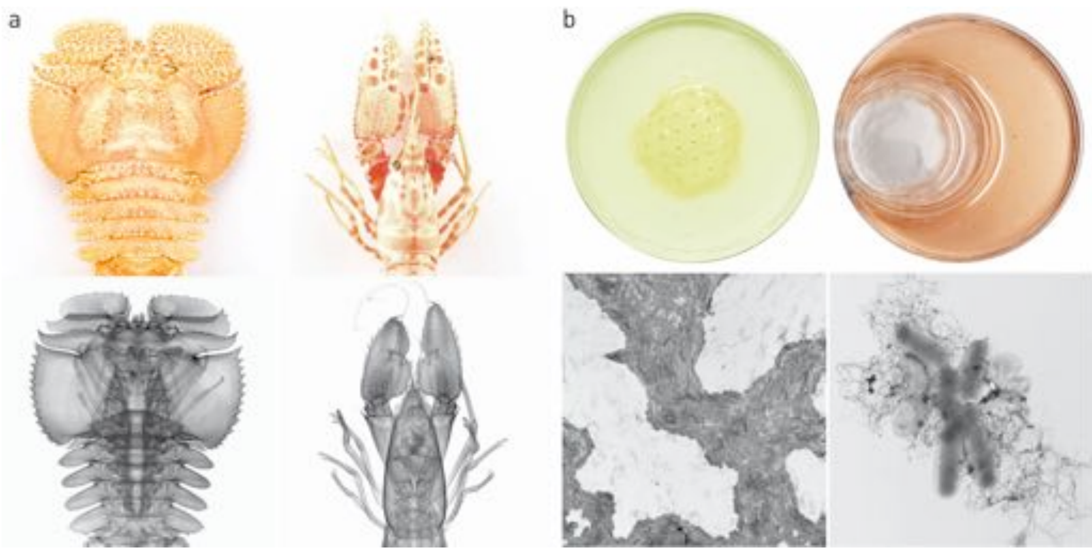

Figure 6: (a) Top: Chitin is naturally produced within crustacean shells in combination with minerals and proteins. **Bottom:** X-ray transmission image of *Ibacus sp and Enoplometopus sp*. Image credit: Dr. James Weaver, Harvard Wyss Institute. **(b) Top:** Photosynthetic cyanobacteria growing within two layers of chitosan. Colorimetric assay quantifying sucrose production in bacterial co-culture (12-24-72h). Image credit: S. Hays, T. Ferrandt and Prof P. Silver, Harvard Medical. **Bottom:** Synthetically engineered *Escherichia coli* colony (1 um length) strain forming biofilm. Synthetically engineered Escherichia coli (1 um length) with protein fibrils attaching gold nanoparticles. TEM images. Image credit: Eléonore Tham, Lu Lab, MIT.

5. CONCLUSIONS: Applications, Future Work, and Contributions

5.1 Applications: Lightweight, Biodegradable and Heterogeneous Structures

We present here variable property biomaterial-based components (**Figure 1)** 3D printed at room temperature, using relatively little energy and mild chemicals. Applications of the design and manufacturing method range in scale and function form lightweight robotics such as flapping micro vehicles, cell growth promoting environments such as biocompatible wearable devices in contact with regenerating tissue, biofuel-producing bacterial culture supports, fully compostable consumables, ecosystem-enhancing constructs that replenish soils with nutrients as they decay, and temporary biodegradable architectural structures or building skins.

5.2 Future Work: Biological Templating

Chitosan is a naturally produced (Figure 6a) biocompatible material that is used in the medical industry as cell scaffold for tissue growth (Li et al. [11], Gutowska et al. [9], Melchels et al. [9]). Consequently, in future iterations of the manufacturing platform presented herein, biological microorganisms can be printed using the pneumatic extruder with fine pressure *tunability*. Bacterial biofuel production pockets will be designed and deposited along with water-storing gels and embedded nutrient and collection devices. Figure 6 illustrates preliminary results of bacterial culture growth on top of deposited chitosan samples (Figure 6b). Biological-driven design will involve further integration of environmental parameters and biological phenomena such as solar and airflow exposure patterns, temperature gradients, photosynthetic rates, nutrient availability, etc. As in leaf venation patterns, multifunctional aspects of hydraulic transport and mechanical protection (Sack and Scoffoni [22]) can be integrated into hierarchical structures generating a true material-based ecosystem.

5.3 Contributions: A novel approach to Material-driven Structural Formation

By deriving fabrication technologies, structural design, and environmental capacities from material-driven research, we unveil novel cross-disciplinary multi-functional properties such as; optical gradation proportional to load-baring capacity; merging of structure and skin functions within the same material system; energy and resources savings due to material environmental responsiveness; emergence of functionally-graded shape induced by time, air and water; or the possibility to flow biofuel-producing organisms within structural nerves. The Ocean Pavilion's lightweight robotically fabricated biomaterial structures represent an ecological and economical approach to materially heterogeneous formation by design, and an innovative exploration into future biocompatible living spaces that can have a high impact in alleviating our planet's resource and health issues.

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